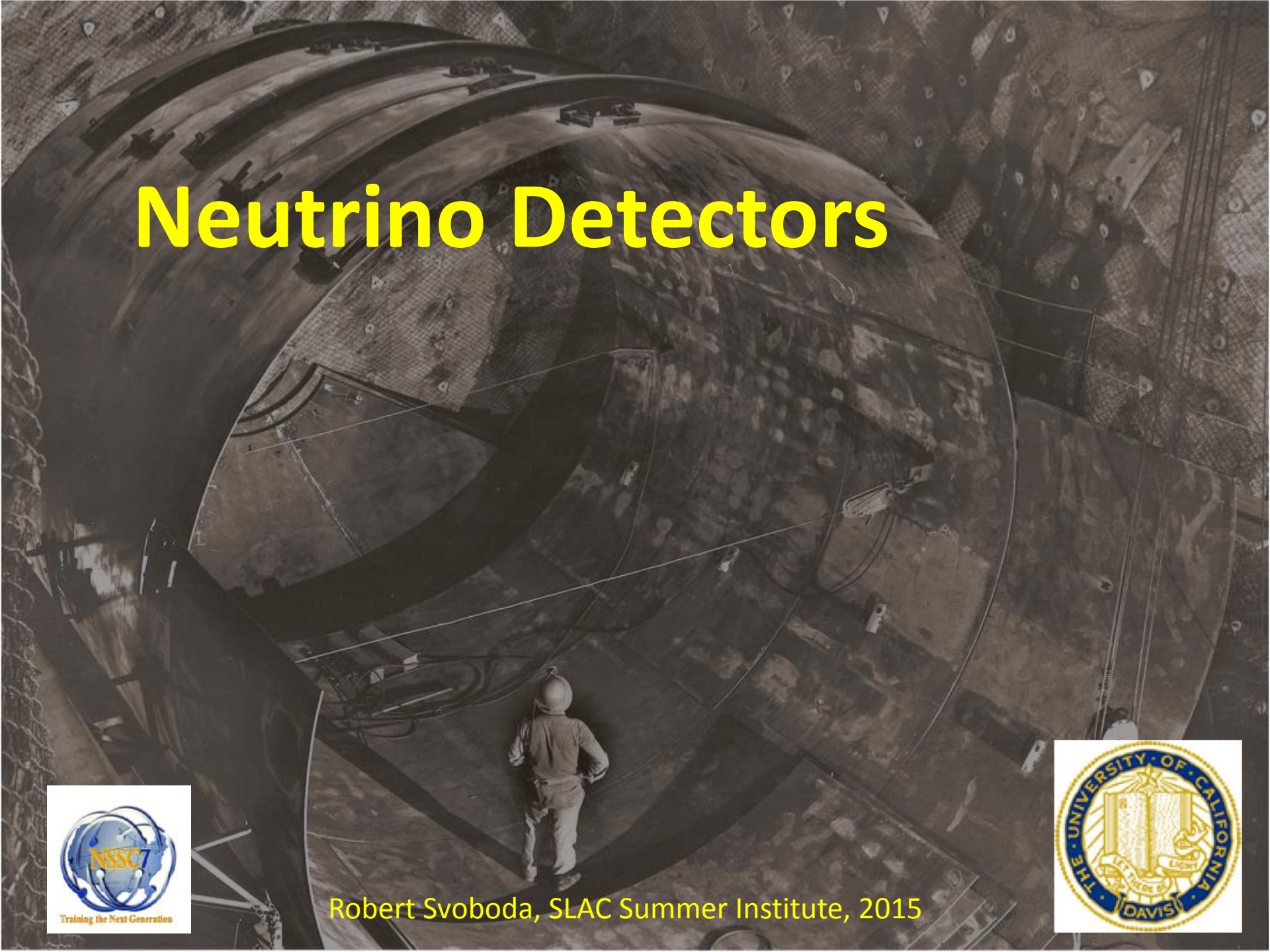
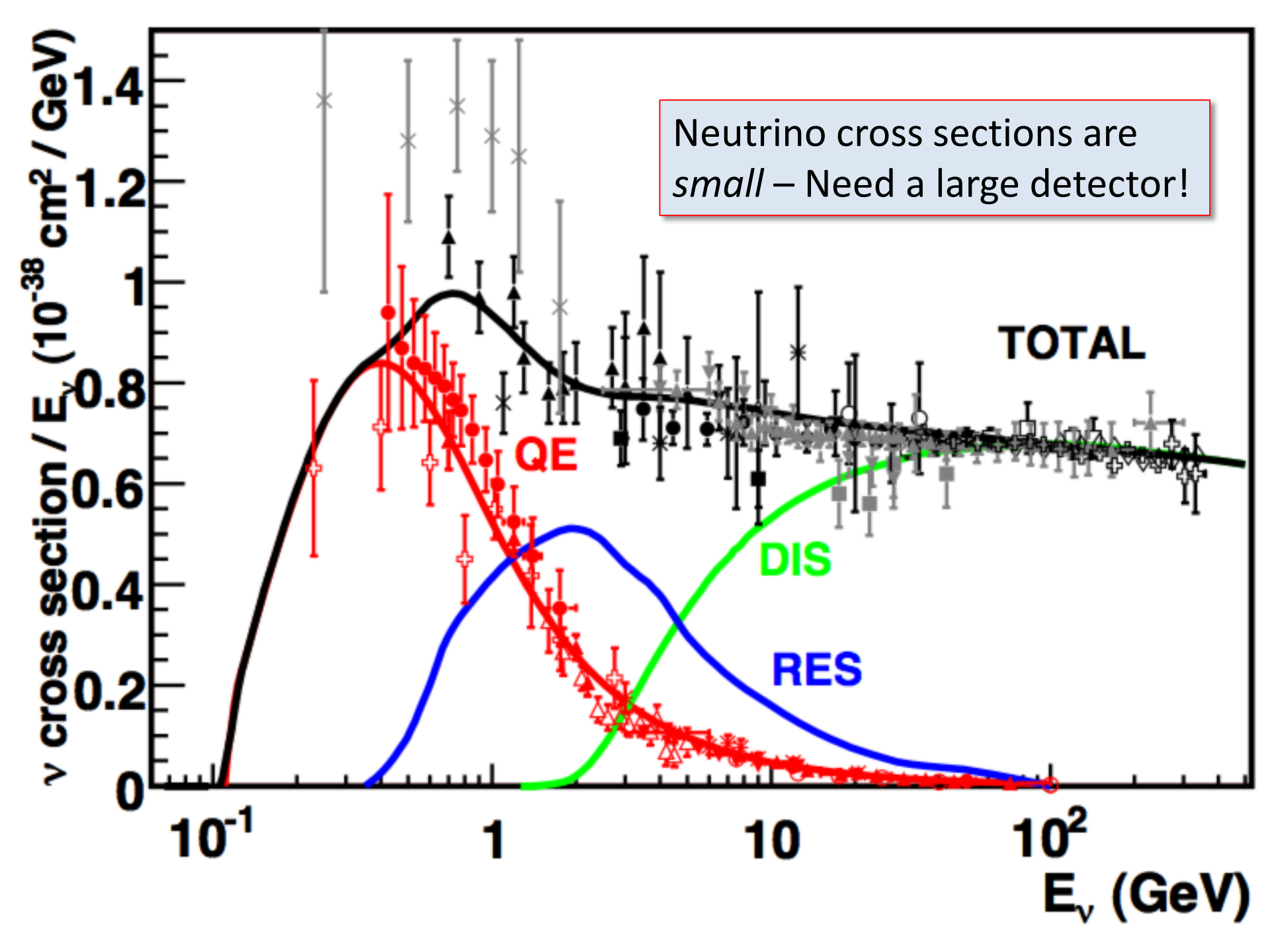
Neutrino Detectors



Robert Svoboda, SLAC Summer Institute, 2015

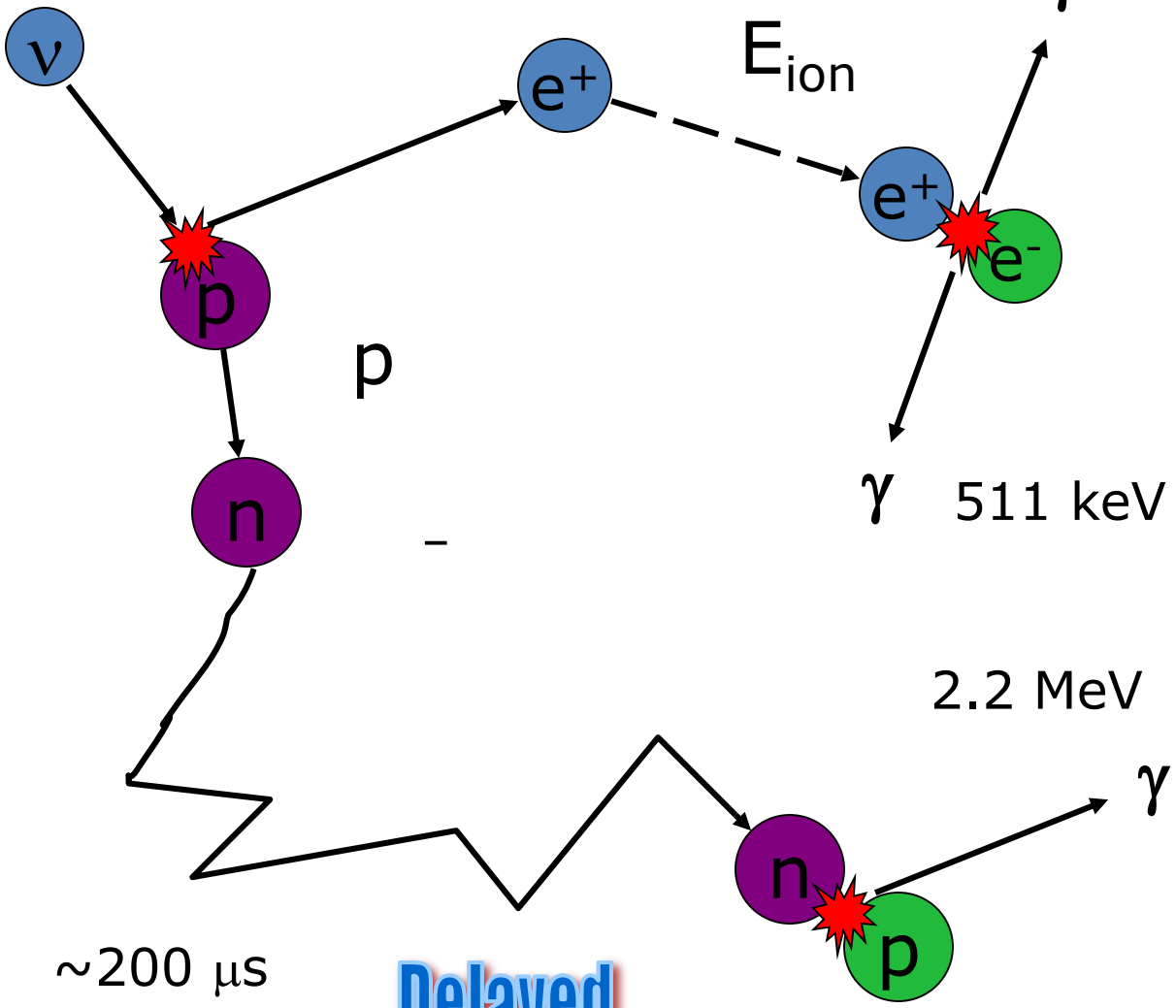

The age old question…
Y'all find any *new physics stuff yet?*
more signal!
Not yet
less background!
…more signal or less background?


Neutrino cross sections are *small* – Need a large detector!
TOTAL
QE
DIS
RES
ν cross section / E_ν (10^-38 cm^2 / GeV)
E_ν (GeV)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
10^-1
1
10
10^2

Intense source – detectors can be ton scale

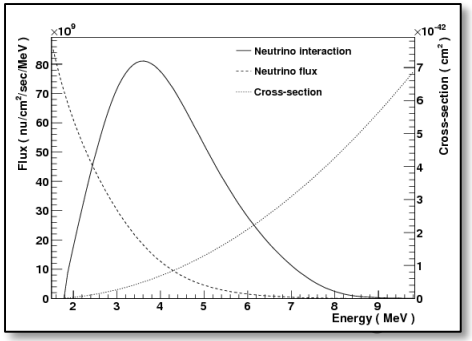
Weak source – detectors must be 10^3-10^5 ton scale

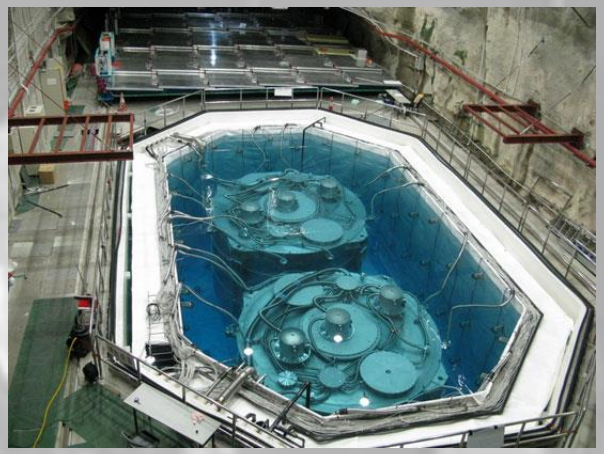
Well-known Inverse Beta Decay reaction – fast timing, free protons



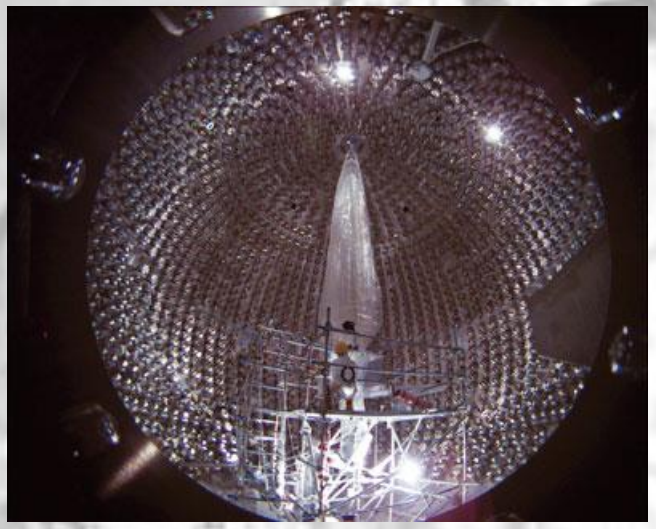
Prompt

Delayed



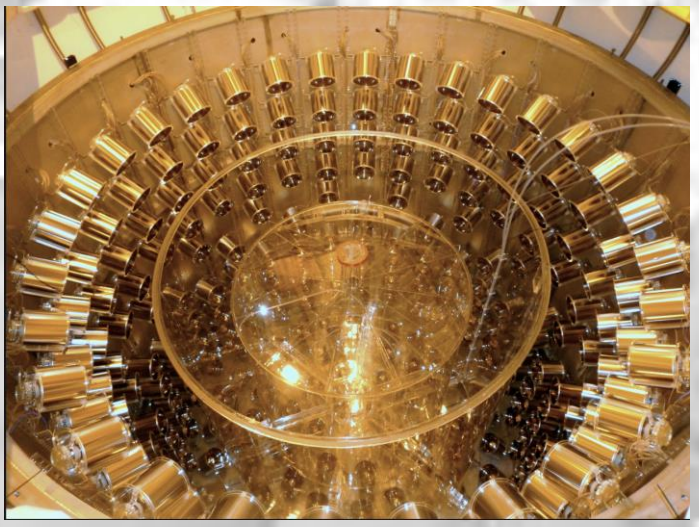


Daya Bay

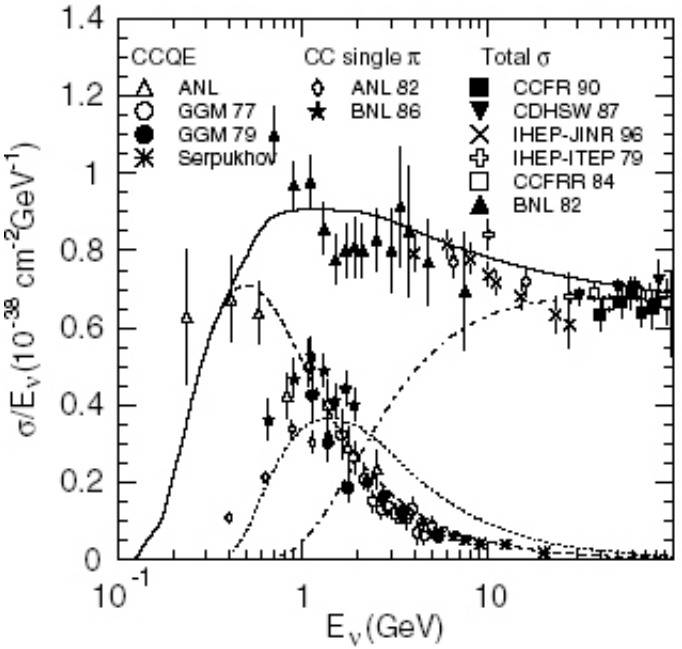


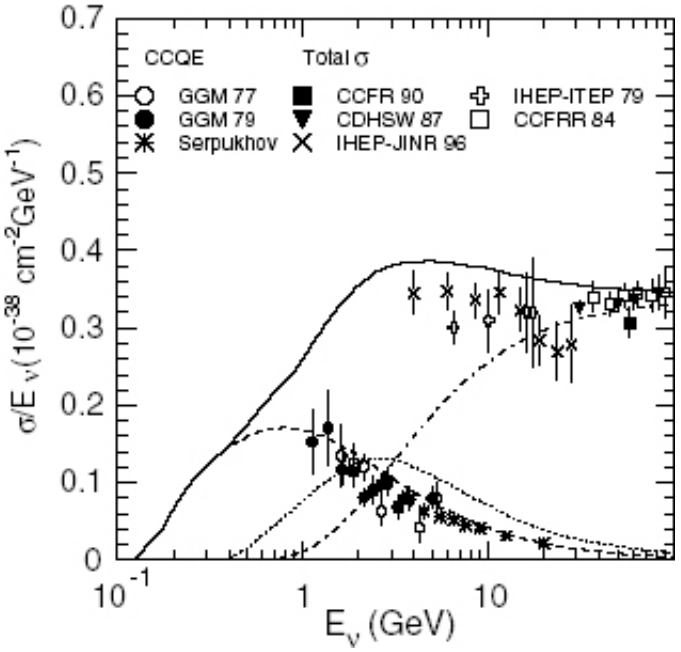
KamLAND

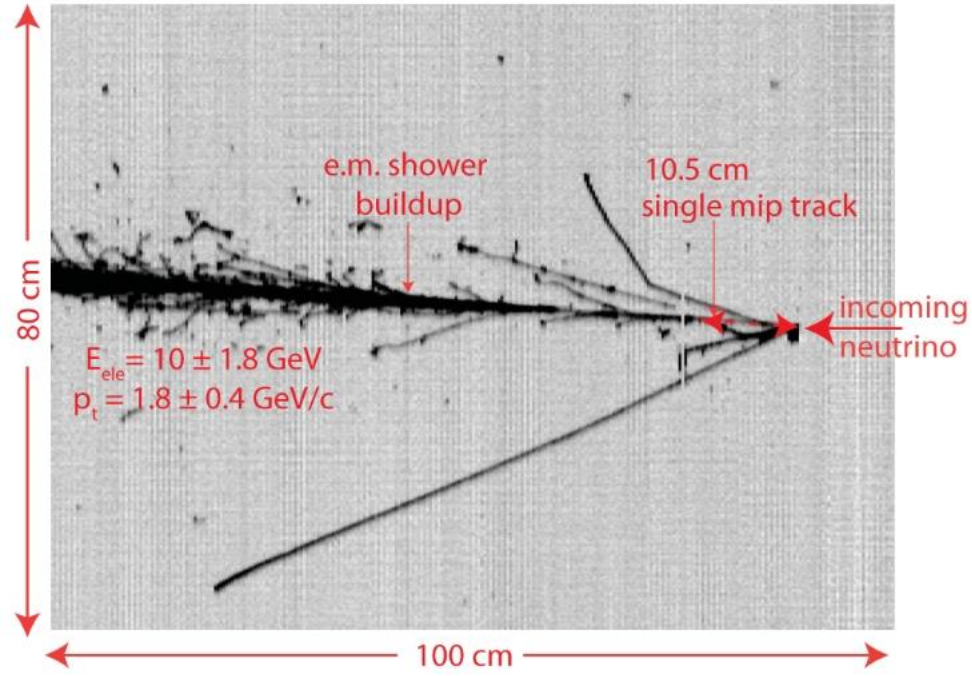
SNO+

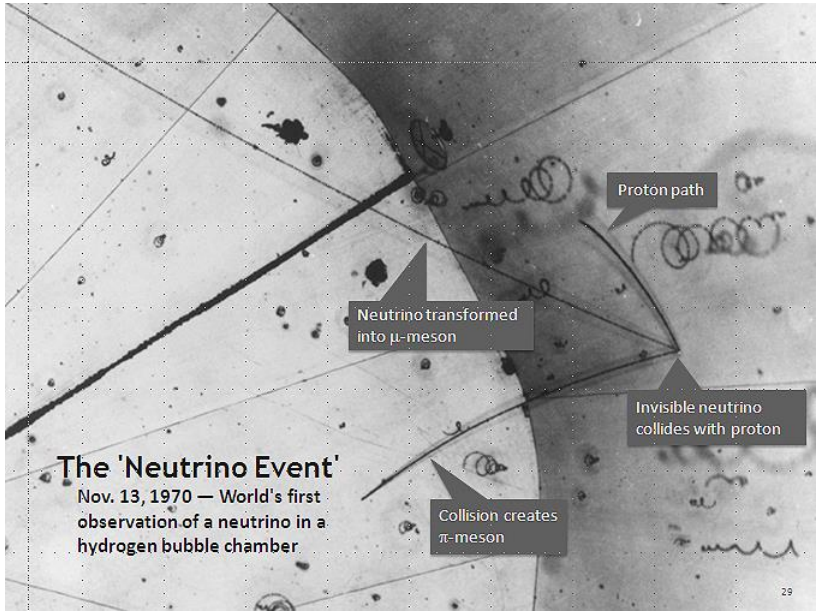


Double Chooz


CCQE
CC single π
Total σ
ANL
GGM 77
GGM 79
Serpukhov
ANL 82
BNL 86
CCFR 90
CDHSW 87
IHEP-JINR 96
IHEP-ITEP 79
CCFRR 84
BNL 82
σ/E_ν (10^-38 cm^-2 GeV^-1)
E_ν (GeV)

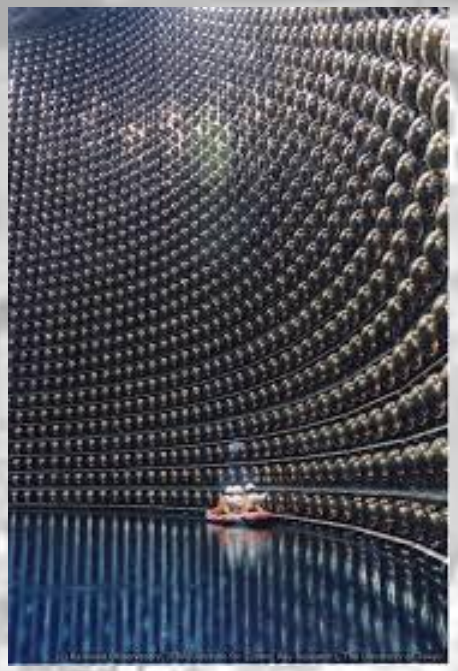

CCQE
Total σ
GGM 77
GGM 79
Serpukhov
CCFR 90
CDHSW 87
IHEP-JINR 96
IHEP-ITEP 79
CCFRR 84
σ/E_ν (10^-38 cm^-2 GeV^-1)
E_ν (GeV)


e.m. shower buildup
10.5 cm single mip track
incoming neutrino
E_ele = 10 ± 1.8 GeV
p_t = 1.8 ± 0.4 GeV/c
80 cm
100 cm


Proton path
Neutrino transformed into μ-meson
Invisible neutrino collides with proton
Collision creates π-meson
The 'Neutrino Event'
Nov. 13, 1970 — World's first observation of a neutrino in a hydrogen bubble chamber
29

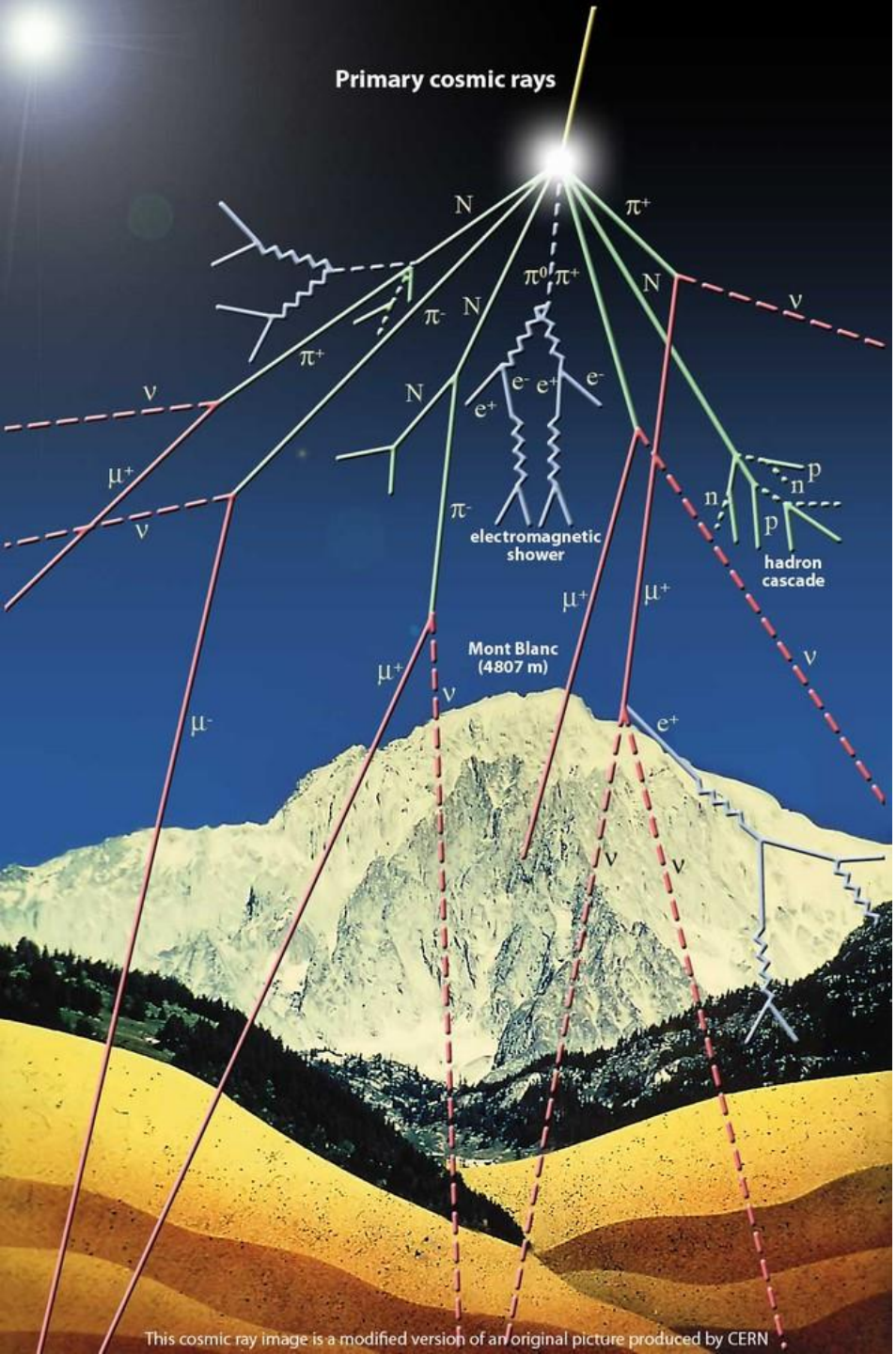
MINOS

Super-K



ICARUS

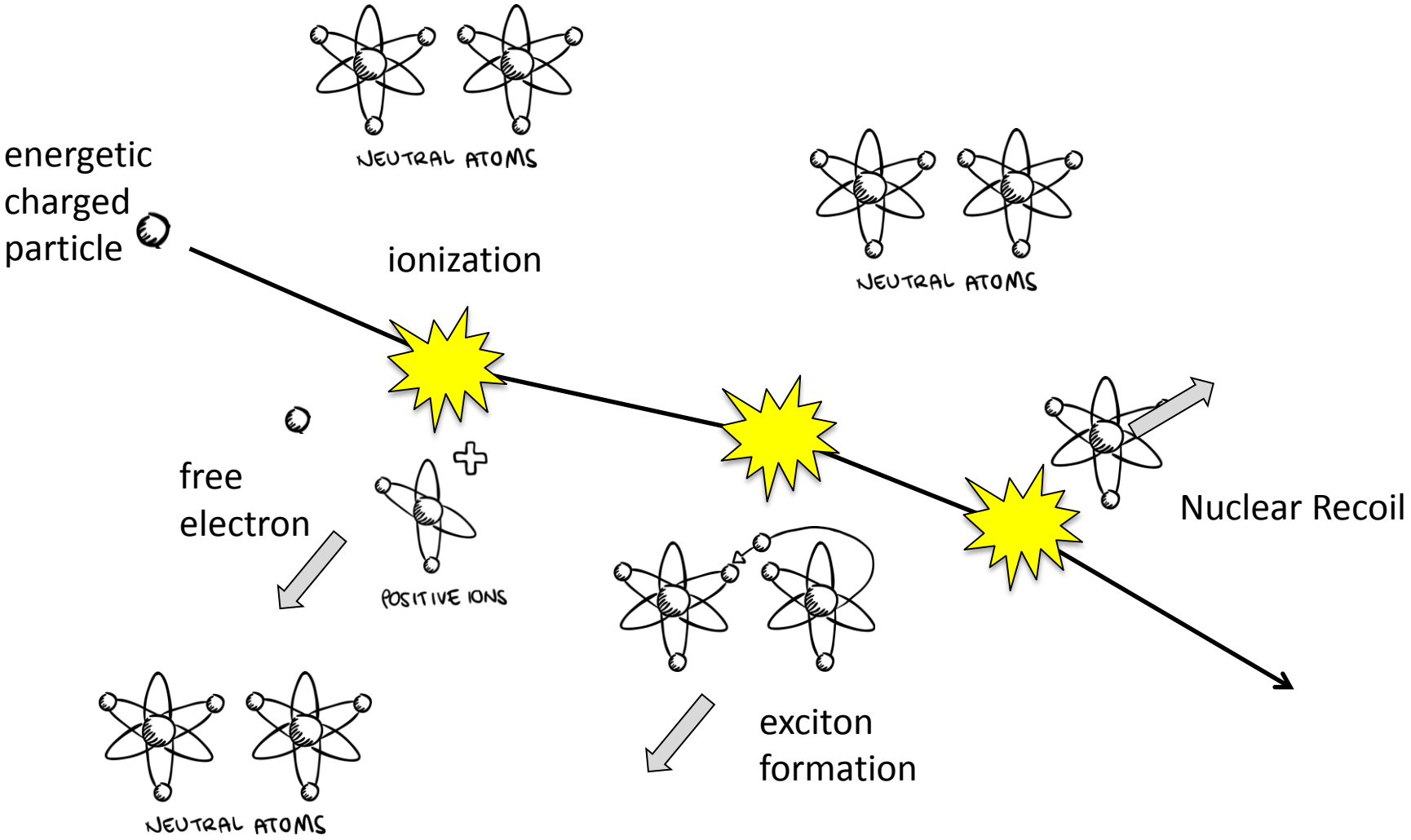
Nova



- muons penetrate deep underground – to km of depth
- muon rate, fast neutrons can be a problem
- spallation products can live for seconds (e.g. ^{16}N) to days (e.g. ^{46}Sc)
- Most large detectors need to be located *underground*


How to detect neutrinos?
Y'all find any *new physics stuff yet?*
collect Charge!
Not yet
collect Photons!
...collect charge or photons?

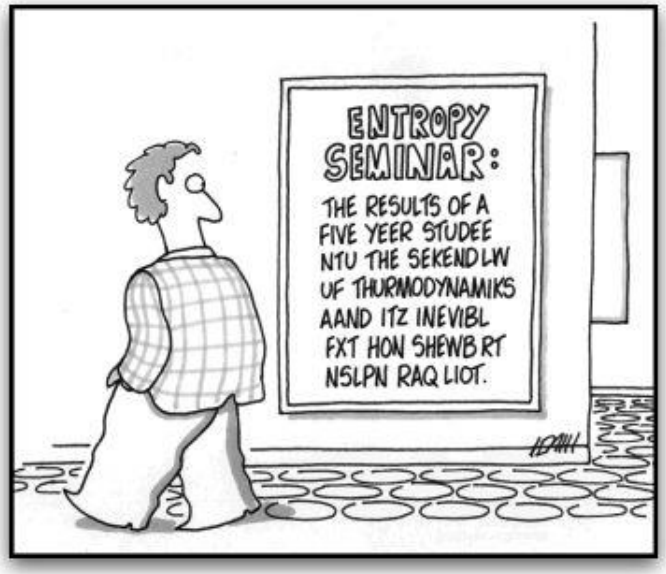
Energy Loss in Matter



Energy Balance

$$E_{Total} = E_{ion} + E_{exciton} + E_{heat}$$

All the energy eventually ends up as heat...



Neutrino Detectors

Detect Photons

- Water Cherenkov
- Organic Liquid Scintillator
- Plastic Scintillator
- Photon Detection

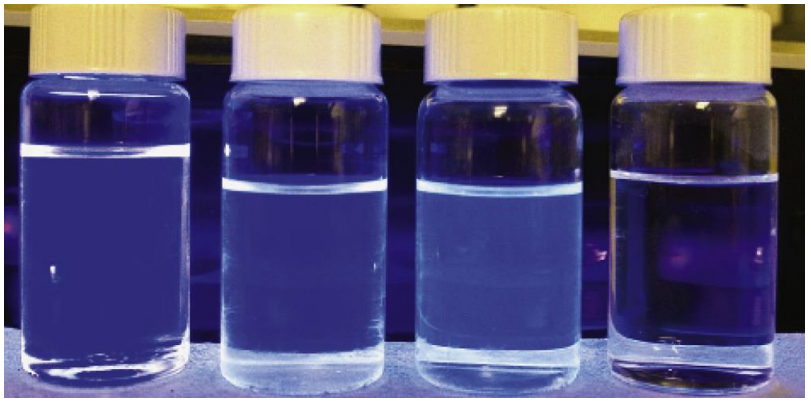
Detect Charge

- Time Projection Chamber (TPC)
- Charge Detection

The technique needs to match what you are trying to measure...

Liquid Scintillator

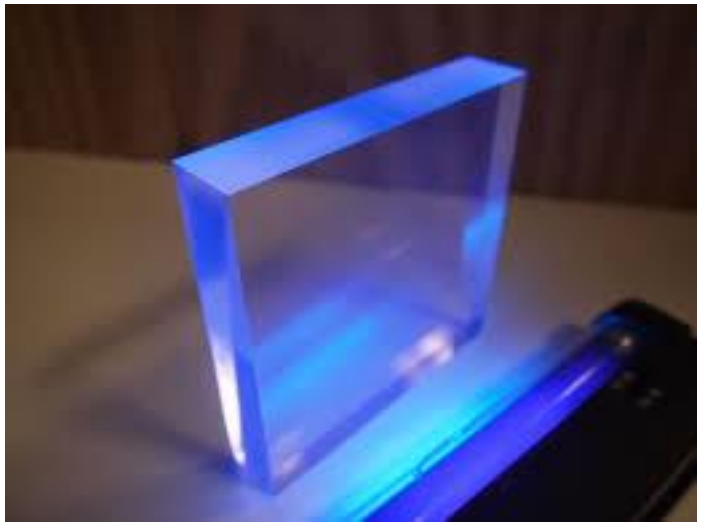
- In use since 1950's
- Organic liquid with waveshifting fluor converts ionization to photons in 400-700 nm range
- Detectors with 0.2 MeV threshold up to ~1 kton have been built
- Fast, free protons, can be loaded with neutron capture agents like gadolinium



Disadvantage: Moderately expensive, combustible, semi-toxic, hazardous waste, light is isotropic – track reconstruction difficult

Plastic Scintillator

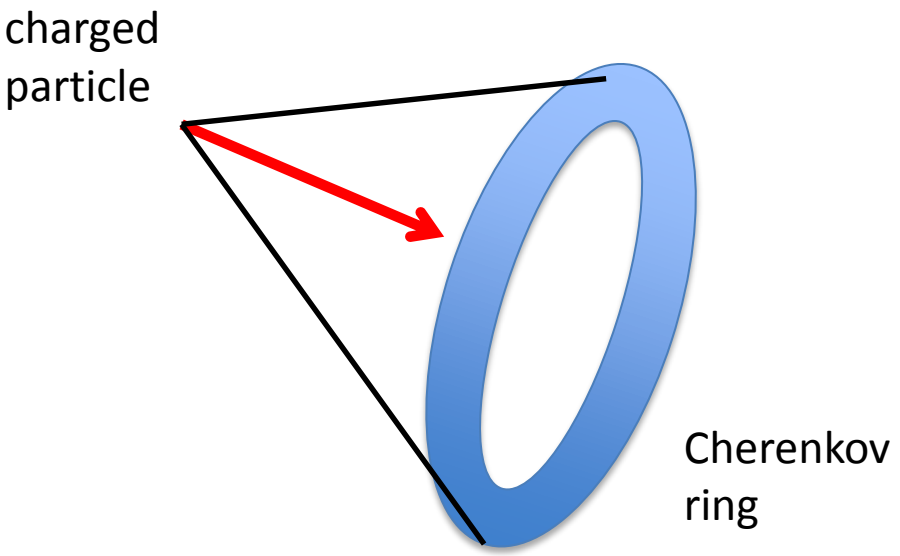
- In use since 1960's
- Can be shaped to fit into large detectors like MINOS or in specialized configurations like MINERVA
- Easier to handle than liquid scintillator
- Still fast with free protons



Disadvantage: Expensive, loading with neutron capture agents difficult, needs segmented readout

Water Cherenkov

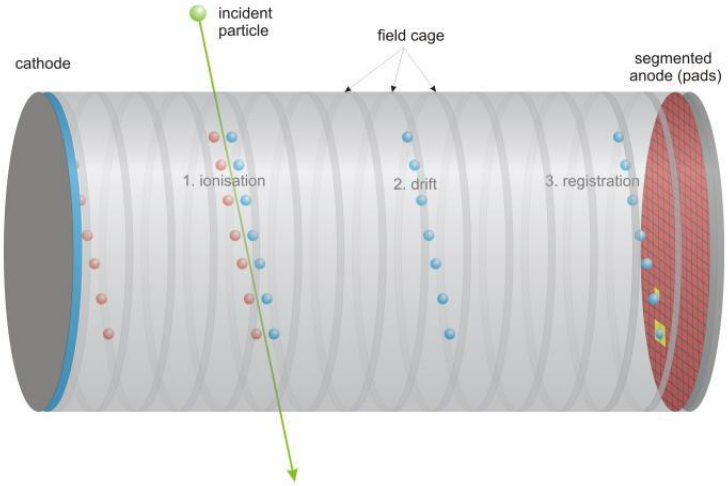
- Large detectors since 1980's. Particles moving faster than c/n give off UV light in a cone shape
- Can reconstruct tracks of particles and determine type from multiple scattering
- Water detectors up to 22 ktons have been built. Megatons in ice!
- Very inexpensive. Can load with neutron capture agent.



Disadvantage: low light yield (2-3% of scntillator), threshold >3 MeV, particles with velocity v<c/n not visible

Liquid Argon TPC

- In development since 1980's. Can drift electrons over meters in liquid noble gases like argon
- Can image tracks of particles with excellent precision. Not subject to Cherenkov threshold
- Scintillate in far UV
- Argon can be obtained in kiloton quantities
- Detectors up to 300 tons have been built



Disadvantage: low light yield (2-3% of scntillator), threshold >3 MeV, particles with velocity v<c/n not visible

How Particles Produce Light

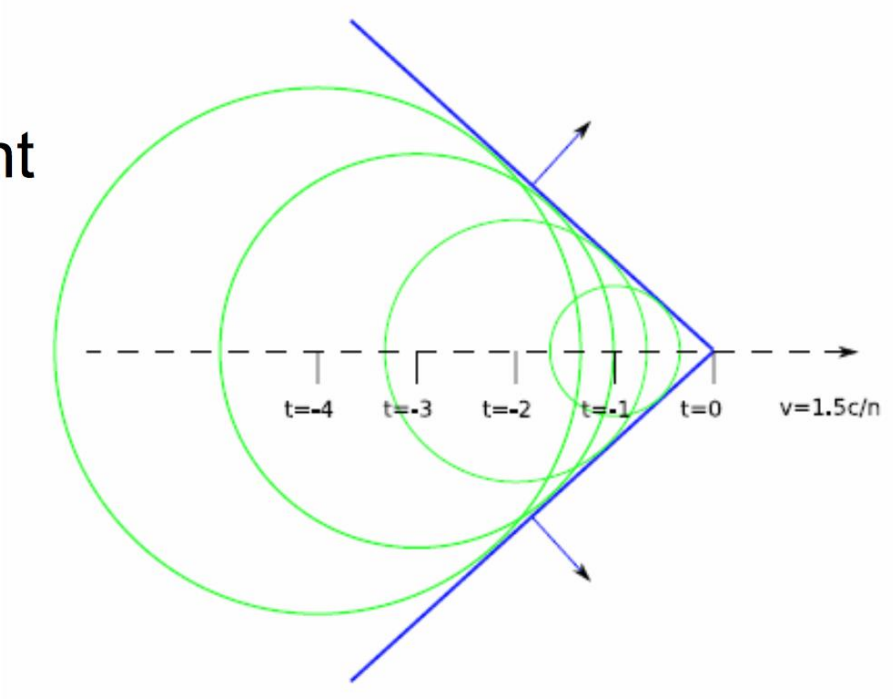
- charged particles can produce light in materials
  - Čerenkov radiation
  - scintillation in some materials due to excitation and ionization
  - transition radiation

- neutral particles (e.g. γ and n) must interact first and the resulting electrons, protons, recoiling nuclei or other charged hadrons produce light

Čerenkov Light

- emitted by charged particles whose velocity exceeds c/n
- results in a coherent shock wavefront that's a cone of light
- half angle given by:
  - $\cos\theta = 1 / [\ \beta\, n(\lambda)\ ]$
  - $\beta = v/c$
  - e.g. 41° in water for $\beta \approx 1$
- spectrum of photons emitted:

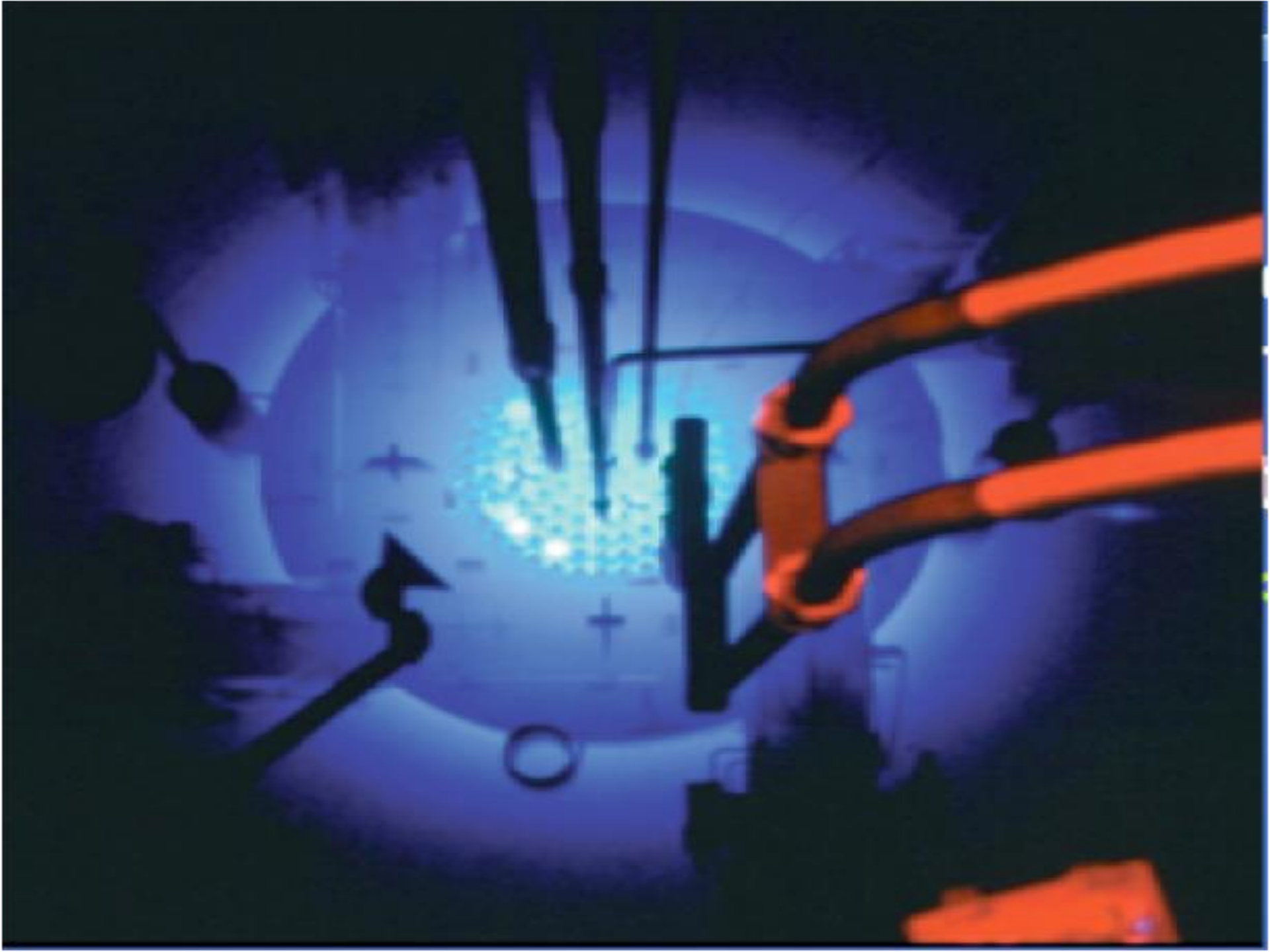
$$\frac{dN}{dx\,d\omega} = \frac{\alpha}{c}\left(1 - \frac{1}{n^2(\omega)\beta^2}\right)$$



from http://wwwmagic.mppmu.mpg.de/publications/theses/JLopez.pdf

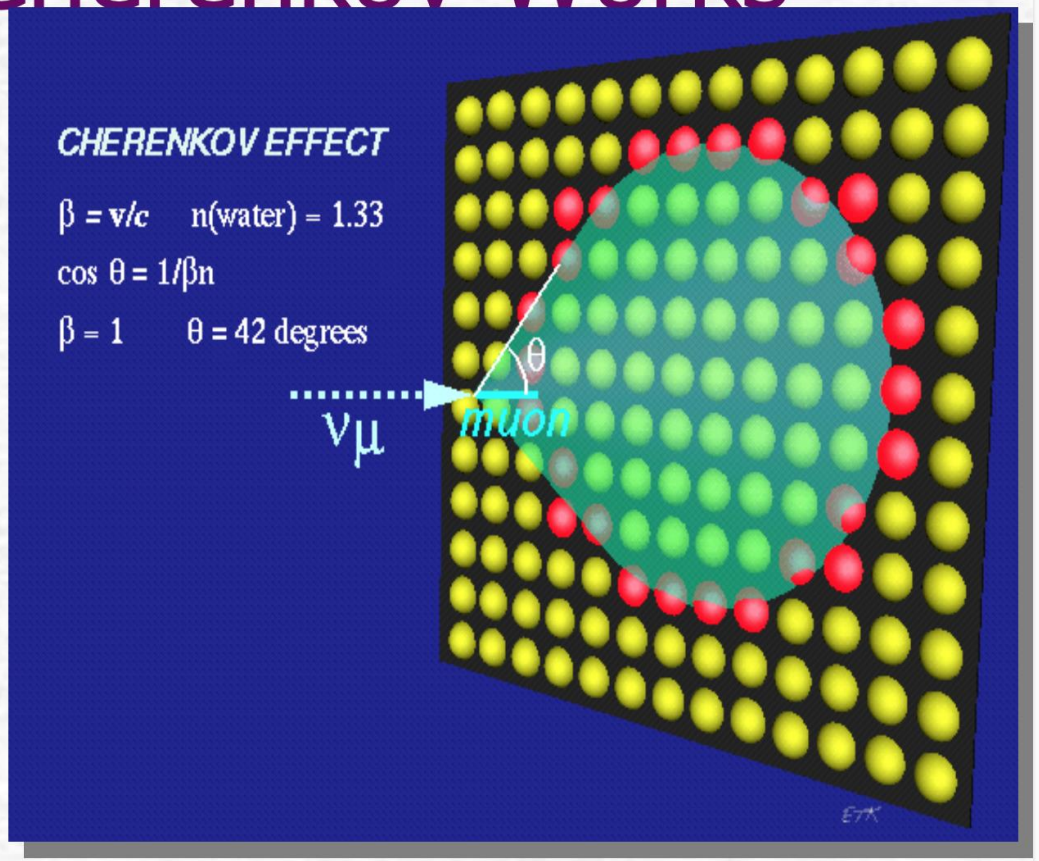
Characteristics of Čerenkov Light

- it's prompt
- basically flat frequency spectrum of the emitted light
  - that's what distinguished it from fluorescence which exhibits bands in the emitted spectrum
- which means it goes as $\frac{dN}{d\lambda} \propto \frac{1}{\lambda^2}$
- hence it's UV and blue light
  - cannot be harder UV because most materials start to absorb at shorter wavelengths and ε must be real



How Water Cherenkov Works

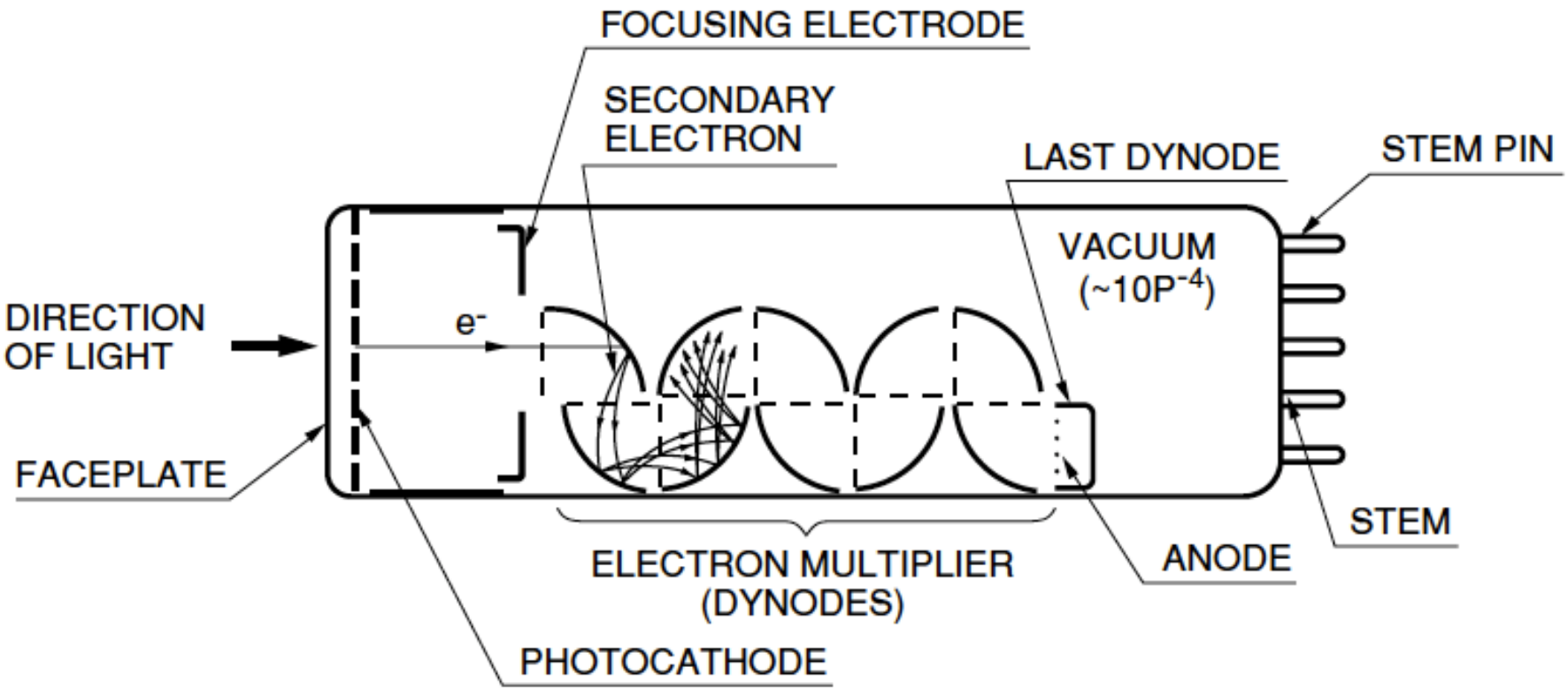
- Cheap target material
- Surface instrumentation
- Vertex from PMT timing
- Direction from ring edge
- Energy from pulse height, range and opening angle
- Particle ID from hit pattern and delayed muon decay signature
- Cherenkov threshold:
  - $\beta > 1/n \sim 0.75$



D.Casper

Water Cherenkov detectors require large, fast photon detectors in the UV/Visible spectral range. Particle reconstruction and ID possible with "CCD-like" ring image

Photomultiplier Tubes (PMT)



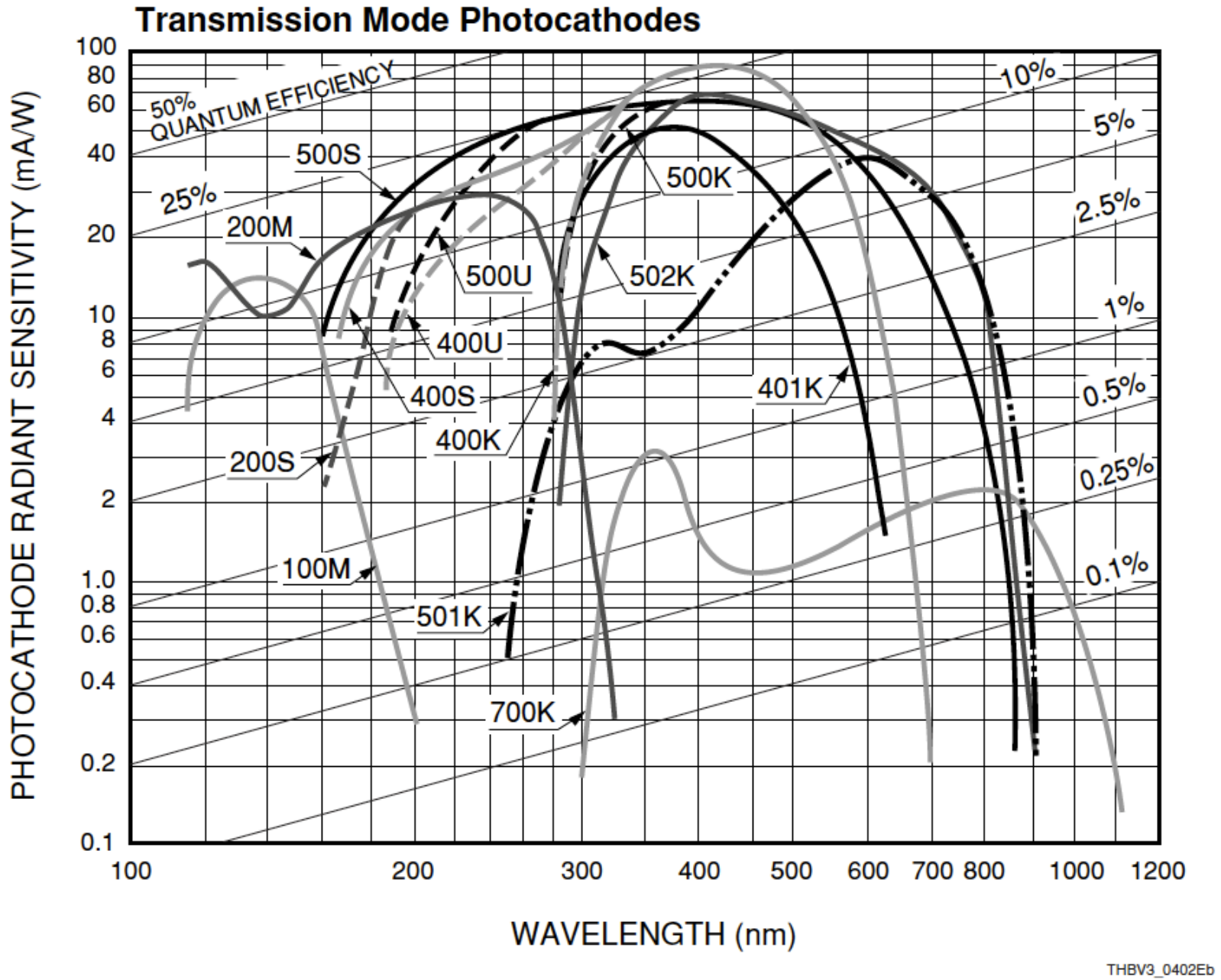
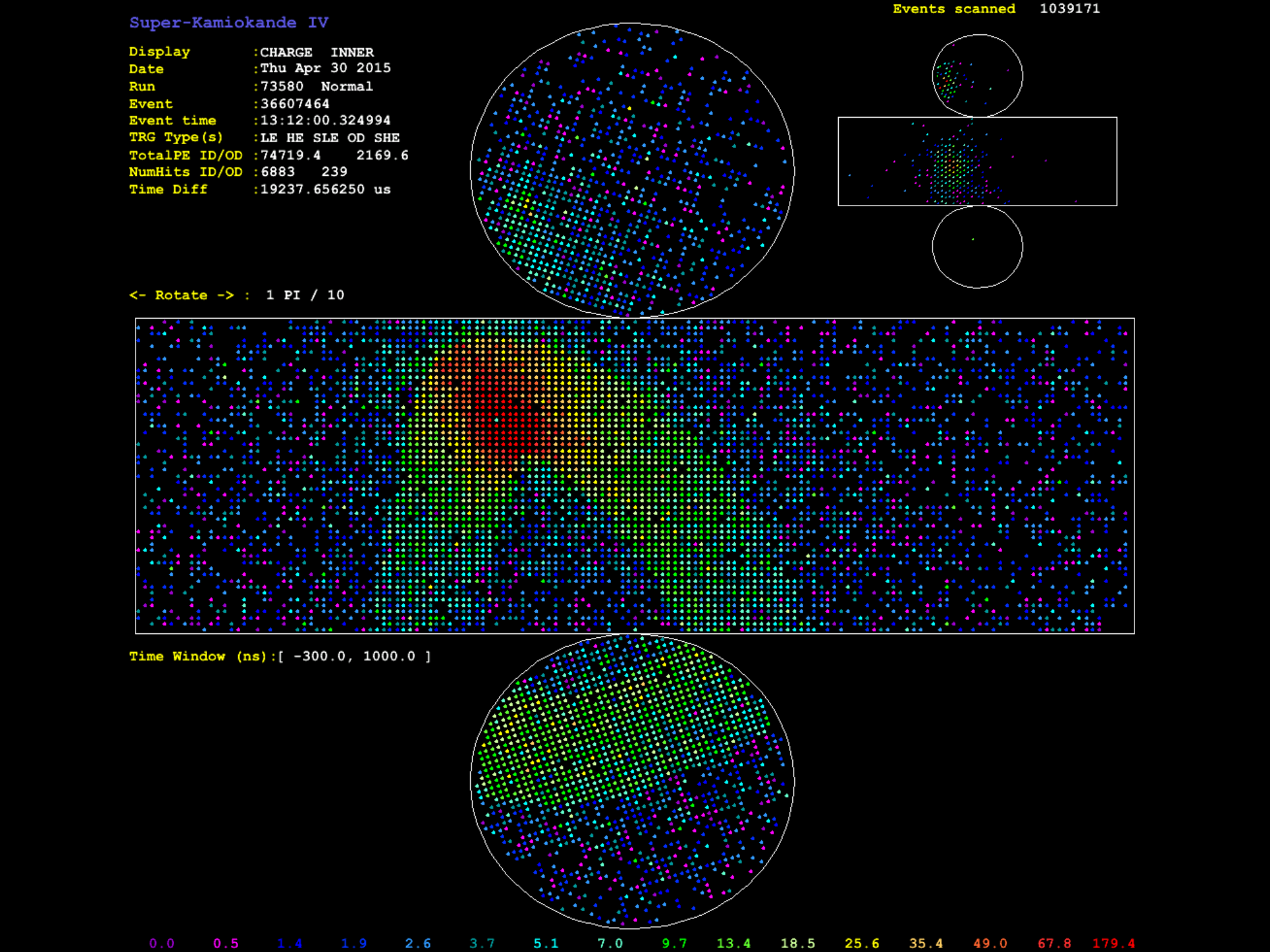
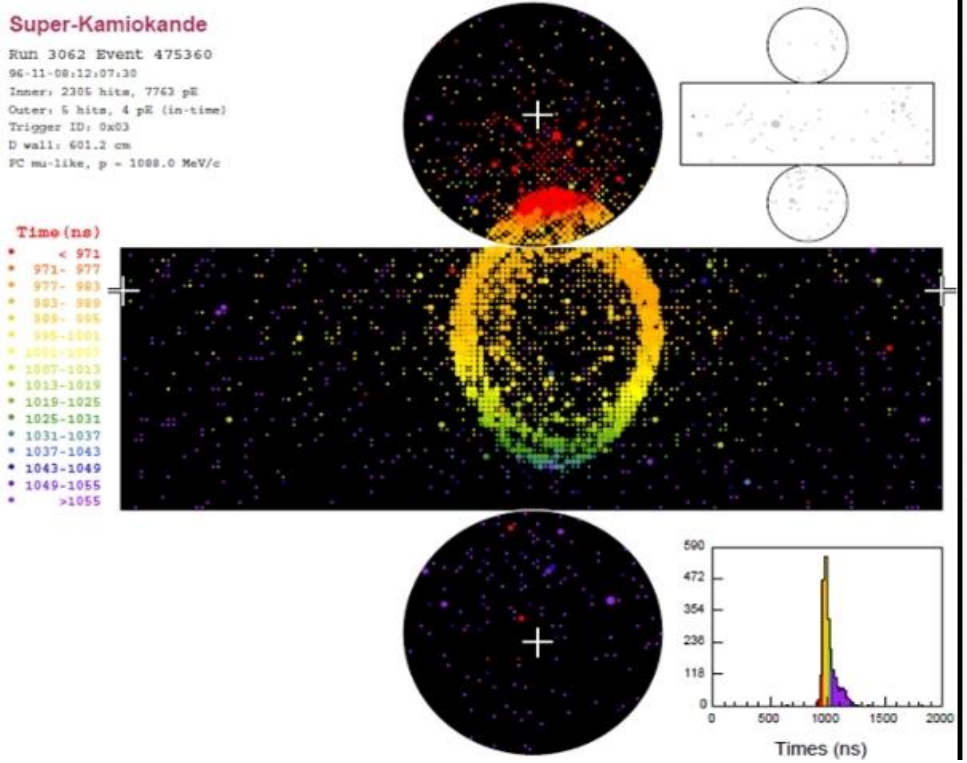
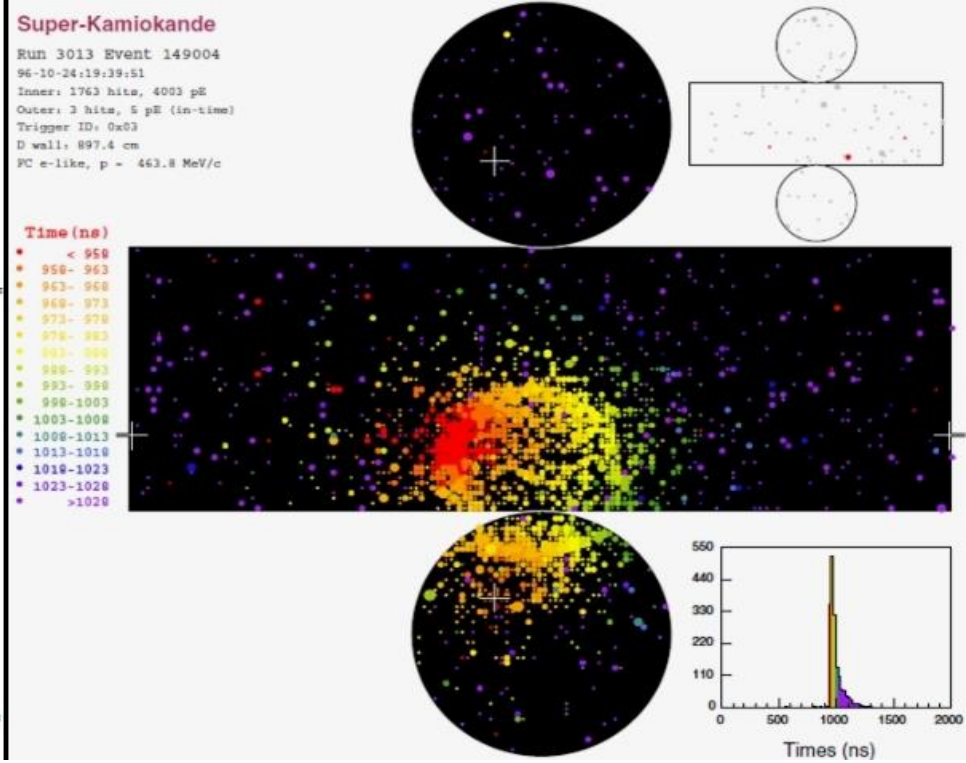


Figure 4-2 (b): Typical spectral response characteristics of transmission mode photocathodes


Super-Kamiokande IV
Events scanned 1039171
Display :CHARGE INNER
Date :Thu Apr 30 2015
Run :73580 Normal
Event :36607464
Event time :13:12:00.324994
TRG Type(s) :LE HE SLE OD SHE
TotalPE ID/OD :74719.4 2169.6
NumHits ID/OD :6883 239
Time Diff :19237.656250 us
<- Rotate -> : 1 PI / 10
Time Window (ns):[-300.0, 1000.0]
0.0 0.5 1.4 1.9 2.6 3.7 5.1 7.0 9.7 13.4 18.5 25.6 35.4 49.0 67.8 179.4





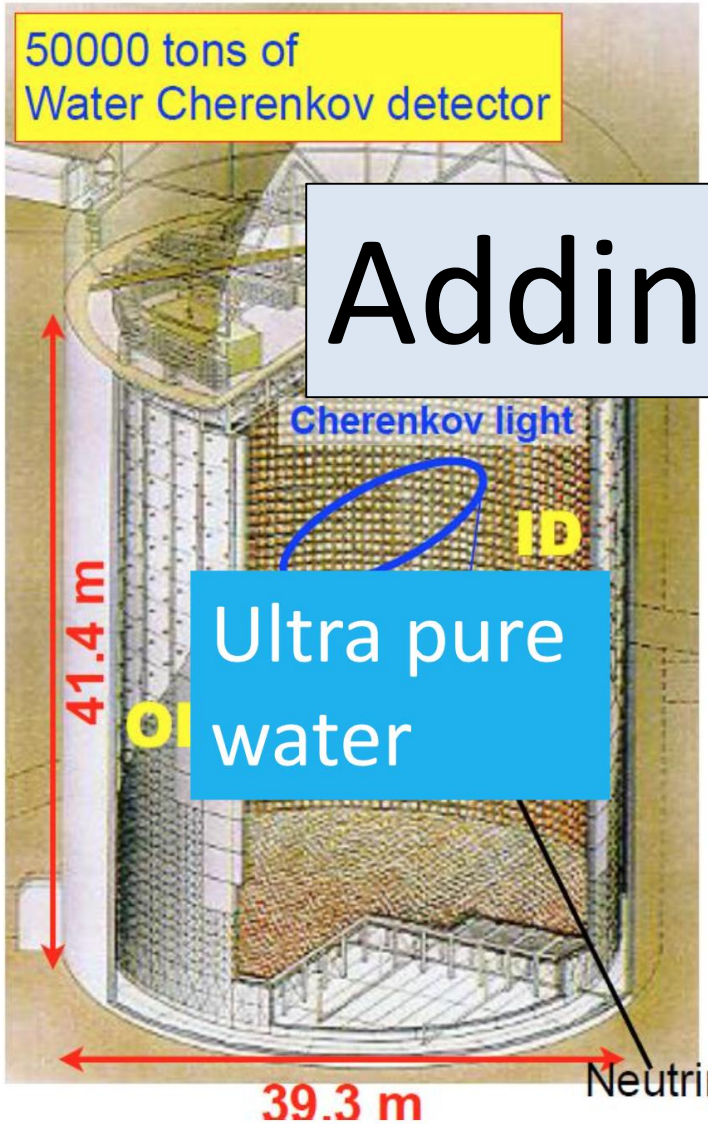
Muon

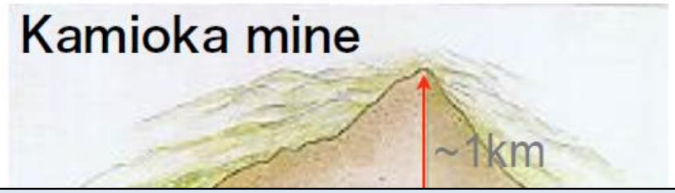
Electron

Scattering makes electron tracks easily distinguishable from muon tracks with very high efficiency (>98%) in CCQE region.


What's New?

Super-Kamiokande





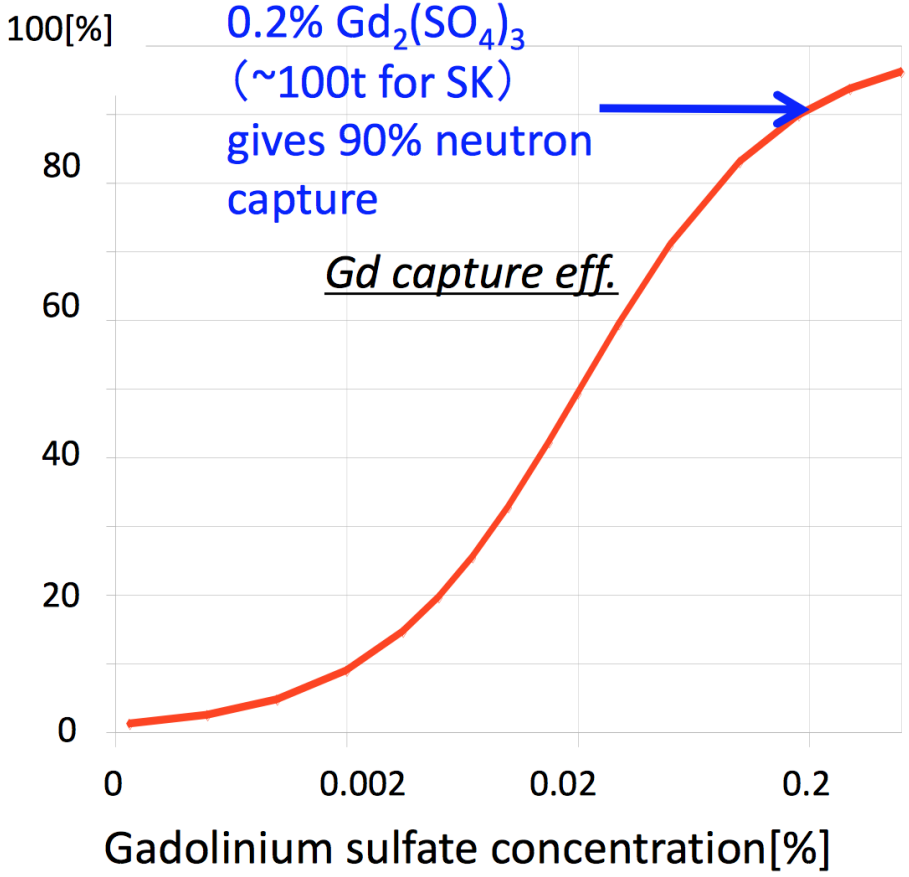
Adding Gadolinium...

Phase	Period	Livetime (days)	Fiducial vol. (kton)	# of PMTs	Energy thr.(MeV)
SK-I	1996.4 ~ 2001.7	1496	22.5	11146 (40%)	4.5
SK-II	2002.10 ~ 2005.10	791		5182 (20%)	6.5
SK-III	2006.7 ~ 2008.8	548	22.5 (>5.5MeV) 13.3 (<5.5MeV)	11129 (40%)	4.5
SK-IV	2008.9 ~	1669	22.5 (>5.5MeV) 13.3 (4.5<E<5.5) 8.8 (<4.5MeV)		**3.5**
		total **4504** days		(coverage)	(Kinetic energy)

Super K-Gd

Beacom and Vagins PRL93,171101 (2004)

- Large cross section for thermal neutron (48.89kb)
- Neutron captured Gd emits 3-4 γ ray in total 8 MeV
- **We can tag $\bar{\nu}_e$ by using the delayed coincidence technique.**



Physics targets:

(1) Supernova relic neutrino (SRN)

(2) Improve pointing accuracy for galactic supernova

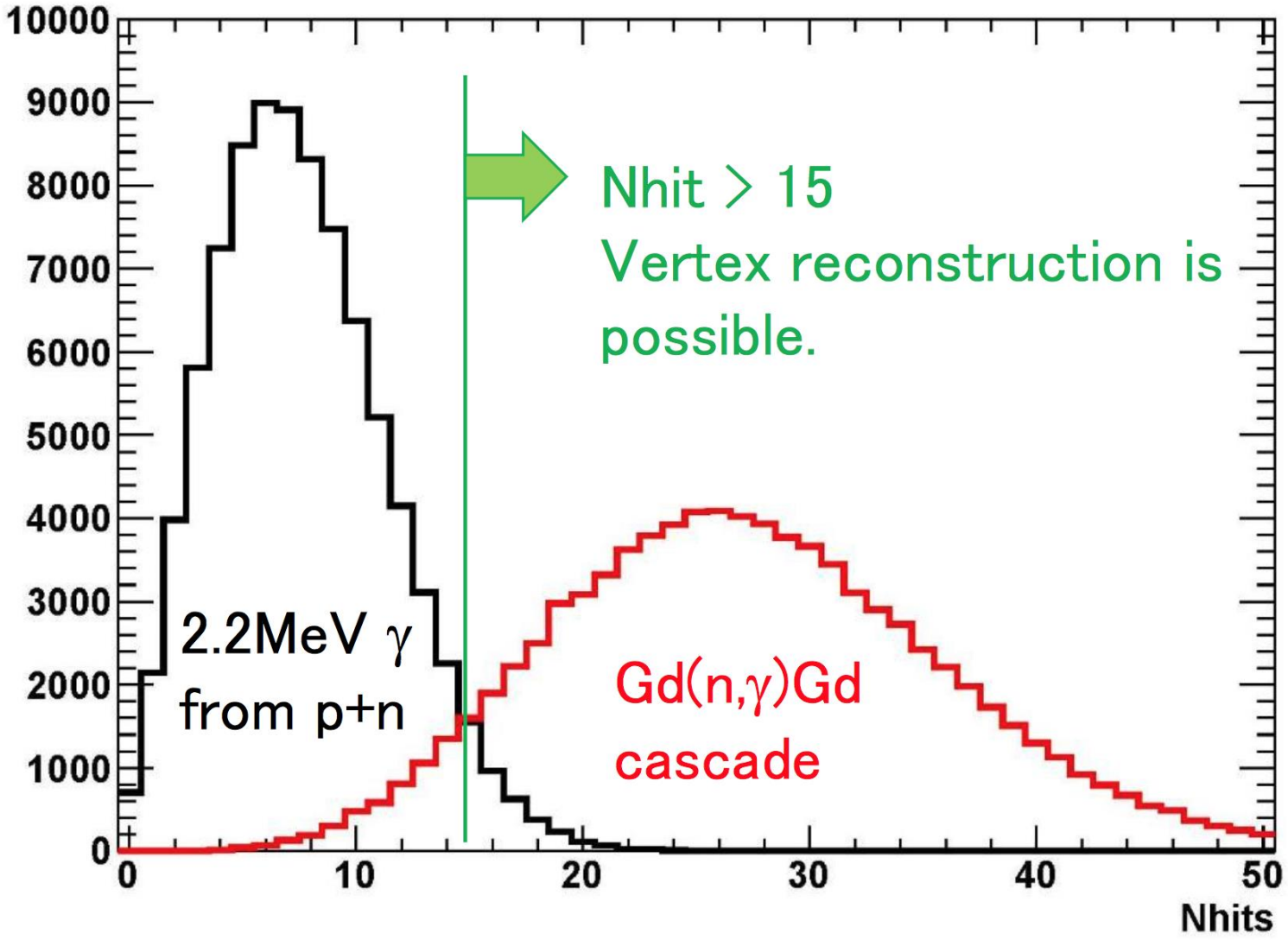
(3) Precursor of nearby supernova by Si-burning neutrinos

(4) Reduce proton decay background

(5) Neutrino/anti-neutrino discrimination (Long-baseline and atm nu's)

(6) Reactor neutrinos

Number of hit PMT (Nhit) distributions



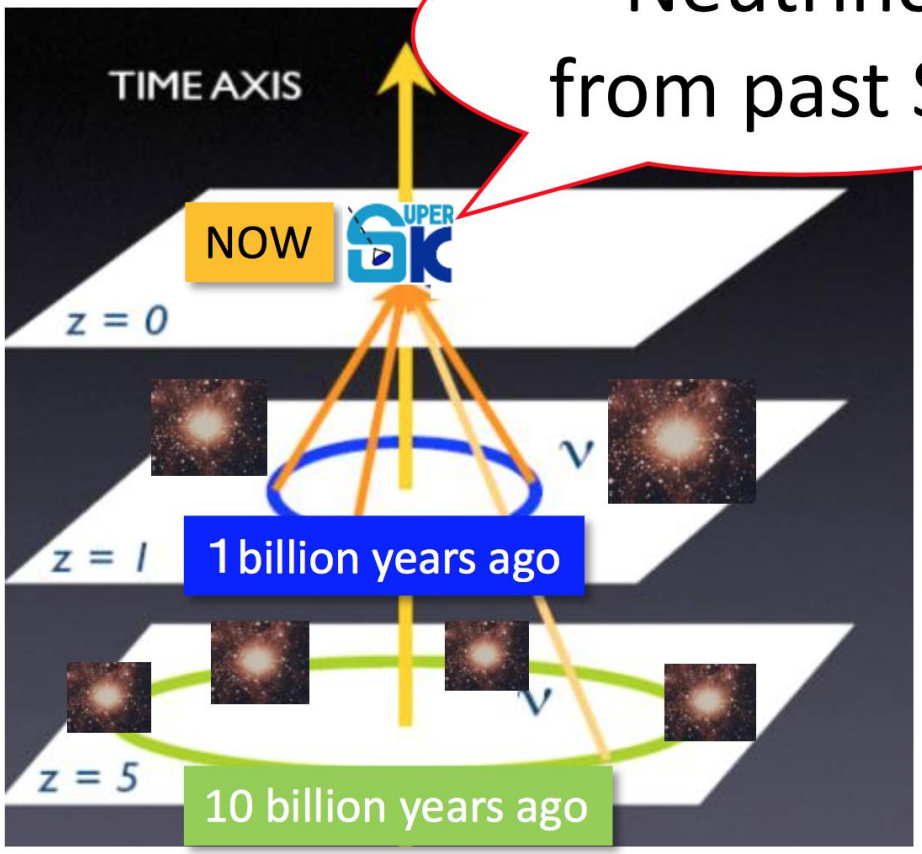
Efficiency and fake probability

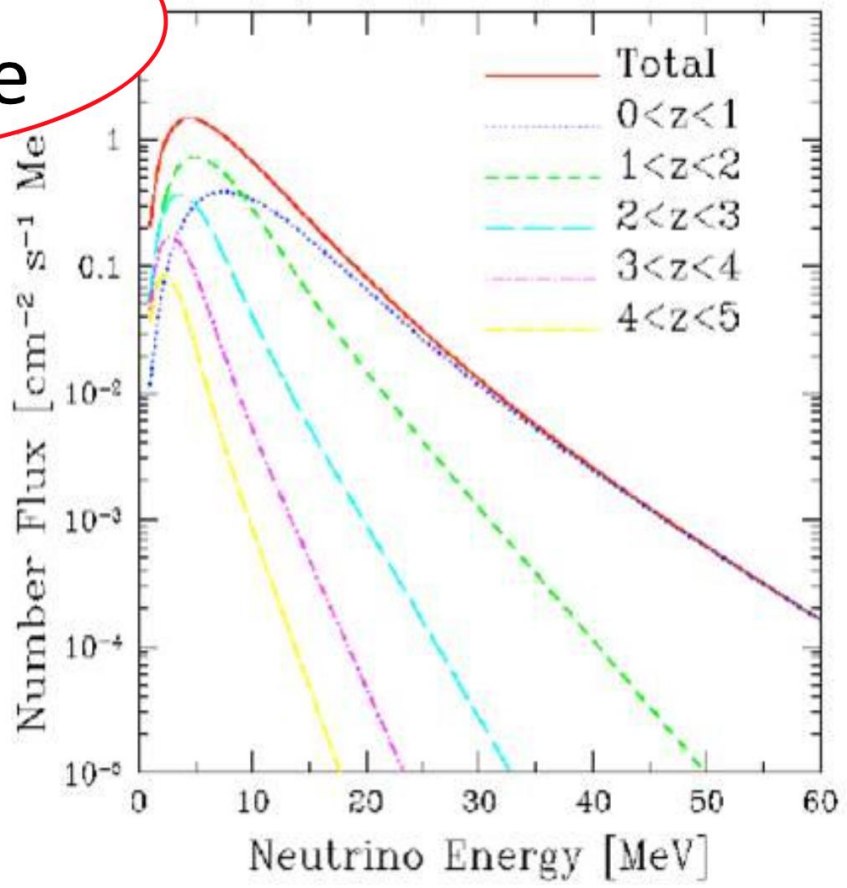
2.2MeV γ: Efficiency: 10～20%, fake probability: ～10^{-2}

Gd(n,γ)Gd: Efficiency: >80%, fake probability: <10^{-4}

Supernova Relic Neutrino (SRN)

10^{10} stellar/galaxy $\times 10^{10}$ galaxy $\times$ 0.3%(become SNe) ~$O(10^{17})$SNe



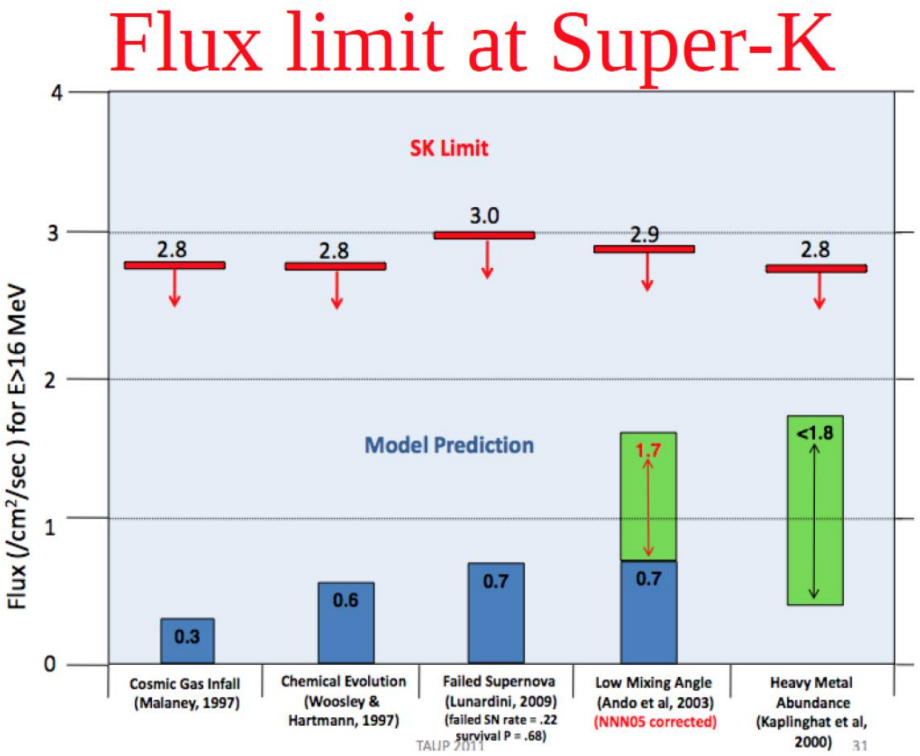


S.Ando, Astrophys.J. 607, 20(2004)

Theoretical flux prediction : 0.3~1.5 /cm2/s (17.3MeV threshold)

Current limits from Super-K background dominated by "stealth" muon events and a threshold limited by muon spallation.

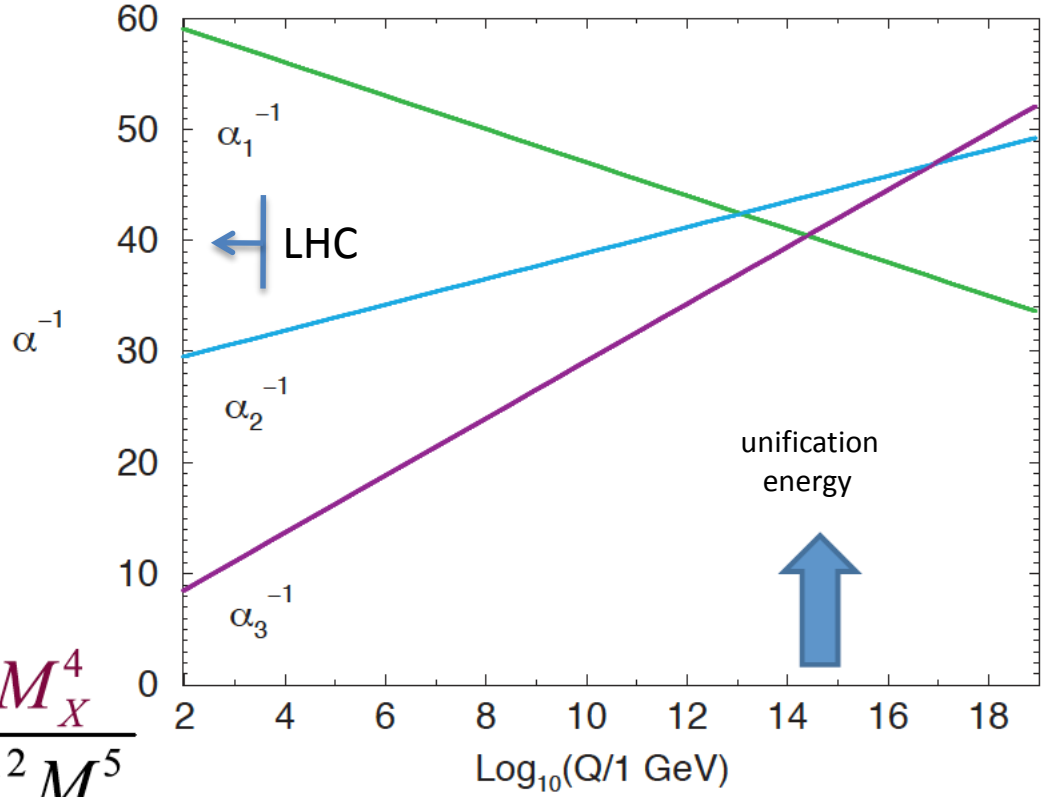
n-Tagging Inverse Beta Decay events from Diffuse SN should increase sensitivity to the levels implied by current models.



Phys. Rev. D 85, 052007 (2012)

Proton Decay: **Is Normal Matter Stable?**

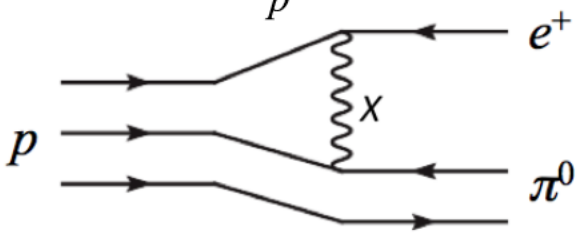
Gauge Coupling Unification



Three of the four forces of nature are thought to become similar in strength at very high energies – far above any conceivable accelerator

$$\tau \approx \frac{M_X^4}{\alpha^2 M_p^5}$$

Simple unification theory ruled out by data – proton decay is an effective way to test such theories

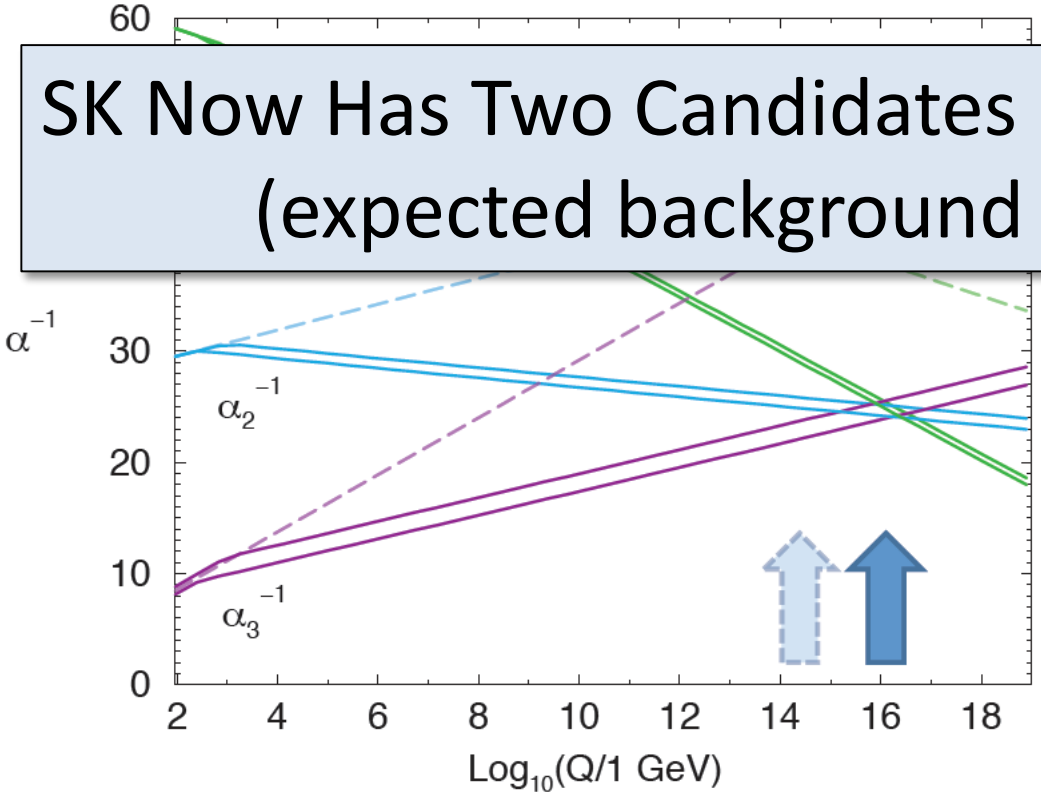


$$\tau(e^+\pi^0) = 4.5\times10^{29\pm1.7}\ years\ \text{(predicted)}$$

>6.6x10^{33} years (PRL 102 2009)

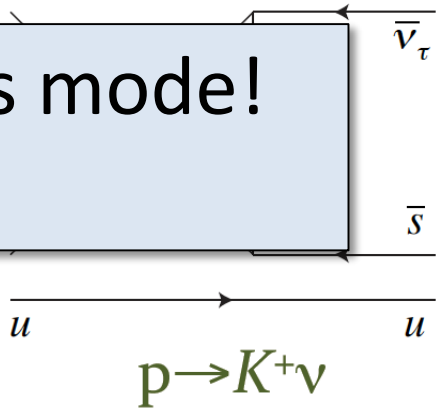
New theories (e.g. SUSY) can push up unification scale

SK Now Has Two Candidates in this mode!
(expected background 0.9)



Unification scale pushed up…

$$\tau(e^+\pi^0) \approx 10^{35-38}\ \text{years}$$



Example of a possible proton decay through supersymmetric particles.

Observation of virtual processes like proton decay is our **only known way** to access physics at these energies

Neutrons from Proton Decay in Water

- 2/10 of protons are free protons. No neutrons.
- 2/10 of protons are in $P_{1/2}$ shell. If they decay nucleus is already in the ground state. No neutrons
- 4/10 of protons are in $P_{3/2}$ shell. If they decay then a $P_{1/2}$ proton will drop down, giving a 6 MeV gamma. No neutrons. (Ejiri gives 94% B.R. for this)
- **~80% of proton decays should give neutrons only indirectly from FSI.** (such FSI usually makes them undetectable anyway) This is fairly model independent. Ejiri's more detailed estimate gives 81%
- Similar numbers for neutron decay.

Will Proton Decay Result in Neutrons?

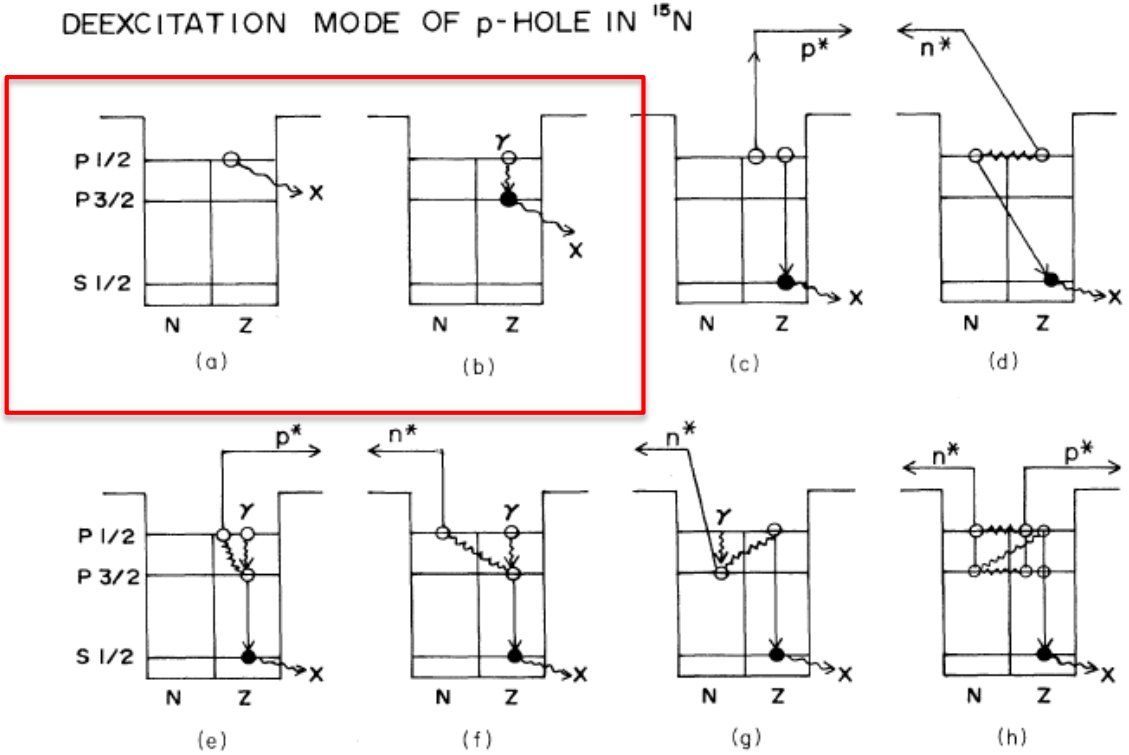


FIG. 1. Deexcitation scheme of a proton hole produced by proton decay ($p \rightarrow x$) in ^{16}O. N and Z stand for neutron and proton shells, respectively. p^* and n^* are protons and neutrons emitted into the continuum region.

0556-2813/93/48(3)/1442(3)/$06.00 48 1442

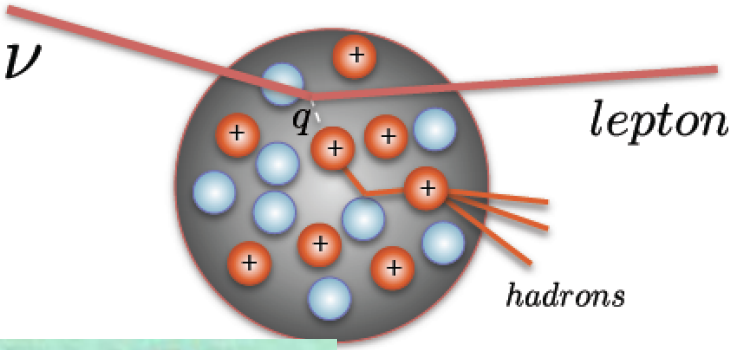
Motivation

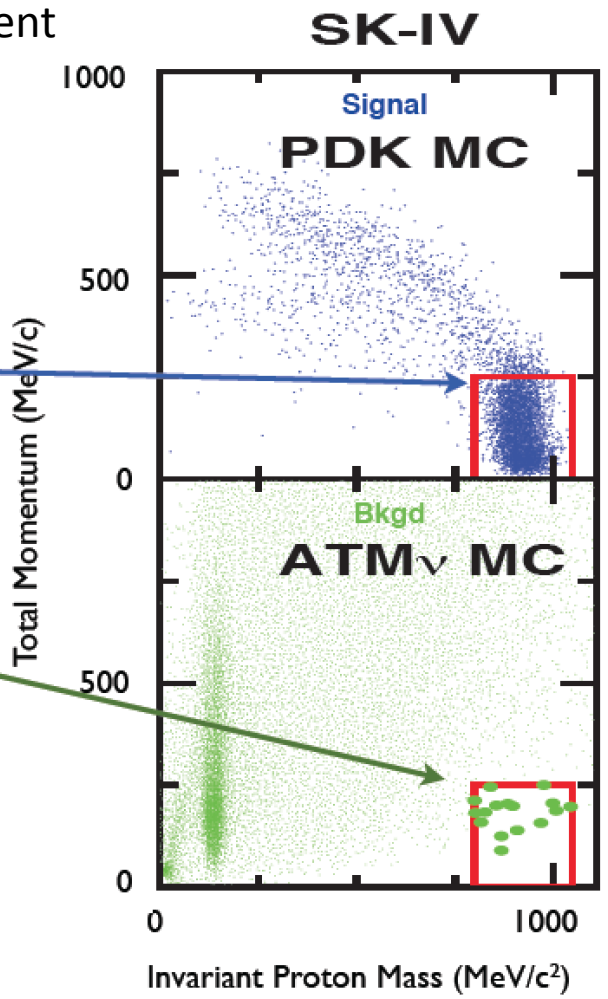
ANNIE Experiment

Backgrounds come almost exclusively from atmospheric neutrino interactions

Proton decay events are expected to only rarely produce neutrons in the final state.

High energy neutrino interactions typically produce neutrons in the final state





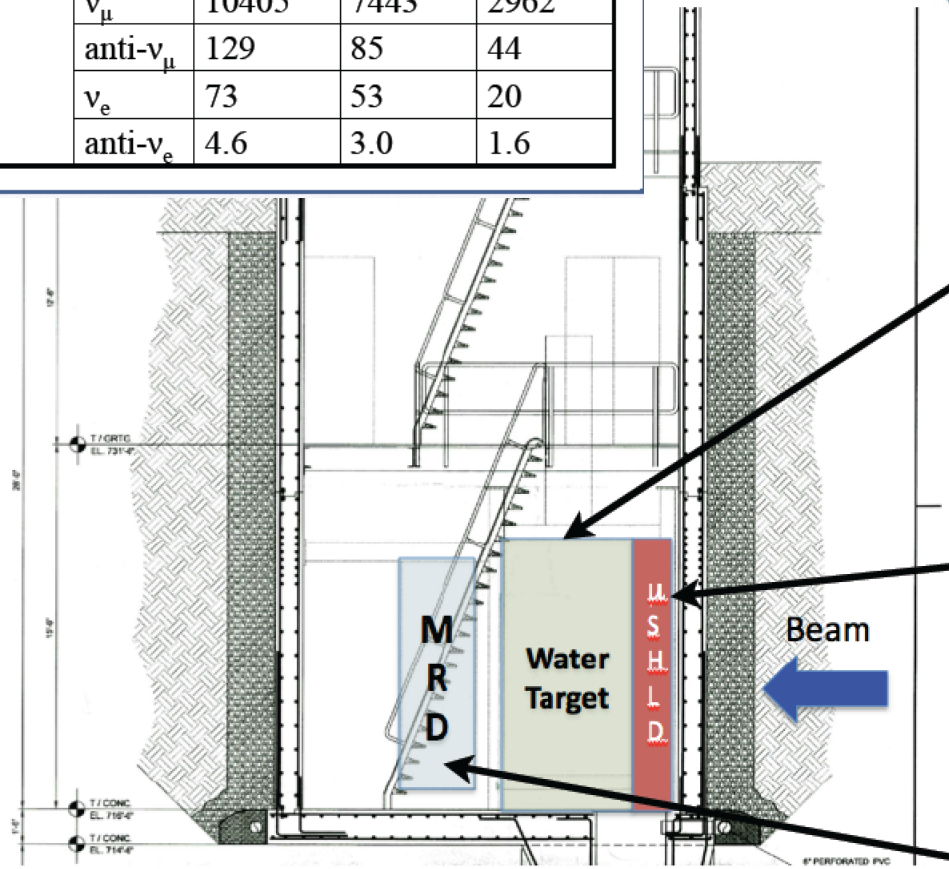
I. Anghel[1,4], G. Davies[4], F. Di Lodovico[11], A. Elagin[9], H. Frisch[9], R. Hill[9], G. Jocher[5], T. Katori[11], J. Learned[11], R. Northrop[9], C. Pilcher[9], E. Ramberg[3], M.C. Sanchez[1,4], M. Smy[7], H. Sobel[7], R. Svoboda[6], S. Usman[5], M. Vagins[7], G. Varner[10], R. Wagner[1], M. Wetstein[9], L. Winslow[8], and M. Yeh[2]

[1]Argonne National Laboratory [2]Brookhaven National Laboratory [3]Fermi National Accelerator Laboratory [4]Iowa State University [5]National Geospatial-Intelligence Agency [6]University of California at Davis [7]University of California at Irvine [8]University of California at Los Angeles [9]University of Chicago [10]University of Hawaii [11]Queen Mary University of London

Rates Expected with 1×10^{20} POT exposure at SciBooNE pit

Djurcic

	Total Events [1/1ton/10^{20}POT]	ν-type	Total (per ν-type)	Charged Current	Neutral Current
Booster Beam (ν-mode, Target = CH_2)	10419	ν_μ	10210	7265	2945
		anti-ν_μ	133	88	45
		ν_e	72	52	20
		anti-ν_e	4.4	3	1.4
Booster Beam (ν-mode, Target = H_2O)	10612	ν_μ	10405	7443	2962
		anti-ν_μ	129	85	44
		ν_e	73	53	20
		anti-ν_e	4.6	3.0	1.6



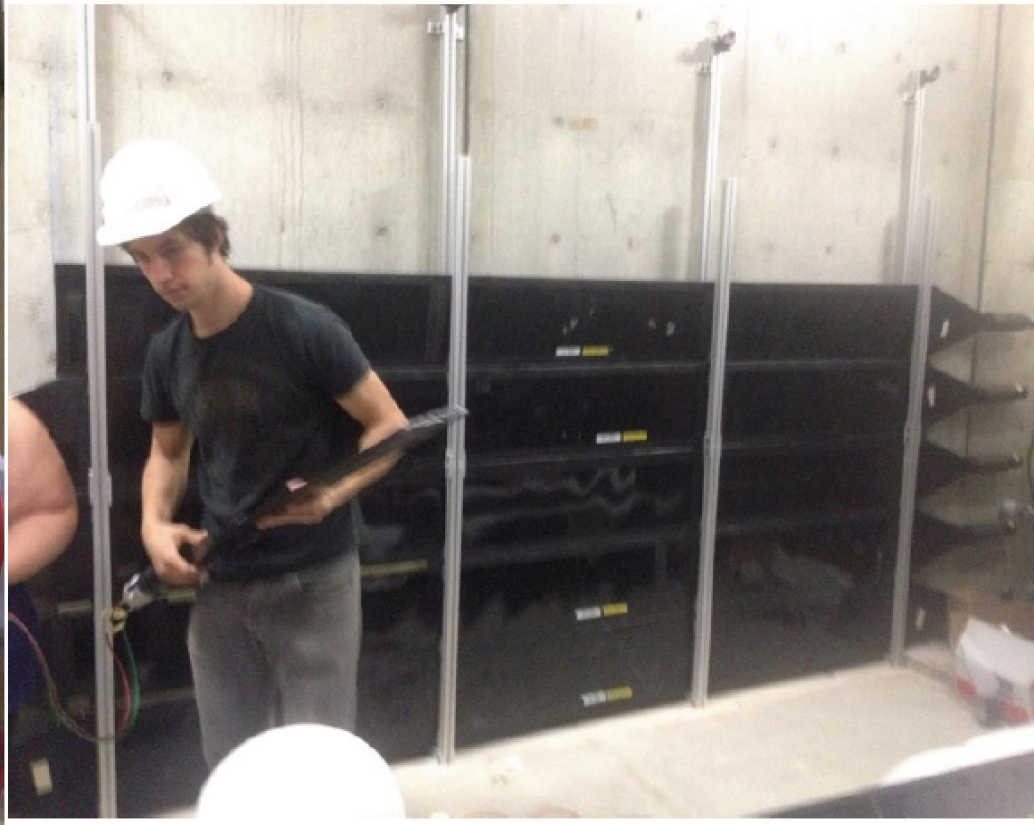
3m x 3m x 3m tank of Gd enhanced water instrumented with photosensors.

Existing veto on muons produced upstream of the detector (FACC)

Existing Muon Range Detector (MRD)

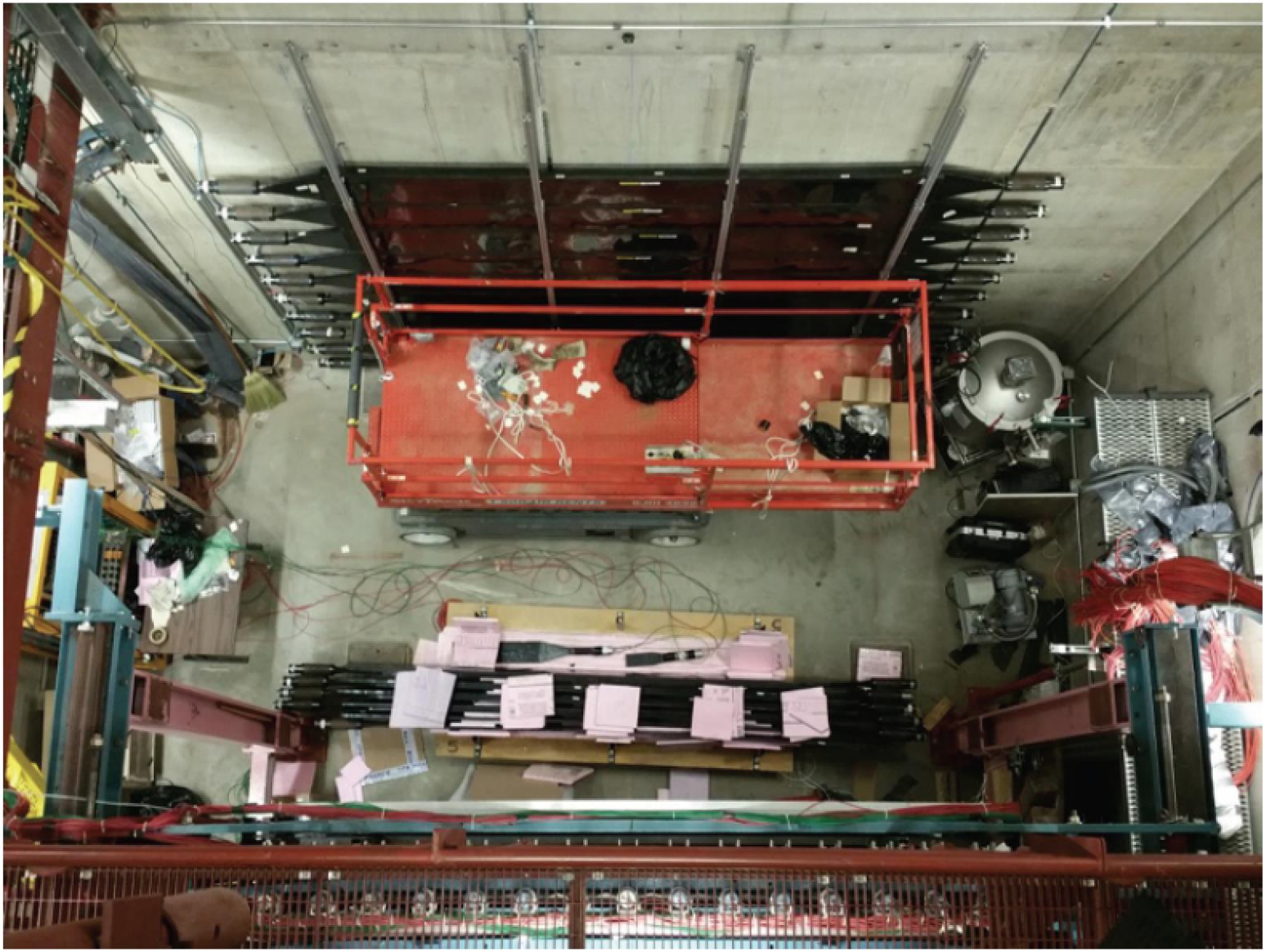
"ANNIE Hall"

(formerly the SciBooNE pit)



For documentation and animation of the wall construction, go to:

https://cdcvs.fnal.gov/redmine/projects/annie_experiment/wiki/Veto_design



Liquid Scintillator Detectors

Scintillation

- the physics definition of scintillation:
  - the process by which ionization produced by charged particles excites a material and light is emitted by the de-excitation
- one of the most common detection techniques in nuclear and particle physics
- earliest use by Crookes in 1903
  - a ZnS-coated screen scintillates when struck by α particles
- then Curran and Baker in 1944
  - coated a photomultiplier tube with ZnS producing the first scintillation counter that didn't require the human eye
- since then many forms of scintillation detectors, large and small, have been developed
- the scintillation process differs in different materials (e.g. inorganic crystals, organic liquids, noble gases and liquids, plastic scintillators)
- we'll briefly examine each type…

Aside: Definitions

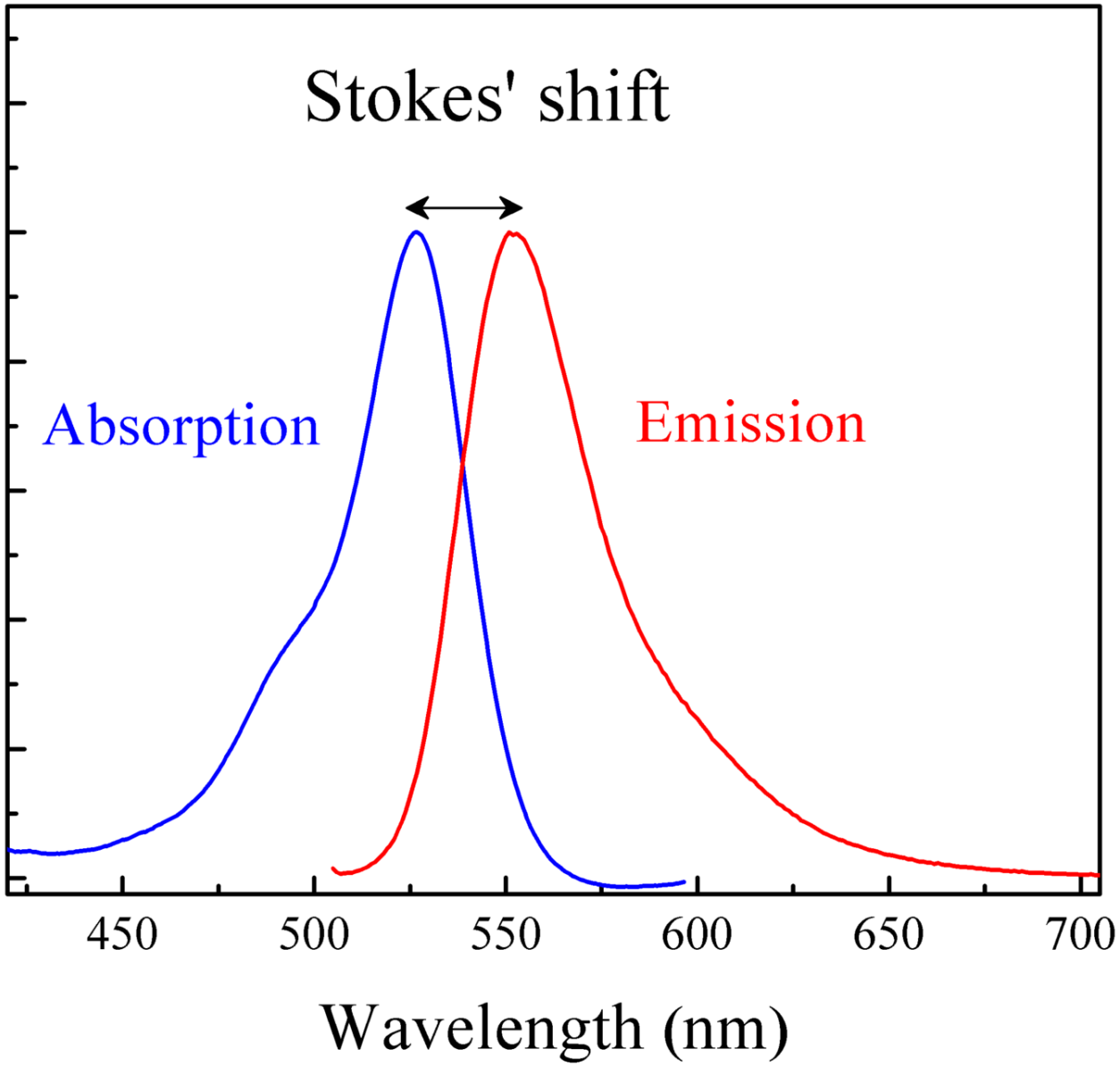
- when you excite a material (not thermally) and it subsequently gives off light, that is *luminescence*
- how it's excited determines the type of luminescence (e.g. *photoluminescence*, *chemiluminescence*, *triboluminescence*)
- *fluorescence* is photoluminescence or scintillation (i.e. excitation produced by ionizing radiation) that has a fast decay time (ns to μs)
- *phosphorescence* is the same, only with a much slower decay time (ms to seconds)

Stokes Shift

an important, general concept to keep in mind for all scintillators

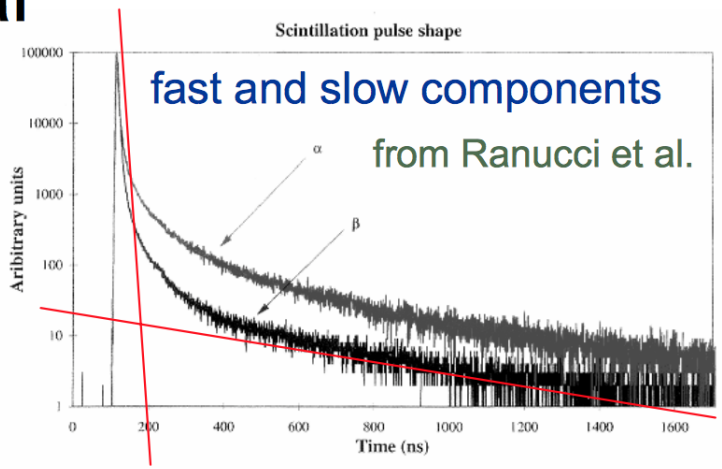
- emitted photons are at longer wavelengths (smaller energies) than the energy gap of the excitation
- the processes that produce this “Stokes shift” are different in different scintillating materials
- this allows the scintillation light to propagate through the material
  - emitted photons can’t be self-absorbed by exciting the material again

from Wikipedia


Stokes' shift
Absorption
Emission
450
500
550
600
650
700
Wavelength (nm)

Scintillator Characteristics of Interest

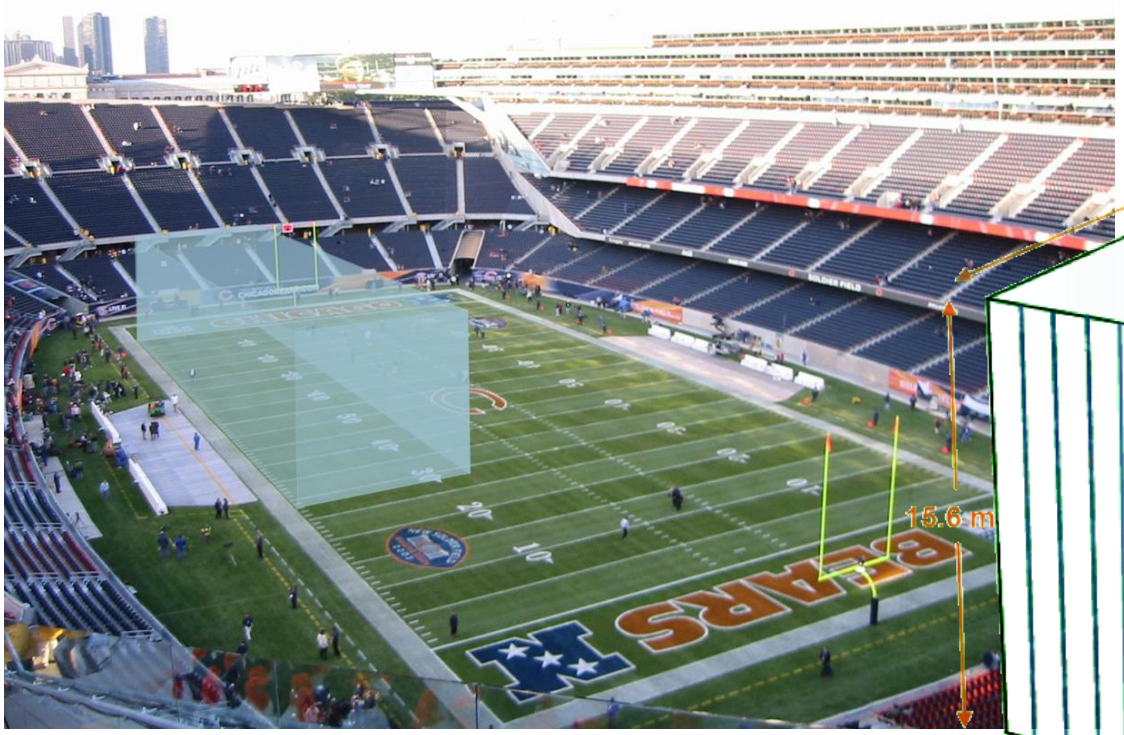
- light yield: high efficiency for converting ionization energy to light output [photons/MeV]
- emission spectrum: overlaps with spectral response of light detector (e.g. PMT)
- decay time: can have several time constants
- density and Z: determine response to γ, e^- and other electromagnetic processes

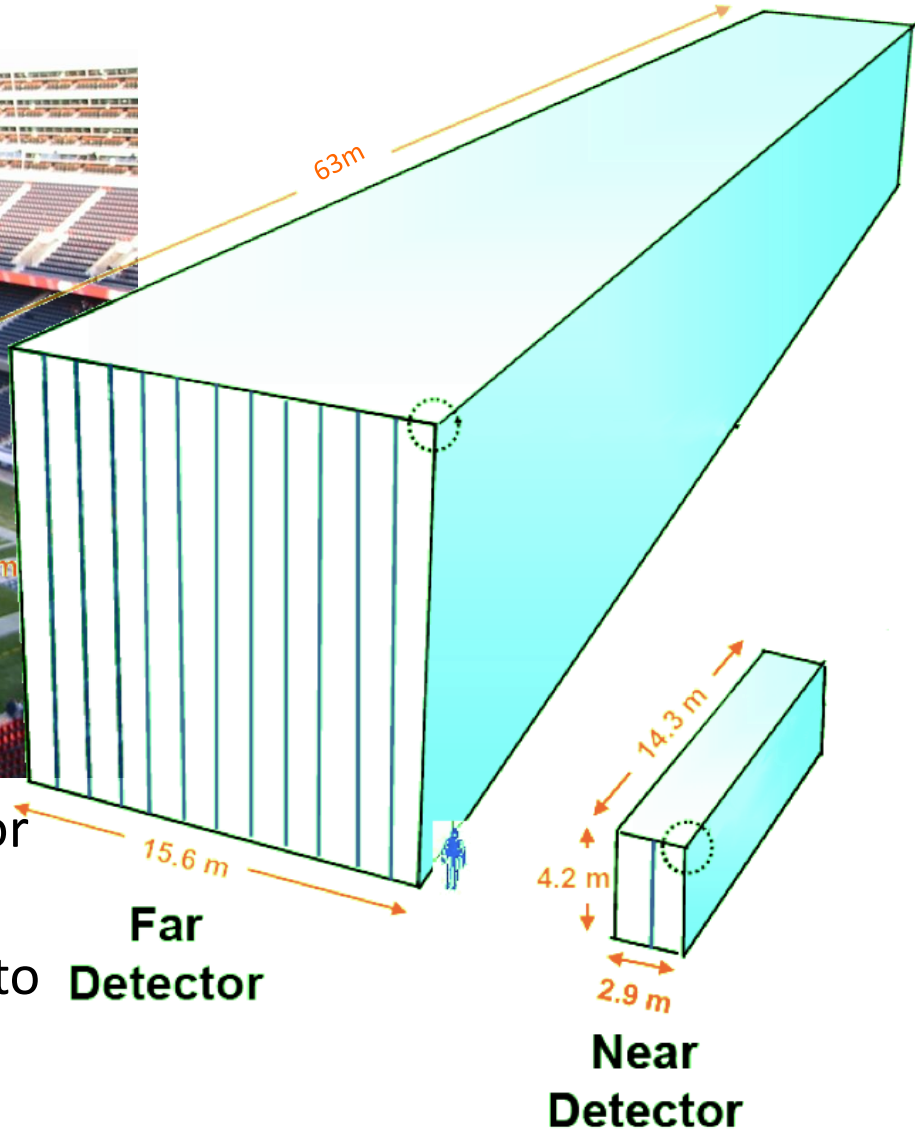


Organic Scintillators

- the scintillation mechanism is determined by the chemistry and physics of the benzene ring
- an organic scintillator will thus scintillate whether it's in a crystal form, is a liquid, a gas, or imbedded in a polymer
- all organic scintillators in use employ aromatic molecules (i.e. have a benzene ring)
- we'll examine the photophysics of aromatic molecules in detail…

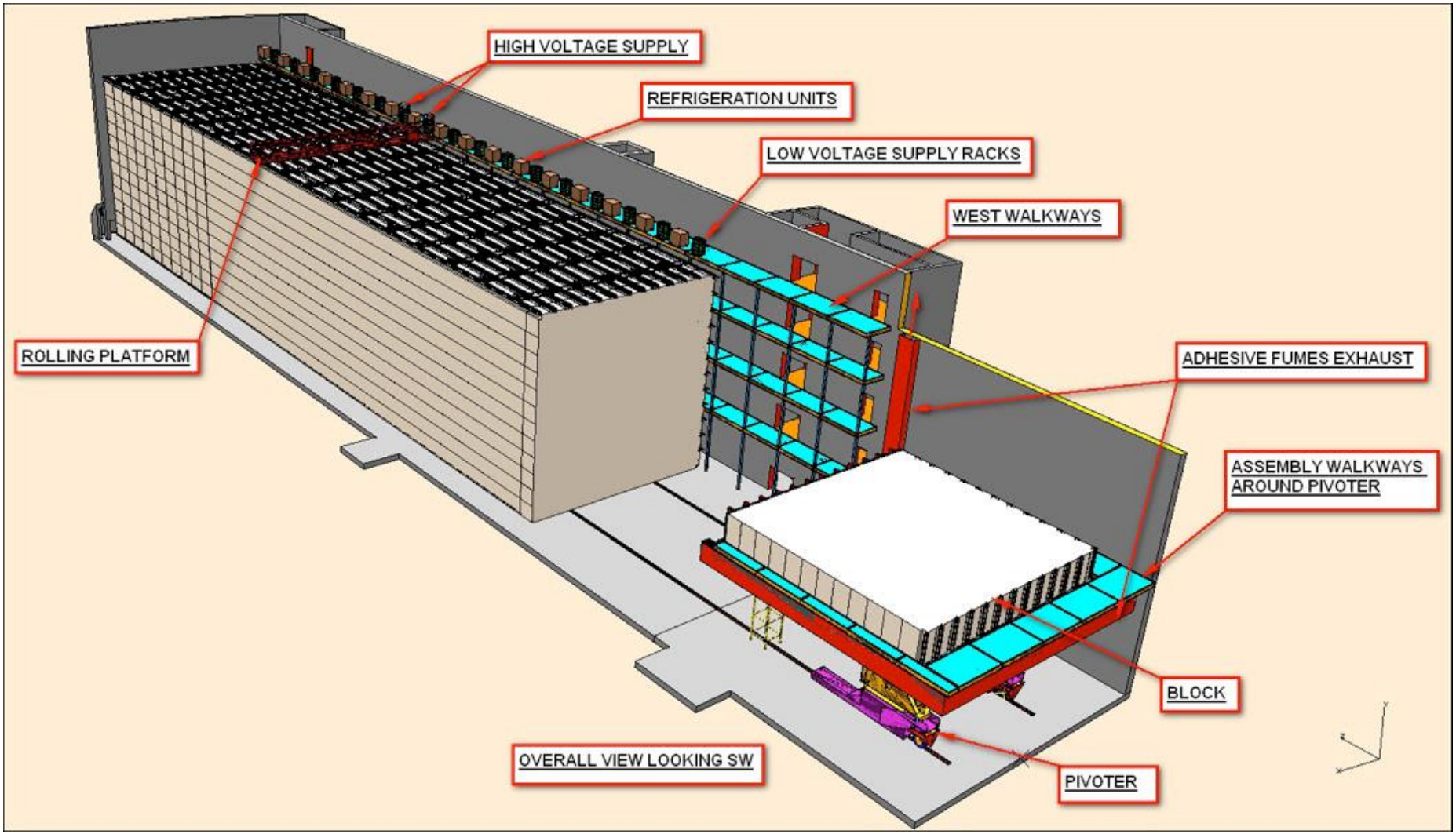
The NOvA Detectors





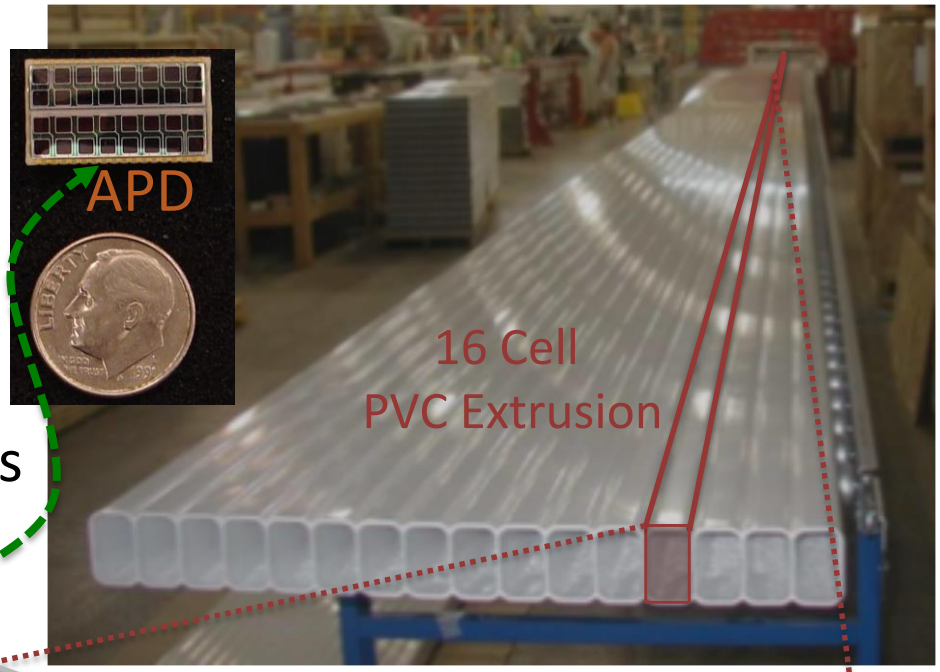
- Massive, Low-Z, 65% active Far Detector
  - 15 kton, 810 km from source
- Functionally equivalent Near Detector to mitigate systematic uncertainties
  - 220 ton Near Detector, 1 km from source

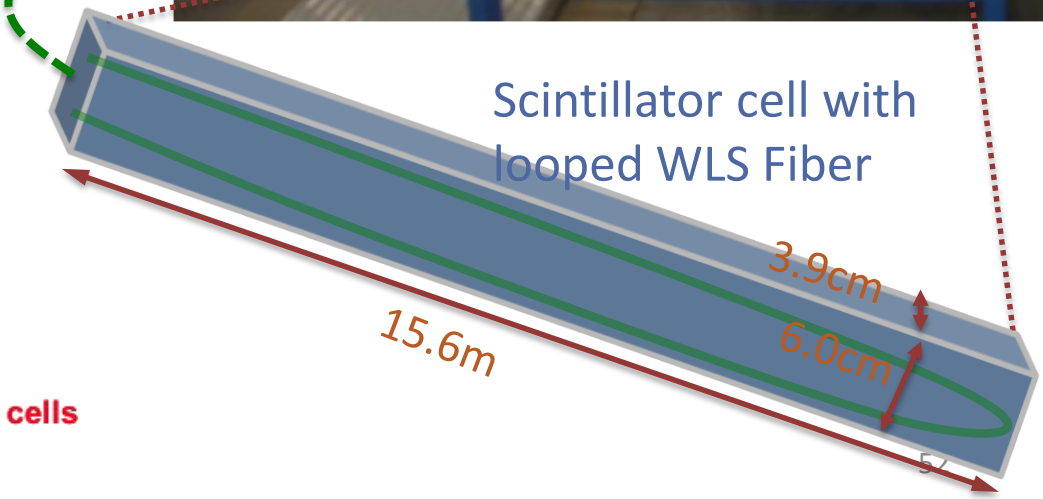
15,000 tons of LS

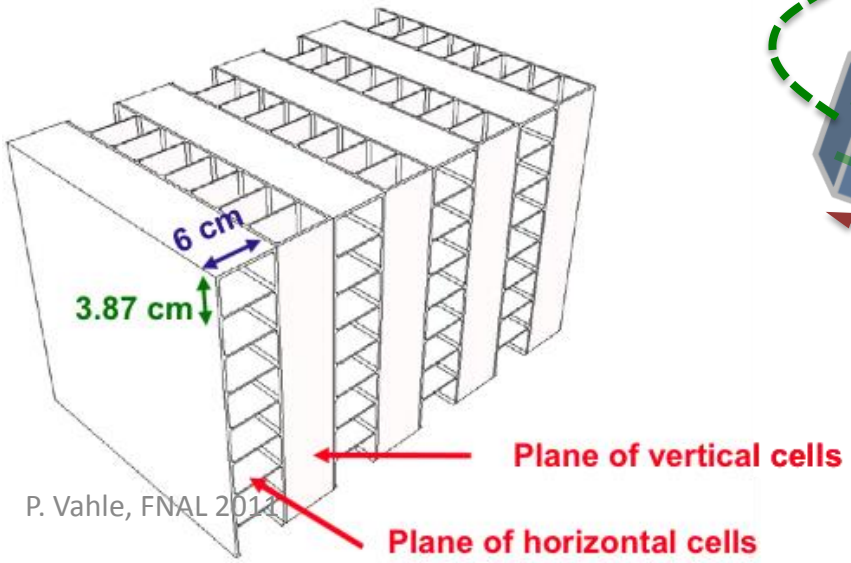


Detector Technology

- PVC extrusion + Liquid Scintillator
  - mineral oil + 5% pseudocumene
- Read out via WLS fiber to APD
  - muon crossing far end=38 PE
- Layered planes of orthogonal views
- 0.15 X_0 per layer

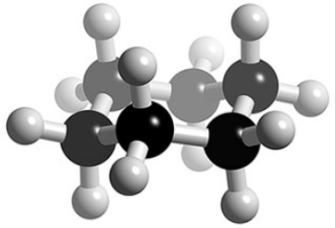






Carbon Bonds

- carbon: $1s^2\ 2s^2\ 2p^2$ electronic ground state
- carbon bonds: $1s^2\ 2s^1\ 2p^3$ and the 2s and 2p orbitals are hybridized
  - sp^3 hybridization is tetrahedral (e.g. diamond, methane, cyclohexane)
    - not luminescent
  - sp^2 hybridization is planar
  - p_z orbital is unchanged
    - double-bonded carbon (e.g. ethylene, benzene)
    - is luminescent and the basis of organic scintillators
  - sp hybridization is linear
    - triple-bonded carbon (e.g. acetylene)
    - also luminescent



from 3Dchem.com

sp3 and sp2 hybridization

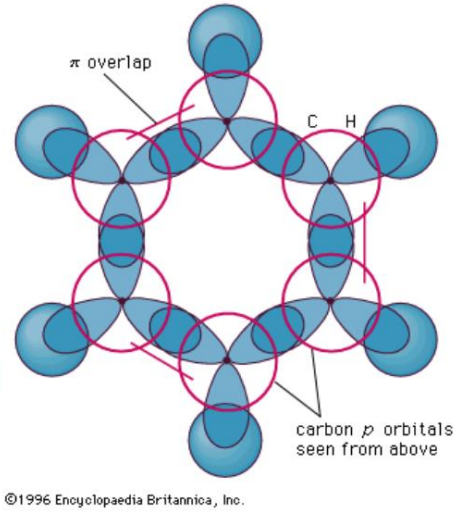
P orbitals are shaped like figure eights and electrons in p orbitals are slightly farther away from the nucleus than electrons in s orbitals. The **sp3** orbital is 25% s character and 75% p character (1 2s orbital, + 3 2p (2px, 2py, 2pz). For sp2 **hybridization** there is 33% s character and 66% p character.

Sp3 hybridization - Khan Academy

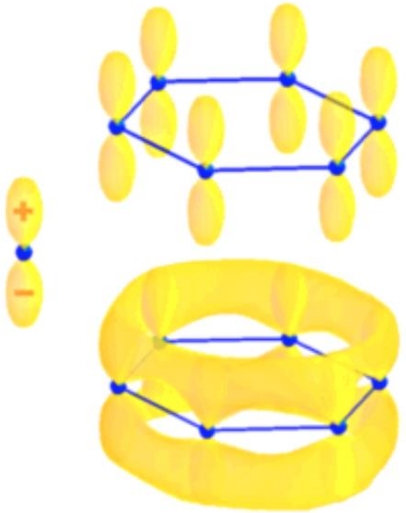
https://www.khanacademy.org/.../**sp3**-hybrid-orbital-jay-fin... Khan Academy

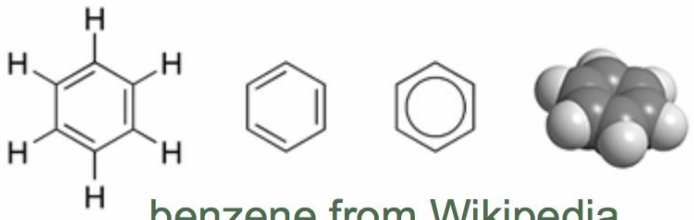
σ-Bonds and π-Bonds

from Encyclopedia Brittanica web



- σ-bonds are in the plane, bond angle 120°, from sp^2 hybridization
- π-orbitals are out of the plane
  - in the benzene ring (and other carbon double bonds) they overlap each other
  - result is the π-electrons are completely delocalized



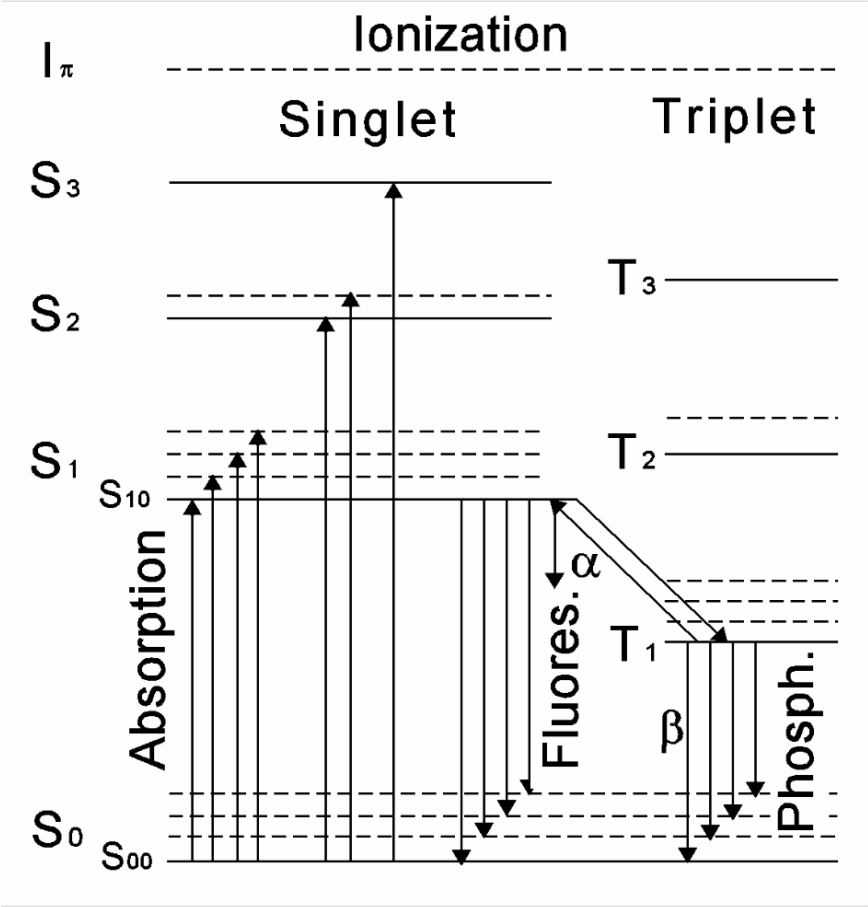


benzene from Wikipedia

from http://www.monos.leidenuniv.nl/smo/index.html?basics/photophysics.htm

π-Electronic States

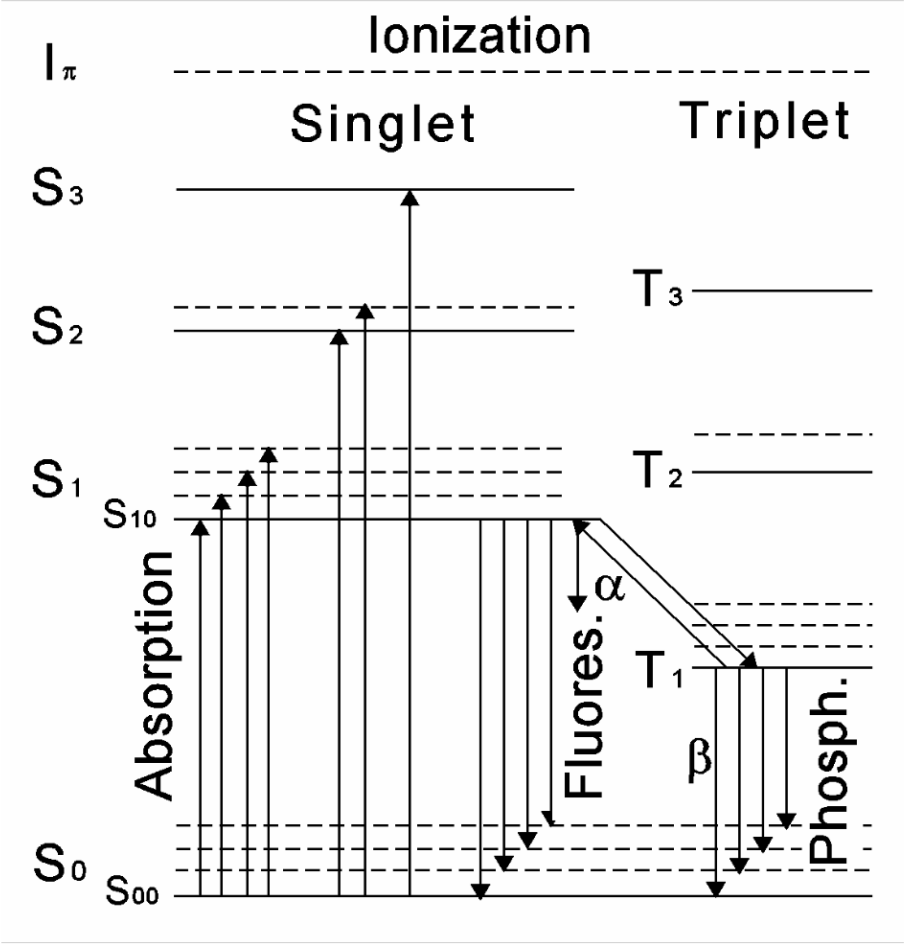
- theory of π-electron excited states uses a "perimeter free-electron model", with electrons going around the ring in both directions, spin up and down
- absorption spectroscopy confirms the theory
- the π-electronic states diagram can be deduced from theory and spectroscopy
  - has vibrational sub-levels (e.g. S_{10}, S_{11}) with ~0.16 eV spacing
- after absorption of a photon or excitation by ionization, the molecule undergoes vibrational relaxation (or internal conversion or degradation) to S_{10}



from M. Kobayashi (KEK), adapted from J.B. Birks

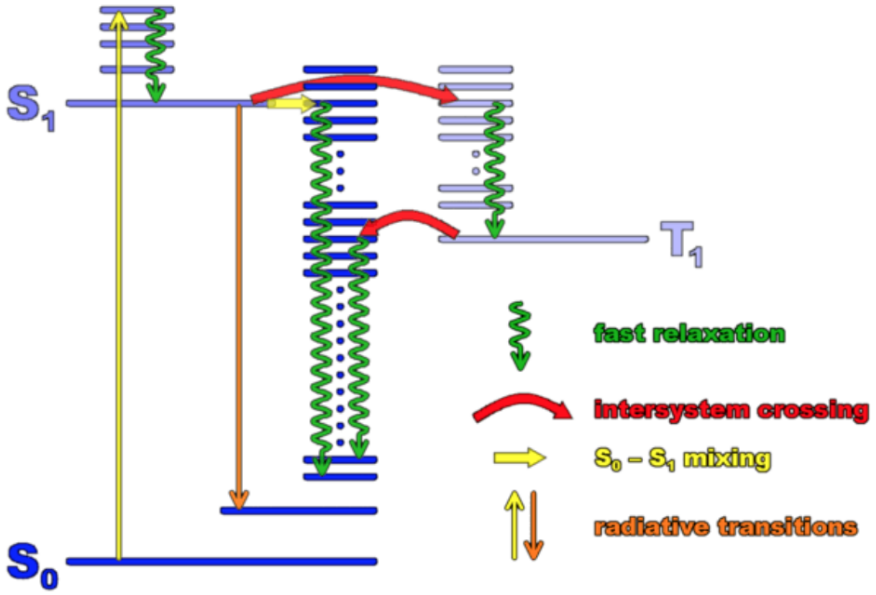
Scintillation in Organic Molecules

- the excited S_{10} state decays radiatively to vibrational sub-levels of the ground state
- the S_{10} lifetime is ~ns
- thus the fluorescence emission spectrum is roughly a "mirror image" of the absorption spectrum (same spacing)
- emitted photons have less energy than S_{00}-S_{10} – that's the important Stokes shift
- there is no S_2-S_0 emission because internal conversion is efficient and fast ~ps
- there are σ-electronic excited states too; but they are at higher energies above S_3



Competing Processes

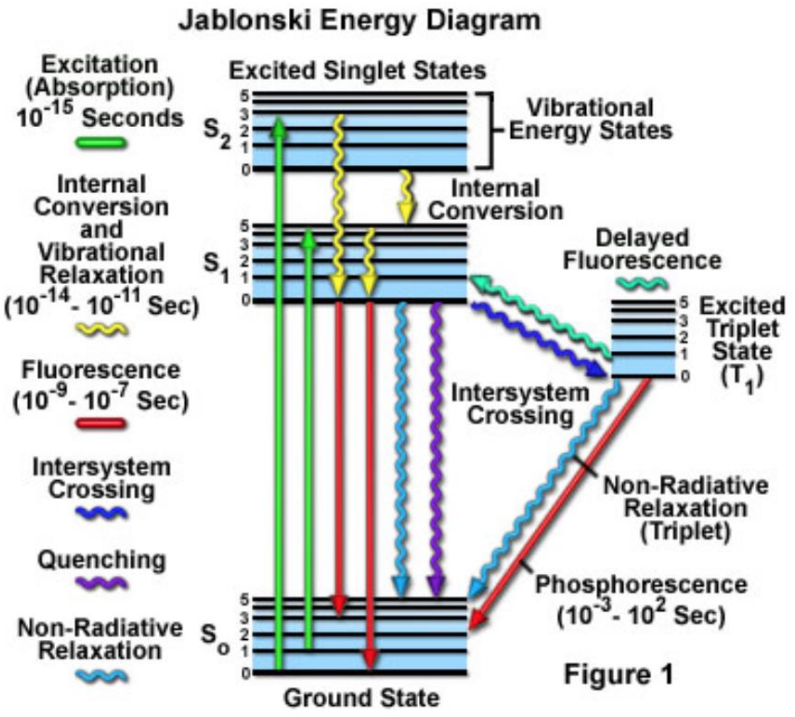
- non-radiative decay
  - due to overlap of an S_0 vibrational state with S_1
- ratio of the radiative rate to the total decay rate (radiative plus non-radiative) is the *fluorescence quantum yield*
- quantum yields of 0.8 or greater are typical for "good" scintillators



from http://www.monos.leidenuniv.nl/smo/index.html?basics/photophysics.htm

Competing Processes cont'd

- an intersystem crossing can occur, populating the triplet state
  - S_0-T_1 and T_1-S_0 cannot occur directly due to angular momentum and parity selection rules
- T_1 has a long lifetime since decay to the S_0 is forbidden
  - this is phosphorescence
- delayed fluorescence from the triplet can also occur
  - $T_1 + T_1 \rightarrow S_1 + S_0 +$ phonons
  - ~μs



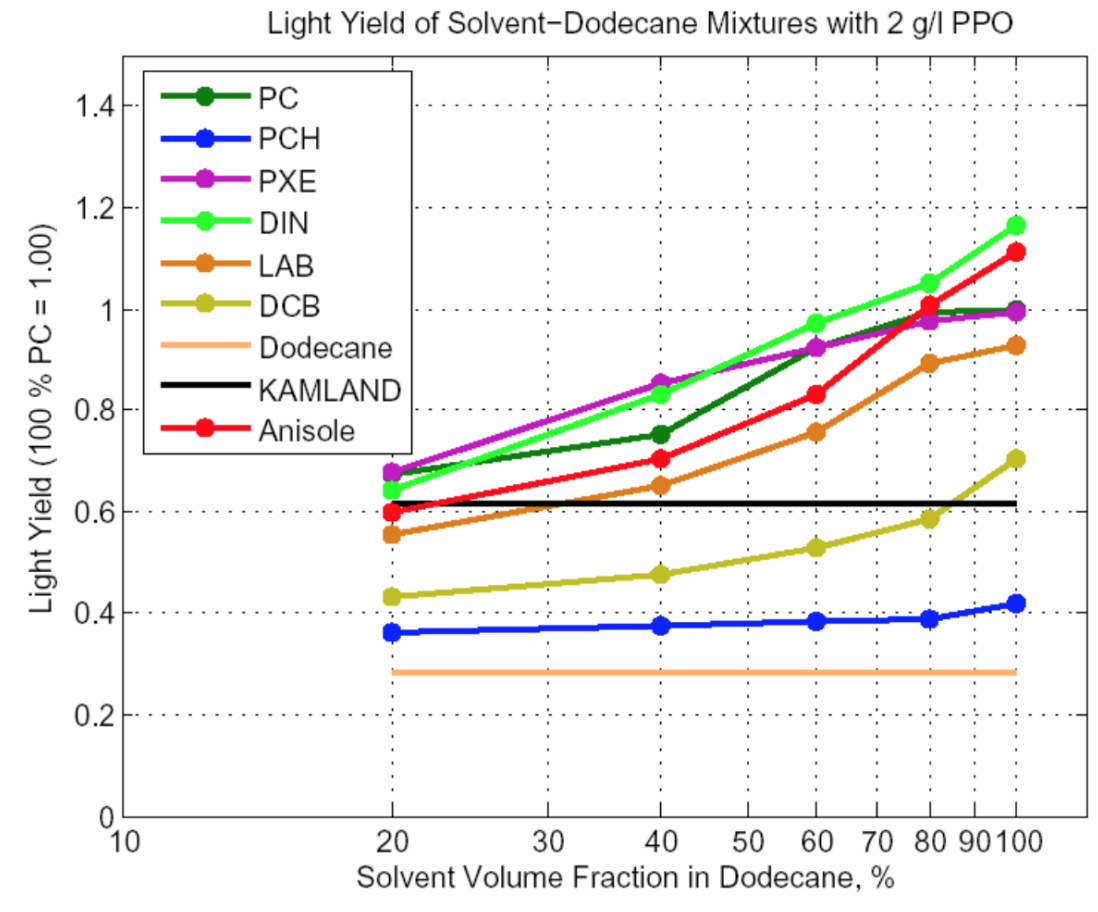
from http://micro.magnet.fsu.edu/primer/techniques/fluorescence/fluorescenceintro.html

Organic Liquids

- **any aromatic organic solvent is a scintillator**
  - e.g. benzene, xylene, pseudocumene (1,2,4-trimethylbenzene)
- **to improve the performance, a scintillating solute is dissolved in the solvent – this is called the fluor**
  - e.g. PPO (2,5-diphenyloxazole), p-terphenyl, butyl-PBD
  - typically g/L quantities
- **this accomplishes the following:**
  - efficient non-radiative transfer of excitation energy from the solvent to the fluor
  - high fluorescence quantum yield of the fluor
  - emission of fluor at even longer wavelengths compared to the absorption of the solvent, further reducing self-absorption
  - typically fast decay times
- **if desired a secondary wavelength shifter (WLS) can be added**
  - e.g. bisMSB, POPOP
  - absorbs the light from the fluor and re-emits it at longer wavelengths that match the spectral response of the light detector
  - typically 10's mg/L quantities
- **the whole cocktail can be diluted in an optically-inert liquid**
  - e.g. mineral oil, dodecane
  - usually done for chemical reasons, though good for transparency too

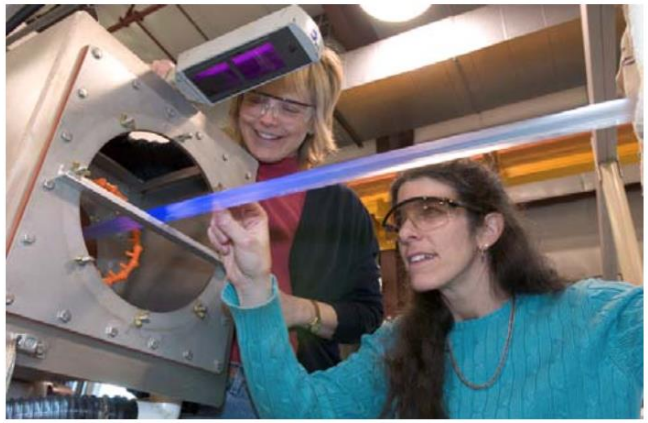
Diluting Liquid Scintillator

- diluting the cocktail in mineral oil or dodecane reduces the light output
- but note that 20% solvent concentration still exhibits ~70% of the light output
- it's not just the fraction of the excitation that was imparted to the solvent
- strongly suggests non-radiative energy transfer takes place between the dodecane and the solvent and/or fluor



Plastic Scintillator

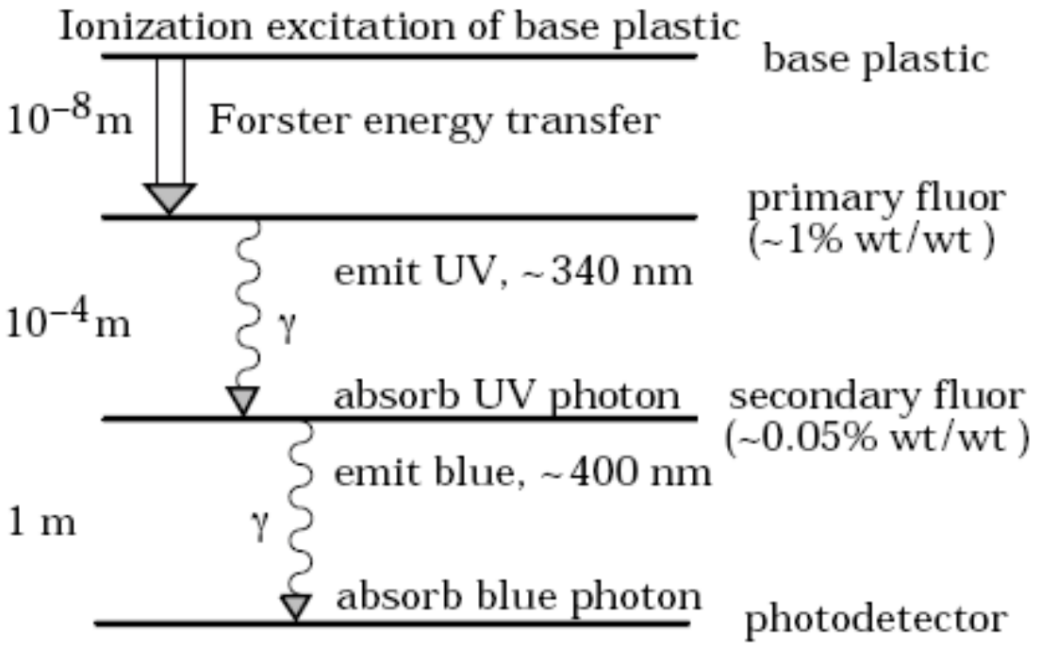
- very common in nuclear and particle physics
- polymer base is typically PVT (polyvinyltoluene) or polystyrene (PVT-based slightly higher light yield)
  - aliphatic plastics (e.g. acrylic) can be used also, but have half the light yield of aromatic plastics
- primary solute is dissolved in the plastic
  - e.g. PBD, p-terphenyl, PBO
- secondary wavelength shifter
  - e.g. POPOP 
  - e.g. BBQ
- same scintillation mechanism



extruded plastic scintillator
for MINERνA from Wikipedia

Scintillation in a Plastic

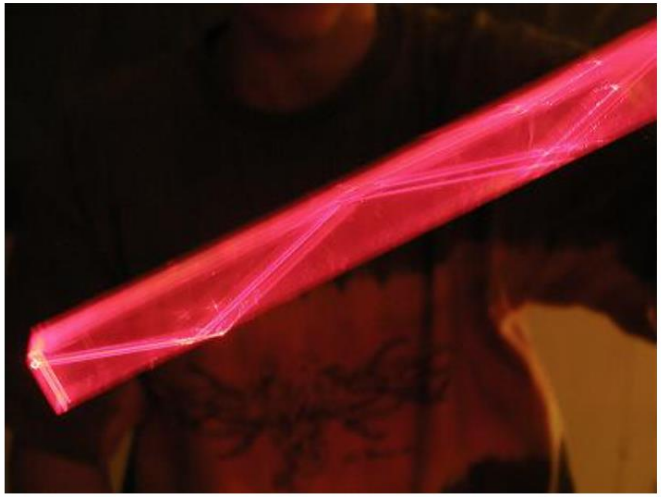
- high concentrations of fluor shorten the decay time and increase the light yield
- at 1% fluor concentration, the average distance between a fluor molecule and an excited base is 10 nm, less than a wavelength of light
- Förster dipole-dipole resonance energy transfer efficiently excites the fluor with a faster decay time and high quantum yield



from Particle Data Group, Review of Particle Detectors

Plastic Scintillator: Advantages and Disadvantages

- reliable, robust, cheap, easy to fabricate into desired shapes
- can be used to detect neutrons by detecting proton recoils (as for a liquid scintillator)
- drawbacks:
  - subject to aging
  - degrades upon exposure to some chemicals (e.g. oils, solvents, fingerprints)
  - suffers radiation damage
  - not resistant to high temperatures
  - surface crazing affects light propagation because a plastic scintillator usually relies on total internal reflection at the surface



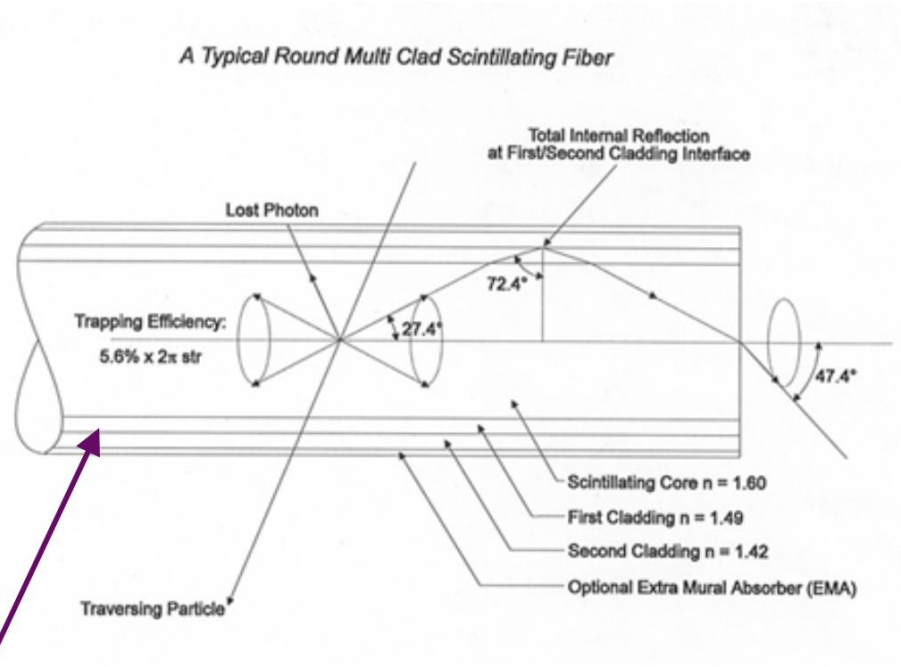
from http://groups.physics.umn.edu/demo/optics/6A4440.html

Care of Plastic Scintillator

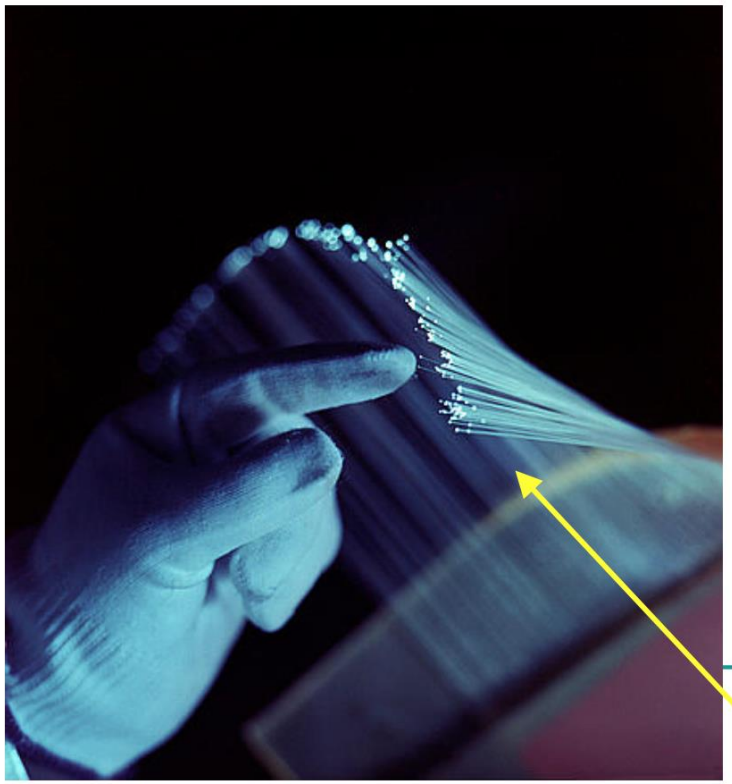
Jeff Wilkes (UW) cleaning up a plastic scintillator from NSF Public Affairs web page

Scintillating Fibres

- the fibre core is
  - glass with activator
  - polystyrene with fluor

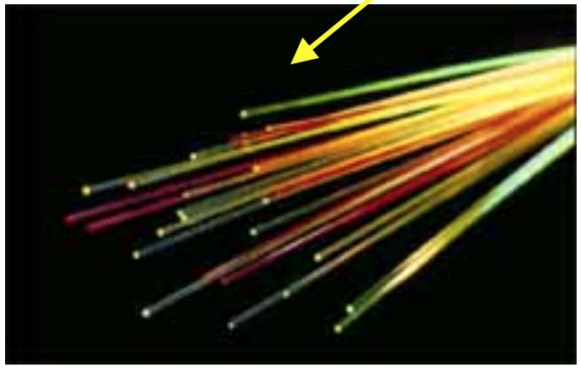


PMMA first cladding
fluorinated PMMA second cladding



glass fibers from Pacific Northwest National Lab

polystyrene core fibres from Saint-Gobain Crystals



Comparing Plastic to Liquid

scintillator	light output	peak λ	decay constant	attenuation length	index of refraction	density [g/cm^3]
BC-400	65%	423 nm	2.4 ns	250 cm	1.58	1.032
BC-404	68%	408 nm	1.8 ns	160 cm	1.58	1.032
BC-416	38%	434 nm	3.3 ns	400 cm	1.58	1.032
BC-428	36%	480 nm	12.5 ns	150 cm	1.58	1.032
PC-based liquid	80%	425 nm	2.5 ns		1.505	0.877
30% PC diluted in mineral oil	60%	425 nm	3 ns	>500 cm	1.48	0.86
LAB-based	75%	425 nm	3.5 ns		1.47	0.87

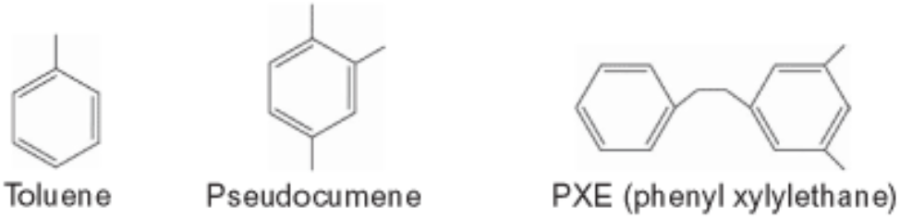
from Saint-Gobain Crystals

note: values for plastics are for commercial products while liquid scintillator cocktails are representative values that can be adjusted by selecting the fluor, the wavelength shifter and their concentrations

note: light yield is quoted as a fraction of anthracene, which is 17,400 photons/MeV

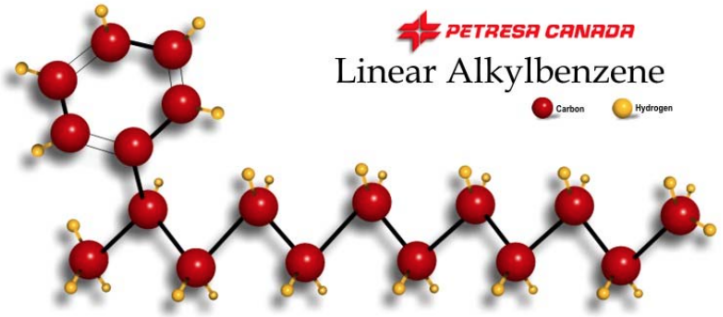

Intermission

Solvents

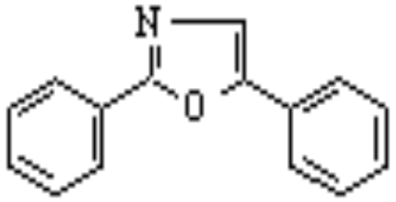


from http://nationaldiagnostics.com/article_info.php/articles_id/117

- pseudocumene is common
  - used in KamLAND, Borexino, Palo Verde, MACRO, many commercial liquid scintillator cocktails
- safer solvents are being used (especially in biology applications)
  - PXE has density 0.985
  - DIN is in many commercial cocktails, miscible with water
    - however absorption is higher so less suited for large detectors
  - LAB (linear alkylbenzene)
    - developed by SNO+ as a scintillator (solvent) for nuclear/particle physics experiments; we're the first experiment to propose using LAB
    - high flash point, low toxicity
    - high light yield (about high as pseudocumene-based liquids)
    - excellent transparency
    - compatible with plastics like acrylic
    - cheap



Binary Mixtures and the Fluor



PPO or 2,5-diphenyloxazole

- the solvent molecule x is excited, relaxes to S_{1x}
- either by radiative or non-radiative transfer, the S_{1y} in the fluor molecule y is excited
  - radiative transfer is absorption and re-emission by the fluor
  - the emission spectrum of the solvent chosen to overlap the absorption spectrum of the fluor
  - S_{1y} is thus slightly lower in energy than S_{1x}
- this has to occur preferentially over non-radiative de-excitation of the solvent molecules S_{1x}
- efficient non-radiative transfer depends on the concentration of fluor in the binary mixture
  - occurs by solvent-solvent dipole resonance interaction (Förster energy transfer) or by thermal diffusion of excited solvent molecules in a liquid
  - occurs by Förster energy transfer between the same or adjacent polymer chains in the plastic

Determining the Efficiency of Energy Transfer

Method 1 (fluorescence emission method): measure the fluorescence excitation and emission of PPO-LAB solution; excitation at 318 nm (LAB excitation), integrate emission range from 340-550 nm (PPO emission)

Method 2 (decay time method): excitation at 250 nm, emission 360 nm, measure the decay times of PPO-LAB solution, compare to the decay time of pure PPO

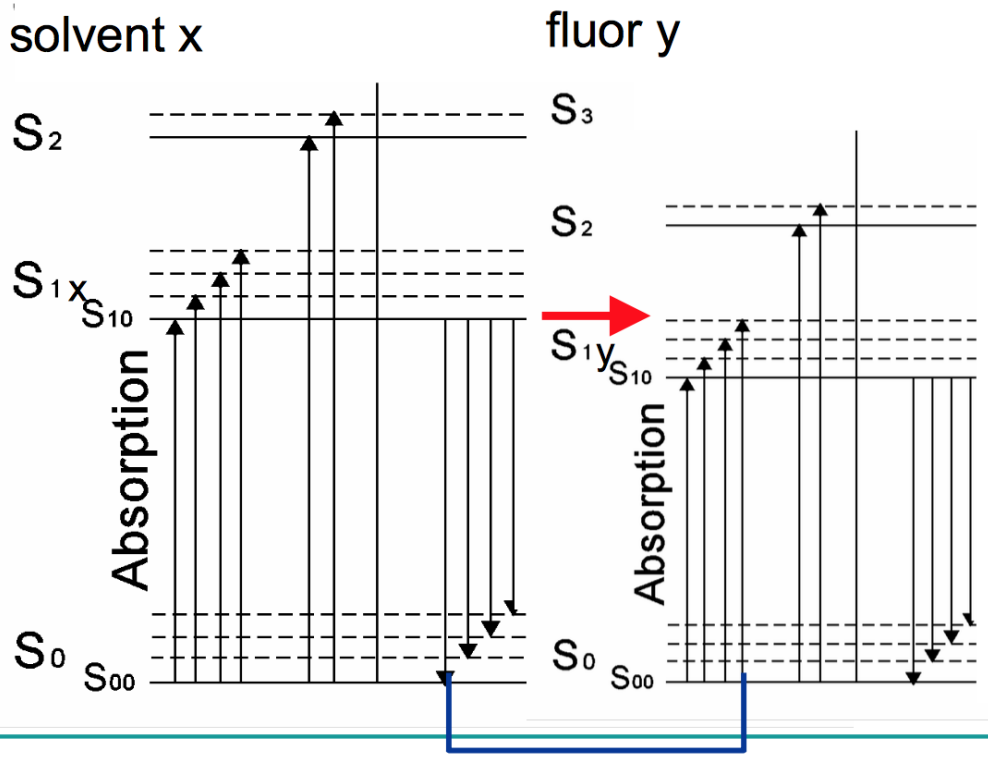
LAB-PPO energy transfer efficiency

PPO [g/L]	Method 1	Method 2
32	n/a	90.7%
4	80%	80%
2	72%	73%
1	60%	61%
0.5	46%	55%
0.25	35%	47%
0.1	23%	n/a
0.02	5.6%	n/a

M.Chen

Energy Transfer: Solvent-Fluor

red: efficient non-radiative transfer is desired



aside: fluor-WLS energy transfer can be *radiative* because of the high quantum yield of the fluor and small WLS concentrations used to maximize transparency

blue: radiative transfer works; reduced by solvent fluorescent quantum yield

Additional Considerations

- quenching, linearity and pulse-shape discrimination (PSD) are related properties
  - PSD is the ability to distinguish between different particles exciting the scintillation by the shape of the light pulse
- these properties can be considered, in general, for all types of scintillators
- most of this discussion is directed at organic scintillators

Impurity Quenching

- presence of oxygen in an organic liquid at ppm levels can strongly quench fluorescence, especially in unitary scintillators
  - greatly reduces light yield
  - shortens lifetimes
- oxygen and other impurities can compete with the fluor in energy transfer from the excited solvent
  - again reducing light yield
- to combat oxygen quenching
  - increase the fluor concentration
  - deoxygenate the scintillator by bubbling with nitrogen or vacuum degassing the liquid
- impurities in an inorganic crystal can quench the excitation, competing with activator centres
  - the obvious solution – grow pure crystals

Ionization Quenching

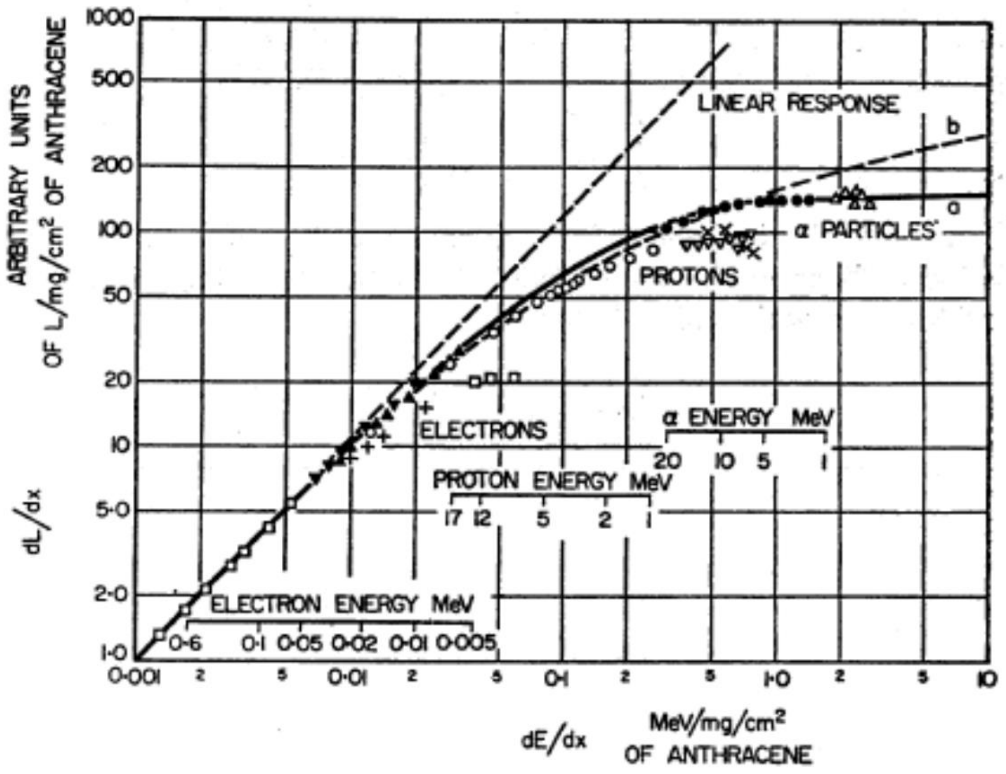
- ionization excites singlet and triplet π-electronic states
  - leading to fast fluorescence and slow delayed fluorescence from the triplet
  - results in multi-component scintillation decay time profile whereas UV excitation produces mainly single time constant fluorescence
- high ionization density can quench the excited singlet π-electrons
  - the fast component is thus reduced for high dE/dx particles
  - picture it as overlapping excitations that interfere with each other
- three important consequences:
  - non-linearity in energy response
  - heavy particles with higher dE/dx (e.g. α) produce less light for the same energy deposit, (by a factor of >10 for α in liquids)
  - the scintillation pulse shape (fast/slow components) is different for heavy particles, enabling pulse-shape discrimination

Ionization Quenching – Birks' Rule

- start with linearity at low ionization density $\frac{dL}{dx} = A\frac{dE}{dx}$
- let the density of excited molecules be proportional to the ionization density $B\frac{dE}{dx}$
- let k be the fraction that is quenched

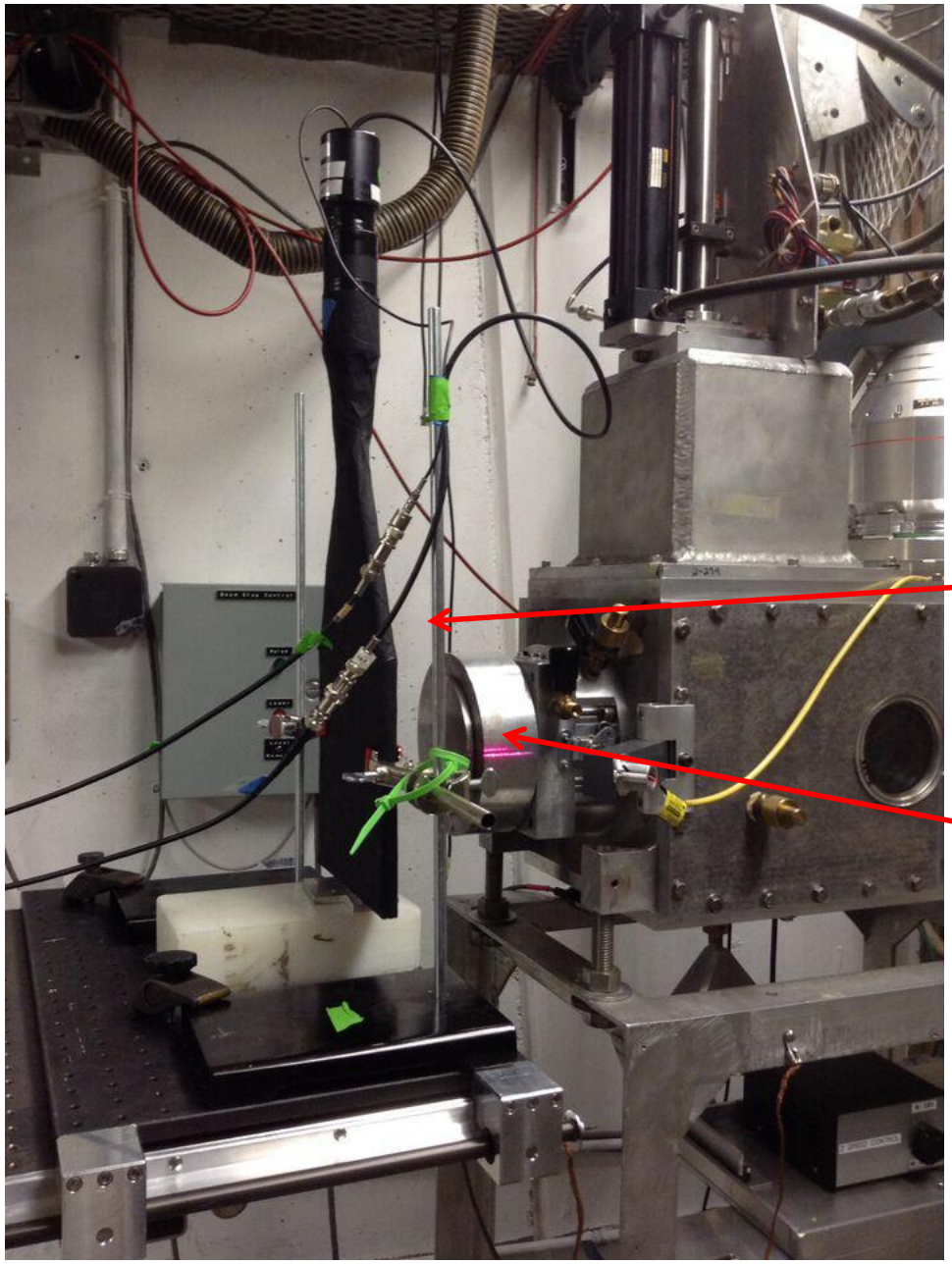
$$\frac{dL}{dx} = \frac{A\frac{dE}{dx}}{1 + kB\frac{dE}{dx}}$$

- for small dE/dx, approaches linearity
- for large dE/dx, approaches saturation $\frac{dL}{dx} = \frac{A}{kB}$



from Birks

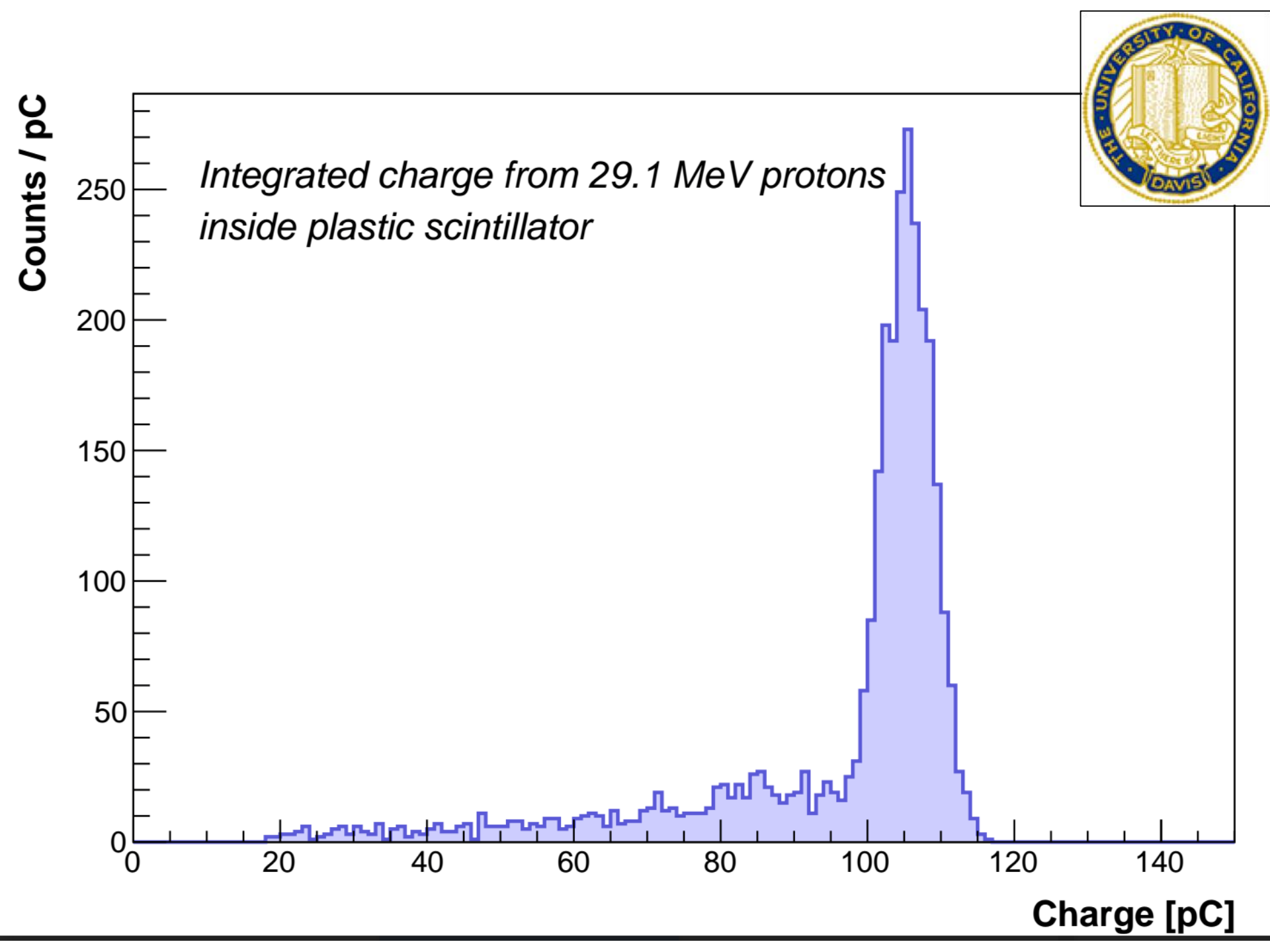
- *for any given scintillator composition, must fit the quenching data to get kB*
- *A is the absolute scintillation efficiency*



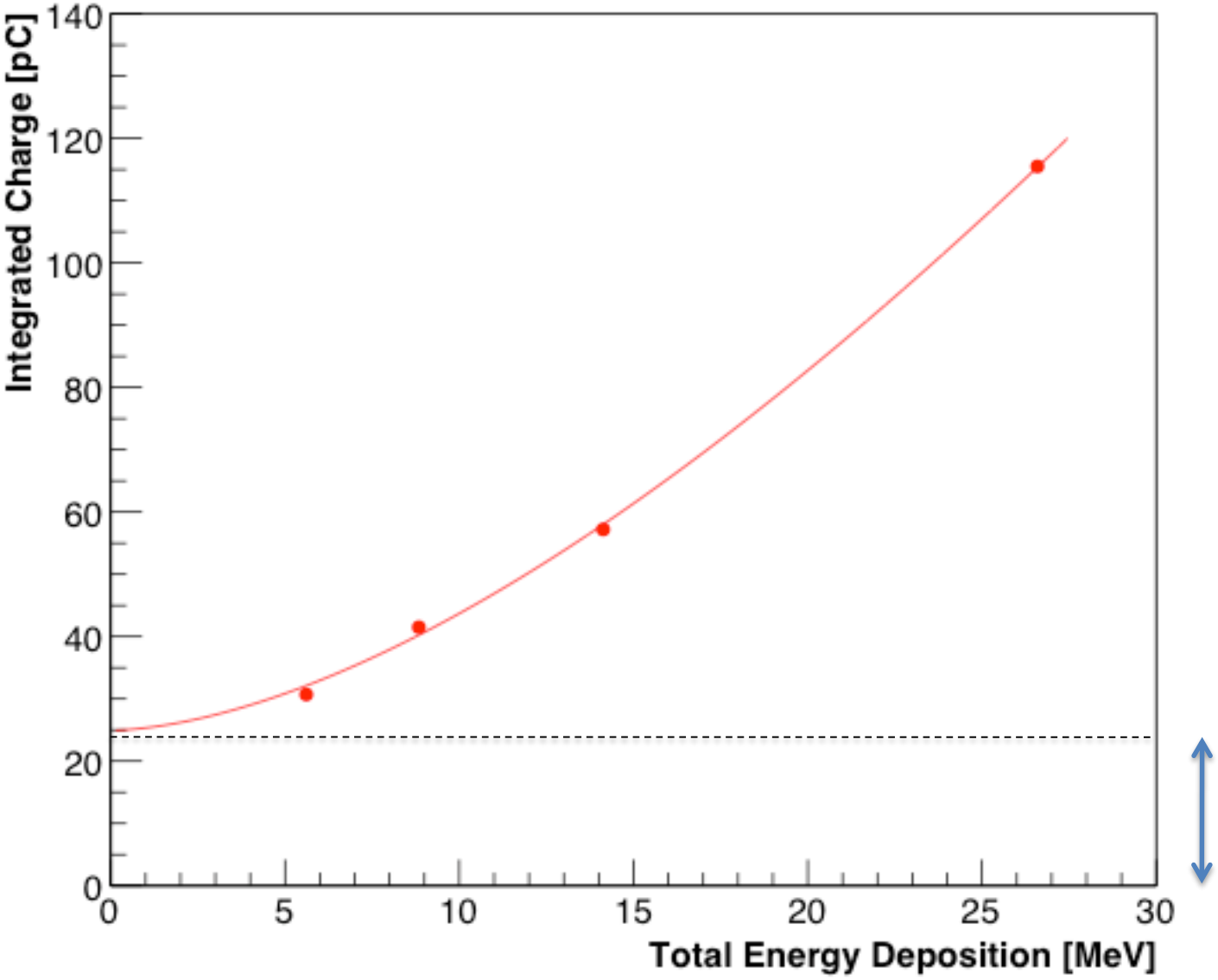
Measuring Birk's constant at CNL. June 2015

Plastic Scintillator

Proton beam pipe window

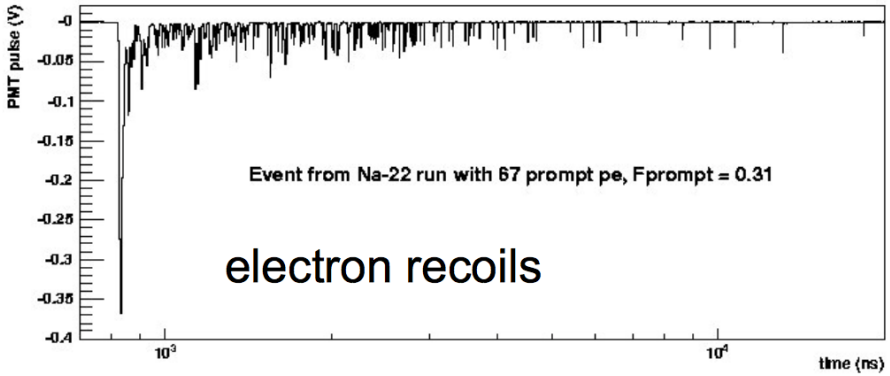

Integrated charge from 29.1 MeV protons
inside plastic scintillator
Counts / pC
Charge [pC]
0
50
100
150
200
250
0
20
40
60
80
100
120
140

Plastic Scintillator Proton Quenching

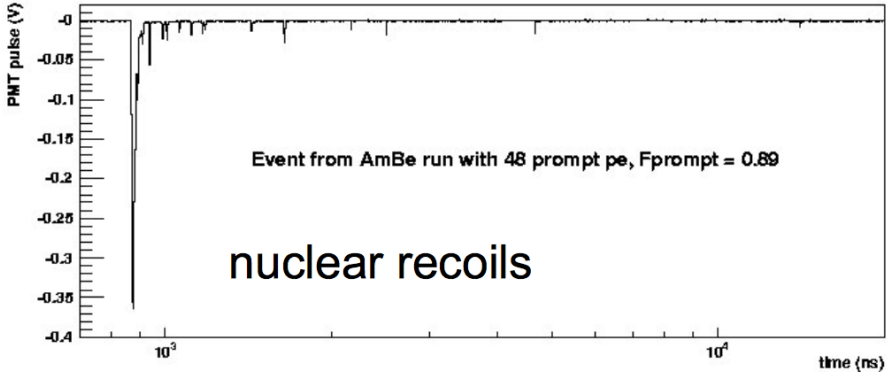


ADC pedestal

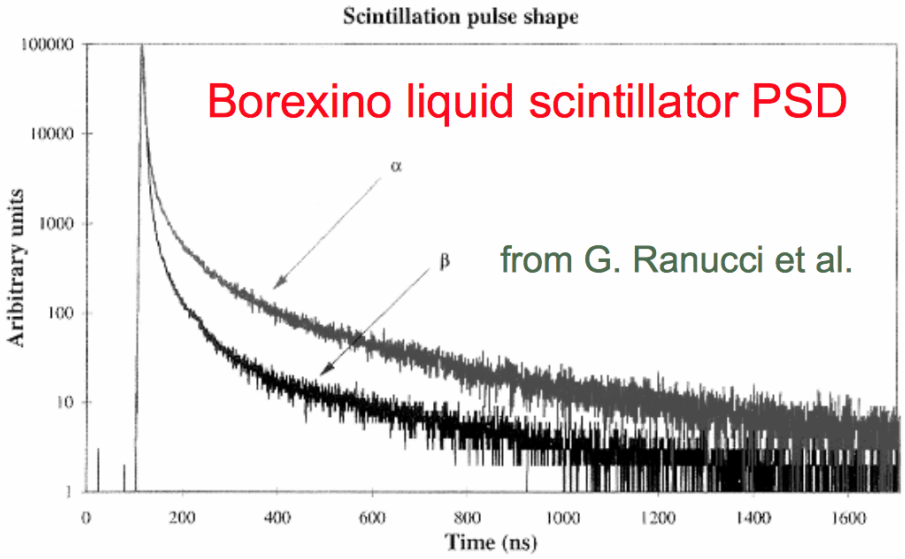
PSD Scintillation Time Profiles

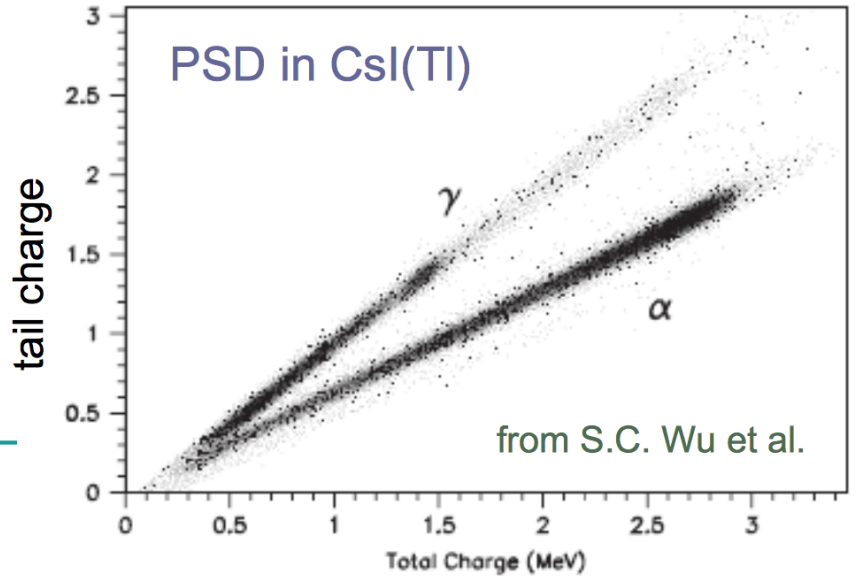


DEAP liquid argon PSD



PSD = Pulse Shape Discrimination





Xenon Scintillation

Ionization in liquid:

- About one electron-ion pair /15 eV of deposited energy

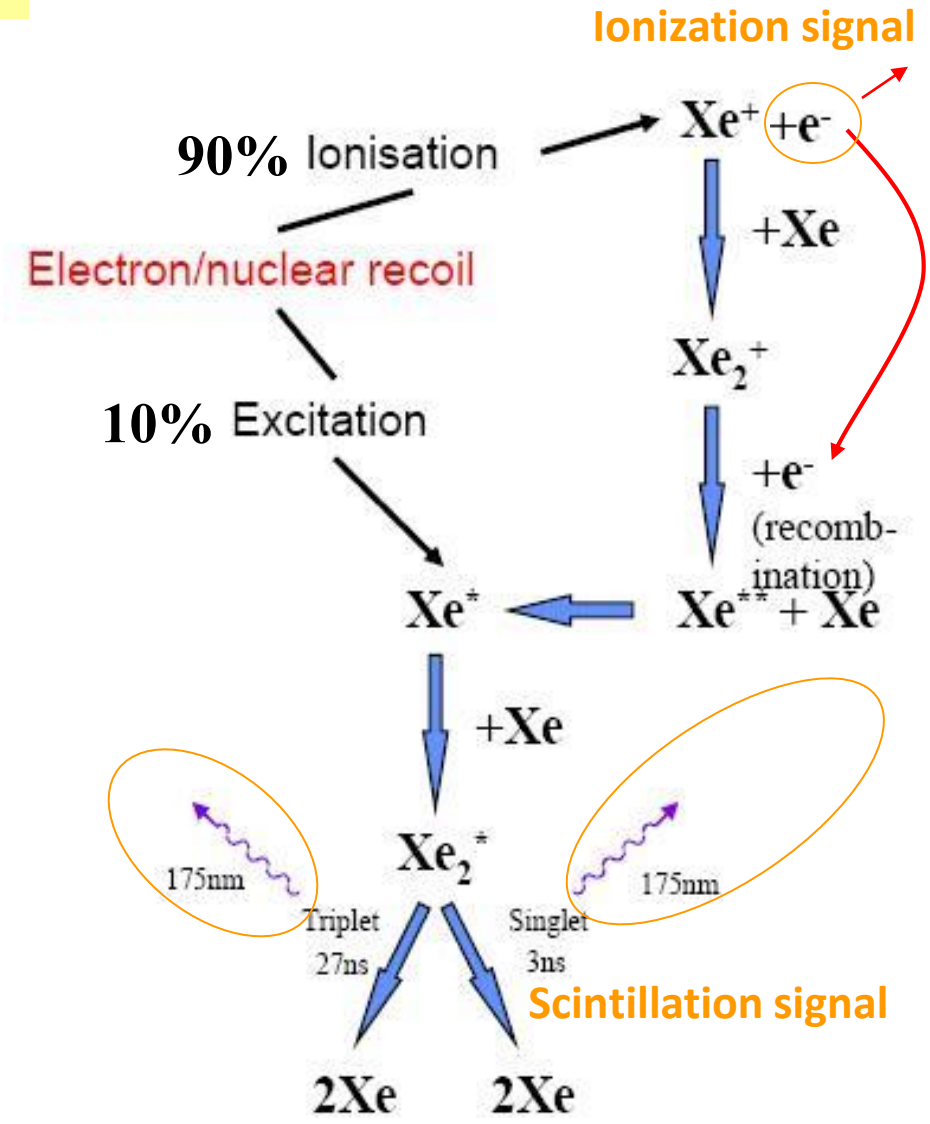
175 nm Scintillation:

- About one photon/20 eV of deposited energy

- Ionization/Scintillation ratio changes with interaction type

Ion pairs more likely to recombine in the dense tracks generated by nuclear interactions

- A strong anti-correlation between ionization and scintillation



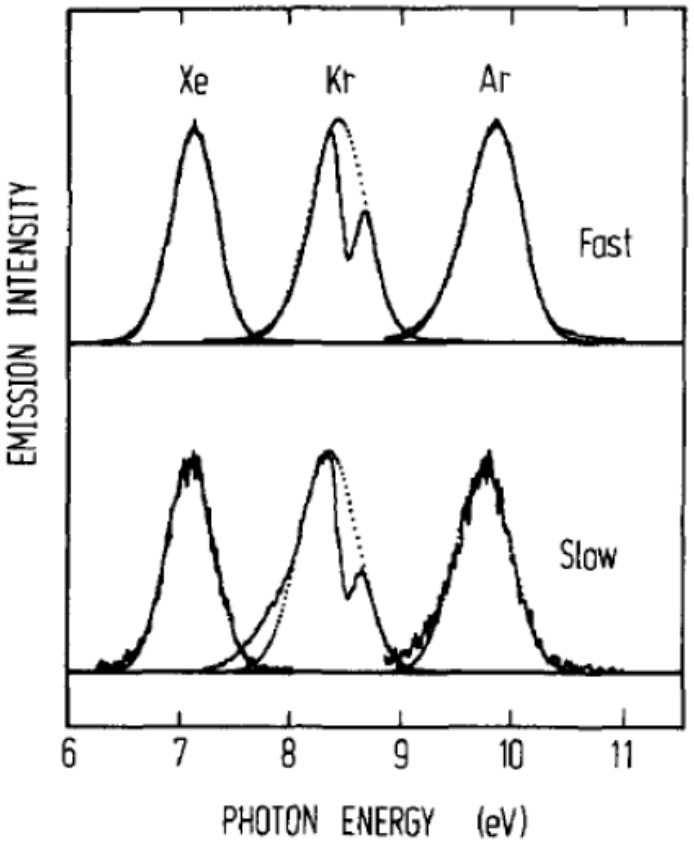
Scintillation in liquid noble elements

Xe is 175 nm

Ar is 128 nm

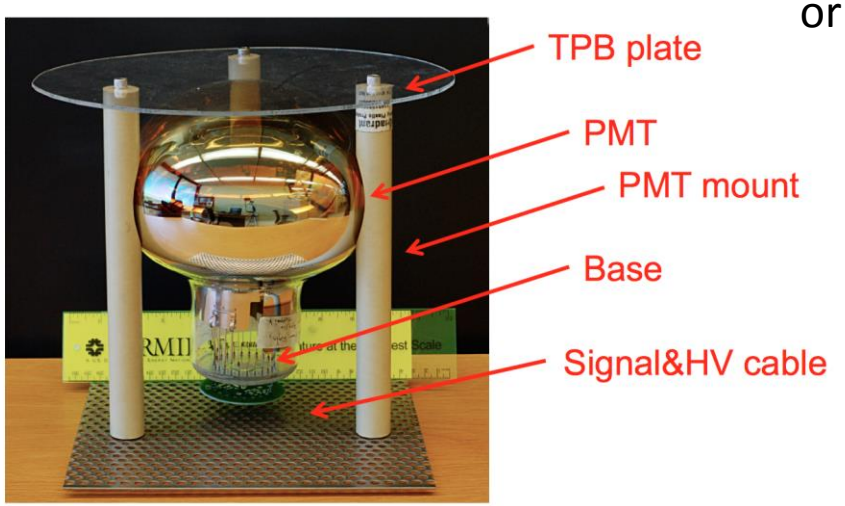
This means that light sensors
need to be match to this wavelength
OR one needs to shift the light to
a longer wavelength.

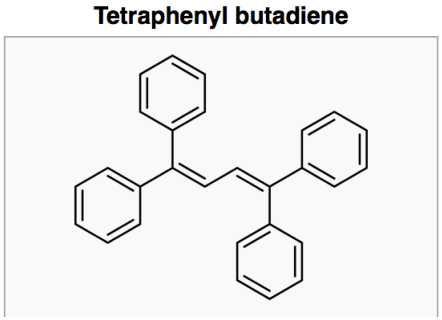
E. Morikawa et al., J Chem Phys
vol 91 (1989) 1469

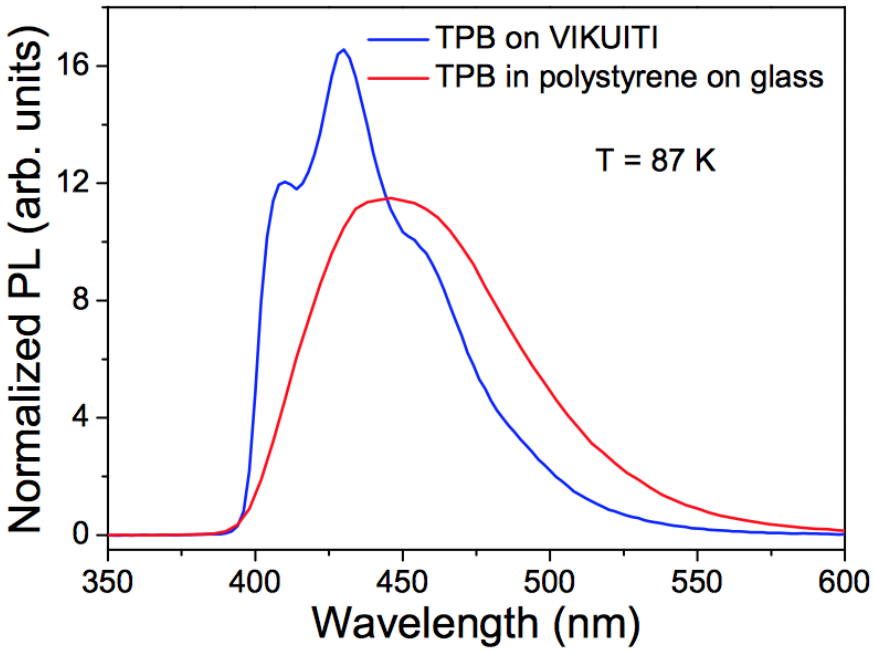


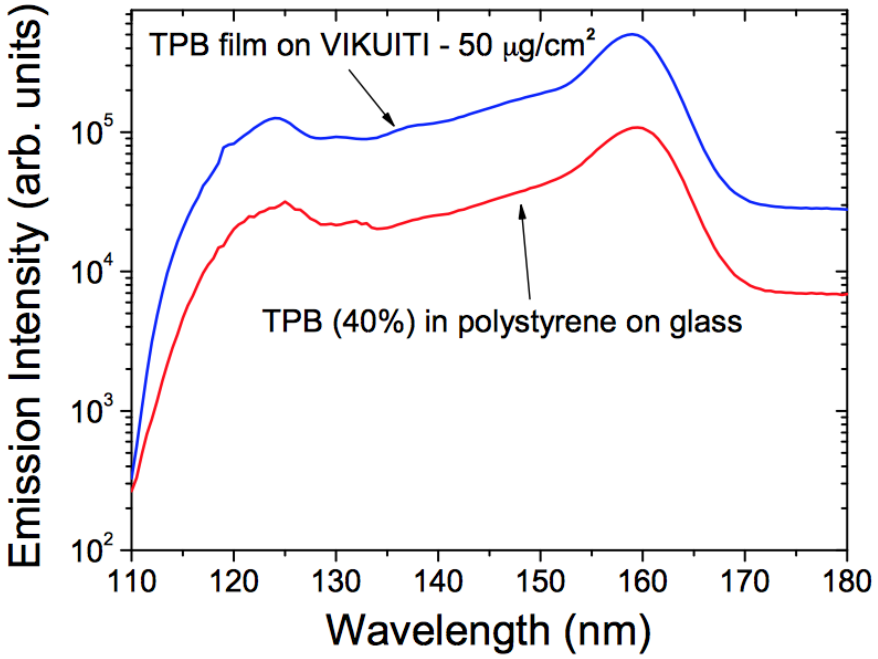
T.Katori

One needs to shift wavelength by coating a wavelength shifter (e.g. TPB) directly onto the PMT front face or on a plate of glass or acrylic in front of the PMT



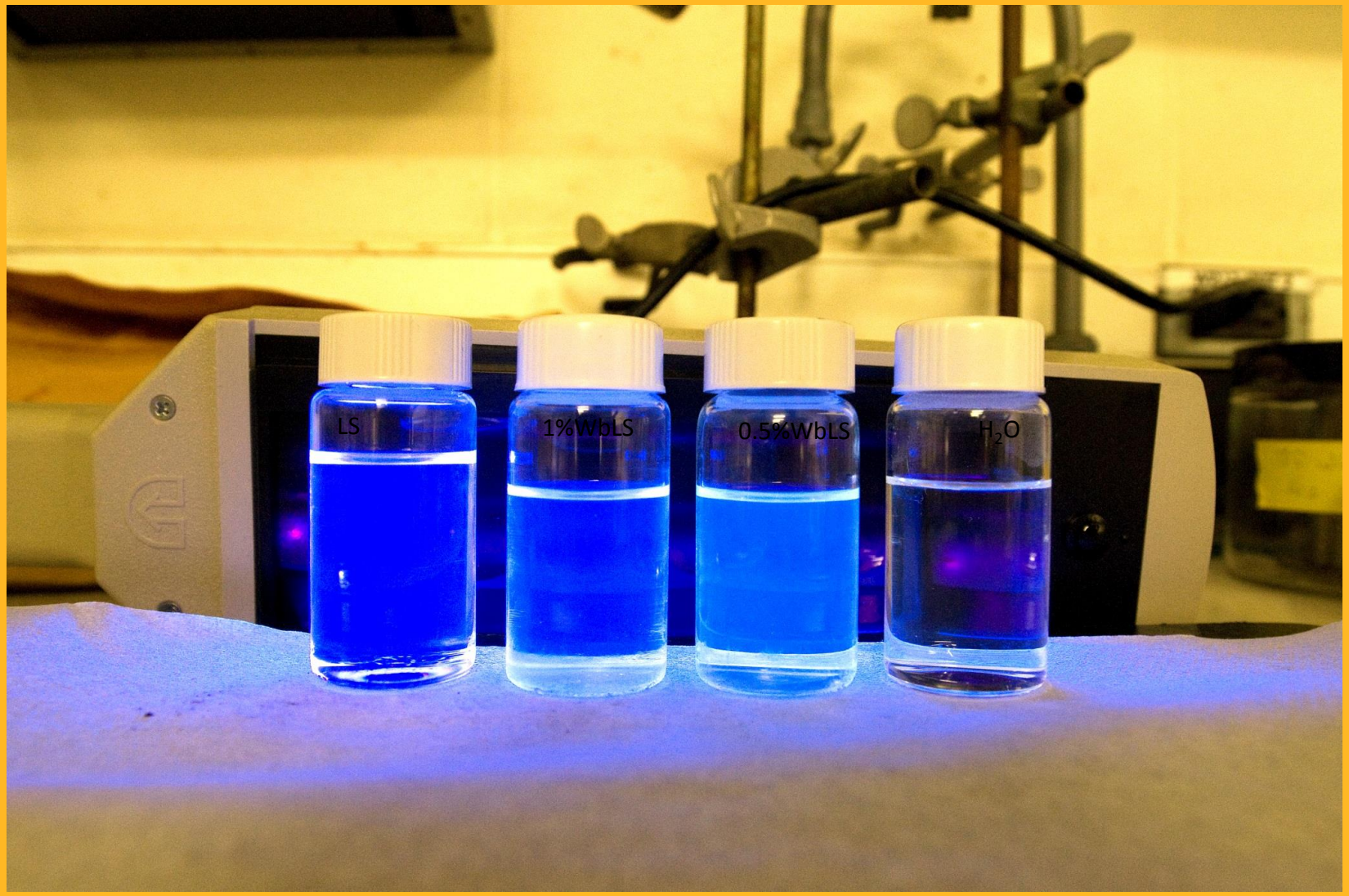






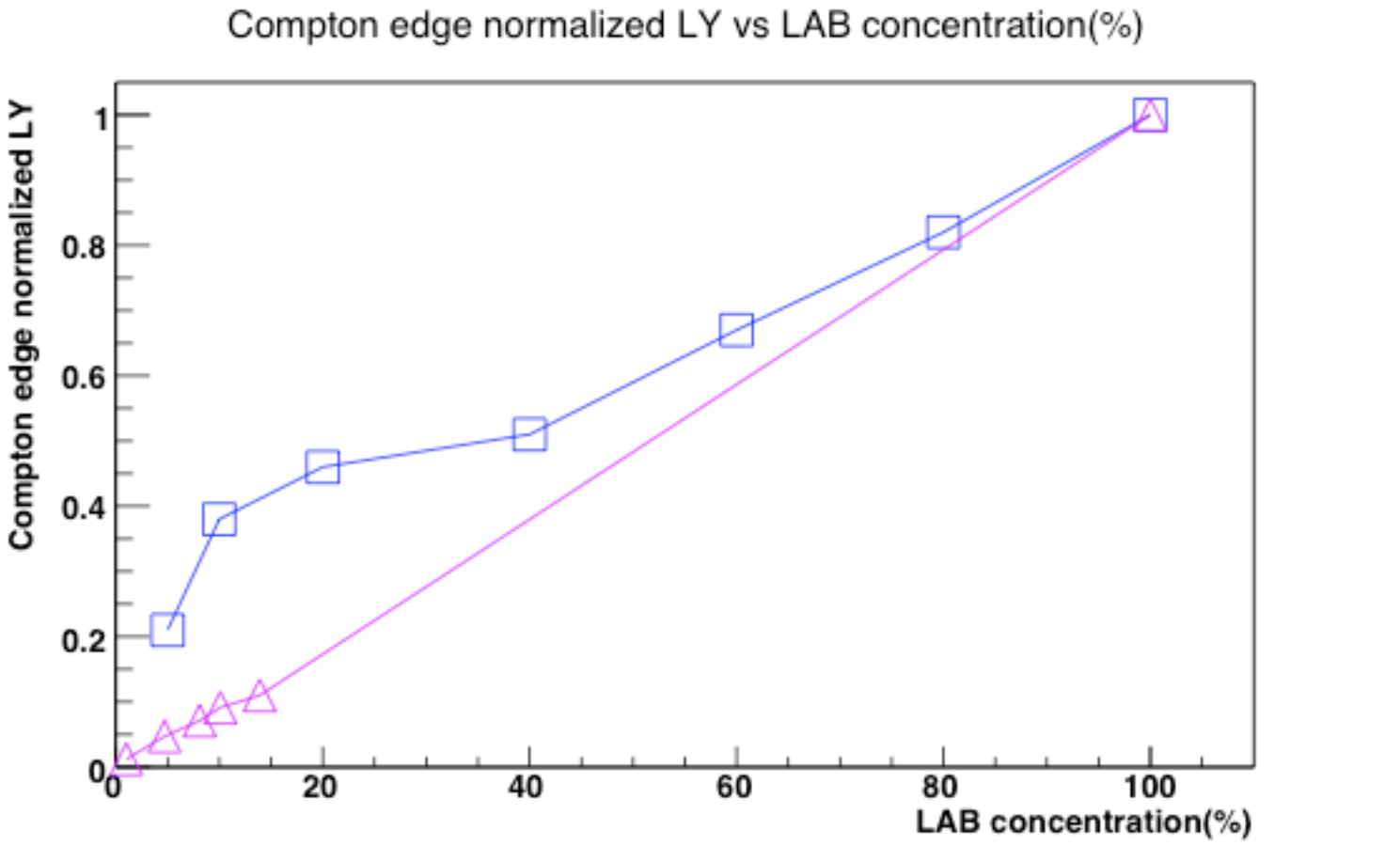
R.Francini, et al. arXiv:1304.6117

Water-base Liquid Scintillator (WbLS)



Different compositions of WbLS (1% ~ 100 optical photons/MeV), in comparison with pure LS and H_2O, under UV light (λ=250nm)

Dilution of WbLS in water allows for tuning light yield as desired to match the physics.



WbLS cocktail in water (violet) and cyclohexane (blue)

What can you do with this?

Advanced Scintillator Detector Concept (ASDC):

A Concept Paper on the Physics Potential of Water-Based Liquid Scintillator

J. R. Alonso,[1] N. Barros,[2] M. Bergevin,[3] A. Bernstein,[4] L. Bignell,[5] E. Blucher,[6] F. Calaprice,[7] J. M. Conrad,[1] F. B. Descamps,[8] M. V. Diwan,[5] D. A. Dwyer,[8] S. T. Dye,[9] A. Elagin,[6] P. Feng,[10] C. Grant,[3] S. Grullon,[2] S. Hans,[5] D. E. Jaffe,[5] S. H. Kettell,[5] J. R. Klein,[2] K. Lande,[2] J. G. Learned,[11] K. B. Luk,[8,12] J. Maricic,[11] P. Marleau,[10] A. Mastbaum,[2] W. F. McDonough,[13] L. Oberauer,[14] G. D. Orebi Gann[a],[8,12] R. Rosero,[5] S. D. Rountree,[15] M. C. Sanchez,[16] M. H. Shaevitz,[17] T. M. Shokair,[18] M. B. Smy,[19] M. Strait,[6] R. Svoboda,[3] N. Tolich,[20] M. R. Vagins,[19] K. A. van Bibber,[18] B. Viren,[5] R. B. Vogelaar,[15] M. J. Wetstein,[6] L. Winslow,[1] B. Wonsak,[21] E. T. Worcester,[5] M. Wurm,[22] M. Yeh,[5] and C. Zhang[5]

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[19] *Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA*
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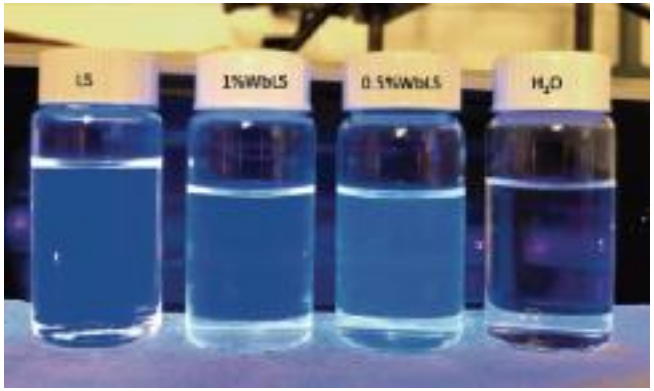
[21] *Institute for Experimental Physics, University of Hamburg, Germany*
[22] *Institute of Physics & EC PRISMA, Johannes Gutenberg-University Mainz, 55128 Mainz, Germany*

arXiv:1409.5864

Advanced Scintillator Detector Concept (ASDC) concept paper posted on archive.



1% gives ~100 optical photons/MeV

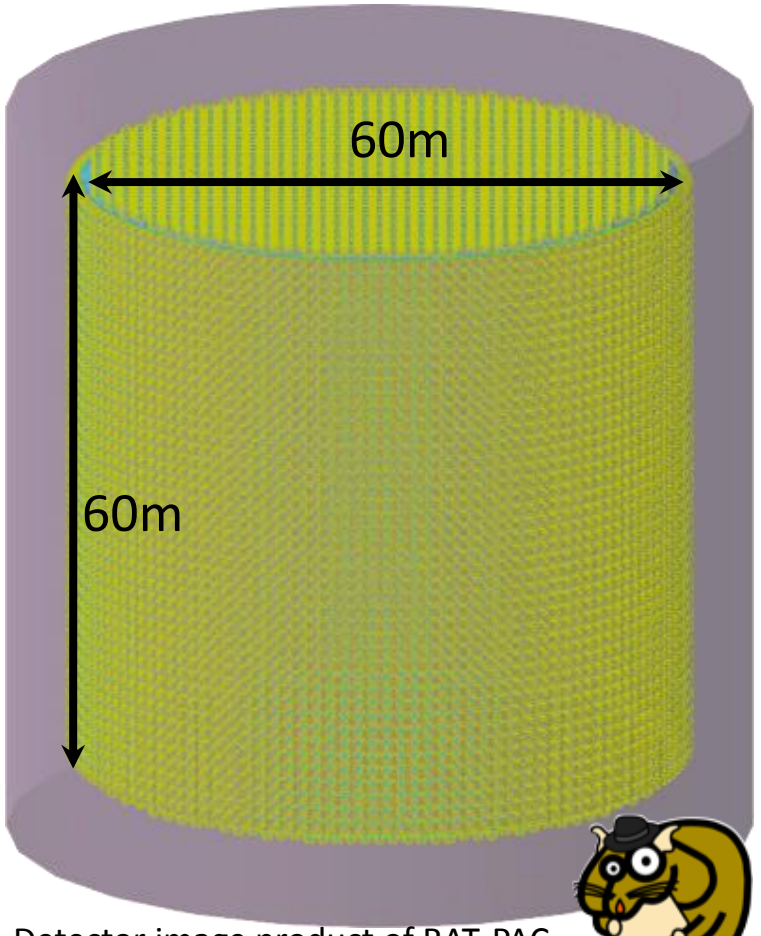
4% WbLS gives approximately four times the light yield of pure water

THEIA:

A realisation of the Advanced Scintillation Detector Concept (ASDC)

Concept paper - arXiv:1409.5864

- 50-100 kton WbLS target
- High coverage with ultra-fast, high efficiency photon sensors
- 4800 m.w.e. underground (Homestake).
- Is Kamioka a possibilty?
- Comprehensive low-energy program: solar neutrinos, supernova, DSNB, proton decay, geo-neutrinos, DBD
- In the LBNF beam: long-baseline program complementary to proposed LAr detector



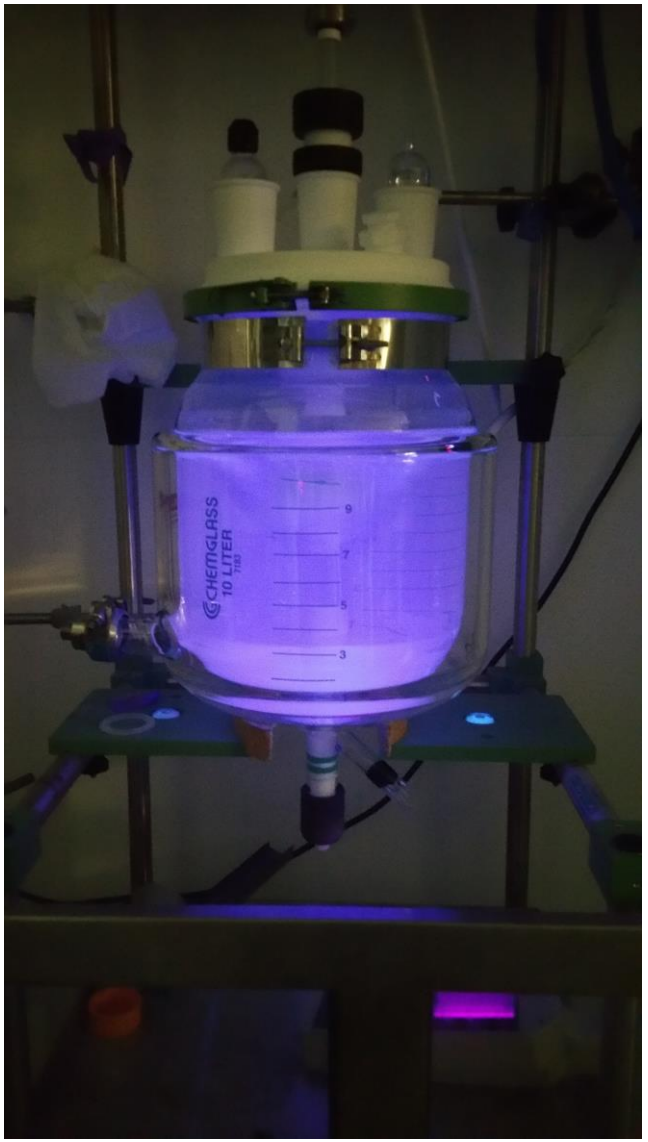
Detector image product of RAT-PAC

〇Broad physics program!

WbLS Development Status

- Light yield studies at BNL and soon at LBNL
- Stability and material compatibility studies at BNL (uncovered one problem so far – butyl rubber adhesive).
- Purification studies at UC Davis using NanoFiltration (NF) to separate organic components from water.
- Scaled up production: 10 liters produced in June with BNL 5 liter reactor. Used for NF and Material studies.
- 100 liter batch under production. Will be used for attenuation length studies (currently have on 1-meter arm). Will use UCI and/or LLNL facility.
- 1-ton BNL prototype approved and under construction.

BNL WbLS production

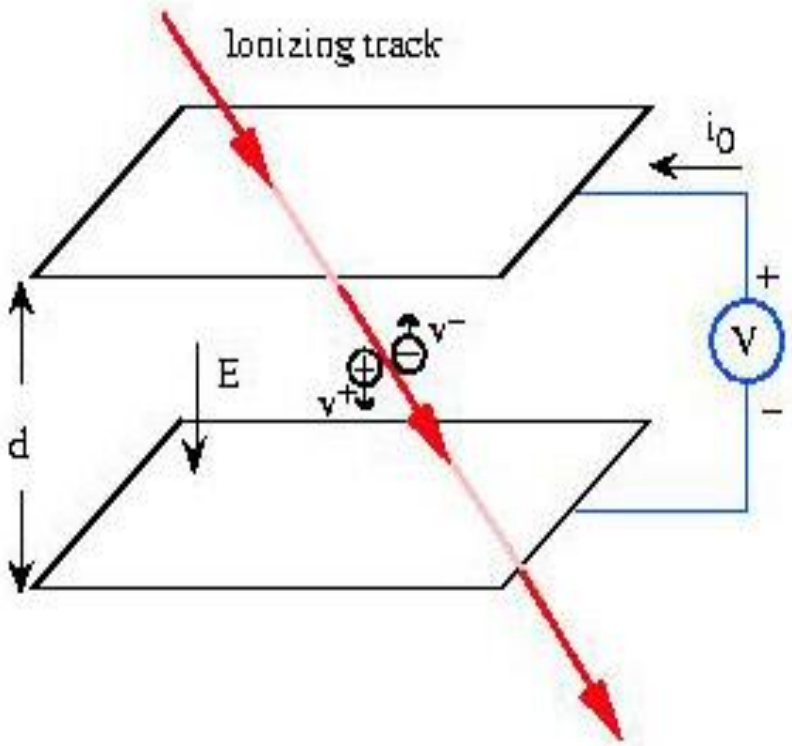


Liquid Argon Time Projection Chamber

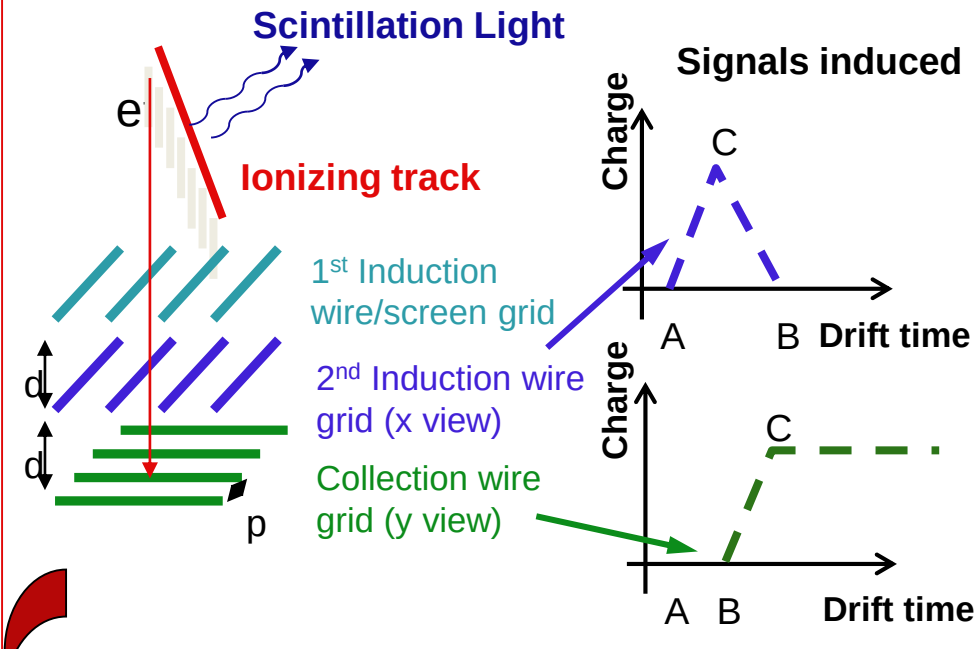
Single Phase LAr TPC

Operating principles

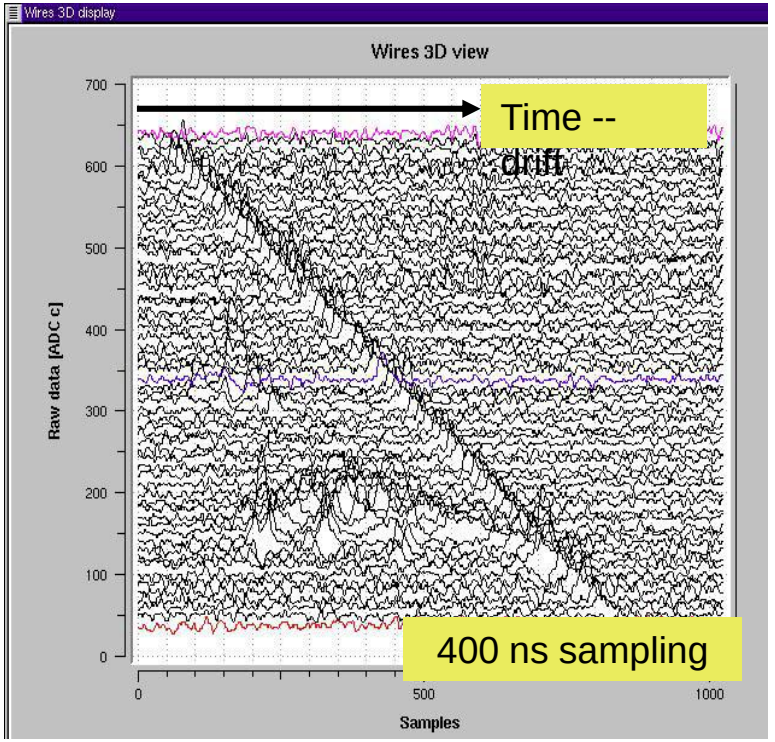
- ionizing events taking place in a volume of LAr (where a uniform electric field is applied) produce electron-ion pairs
- These charges drift along the field lines. The motion of the much faster electrons induces a current on the anode. The electrons can drift several metres if the LAr is highl purified (electronegative impurities < 0.1 ppb O_2 equiv.)

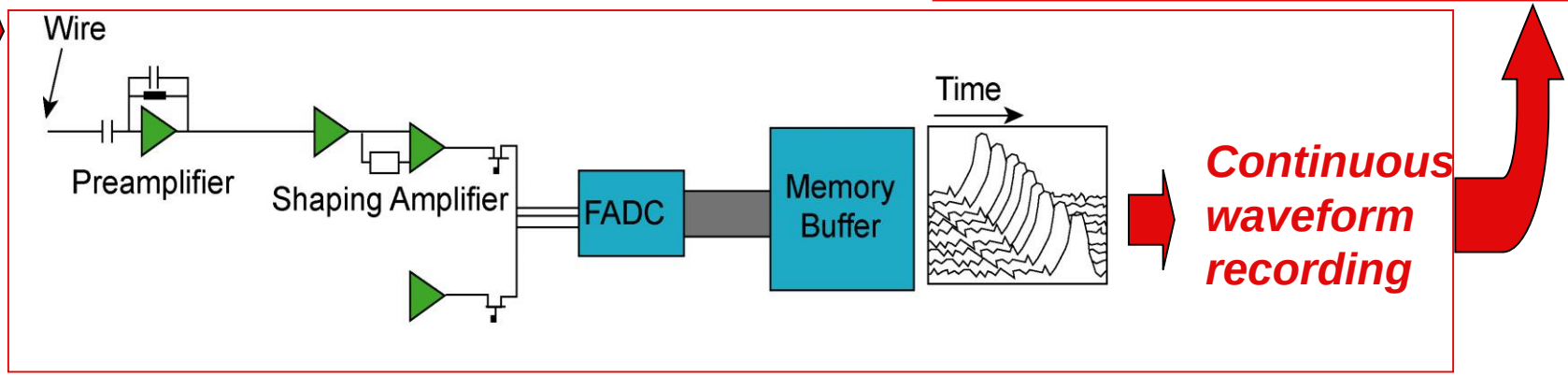


Non-destructive multiple readout



Raw Data from a 10 m³ prototype



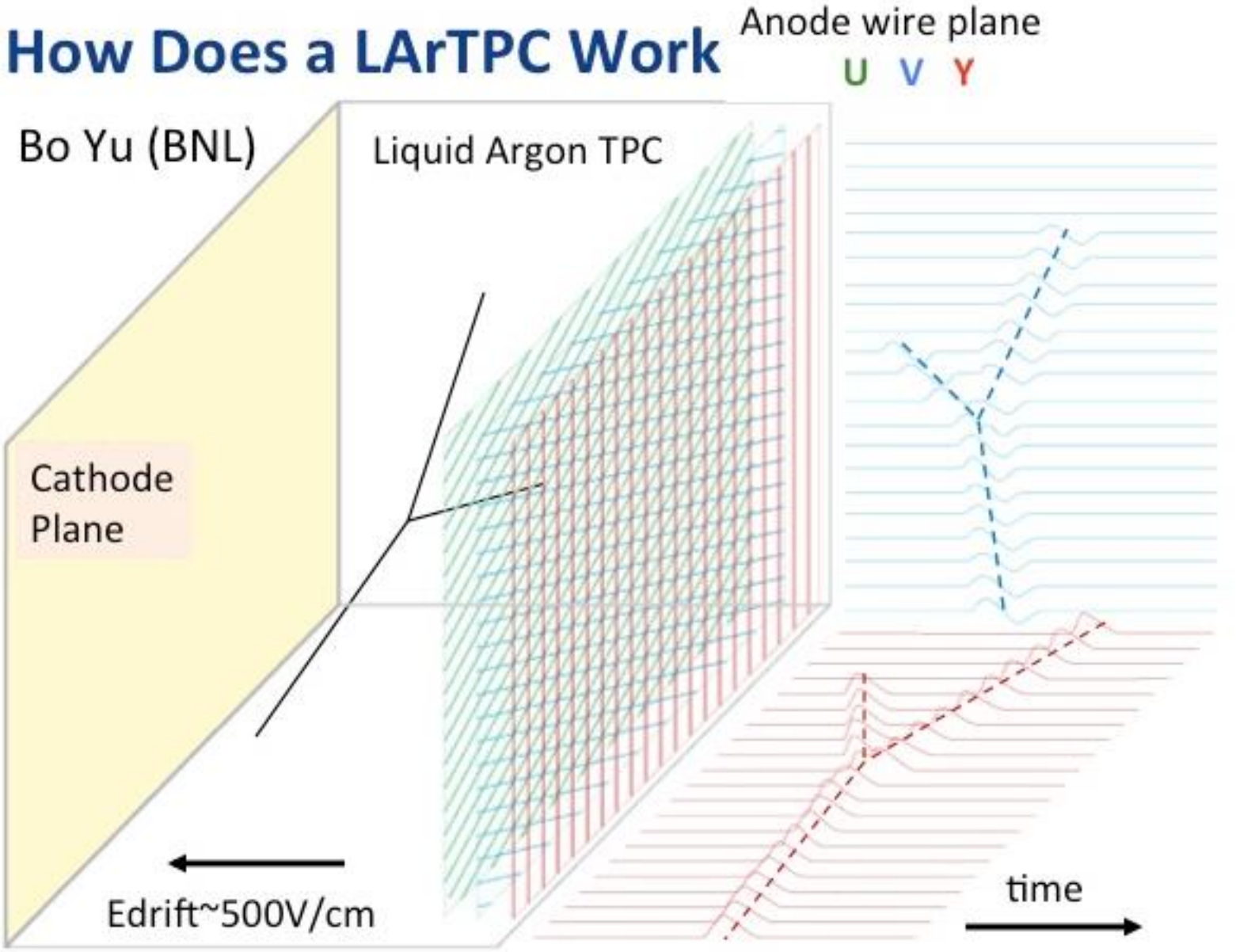


- No charge multiplication occurs in LAr
- LAr is also a very good scintillator scintillation light (l = 128 nm) provides a prompt signal to be used for triggering purposes and for absolute event time measurement

- High electron mobility **(~500 $cm^2V^{-1}s^{-1}$)**
- Possibility of extreme purification **(<0.1 ppb O_2)**
- ↳Long electron life time (>ms) and drift paths (>m)
- High electron-ion pairs yield **(~ 10000 e^- for 2 mm of a m.i.p. track)**

  density: 1.4 g/cm^3 **dE/dx: 2 MeV/c**
- Available in large quantities **(GAr ~ 0.9% of air)**

How Does a LArTPC Work



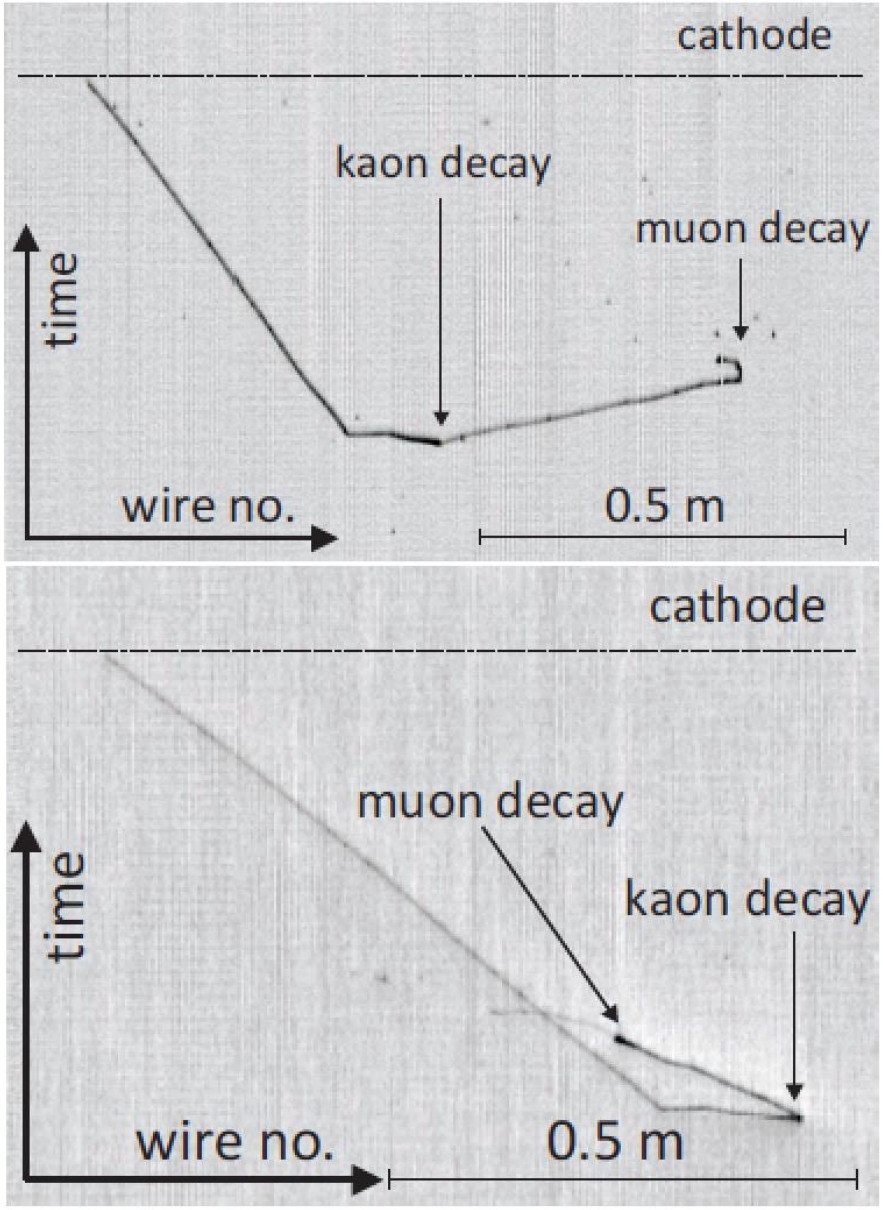
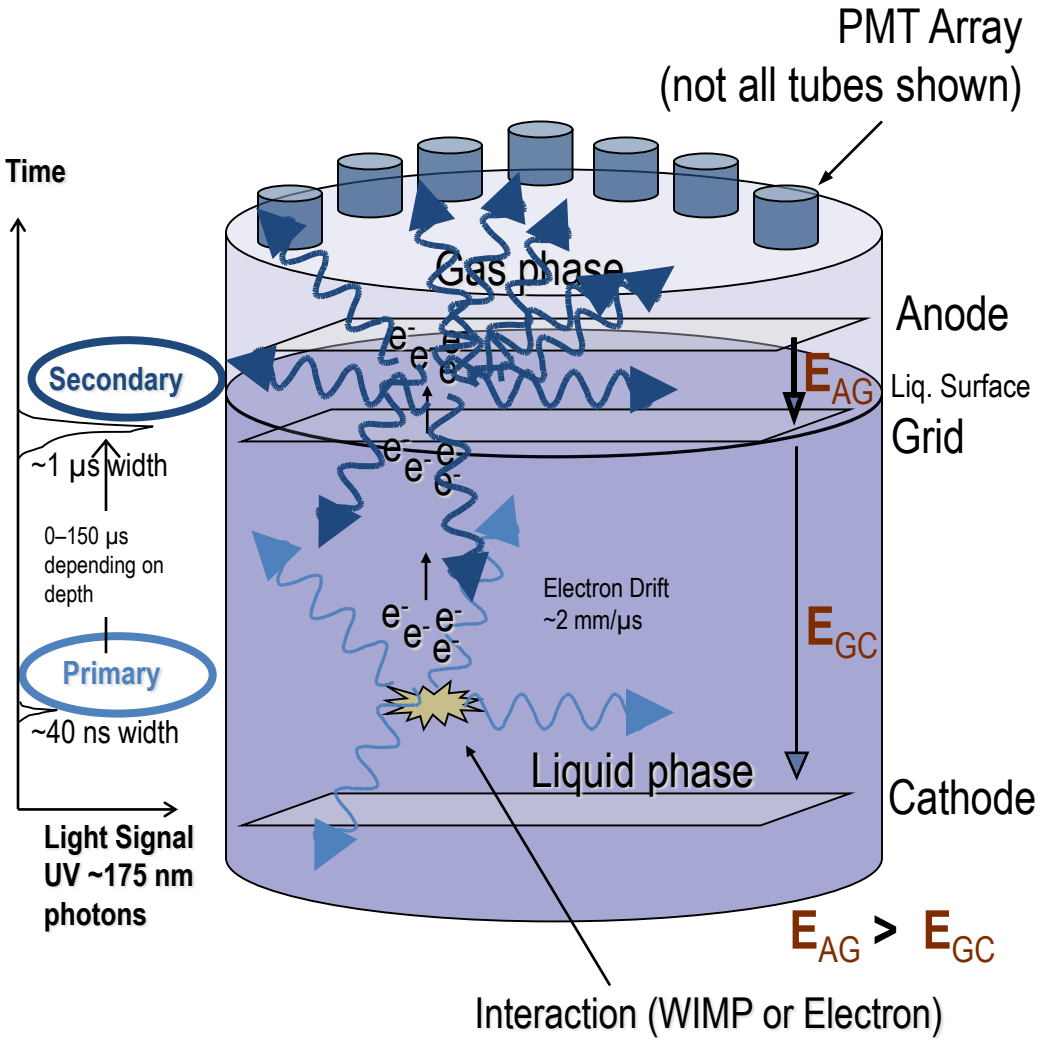
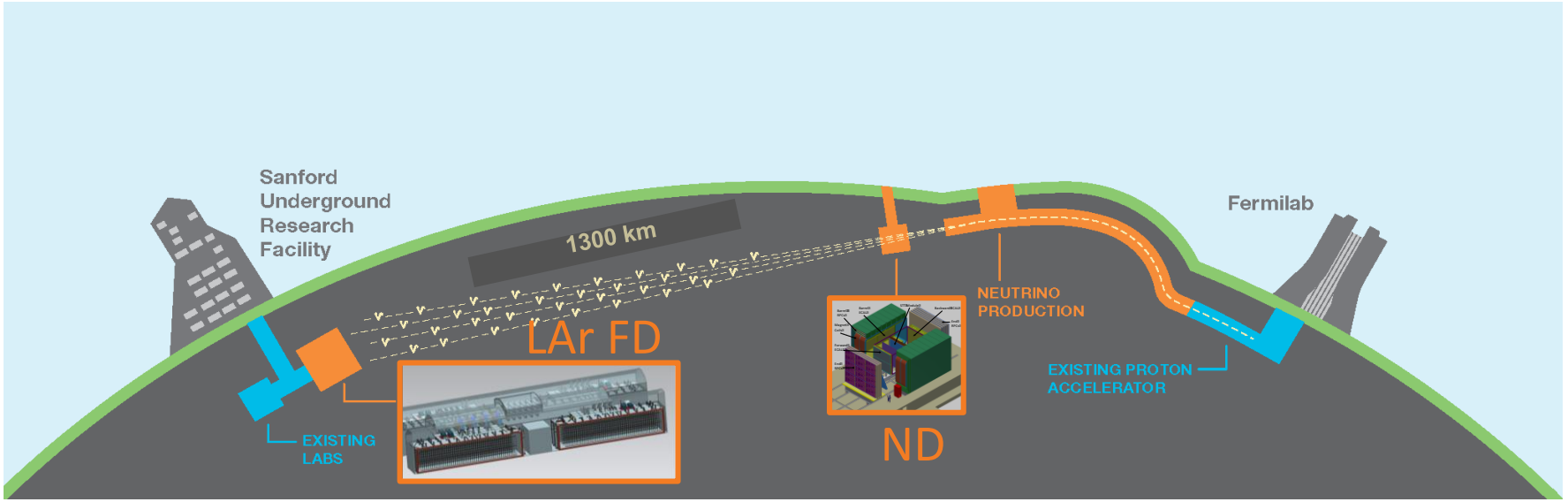


Figure 4.3: Event display for a decaying kaon candidate $K \to \mu\nu_\mu$ $\mu \to e\nu_e\nu_\mu$ in the ICARUS T600 detector observed in the CNGS data (K: 90 cm, 325 MeV; μ : 54 cm, 147 MeV; e : 13 cm, 27 MeV). The top figure shows the signal on the collection plane, and the bottom figure shows the signal on the second induction plane [82].

Dual PhaseTechnique

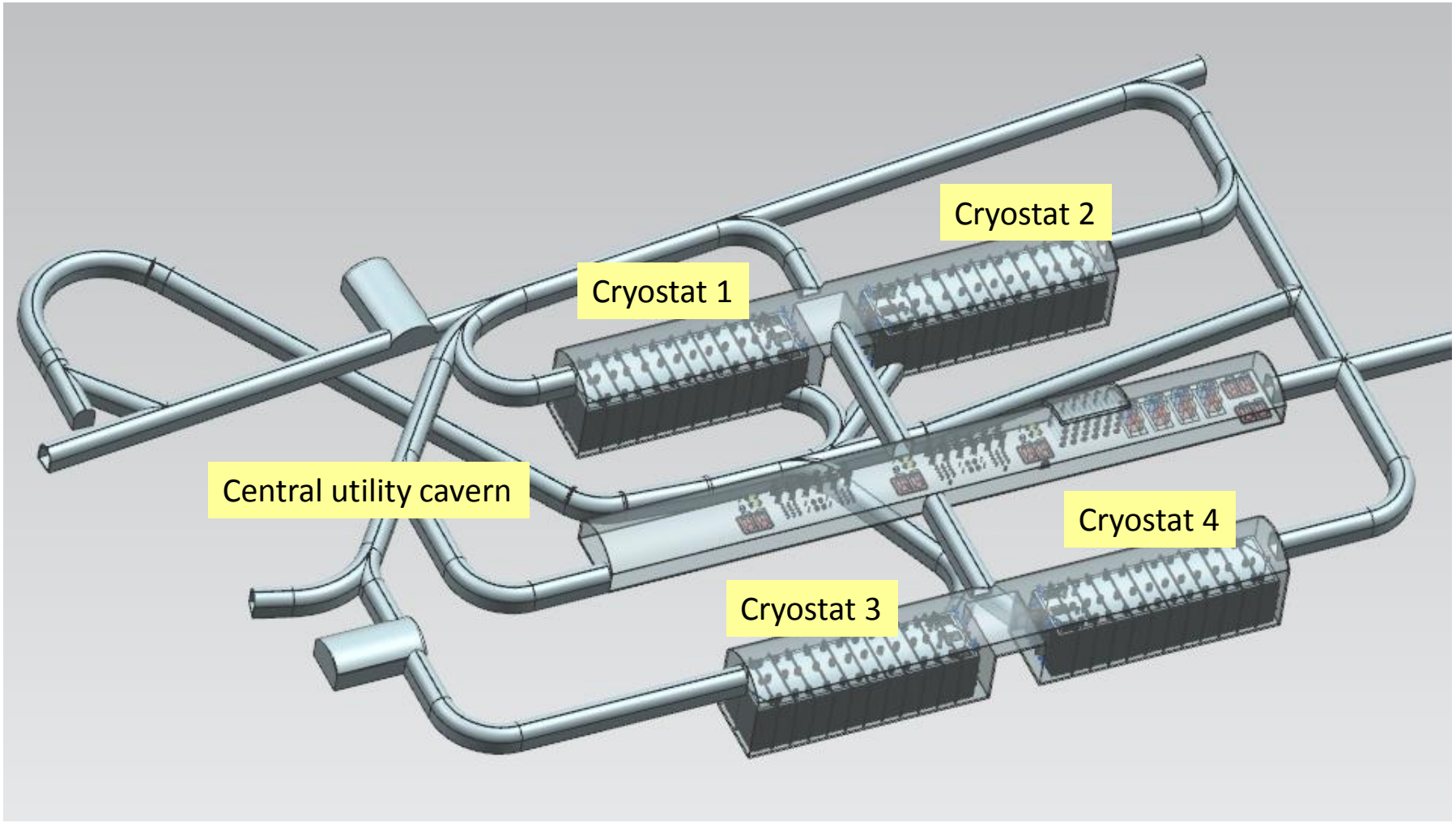


DUNE experiment overview



- 1.2 MW wide-band neutrino beam from FNAL, upgradeable to 2.4 MW
- Highly-capable near detector
- LAr 40-kton fiducial mass far detector
  @ Sanford Underground Research Facility in SD
  - 1300 km baseline
  - 4850 ft (2300 mwe) depth
  - Four 10 kt modules, installation starting 2021

LBNF far detector facilities for DUNE

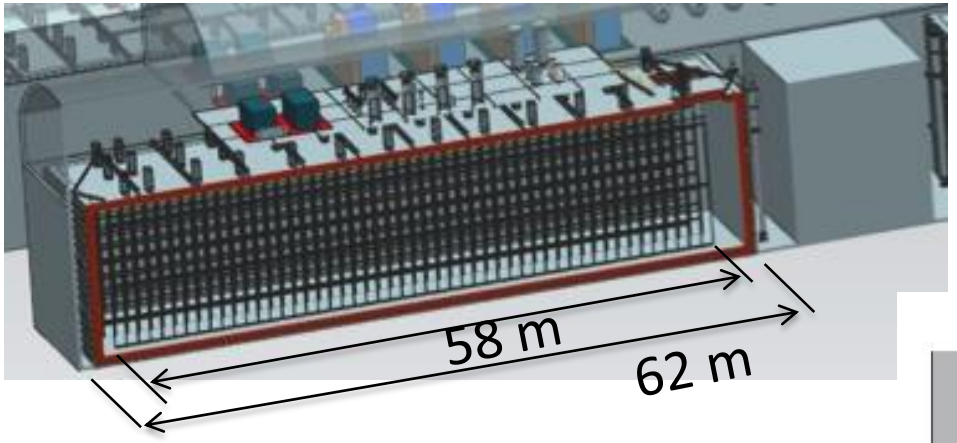


Cryostats: (CERN-FNAL design team) 17.1 kt LAr each

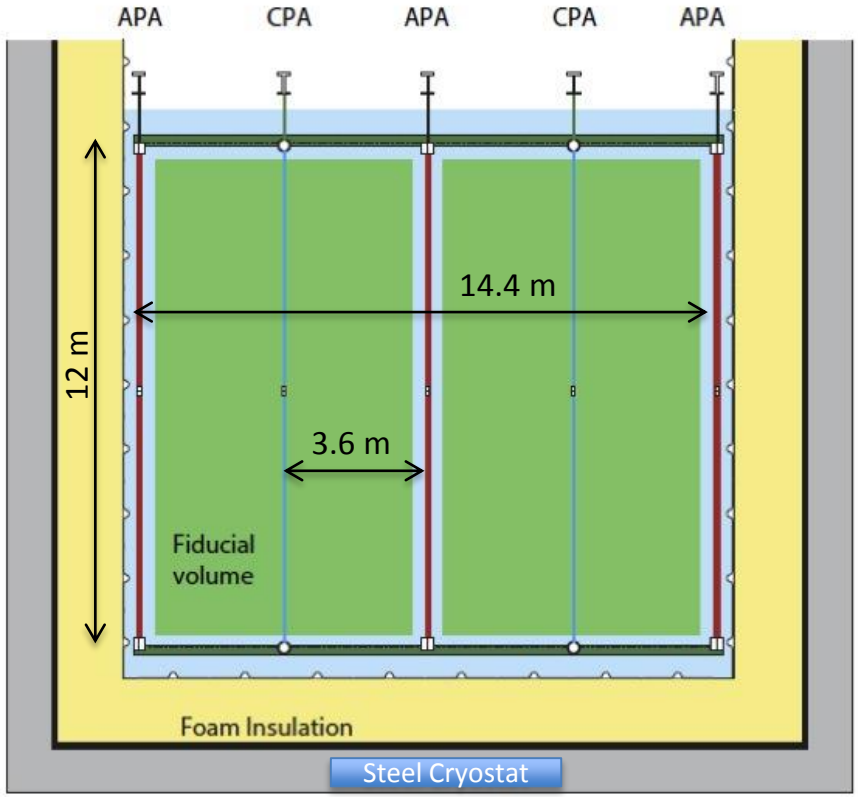
Free-standing steel-supported membrane cryostats

Central utility cavern: cryogenics support equipment

Single Phase Detector



Reference design
(for first module):
horizontal-drift single-phase
time-projection chamber



17.1-kt total, 13.8-kt active,
11.6-kt fiducial mass

3 Anode Plane Assemblies (APA)
w/ cold electronics

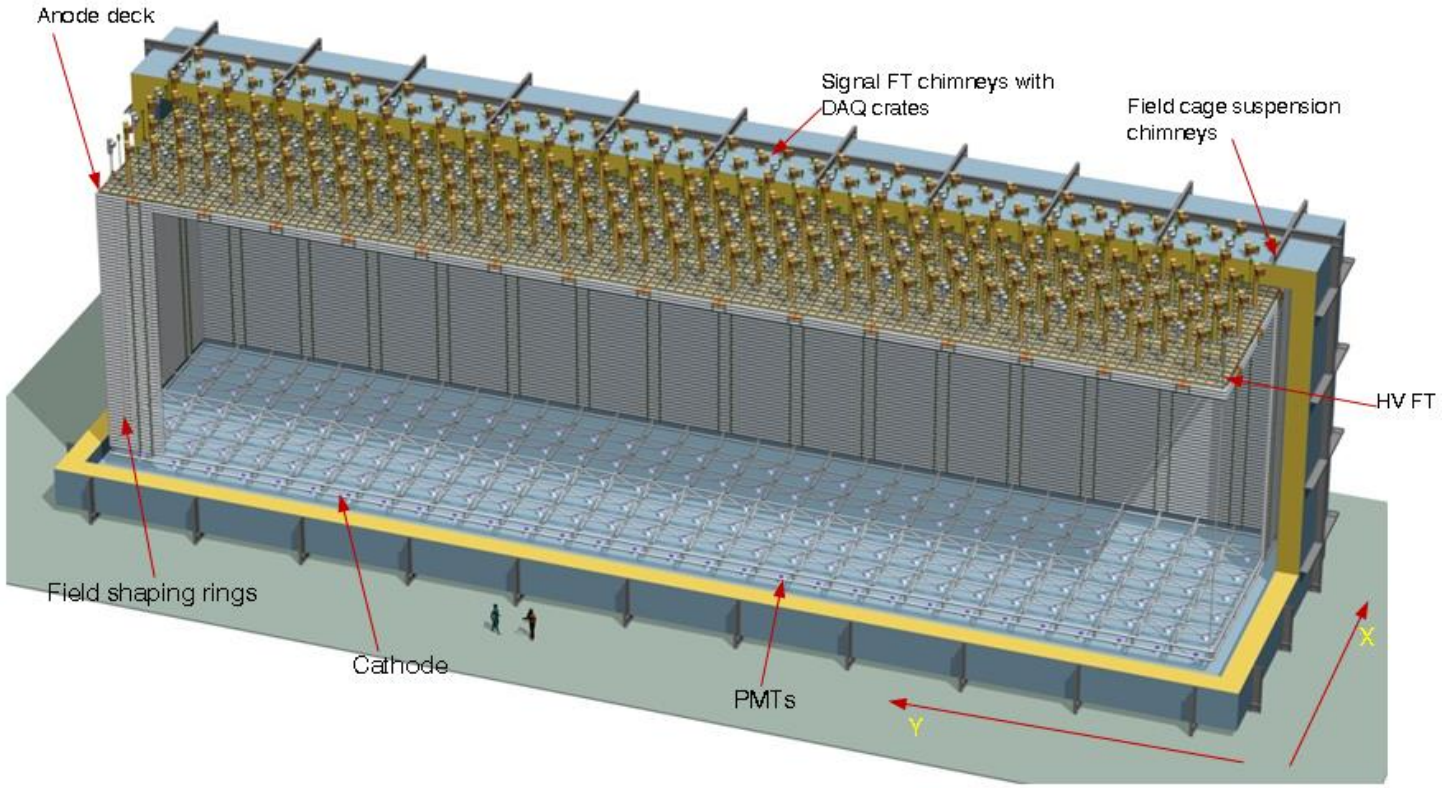
Cathode planes (CPA) at 180 kV
3.6 m max drift length

Photon detectors for fast
event timing (non-beam physics)

Dual Phase Detector

Dual-phase TPC is alternative design:
vertical drift w/ multiplication and readout at liquid-gas interface
Significant R&D by LBNO collaboration

Could be implemented for module(s) 2-4



More from G.Feldman later in the school...

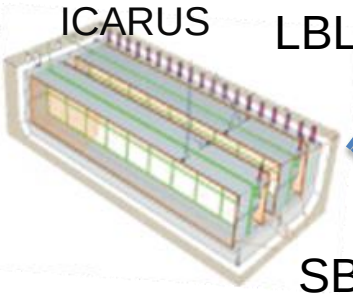
CERN neutrino platform + FNAL prototyping + experience from FNAL SBN program

Single phase

ICARUS

LBL

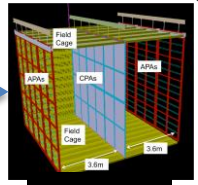
SBL

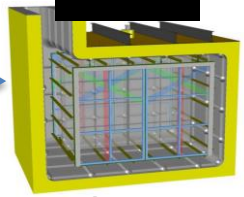


35-t prototype

MicroBooNE

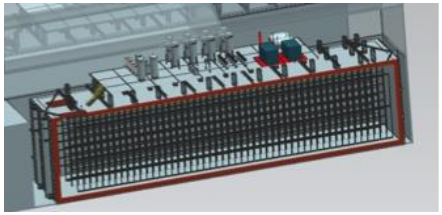
DUNE SP PT @ CERN





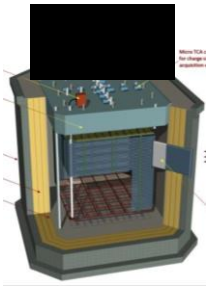
SBND

DUNE Reference Design



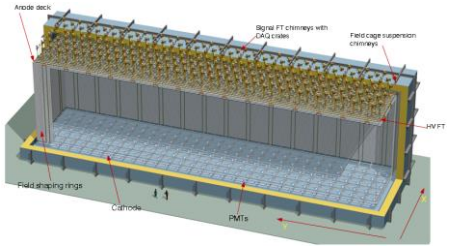
Dual phase

WA105: 1x1x3 m^3



WA105

DUNE Alternative Design



Liquid Argon TPC

Advantages

- tracks recorded at sub 1mm level. Easy to distinguish multiple and/or complex events
- recoil hadrons visible even below Cherenkov threshold
- Argon is a scintillator
- Argon is relatively cheap (comparable to scintillator)
- **Significant ν_e cross section at low energy**

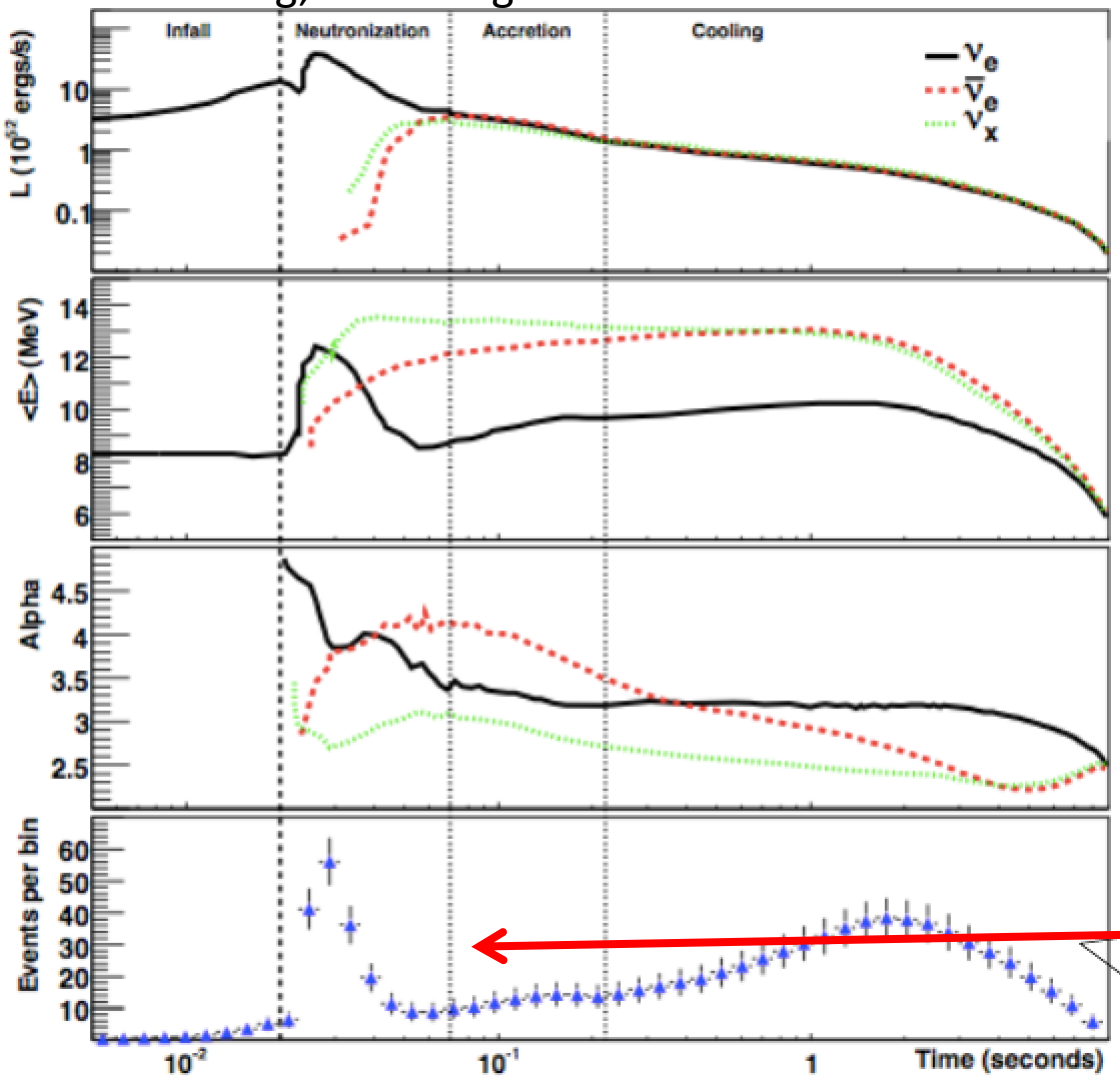
Disadvantages

- Drift is slow compared to Cherenkov or scintillation
- Need scintillation light collection for a "t0"
- Complex nucleus compared to oxygen or carbon
- No free protons
- No neutron capture tagging

The Long(er) Baseline Neutrino Experiment

Detection of a SN neutronization burst requires ν_e sensitivity.

K.Scholberg, "Garching" model used



Burst is only 20 ms long and is essentially all ν_e

Mean energy of events is low, 10-12 MeV

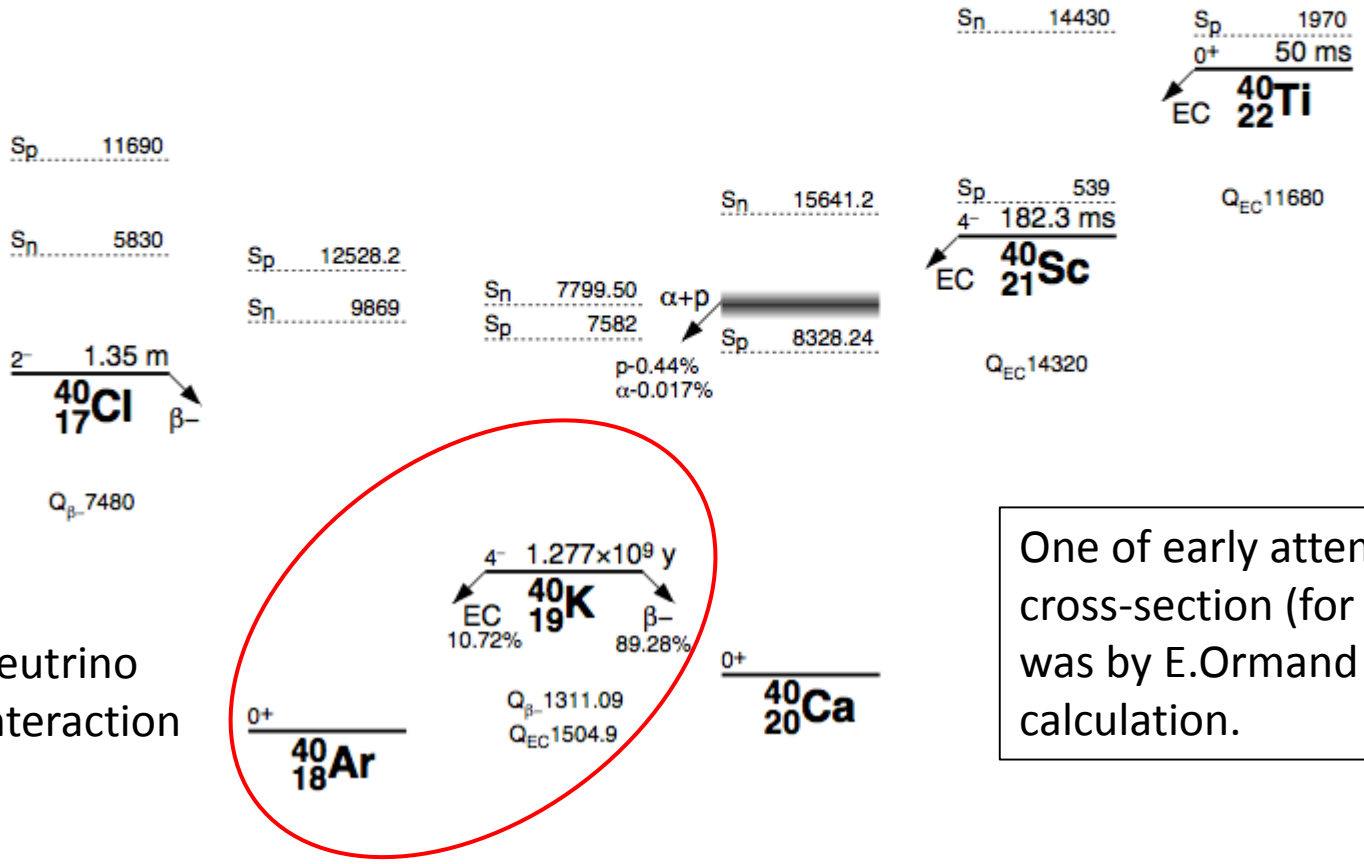
IMB/Kamiokande detected higher energy cooling neutrinos, not neutrinos from the neutronization process

Potential for ν_e detection in liquid argon by LBNE

Do we really know how to detect a supernova with a liquid argon TPC?

cross-sections?
triggering?
timing?

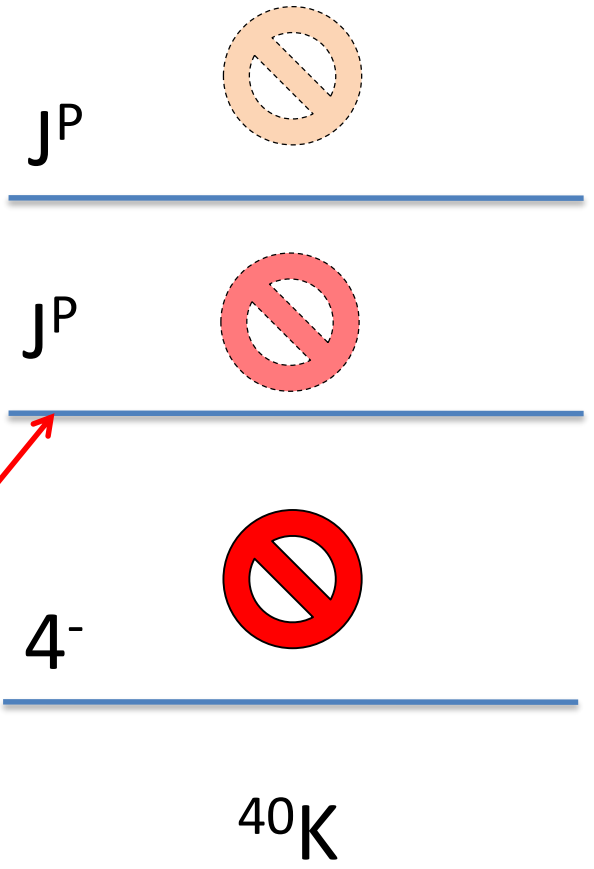
$\nu_e + {}^{40}Ar \rightarrow {}^{40}K_{g.s.} + e^-$ has a low threshold, but rarely occurs due to $0^+ \rightarrow 4^-$ (3^{rd} forbidden) transition. Most all of the cross section is into excited states of ^{40}K.



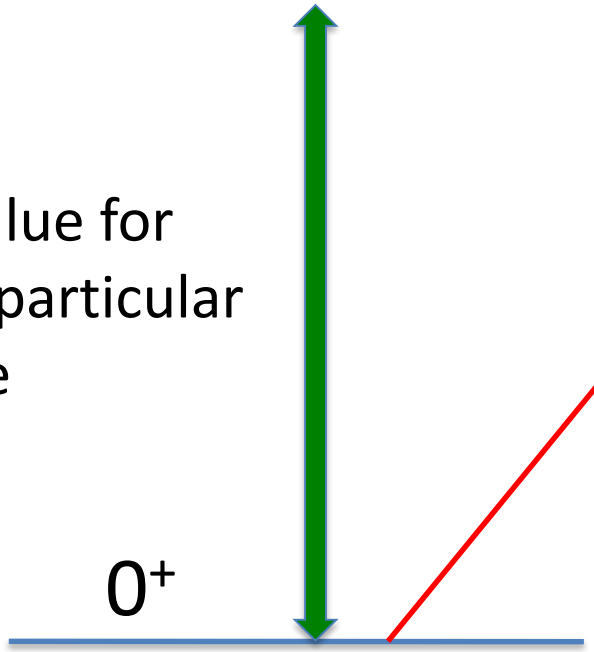
neutrino interaction

One of early attempts to calculate cross-section (for solar neutrinos) was by E.Ormand using shell model calculation.

~30 relevant excited states of various filling "strength".



Q-value for this particular state

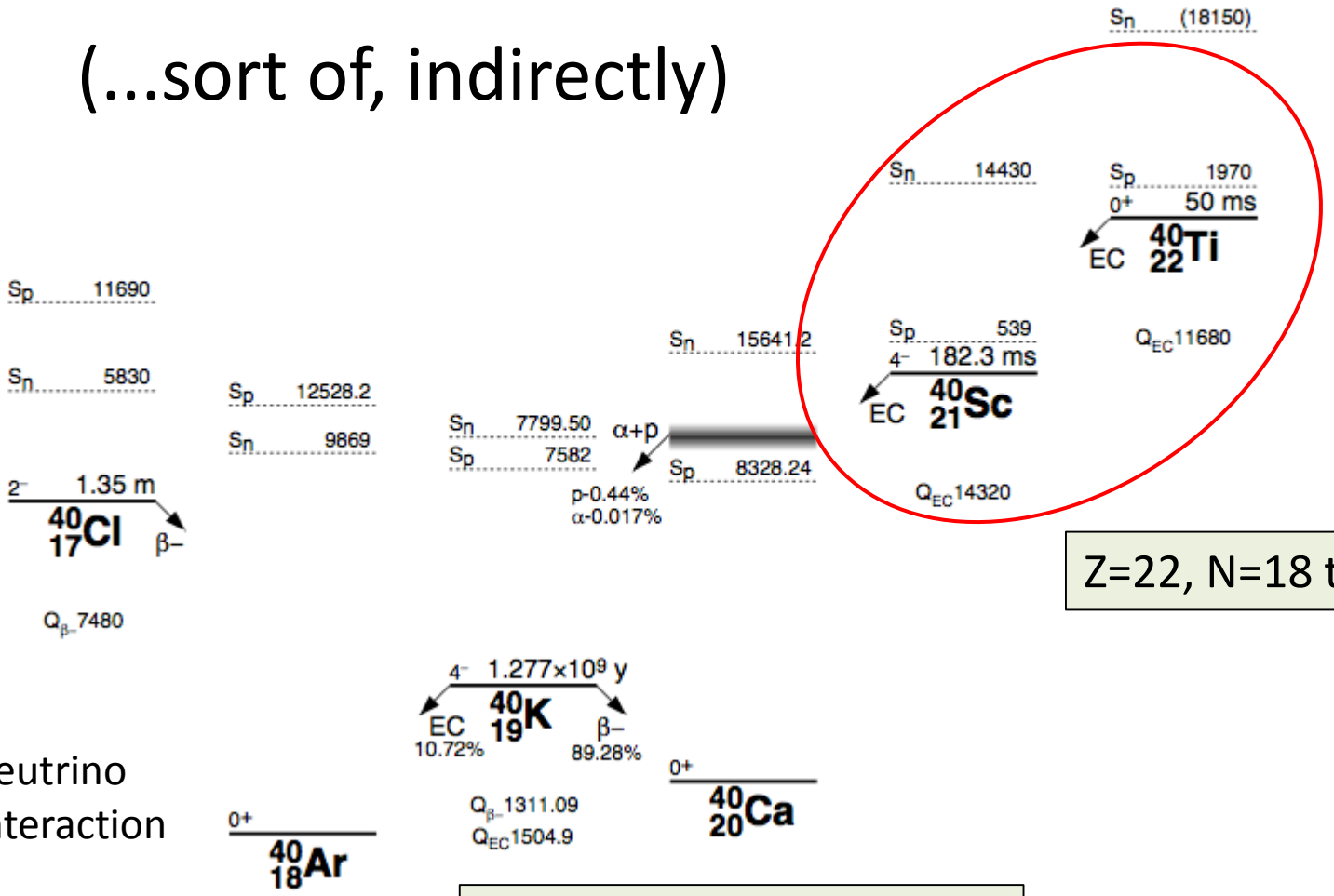


$$E_{e-} = E_\nu - Q - K_{recoil}$$

Can we just measure the strengths?

A=40
NP A521, 1(1990)

(...sort of, indirectly)



Z=22, N=18 to Z=21, N=19

neutrino interaction

Z=18, N=22 to Z=19, N=21

PHYSICAL REVIEW C VOLUME 58, NUMBER 6 DECEMBER 1998

Neutrino absorption efficiency of an ^{40}Ar detector from the β decay of ^{40}Ti

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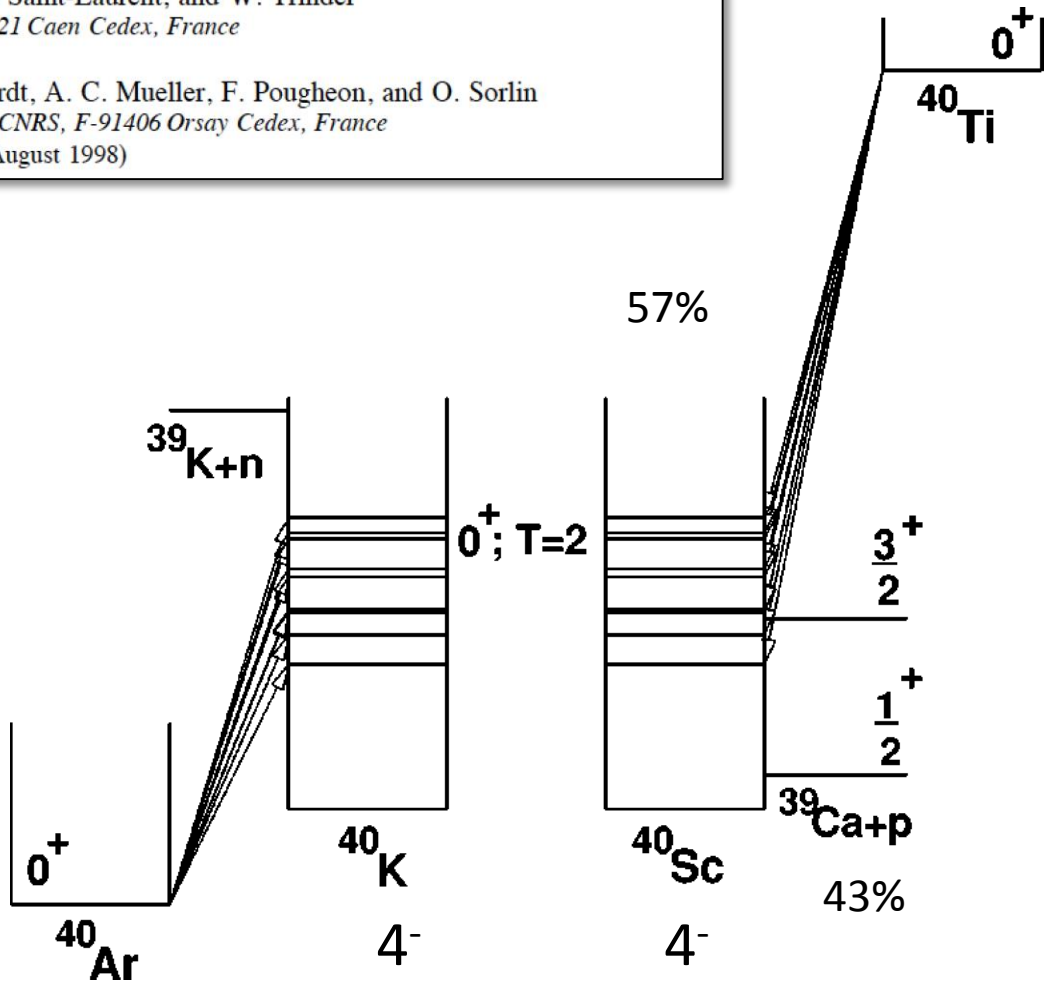
(Received 4 August 1998)

Make 40-Ti via heavy ions on a thin, heavy target (e.g. Cr on Ni). Embed ions in silicon detector.

Use TOF and dE/dx to separate 40-Ti out from ion "soup"

Observe beta decay to 40-Sc excited states, which decay via delayed proton emission



Transition Strengths and ν_e Cross Sections

TABLE VII. β decay of ^{40}Ti and the neutrino-capture cross section of ^{40}Ar. (Cross sections for ^{8}B and supernova ν's are computed with a 5 MeV threshold on the total energy of the outgoing electron.) The isobaric correspondences suggested in this table are based solely on excitation energies and J^{π} assignments.

E_x(keV)(^{40}Sc)	B(F)+B(GT)	E_x(keV)(^{40}K)	J^{π}(^{40}K)[a]	$\sigma_B(10^{-43}\text{cm}^2)$[b]	$\sigma_{SN}(10^{-43}\text{cm}^2)$[c]
2281±8	0.90±0.04	2289.88±0.03	1^+	3.19±0.14	38.04±1.69
2752±8	1.50±0.06	2730.38±0.04	1^{+d}	4.14±0.14	59.86±2.00
2937±13	0.11±0.02	2950.70±0.50		0.27±0.05	4.28±0.78
3143±20	0.06±0.01	3109.75±0.04	$(1,2)^+$	0.13±0.02	2.29±0.38
3334±19	0.04±0.01	3146.44±0.09	1	0.09±0.04	1.52±0.76
3569±56	0.01±0.01	3293±10		0.02±0.02	0.37±0.37
3652±10	0.16±0.02	3738.50±0.05	1^+	0.24±0.02	5.62±0.35
3786±10	0.26±0.03	3797.58±0.06	1^+	0.39±0.03	9.06±0.70
3861±49	0.01±0.01	3840.25±0.05	$(1,2)^+$	0.02±0.02	0.35±0.35
4067±24	0.05±0.02	3898±8		0.07±0.03	1.72±0.69
4111±30	0.11±0.03	3996±10	U	0.14±0.03	3.74±0.68
4267±10	0.29±0.03	4352±5	U	0.28±0.03	9.38±0.97
4364±8	3.84±0.17	4384.00±0.30	0^+;2	3.75±0.17	124.07±5.49
4522±16	0.31±0.05	4697±10	U	0.24±0.04	9.57±1.54
4655±12	0.38±0.06	4761±5	$(1,2)^+$	0.27±0.04	11.64±1.53
4825±21	0.47±0.08	4788.65±0.17	1^+	0.33±0.06	14.34±2.44
5017±27	0.36±0.09	4848±10		0.24±0.06	10.91±2.73
5080±35	0.23±0.07	5027±5		0.13±0.05	6.80±2.36
5223±32	0.03±0.03			0.02±0.02	0.87±0.87
5696±23	0.11±0.04			0.03±0.01	2.97±1.08
6006±21	0.13±0.05			0.03±0.01	3.37±1.30
Total	9.36±0.26			14.02±0.30	320.77±8.27

- The transition strengths were calculated via

$$B_i(GT) + B_i(F) = \frac{KR_i}{t_{1/2} f(E_i)}$$

- Neutrino cross sections were then calculated via

$$\sigma(E_\nu) = \frac{G_F^2 \cos^2(\theta_{ud})}{\pi \hbar^4 c^3} \sum_i p_i W_i F(Z, W_i)[B_i(GT) + B_i(F)]$$

MARLEY

Model of **AR**gon **L**ow **E**nergy **Y**ield

- Neutrino cross sections were then calculated via

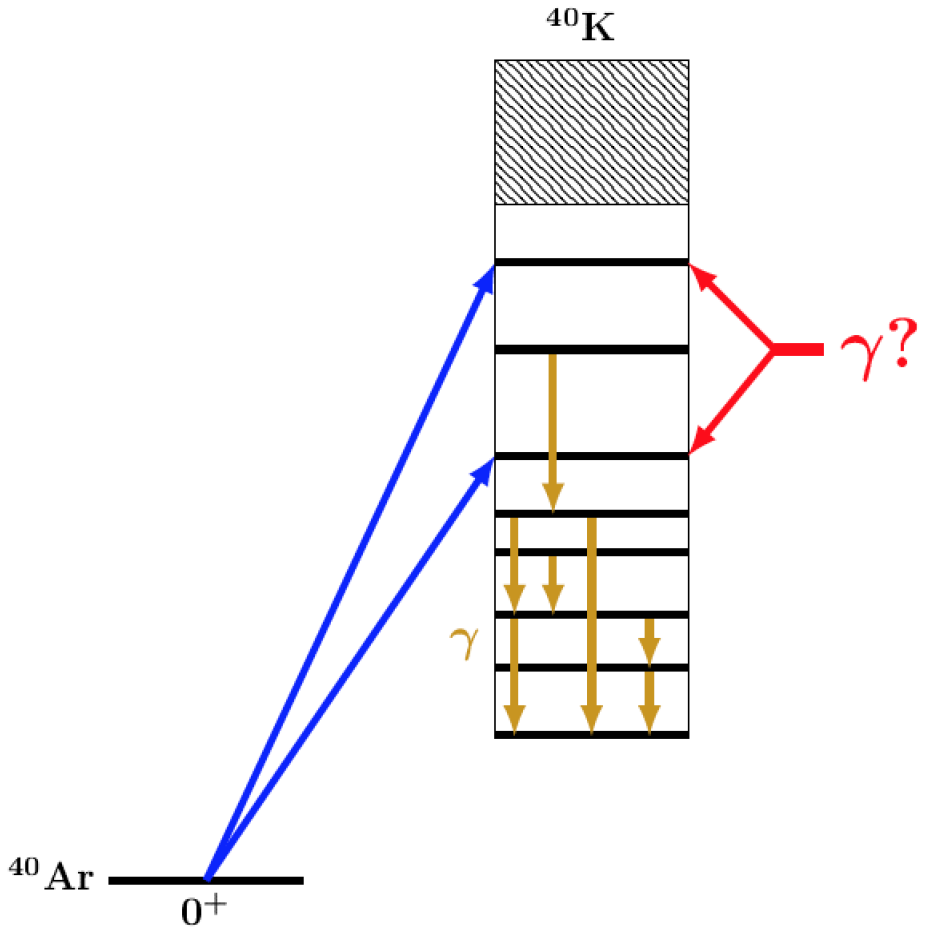
$$\sigma(E_\nu) = \frac{G_F^2 \cos^2(\theta_{ud})}{\pi \hbar^4 c^3} \sum_i p_i W_i F(Z, W_i)[B_i(GT) + B_i(F)]$$

...based on 40-Ti measurements

What about gamma cascades?

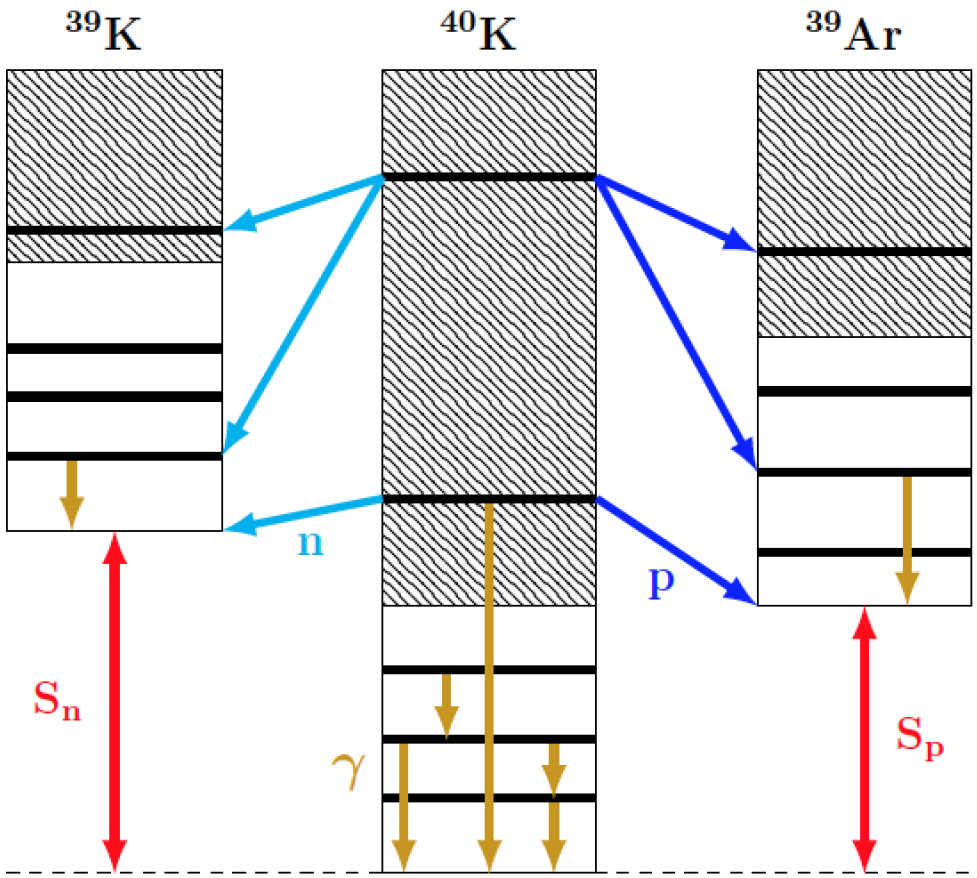
without these neutrino energy cannot be reconstructed

Predicting γ signal is difficult when there are no data



- Make educated guesses about level J^πs
- Use models (e.g., Weisskopf estimates) to approximate γ branching ratios
- Revert to ENSDF data whenever available

Unbound states are even more problematic



- Supplement any available data with nuclear structure and decay models
- Most previous work has ignored these details
- We are currently investigating the best approach

(Help!)

Maybe it would be better to try and measure the cross section directly. At least verify to the 10% level before spending >$100M to go underground

We are thinking about this...

Summary

- Incredible rich field of neutrino detection
- 1 MeV-100 TeV
- Range of detector technologies to adapt to needed measurements
- ... a real need for R&D to expand the capabilities of existing technology and develop new ones
- CPAD meetingin Arlington Texas – **y'all come!**

NEW TECHNOLOGIES FOR DISCOVERY

Organized by the Coordinating Panel for Advanced Detectors of the Division of Particles and Fields of the American Physical Society

October 5 - 7, 2015 - University of Texas at Arlington

Welcome to the CPAD Instrumentation Frontier Meeting at UTA

This 2.5 day workshop will provide an evaluation of the Detector R&D program being carried out in support of the High Energy Physics science mission. The goal of the workshop is to determine if the existing program meets the science needs of the five science drivers identified by P5 within the twenty year P5 vision. The program will place an emphasis on proposing new ideas for detection technologies, articulating grand challenges for the field and identifying instrumentation opportunities to enhance the program as an enabler of our science. In addition to plenary sessions and parallel session working groups there will also be an Instrumentation Slam. We guarantee new instrumentation ideas! The outcome of the workshop will be a formulation of the needs of the field to ensure a vibrant long term future.

The workshop is organized by the Coordinating Panel for Advanced Detectors (CPAD)* of the Division of Particles and Fields of the American Physical Society.

http://www.uta.edu/physics/cpad2015/