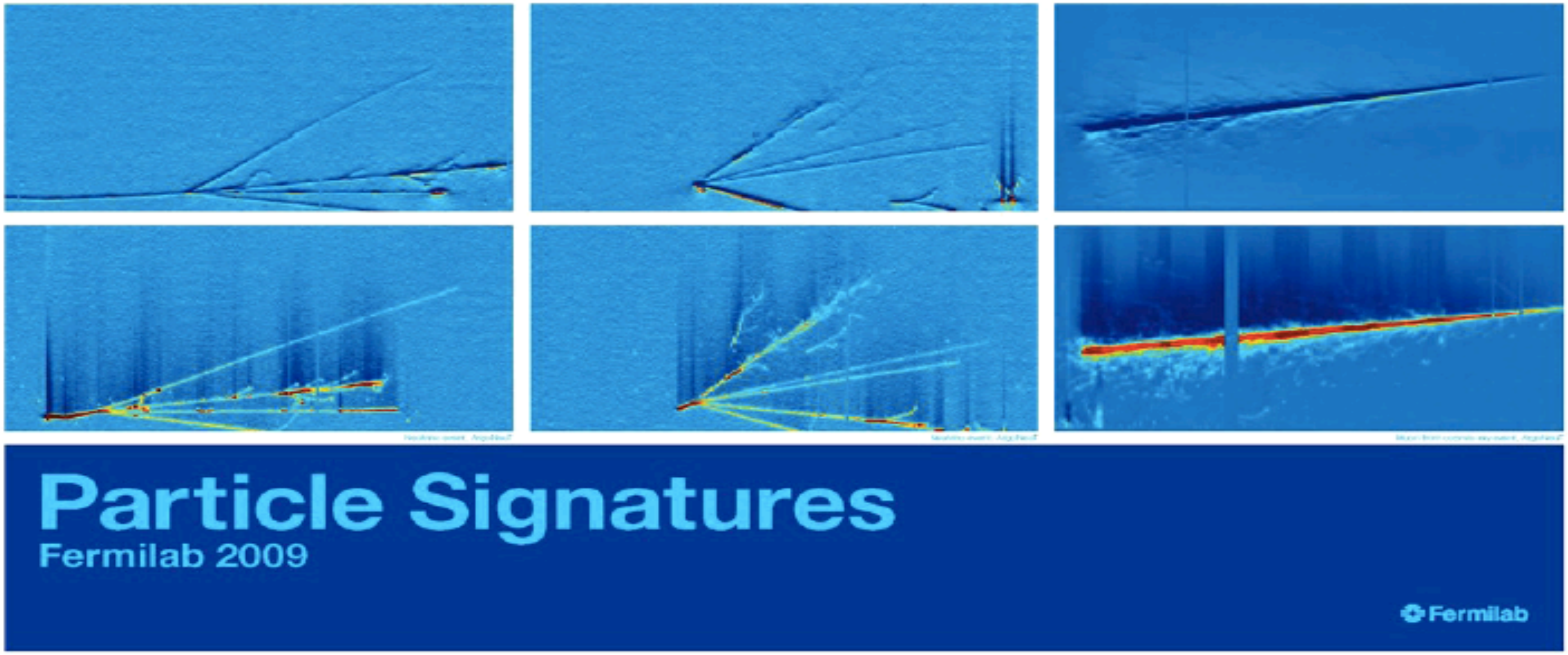


Liquid Argon Detector Technology

Roxanne Guenette
University of Oxford

"The Allure of Ultrasensitive Experiments" Lecture Series
11 February 2014
Fermilab

Outline

- Traditional neutrino detectors and brief history of LArTPCs
- Principle and Theory behind LAr detectors
- Technical details on the detectors
- Physics of neutrino LArTPCs
- Future prospects…

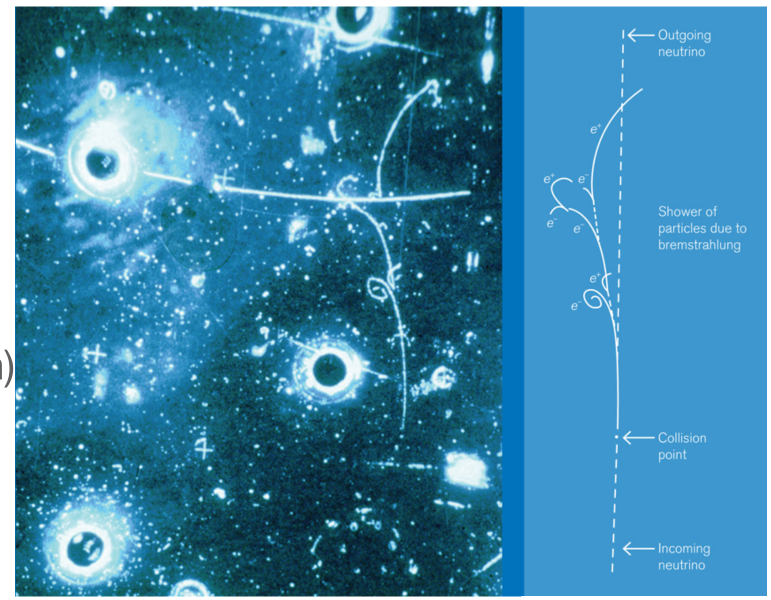
Traditional neutrino detection technologies

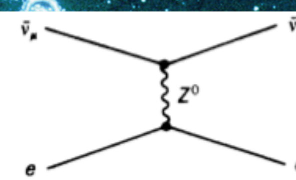
Bubble Chambers: e.g. Gargamelle

- Long era of BC in particle physics (1952 to 1970's)
- Culminated with the discovery of Neutral Current interaction (1973)

Drawbacks:

- ➢ Low density
- ➢ Slow response time (~1sec. for recompression)
- ➢ Not scalable to very large scale



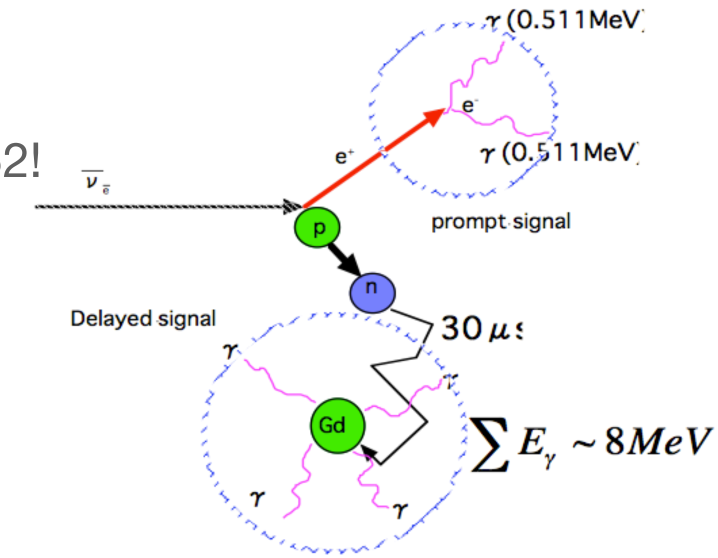


$$\bar{\nu}_\mu e \longrightarrow \bar{\nu}_\mu e$$

Traditional neutrino detection technologies

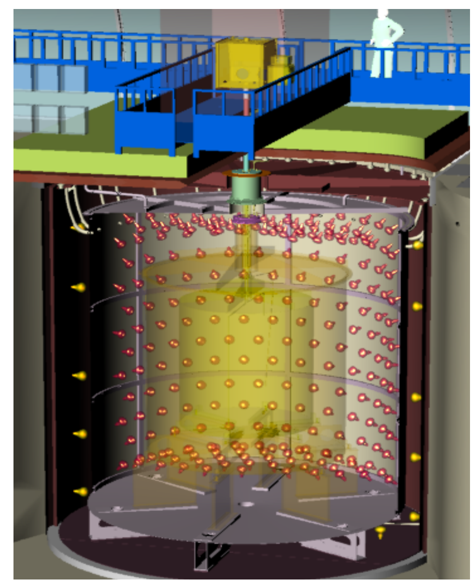
Doped Liquid Scintillators:

- Used in the neutrino discovery experiment in 1952!
- Can reach lower detection energies (opens the scientific reach)



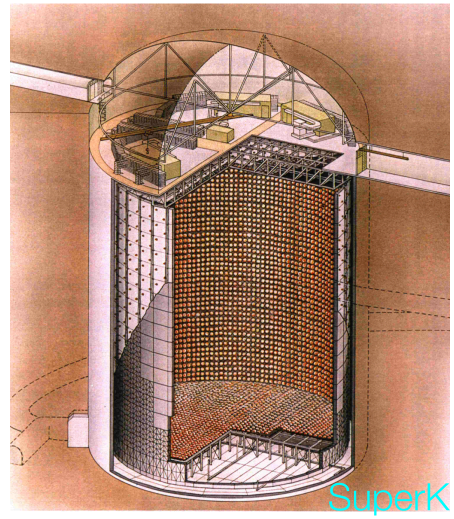
Limitations:

- ➢ Scalability limited due to light attenuation length
- ➢ Need low radiation material container and radiation buffers
- ➢ Background limited since only coincidence signals are detected (random coincidences, fast neutrons, $^{8}He/^{9}Li$, …



Traditional neutrino detection technologies

Water Cherenkov:

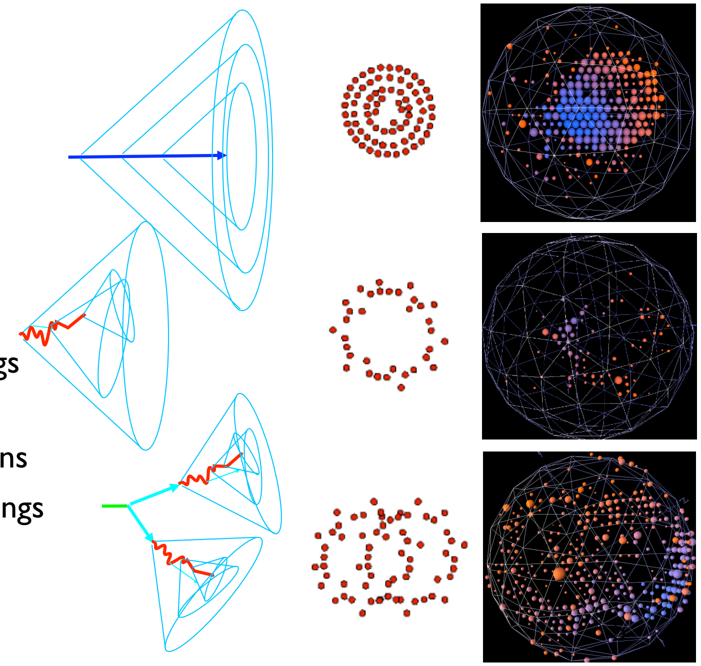


- Discovery of neutrino oscillations!
- Allows very large volumes (SuperK = 50ktons)
- Technology very well understood

Limitations:

- ➢ Background limited due to e/γ identical signature
- ➢ Particles below Cherenkov threshold not detected
- ➢ Big! Need big cavern ($$$)

- Muons
  - full rings
- Electrons
  - fuzzy rings
- Neutral pions
  - double rings



A brief history of LAr technology

- 1968: L.W. Alvarez first proposes the use of Liquid Noble Gases for particle detectors

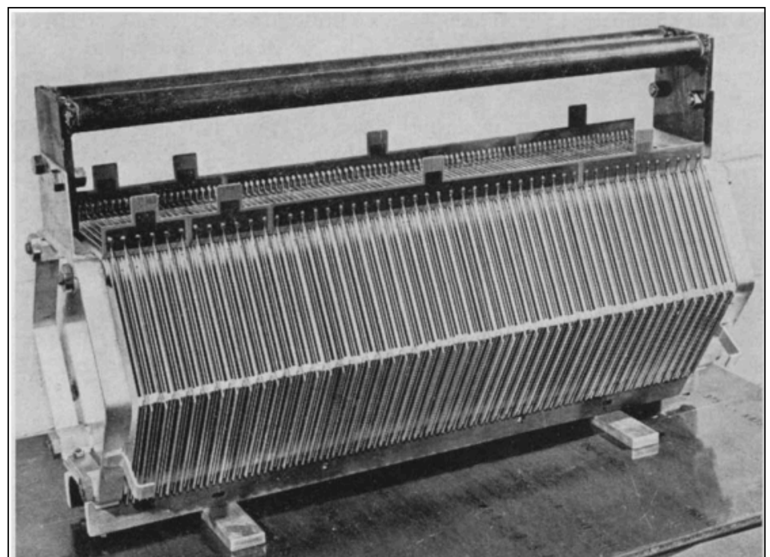
- 1974: W. Willis and V. Radeka propose the use of LAr ionization chambers

  - ➢ LAr one of best materials to answer traditional calorimeters limitations

i) it is dense (1.4 g/cm^3);
ii) it does not attach electrons;
iii) it has a high electron mobility (~5 mm/μs at 1 kV/mm);
iv) the cost is low ($0.14→0.50/kg, depending on source and quantity);
v) it is inert, in contrast to flammable scintillators;
vi) it is easy to obtain in a pure form and easy to purify;
vii) many electronegative impurities are frozen out in liquid argon.

The disadvantage is that the container must be insulated for liquid-argon temperature (86 K).

Willis & Radeka, NIM 120 (1974)



A brief history…

- In the 70's, neutrino detectors fall into 2 categories:
  - ➢ Small sensitive mass and high resolution bubble chambers
  - ➢ More massive electron detectors (only few event features are detected)
- Need for novel neutrino detection technology that combines larger mass with high resolution event

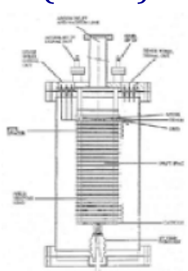
→ Carlo Rubbia proposes LArTPC (1977)

A brief history…

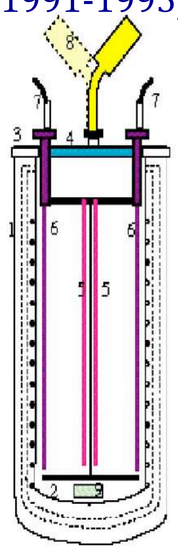
- 1985: ICARUS proposal at Gran Sasso

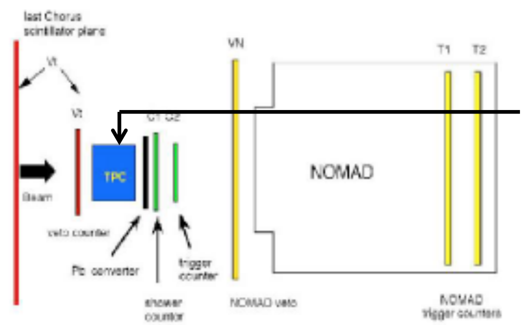
- Tremendous R&D efforts leading to the construction of the ICARUS T600 detector (2001/2010)

First LArTPC. 24 cm chamber (1987)

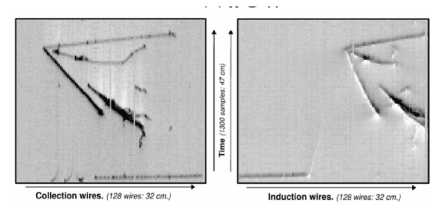


3 ton demonstration of large LArTPC (1991-1995)





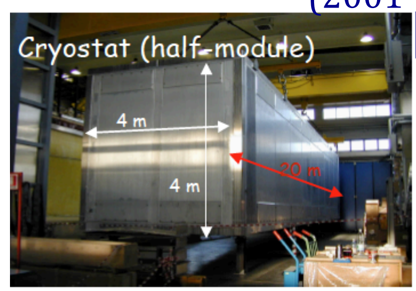
50l prototype in neutrino beam (1997-1999)

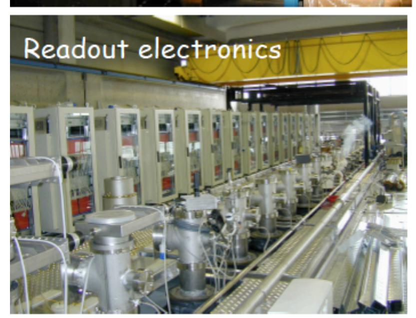


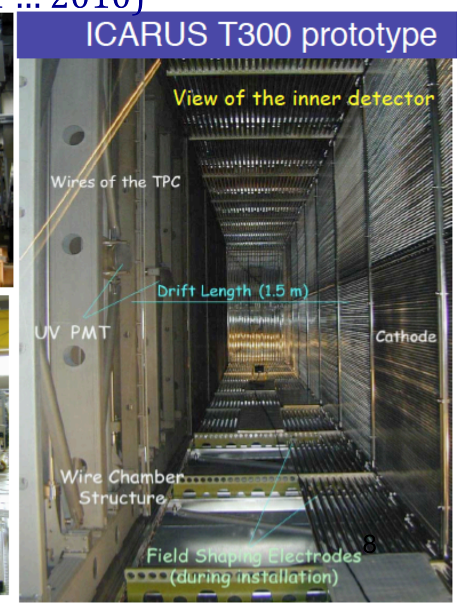
ICARUS 50 L in WANF neutrino beam

T15 (15 t LArTPC) prototype (1999/2000)

T600 (600 t LArTPC) (2001 ... 2010)

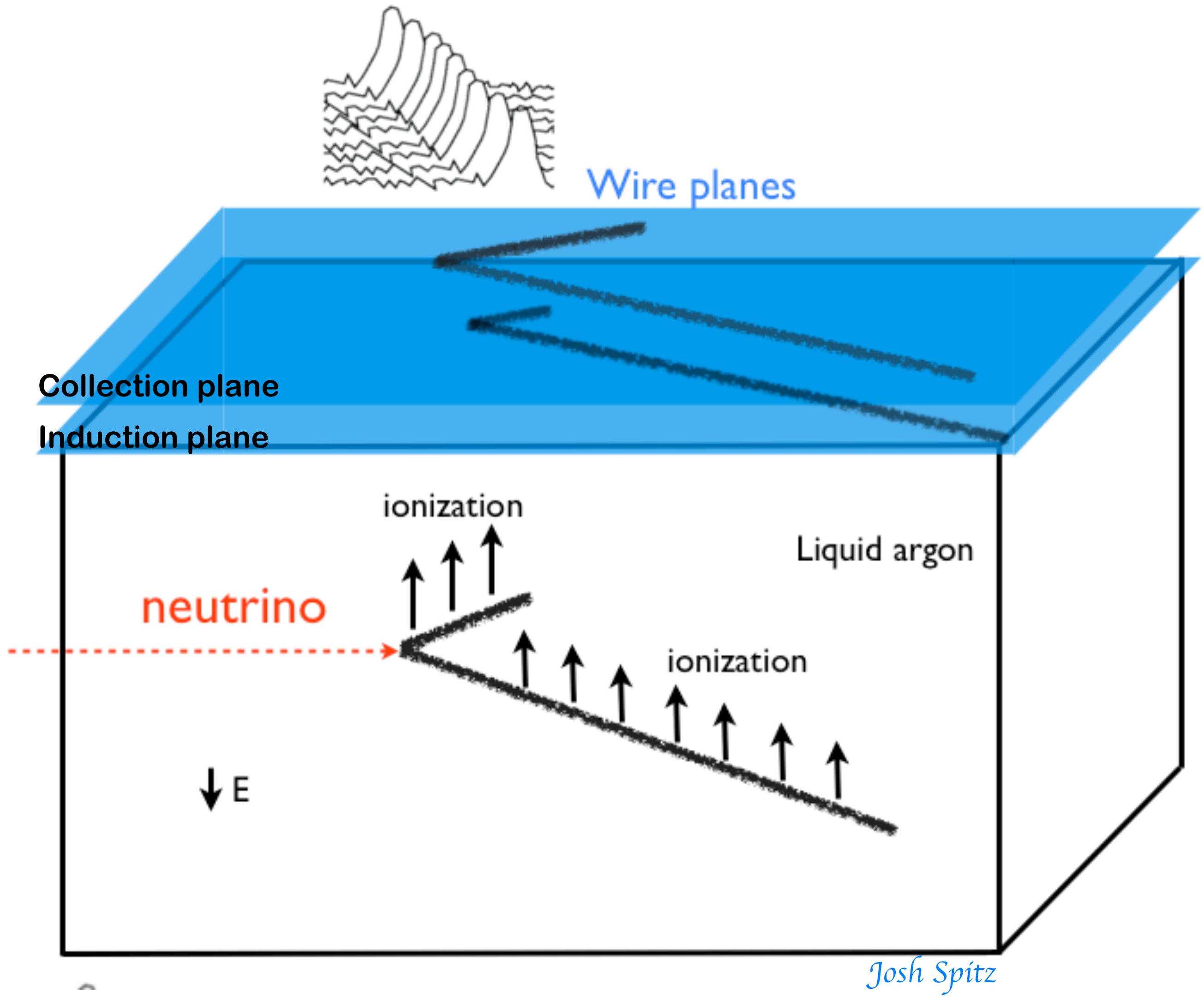


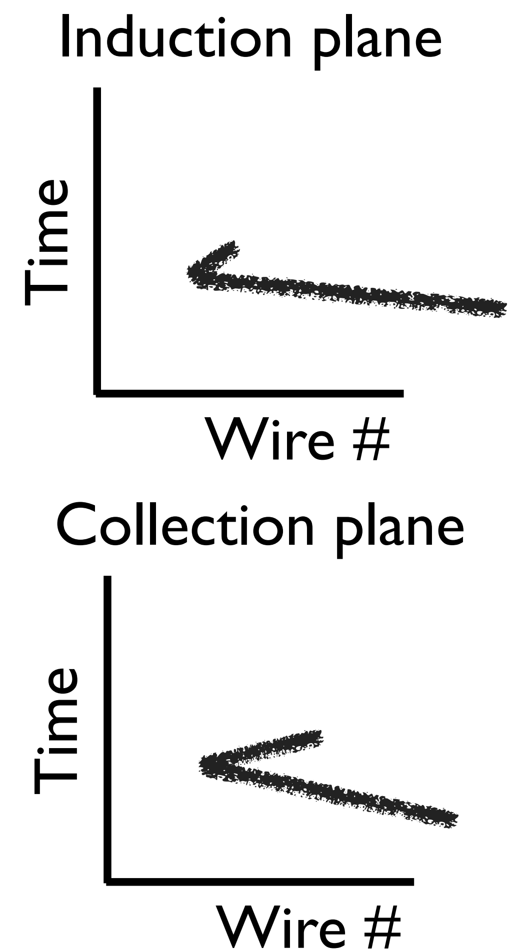




Principle of LArTPC

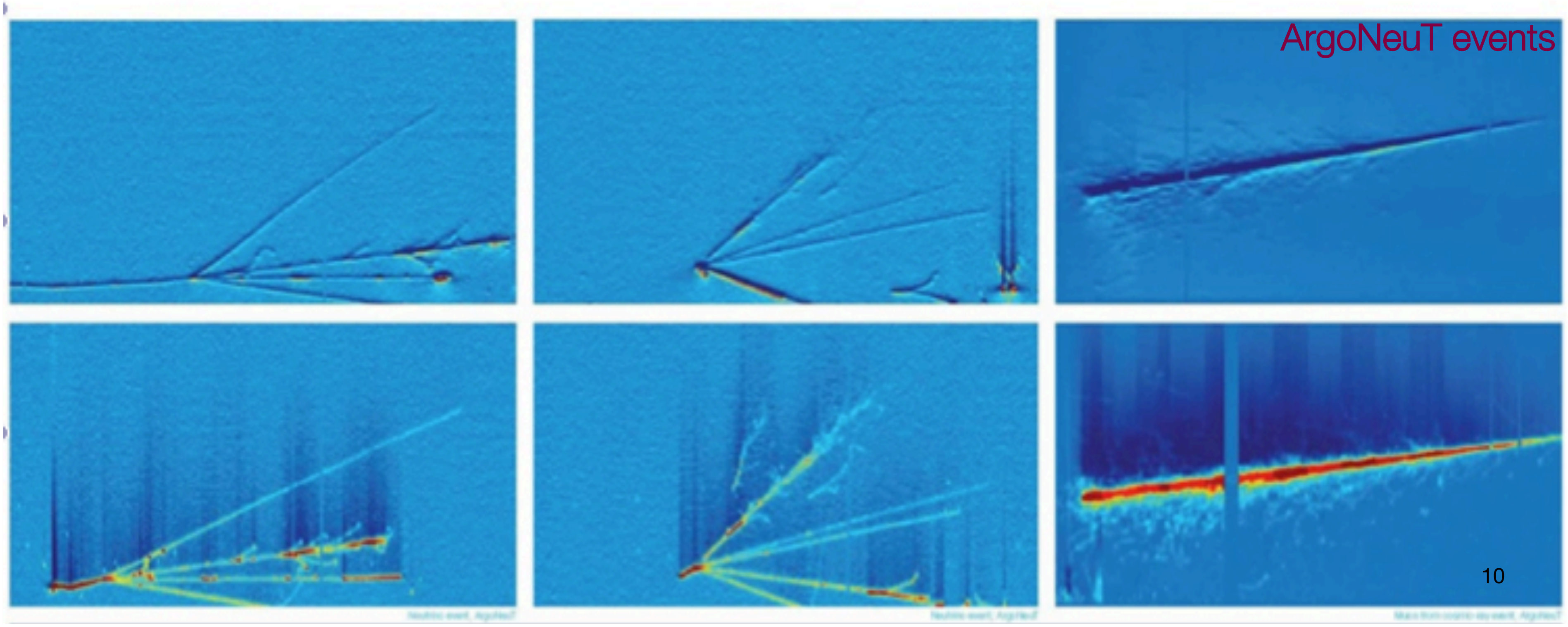
Liquid Argon Time Projection Chamber





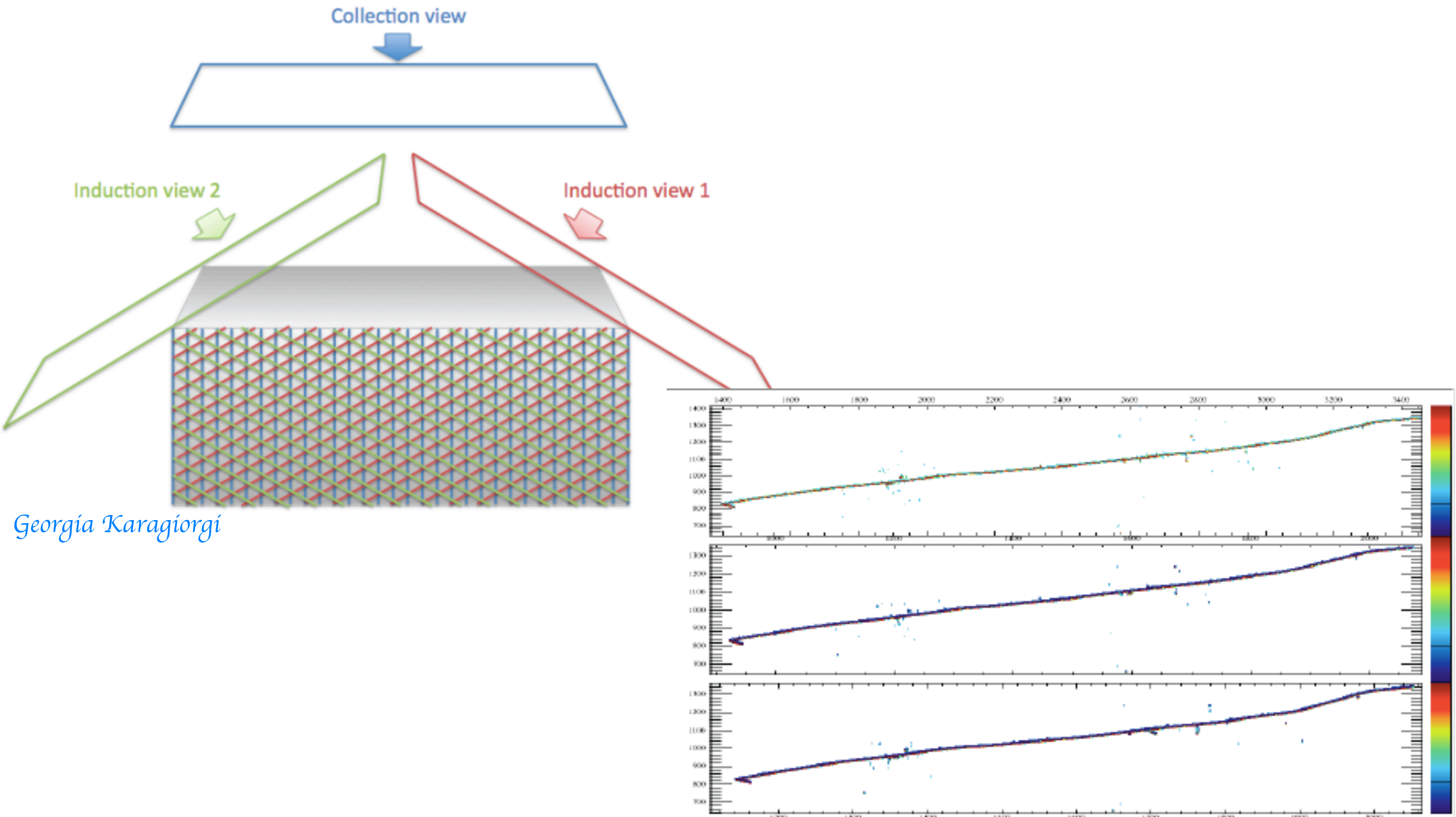
LAr TPCs

- ✓ 3D imaging
- ✓ High neutrino detection efficiency
- ✓ Excellent background rejection
- ✓ Good calorimetric reconstruction



LAr TPCs

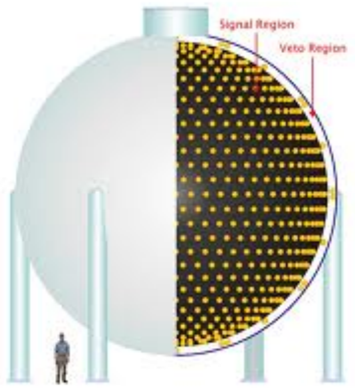
The 3D view

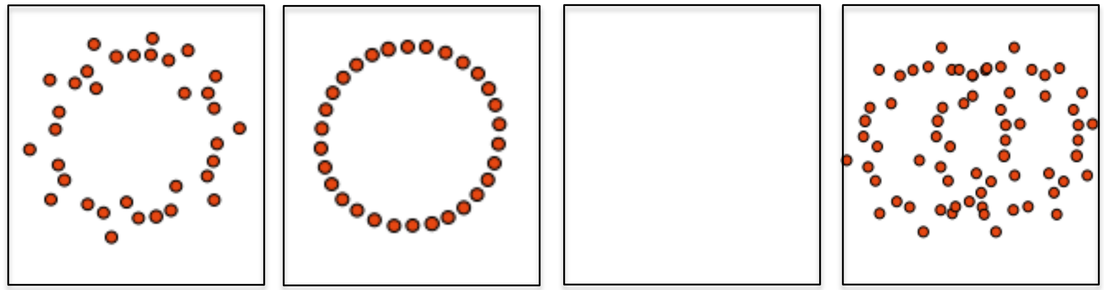


Georgia Karagiorgi

LAr TPCs

MiniBooNE

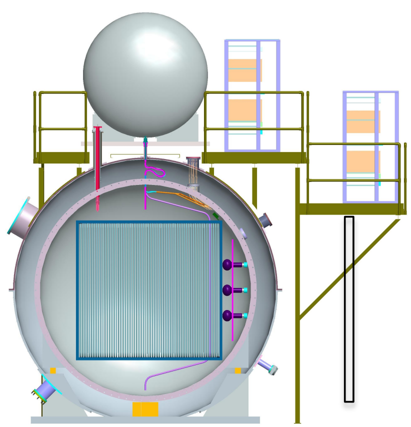


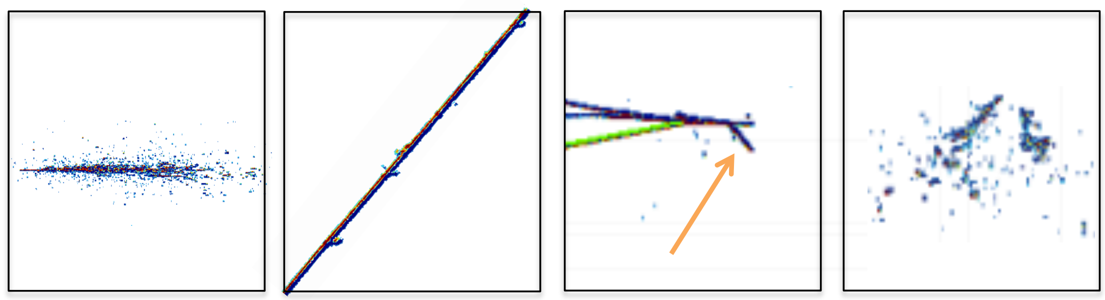


Electron, Photon | Muon | Proton | $\pi^0 \rightarrow \gamma + \gamma$

(Cherenkov Detector)

MicroBooNE

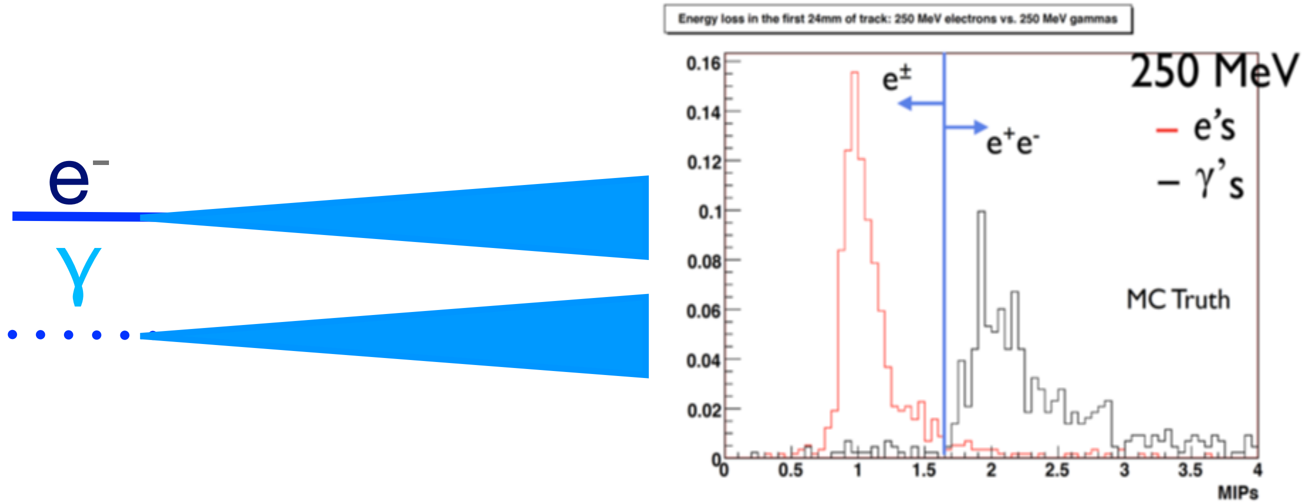




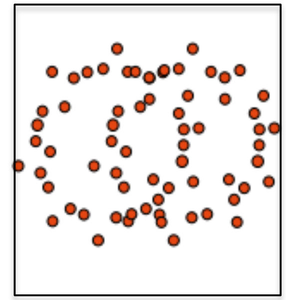
Electron, Photon | Muon | Proton | $\pi^0 \rightarrow \gamma + \gamma$

(LArTPC)

LA



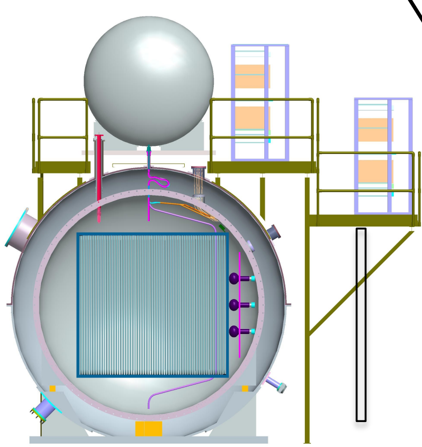
dE/dx for electrons and gammas in first 2.4 cm of track

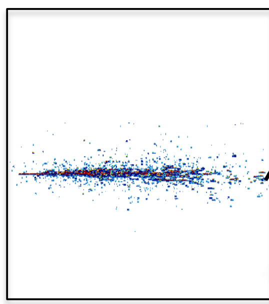


$\pi^0 \rightarrow \gamma + \gamma$

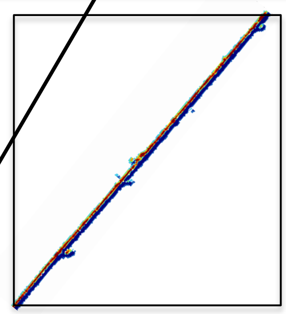
Detector)

MicroBooNE

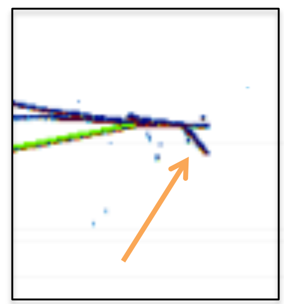




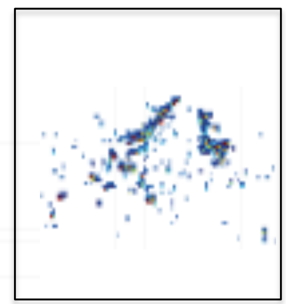
Electron, Photon



Muon



Proton



$\pi^0 \rightarrow \gamma + \gamma$

(LArTPC)

Why Ar?

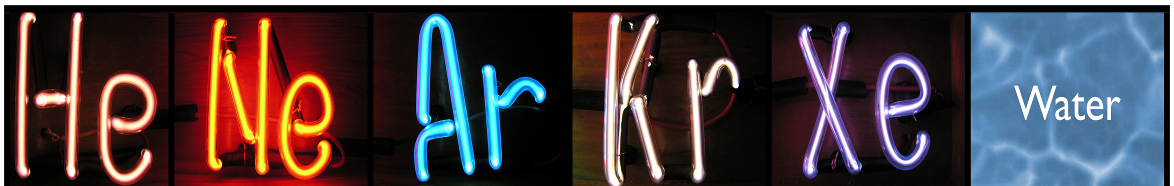
- Ionization electrons can be drifted over long distances (no electron attachment)
- Scintillation light used for detection (Ar is transparent to it's own scintillation)
- Very good dielectric properties allow high voltages in detector

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm^3]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation [γ/MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	

Mitch Soderberg

Why Ar?

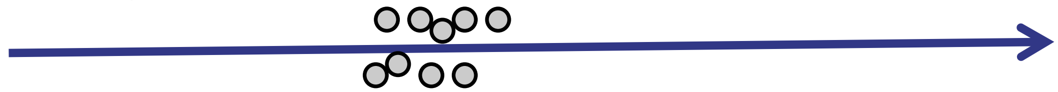
- In 2014, what matters is:



	He	Ne	Ar	Kr	Xe	Water
Price	~10$/l	~100$/l	< 1$/l	~300$/l	~3000 $/l	Depends on the country

Ionization, transport and recombination

- Charged particles deposit energy (dE/dx) and ionize the LAr

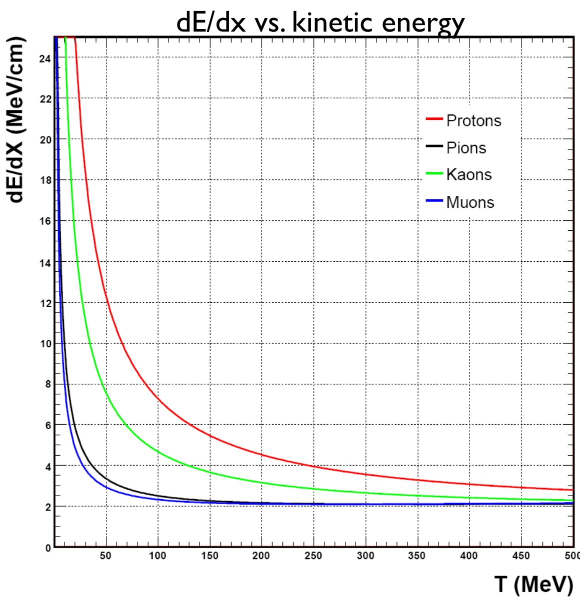


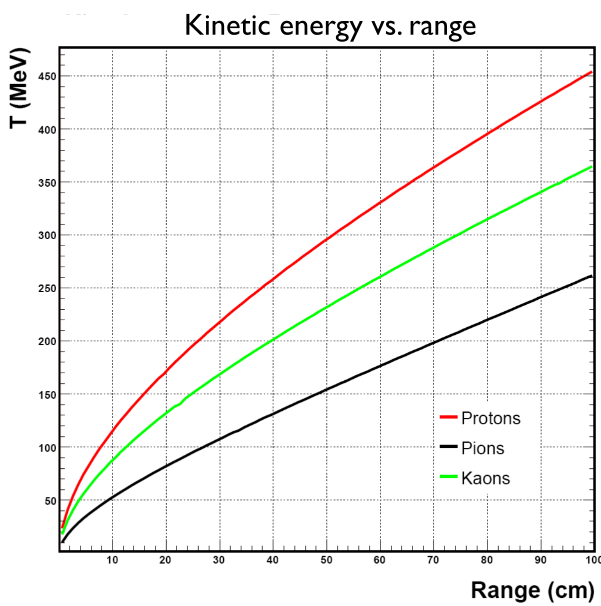
- Number of ionization e⁻ depends on energy deposited by particle

N_e = 42370 (e^-/MeV) * E (MeV)

from mean e^-/ion pair production energy for Ar = 23.6 eV

$$W_i = E_i + \frac{N_{ex}}{N_i} E_{ex}$$





$$\mathrm{Ar} + \mathrm{P} \longrightarrow \mathrm{e}^- + \mathrm{Ar}^+ + \mathrm{P}$$
$$\mathrm{e}^- + \mathrm{Ar} \longrightarrow \mathrm{e}^- + \mathrm{Ar}^+ + \mathrm{e}^-$$
$$\mathrm{Ar}^+ + \mathrm{Ar} \longrightarrow \mathrm{Ar}_2^+$$

$$\mathrm{Ar} + \mathrm{P} \longrightarrow \mathrm{Ar}^{**} + \mathrm{P}$$
$$\mathrm{Ar}^{**} \longrightarrow \mathrm{Ar} + \gamma$$
$$\mathrm{Ar}^{**} \longrightarrow \mathrm{Ar}$$

M. Luthi

Ionization, transport and recombination

- Ionization e⁻ are drifted by Electric Field

$$v_{e^-,DRIFT} = (1 + p1(T - t0)) \times (p3\,E\,Ln[1 + p4/E] + p5E^{p6}) + p2(T - t0)$$

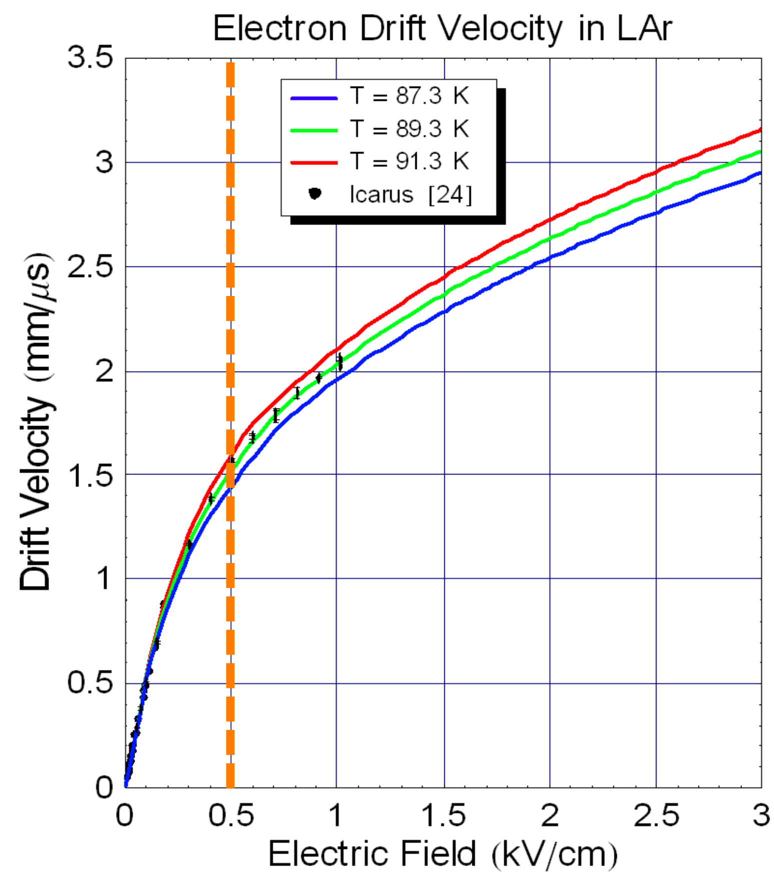
valid for $87 \le T \le 94$ *and* $0.3 \le E \le 0.8$

T = temperature in K

E = electric field in kV/cm

$p1 = -0.0462553$ $p2 = 0.0148508$ $p3 = 1.64156$ $p4 = 1.273$

$p5 = 0.0086608$ $p6 = 4.71489$ $t0 = 104.326$



For MicroBooNE at 500 V/cm:
1.5mm/μs -> 1.6ms max

A.M. Kalinin et al., Atlas Internal LARG-NO-058, (1996)

Ionization, transport and recombination

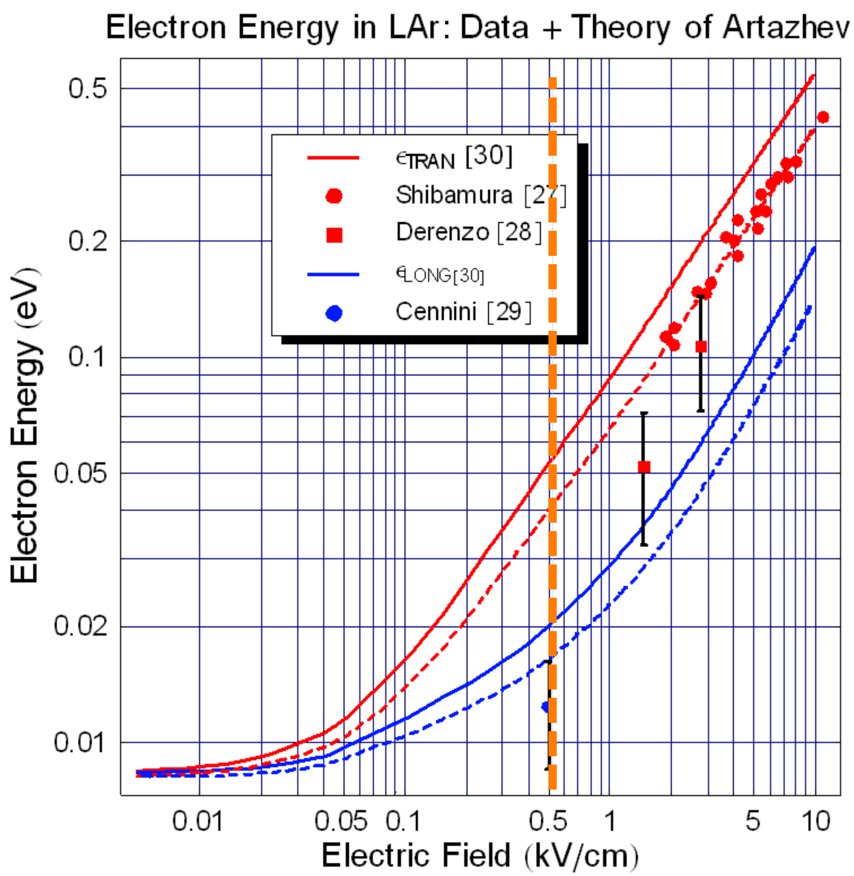
- Ionization e^- are get diffused
- RMS spatial spread:

$$\sigma_{T(L)} = \sqrt{\frac{2\,\varepsilon_{T(L)}\,\Delta z}{E}}$$

Δz the drift distance
E = electric field in kV/cm

$$D = \mu\,\varepsilon$$ (μ = electron mobility)

For MicroBooNE at 500 V/cm:
D_{Trans} = 12.8 cm^2/s (0.2mm^2 max)
D_{Long} = 5.3 cm^2/s (0.08mm^2 max)



V.M. Atrazhev & I.V. Timoshkin,, IEEE Trans. Dielectrics and Electrical Insulation 5, 450, (1998)

Ionization, transport and recombination

- Recombination and impurities can reduce the charge collected

Birk's Model

$$R_C = \frac{Q}{Q_\infty} = \frac{A}{1 + \frac{k}{\mathcal{E}} \times \frac{dE}{dx}}$$

$$A_{3t} = 0.800 \pm 0.003$$

$$k_{3t} = 0.0486 \pm 0.0006 \text{ kV/cm} \frac{\text{g/cm}^2}{\text{MeV}}$$

S.Amoruso et al., NIM A523, 275, (2004)

Modified Box Model

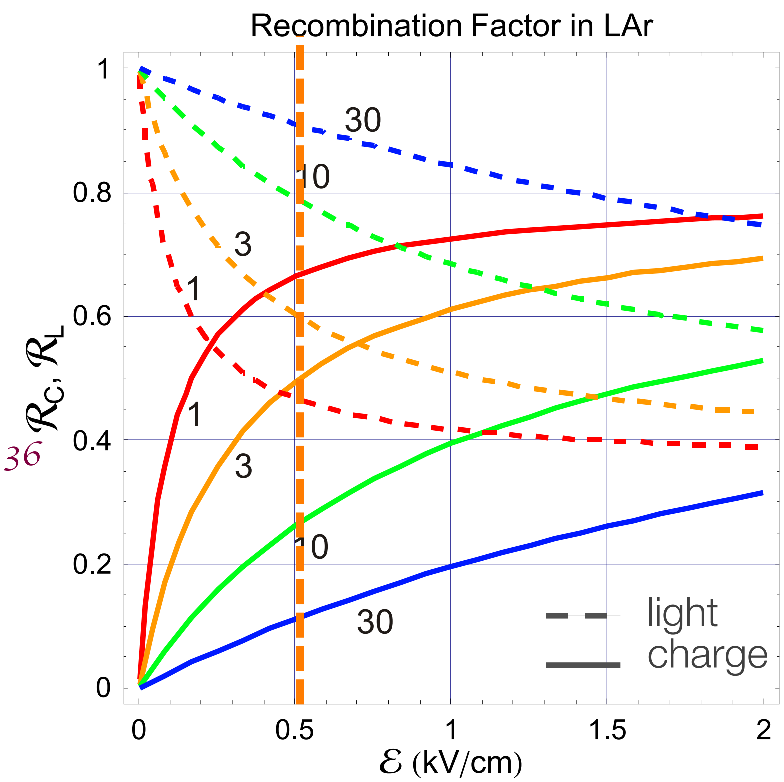
Thomas and Imel., Phys. Rev. A, 36 (1987)

$$\frac{\ln(A + B/\mathcal{E}\ dE/dx)}{B/\mathcal{E}\ dE/dx}$$

$$A = 0.930$$

$$B = 0.212\ (g/MeV cm^2)(kV/cm)$$

R.Acciari et al., JINST 8, (2013)

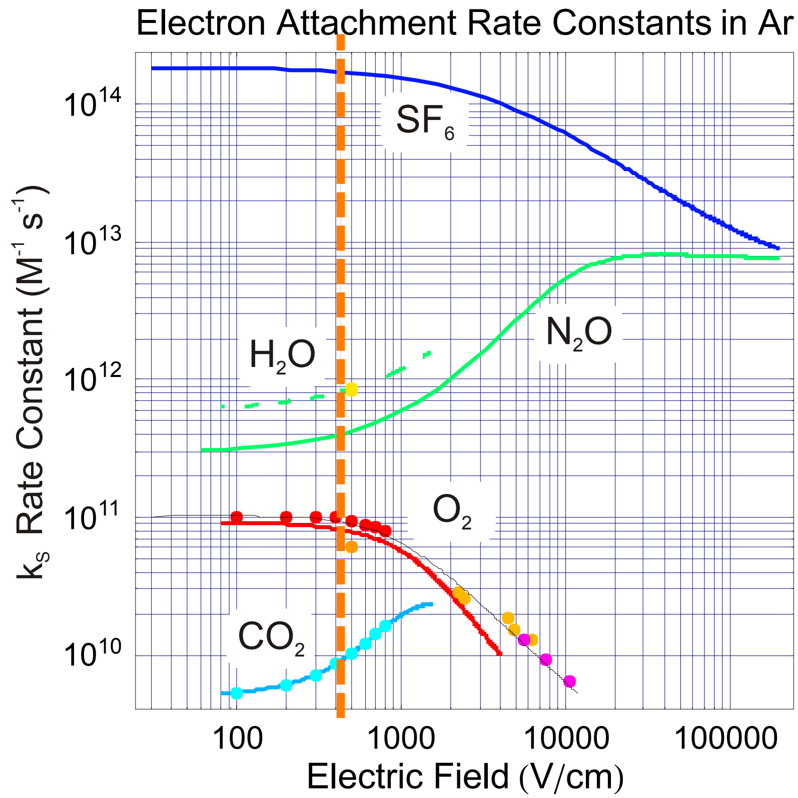


Ionization, transport and recombination

- Recombination and impurities can reduce the charge collected

$$Q_{eff} = Q_0 \exp(-t/\tau_e)$$

$$\frac{1}{\tau_e} = k_e [O_2]$$



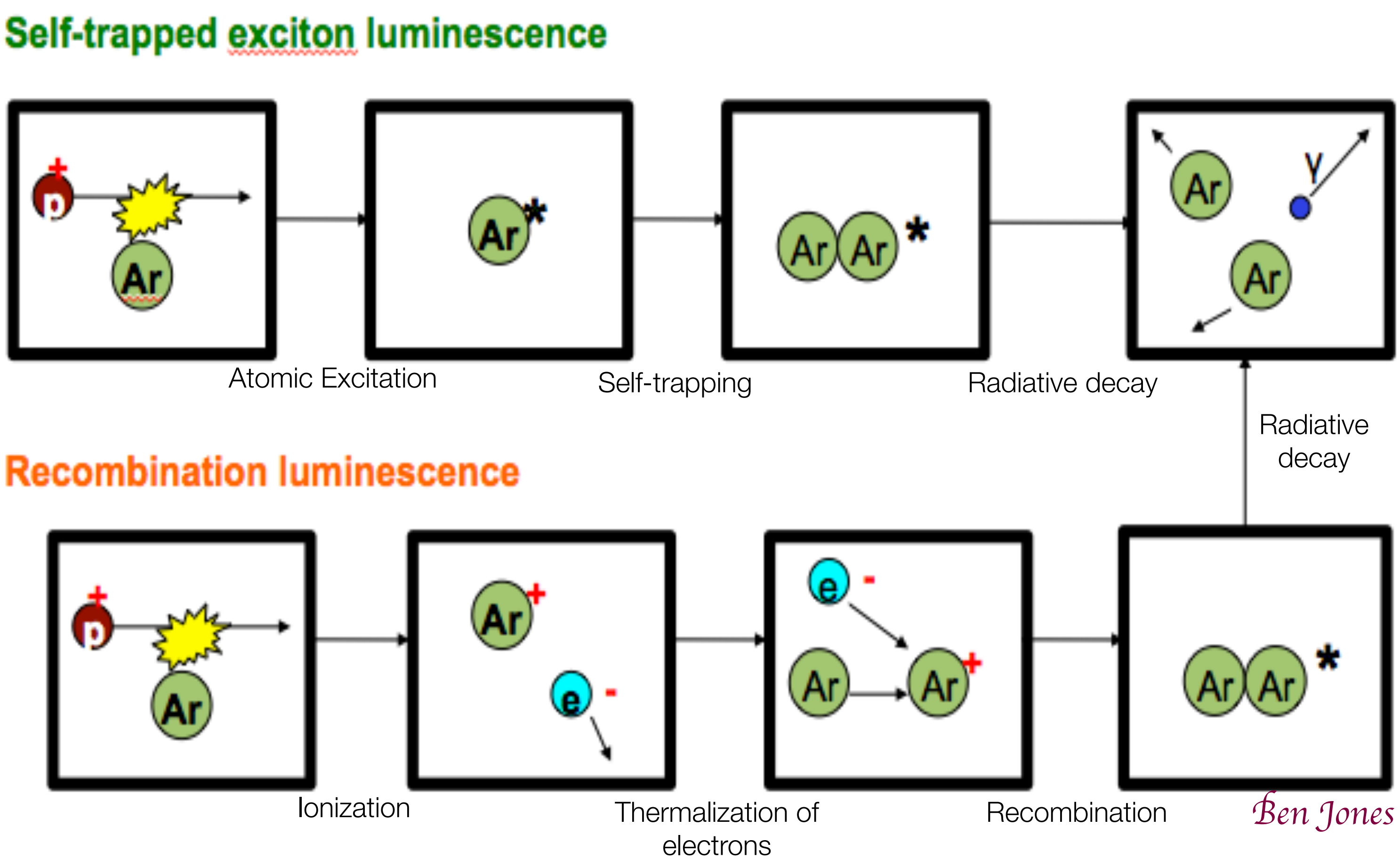
33. G. Bakale, U. Sowada, and W.F. Schmidt, *Effect of electric field on electron attachment to SF_6, N_2O, and $_{O2}$ in liquid argon and xenon*, J. Phys. Chem. **80** (1976) 2556.

34. A. Bettini, *et al.*, *A study of the factors affecting the electron lifetime in ultra pure liquid argon*, NIM **A305** (1991) 177.

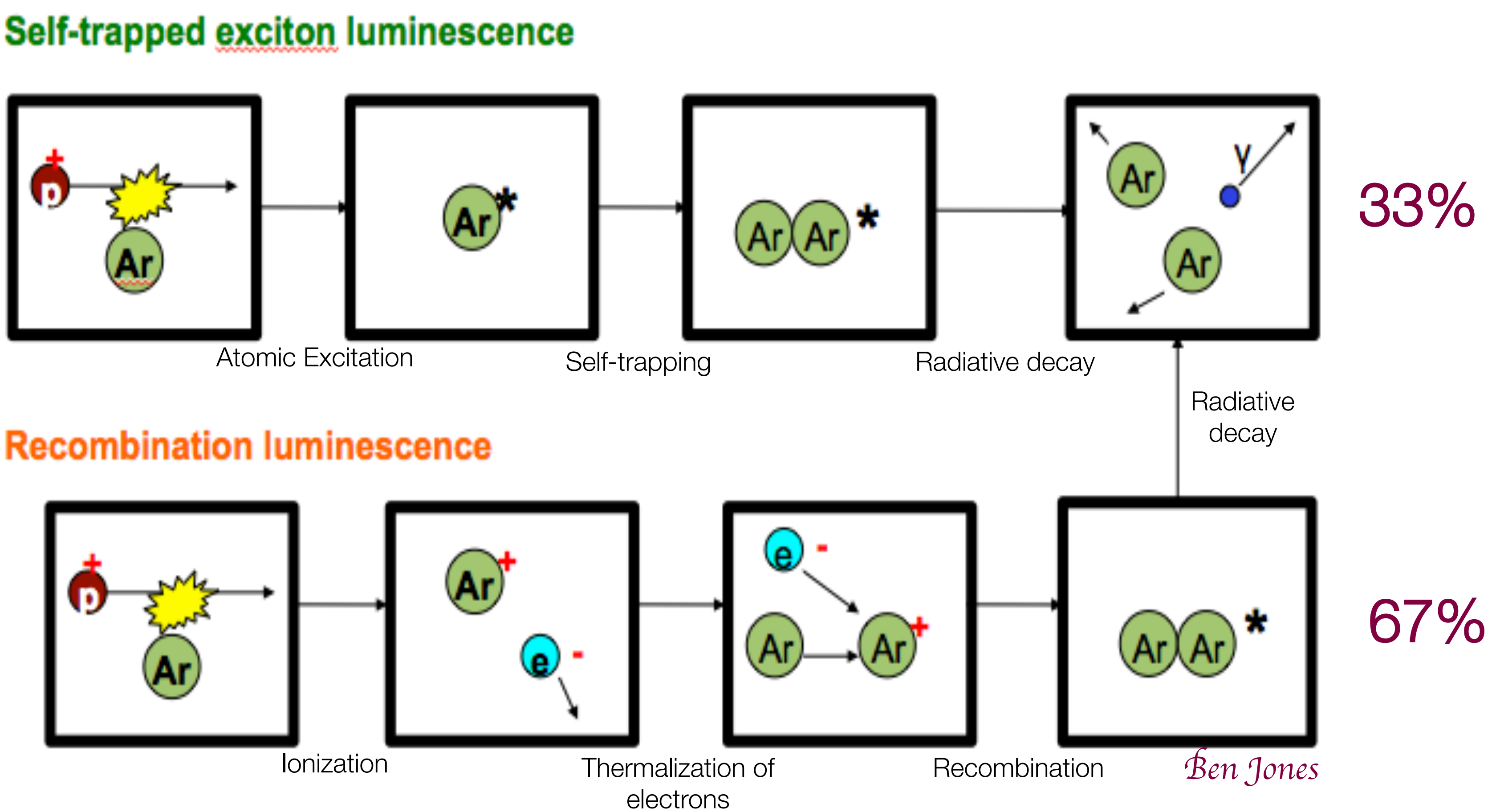
35. E. Aprile, K.L. Giboni, and C. Rubbia, *A study of ionization electrons drifting large distances in liquid and solid argon*, NIM **A241** (1985) 62.

36. M. Adams, *et al.*, *A purity monitoring system for liquid argon calorimeters*, NIM **A545** (2005) 613.

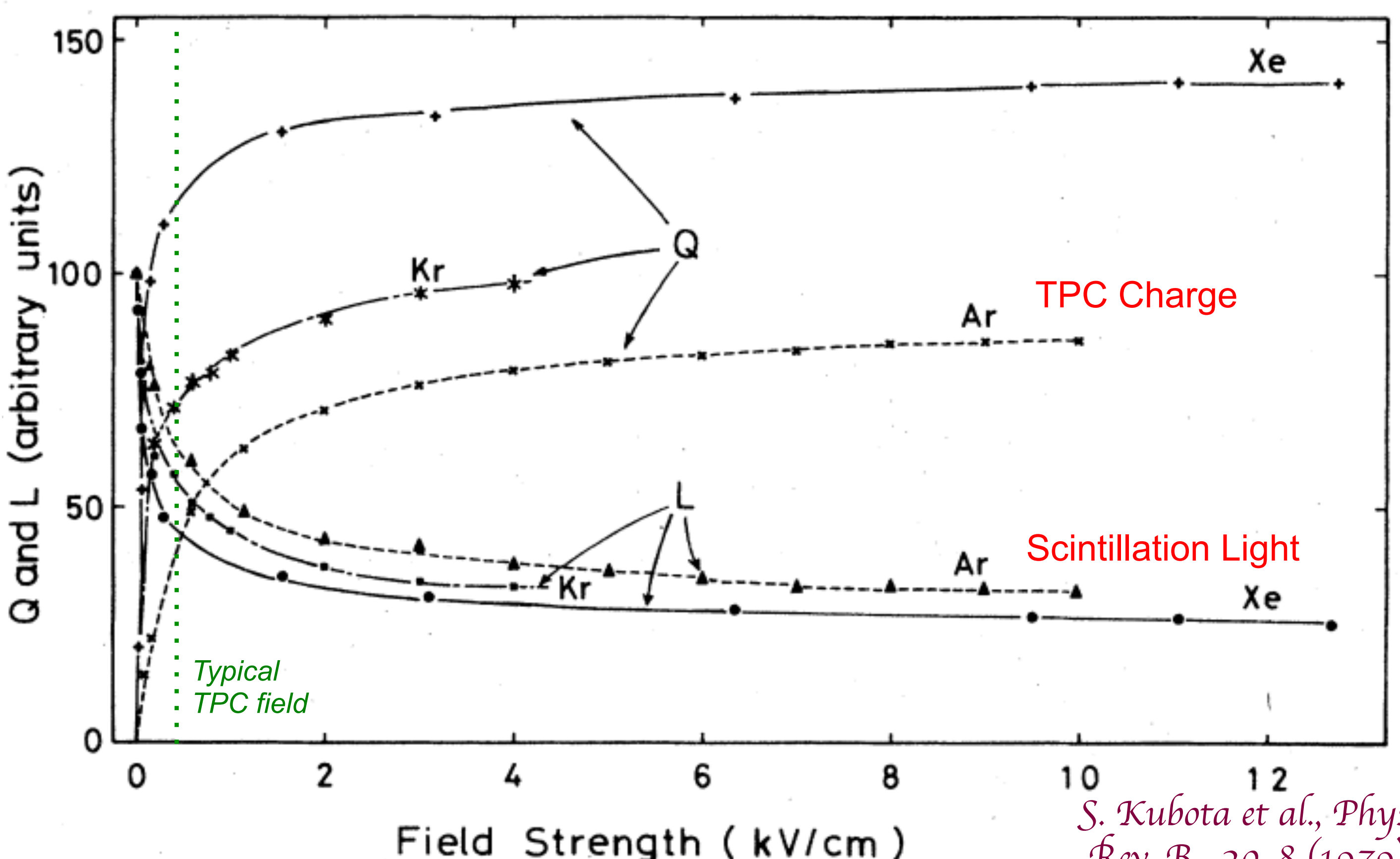
LArTPCs and scintillation light



LArTPCs and scintillation light

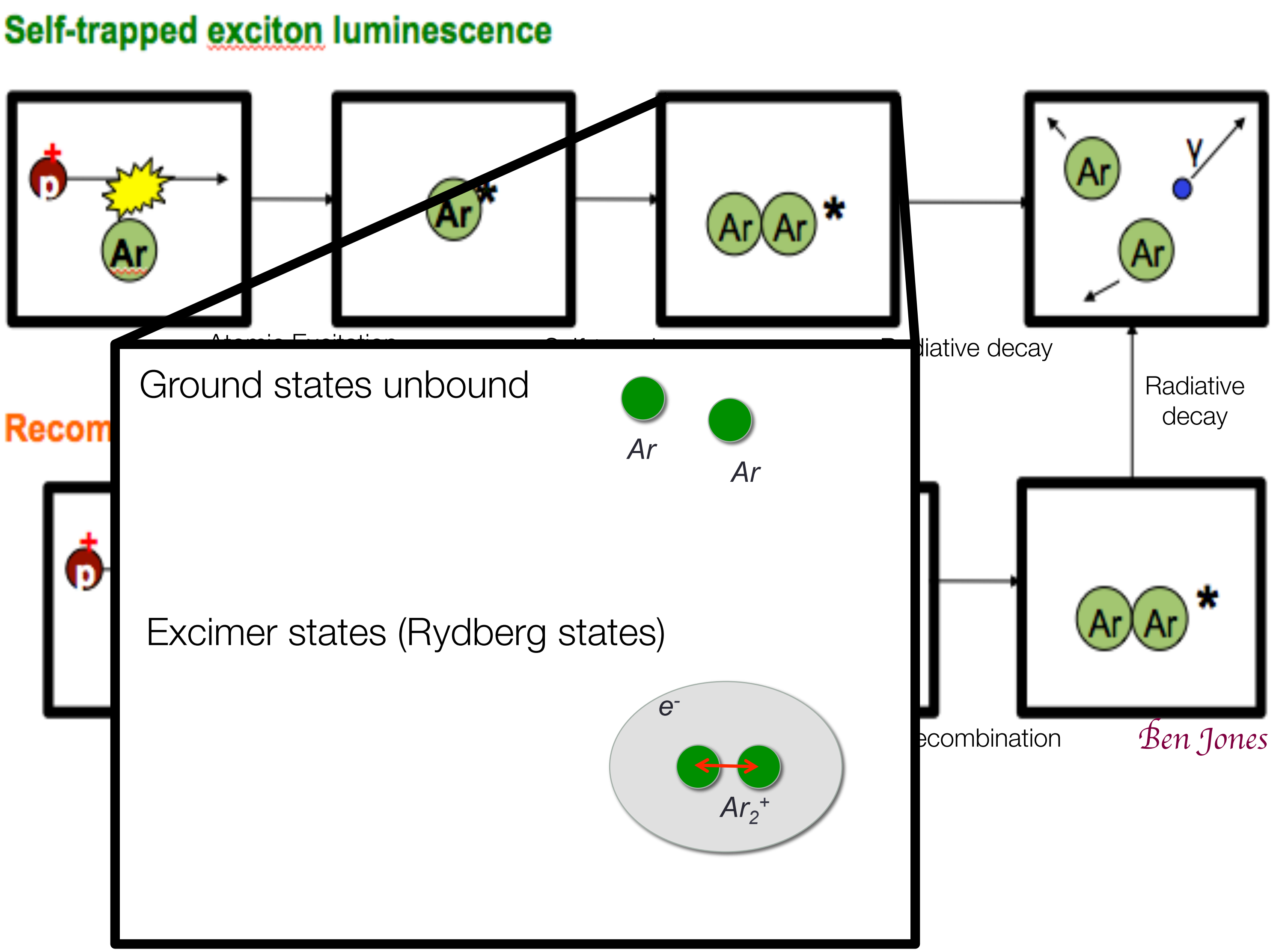


LArTPCs and scintillation light



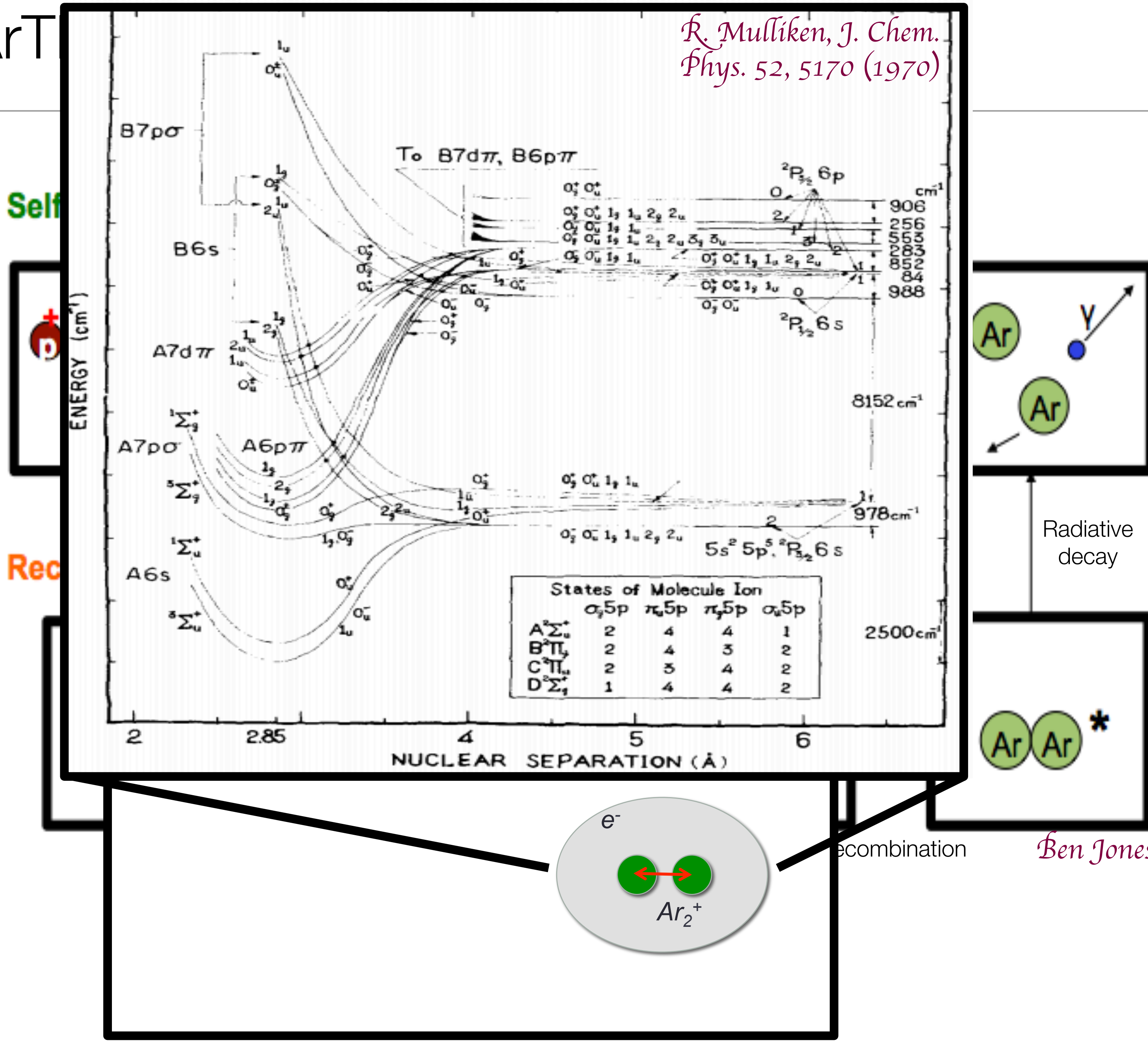
S. Kubota et al., Phys. Rev. B, 20, 8 (1979)

LArTPCs and scintillation light



Xe_2 Rydberg states

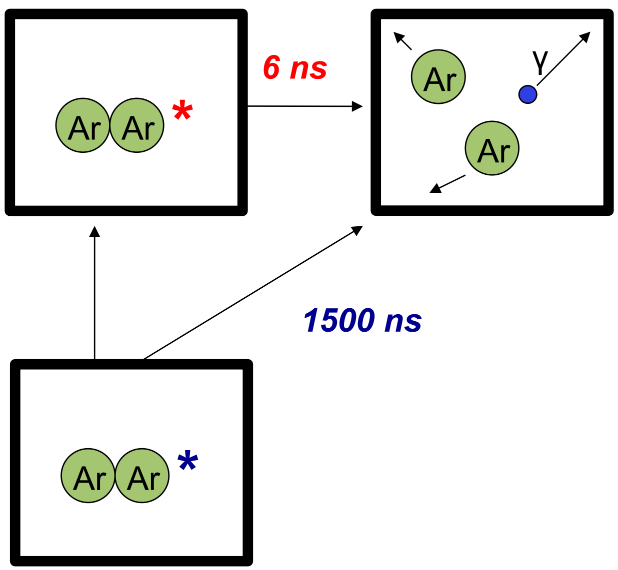
LArT



Ben Jones

LArTPCs and scintillation light

- The singlet and triplet have different time constant



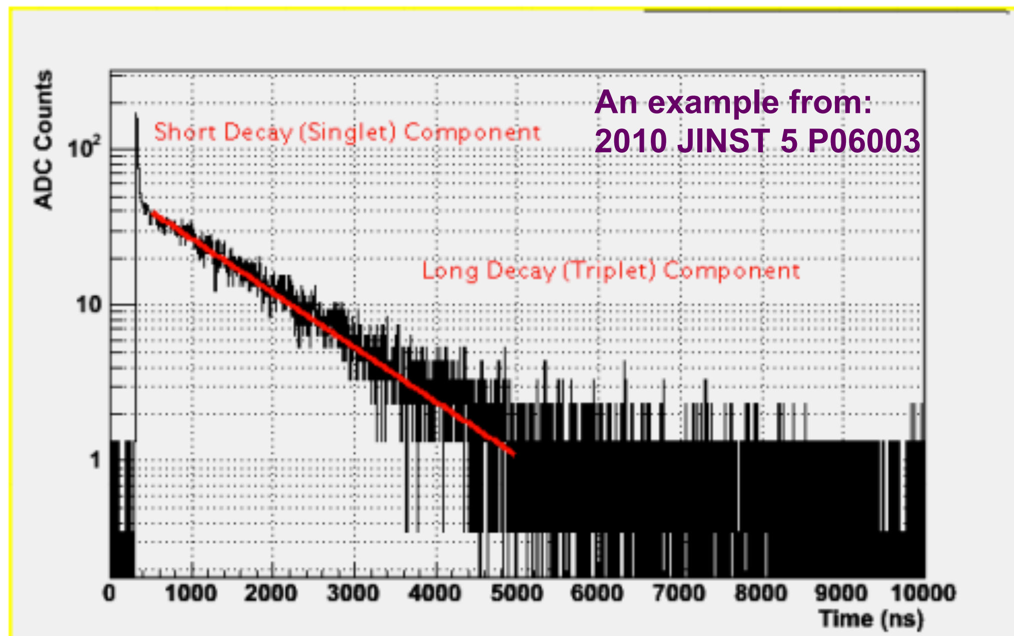
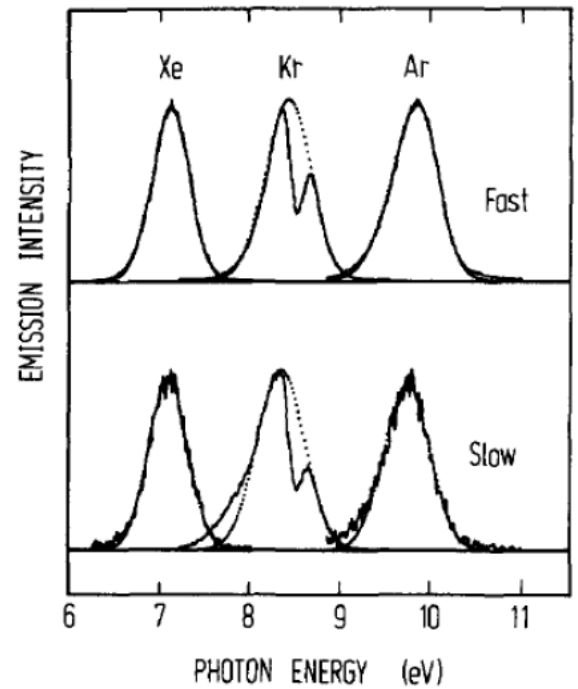


Fig. 4. *Typical (single) waveform recorded during the N_2 test. Event with large energy deposition from cosmic muon (mip) crossing the LAr cell.*

LArTPCs and scintillation light

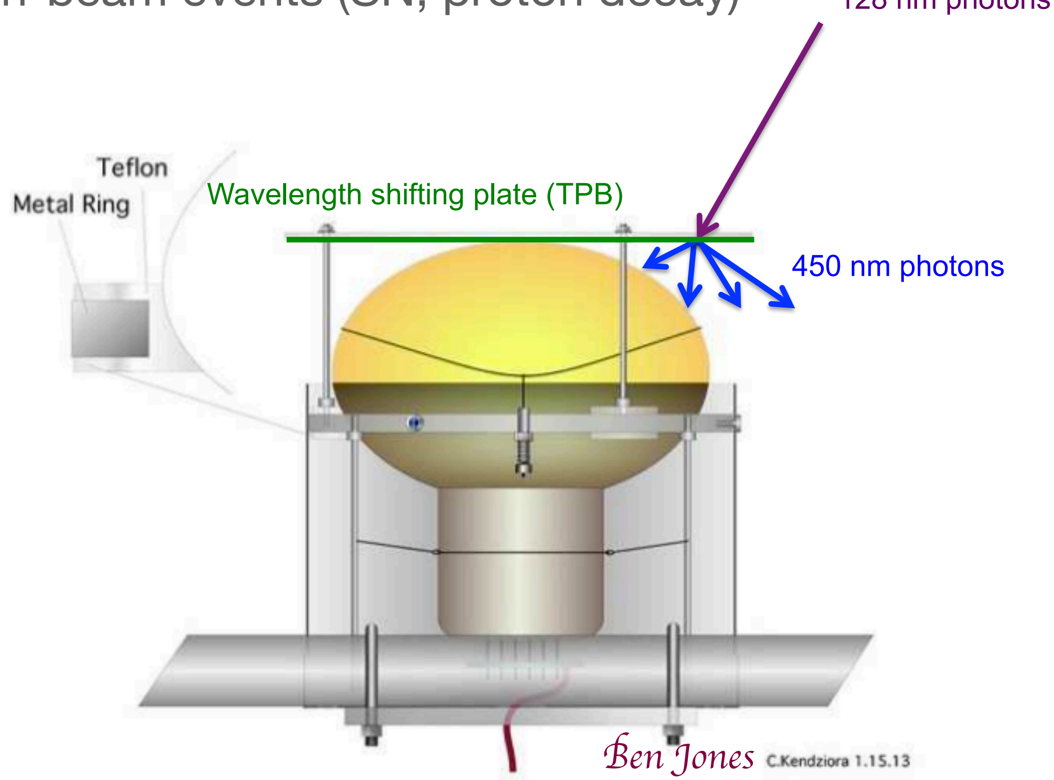
- Liquid argon produces scintillation light at a wavelength of 128 nm.
- Light yield ~ few 10,000's of photons per MeV (dependences on E field, particle type and purity)
- Argon is transparent at 128nm, which makes LAr scintillation detectors very scalable.
- Coupling scintillation detection with charge detection (*e.g.* in a TPC) offers many benefits



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

LArTPCs and scintillation light

- Precise (*O(ns)*) timing information on neutrino events to reject cosmic rays
- Can help reducing detection E_{thresh}
- Trigger for non-beam events (SN, proton decay)



LAr TPC challenges

- Purity in very large volumes
  - ✓ Long drift distances
  - ✓ No evacuation
- High voltages (to allow long drift distances)
- Low noise electronics at low cost (650k channels!)
- Scalability
- Costs
- Automated event reconstruction

Technical details on LArTPC

- Cryogenics (cryostat, purity)
- TPC (active detector) (Wire planes)
- Electronics (warm or cold)
- Calibration

Cryogenics of LArTPC

Cryogenics components and requirements

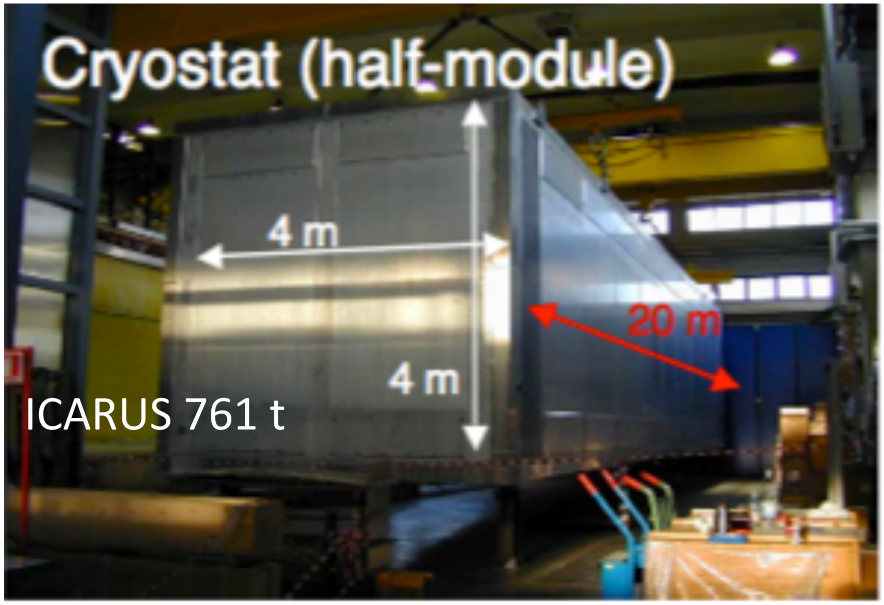
Components

- Cryostat
- Cryogenic plant (cryogen delivery, storage and filling)
- Circulation and purification of LAr

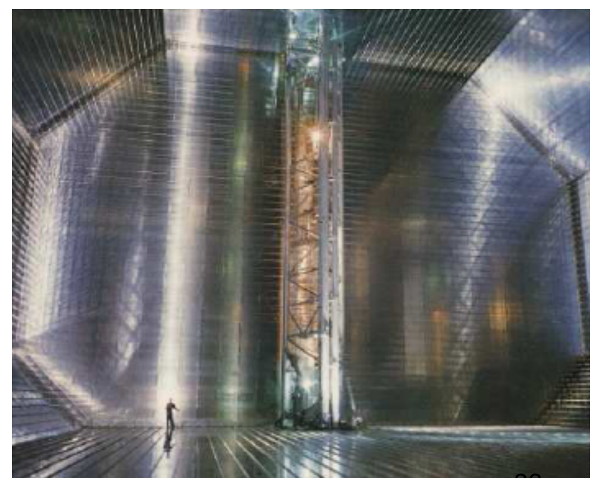
Requirements

- Maintain high LAr purity
- Cryostat insulation:
  - ➢ Low thermal loss < $15 W/m^2$
  - ➢ Temperature variation in the cryostat < 1ºK
  - ➢ Prevent LAr bubble formation
- Scalability
- Safety (underground operations)

Cryostats

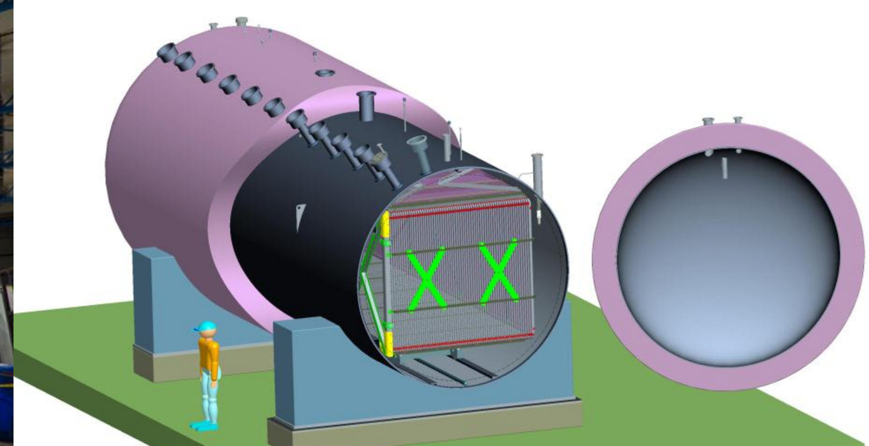


Foam insulated



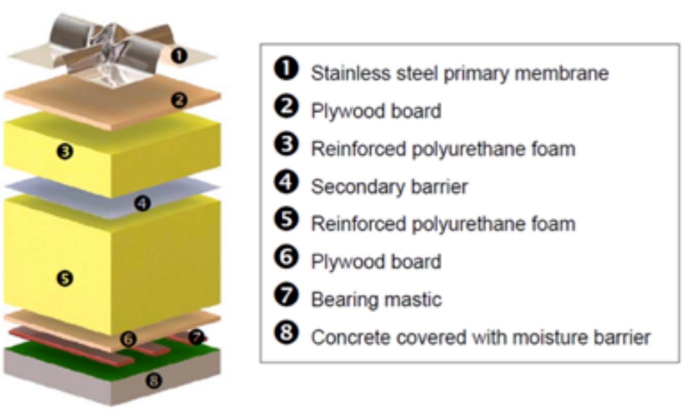
MicroBooNE cryostat

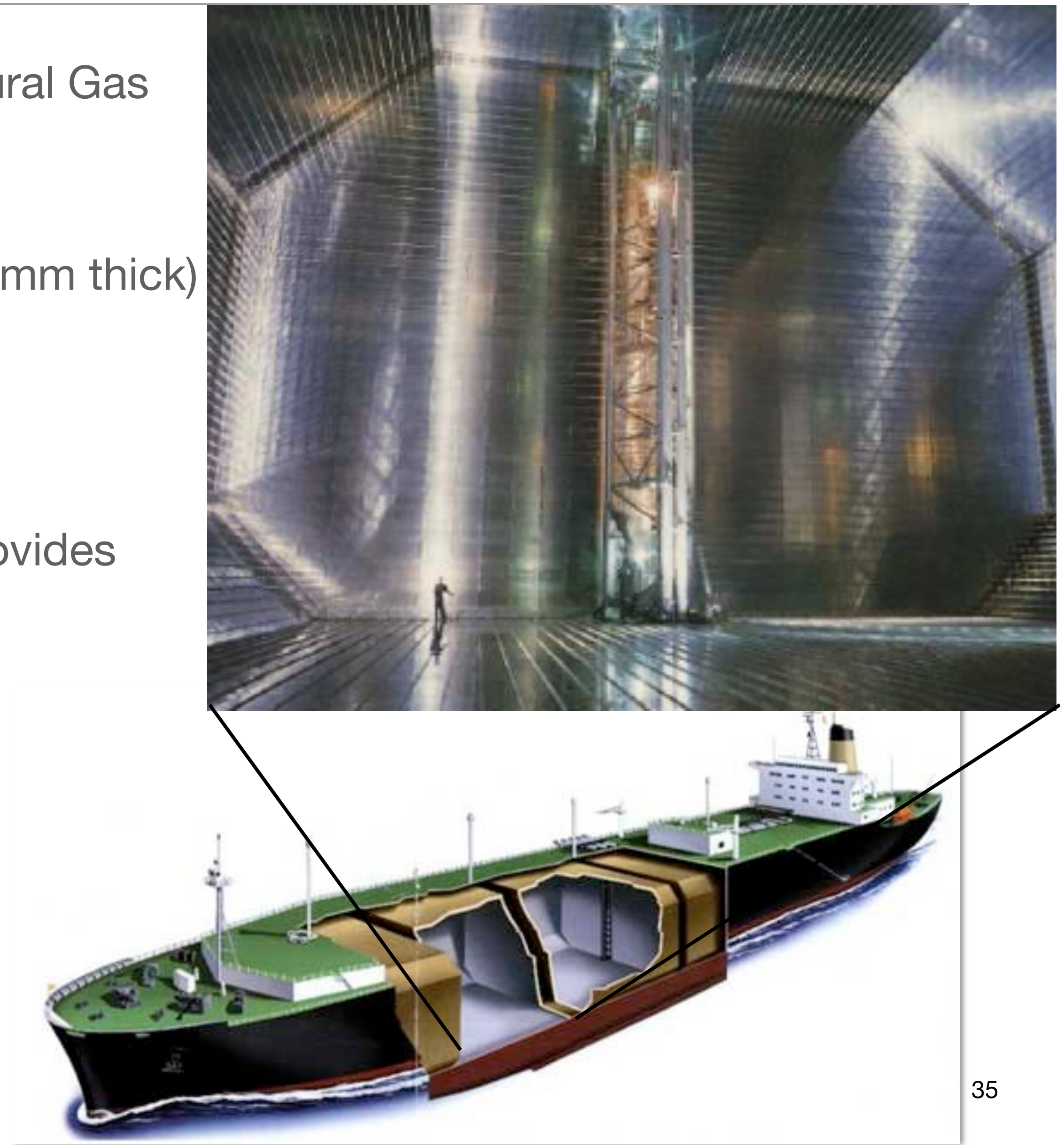
- Cylindrical cryostat (3.5m diameter x 12m long, 88mm thick)
- 170t of LAr (~80t of active volume)
- Foam insulated from outside



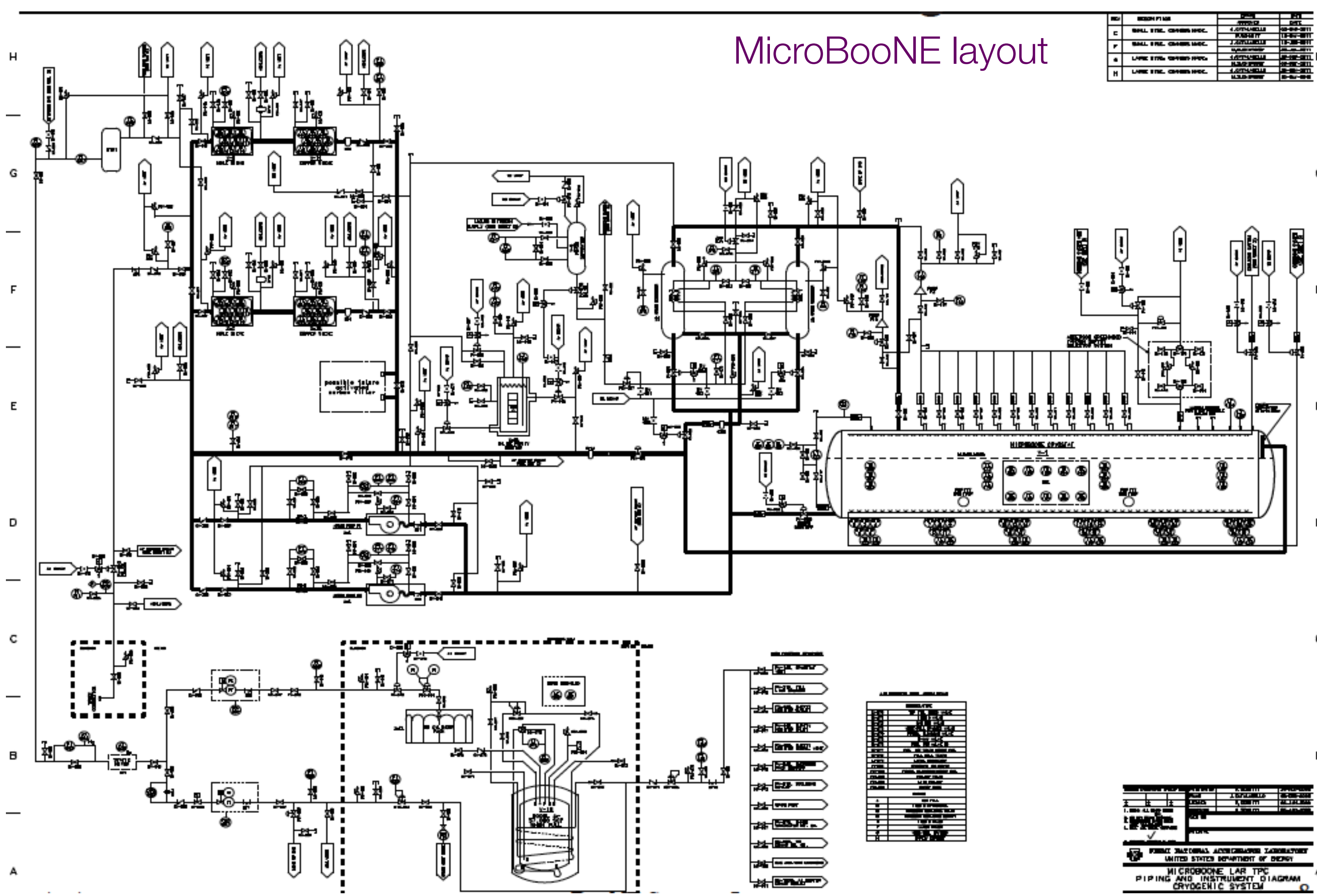
Membrane Cryostat for LBNE

- Already used in Liquefied Natural Gas tankers
- Stainless steel membrane (2-3mm thick)
- Foam insulated
- Surrounding rock/concrete provides mechanical support





Cryogenics plant



Purity system

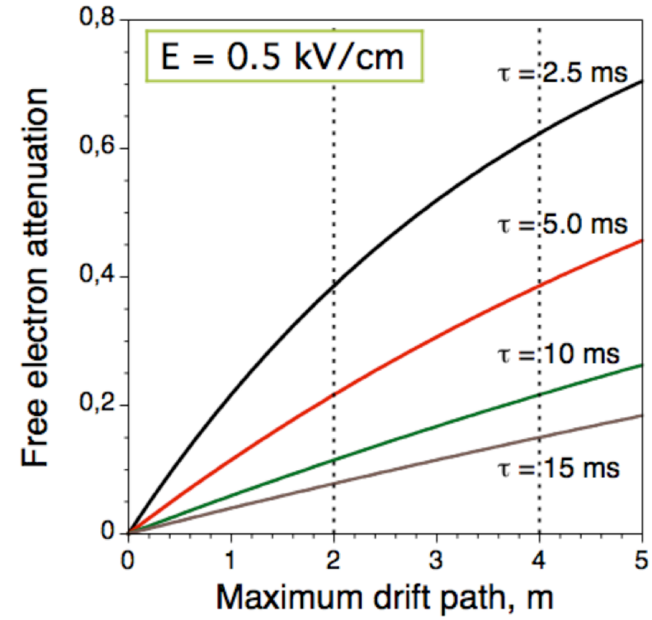
- Electronegative contaminants (O_2,N_2 or H_2O) will attached drifting electrons

$$Q_{eff} = Q_0 \exp\left(-t/\tau_e\right) \qquad \frac{1}{\tau_e} = k_e [O_2]$$

- Purity requirements: O_2 < 100 ppt, N_2 < 1 ppm

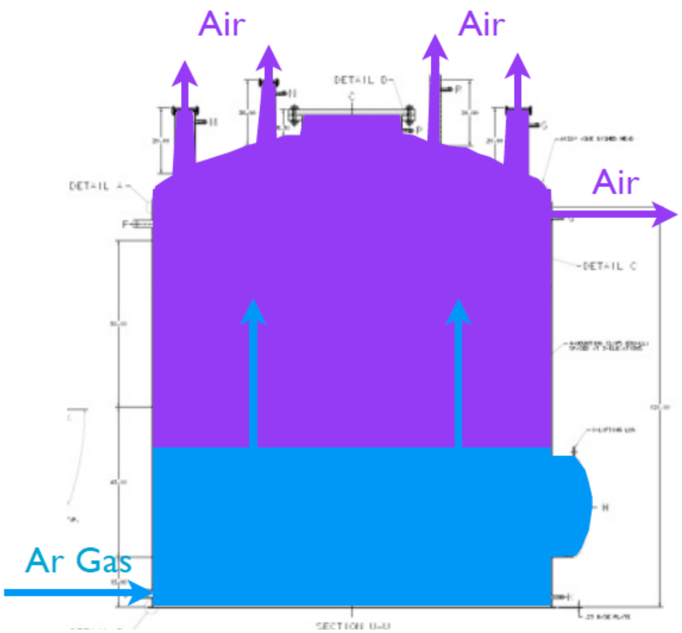
- Note: Research grade commercial LAr
~ 1ppm H_2O and O_2, ~3ppm N_2

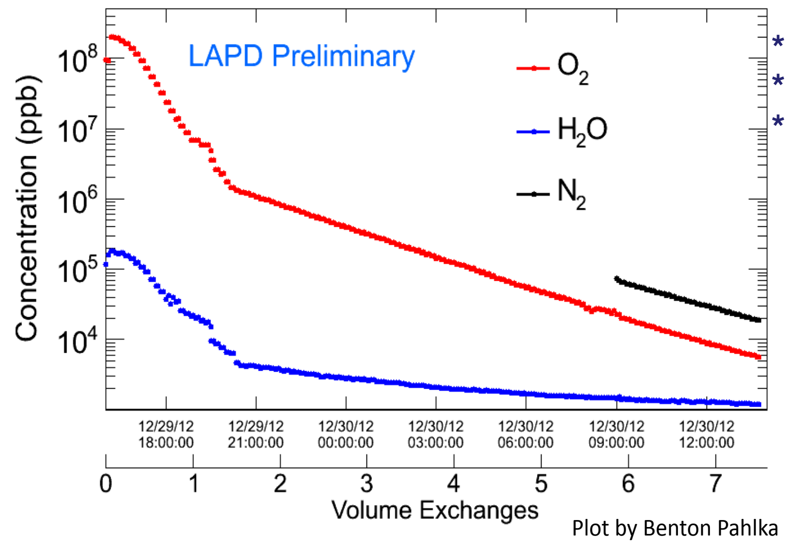
- Recirculation through filters will ensure purity stability



Purity system (filling)

- LAPD successfully demonstrated that purging vessel with argon gas



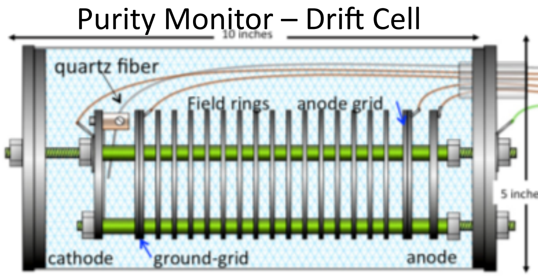


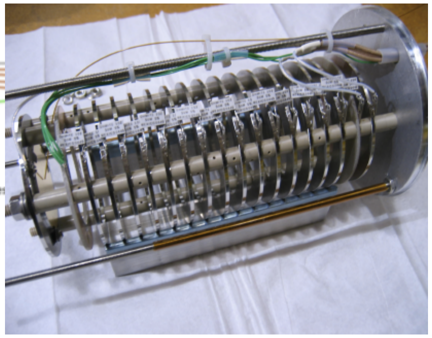
*** O_2 from 21% to 6 ppm**
*** N_2 from 78% to 18 ppm**
*** H_2O from 200 to 1.2 ppm**

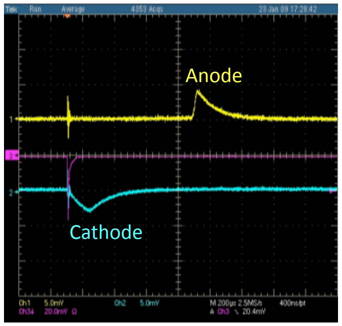
- Gas recirculation through filters (heating for H_2O evaporation)
- Cool down of the vessel (slowly!)
- Filling with the LAr direct from trucks

Purity control and monitoring

- Purity monitors



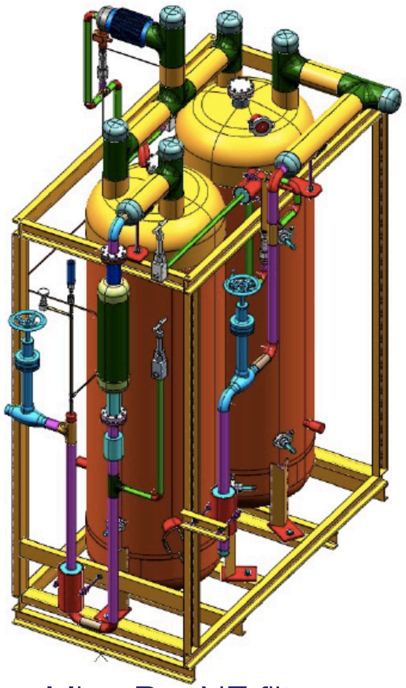




$$Q_{anode} = Q_{cathode} \times \exp(-t_{drift} / \tau)$$

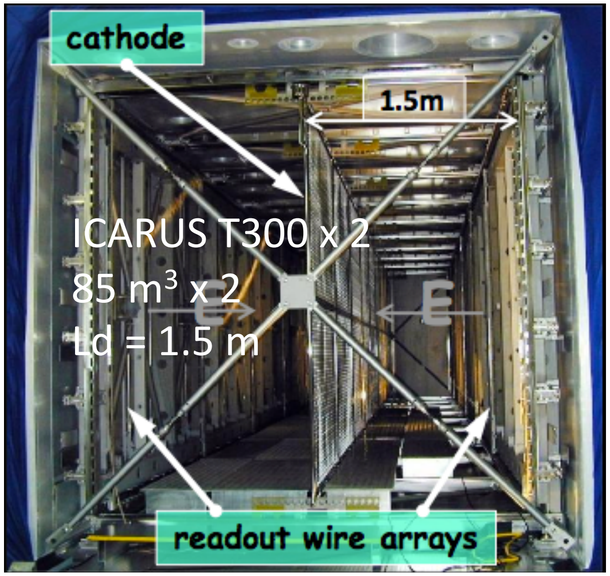
- Filters:

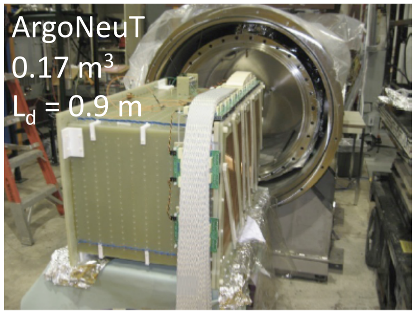
  - Molecular sieve: Removes H_2O and some N_2
  - Cu filters: Removes O_2
  - They can be regenerated (when they get saturated)

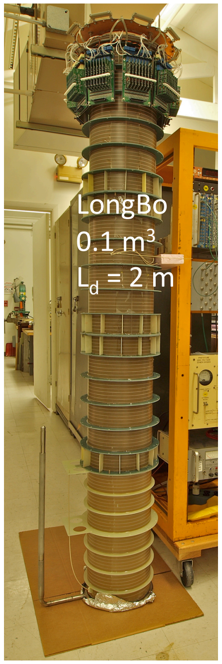


MicroBooNE filters

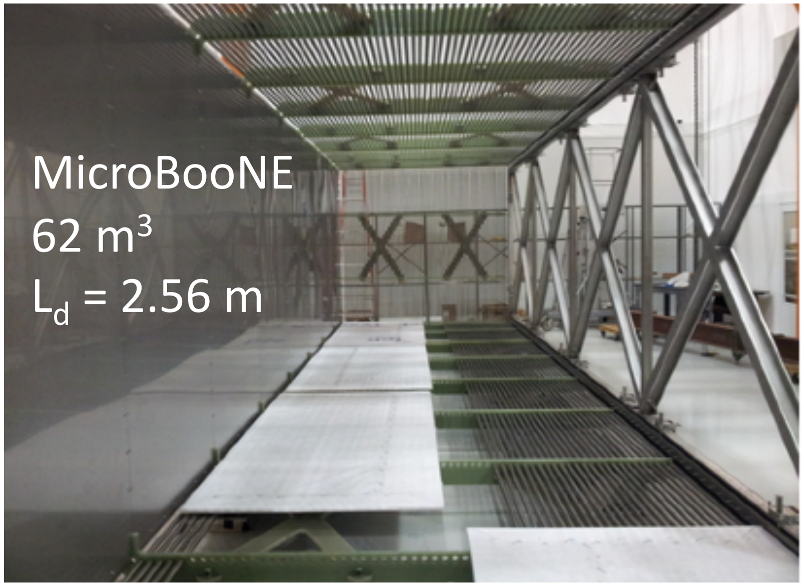
TPC


cathode
1.5m
ICARUS T300 x 2
85 m³ x 2
Ld = 1.5 m
E
E
readout wire arrays

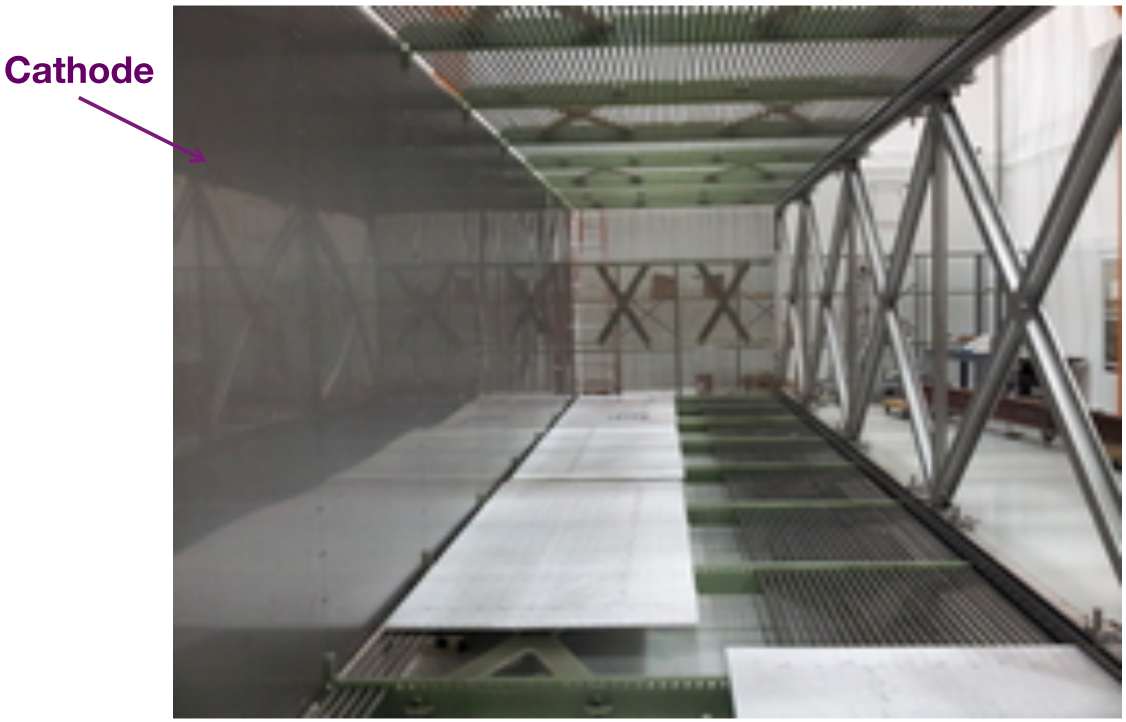

ArgoNeuT
0.17 m³
L_d = 0.9 m


LongBo
0.1 m³
L_d = 2 m


ARGONTUBE
0.63 m³
L_d = 5 m

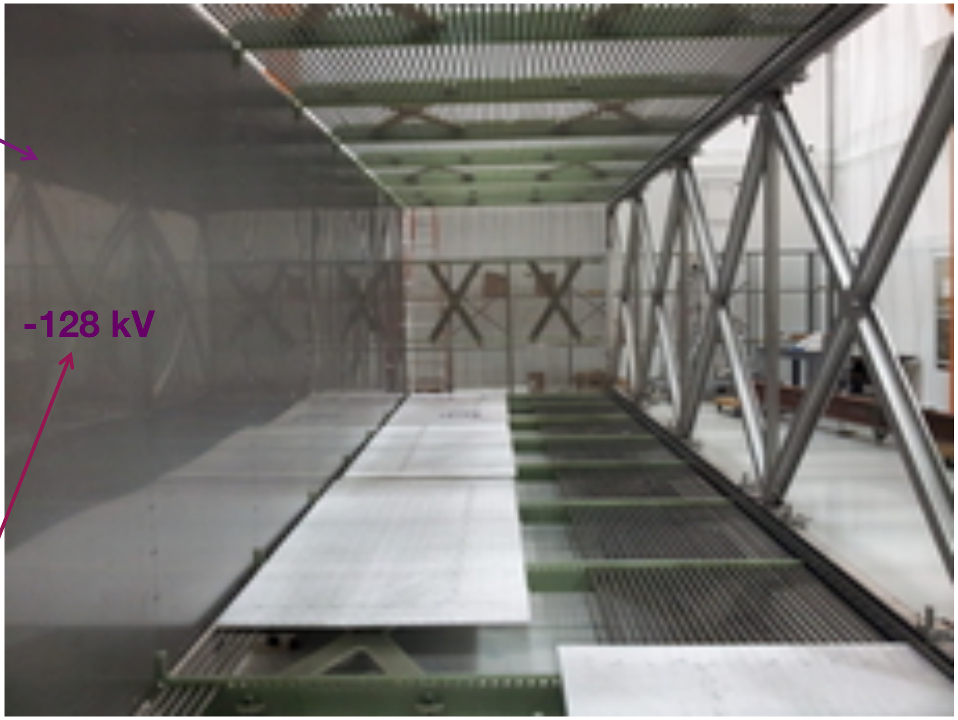

MicroBooNE
62 m³
L_d = 2.56 m

TPC

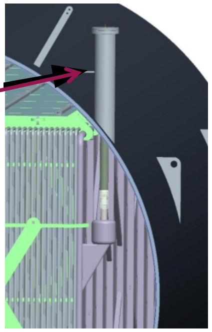


TPC

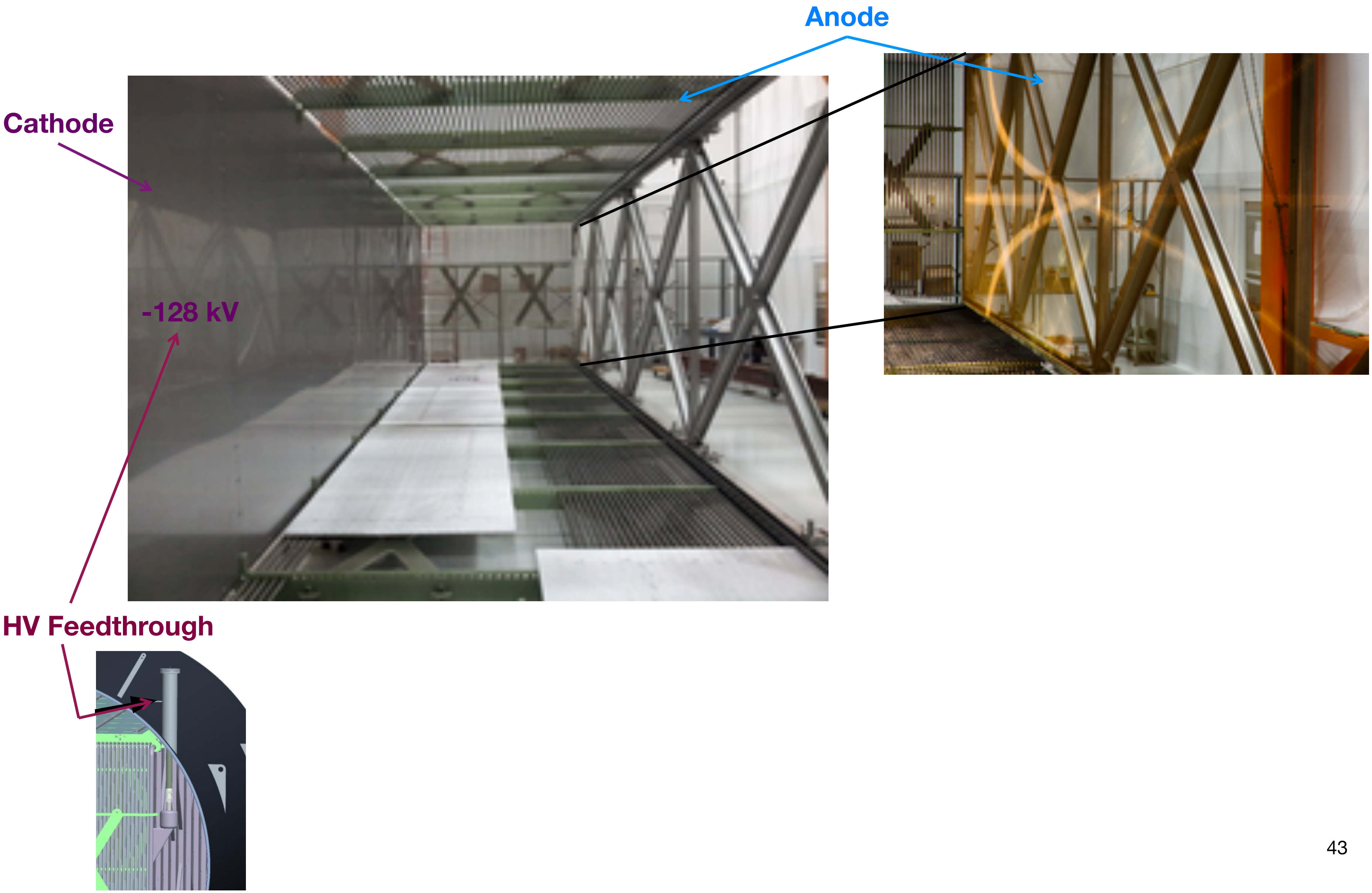
Cathode



HV Feedthrough



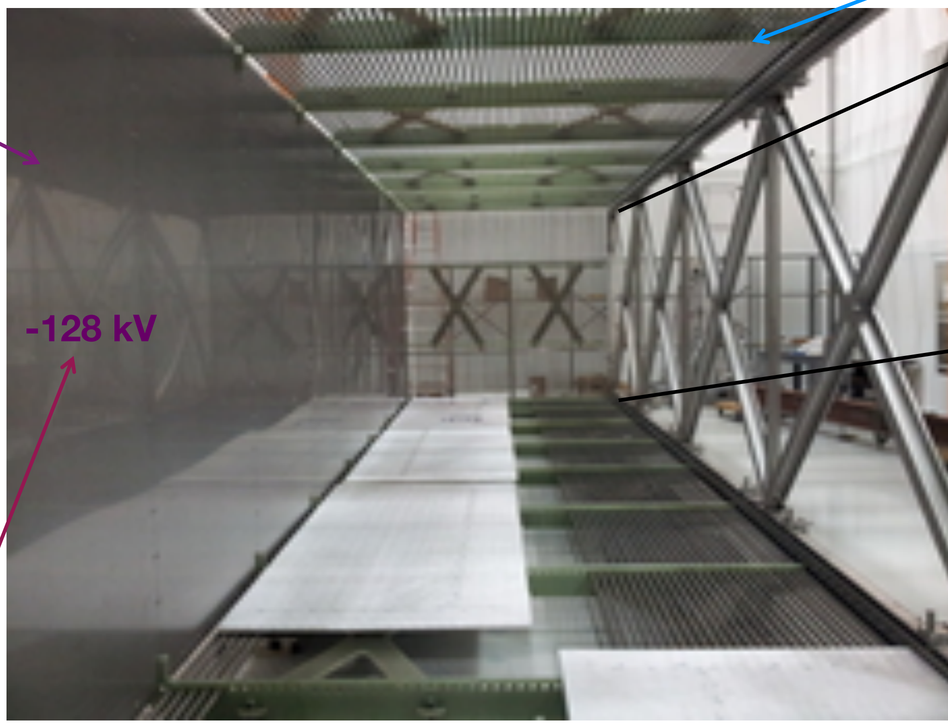
TPC



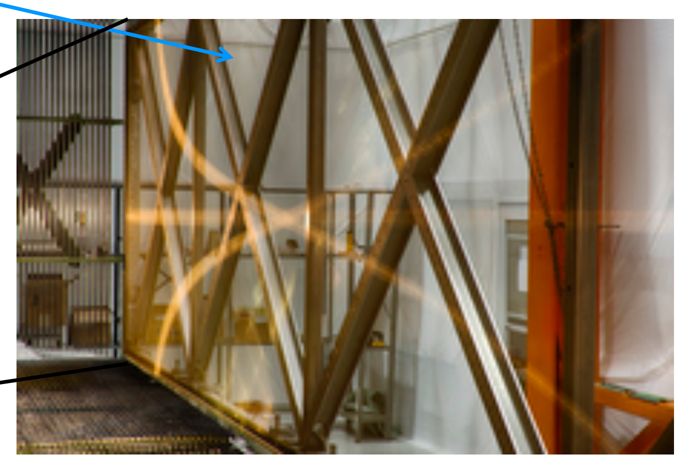
TPC

Anode

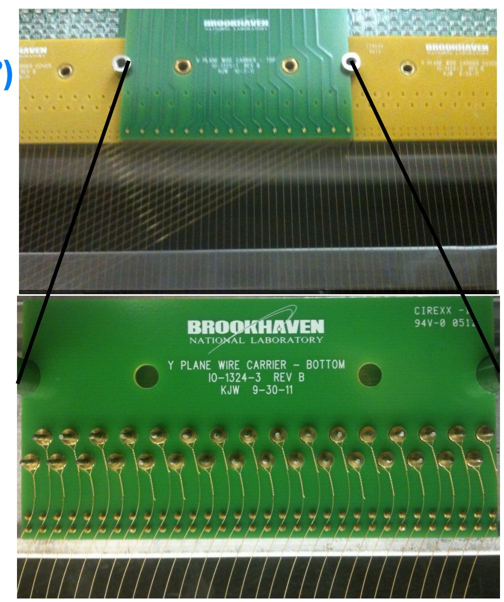
Cathode



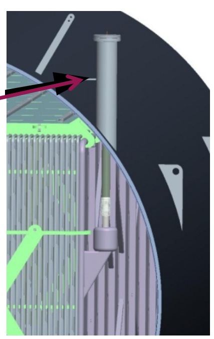
-128 kV



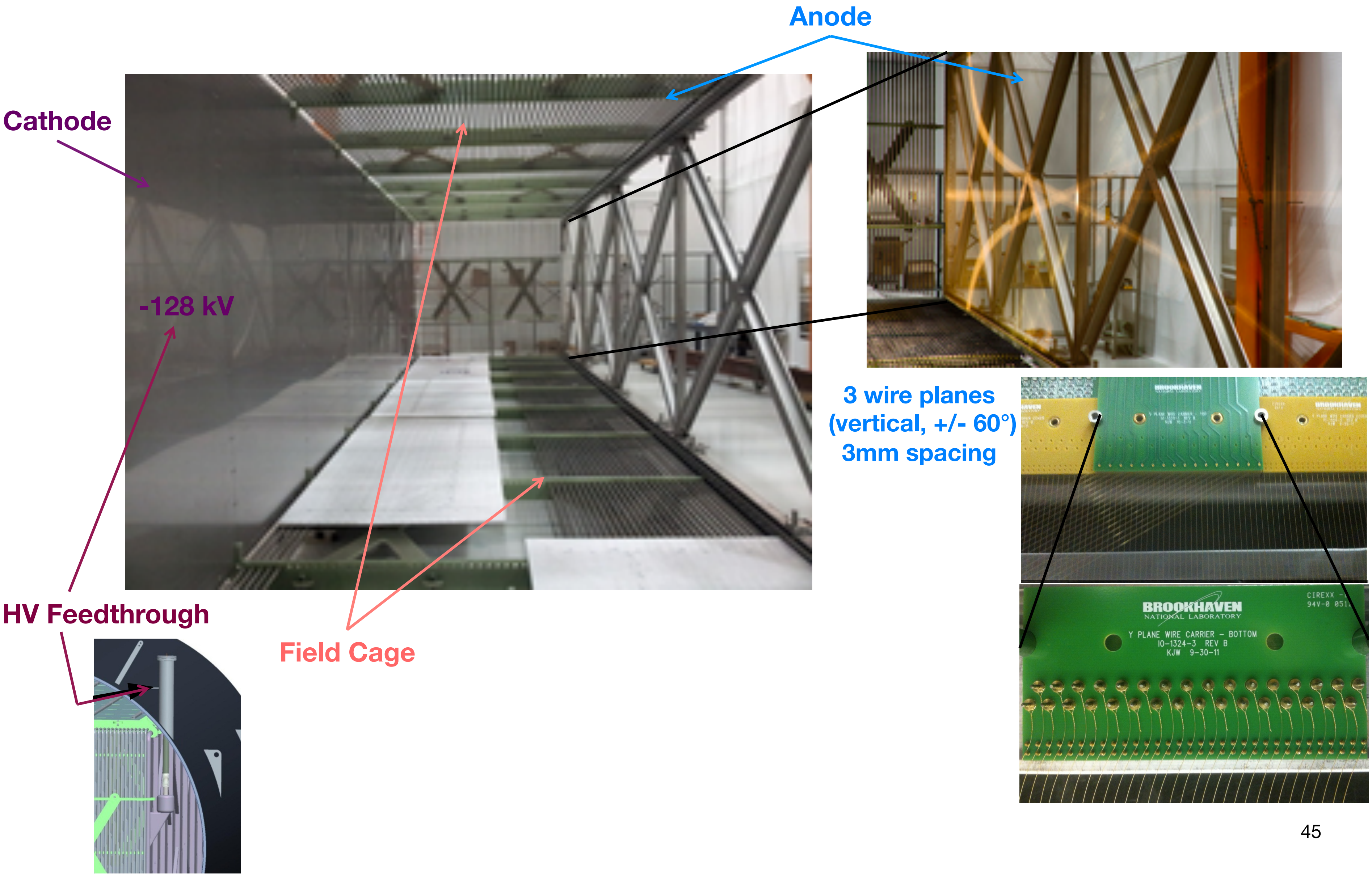
3 wire planes
(vertical, +/- 60°)
3mm spacing



HV Feedthrough



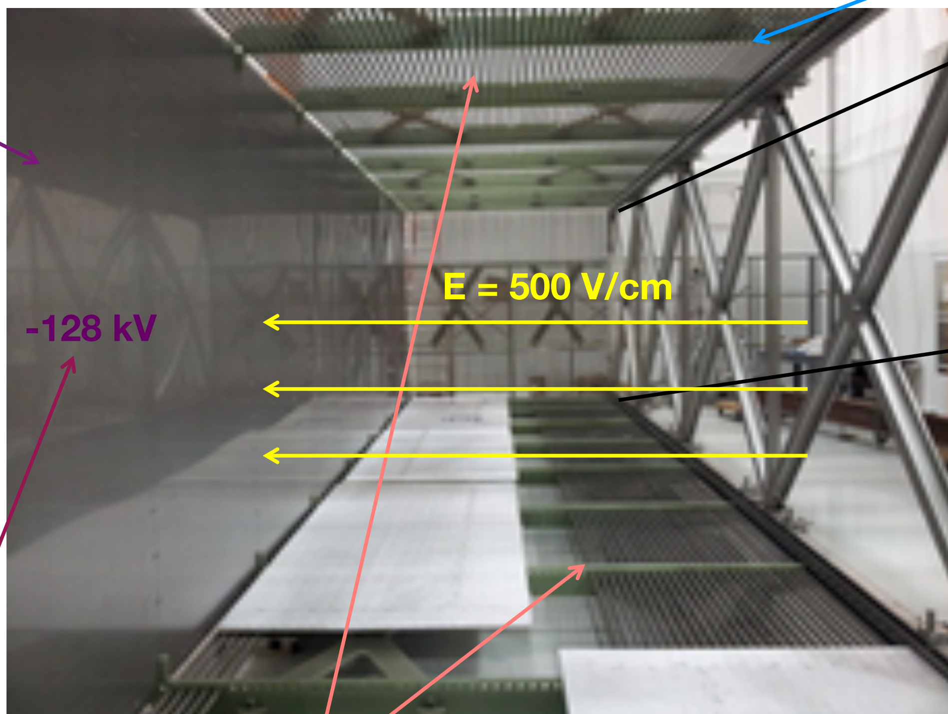
TPC

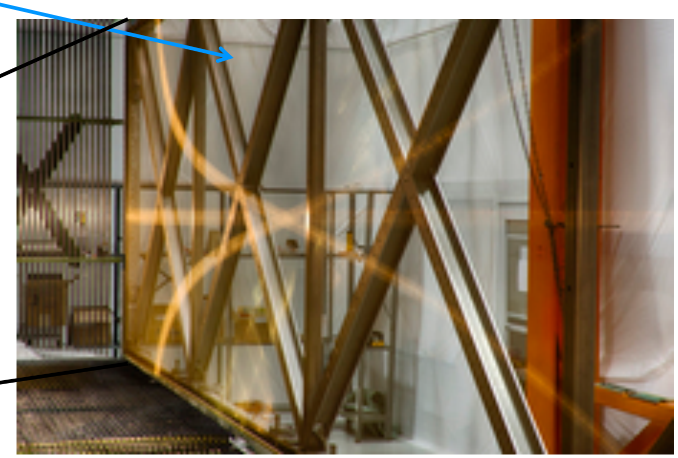

Anode
Cathode
-128 kV
HV Feedthrough
Field Cage
3 wire planes
(vertical, +/- 60°)
3mm spacing
BROOKHAVEN
NATIONAL LABORATORY
Y PLANE WIRE CARRIER - BOTTOM
IO-1324-3 REV B
KJW 9-30-11

TPC

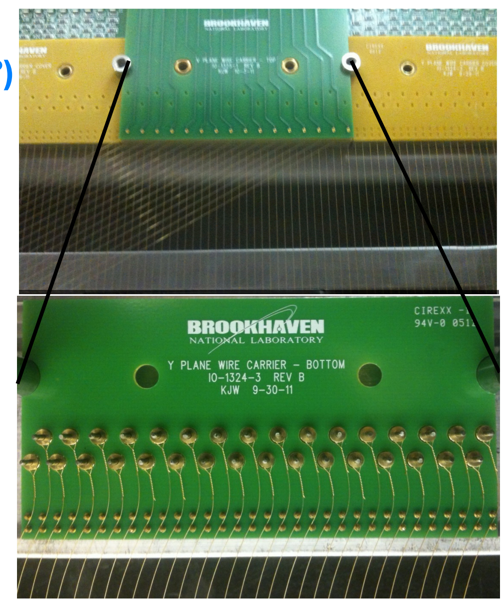
Anode

Cathode

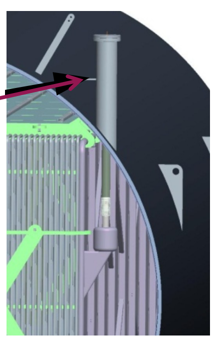




3 wire planes
(vertical, +/- 60°)
3mm spacing



HV Feedthrough



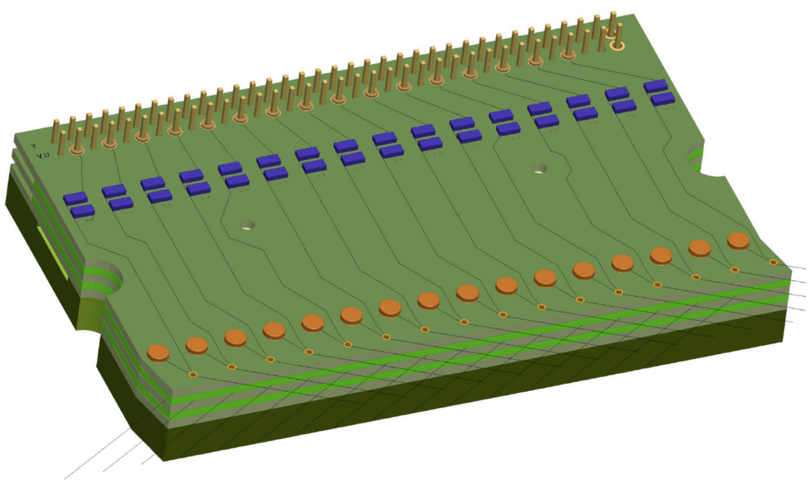
Field Cage

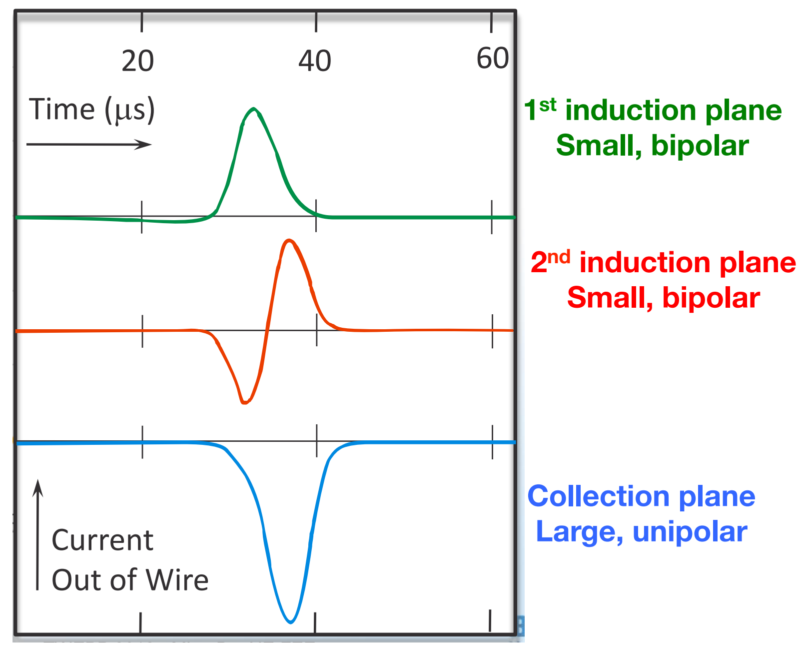
Tubes are connected with 250MΩ resistors for field uniformity

Readout Electronics

- Cold electronics, warm interface electronics, digitizing and data handling electronics, cabling and signal feedthroughs

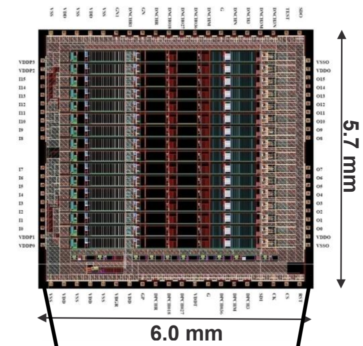
- Process signals from all the TPC wires (e.g. 8256 for MicroBooNE)



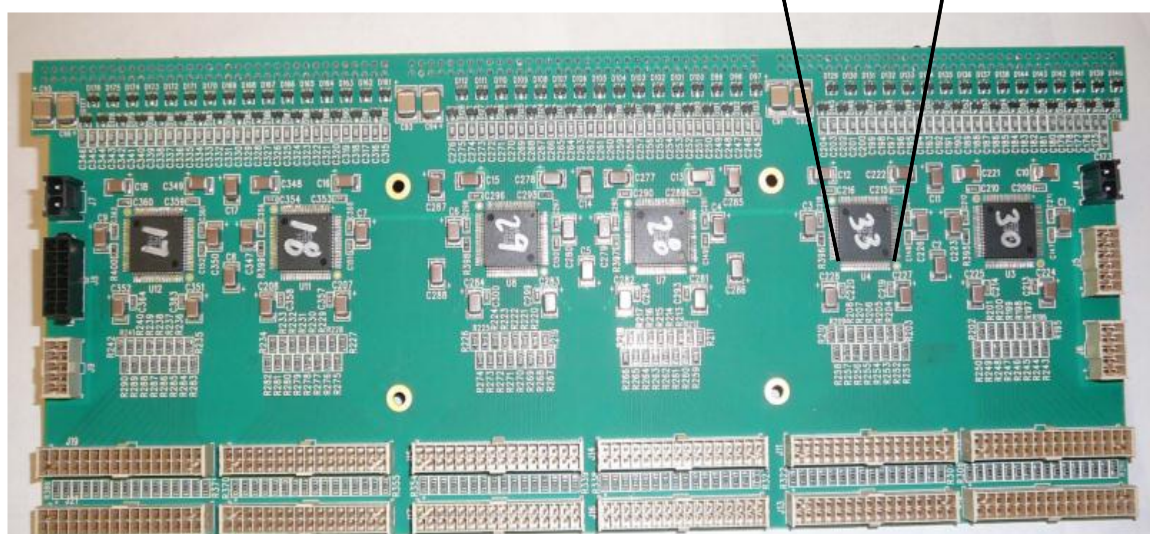


Front End Electronics

- CMOS front end ASIC
  - ➢ Charge amplifier and high-order filters
  - ➢ Adjustable gain and filter time constant
  - ➢ Selectable collection/induction mode and ac/dc coupling
  - ➢ Designed for long cryo-lifetime



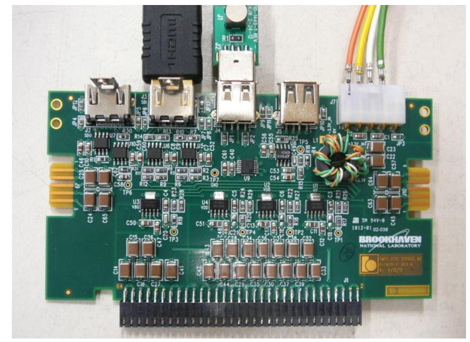
- Custom cold motherboard
  - ➢ Connections for detector signal
  - ➢ ASIC control and monitoring
  - ➢ Bias voltage to wire planes



Warm interface Electronics

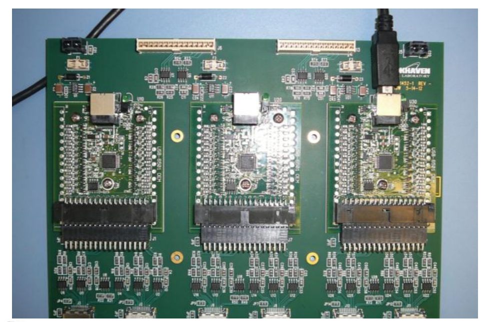
- Intermediate Amplifier

- Service Board

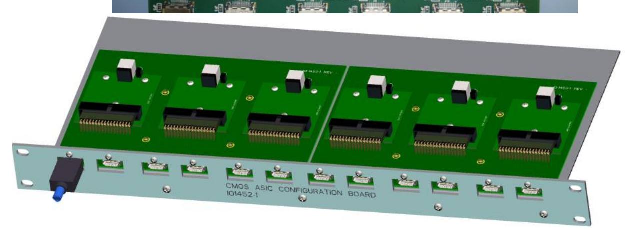


  - Provide low voltage to ASICs and to intermediate amplifiers
  - Pulse injection to ASIC

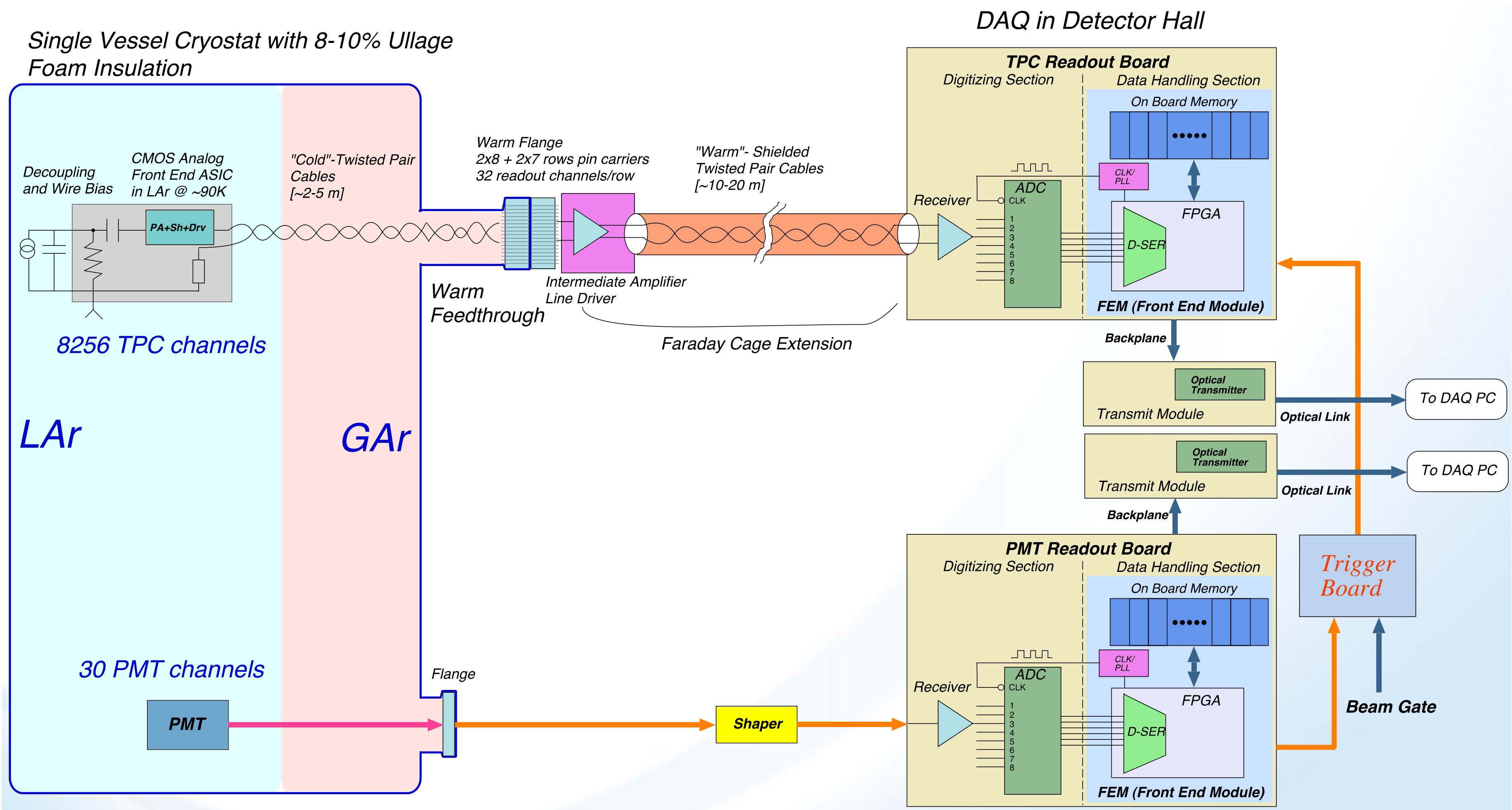
- ASIC Configuration Board



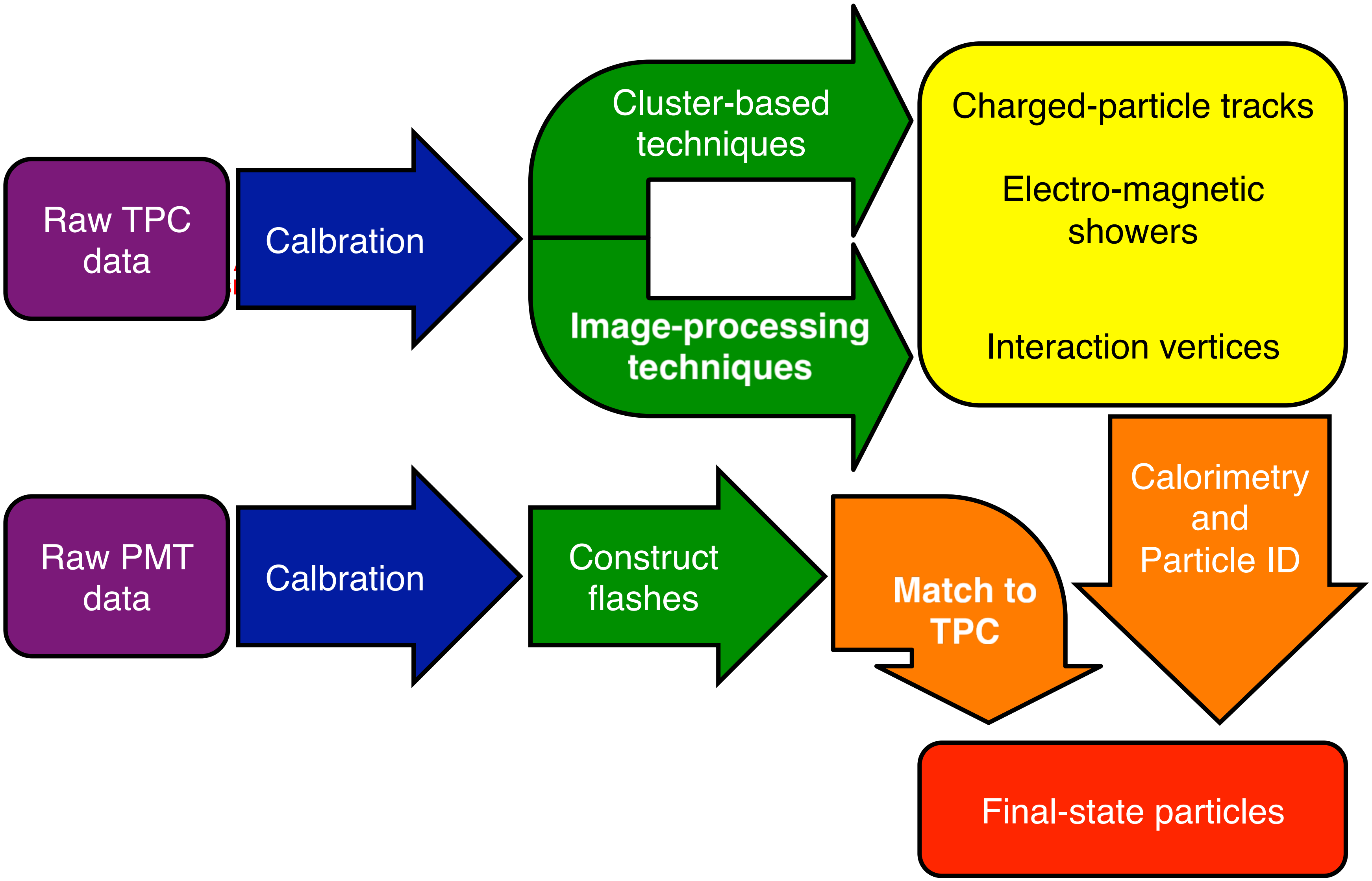
  - ASIC configuration and monitoring between ASICs and DAQ PC



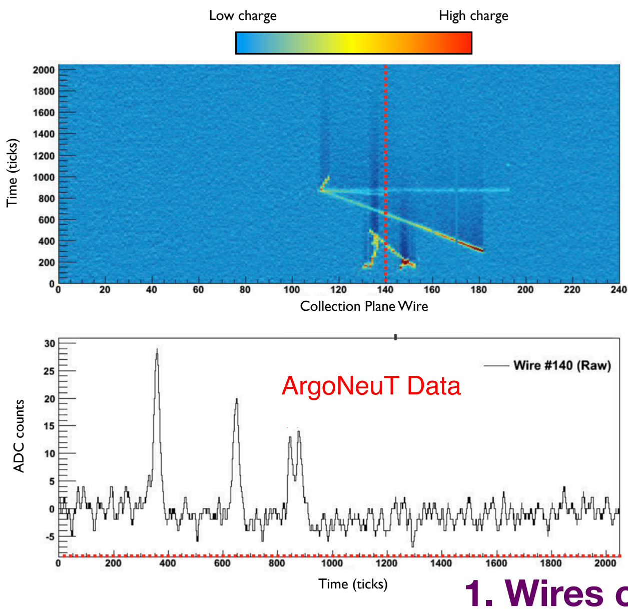
Electronics

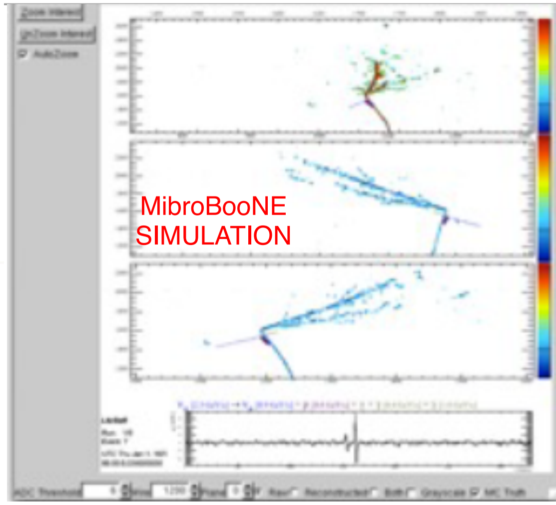


Event Reconstruction

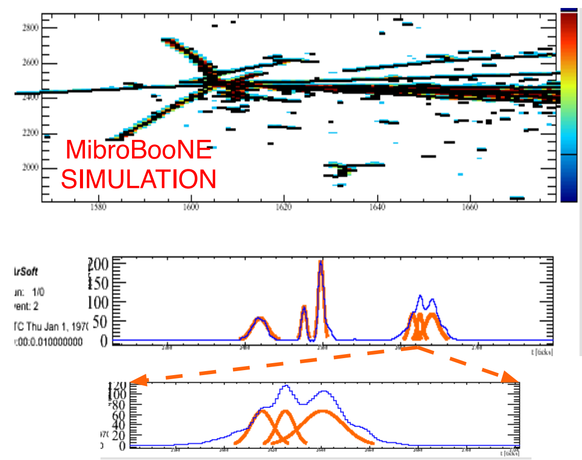


Event Reconstruction

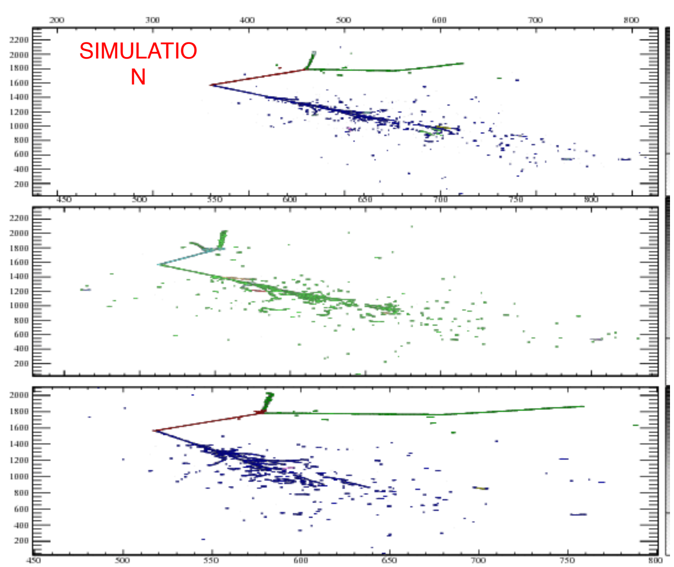




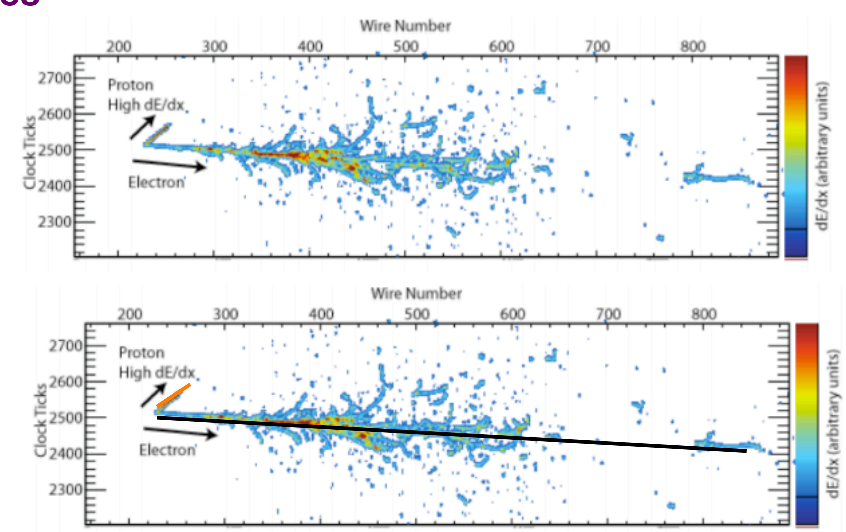
1. Wires collect charges



2. Find hits by fitting Gaussians



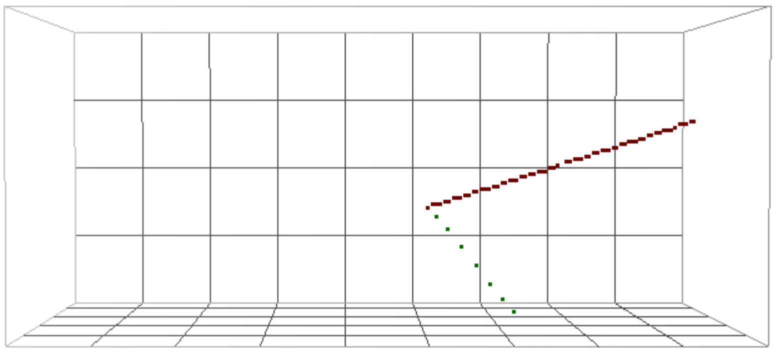
3. Clustering



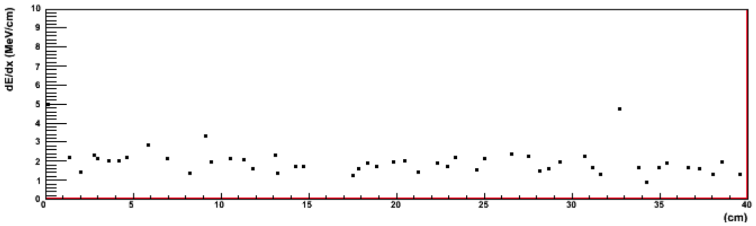
4. Shower and track finding

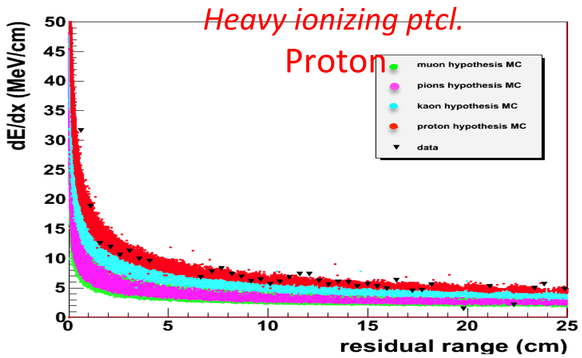
Event Reconstruction

5. 3D reconstruction



6. Calorimetry and PID





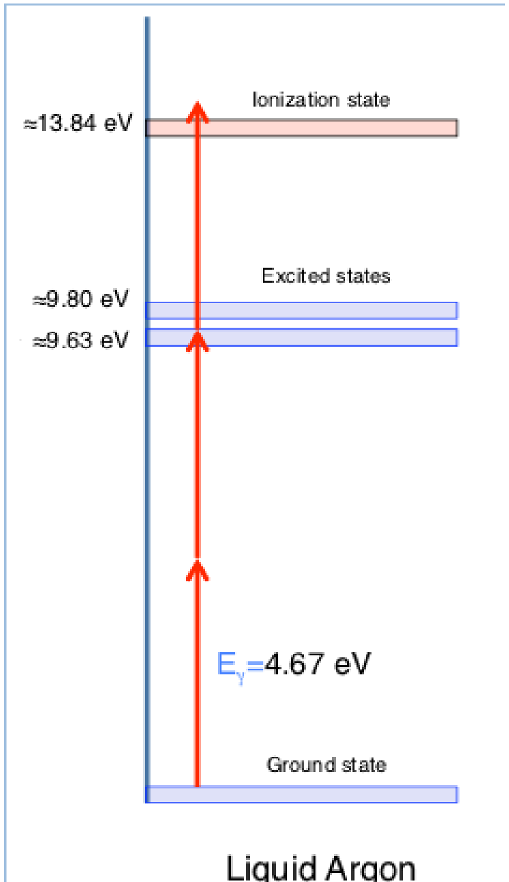
Calibration

- Electronics calibration
  - ➢ Check response to injected pulses across test capacitors
  - ➢ Extract pedestal, noise, gain, and shaping time per channel
- Laser calibration
  - ➢ Distortions to **E**-field from positive ions and LAr circulation
  - ➢ Use laser light at 266nm to measure distortions
  - ➢ Mechanical mirror system
- Cosmic muon sample
  - ➢ Will have ***large*** sample of cosmic muons to calibrate against
  - ➢ **E**-field distortions, dQ/dx calibration, absolute energy from Michel electrons, etc.

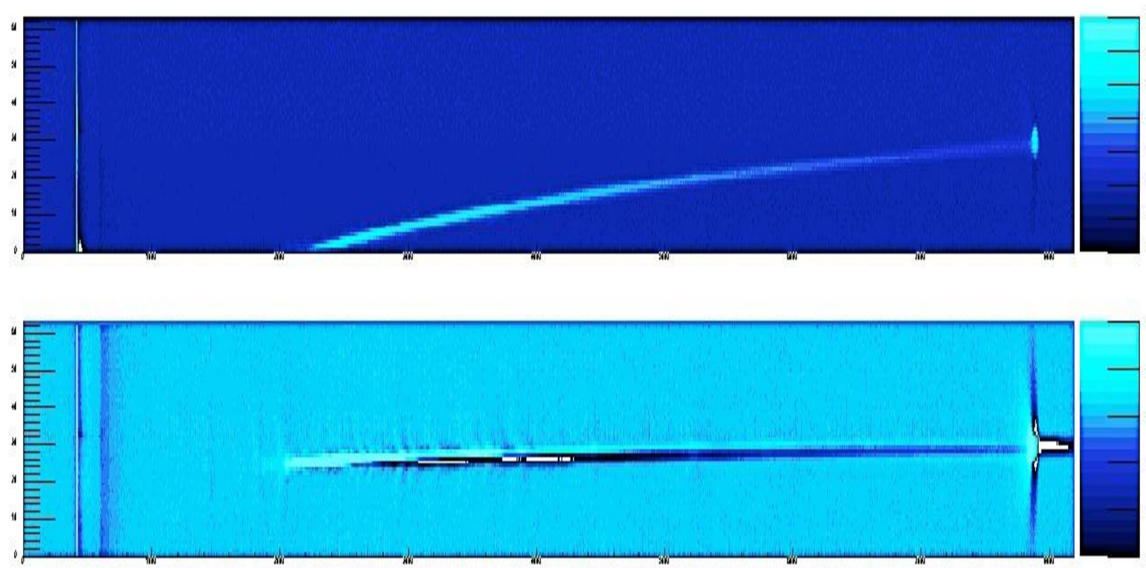
Laser system

- ~14 eV is required to ionize LAr

- Laser has to have enough intensity for 3 photon absorption



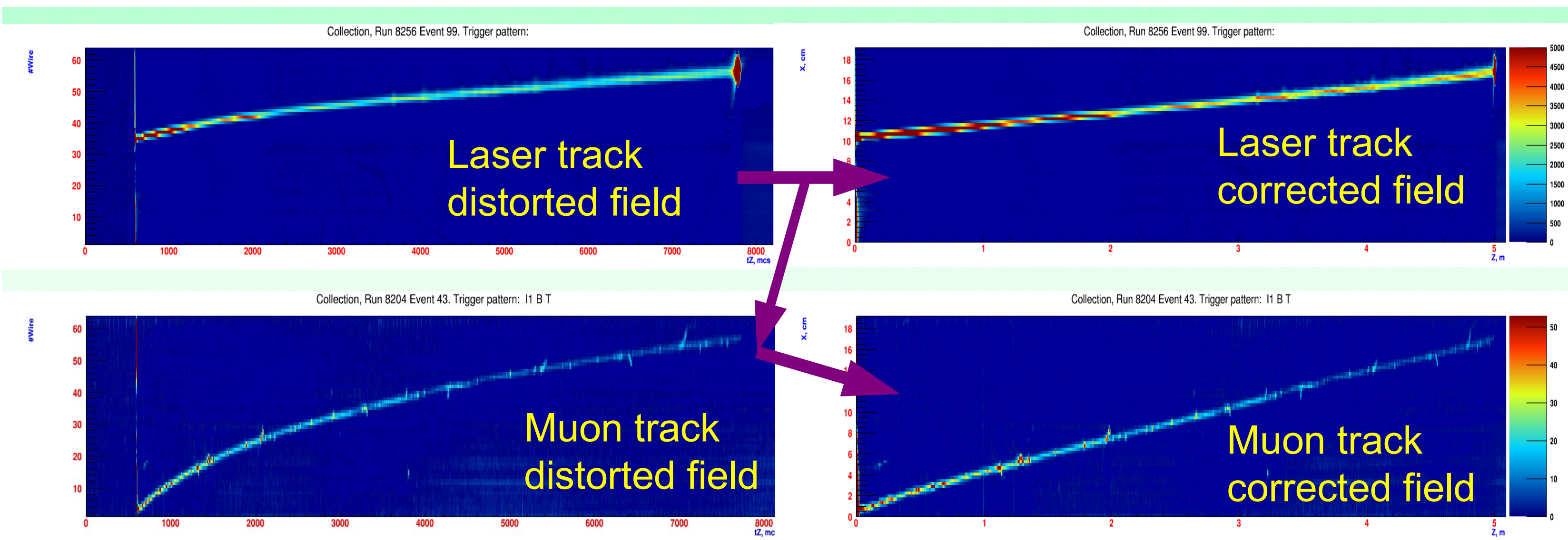
Igor Kreslo



Bern University laser system for MicroBooNE

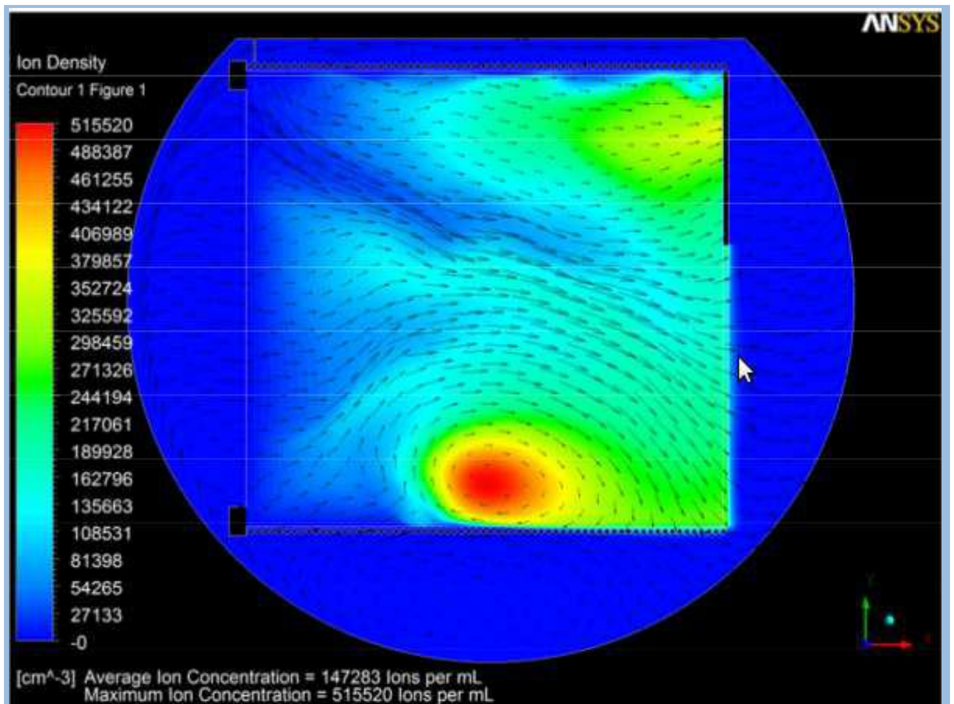
Laser system

- Laser can be used for drift field calibration



Laser system: Why??

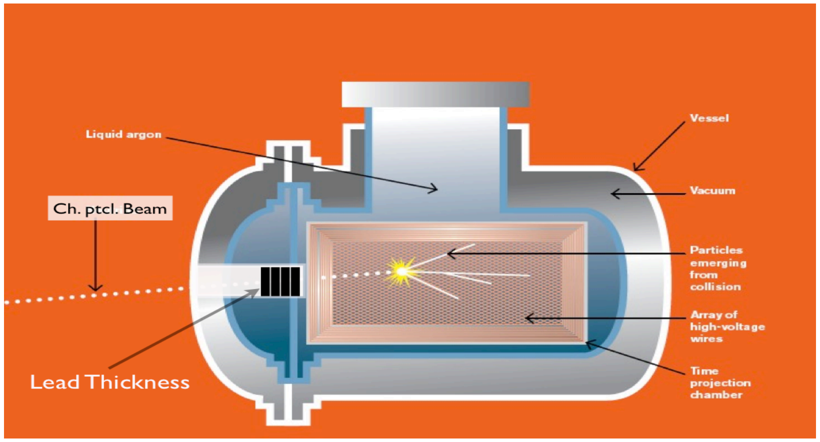
- Cosmic rays produce Ar^{+} ions
- Ion drift velocity is only O(~*cm/s*)
- Ar^{+} accumulate and cause filed distortions



Eric Vorin for MicroBooNE

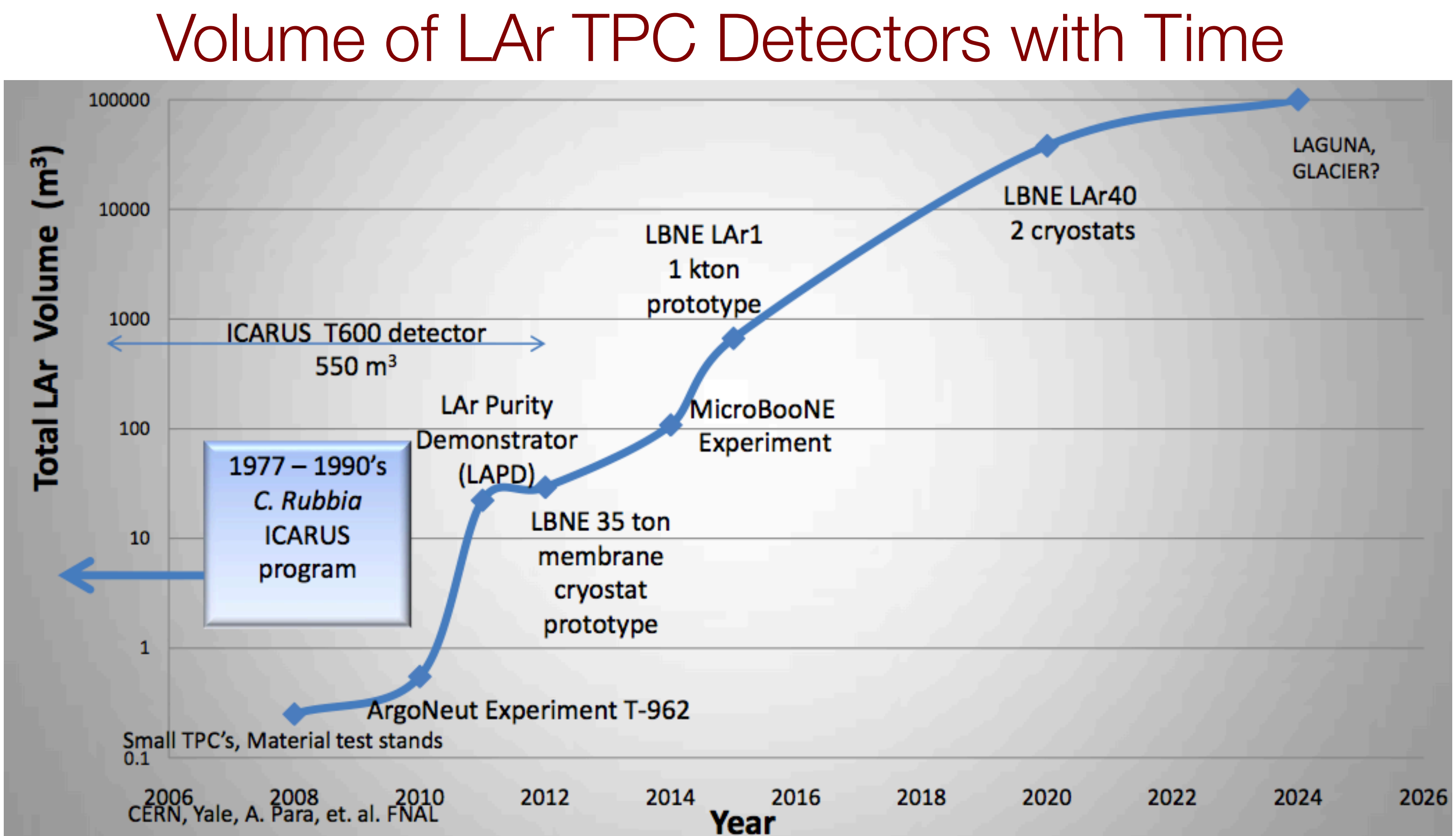
Calibrating LArTPCs: LArIAT (Liquid Argon In A Test Beam)

- Electromagnetic shower energy resolution
- Hadron shower energy resolution
- Directionality of through going particle (e.g. muons) using delta rays
- Particle ID
- dE/dx for the different particles
- Light collection efficiency



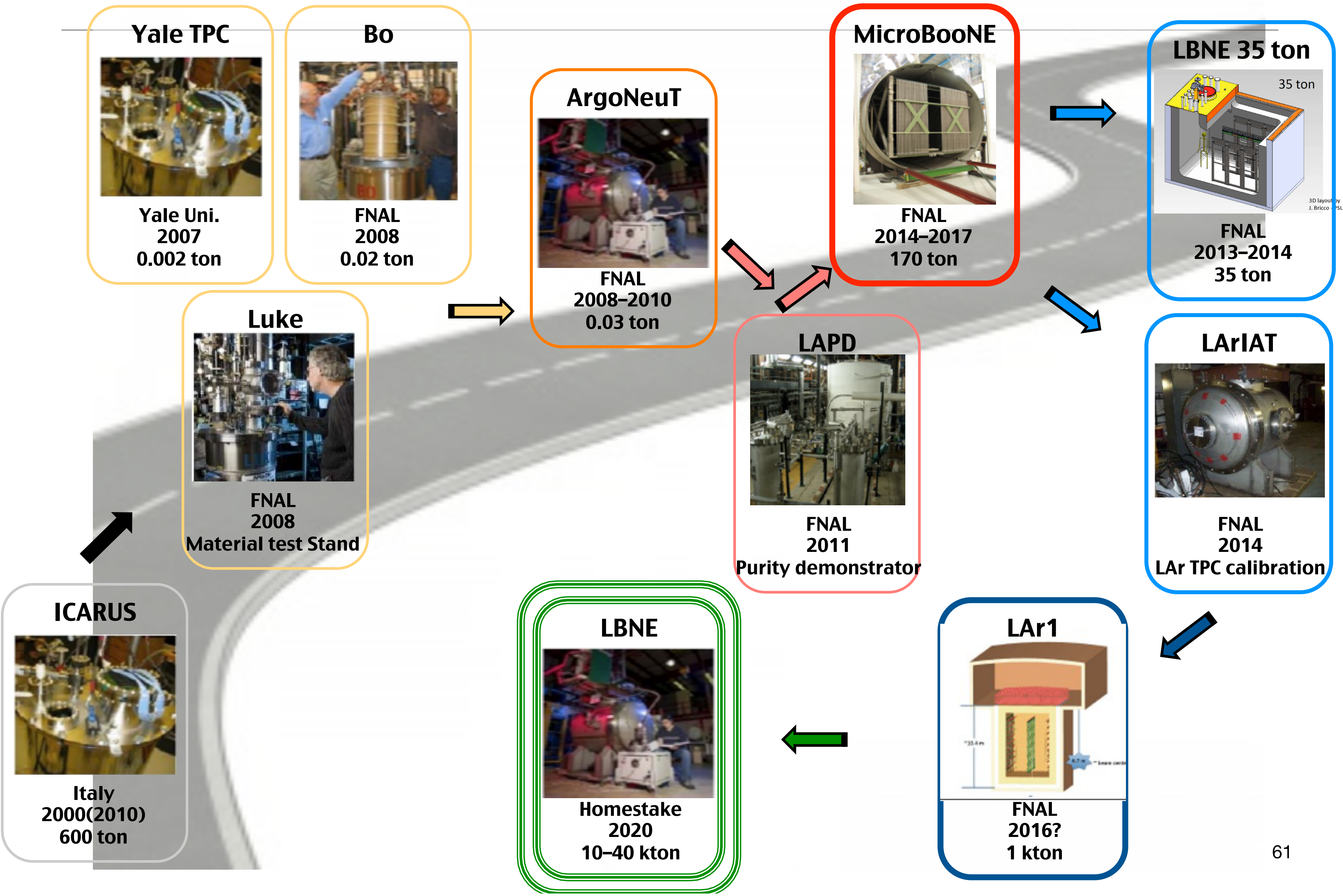
The LAr detector rises

The LAr detector rises



Russ Rucinski, TIPP 2011

The road to the next generation



Future prospects

- MicroBooNE has been constructed and will be commissioned soon

Cryostat Volume	170 Tons
TPC Volume (l x w x h)	89 Tons (10.4m x 2.5m x 2.3m)
# Electronic Channels	8256
Electronics Style (Temp.)	CMOS (87 K)
Wire Pitch (Plane Separation)	3 mm (3mm)
Max. Drift Length (Time)	2.5m (1.5ms)
Wire Properties	0.15mm diameter SS, Cu/Au plated
Light Collection	32 8″ Hamamatsu PMTs

LAr1-ND and LAr1

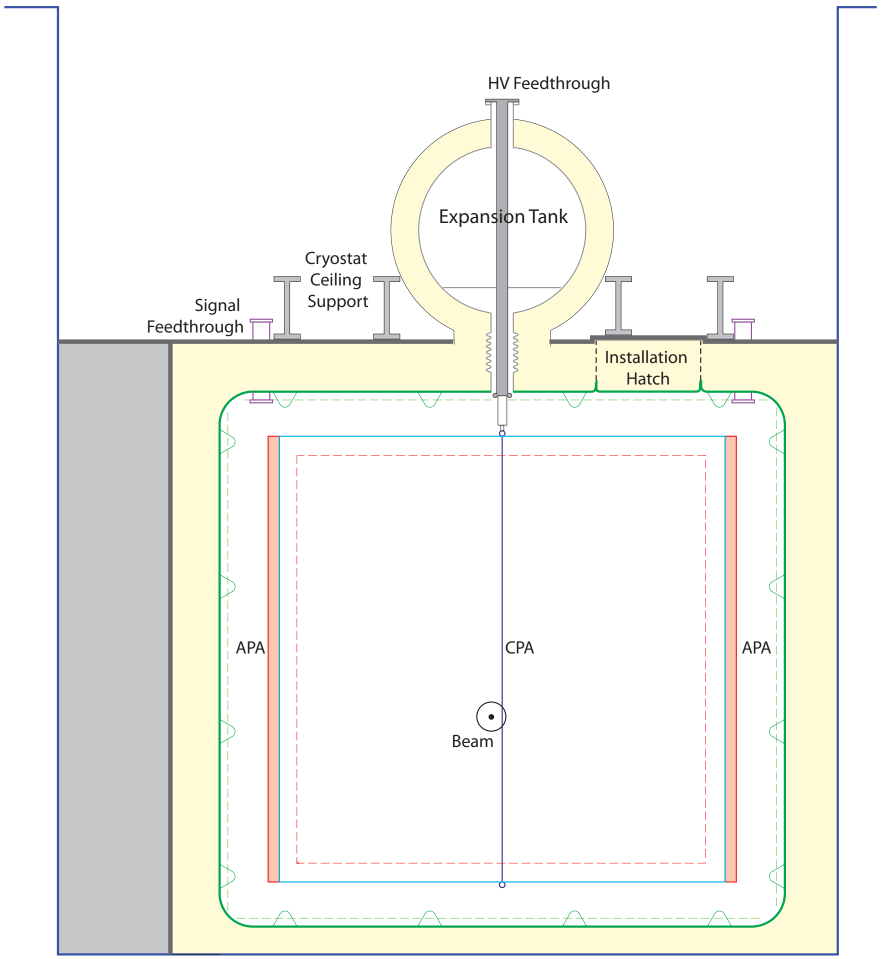
Existing enclosure vacated by SciBooNE detector

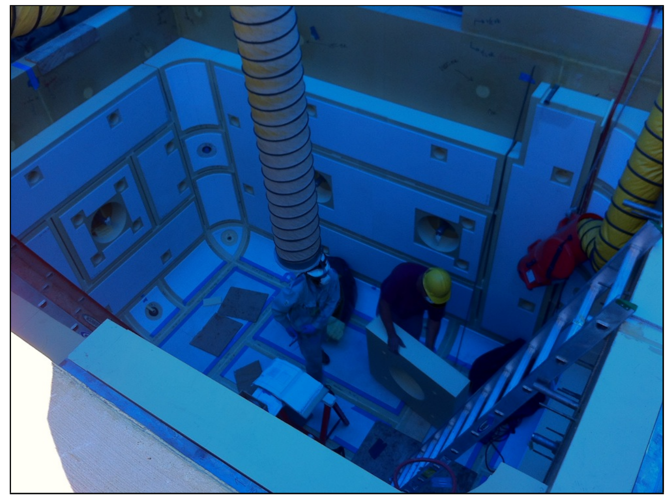
Phase 0: MicroBooNE
86 t active volume TPC
L = 470 m
start in 2014

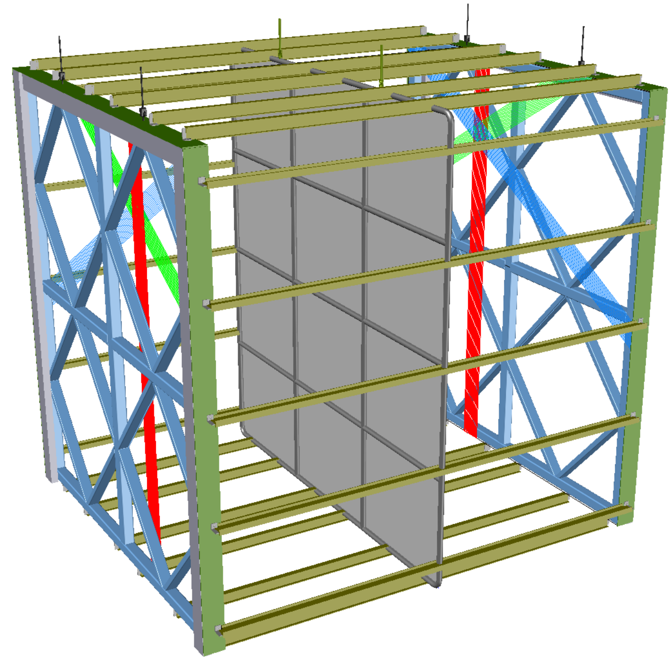
Phase 1: LAr1-ND
82 t active volume TPC
L = 100 m
2017-2018

Phase 2: LAr1-FD
1000 t active volume TPC
L = 700 m
2020+

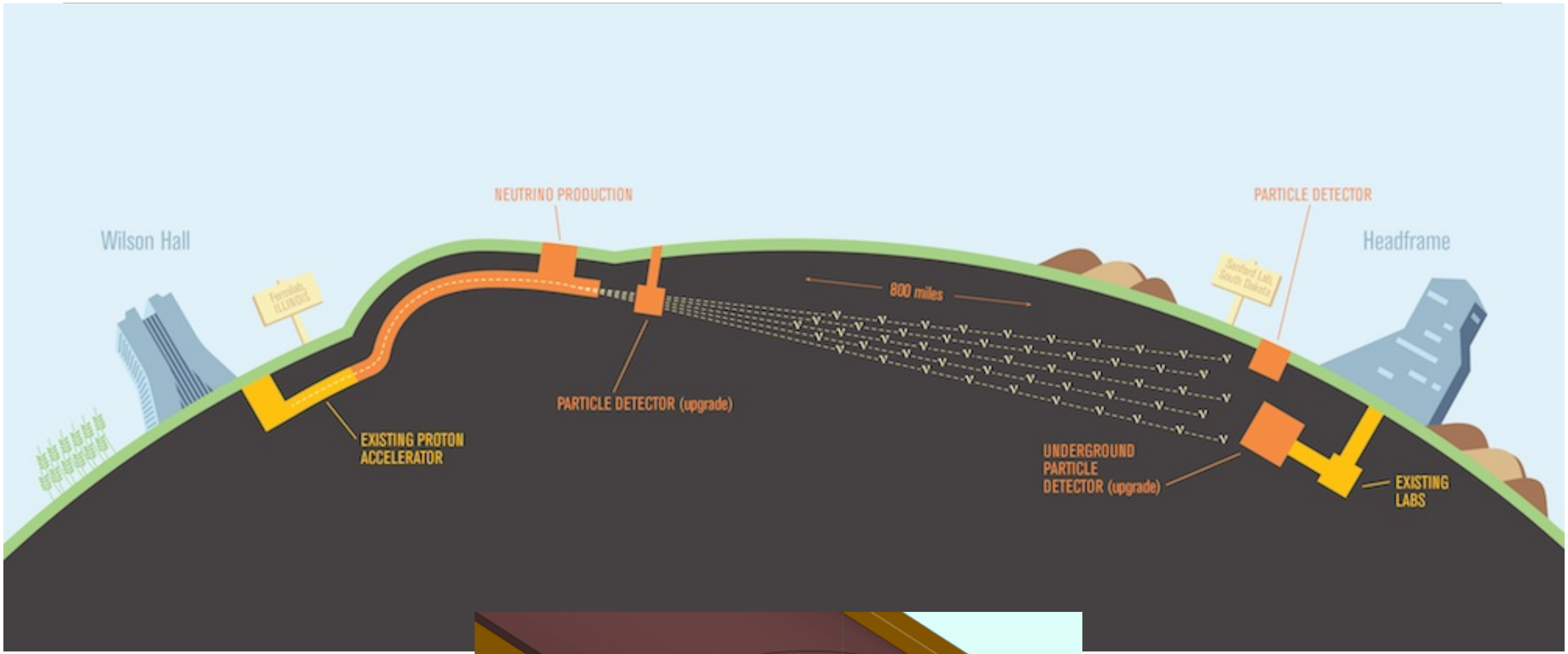
LAr1-ND detector

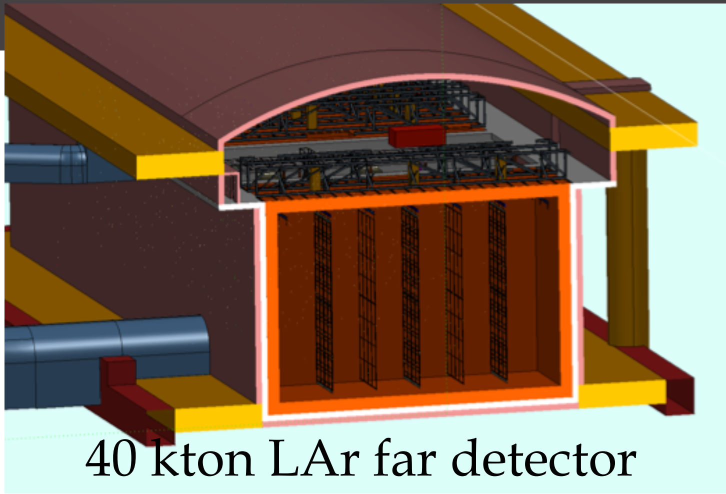






LBNE


NEUTRINO PRODUCTION
Wilson Hall
PARTICLE DETECTOR
Headframe
800 miles
PARTICLE DETECTOR (upgrade)
EXISTING PROTON ACCELERATOR
UNDERGROUND PARTICLE DETECTOR (upgrade)
EXISTING LABS

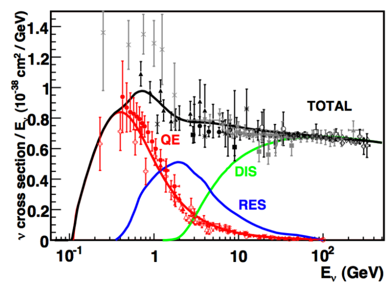

40 kton LAr far detector

Neutrino physics with LArTPC

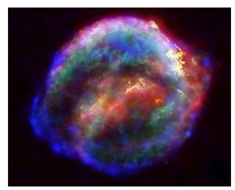
- Neutrino oscillation studies

- Sterile neutrino searches

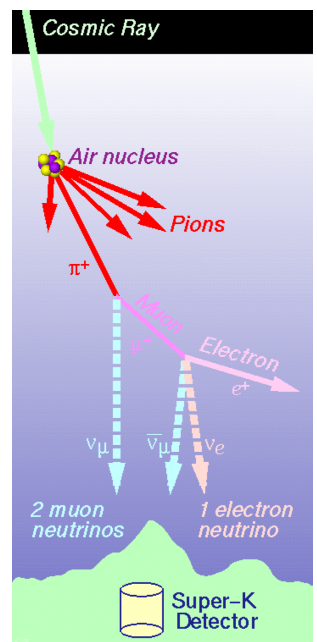
- Cross-section measurements



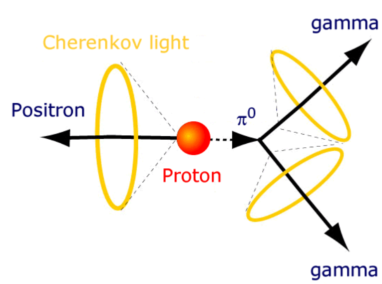
- Supernova neutrinos



- Atmospheric neutrinos



- Nucleon decay



ArgoNeuT

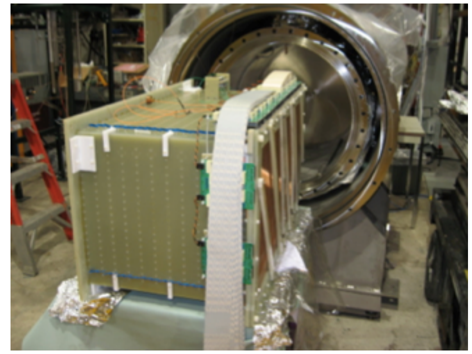
- 175 litres in NuMI beam (2009-2010)

- Physics results!

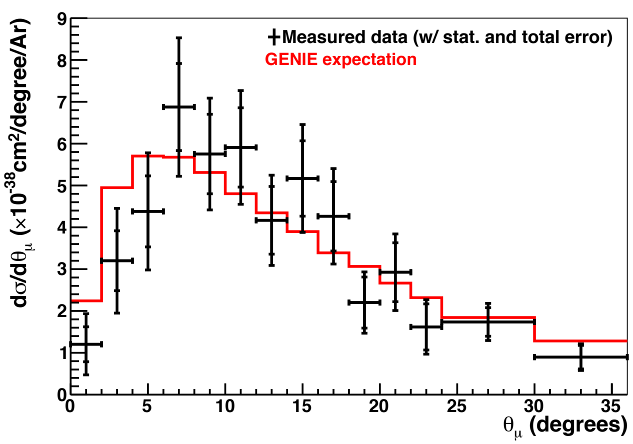
First Measurements of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon,
C. Anderson et al., Phys. Rev. Lett. 108 (2012)

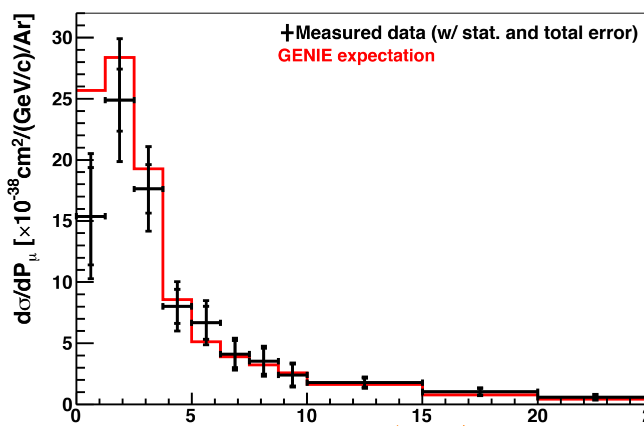
A study of electron recombination using highly ionizing particles in the ArgoNeuT Liquid Argon TPC,
R.Acciarri et al., JINST 8 (2013).

- Hints for Final State Interactions!



Cryostat Volume	500 Liters
TPC Volume	175 Liters
# Electronic Channels	480
Wire Pitch	4 mm
Electronics Style (Temperature)	JFET (293 K)
Max. Drift Length (Time)	0.5m (330μs)
Light Collection	None

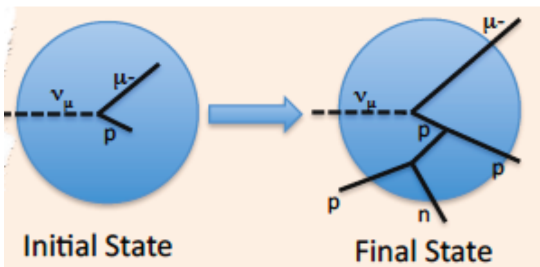


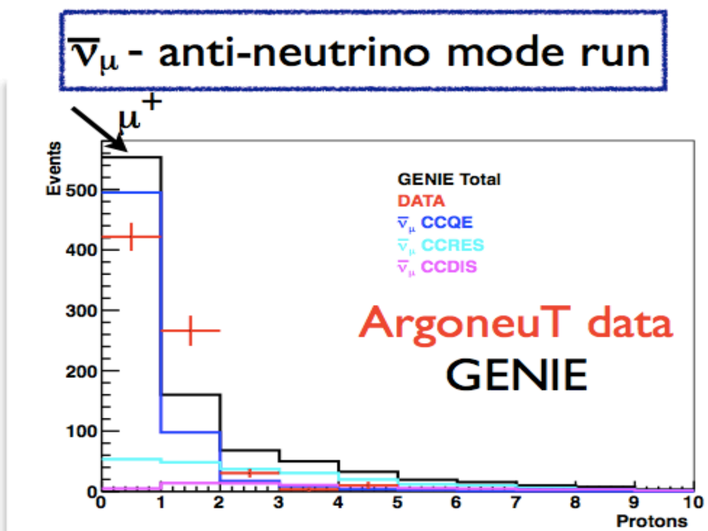


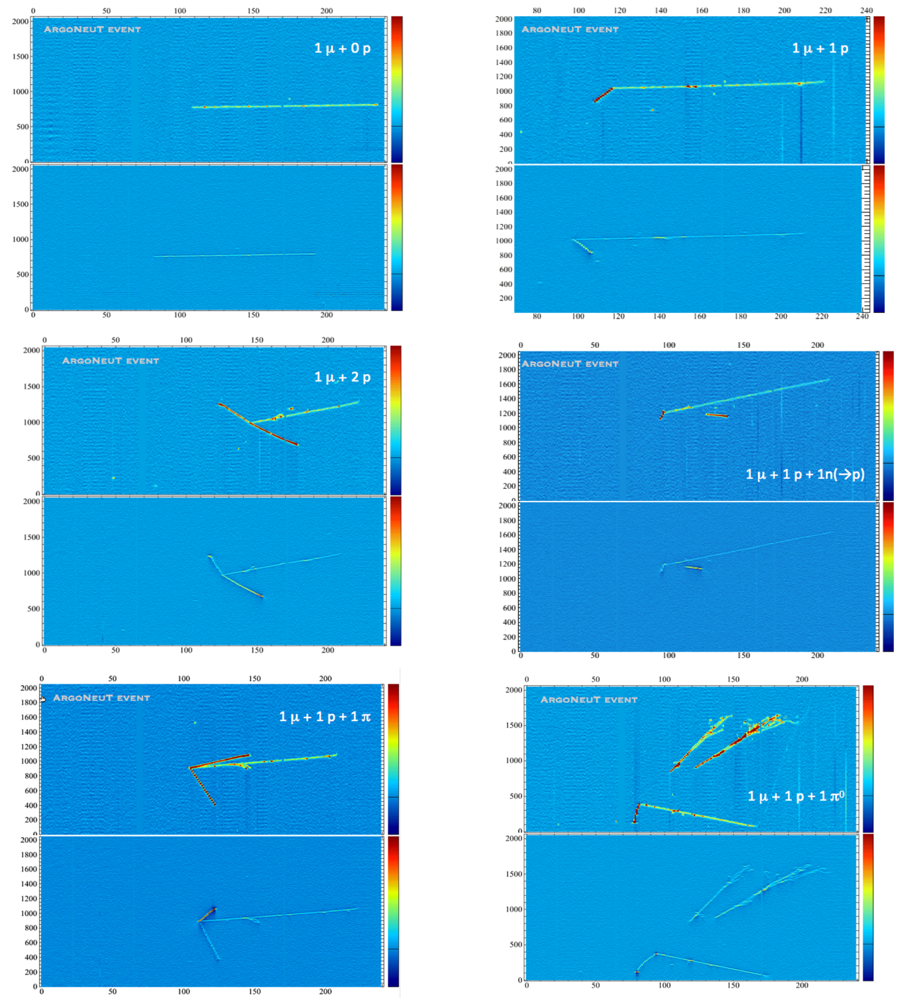
C. Anderson et al., Phys. Rev. Lett. 108 (2012)

Cross-section measurements

- Great advantage of LAr detectors
- Lower E_{tresh} and greater resoution







- K. Partyka (for the ArgoNeuT Coll.), NuINT 2013
- O. Pallamara (for the ArgoNeuT Coll.), SLAC Intensity Frontier Neutrino Workshop 2013

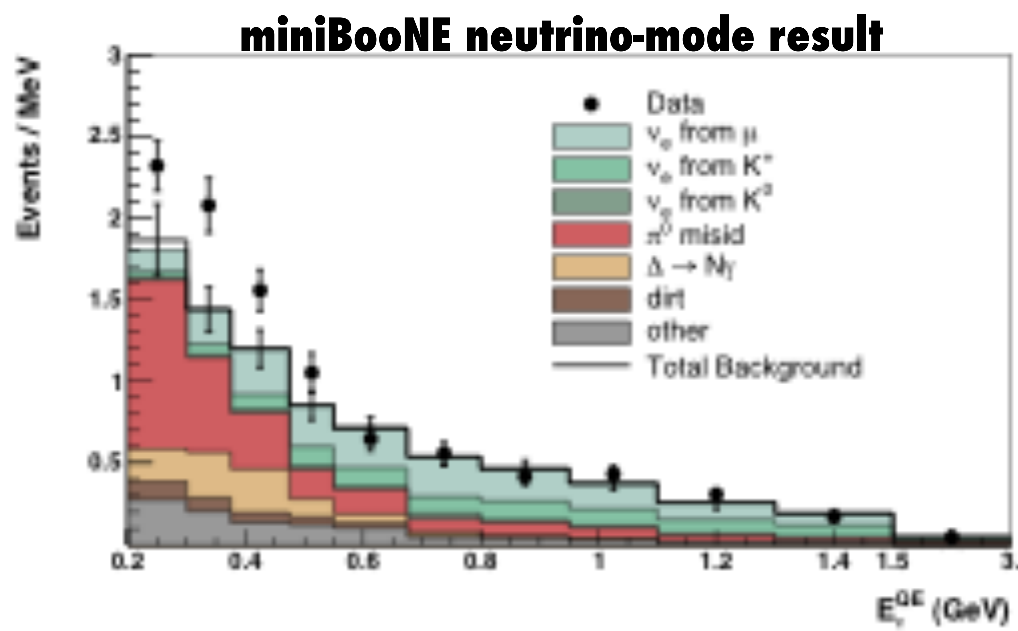
MicroBooNE and the low energy excess

- MiniBooNE experiment observed an excess (3σ) at low energies (200 MeV - 475 MeV) in neutrino mode

- The excess events are electron-like: e^-/γ

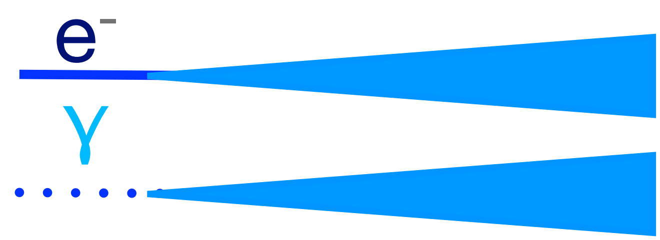
- MiniBooNE cannot distinguish between electrons and photons

- Need a new detection technology:
  → **MicroBooNE**



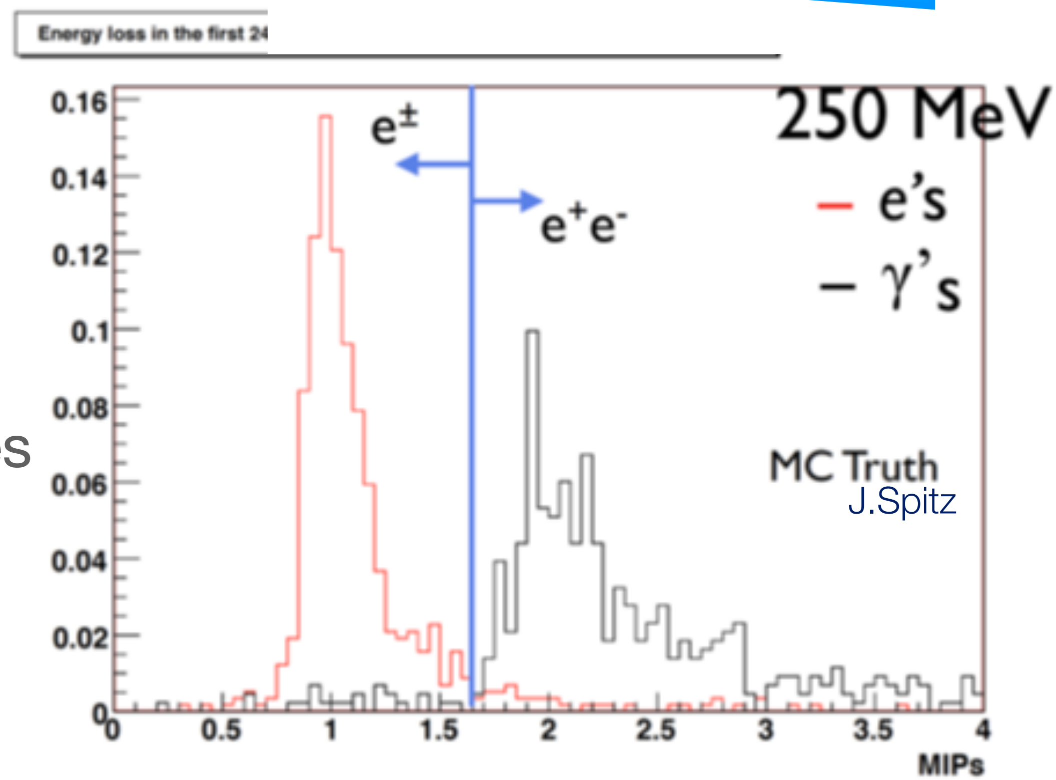
Phys.Rev.Lett.102, 2009

MicroBooNE and the low-energy excess



MicroBooNE:

- Distinction between e/γ
- ν_e efficiency ~2x better
- Sensitivity at lower energies

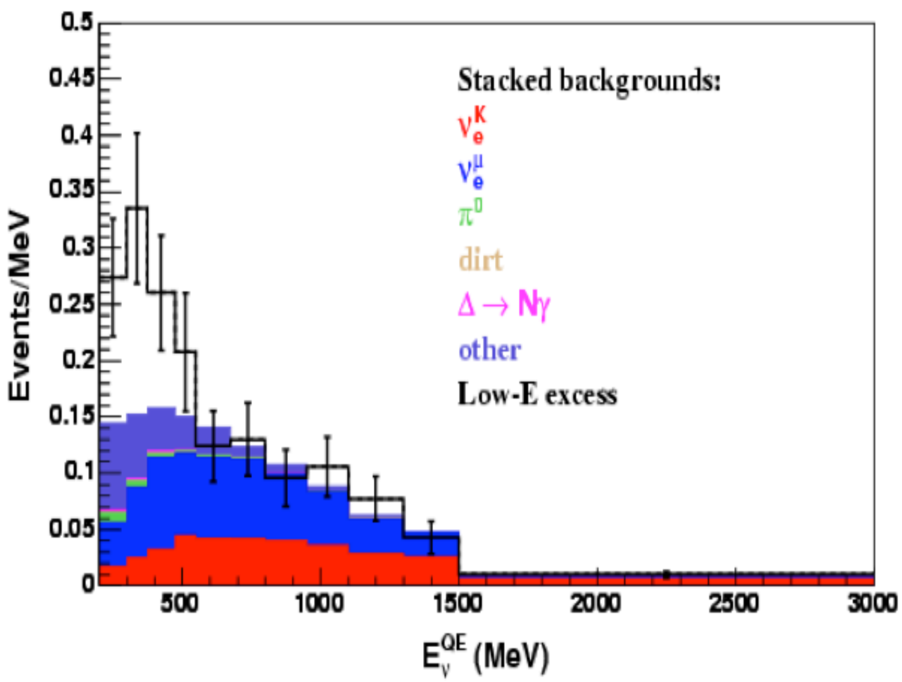


dE/dx for electrons and gammas in first 2.4 cm of track

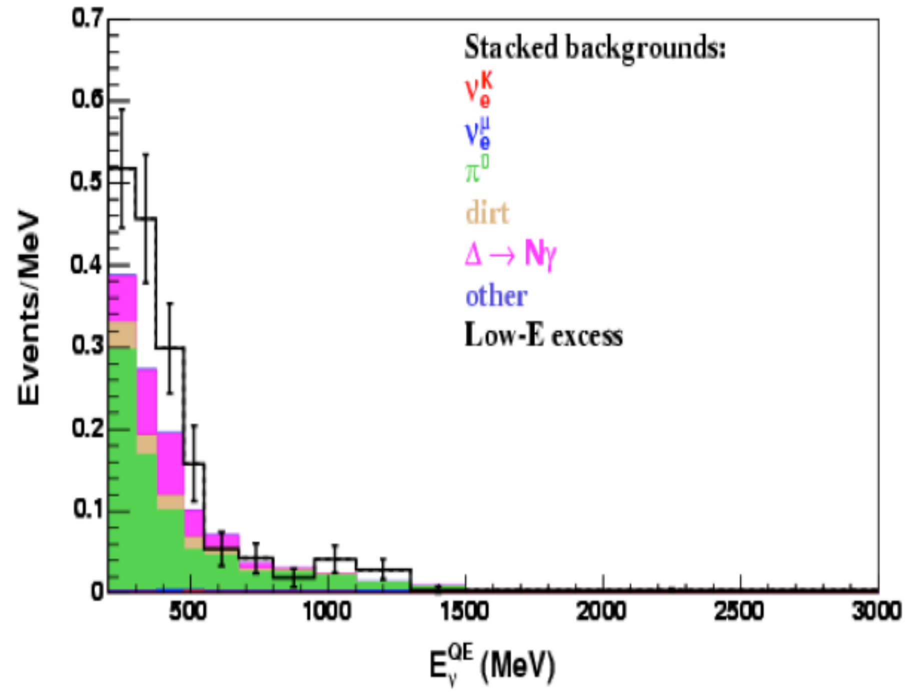
MicroBooNE addressing the MiniBooNE excess
(6.6x10^{20} POT neutrino mode)

For microBooNE, as a counting experiment: 5σ sensitivity if excess is ν_es,
4σ sensitivity if excess is γs

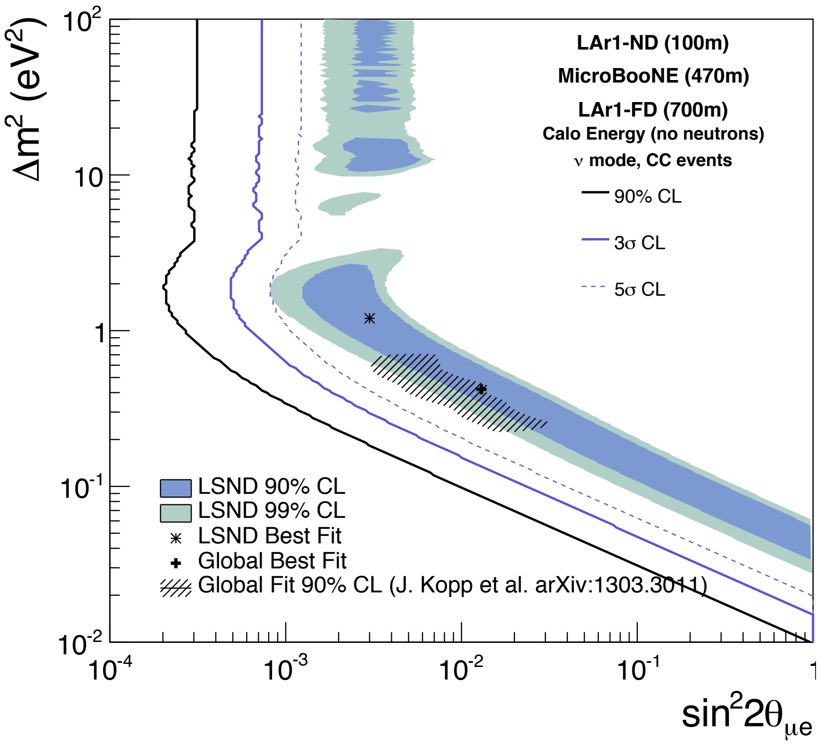
electron case



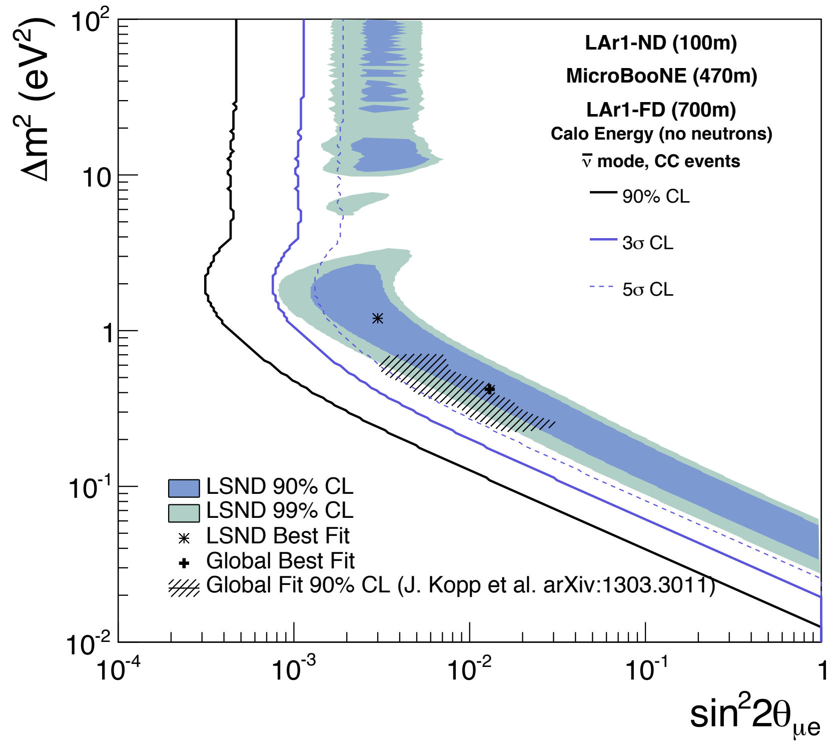
photon case



LAr1 sensitivity to sterile neutrinos



6.6x10^20 POT exposure
neutrino mode

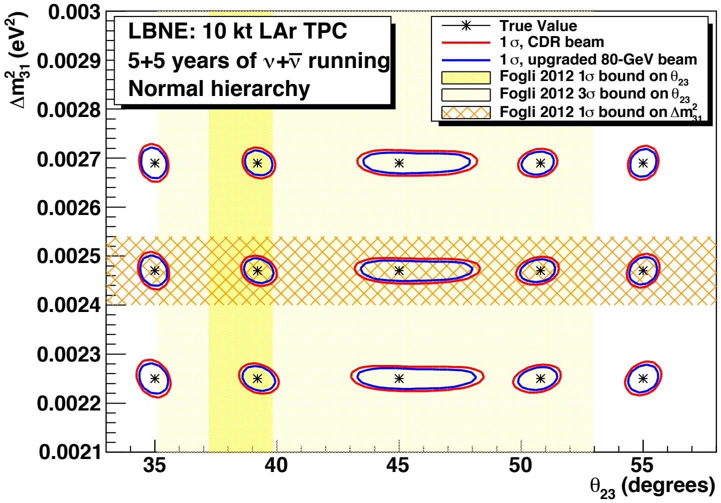


10×10^{20} POT exposure
anti-neutrino mode

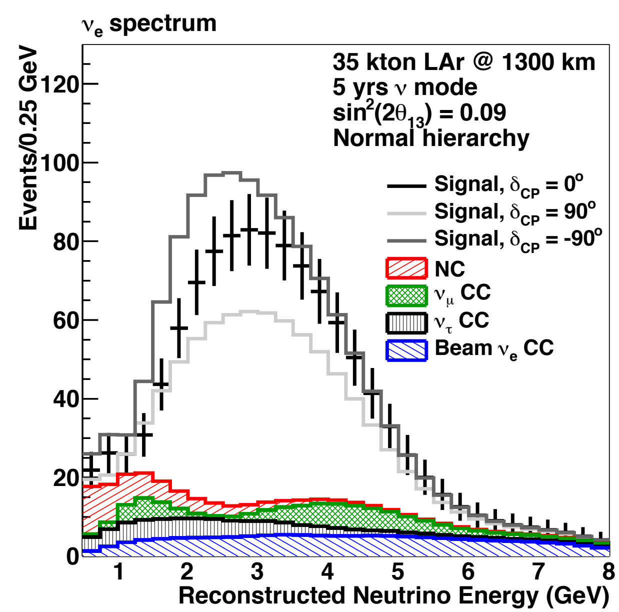
arXiv: 1309.7987

Oscillation physics

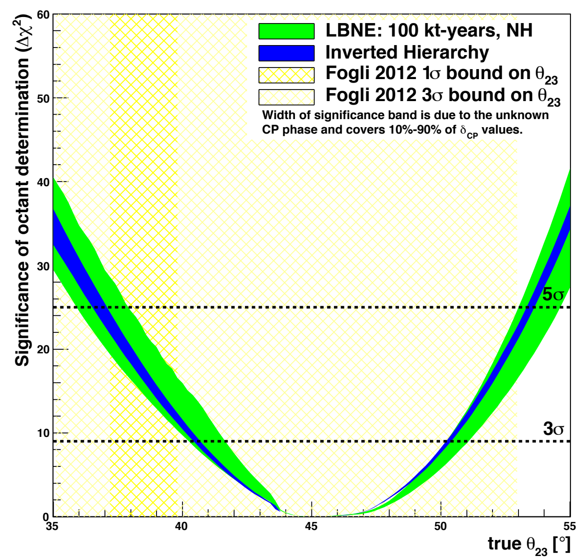
- Precision measurements of oscillation parameters
- θ_{13}, θ_{23}, Δm^2_{23} θ_{23} octant



arXiv: 1307.7335

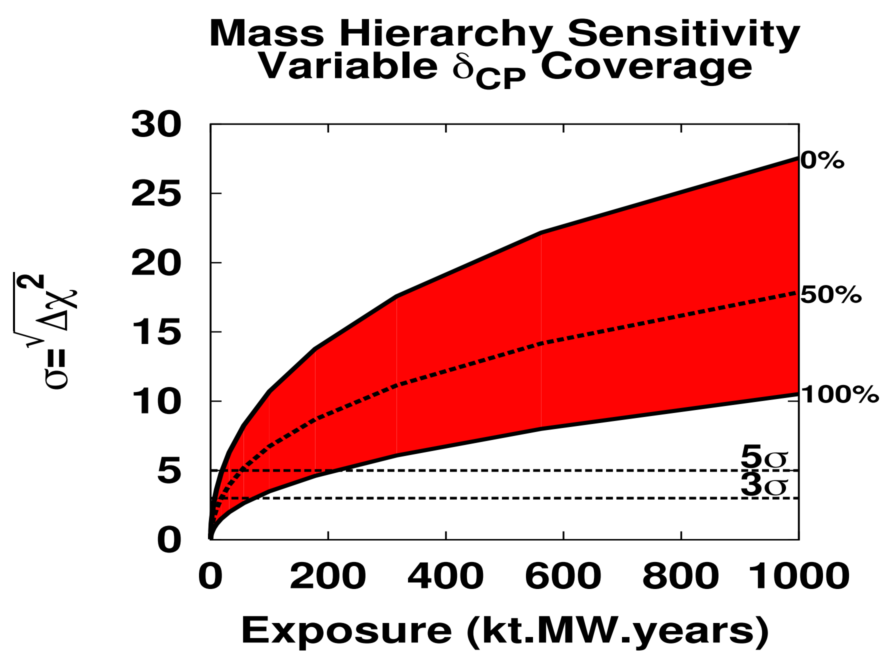


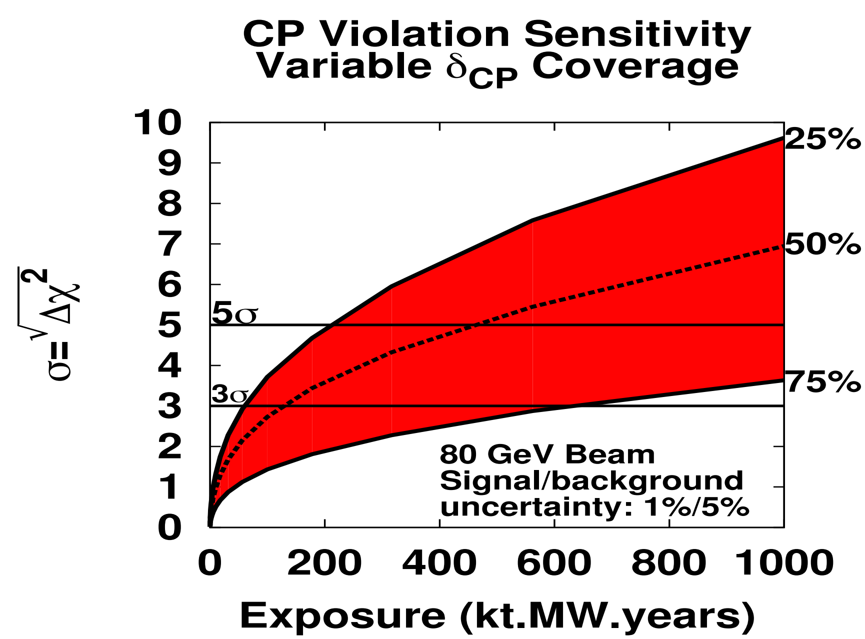
Octant Sensitivity



Oscillation physics

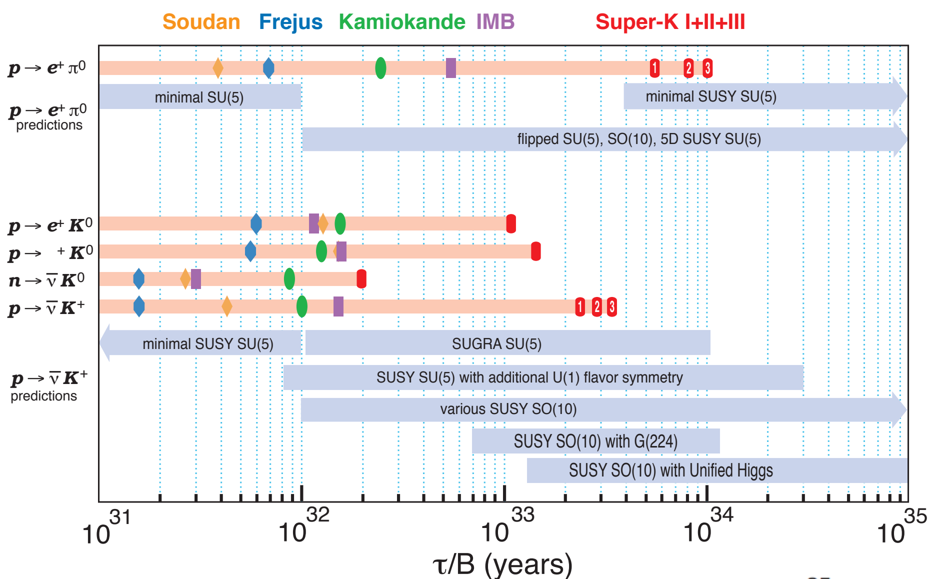
- Identifying the mass hierarchy
- Search for CP violation

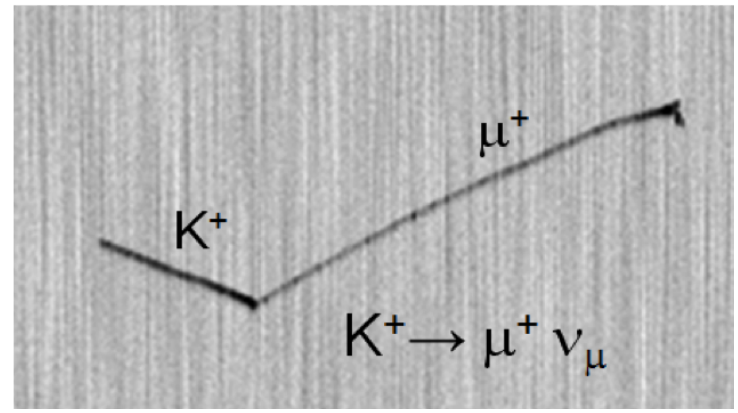


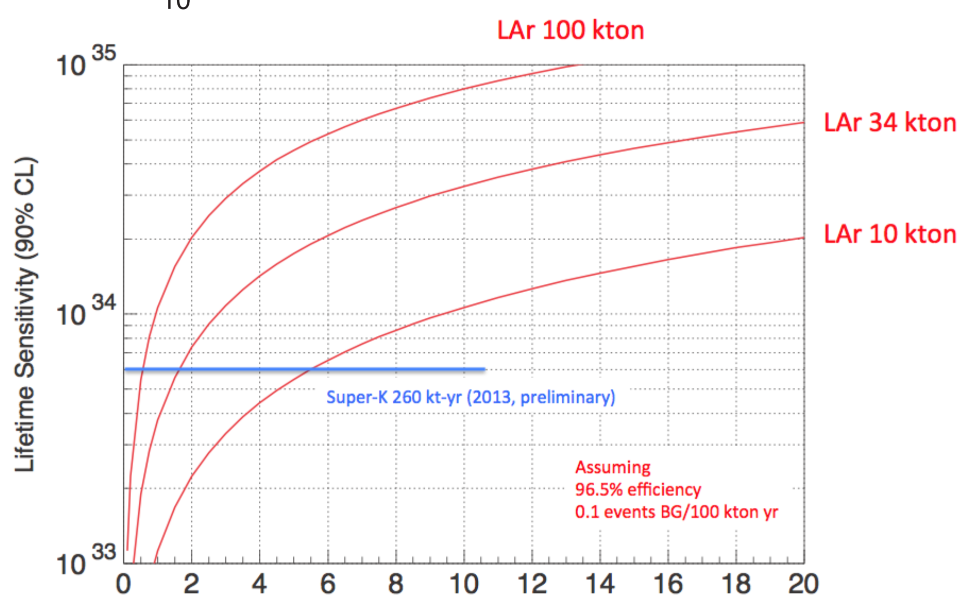


arXiv: 1307.7335

Proton decay searches

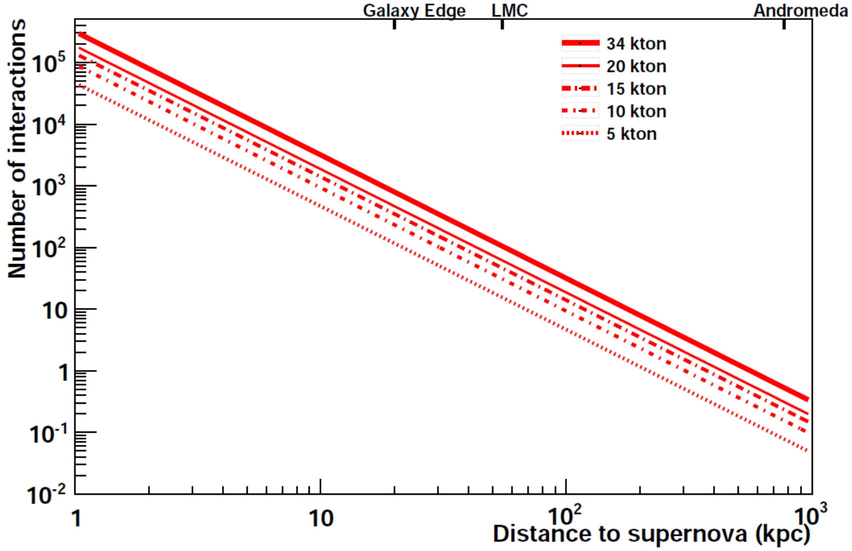


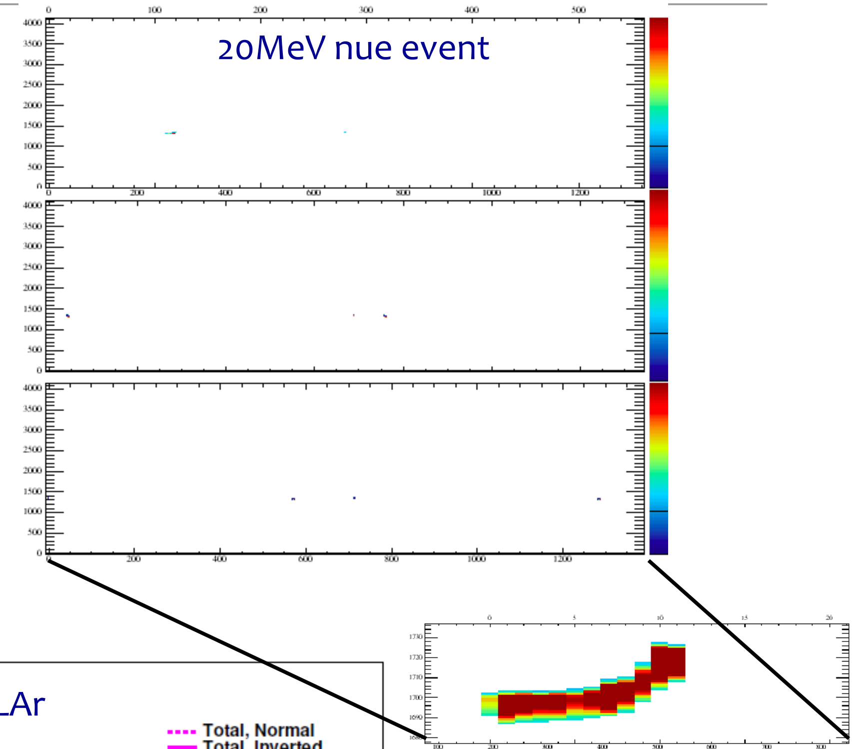


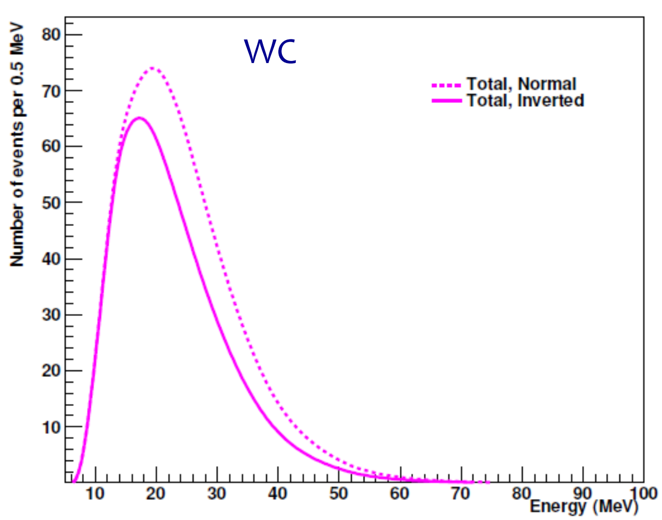


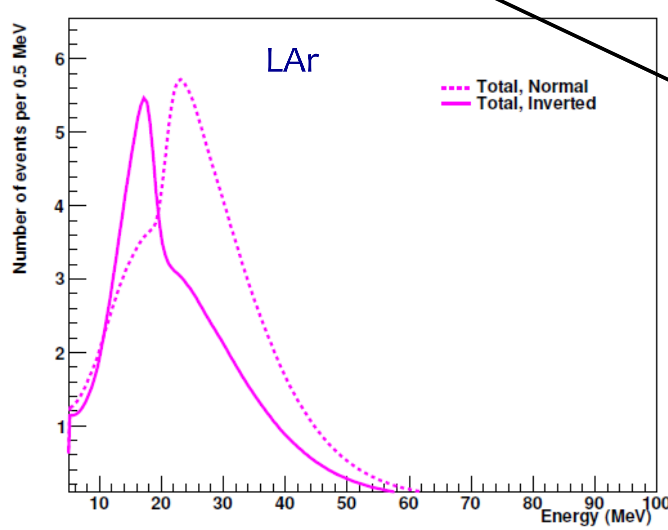
arXiv: 1307.7335

Supernova neutrinos









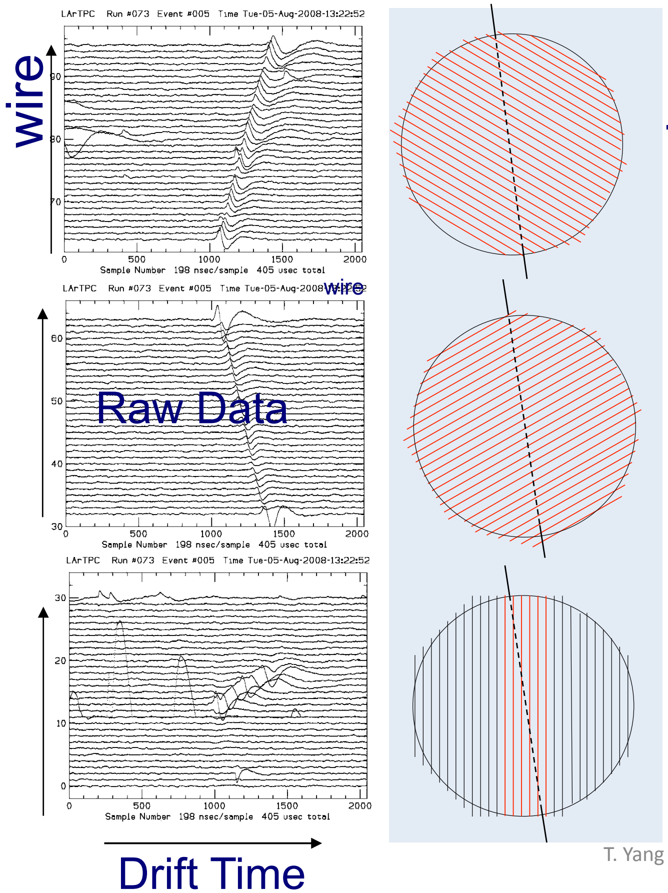
arXiv: 1307.7335

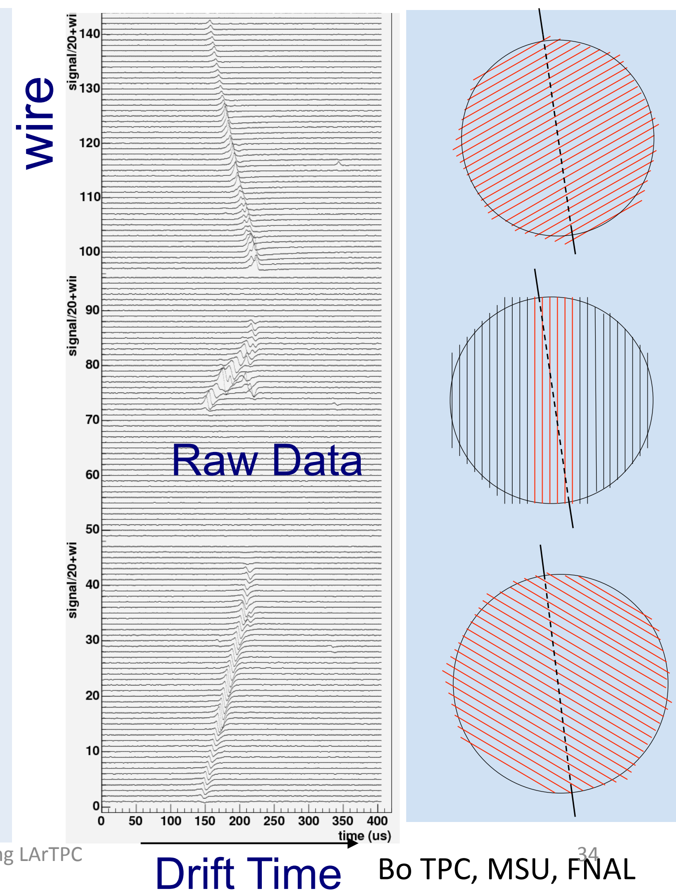
Conclusions

- LAr technology seems optimal for neutrino detection
- Worldwide R&D effort to answer the remaining challenges
- Physics potential has already been demonstrated (ArgoNeuT)
- MicroBooNE will be critical for the future of this technology
- LAr detectors will allow to study neutrino properties with unprecedented sensitivity
- Results may be surprising!

Warm amps S/N = 15

Amps in liquid S/N >30





T. Yang LArTPC

Bo TPC, MSU, FNAL