Liquid argon and other detection techniques (and requirements)

An attempt to consider what is necessary/sufficient for a physics program.

Sources:

- FASER, FASER-nu proposals.
- Event rates from Felix Kling and from 2002.03012 (our work)
- Light DM detection far forward…2101.10338
- Liquid argon facility considerations - Resnati (may 2021)
- Civil Engineering study March 1-4, 2021 (John Osborne via Jamie Boyd)
- microboone/protodune TDRs
- First LHC neutrino events ! 2105.06197

Milind Diwan Brookhaven National Lab. 5/24/2021

BROOKHAVEN NATIONAL LABORATORY

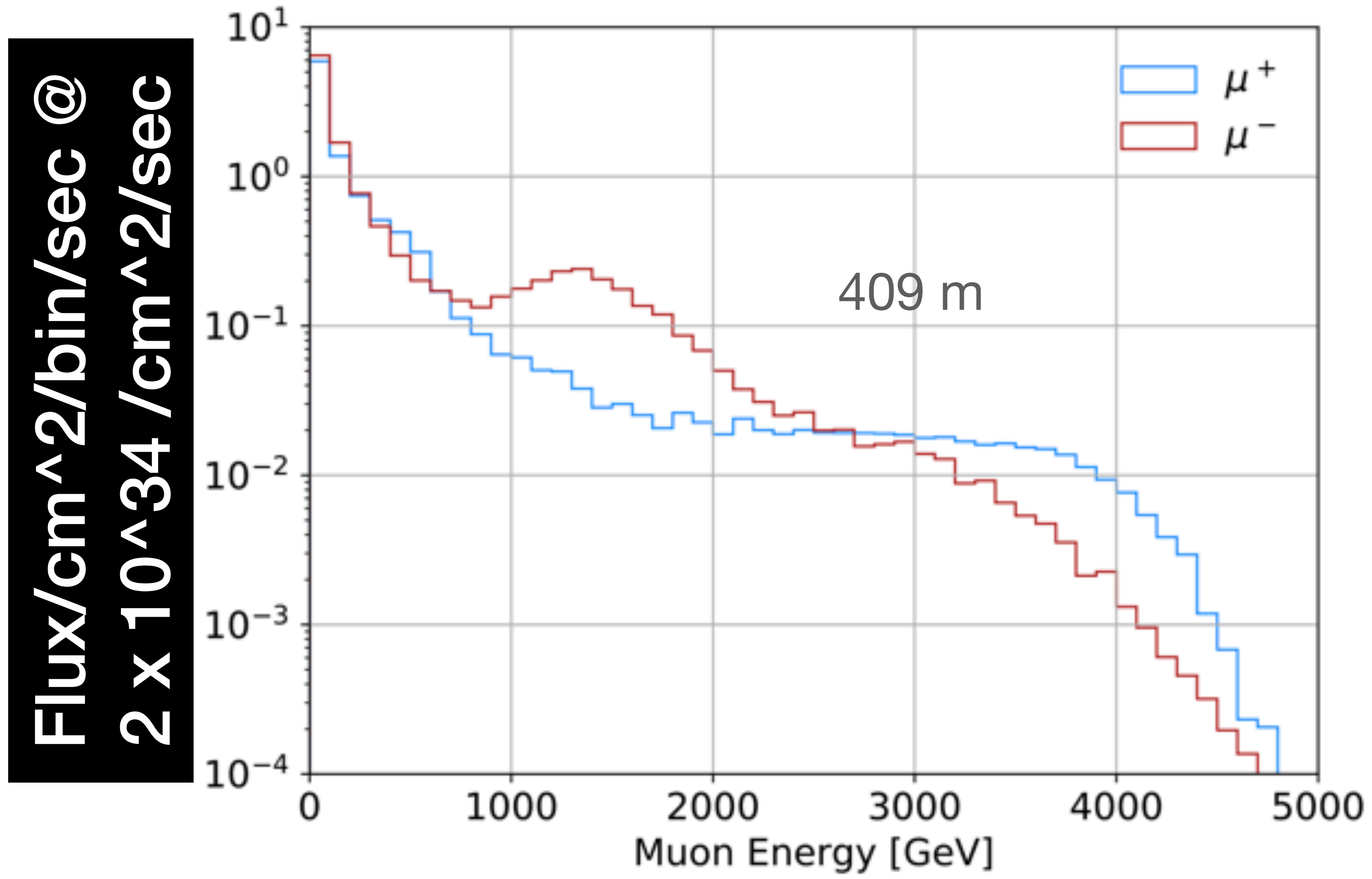
Basic beam/source parameters for HL-LHC

Parameter	Value	Comment
p-p Collision energy	14 TeV	
Crossing frequency	40 MHz	
Bunch spacing	25 ns	Use to reject non beam backgrounds
Bunch length	90 mm	
Half Crossing angle	250 micro-rad	Will move the axis (sideways?) by 15 cm at 612 m
Crab crossing	yes	Will spread collisions over larger length
Peak Luminosity	5×10^{34} /cm^2/sec	Could go higher by 50%.
Total/inelastic X-sec	111/85 mbarn	
peak N events/crossing	135	Spread out over ~9 cm and 300 ps
Total integrated Lumi	3000 /fb	10 times more than run II
Per year Lumi	350 /fb	This could be important for physics output
Start of operations	Year 2027	Reviews, Underground construction, and detector installation must complete.
Years of operation	10 years	Is it possible to change or upgrade detectors during this time ?
p-Pb (NN Luminosity)	>100 /pb @ ecm(NN) ~ 8 TeV	This is in a short run. orders of magnitude less than p-p.

Bordry 2018

Experimental conditions

Approximate fluxes, rates of backgrounds



- **This rate will be lower at 612 m.**
- **Both charged and neutral hadron interactions present significant background.**
- **Total neutrino interaction rate normalized to per ton per fb^{-1}**
- **Observed nu rate: ~45/ton/fb^{-1} at 480 m**

Minimum distance	612 m
Total Lumi/max lumi	3000/fb ; 5x10^{34} /cm2/sec
pseudorapidity coverage	>6.4, (~5.4-6.0 for off-axis)
Mu+/Mu- flux > 10 (100) GeV	1.5/0.93 (0.94/0.39) 10^{4} /cm^{2}/fb^{-1}
track density (from data)	1.7x 10^{4}/cm^{2}/fb^{-1}
max track density per sec (per crossing)	0.85/cm^{2}/sec (2x10^{-8}/cm2/crossing)
Neutral hadron flux > 10 GeV (10^{-4} of muons)	~3 /cm^{2}/fb^{-1}
Total neutrino rate (all flavors)	~50/ton/fb^{-1}

2105.06197

Detector capabilities needed for neutrino physics and DM physics
Neutrino event rates are somewhat on the low side for various predictions. Ref: F.Kling

Highlighted boxes correspond to Liquid argon capability.

Physics	Signature	Signal rate/3000/fb into a 1x1x7 m detector at 620 m.	Detector mass needed for physics	Capabilities
Measure nu-tau flux	Decay signature of tau. Kink over few mm	200/ton	10 tons.	Vertex reconstruction with kink detection. Muon ID to reduce background.
nu-tau oscillations	Distortion in energy spectrum of total energy.	200/ton	~100 tons if using kinematic reconstruction with exclusive decays.	Kinematic reconstruction with tracking and calorimetry. CC nu-tau interaction energy measurement
nu_mu/nu_e cross section	Long muon track or high density EM shower.	numu: 25k/ton (mainly from Pi decays) nue: 5k/ton	10 tons	Excellent muon and electron ID. Calorimetry for energy measurement Include hadronic absorber
Charm production	Electron neutrinos > 500 GeV	nue: 5k/ton	10 tons	Excellent electron ID with low background.
Electro-weak measurements	$\nu_\mu\ \bar{\nu}_\mu DES\ CC/NC$	20k/ton, 6k/ton for CCnu and CCbarnu 13k/ton for NC	100-1000 tons	Muon Charge identification, CC/NC separation. Hadronic calorimeter.
neutrino electron elastic scattering. Inverse muon decay.	Extremely forward electro-magnetic shower. Very forward Muon	6/ton (inclusive) 20/ton (IMD)	100 tons	Excellent electron ID, and kinematic resolution. IMD might be important for flux normalization.
Light DM physics	Very forward electromagnetic showers	BSM	10 tons	Excellent electron ID, kinematic resolution.

Event rate table (real theoretical errors on these numbers will come from studies from Bai, et al., 2002.03012 … In progress)

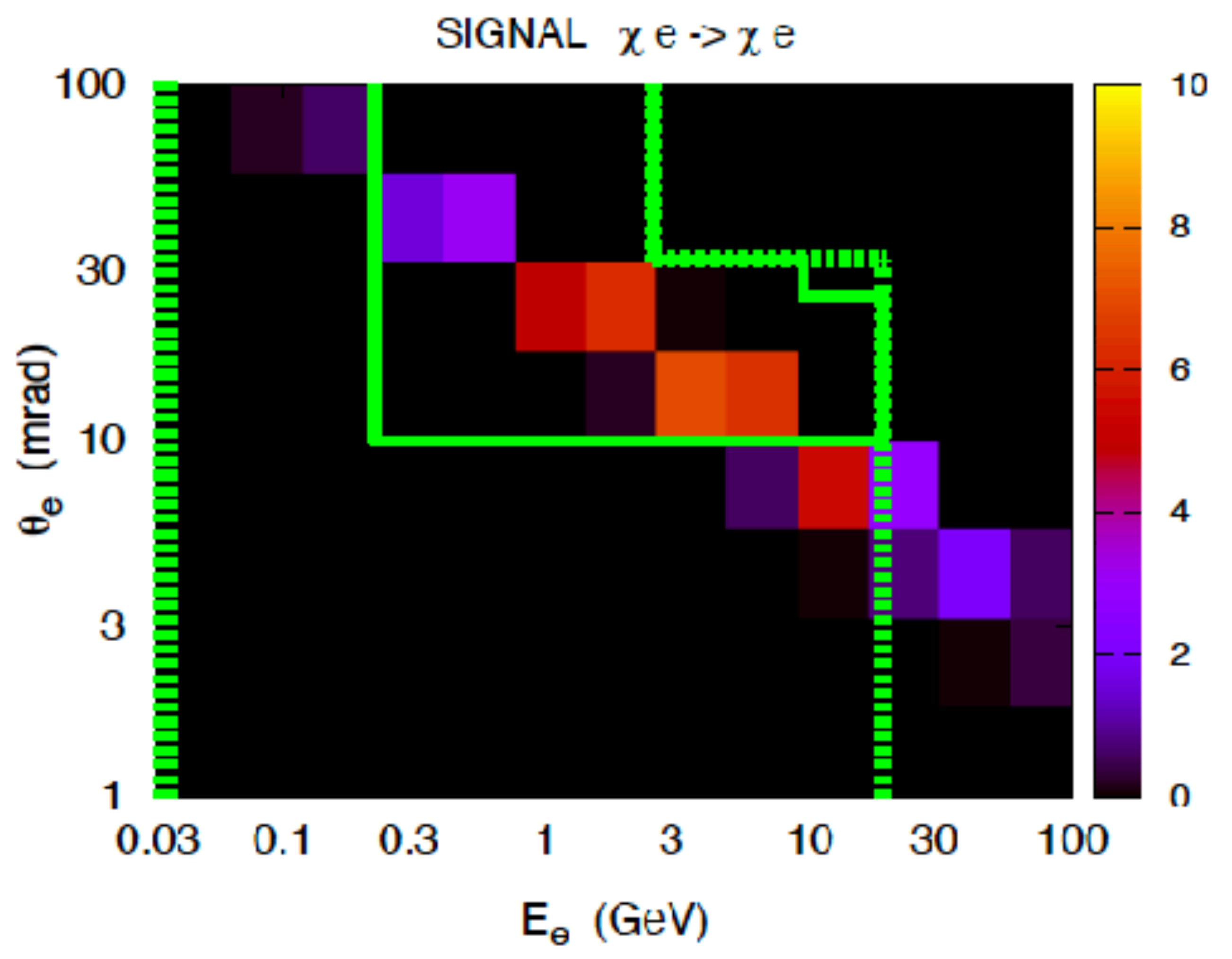
Rate depends on the angular acceptance as well as mass. This creates some peculiarities. Simulation uncertainties add to the variation. The numbers in white columns are from F. Kling.

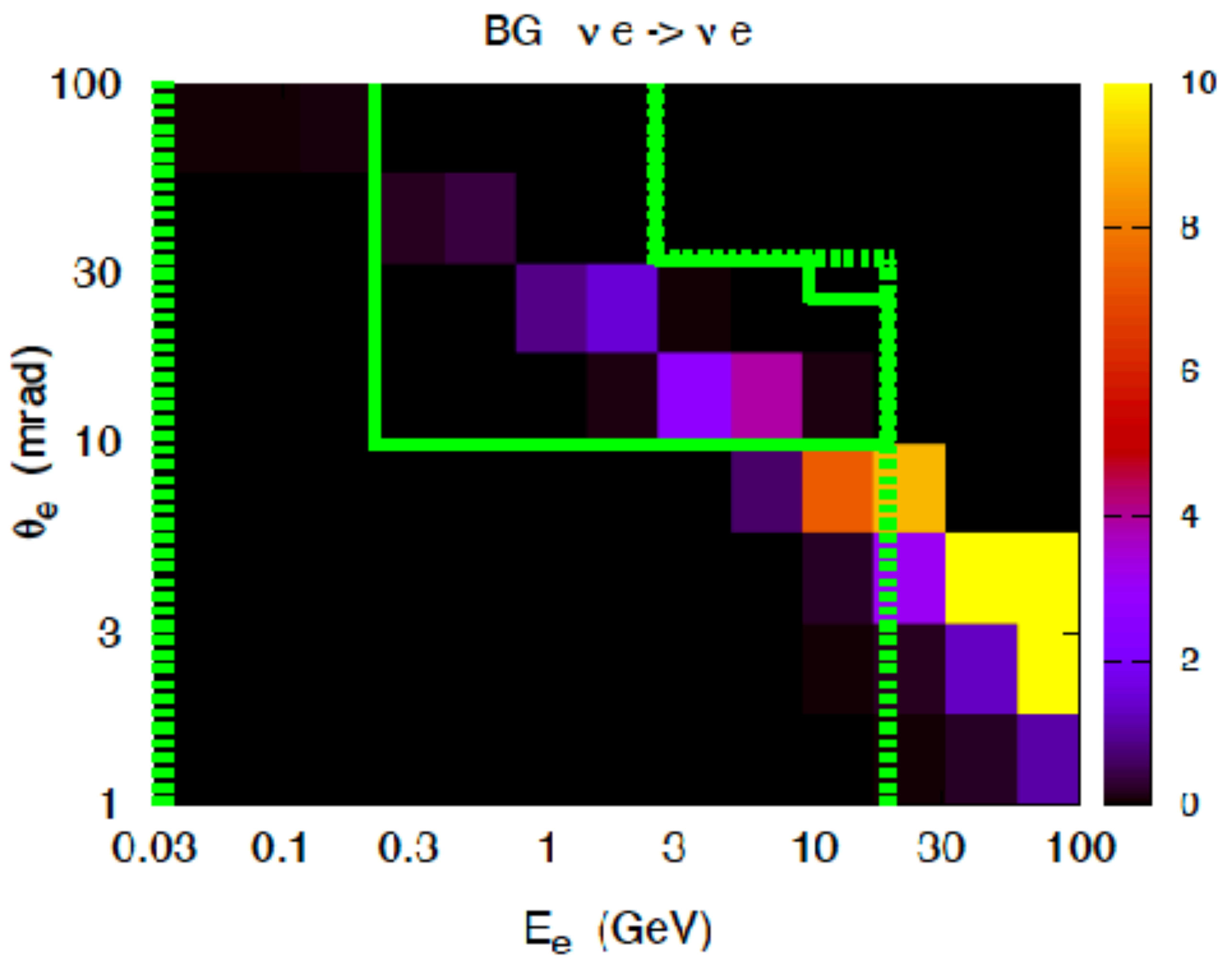
calculation	faser-pilot	faser-nu	faser-nu	faser-nu	Faser-nu LOI	Faser-nu LOI -fixed	flare-10	From JB for Flare-10
generator	SIBYLL	SIBYLL	DPMJET	Pythia8	average	average	SIBYLL	approx
Normalization mass*fb	ton*fb	1 ton*fb	1 ton*fb	ton*fb	1 ton*fb	1 ton*fb	1ton*fb	1ton*fb
angular range	~10cm/ 480m	25 cm/ 480m	26 cm/ 480m	27 cm/ 480m	25 cm/ 480m	26 cm/ 480m	1 m / 620 m	1 m / 620m
numu/anti-numu	**23.0/6.0**	22/5.9	32.2/9.2	24.5/7.7	101/31	24.8/7.6	7/2.1	43
nue/anue	**3.7/2.1**	3.42/1.97	16.2/4.7	3.5/1.8	5.03/2.66	4.5/2.4	1.1/0.53	10
nutau/ anutau	**0.063/0.034**	0.078/0.034	0.36/0.18	0.084/0.048	0.08/0.04	0.08/0.04	0.049/0.019	0.13

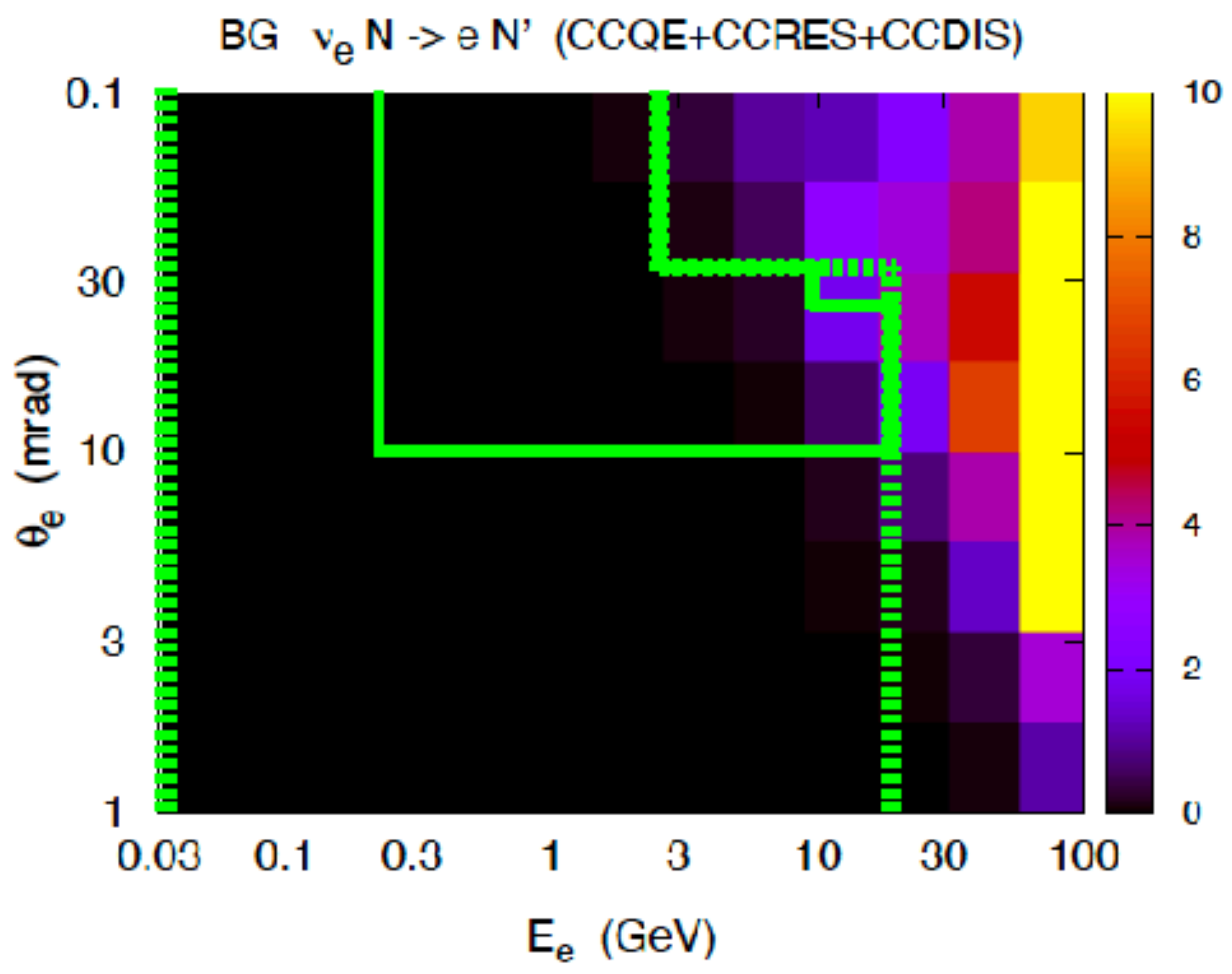
mistake

Observed total: 45/ton/fb

LAR and light DM search (primary science driver)







Signal is a single isolated forward electron.

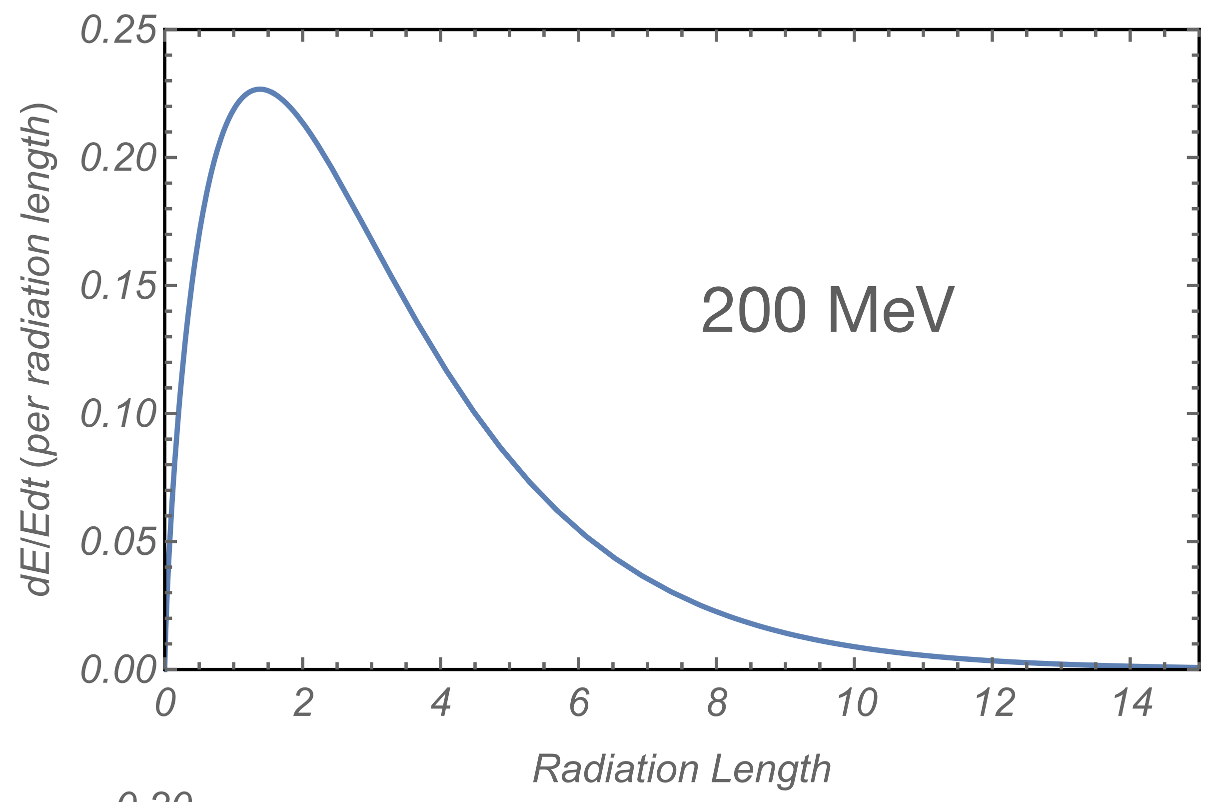
Signal is at low energy < 20-30 GeV and angle > 0.5 deg.

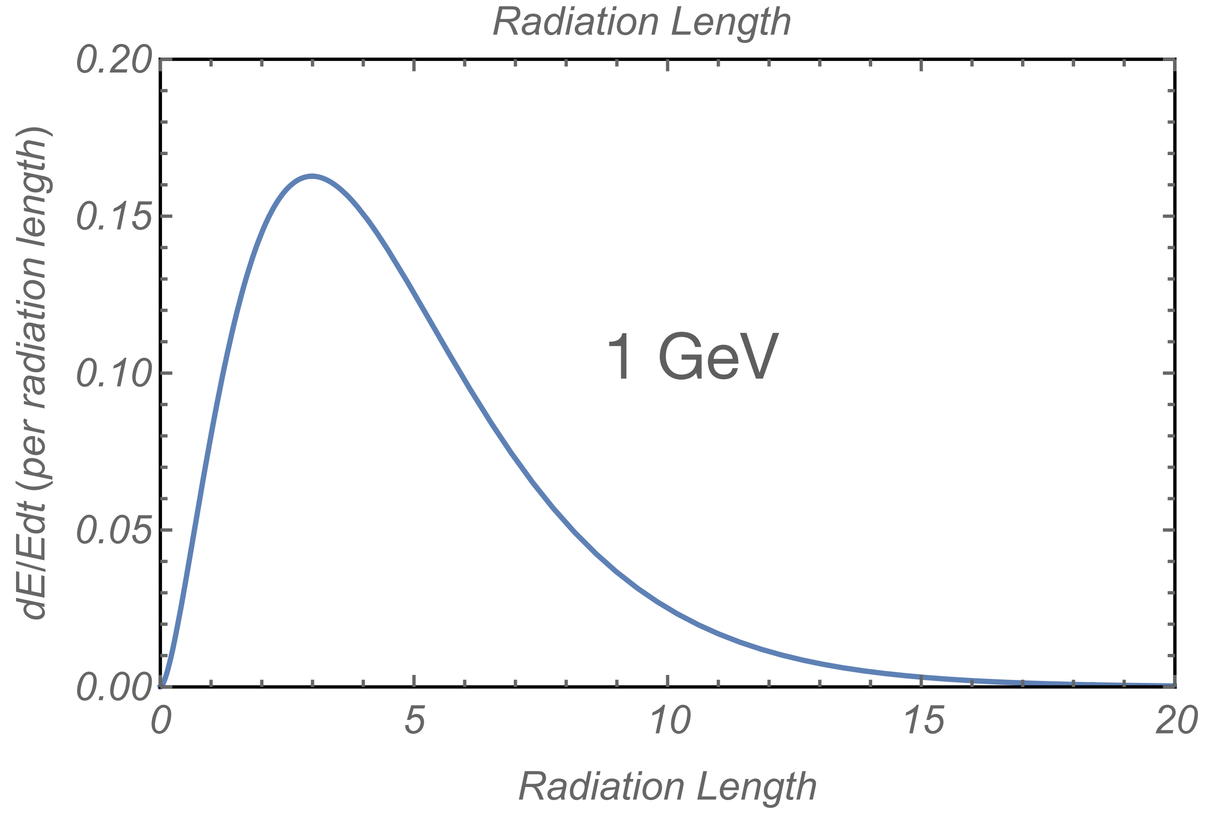
Main background is neutrino electron elastic scattering.

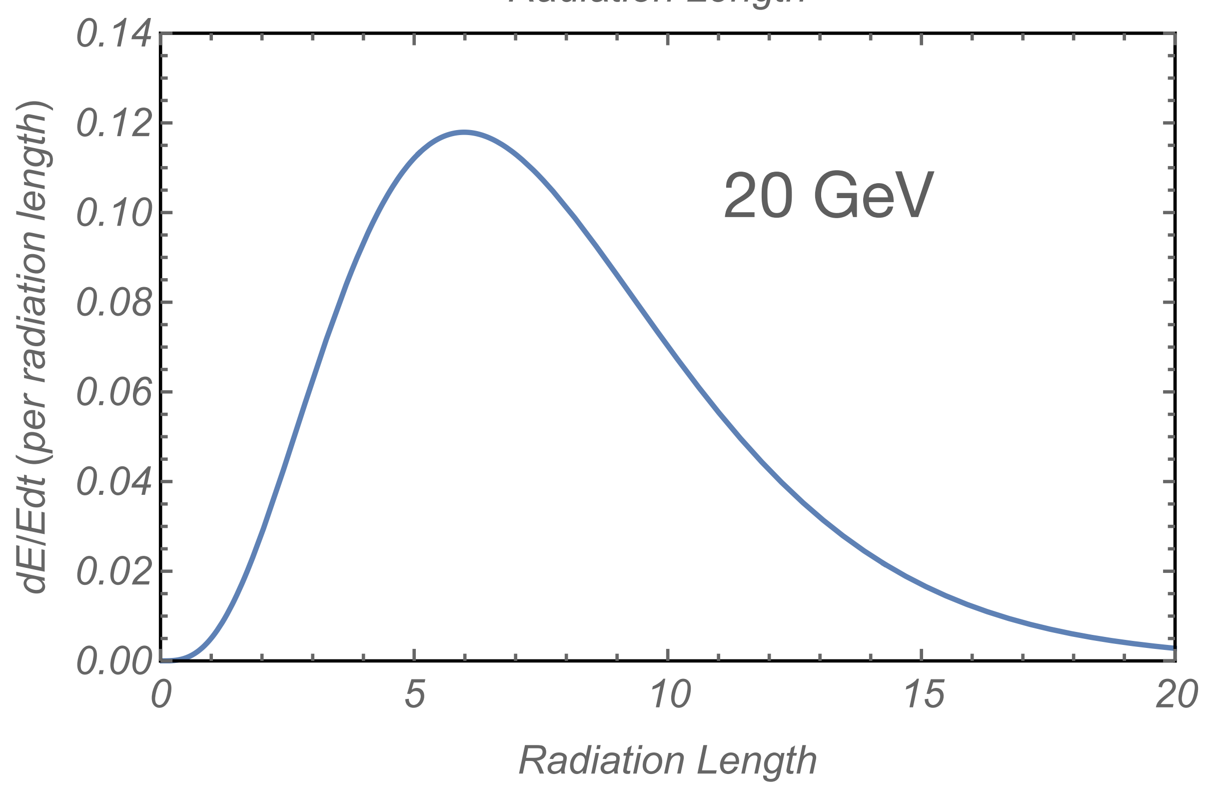
Must measure angle with uncertainty of ~0.1-0.2 deg or < 5mrad.

And must contain the EM shower to measure the energy well.

Liquid argon EM containment and angular resolution. These are crude arguments that need simulation effort.

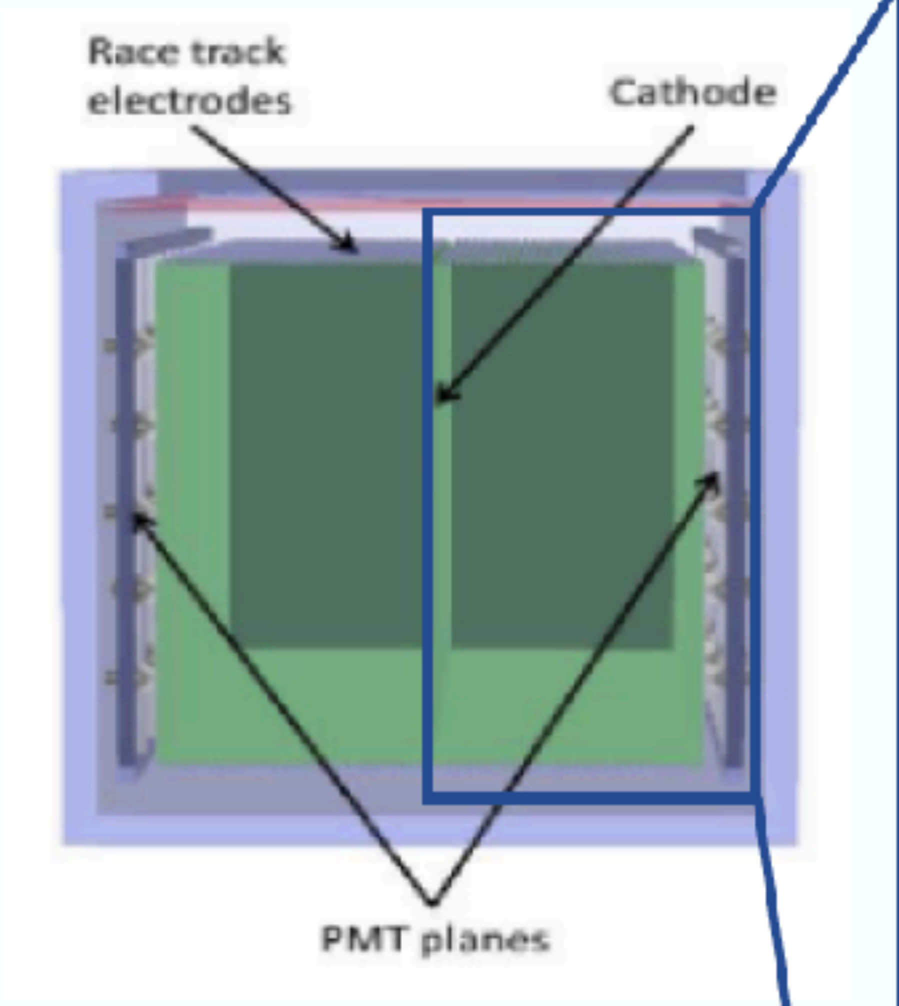




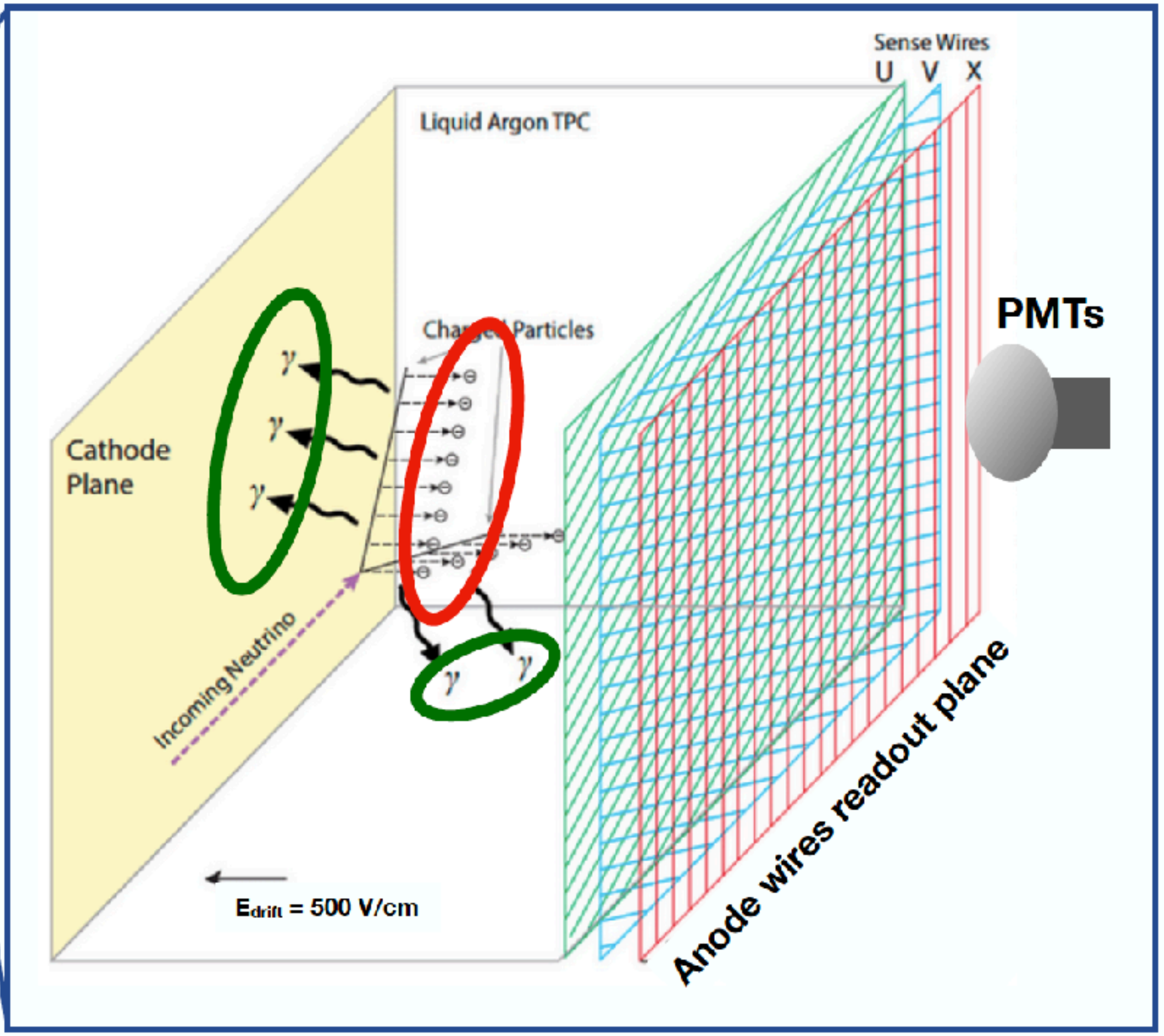


- LAr radiation length is 14 cm.
- Normalized mean shower profiles show the expected energy loss.
- To contain 20 GeV shower sufficiently we need > 15 rad lengths.
- The angle needs to be measured within 1-2 rad lengths. This means a position resolution better < 3 mm is needed over ~30 cm.
- With > 20 good samples at ~3 mm resolution we should be able to get < 5 mrad resolution.

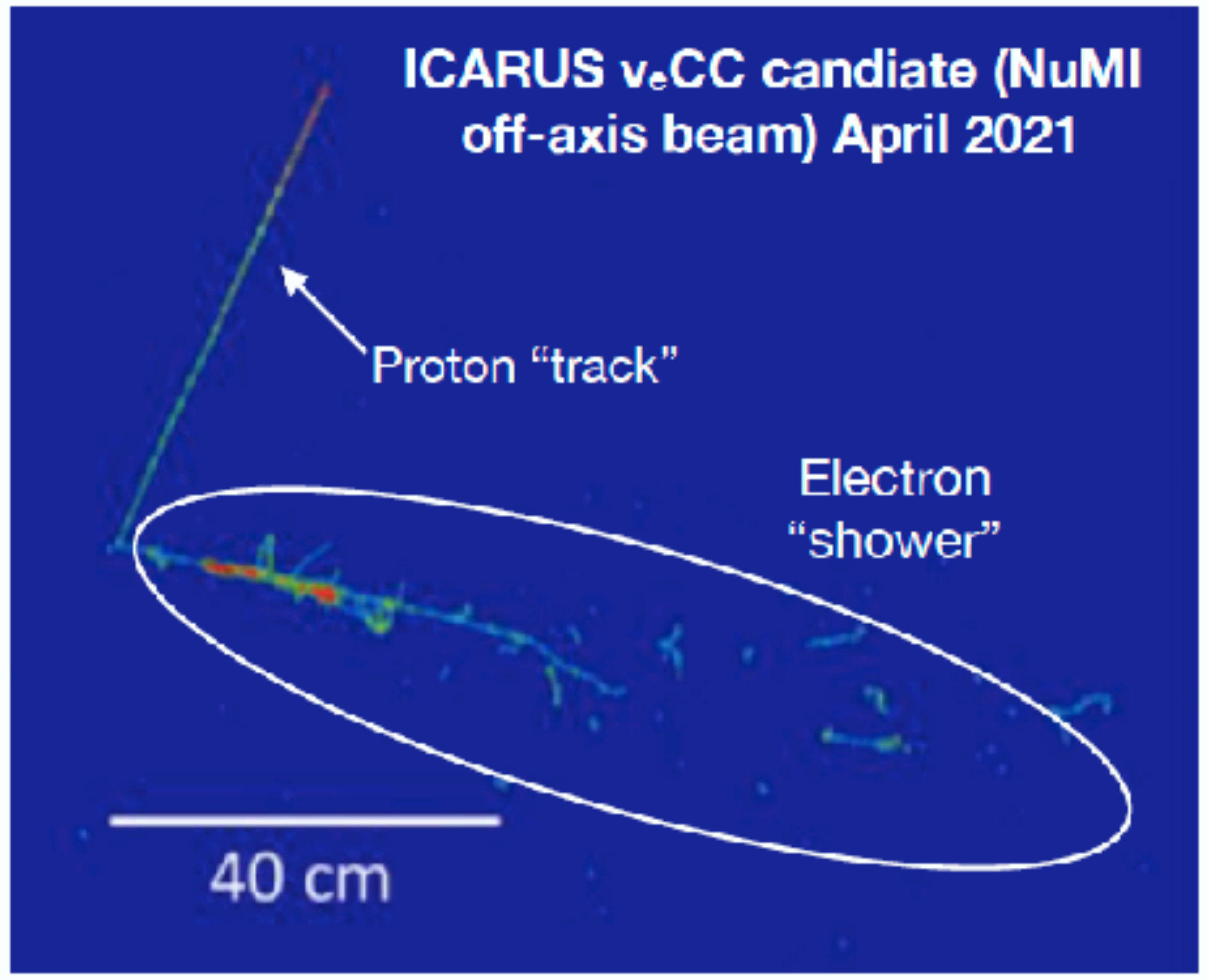
Liquid argon scientific capabilities



ICARUS LArTPC:
- 2 cryostat modules
- 2 LAr TPC per module
- 90 PMT per TPC = 360 PMTs in total
- 53248 wires ~ 3 mm spacial resolution



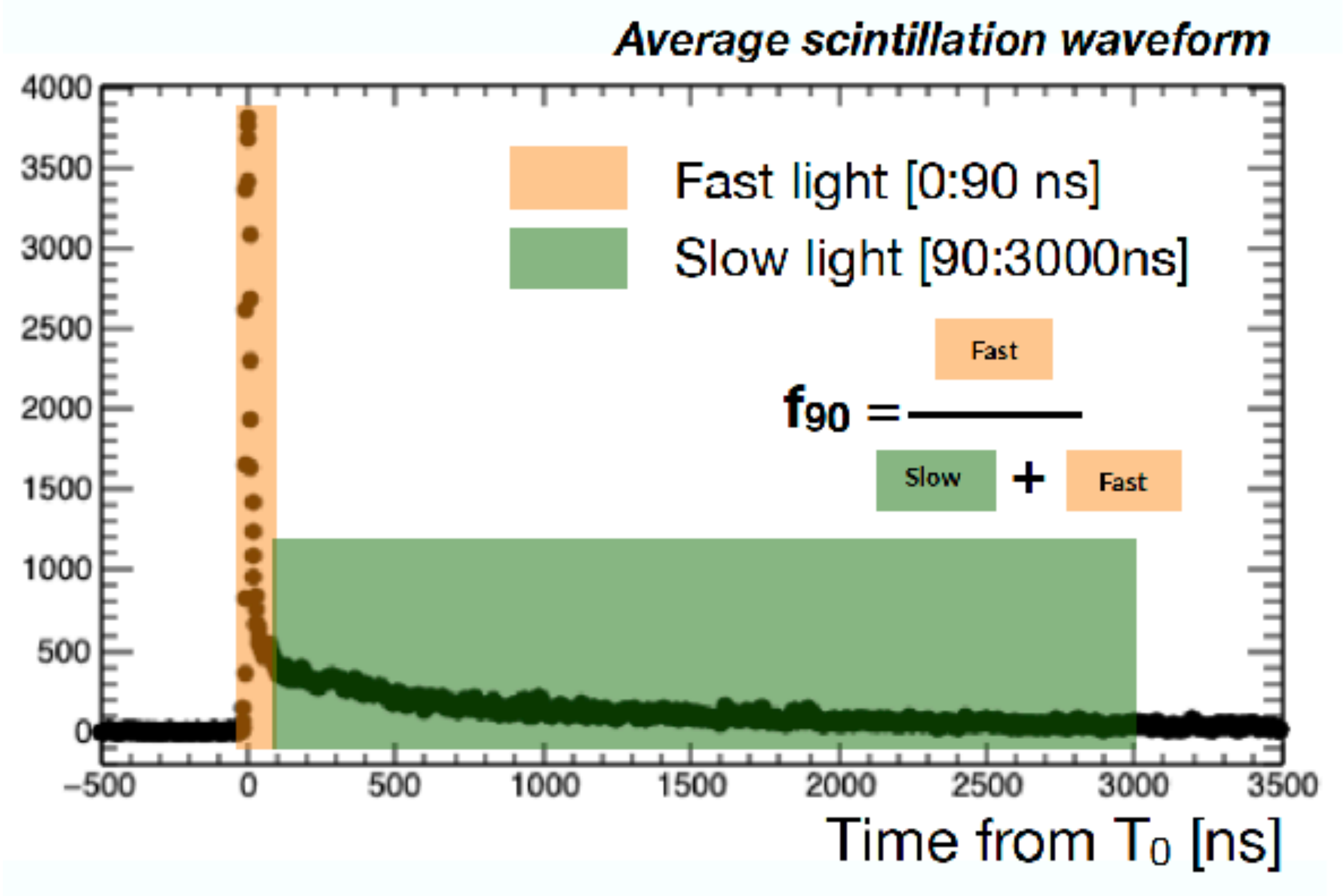
Charge from Ar ionization drift **(time ~1m/mm)** to the anode wire readout. Image of the event interaction is created



Scintillation light from de-excitations of Argon dymers
- Singlet state : **fast light** component (~ **6 ns**)
- Triplet state: **slow light** component (**~1.6 μs**)
- Light yield ~**20k photons /MeV** (@500 V/cm drift)
- Wavelength: 125 nm

- Liquid argon density is 1.4 gm/cc
- Radiation length ~ 14 cm and nuclear interaction length of 85 cm.
- Excellent muon/gamma/ electron identification.
- Good choice for neutrino cross section measurement, higher mass is needed for nu+e elastic scattering.

Liquid argon scientific and technical issues



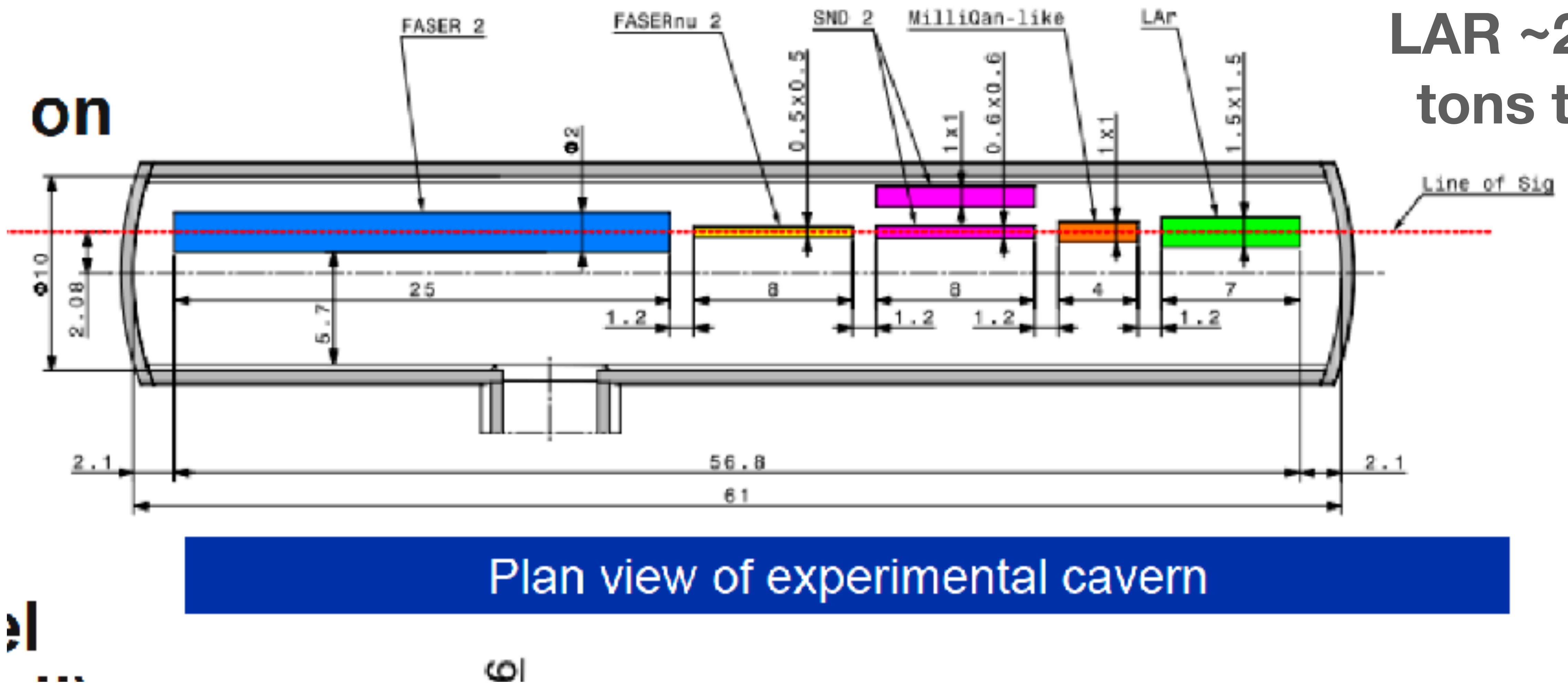
Given the slowness of the drift, we need to consider the scintillation as the primary readout to isolate events from bunch crossings.

- Liquid argon time projection chamber will have drift time of ~0.6 msec if drift length is 1 m. During this time there will be 24000 bunch crossings.
- **For a liquid argon detector with cross section of ~2 m^2 there will be <8.5 tracks through the detector and ~10^{-3} neutral hadrons. These must be separated from neutrino events.**
- For extremely forward events, the wire readout is problematic because of isochronous events (all wires get hit at the same time).
- To reduce geometry related ambiguity, pixel readout should be considered.
- A high density photon readout is needed to measure the time of the events to isolate events related to bunch crossings.
- Possible Analysis path: isolated events for each crossing -> reject those entering the detector -> match the pattern to TPC pixel readout.

LAR design choices

Item	parameter	Comment
Total mass	20-30 tons	Total mass needed to allow enough space for cryogenic equipment, anode planes, electronics, etc.
Fiducial mass	~10 tons	10 tons are needed for sufficient DM sensitivity over 3000/fb and good statistics for neutrino cross section and other basic measurements.
Size	2m (wide) x1m (height) x 7m (long)	sufficiently long for shower containment.
Drift length and time	~1 m (0.62 msec)	This is at 500 volts per cm. Total voltage is 50000 volts.
Readout geometry	Wire planes or pixels.	If there are wire planes, a study is needed about how many planes and what angles. Secondly, the isochronous tracks will be problematic and wire planes may have to be tilted w/r/t beam
Position resolution	3 mm	Wire or pixel pitch needs to be as low as possible while maintaining good S/N.
Photon sensors	PMTs or SiPM	Density and angular coverage of photon sensors needs study. In case of pixels, we may have to put them on top and bottom between field cage gaps.

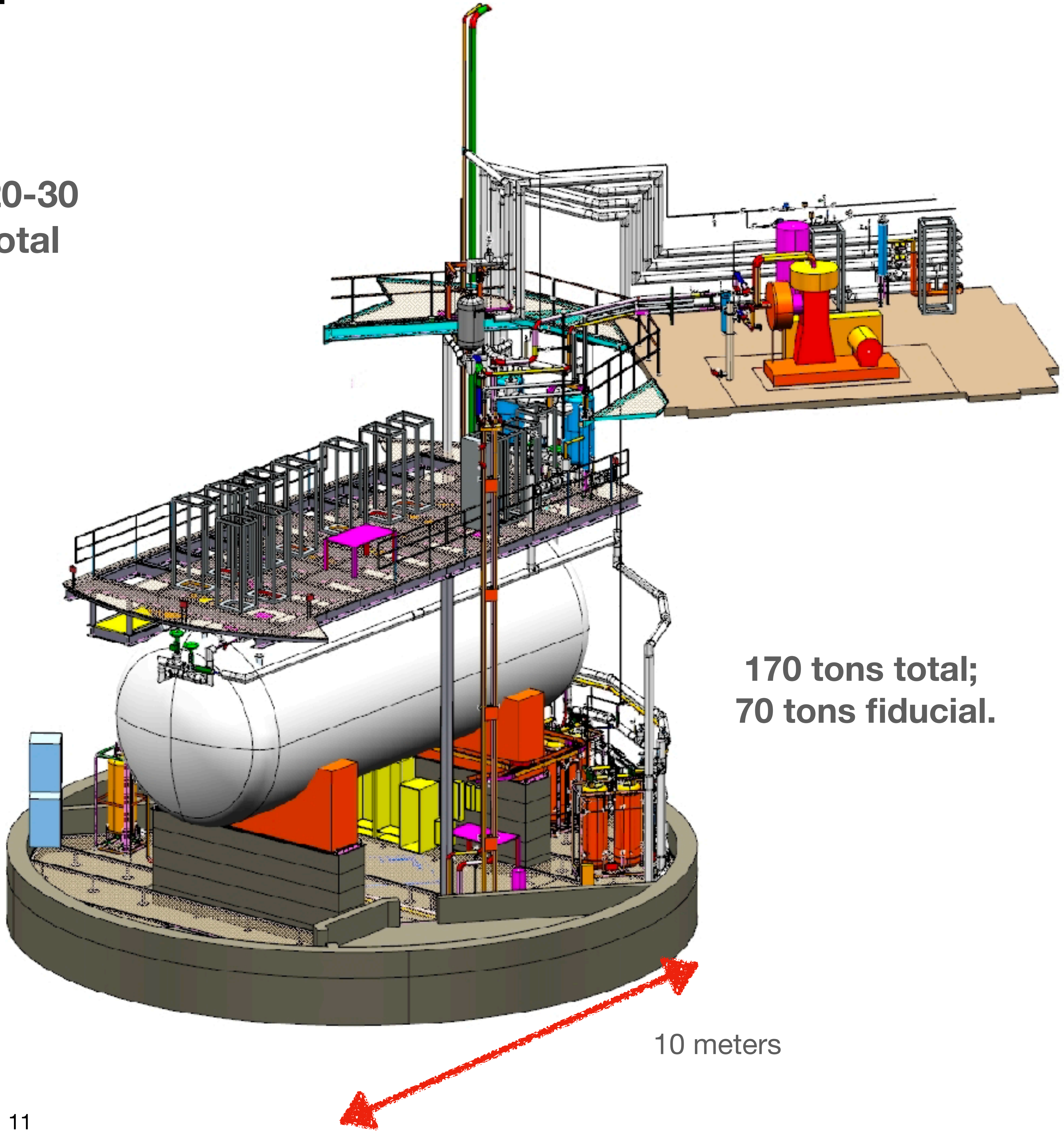
Space considerations (based on old pictures)



Plan view of experimental cavern

LAR ~20-30 tons total

- overhead Crane might be a good idea for such a long 60 m tunnel.
- Considerable space is needed for cryogenic and support equipment for the liquid argon detector.
- The space probably does not scale with the size of the detector.
- Possible to consider a parallel tunnel for support equipment ?



170 tons total;
70 tons fiducial.

Conclusion

- **Presented a very preliminary survey of scientific requirements and detector capabilities that are needed. An integrated approach to the detectors in the FPF will yield the best science.**
- DM search possibly drives the detector requirements, but then neutrino physics must also be considered.
- The physics interest for LAR as presently seen is (in increasing difficulty)
  - neutrino cross sections in the 1TeV range,
  - tau neutrino flux and associated heavy flavor physics,
  - DM search with EM showers.
- Liquid argon has excellent EM-shower and muon ID and could be a good candidate for these measurements.
- For a liquid argon TPC, the rate of muon background is comparable to the cosmic ray backgrounds in present short baseline detectors at FNAL. However it is beam related, and therefore timing cannot be used to reject it.
- Given the geometry (extremely forward), a pixel readout and high density scintillation measurement is needed to isolate neutrino events for each bunch crossing and contained in the detector.