# FLArE


Jianming Bian (University of California, Irvine)

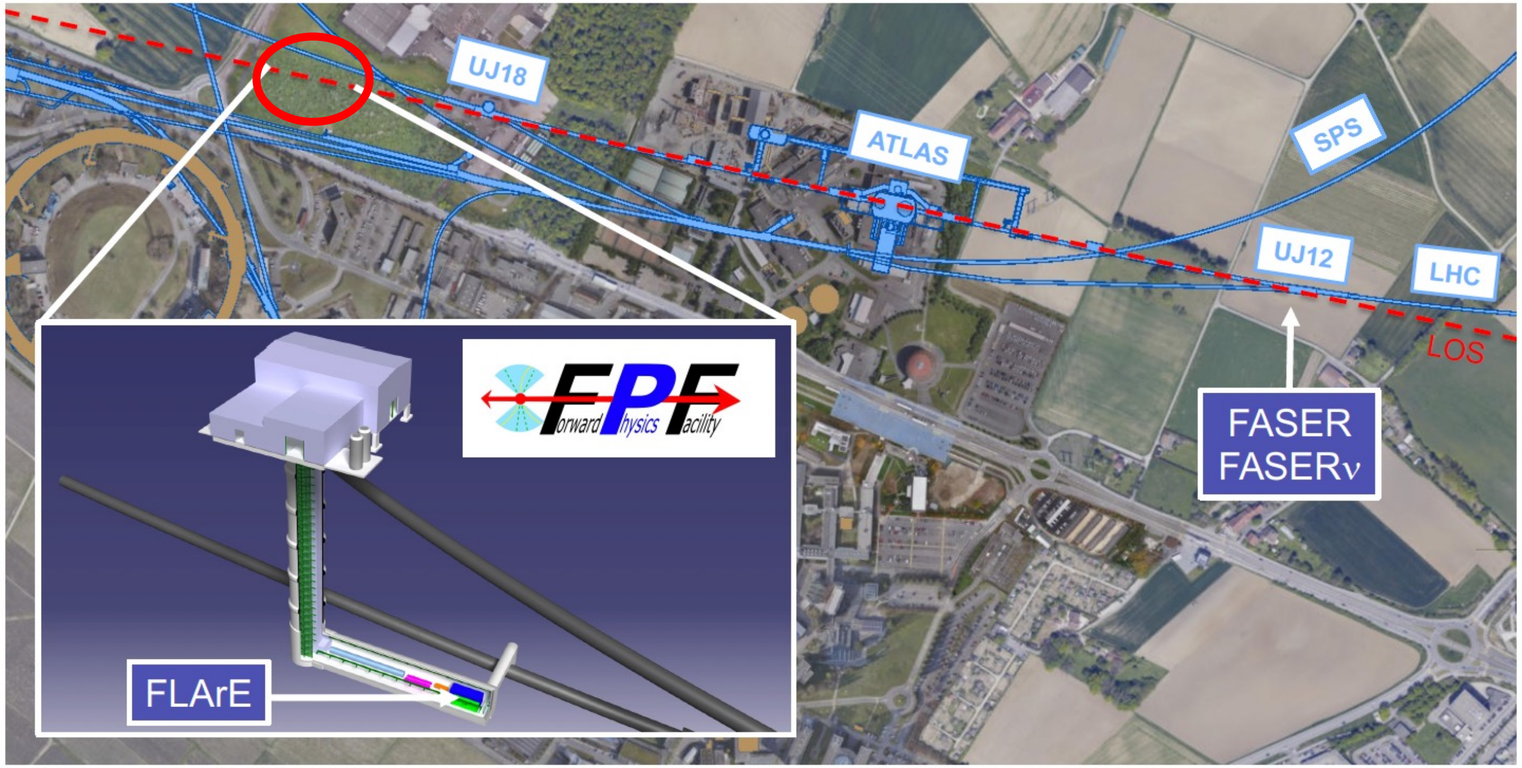
Milind Diwan (Brookhaven National Lab)


2022 Jan 31

The 4th Forward Physics Facility Meeting

# Introduction

- FLArE: a noble liquid time projection chamber (TPC) detector to detect very high-energy neutrinos and search for dark matter at LHC@CERN
- A central goal of FLArE is to extend the nascent collider neutrino program into the HL-LHC era. With an active detector mass of 10 tonnes, 10 times bigger than FASERν, and the enhanced luminosity of the HL-LHC relative to Run 3, one can expect 200 times more neutrino events at FLArE than at FASERν.




- FLArE's location at the LHC in the proposed Forward Physics Facility (FPF): The FPF will be located 620-680 m west of the ATLAS IP along the line of sight (LOS). Also shown is the location of FASER and FASERν, which are also located along the LOS, but 480 m east of the ATLAS IP

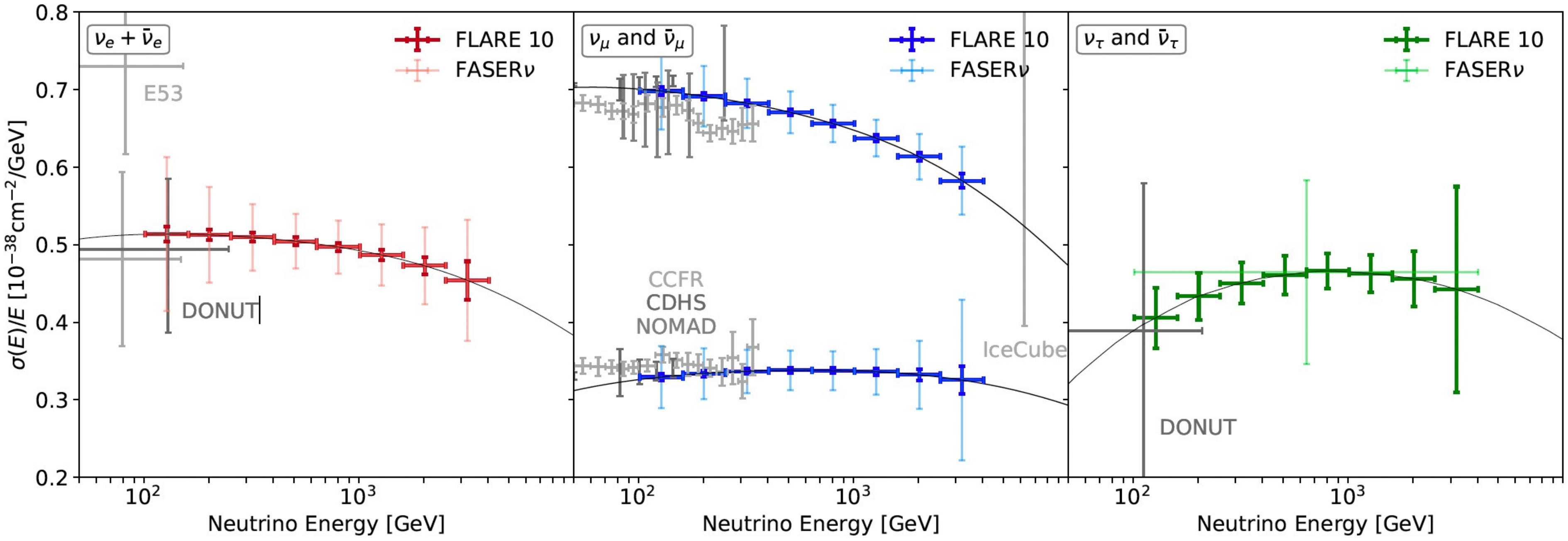
# Physics Goals

Neutrino physics

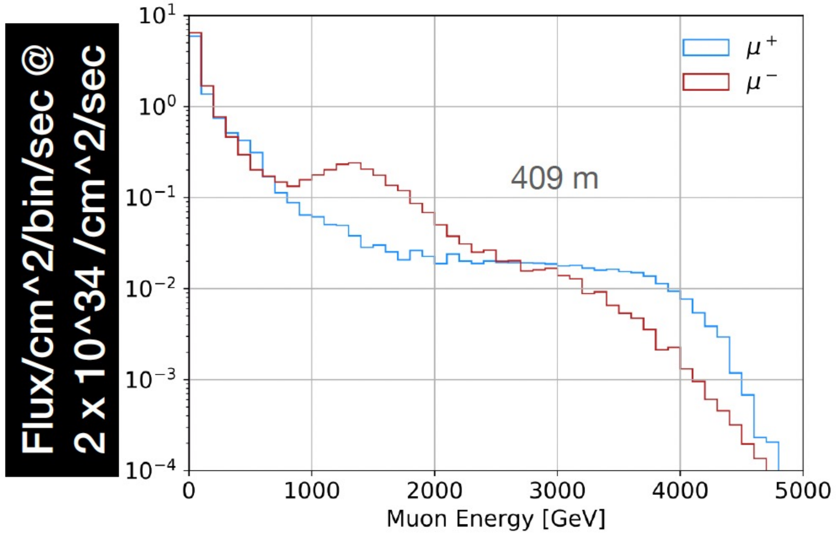
- Measure the flux of tau neutrinos
- Limit the oscillations of tau neutrinos into other neutrinos over the parameter range defined by the energy spectrum and distance
- Determine the cross section of neutrino interactions in the energy range of hundreds of GeV to few TeV
- QCD physics with far forward neutrinos

Dark matter search sector

- Detection of dark sector photon decays in the detector volume
- Detection of light dark matter scattering in detector
- Search for milli-charged dark matter particles



# Experimental conditions (without sweeping magnet) Approximate fluxes, rates of backgrounds




| | |
|---|---|
| **Minimum distance** | 612 m |
| **Total Lumi/max lumi** | 3000/fb ;  $5\times10^{34}$ /cm2/sec |
| **Lumi per day** | ~1 /fb assuming 10 year running |
| **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 ($2\times10^{-8}$/cm2/crossing) |
| **Tracks in detector/1 ms** | 8.5/m^2/1msec |
| **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**

- 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

# PDF uncertainties in theoretical predictions for far-forward tau neutrinos at the LHC

Mary Hall Reno for Weidong Bai, Milind Diwan, Maria Vittoria Garzelli, Yu Seon Jeong, Fnu Karan Kumar, MHR (2021/12/9)

## $\nu_\tau + \bar{\nu}_\tau$ Events Run 3

| $\mathcal{L} = 150$ fb$^{-1}$ | $\nu_\tau$ | $\bar{\nu}_\tau$ | $\nu_\tau + \bar{\nu}_\tau$ | $\nu_\tau + \bar{\nu}_\tau$ | | |
|---|---|---|---|---|---|---|
| $(\mu_R,\ \mu_F)$, $\langle k_T \rangle$ | (1, 1) $m_{T,2}$, 0.7 GeV | | | | | |
| | | | | scale(u/l) | PDF(u/l) | $\sigma_{\rm int}$ |
| SND@LHC $7.2 < \eta_\nu < 8.6$, 830 kg | 2.8 | 1.3 | $4.2^{+3.8}_{-3.3}$ | +3.7/-3.1 | +0.8/-1.2 | $\pm 0.1$ |
| FASER$\nu$ $\eta_\nu > 8.9$, 1.2 ton | 8.2 | 3.9 | $12.1^{+11.6}_{-9.8}$ | +11.3/-9.0 | +2.8/-3.9 | $\pm 0.3$ |
| $(\mu_R,\ \mu_F)$, $\langle k_T \rangle$ | (1, 2) $m_T$, 1.2 GeV | | | (1, 1) $m_{T,2}$, 0.7 GeV | | |
| PDF | PROSA FFNS | | | NNPDF3.1 | CT14 | ABMP16 |
| SND@LHC $7.2 < \eta_\nu < 8.6$, 830 kg | 5.1 | 2.4 | 7.5 | 4.0 | 6.6 | 5.0 |
| FASER$\nu$ $\eta_\nu > 8.9$, 1.2 ton | 13.5 | 6.4 | 19.9 | 12.8 | 23.5 | 15.6 |

## $\nu_\tau + \bar{\nu}_\tau$ Events HL

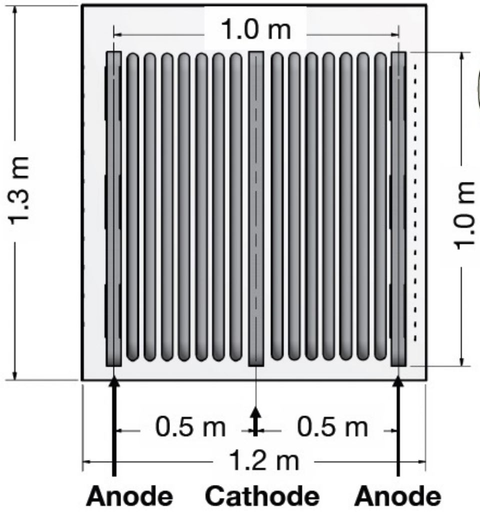
| $\mathcal{L} = 3000$ fb$^{-1}$, 1 m | $\nu_\tau$ | $\bar{\nu}_\tau$ | $\nu_\tau + \bar{\nu}_\tau$ | $\nu_\tau + \bar{\nu}_\tau$ | | |
|---|---|---|---|---|---|---|
| $(\mu_R,\ \mu_F)$, $\langle k_T \rangle$ | (1, 1) $m_{T,2}$, 0.7 GeV | | | | | |
| | | | | scale (u/l) | PDF (u/l) | $\sigma_{\rm int}$ |
| $\eta \gtrsim 6.9$ | 3260 | 1515 | $4775^{+4307}_{-3763}$ | +4205/-3494 | +926/-1391 | $\pm 112$ |
| $(\mu_R,\ \mu_F)$, $\langle k_T \rangle$ | (1, 2) $m_T$, 1.2 GeV | | | (1, 1) $m_{T,2}$, 0.7 GeV | | |
| PDF | PROSA FFNS | | | NNPDF3.1 | CT14 | ABMP16 |
| $\eta \gtrsim 6.9$ | 5877 | 2739 | 8616 | 4545 | 7304 | 5735 |

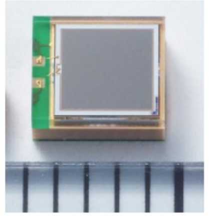
1 m tungsten, namely 60.63 ton

# FLArE Detector Preliminary Sketch

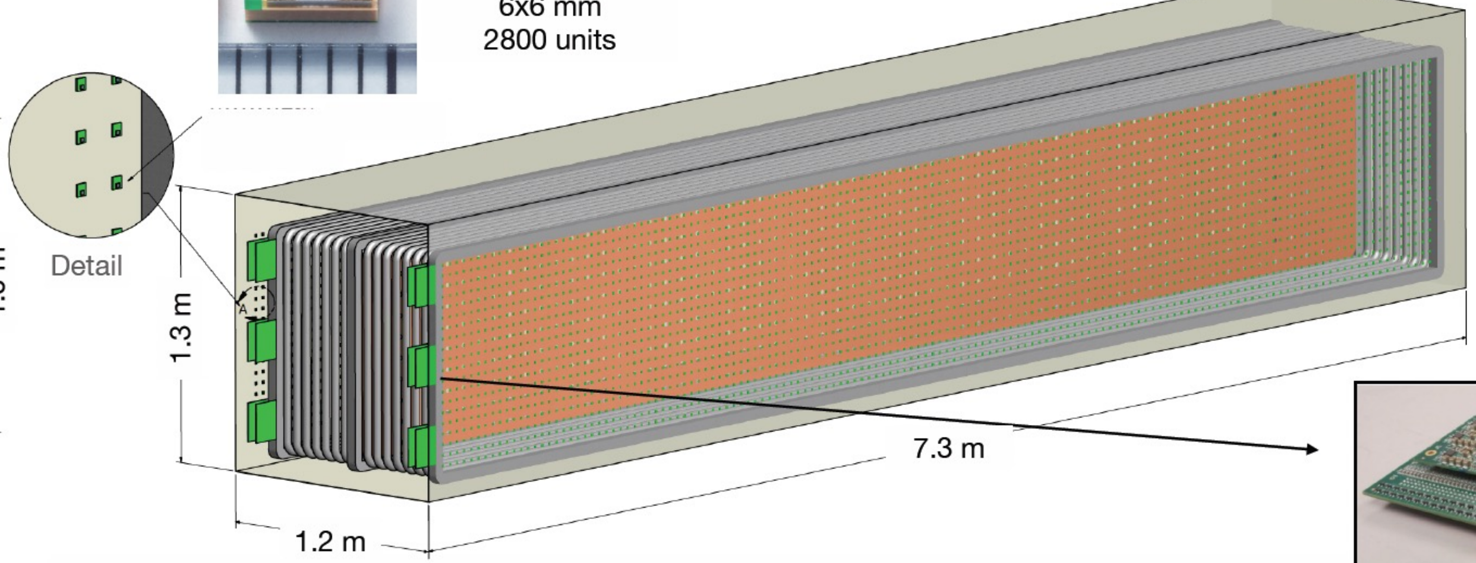
| Volume | 11.5 m^3 |
|---|---|
| LAr | 16 ton |
| LKr | 27.5 ton |
| menbran | 0.5 m |
| heat loss | 290 W |

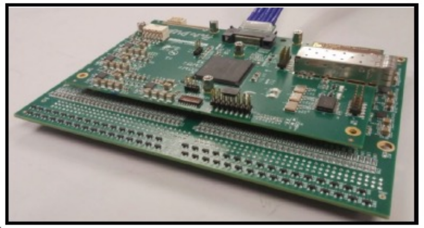
**TPC-side view 2**



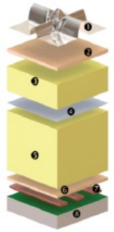



Hamamatsu
S14160 SiPM
6x6 mm
2800 units

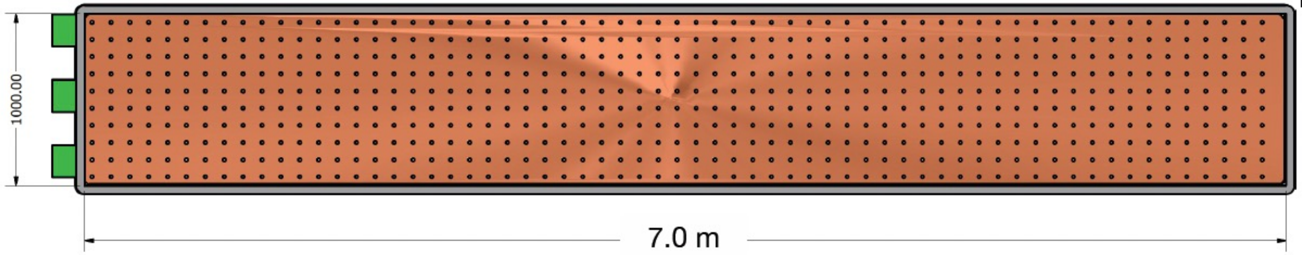


**DUNE Front End Motherboard**



**Cryostat Insulation**




**TPC anode plane -side view 1**

# Parameters for the FLArE Detector

| | Value | Remarks |
|---|---|---|
| Detector length | 7 m | Not including cryostat |
| TPC drift length | 0.5 m | 2 TPC volumes with HV cathode in center |
| TPC height | 1.3 m | |
| Total LAr mass | $\sim 16$ tonnes | Volume in the cryostat |
| Total LKr mass | $\sim 27.5$ tonnes | As an option |
| Fiducial mass LAr/LKr | 10/17 tonnes | |
| Charge readout | wires or pixels | Hybrid approach is possible |
| Light readout | SiPM array | Needed for neutrino trigger |
| Background muon rate | $\sim 1/\text{cm}^2/\text{s}$ | Maximum luminosity of $5 \times 10^{34}/\text{cm}^2/\text{s}$ |
| Neutrino event rate | $\sim 50/\text{tonne}/\text{fb}^{-1}$ | For all flavors of neutrinos |
| Cryostat type | Membrane 0.5 m | Thickness of membrane |
| Heat loss | $\sim 300$ W | |

# Issues to be resolved in design process

We are seeking resources to support design and R&D

| Item | Choice | Comments |
|---|---|---|
| **Liquid fill** | LAr or LKr or keep both options open | If we made the choice for LKr only then detector could be much smaller for same mass. |
| **Cryostat and TPC dimensions** | Keep the total to active volume ratio small (for LKr) | Cryostat, field cage, HV design must be integrated. |
| **Cathode/anode** | Central cathode with two anode planes. (makes two drift volumes) | Doubles channels, but better for HV safety. cathode must be transparent to light |
| **Photon readout** | SiPM's. Cannot use PMTs to keep the unused volume small. | Will need large number of channels. |
| **Wavelength shifter for scintillation light** | LAr: 128 nm, LKr: 150 nm | Will require R&D to understand this issue. |
| **SiPM density, timing resolution and trigger** | This requires detailed simulations and R&D. **A minimum density is needed for recognizing contained events versus muons for trigger.** Timing resolution is needed to associate with LHC bunch. | |
| **Anode electrode design** | Pixels versus wires | Simple wire geometry may not be possible because of straight thru muons. Need Simulation input |
| **Anode readout pitch** | 2 or 5 mm (LKr has higher signal) | Depends on kinematic resolution needed and also signal to noise. |

# LAr vs. LKr, Milind Diwan, 1/6/2022

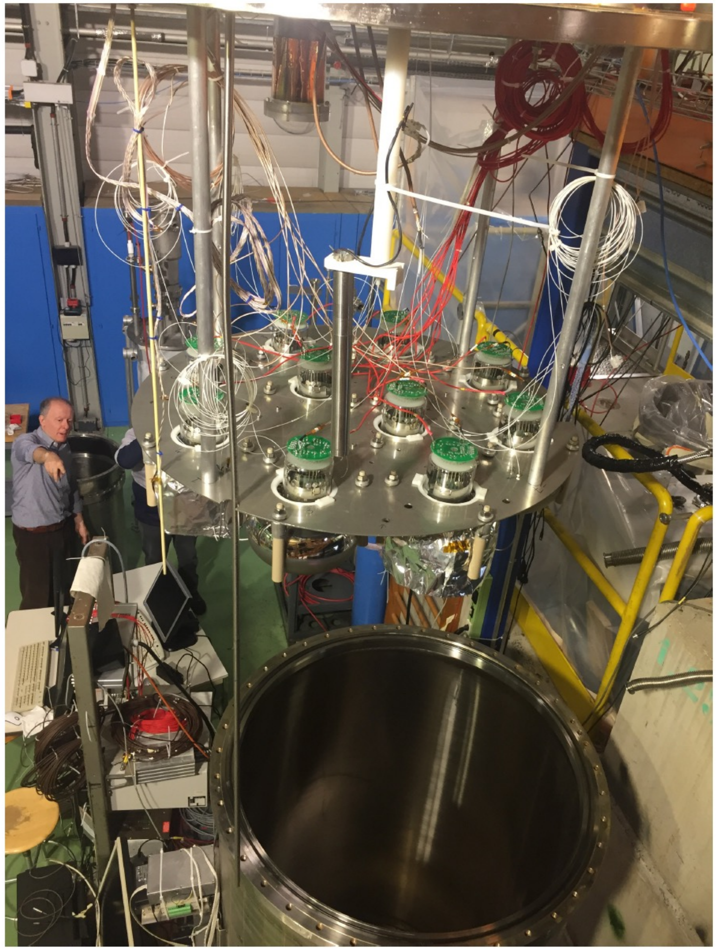
*Given the high radioactivity in krypton, the LKr option needs further evaluation.*

| | **Liquid Argon** | **Liquid Krypton** |
|---|---|---|
| **Z, A** | **18, 39.9** | **36, 83.8** |
| **Density** | 1.4 gm/cc | 2.4 gm/cc |
| **Radiation Length** | 14 cm | 4.7 cm |
| **Moliere Radius** | 9 cm | 5.8 cm (NA48 says 4.7) |
| **nuclear interaction length** | 119.7 gm/cm2, 85.8 cm | 149.7 gm/cm2, 61.8 cm |
| **pion interaction length** | 149.0 gm/cm2, 106.7 cm | 177.6 gm/cm2, 73.47 cm |
| **critical energy e (mu)** | 32 MeV (485 GeV) | 17 MeV (277 GeV) |
| **Minimum ionization** | 2.105 MeV/cm | 3.28 MeV/cm |
| **Ionization (eV) (atom)** | 15.8 eV | 14.0 eV |
| **Boiling point** | 87.3 K | 119.9 K |
| **index of refraction** | 1.23 | 1.3 |
| **scintillation wavelength** | 125 nm | 147 nm |
| **Yield** | 40000/MeV | 25000/MeV |
| **Triplet lifetime** | 1. 6 micros | 0.09 micros |
| **Drift velocity at 500 V/cm** | 1.6 mm/micro-sec | 2.1 mm/micro-sec |
| **Radioactiviity** | Ar39, Ar42 | Kr81, Kr85 |
| **Air abundance (ppm)** | 9300 | 1.14 |

https://pdg.lbl.gov/2012/AtomicNuclearProperties/HTML_PAGES/289.html
https://periodictable.com/Isotopes/018.42/index2.dm.html

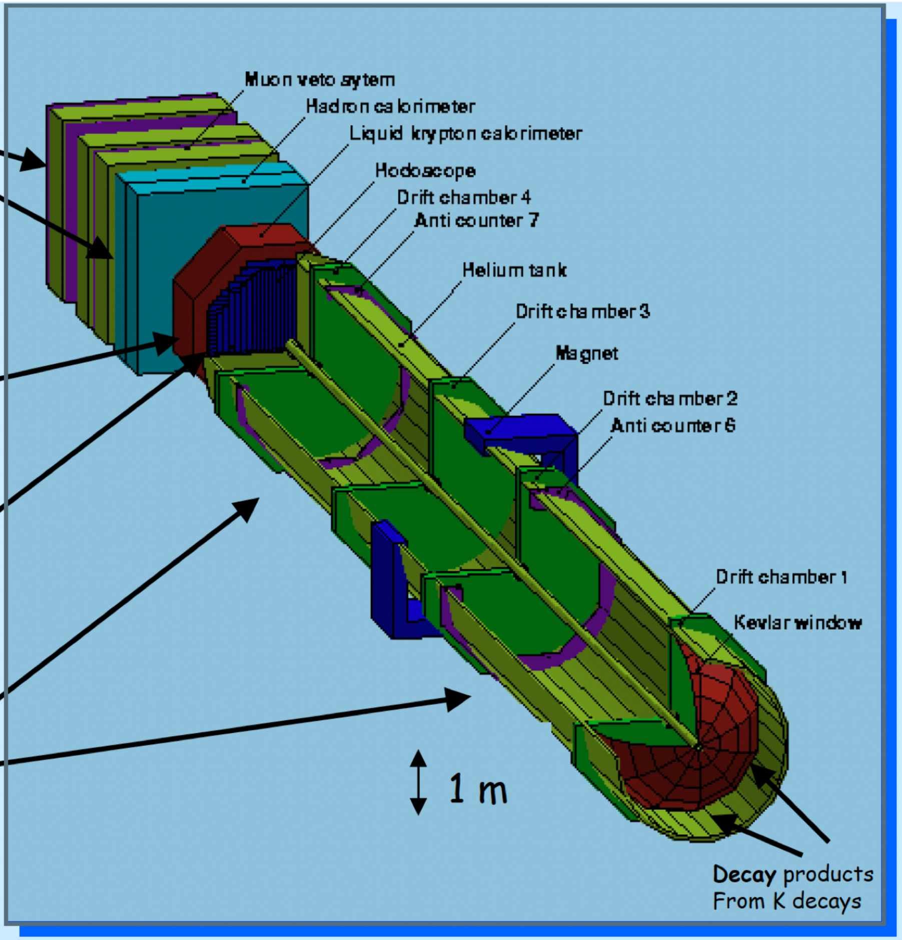
# CERN R&D facilities for FLARE Pictures and specs for some cryostats in building 182, Milind Diwan 11/18/2021

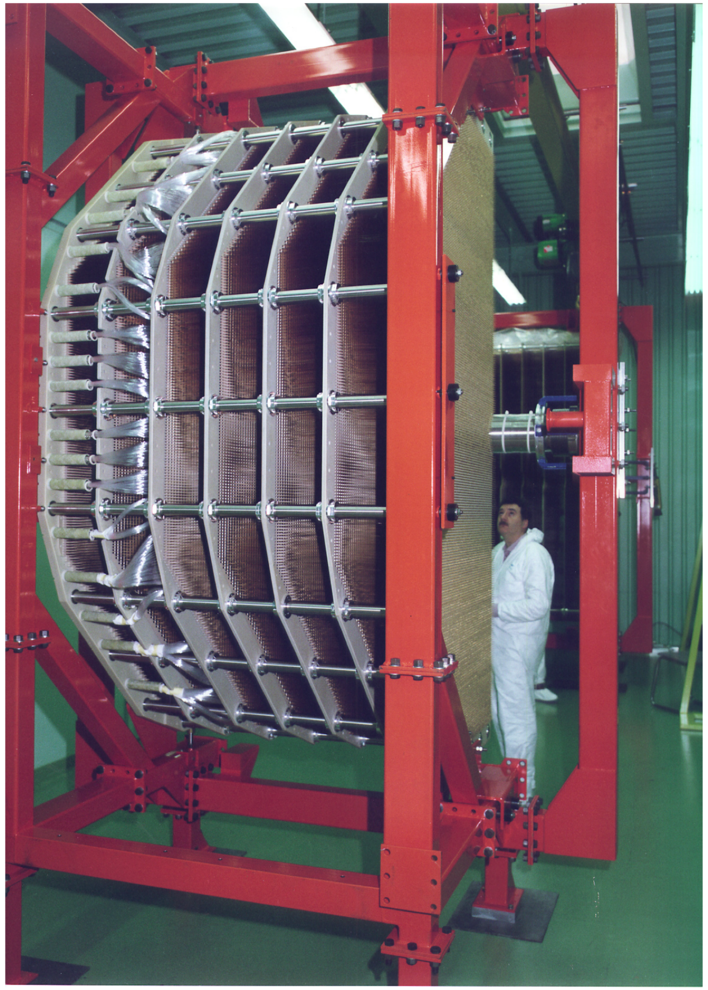
CERN and other R&D facilities will be needed to develop the readout



# The NA48 Liquid Krypton Calorimeter, Sandro Palestini, CERN, 20 January 2022

- Muon veto and hadron calorimeter (background, trigger)
- Quasi homogeneous liquid krypton calorimeter to detect $\pi^0\pi^0$ events
- Scintillation hodoscope (trigger and timing $\pi^+\pi^-$)
- Magnetic spectrometer to detect $\pi^+\pi^-$ events



# Measuring Light and Charge Yields in LKr, Dr Aleksey Bolotnikov (BNL) (2021/12/9)

- Both the light and charge signals provide valuable information needed for events reconstruction in TPC
- The total deposited energy is shared to produce UV scintillation photons and electron-ion pairs –correlated signals
- In LXeTPCs, e. g., in nEXO, the light and charge signals are added together to overcome fluctuations of the election-ion recombination to improve energy resolution

LKr at BNL

Measurements in LXe done by Columbia group using electrons and alpha-particle

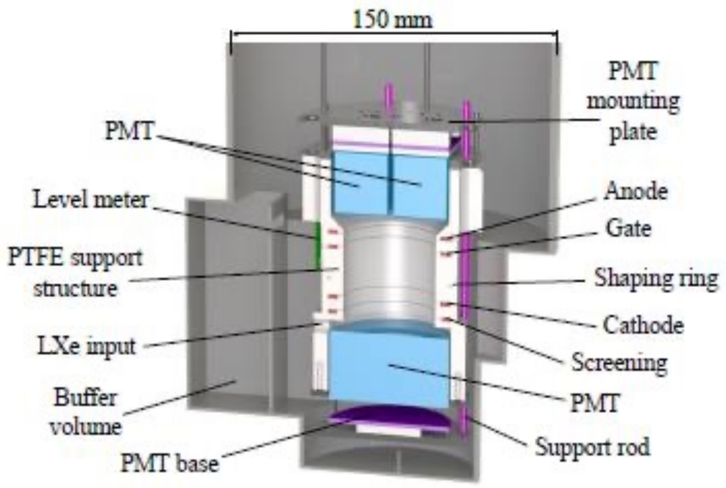



FIG. 1. Schematic drawing of neriX TPC. Plot from [18].

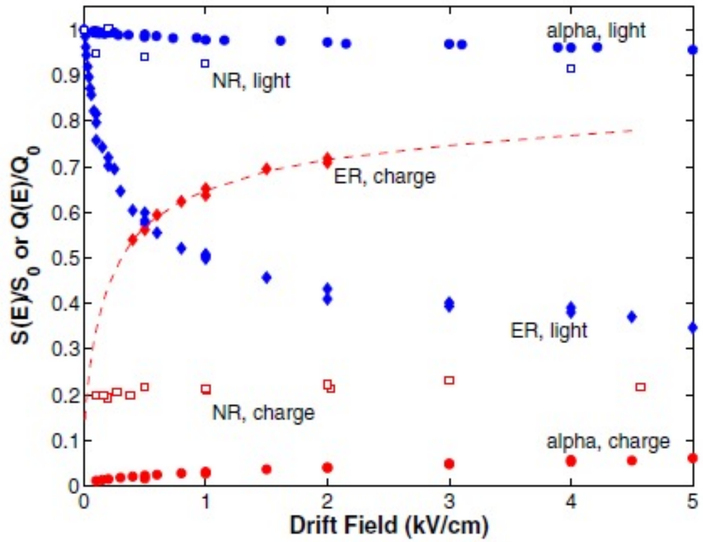



FIG. 3 (color online). Field dependence of scintillation and ionization yield in LXe for 122 keV electron recoils (ER), 56.5 keVr nuclear recoils (NR) and alphas.

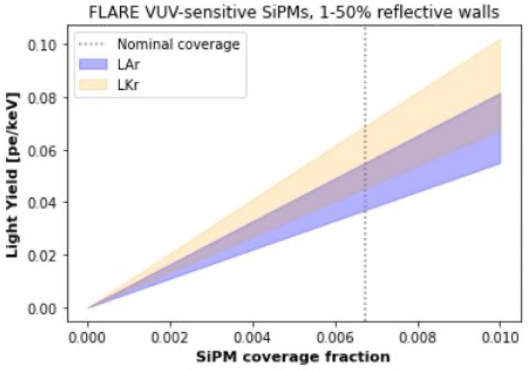
Kr storage at Physis

# Preliminary considerations on light collection & detection

Marcin Kuźniak, AstroCENT, (analytic model implemented by Sarthak Choudhary)

- Adequate light yield (>100 pe/MeV) can be obtained with modest coverage
- Need to optimize the design for trigger and pattern recognition

## VUV sensitive SiPMs




Lower scinitillation yield of LKr partly is compensated by higher PDE.

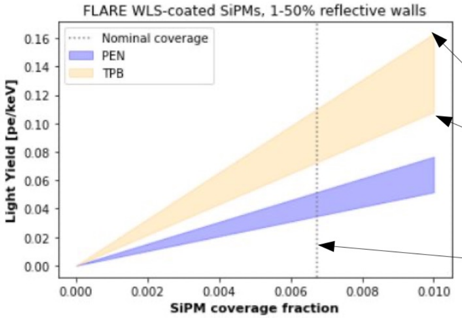
Highly approximate!

Reflectivity of SiPMs can play a significant role – did not treat that rigorously for this plot.

VUV sensitive configuration:
**0.03 – 0.07 pe/keV**

## Light yield predictions: Ar

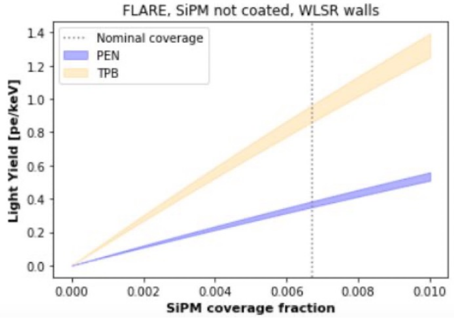
Assuming WLS efficiency of 1 for TPB and 0.47 for PEN, **using blue sensitive SiPMs**




Walls can be:
- 50% reflective (e.g. ESR reflector on APAs only)
- Nearly black
- (not a huge difference in this case)

This is 2800 6mm x 6mm SiPMs on each APA

Low reflectivity configuration:
**0.03 – 0.1 pe/keV**



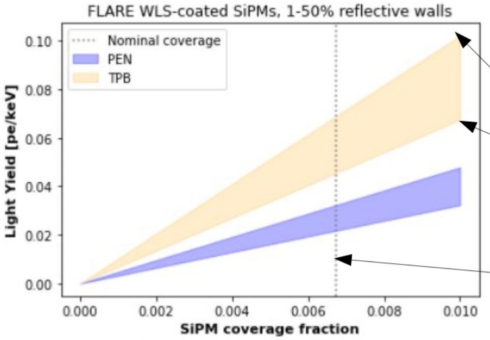

Here all surfaces (both APAs and the inside of the field cage are lined with WLS and ESR reflectors).

(Here SiPMs are not WLS-coated, adding WLS brings modest (<10%) enhancement.)

High reflectivity configuration:
**0.3 – 1 pe/keV**

## Light yield predictions: Kr (i.e. Ar rescaled by 25/40)

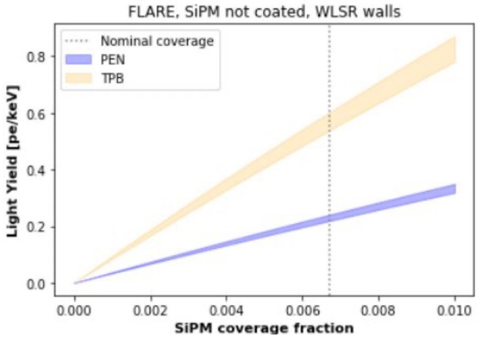
Assuming WLS efficiency of 1 for TPB and 0.47 for PEN, **using blue sensitive SiPMs**




Walls can be:
- 50% reflective (e.g. ESR reflector on APAs only)
- Nearly black
- (not a huge difference in this case)

This is 2800 6mm x 6mm SiPMs on each APA

Low reflectivity configuration:
**0.02 – 0.07 pe/keV**




Here all surfaces (both APAs and the inside of the field cage are lined with WLS and ESR reflectors).

(Here SiPMs are not WLS-coated, adding WLS brings modest (<10%) enhancement.)

High reflectivity configuration:
**0.2 – 0.6 pe/keV**

# EM Shower simulation

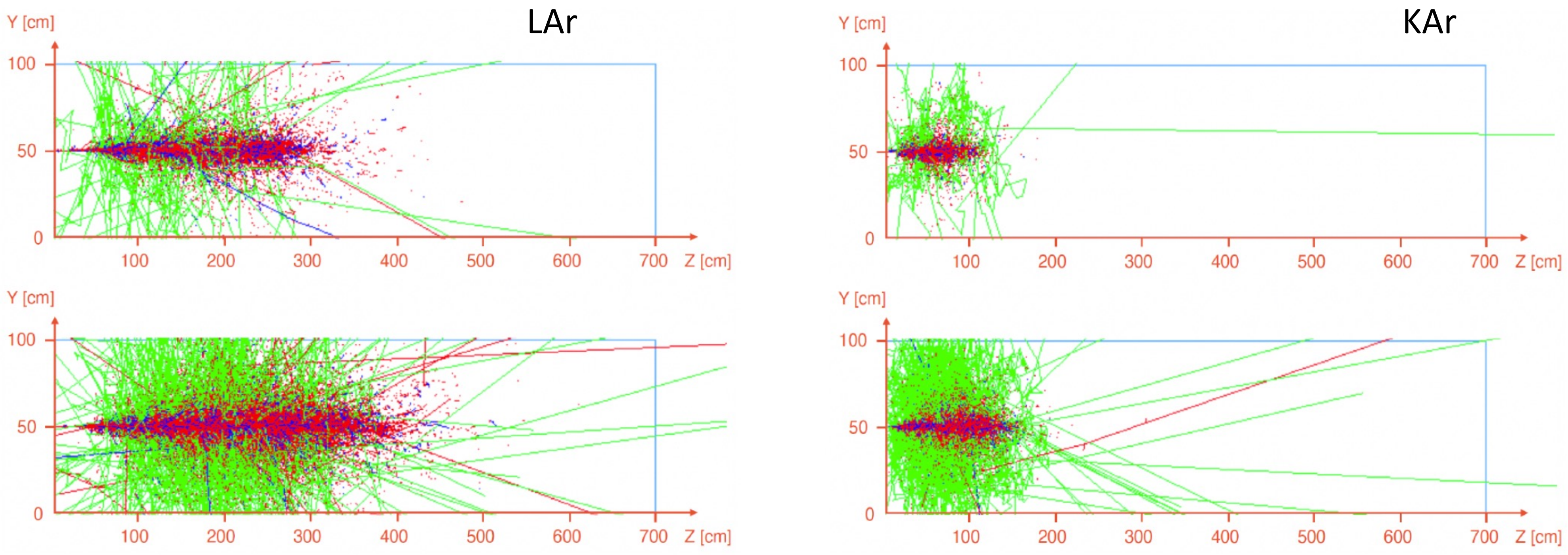
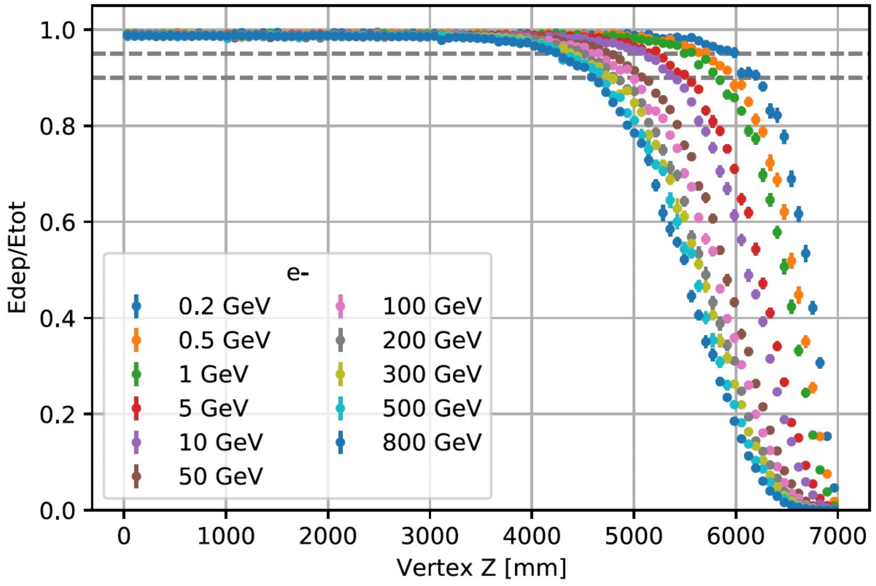
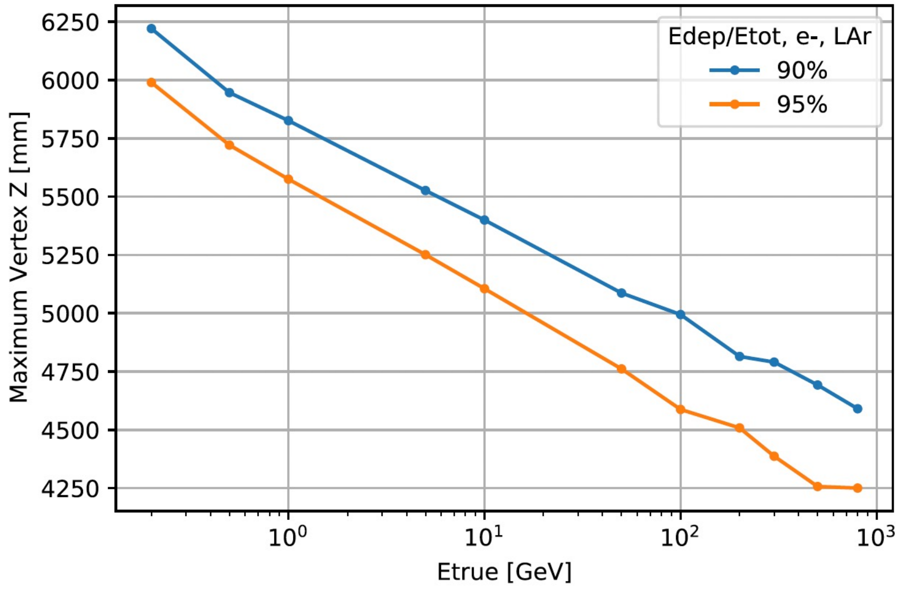



FIG. 5. GEANT4 simulations of electromagnetic showers in LAr (left) and LKr (right) produced by 200 GeV (top) and 1 TeV (bottom) electrons. The showers start at $z = 0$, and all particles, except photons, are shown, with the color indicating the particle's charge: negative (red), neutral (green), and positive (blue). The shower depth in LKr is shorter due to it's smaller radiation length.

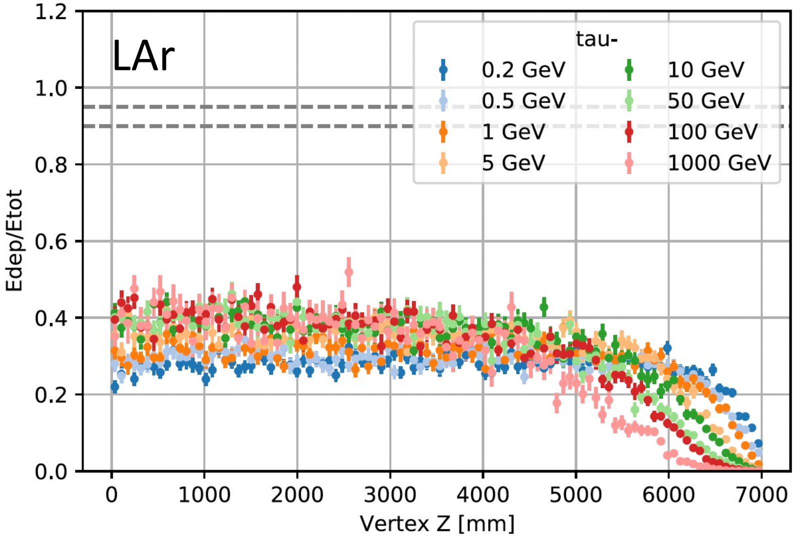
# Electron and tau containment

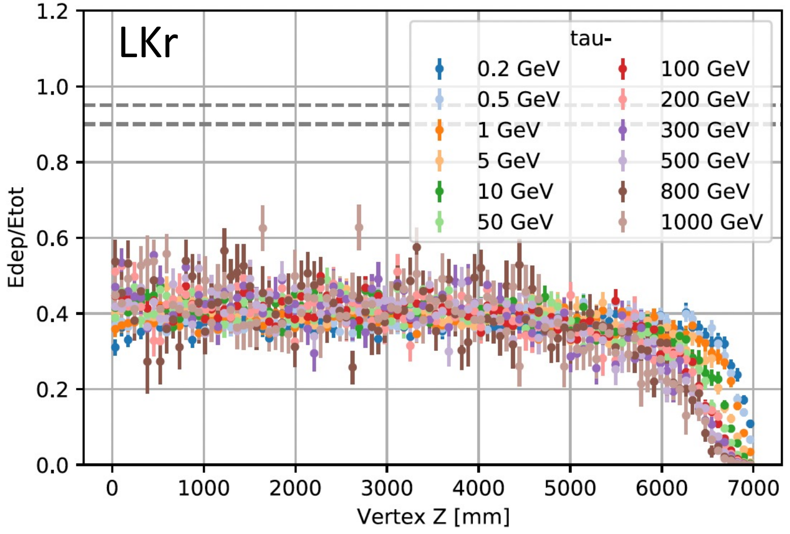



| Decay mode | Branching ratio |
|---|---|
| Leptonic | 35.2% |
| $e^-\bar{\nu}_e\nu_\tau$ | 17.8% |
| $\mu^-\bar{\nu}_\mu\nu_\tau$ | 17.4% |
| Hadronic | 64.8% |
| $\pi^-\pi^0\nu_\tau$ | 25.5% |
| $\pi^-\nu_\tau$ | 10.8% |
| $\pi^-\pi^0\pi^0\nu_\tau$ | 9.3% |
| $\pi^-\pi^-\pi^+\nu_\tau$ | 9.0% |
| $\pi^-\pi^-\pi^+\pi^0\nu_\tau$ | 4.5% |
| other | 5.7% |

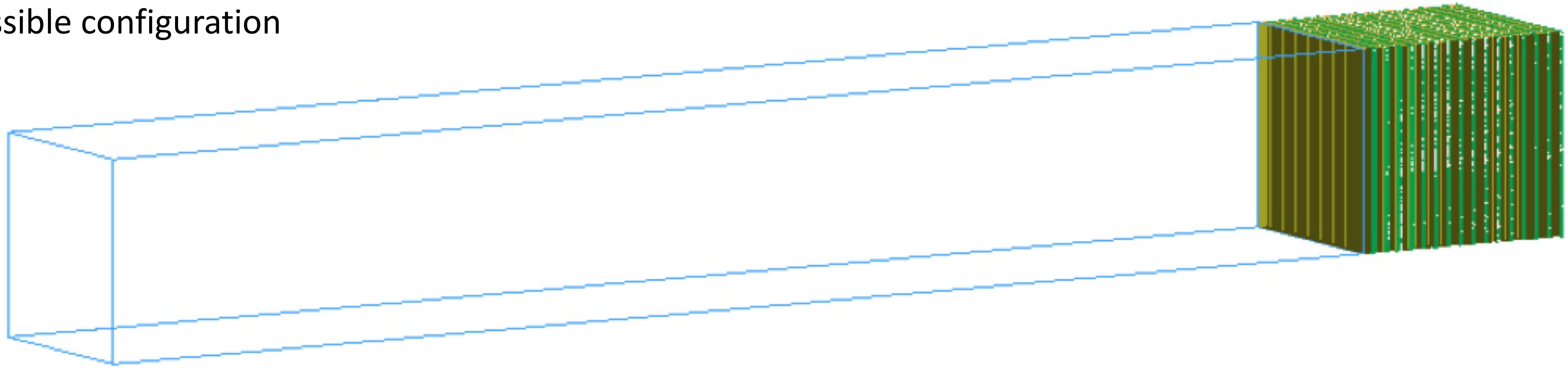
*https://arxiv.org/pdf/2007.00015.pdf*



# Downstream Hadronic Calorimeter to Improve Containment

Possible configuration



Downstream Hadronic Calorimeter:

- 1.0x1.0 meters
- ~100-160 cm of Fe/scintillator panels, 6-10 interaction lengths
- 5 cm Fe, 1-cm scintillator with X view, and 1-cm with Y view
- Resolution for hadronic showers: 20-40%/Sqrt(E)
- The materials of the cryostat at the down stream will need to be kept <0.1 interaction length
- Muon ranger not included, can add if needed

*These are very preliminary parameters.*

# Light Dark Matter Search in FLArE

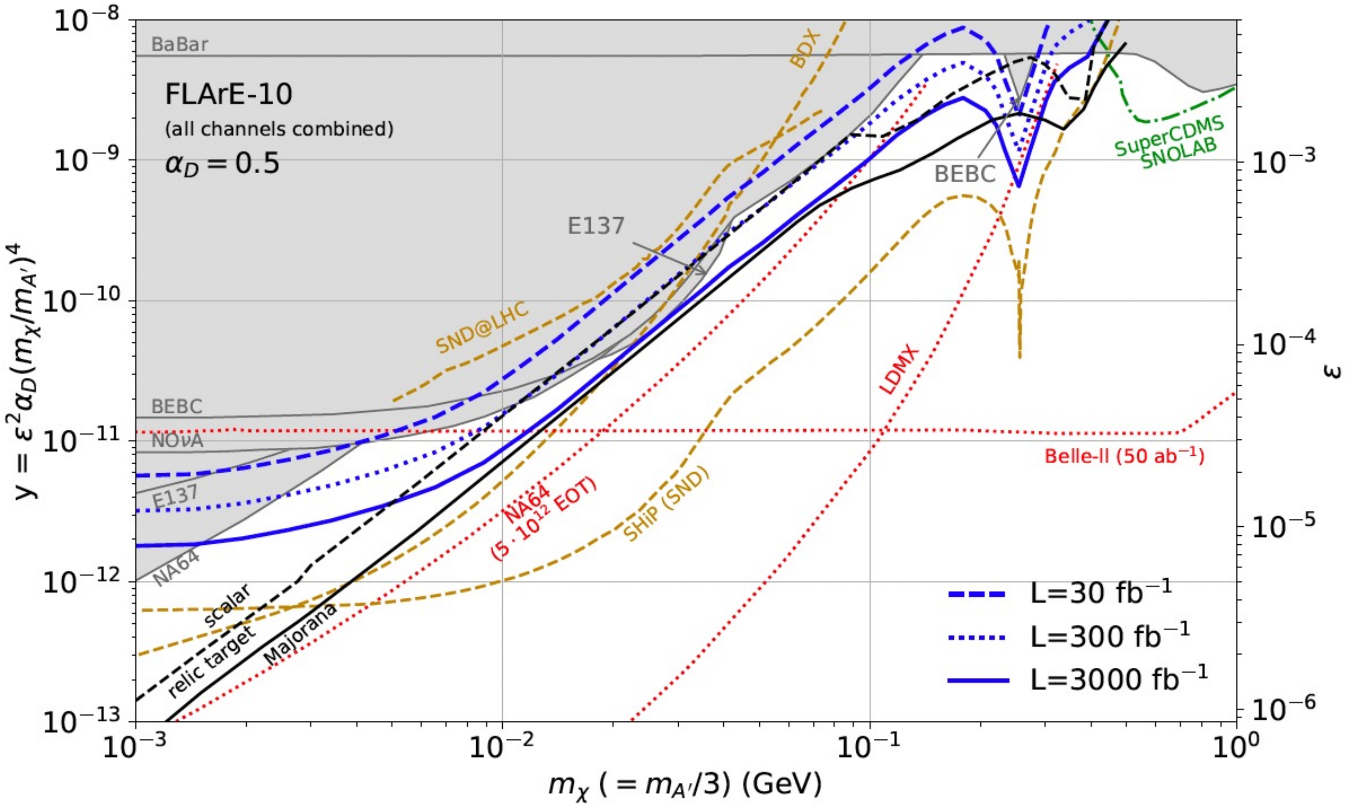
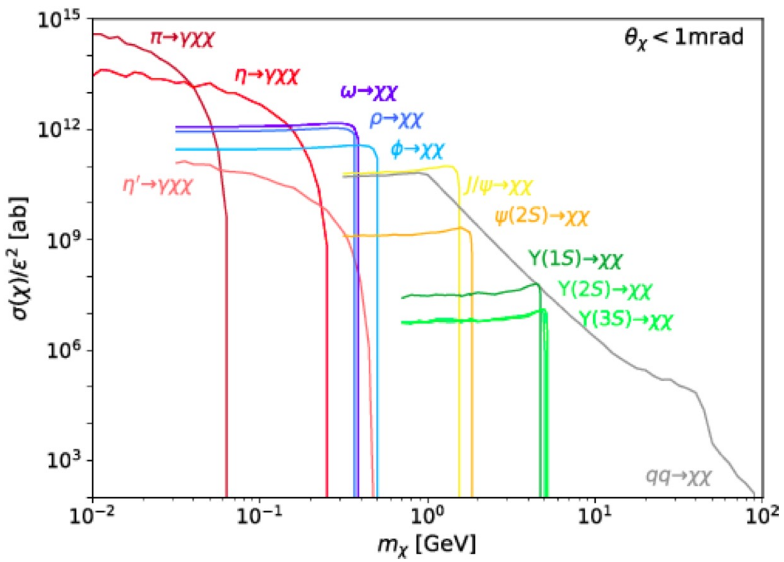



FIG. 3. FLArE's projected sensitivities for light DM detection. FLArE can discover dark matter in the parameter space above the blue contours for the integrated luminosities indicated. The gray shaded region is currently excluded, the regions above the black "relic target" contours are cosmologically preferred, and the other colored contours are projections for other experiments.

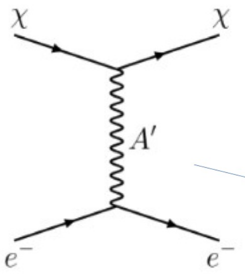
# FLArE search for millicharged particles etc.

Sebastian Trojanowski, AstroCeNT, Nicolaus Copernicus Astronomical Center Polish Academy of Sciences, Dec 9, 2021

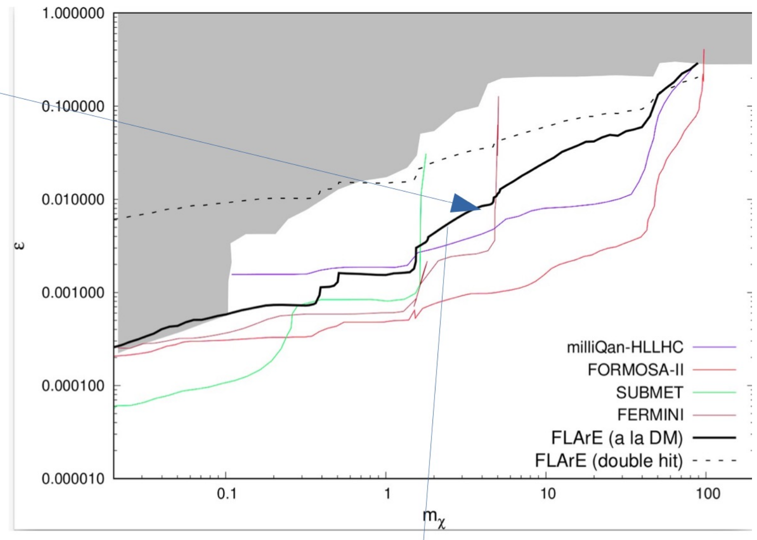
## FLArE search strategy: a la DM scattering



S. Foroughi-Abari, F. Kling, Y.-D. Tsai, FORMOSA, 2010.07941



30 MeV < $E_e$ < (3 GeV)




ν-induced BG is suppressed
we assume μ-induced BG is rejected

# Summary

- Preliminary design for the noble liquid detector for FPF (FLArE)
- Detector capability and event rate preliminarily studied
- Progress in LAr/KAr choices, photon detection, detector simulation and physics reach studies
- Include a hadronic calorimeter to improve detector containment
- The detector geometry will need to be further optimized
- Also working on: overall integrated approach, triggering , and background suppression study