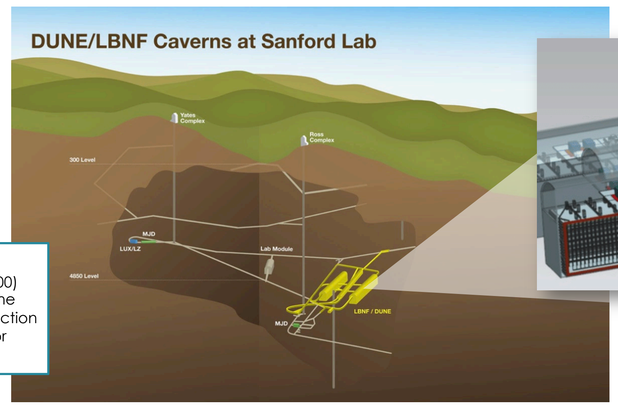
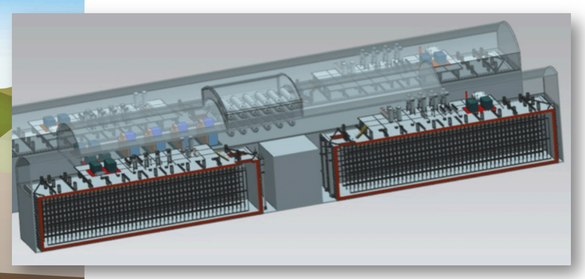
Deep Neural Networks for Rare Event Searches in DUNE

Georgia Karagiorgi[1], *for the DUNE Collaboration*
[1]Columbia University

The **Deep Underground Neutrino Experiment (DUNE)** offers a large, fully active **liquid argon time projection chamber** (LArTPC) as its far detector, extremely well shielded from cosmic radiation due to its **underground** placement, and sensitive to **physics signals down to a few MeV**.

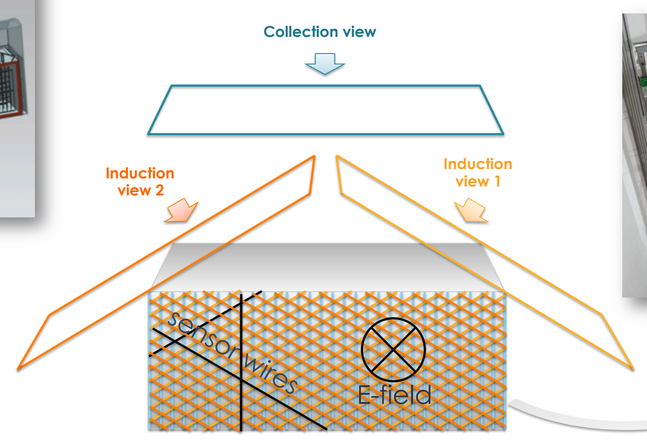


At 4850 ft level, O(1000) muons per day are the dominant type of interaction in DUNE far detector

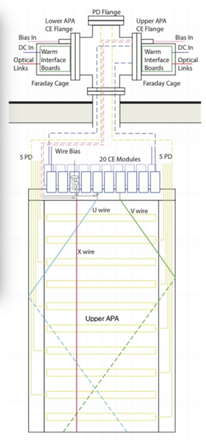


The far detector consists of four LArTPC modules, each 10 kton in fiducial mass, and of either "single phase"(liquid) or "dual phase" (liquid and gas) design.

"Single-phase" design: The detector is segmented in units of Anode Plane Assemblies, or APAs. Each one reads out **drifted ionization charge** from a volume of liquid argon on either side of a sensor wire array. Data is recorded in the form of high-resolution 2D-projected views of charged particle trajectories in the liquid argon, streamed continually at a rate of a few TB/s.

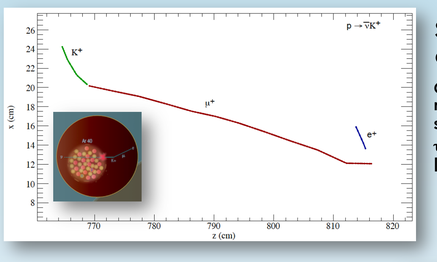


APA wire frame



This positions the experiment very well for **off-beam, rare event searches**:

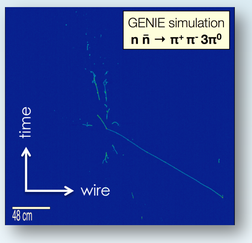
baryon number violation



Simulated p→K⁺ν event in a LArTPC

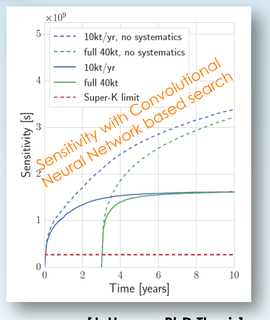
Golden proton decay mode: Assuming >90% signal efficiency, $\tau/BR > 3.8 \times 10^{34}$ years [DUNE CDR]

Simulated neutron-antineutron oscillation event in a LArTPC: "star event" topology



Baryon-number violating ($\Delta\mathcal{B}$=2) process.

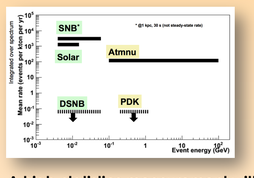
Nucleus-bound neutron oscillation, followed by annihilation with neighboring nucleon (p or n) inside the parent nucleus.



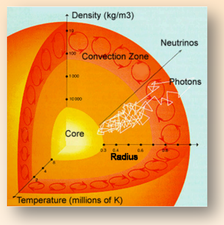
[J. Hewes, PhD Thesis]

solar neutrinos

DUNE might be able to observe >10,000 solar neutrinos (hep and ^{8}B) per year (few-15 MeV), per 10 kton module



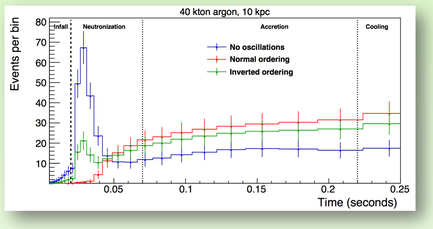
A high-statistics measurement with sufficient energy and angular resolution allows a sensitive measurement of the "Day-Night Asymmetry," probing both solar and terrestrial matter effects.



galactic supernova core-collapse

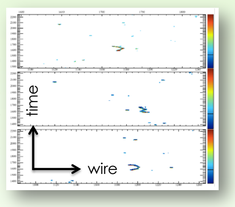
In the event of a galactic supernova (SN) burst, DUNE expects to observe up to thousands of SN neutrino interactions in the DUNE far detector (few-50 MeV).

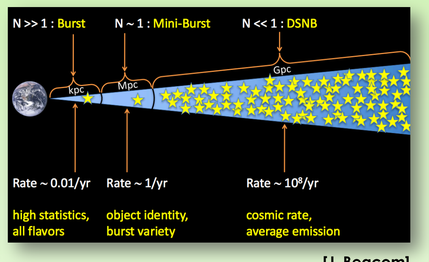
Also expected: ~few supernova relic neutrino interactions per year (few-50 MeV)



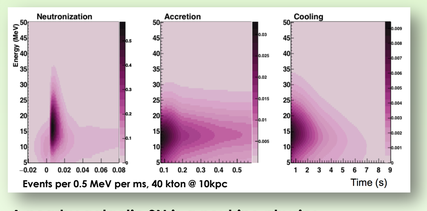
Early time structure of SN neutrino flux (presence or absence of neutronization burst) highly sensitive to mass hierarchy.

A supernova neutrino interaction in DUNE is a localized (~few cm^2) e$^-$ accompanied by de-excitation photons from a $\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$ interaction





[J. Beacom]

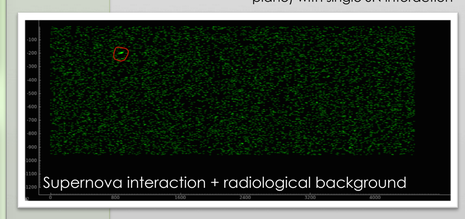


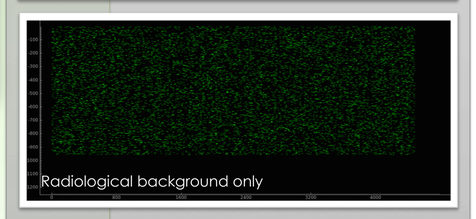
A nearby galactic SN is a neutrino physics laboratory. Measurements of the time, flavor, and energy structure of the neutrino flux provide information on neutrino physics as well as astrophysical dynamics.

(Pile-up from) radiological backgrounds (RAD) in the detector pose a challenge

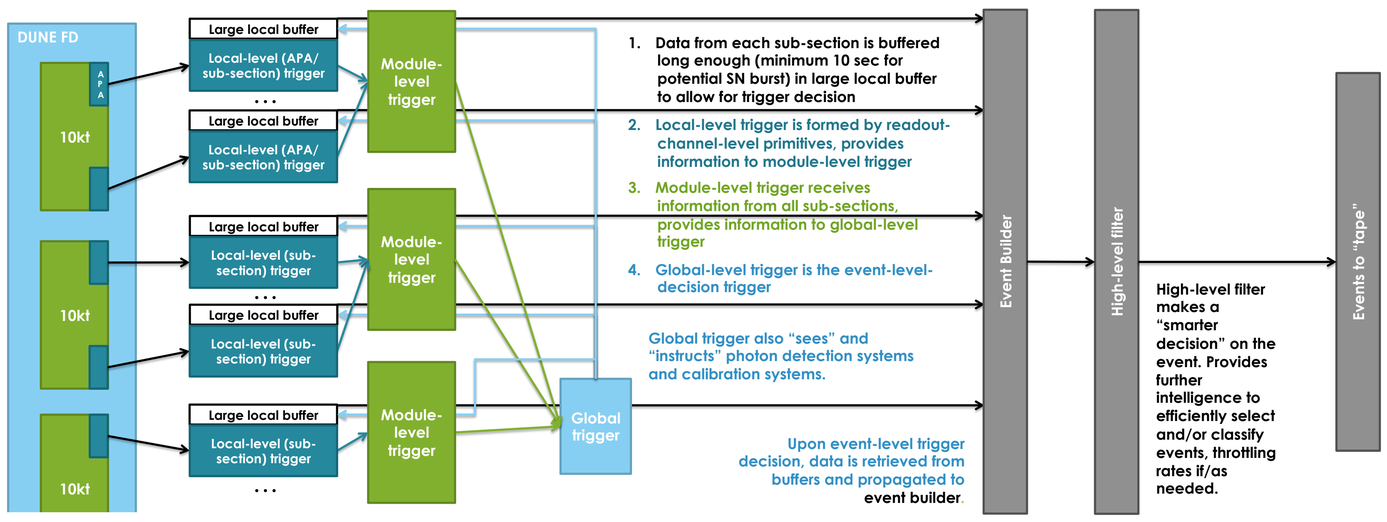
(Ar39, Ar42, Kr85, Rn222, Po210, ...)

Single-APA image (collection plane) with single SN interaction





DUNE far detector DAQ architecture



The DUNE far detector "single-phase" TPC data acquisition system (DAQ) must be **highly efficient at detecting rare physics-related activity above radiological backgrounds and detector noise**, and capable of processing the data in real time with zero dead-time.

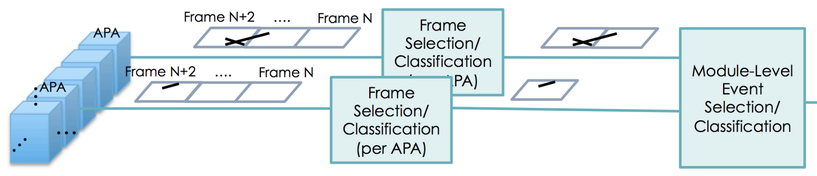
An effective 10^4 data reduction factor is needed to cope with back-end requirements (<30 PB/year to permanent storage)

Data Source	Occurrence Frequency in 10 kton Module	Data Volume Per Year
Beam interactions*	~0.0002 Hz	30 TB
Cosmics and atmospherics*	~0.05 Hz	10 PB
Radiologicals**	1/month	< 1 PB
Front-end calibration	4 runs/year; 100 measurements per ADC point	200 TB
Radioactive source calibrations	<10 Hz, single APA	100 TB
Laser calibrations	10^6 laser pulses per year, with lossy data reduction	200 TB
Random triggers	45/day	60 TB
Local-level "trigger primitives"	6B per "trigger primitive" set, Ar39 dominated	6 PB

*10 MeV threshold and beam timing applied
**Assumed to be dominant contribution to supernova readout (1/month fake rate), 30 second readout

Employing **Deep Neural Networks** for real-time image analysis of data for triggering or event filtering purposes:

Raw data from DUNE TPC are conveniently packaged in image format, and ideally suited for image classification applications. Inference times can be long, up to ~ms. Qualitatively:



"Frame-by-frame" identification of "interesting activity", either at APA/Local level, or at Module level (in the form of high-level trigger).

Preliminary studies on "frame-by-frame" classification rates: ***How well? And how fast?***

Classification sample

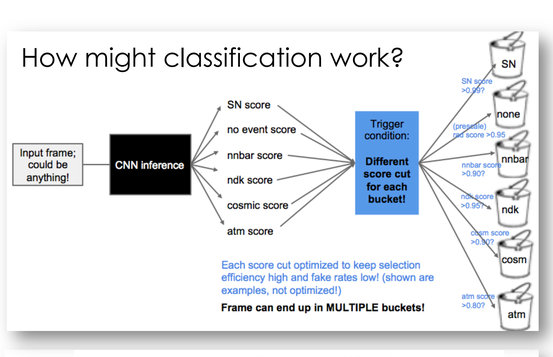
Generated sample

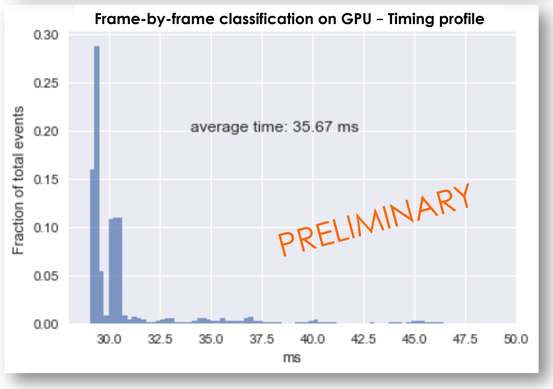
	SN class (%) score>0.98	RAD class (%) score>0.53	nnbar class (%) score>0.91	atmo. ν class (%) score>0.67	NDK class (%) score>0.38	Cosmic class (%) score>0.82
SN	53.13	5.66	0.0	0.25	0.20	0.12
RAD	0.0	90.29	0.0	0.0	0.0	0.0
nnbar	0.0	0.0	90.33	0.48	2.12	0.08
atmo. ν	1.71	5.19	8.63	21.81	30.42	2.29
NDK	0.13	0.63	0.35	1.96	90.17	0.33
Cosmic	0.15	6.71	0.38	1.84	5.10	69.66

PRELIMINARY

Classification rate = 100% $\dfrac{\text{number of images with classification score > cut}}{\text{total number of images of truly that particular class}}$

Cuts chosen for minimizing fake rate from empty frames (RAD)





- GPU specs: NVIDIA GeForce TITAN X 12GB
- vgg16 convolutional neural network trained on ~50-60k events per sample
- **Average inference time per image: 35.7 ms**
- **Target time: ~few ms**
- Can potentially accelerate through smaller network/smaller images