Novel Light Detection Technology for Liquid Argon Neutrino Detectors

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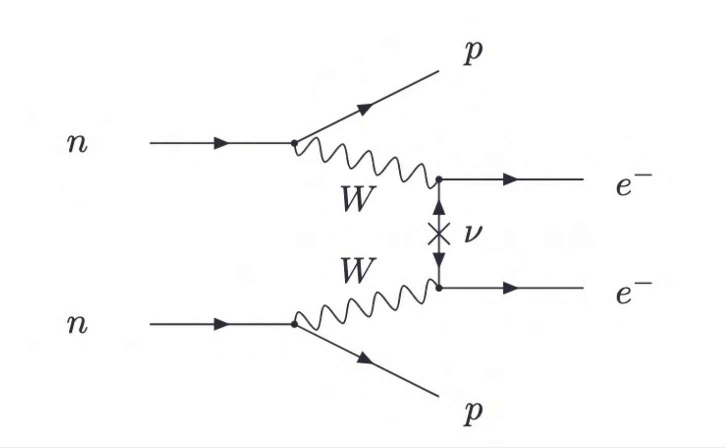
Neutrino Physics Frontiers

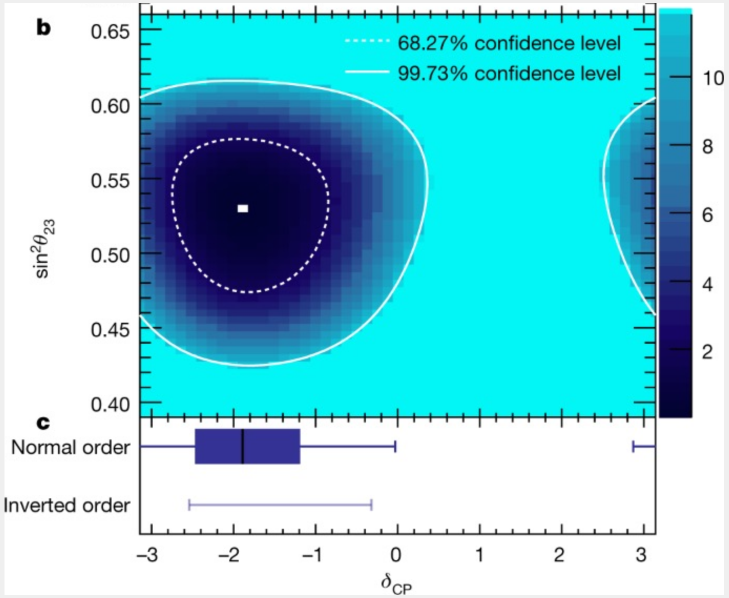
Neutrino Mass

- Mass Generation: Dirac or Majorana? ($0\nu\beta\beta$)
- Effective mass (β decay)



CP Violation in Leptonic Sector

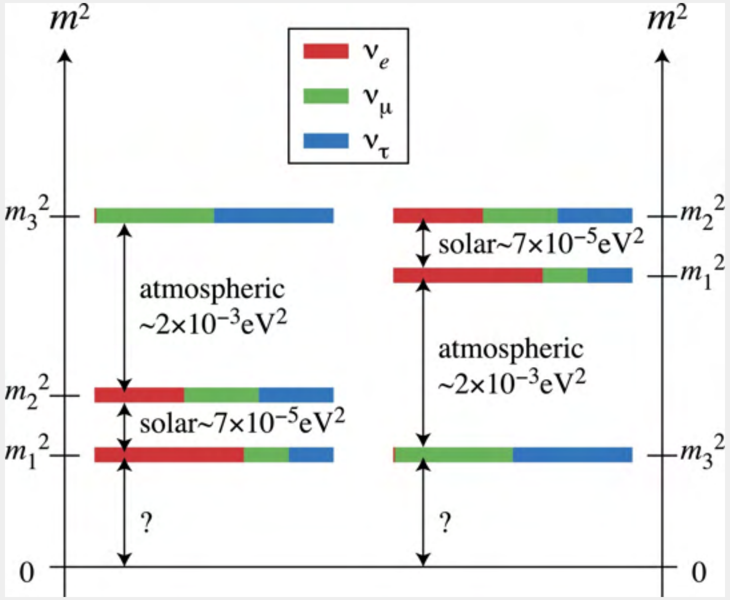
- Probably explain Baryon asymmetry?
- T2K: $\delta_{CP} \notin [165^{\circ},-2^{\circ}]$ @ 3σ



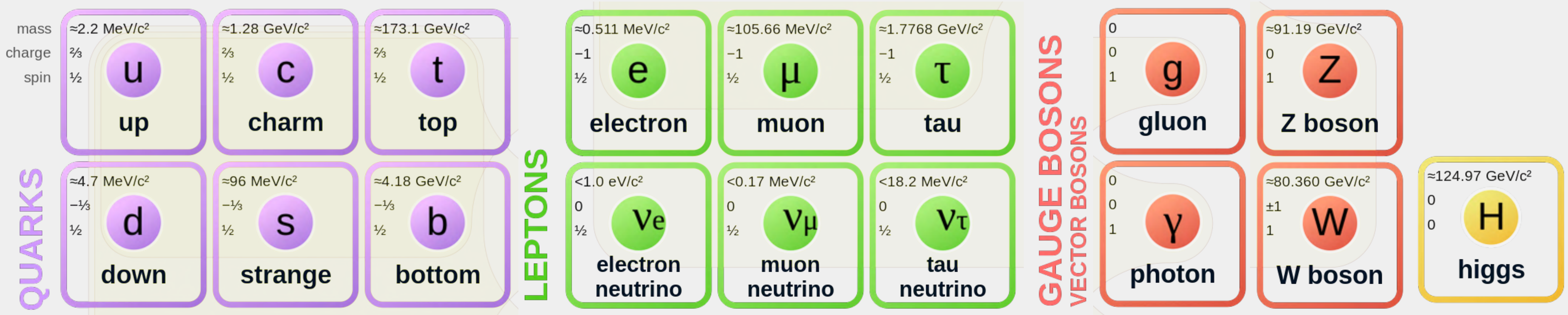
arXiv: 1910.03887

Mass Hirarchy / Ordering

- Only Δm^2 “known”
- MSW: longer baseline → higher sensitivity



Neutrino oscillation



PMNS Matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1&0&0\\ 0&c_{23}&s_{23}\\ 0&-s_{23}&c_{23}\end{pmatrix}}_{atmospheric}\underbrace{\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta_{\mathrm{CP}}}\\ 0&1&0\\ -s_{13}e^{i\delta_{\mathrm{CP}}}&0&c_{13}\end{pmatrix}}_{reactor}\underbrace{\begin{pmatrix}c_{12}&s_{12}&0\\ -s_{12}&c_{12}&0\\ 0&0&1\end{pmatrix}}_{solar}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

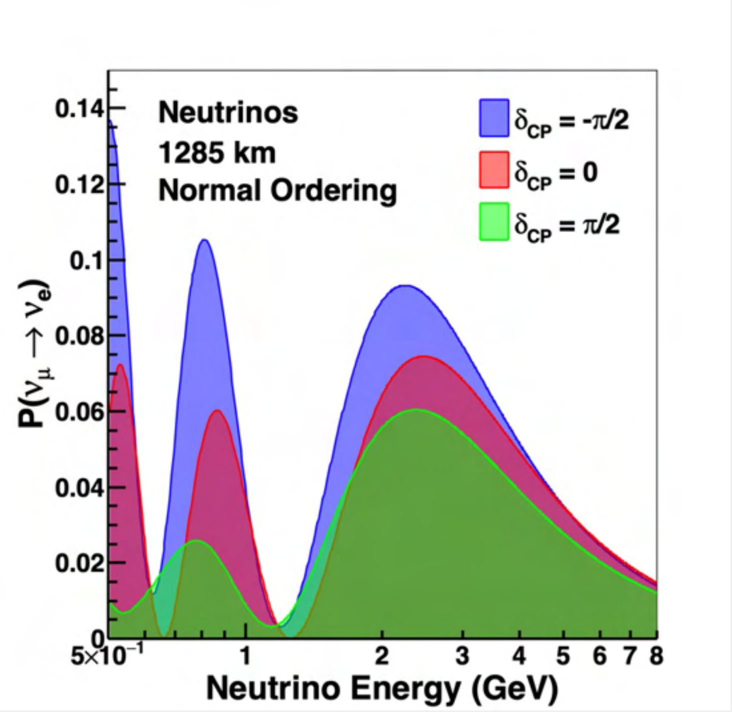
$$s_{ij} \equiv \sin\theta_{ij}$$
$$c_{ij} \equiv \cos\theta_{ij}$$

↓

Two flavor oscillation example

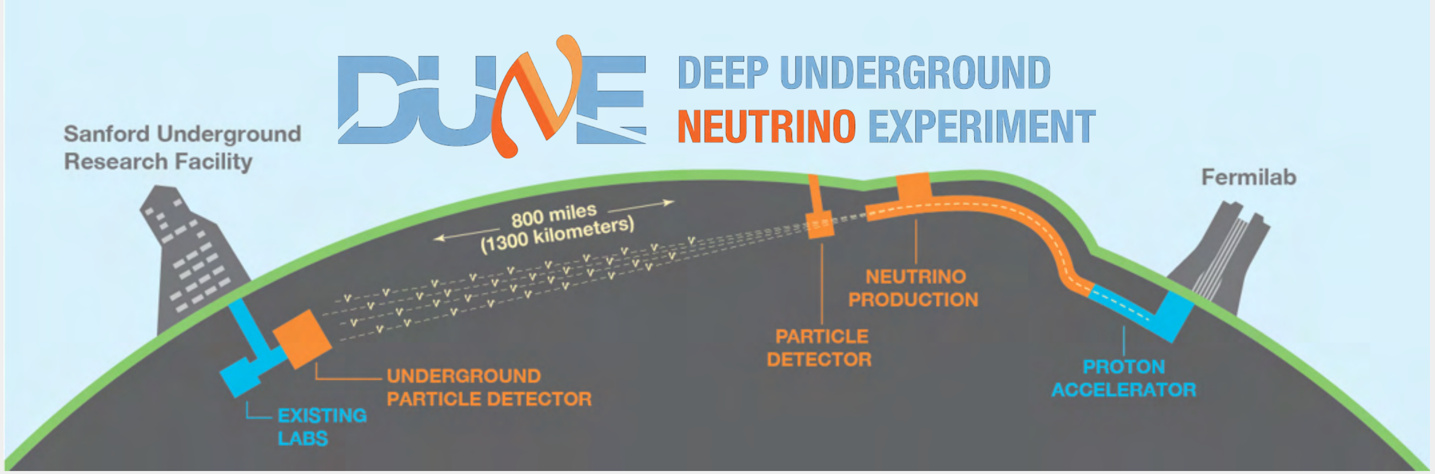
$$P(\nu_\mu \to \nu_e; L; E) = sin^2 2\theta_{12} sin^2\left[1.27\ \Delta m^2_{12}(\mathrm{eV}^2)\frac{L(\mathrm{Km}))}{E(\mathrm{GeV})}\right]$$

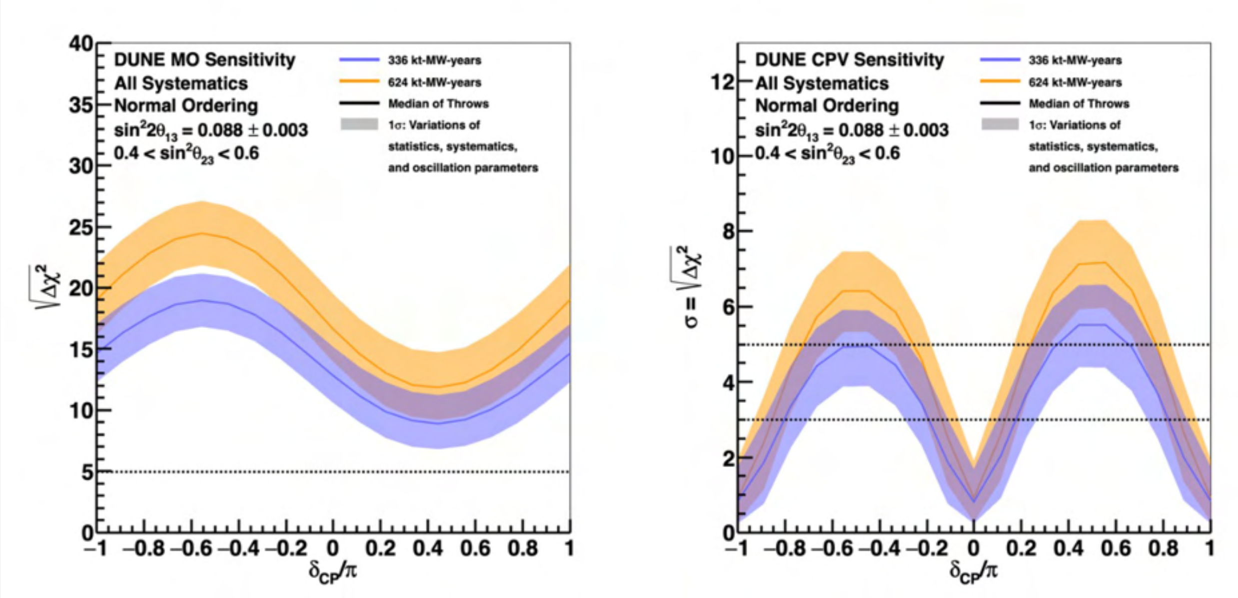
→



Deep Underground Neutrino Experiment (DUNE)

- Long baseline oscillation experiment (1300 km)
- Main goals:
  - δ_{CP}
  - Mass ordering
  - Non-beam physics (e.g. supernova ν)
- How to increase statistics?
  - High intensity ν_μ ($\bar{\nu}_\mu$) beam: 2.4 MW
  - High detector mass: 40kt FD, 67t ND

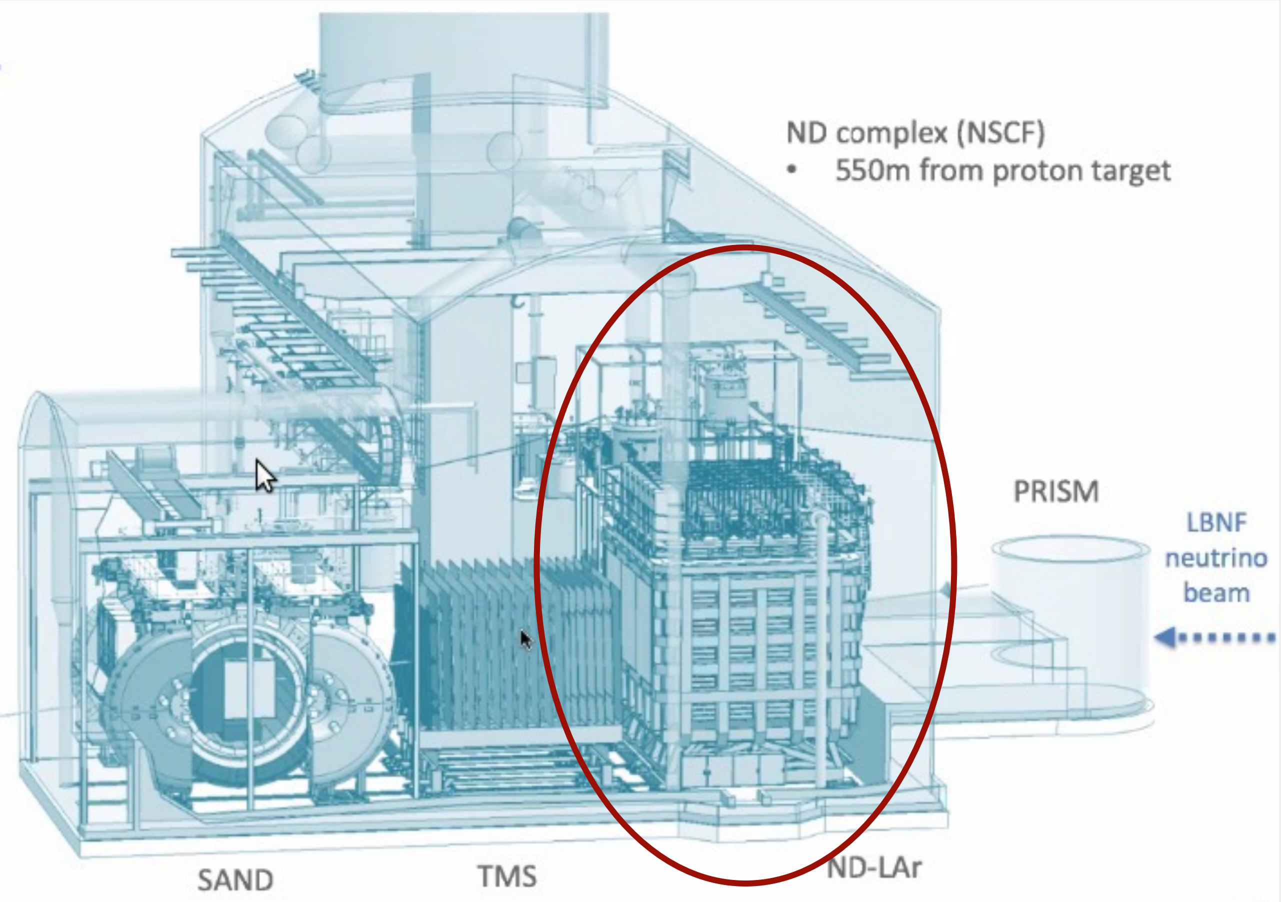




arXiv: 2203.06100

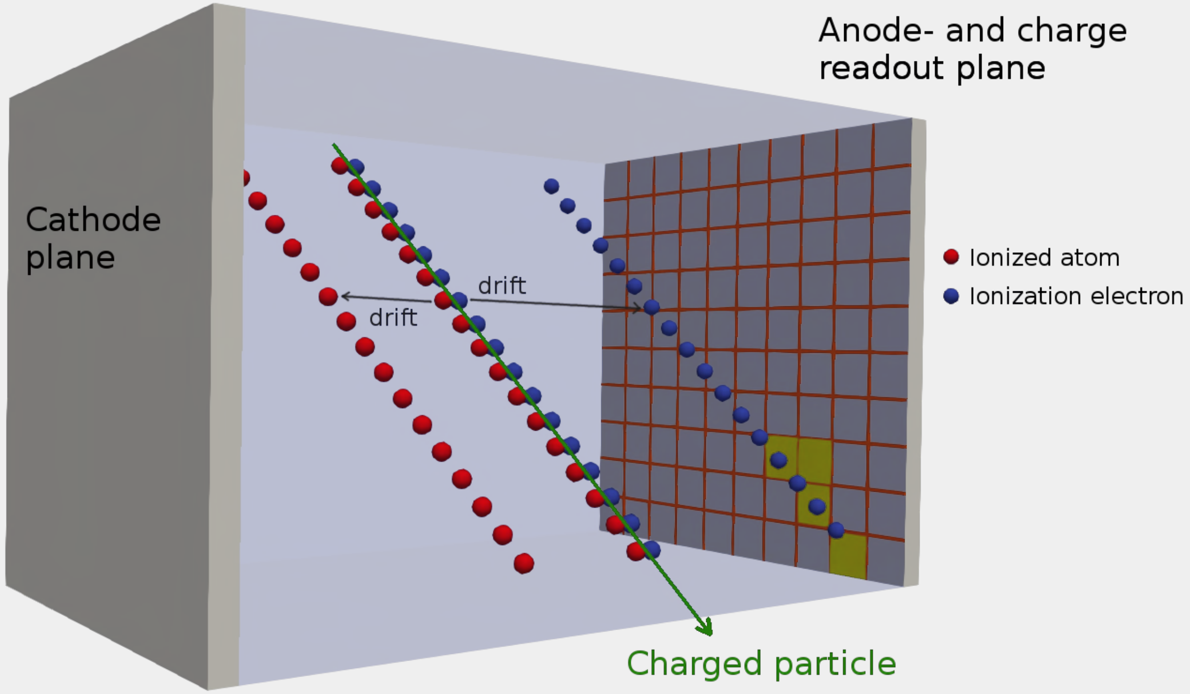
Near Detector Complex

- Precission measurements of neutrino flux and cross section needed for oscillation analysis
- Three detectors:
  - Liquid Argon TPC (ND-LAr)
  - Muon spectrometer (TMS / ND-GAr)
  - Flux monitoring system (SAND)
- ND-LAr: Constrain uncertainties by using same target as FD: Liquid Argon



Liquid Argon TPC

- Use liquid argon as target and detection medium
- Time Projection Chamber:
  - Charged particle pass: **ionisation + scintillation**
  - Drift e^- to **charge readout** plane by electric field
  - Measure drift time from interaction time (T0) using **light readout** to determine coordinate in drift direction
- Why Argon?
  - Ionisation: long e^- lifetime, (relatively) low energy per e^--ion pair
  - Scintillation: $\mathcal{O}$(1ns) fast light component, transparent at emission wavelength (128nm)
  - Affordable in large amounts



Scitillation Light

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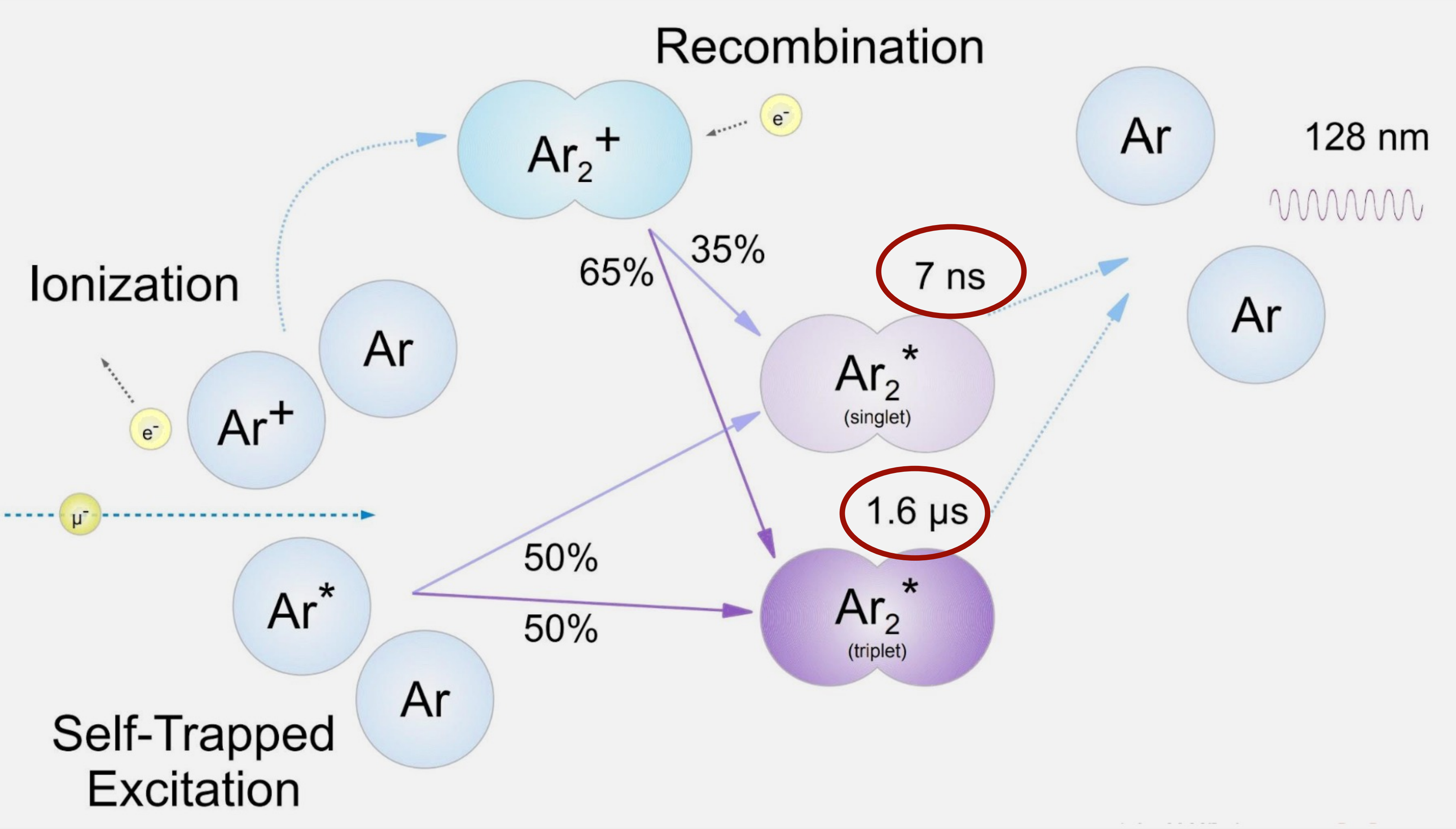

Common applications of light signal

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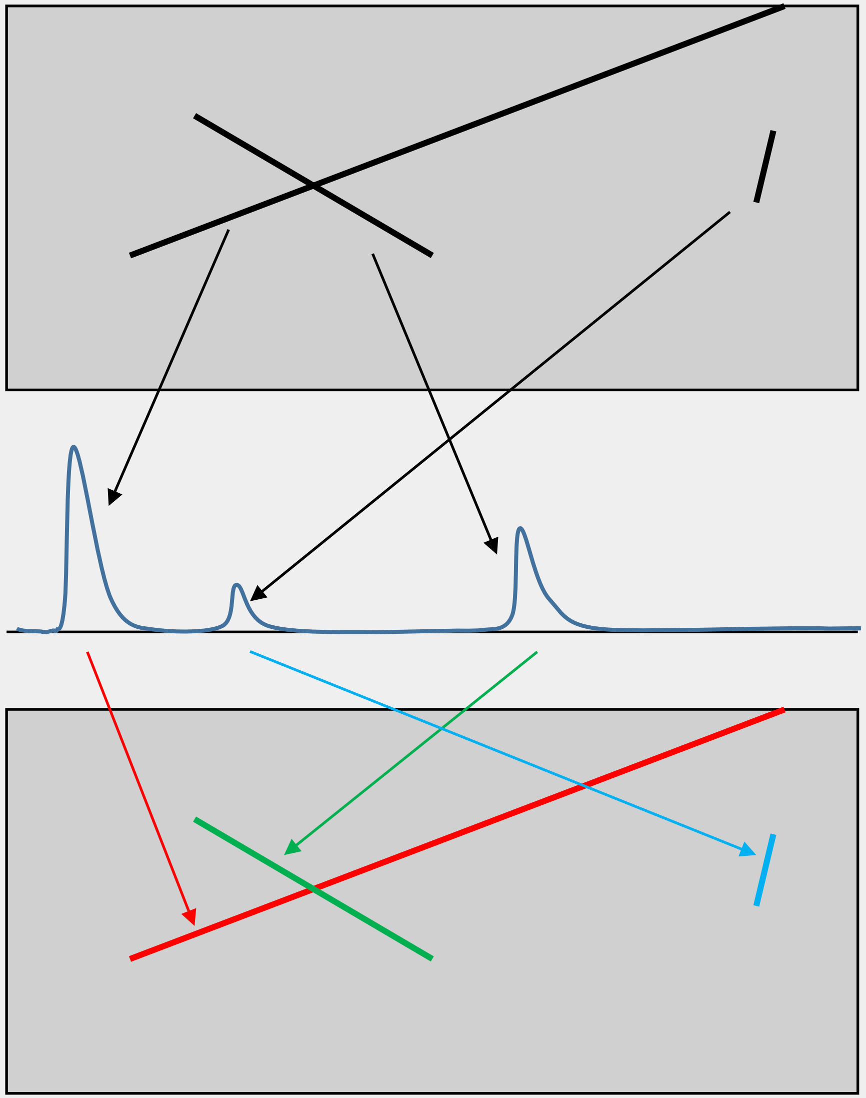
- **Set T0**:
  - Time marker to determine drift time of electrons
  - Achive 3D imaging
  - Can partially be replaced by beam trigger (Smeared by spill duration)
- **Trigger** charge readout:
  - Provide external trigger for charge readout
  - Reduce data rate by using light trigger in coincidence with beam trigger (e.g. in ICARUS, Micrboone)
- **Event buidling:**
  - Use light trigger to do offline event building for continous/self-triggering charge readout

Can we use the light data for more?
Yes! See next slides

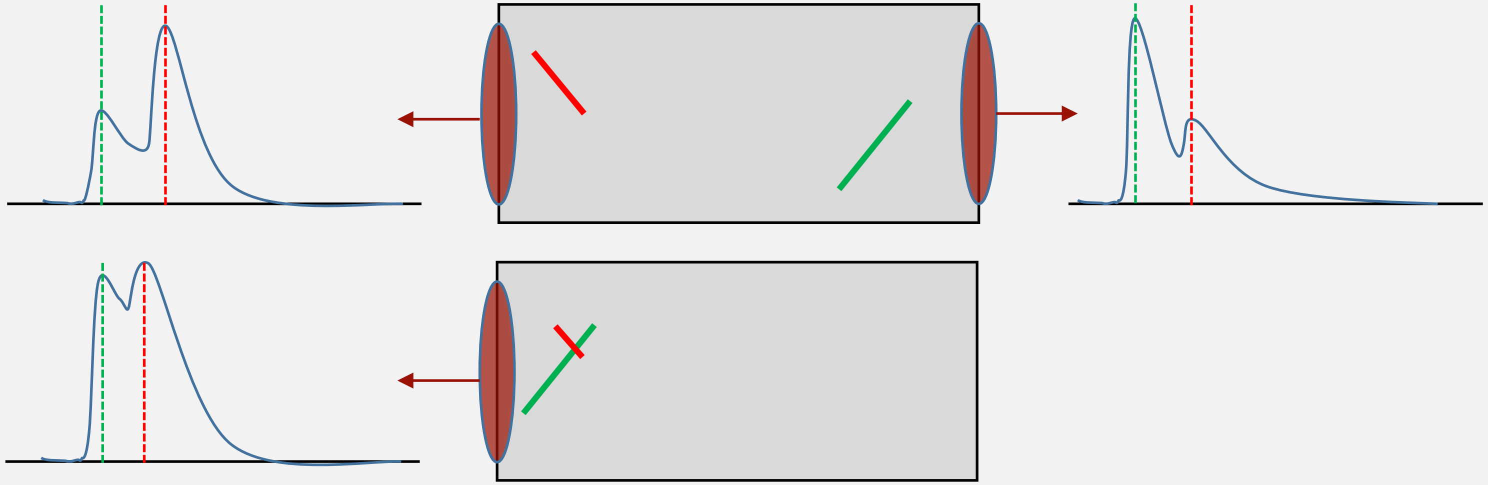
In-spill timing

- Charge readout limited by slow drift velocity ($\mathcal{O}$(0.1cm/µs) e.g. 310µs/50cm @0.5kV/cm),
- Common spill duration $\mathcal{O}$(10µs)
  - ⟹ All tracks from single spill overlaid:
- Fast component of scintillation light: $\mathcal{O}$(1ns)
  - ⟹ Resolve spill time structure
  - ⟹ Disentangle pile up events
  - ⟹ Tag deteached deposits?
  - ⟹ Time of flight measurements? (e.g. for neutron or kaon measurements)



In-spill timing

Required: Highly efficient charge-light matching



Spatial resolution

Time resolution

Limited by:

- Rayleigh scattering (L_R≈ 55 cm to 95 cm*)
- Deconvolution capability

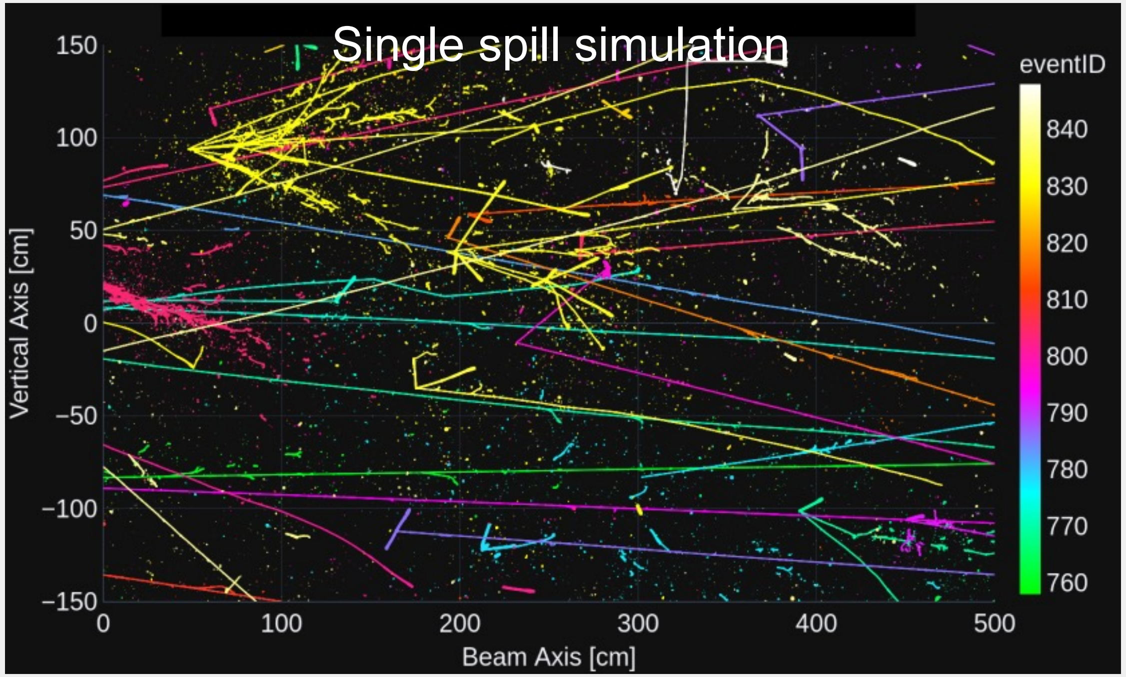
**The measured Rayleigh scattering length varies greatly between the values obtained in ProtoDUNE and measurements done in dark matter experiments.*

Unprecedented neutrino pile up

- DUNE ND-LAr: 7 x 5 x 3 m^3
- ~50 ν interactions per Spill (FHC)
- Drift time at 0.5 kV/cm: >4 ms for 7m
- For Monolithic Design:

(LIGHT) PILEUP

⇒ Optical Segmentation!

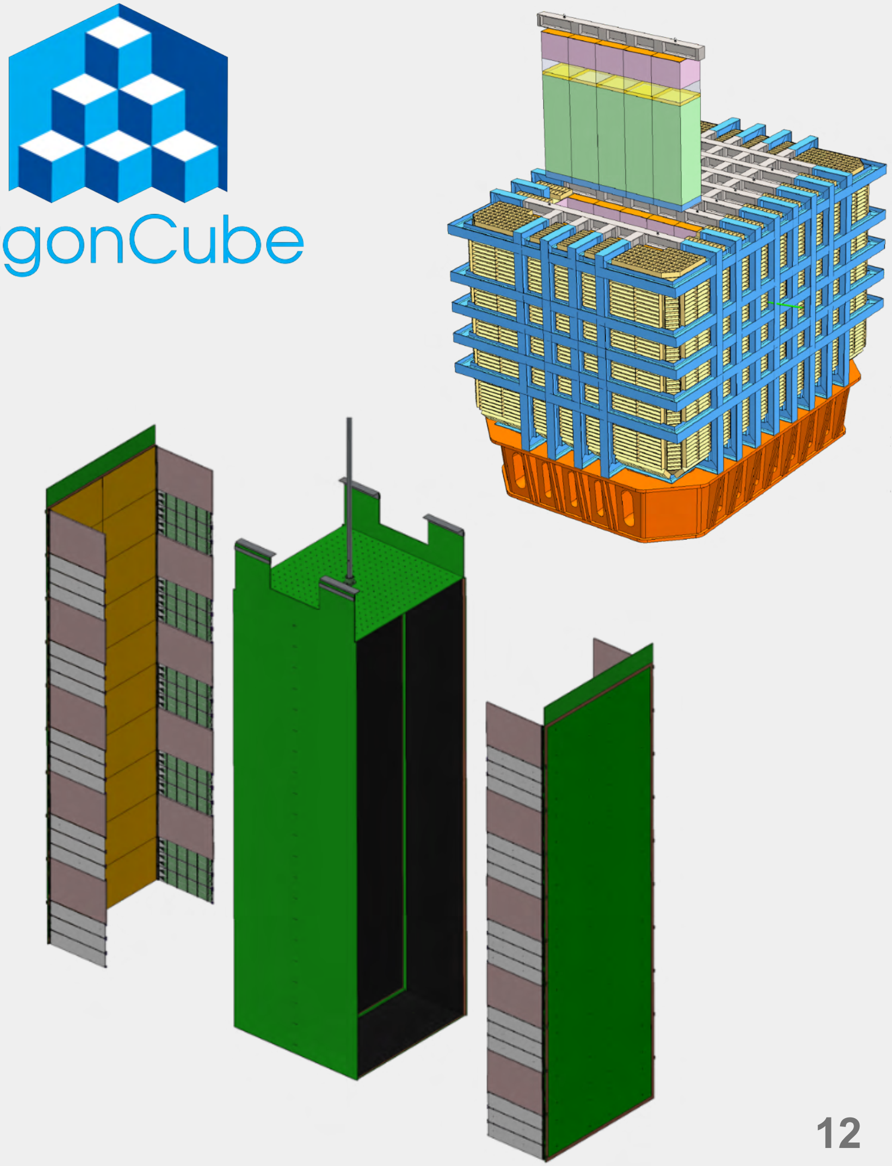


Simulation: P. Koller

ND-LAr: ArgonCube Concept

- ND-Lar: 5 x 7 modules (1m x 1m x 3m)
- One module : Two TPCs (70 TPCs!)
- **TPCs optically isolated**

ArgonCube



New Technologies

- **Resistive shell** homogeneous E-field shaping (SLAC)
- **Pixelated** charge readout with cold amplification and digitisation – LArPix (LBNL)
- **Large area - dielectric** VUV light detection – ArCLight (UniBe) + LCM (JINR)

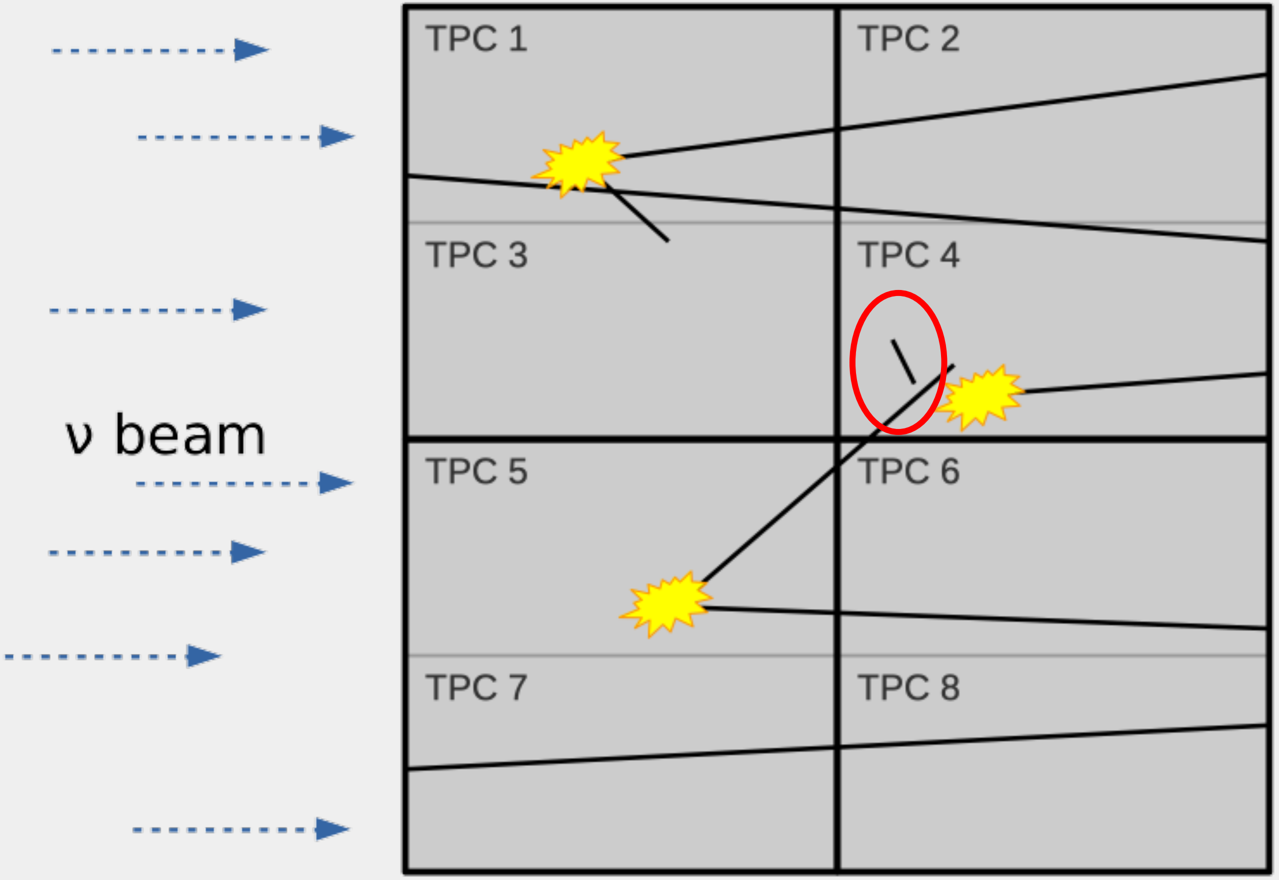
Light readout requirements:

- Large sensitive area
- Large dynamic range
- Fast readout
- Spatial resolution
- Minimal dead volume

Detached energy deposits

- Missing energy in neutrino energy reconstruction due to invisible neutral particles
- Detached recoils (Ar or p^+) or secondary particles

⇒ Need fast light information for matching original vertex



Example: 4 modules, 8 TPCs

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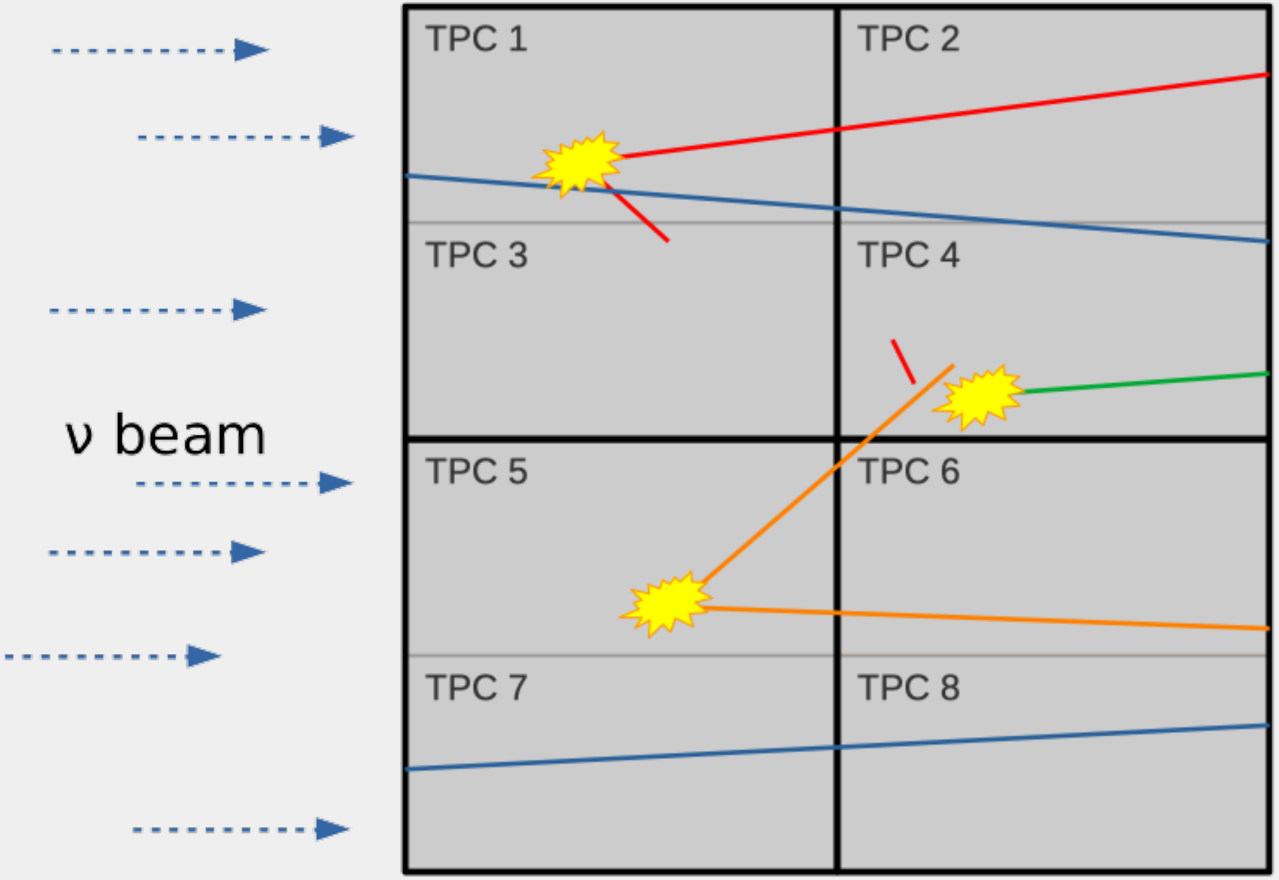
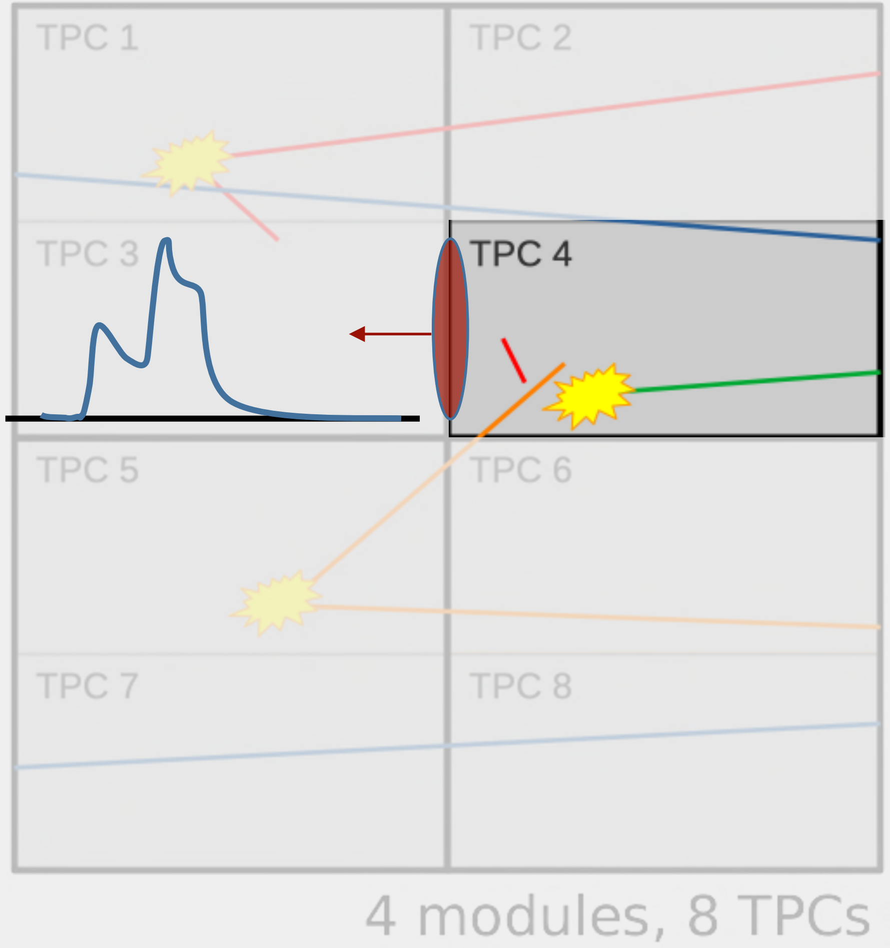


Example: 4 modules, 8 TPCs

Single TPC pile up

- In-spill change light matching reduced to single TPC
- Pile up issue still present but much simpler
- Depending on deconvolution capability
- Main challenges:
  - Similar energy deposits
  - Small energy deposits

⇒Improve spatial resolution

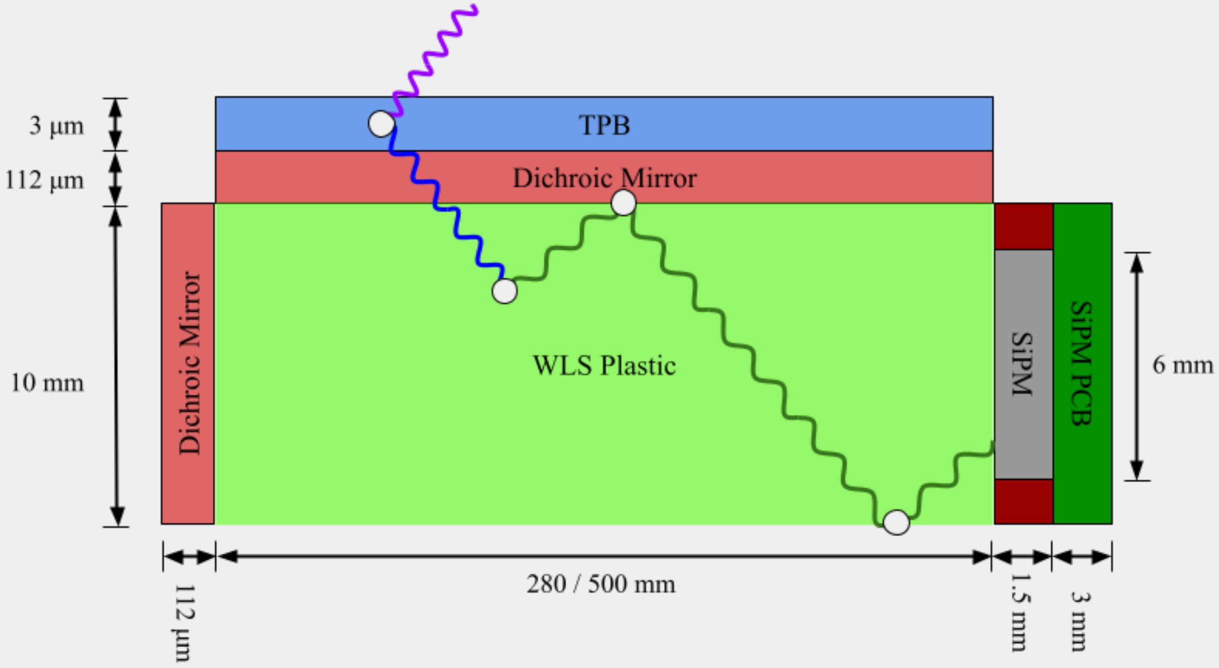


4 modules, 8 TPCs

ArCLight

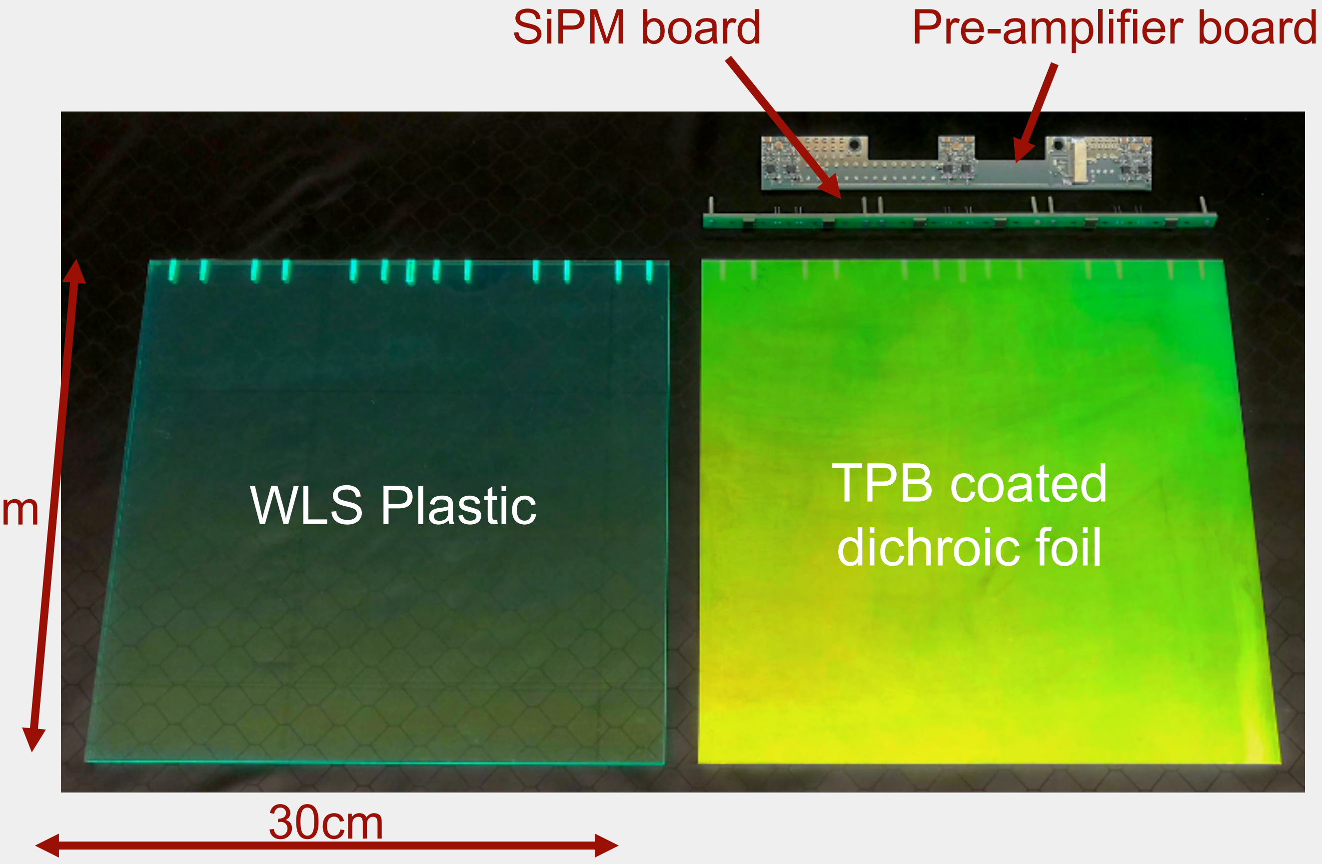
- **Ar**gon**C**ube **Light** detector
- Light trap principle similar to ARAPUCA
- Silicon Photo Multiplier (SiPM) readout
- 6 SiPMs per tile

1. Tetraphenyl butadien (**TPB**) wavelength shift (WLS):
   128nm → 430nm
2. Photon passes **dichroic mirror**
3. **WLS plastic** (EJ-280) wavelength shift:
   430nm → 490nm
4. Photon reflected by dichroic mirror or plastic-LAr interface (total internal reflection)
5. Photon hits **SiPM**



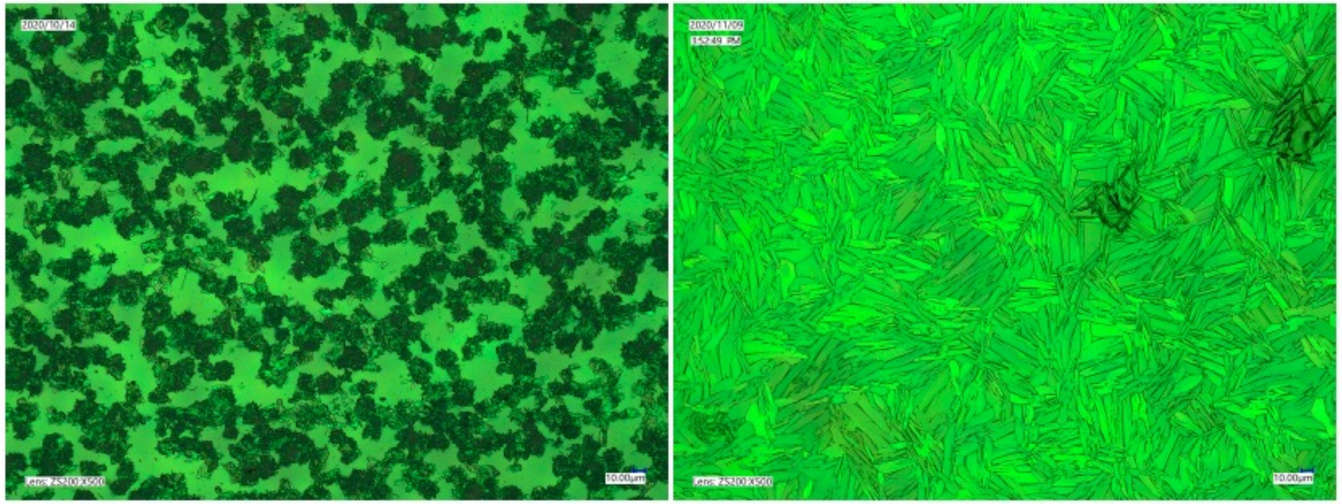
ArCLight Protoypes

- Extensive testing with 30 x 28 cm prototypes
- Finalising production setup for final 30x50cm
- Production steps:
  1. Prepare WLS plastic with mounting holes
  2. Coat dichroic mirror foil with TPB (see next slide)
  3. Laminate foil on WLS plastic
  4. Attach SiPM PCB (total 6 SiPMS)
  5. Mount pre-amplifier board

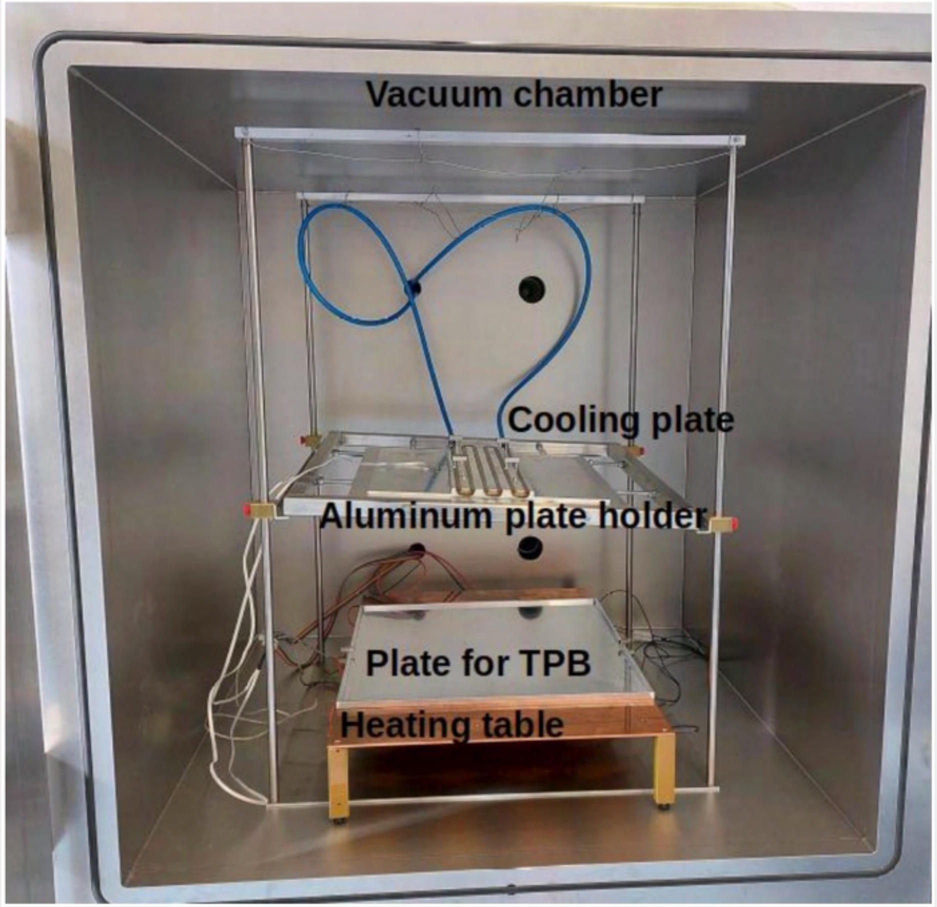


TPB coating

- First prototypes: Air brush coating
    - Non-uniform and small surface coverage
- Solution: Vacuum evaporation deposition
    - Reaching coverage >90% and high uniformity
    - Reproducable

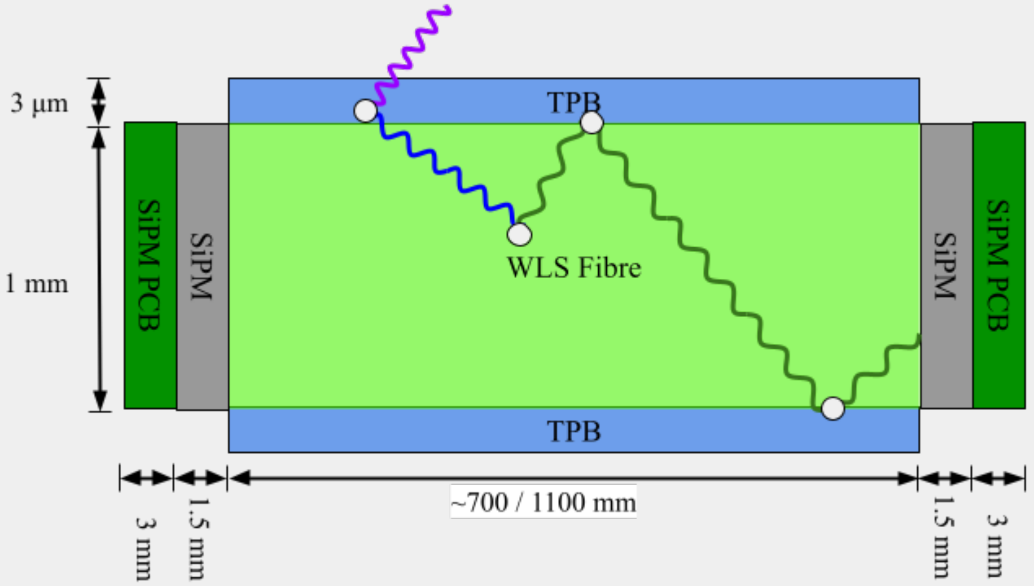


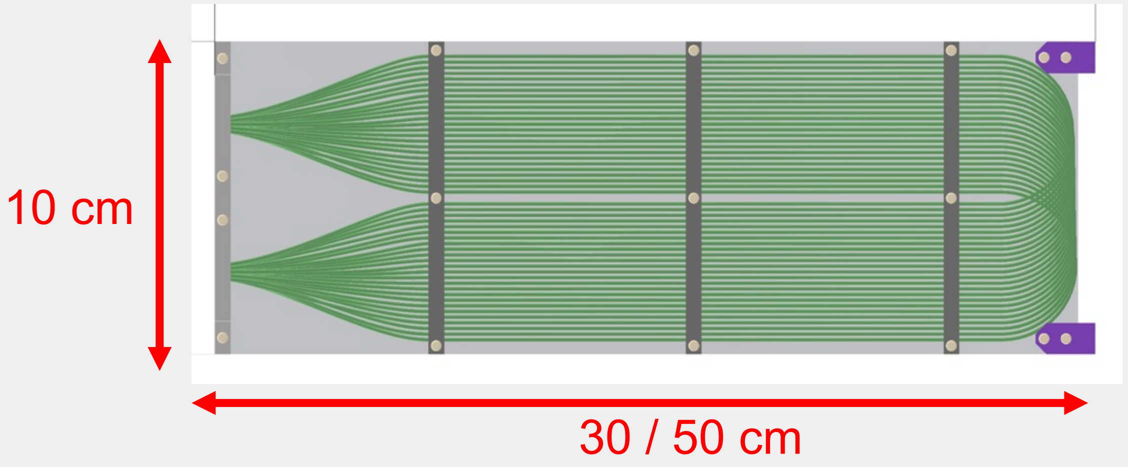
(a) Air brush (b) Evaporation deposition



LCM

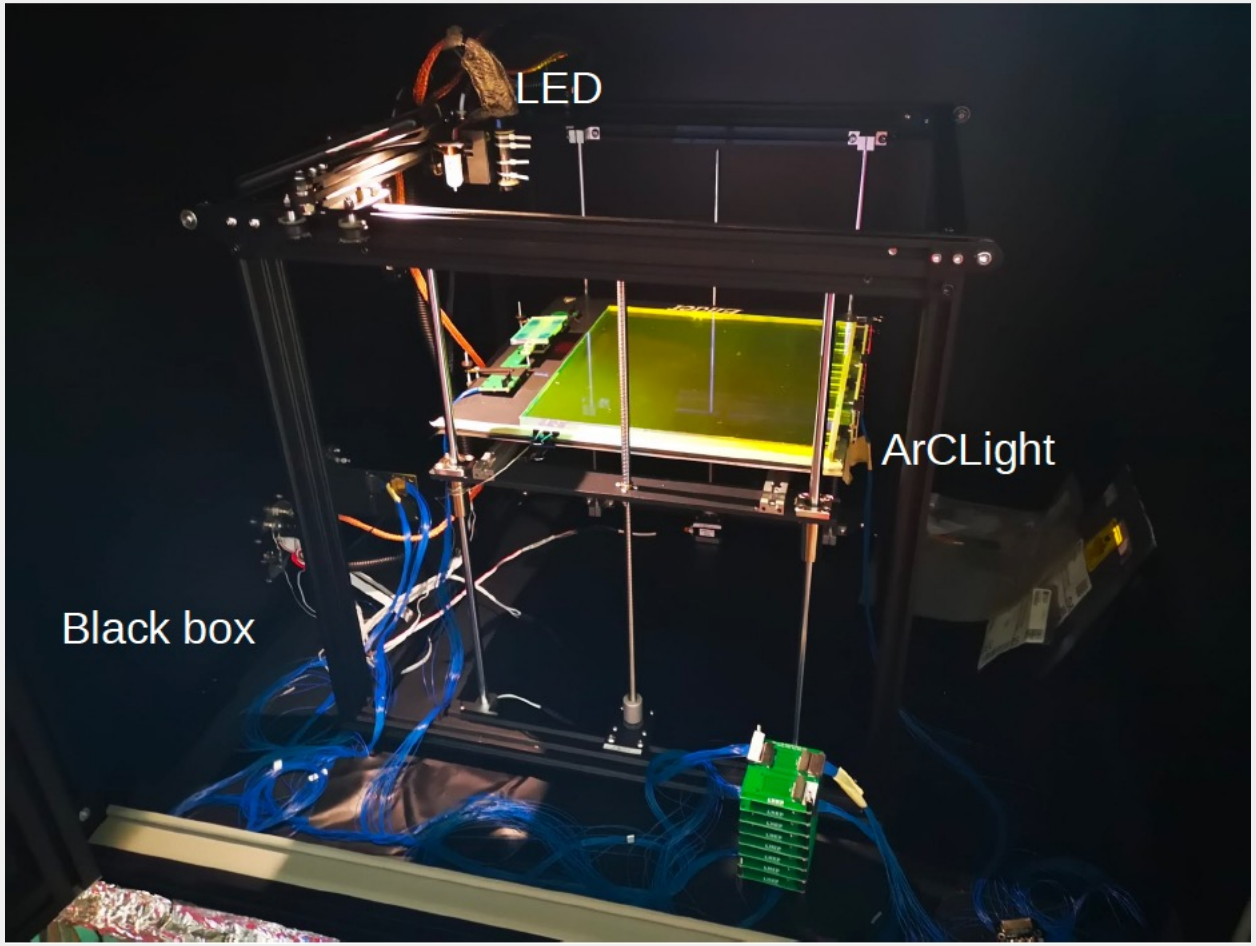
- TPB coated WLS fibres in 2D arrangement
- 25 individual fibres coupled to 2 SiPMs
- High photon detection efficiency
- Spatial resolution limited by detector size





Test stand

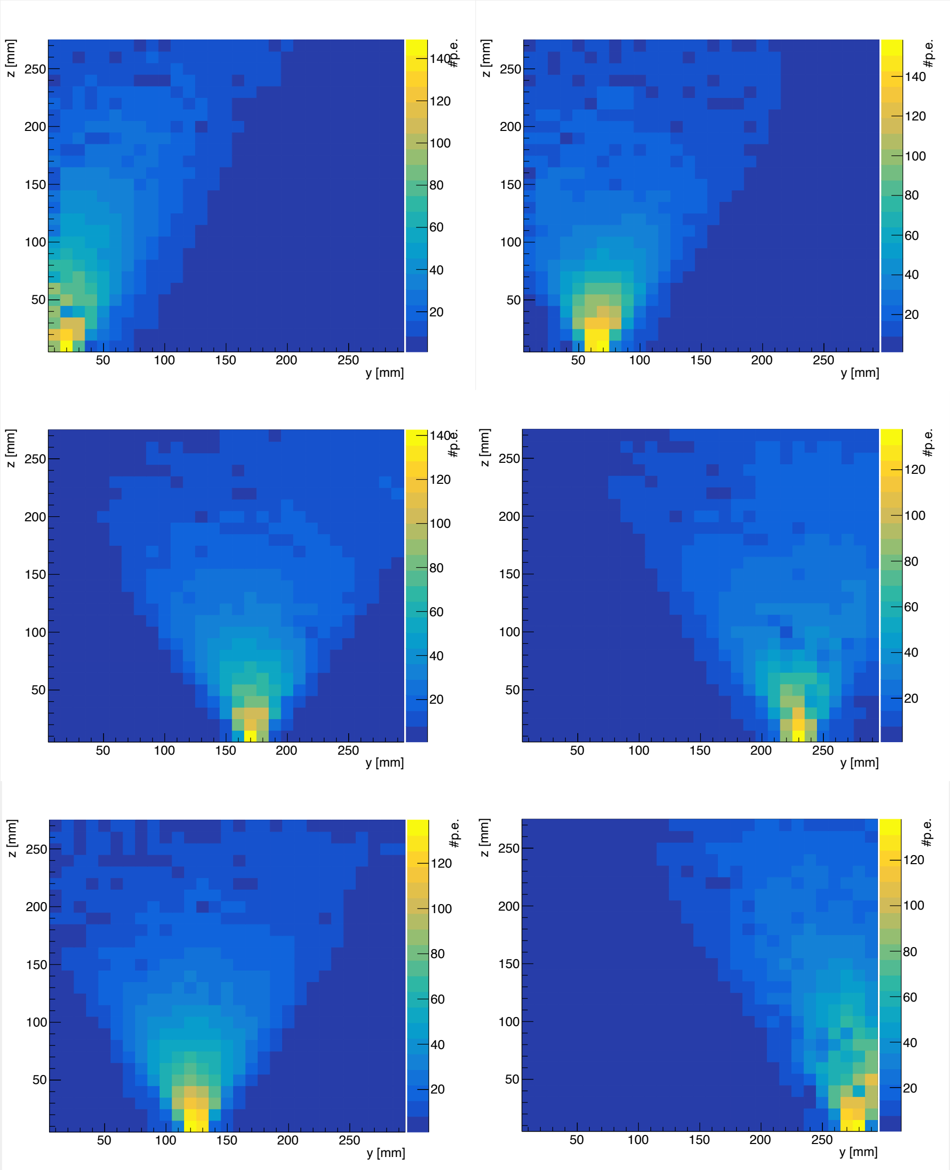
- Repurposed 3D printer as CNC stage
  - Pulsed UV LED installed on printer head
  - Scanning detector suface in steps on a 2D grid
  - Measure ~10k pulses per position
- Adjustable apperture for control of light cone
- Permanent mounted SiPM for LED stability measurement



ArCLight: Spatial resolution

- Individual sensitive area for each SiPM
- Specific distribution of light intensity across all SiPMs
- Apply reconstruction algorightm to reconstruct original light emission position
- Center of gravity approach:
  - Calibrate #photons per SiPM
  - Calculate mean SiPM position applying #photons as weights
- With center of gravity approach: $\sigma_y \simeq 50$ mm

⇒ Develop more sophisticated reconstruction method!



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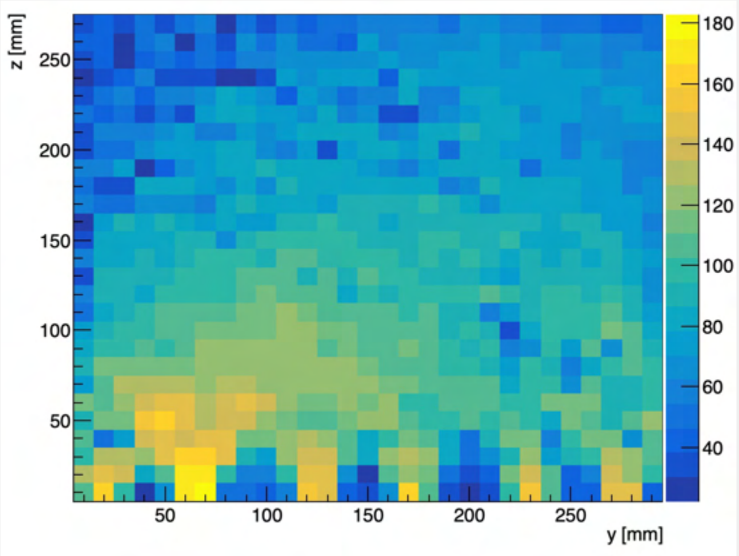
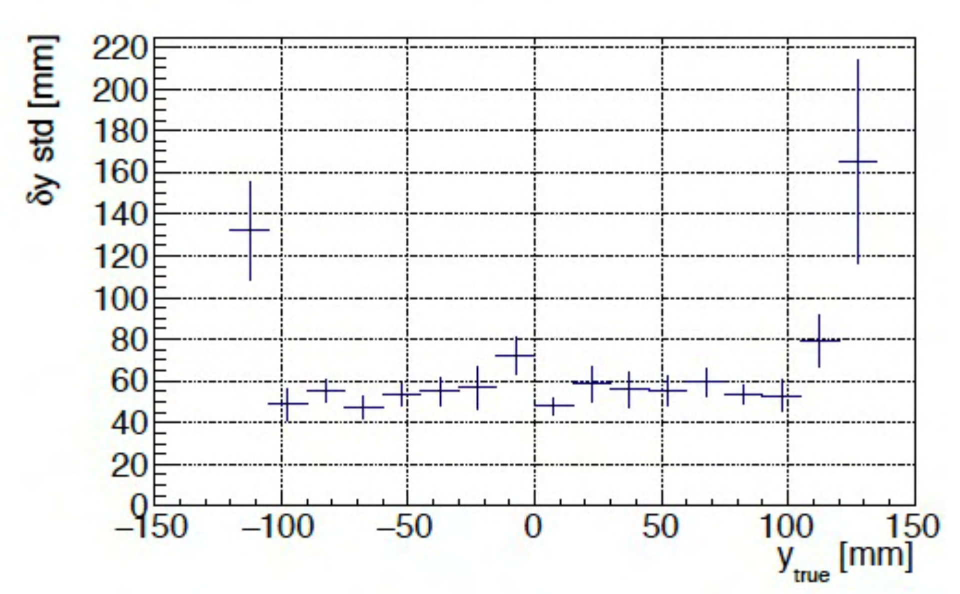
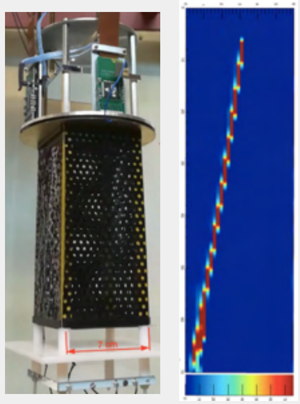




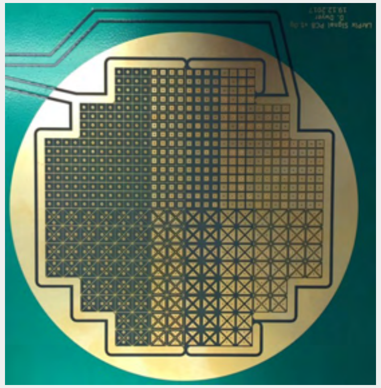
ND-LAr Prototyping Campaign

Isolated tests of novel technologies

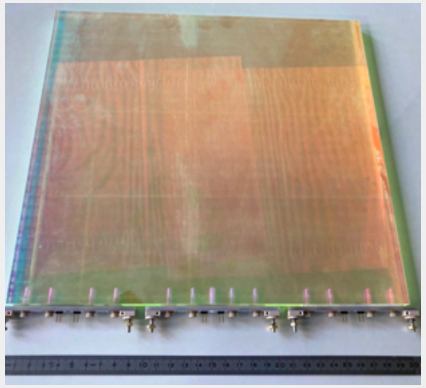
Resistive Shell



Pixelated r/o

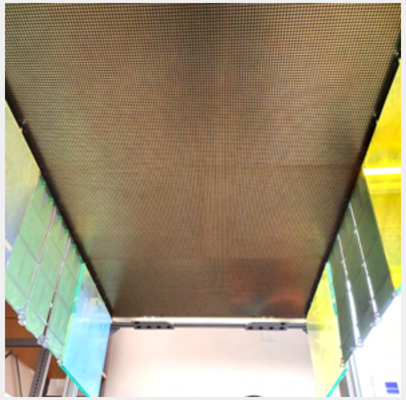


ArCLight / LCM



Single Module for 2x2

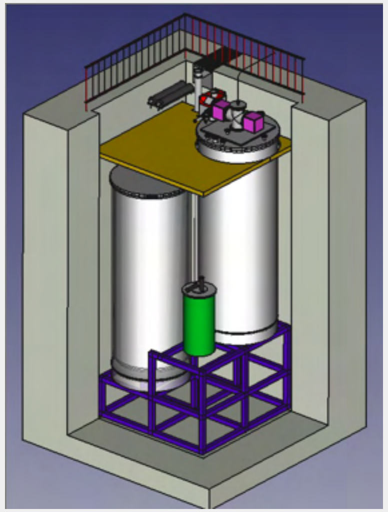
First test of integration of all subsystems

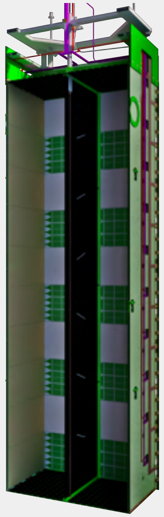


2x2 Demonstrator @ NuMI

First combined test of multiple modules in a neutrino beam

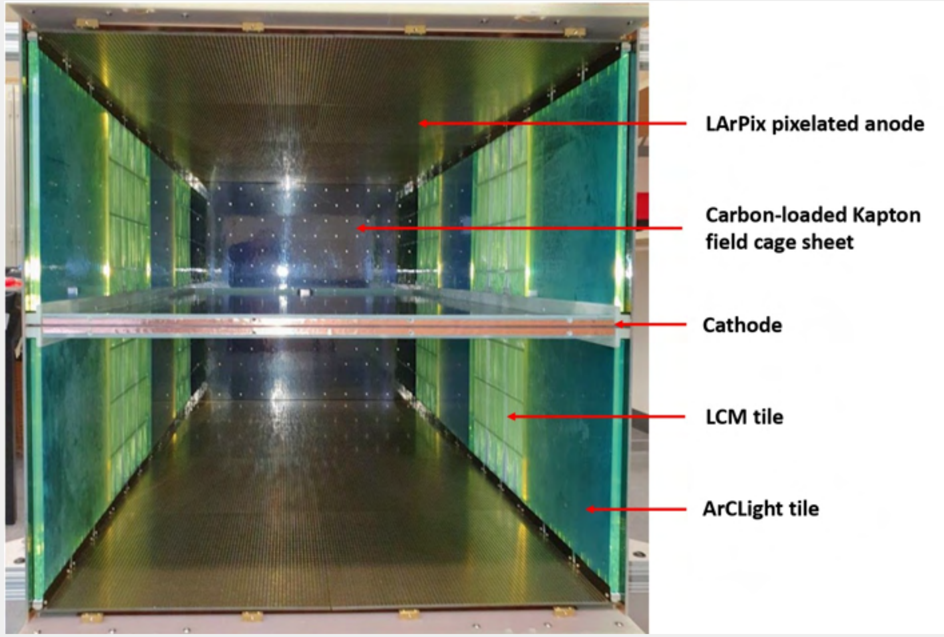
Full Size Demonstrator

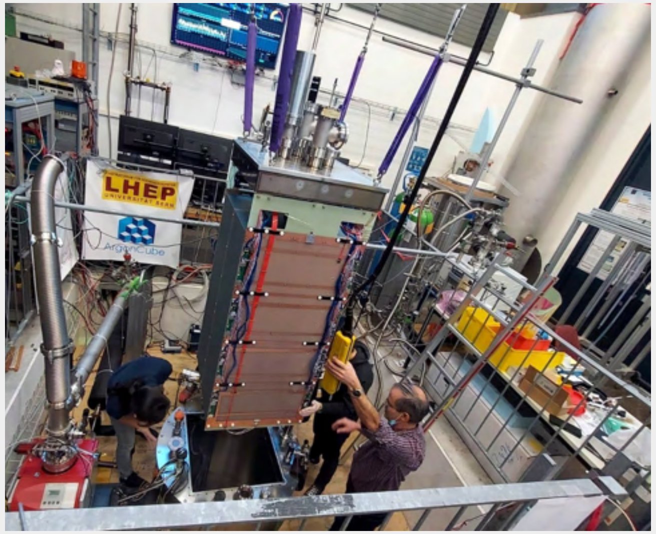




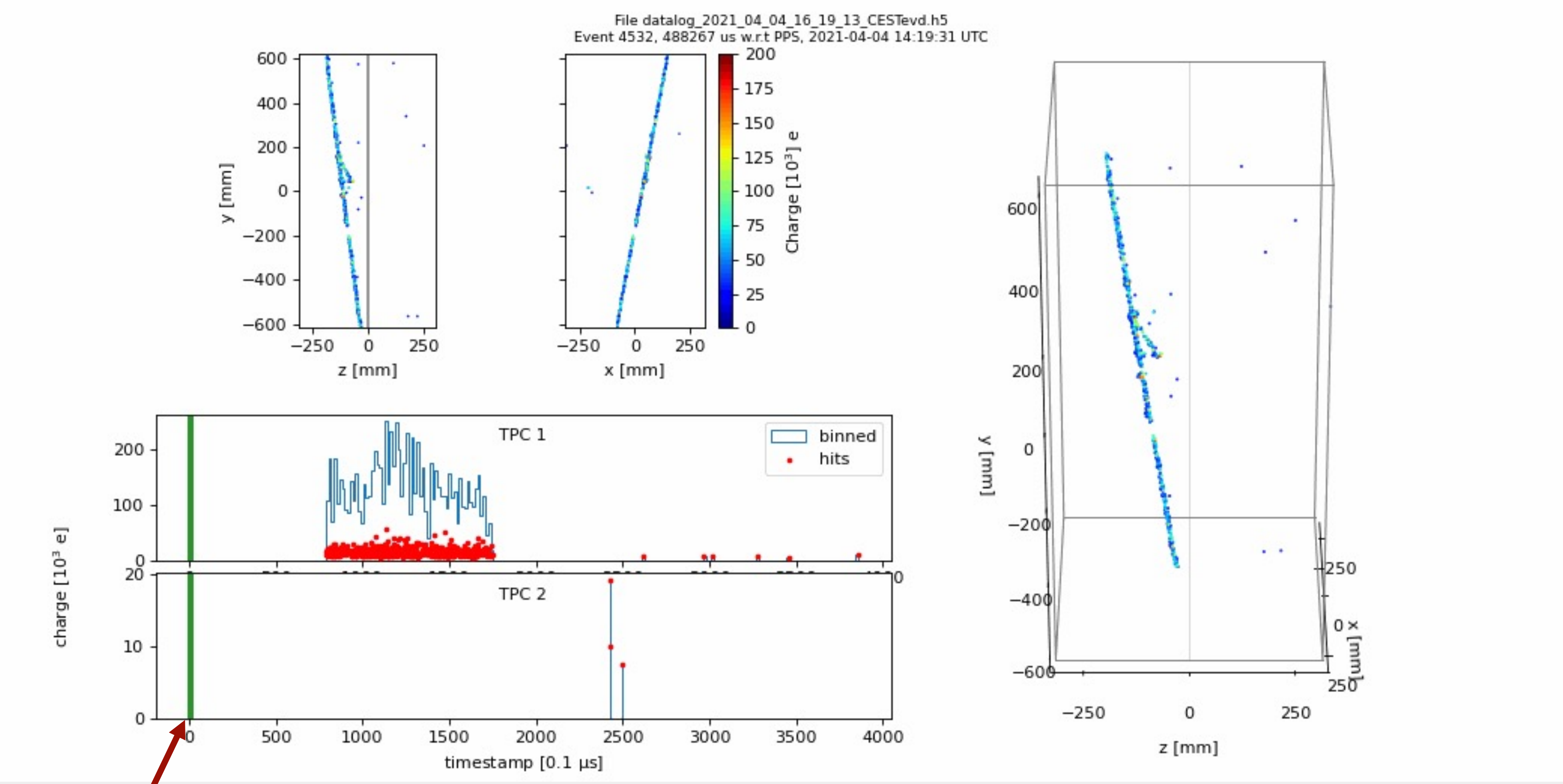
SingleModule

- 2021-2023: Succesfully tested four single modules
- Module size: 0.6m x 0.6m x 1.5m
- $\mathcal{O}(100)$ million cosmic ray events recorded
- Integrated detector performance studies
  - Basic light readout studies (e.g. PDE)
  - Basic charge readout studies
  - Electric field studies
  - Charge+Light integration





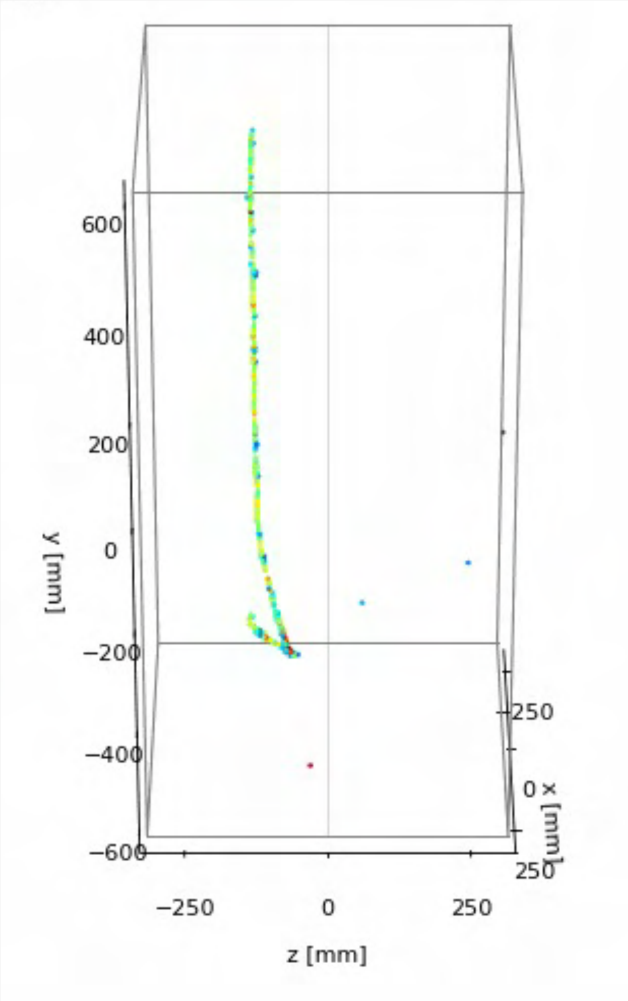
SingleModule: T0



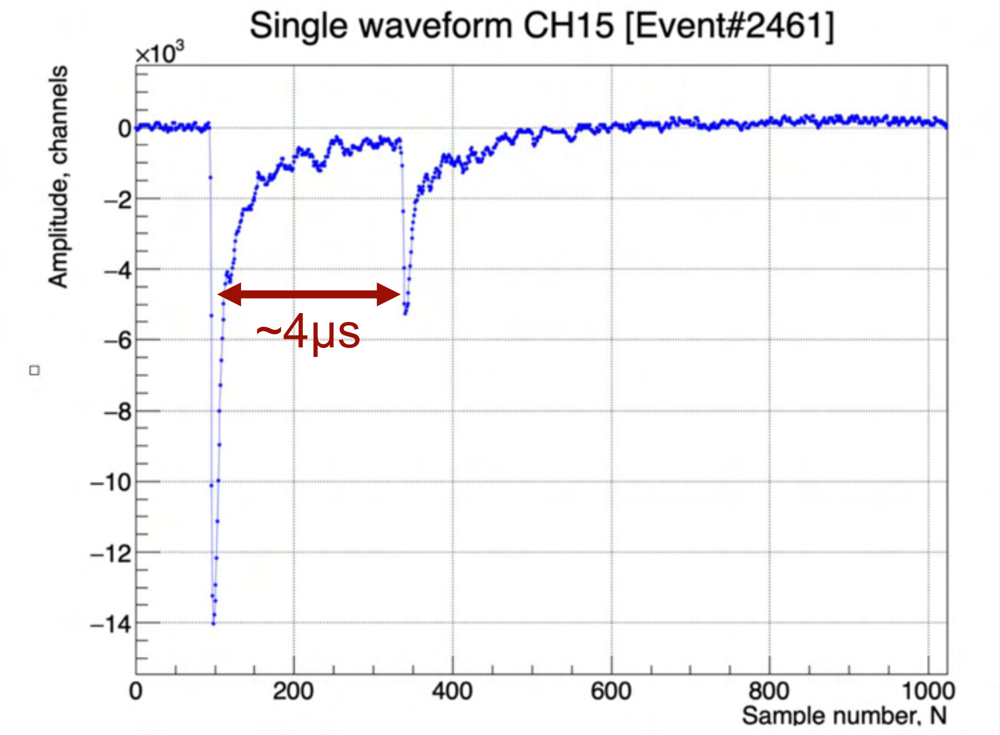
Light T0 marker

SingleModule: Michel electron

Charge



Light



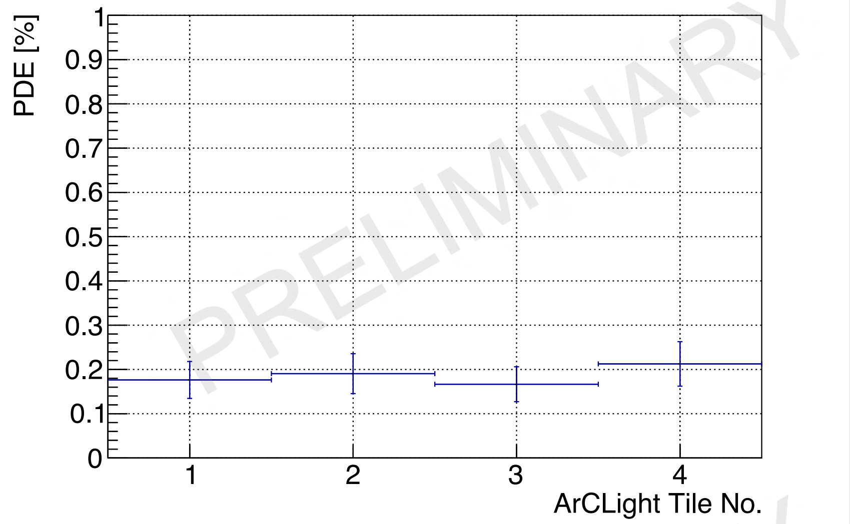
1 sample ≃ 16ns

Photon Detection Efficiency (PDE)

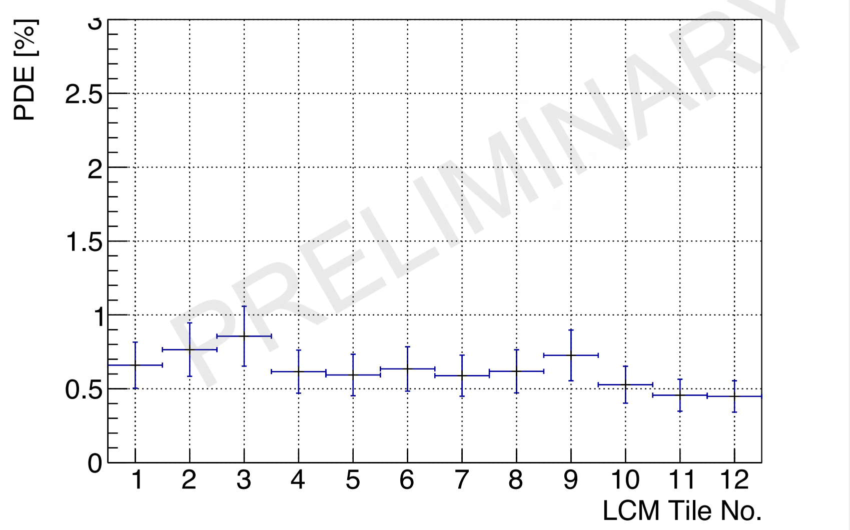
- LAr: ~4.7k photons/mm for a MIP (@0.5V/cm)
- For e.g. 5MeV threshold: Minimum PDE **~0.16%**

- How to measure PDE?
  - Using top-bottom crossing tracks (muons)
  - $PDE = \frac{\#\, measured\ photo\ electrons}{\#incoming\ photons}$
  - Charge track information to calculate light yield per light detector
  - Compare to #photo-electrons per detector
- Measured PDE (Module 1):
  - ArCLigtht **0.187(22)%**
  - LCM **0.62(13)%**

LCM

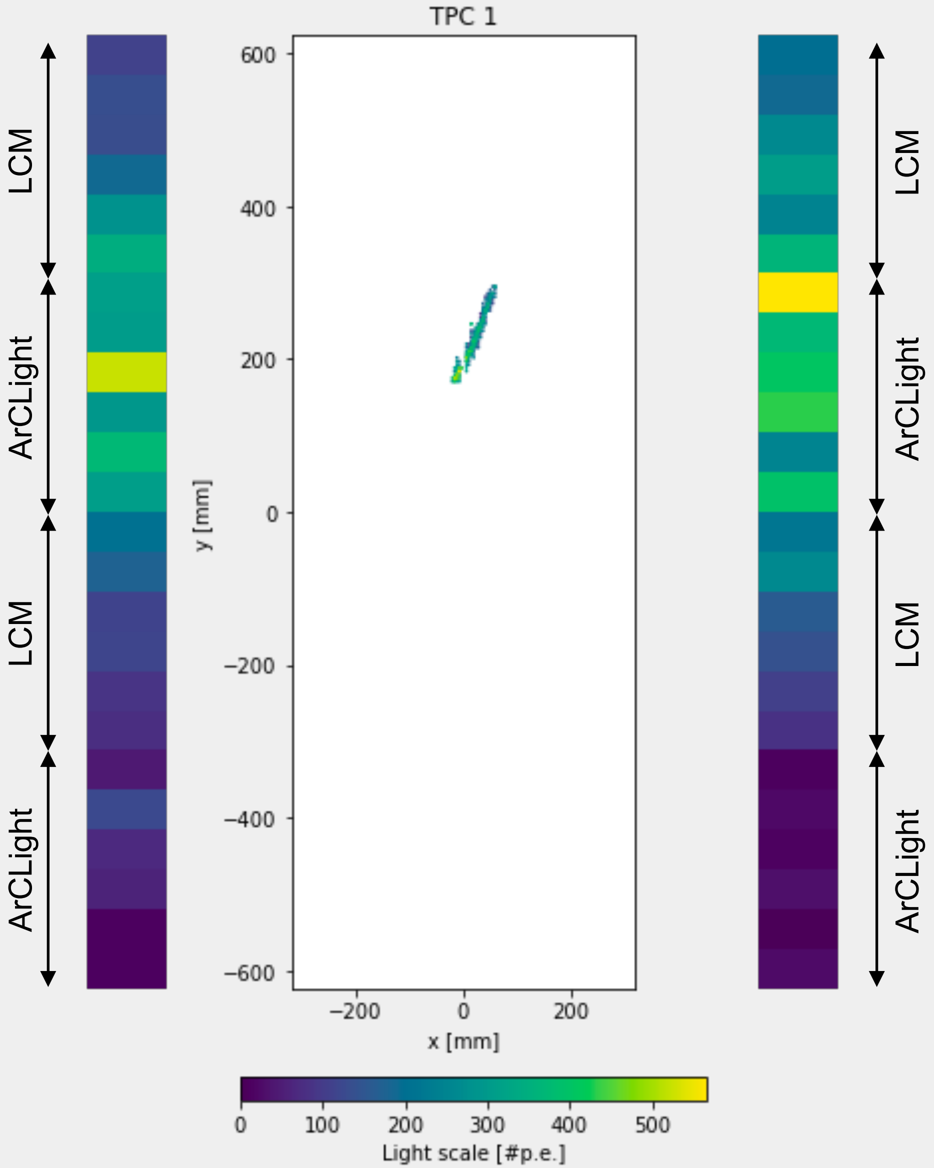


ArCLight



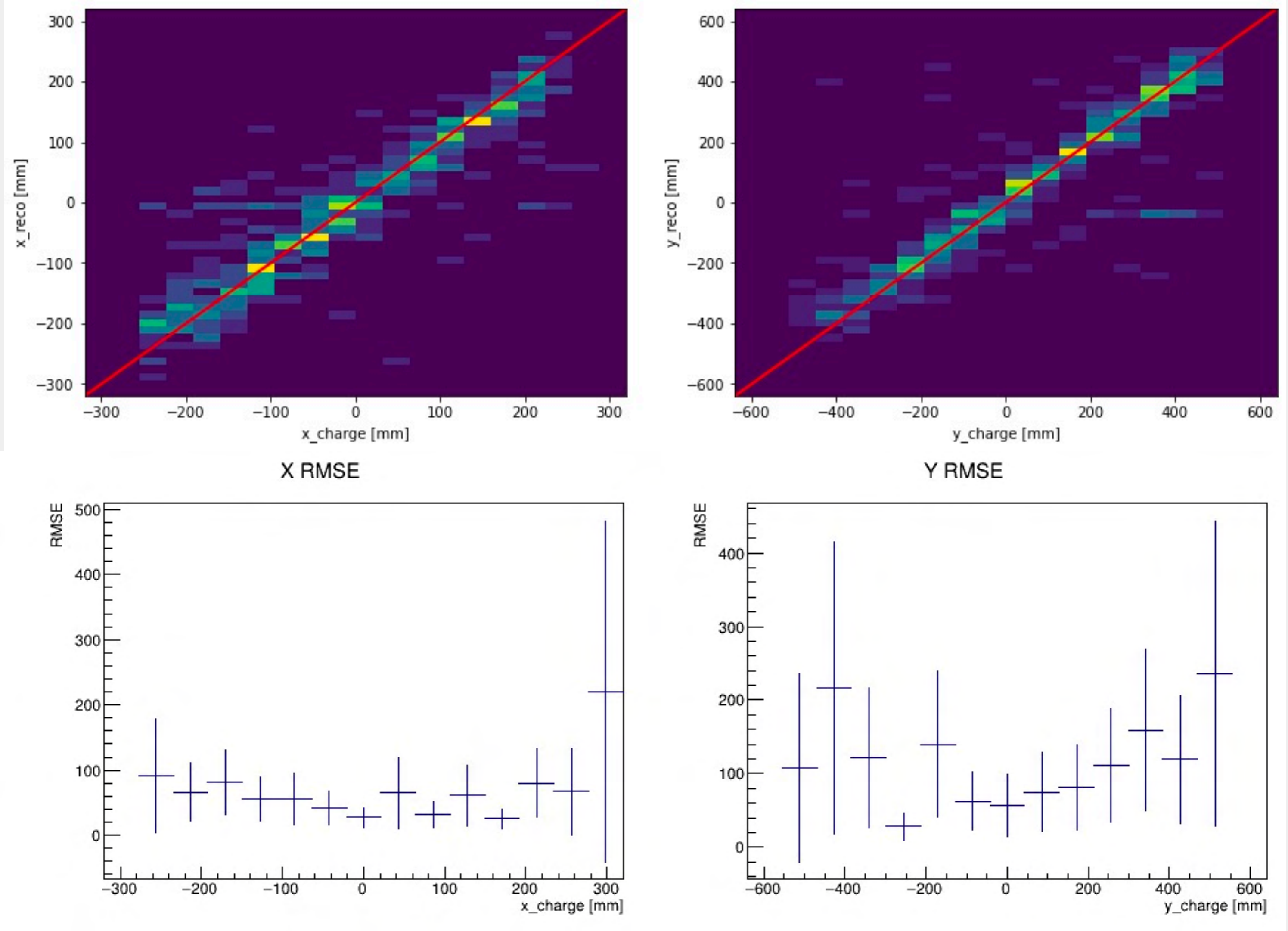
SingleModule: Spatial resolution

- First try to reconstruct center of charge deposition using light data only
- Test the spatial resolution of the light readouts
- Early development for charge-light matching and therefore the $\mathcal{O}$(ns) timing separation (in-spill timing)
- Sample:
  - Short length (<200mm)
  - High ionising particles
  - Fully contained
  - Matching light-charge events
  - No light detector crossing
- Small sample: ~1500 events



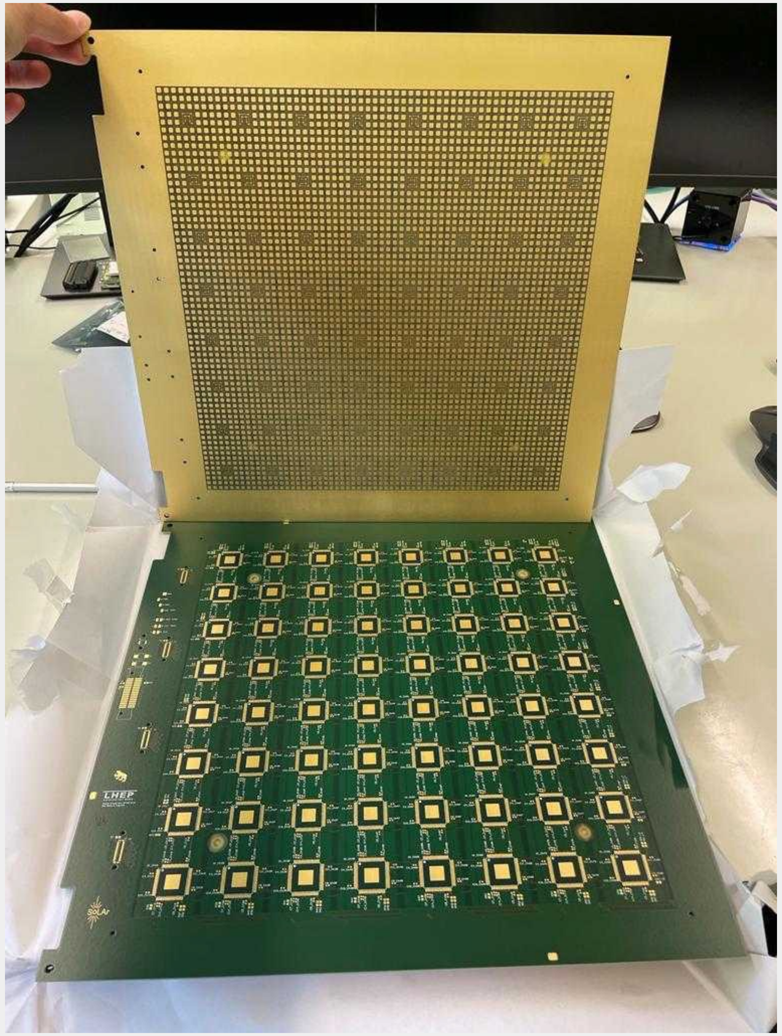
SingleModule: Spatial resolution

- Train simple NN directly on SingleModule data (x, y coordinate only)
- Working on improved simulation to get large training sample
- Plan to combine with the charge reconstruction (e.g MLreco) for charge-light matching and investigate the in-spill time separation



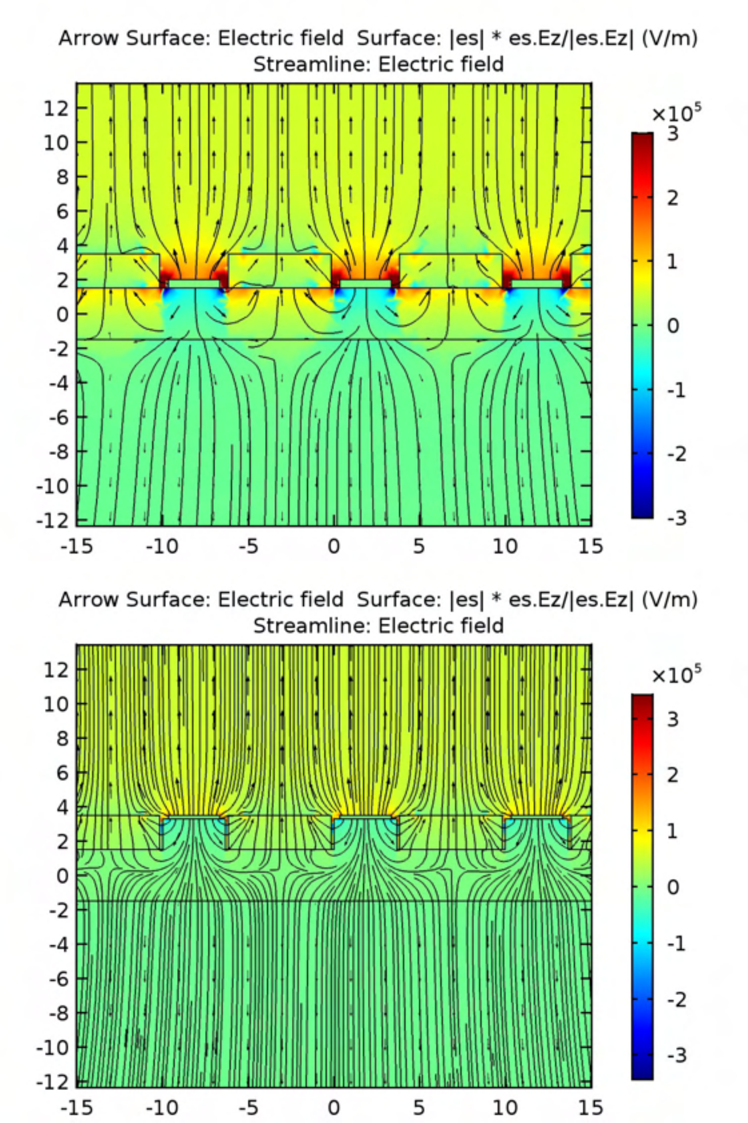
Outlook: Future detectors

- Major technology developments ongoing for future light readout systems!
  - Digital SiPMs (e.g. 3DdSiPM) or cold ASIC digitisation (e.g. LightPix)
  - VUV sensitive SiPMs (e.g. Hamamatsu S13370-2221)
- SoLAr: Aim is to reach to the required sensitivity for Solar hep neutrinos and other low energy physics at MeV energy scale.



Outlook: SoLAr

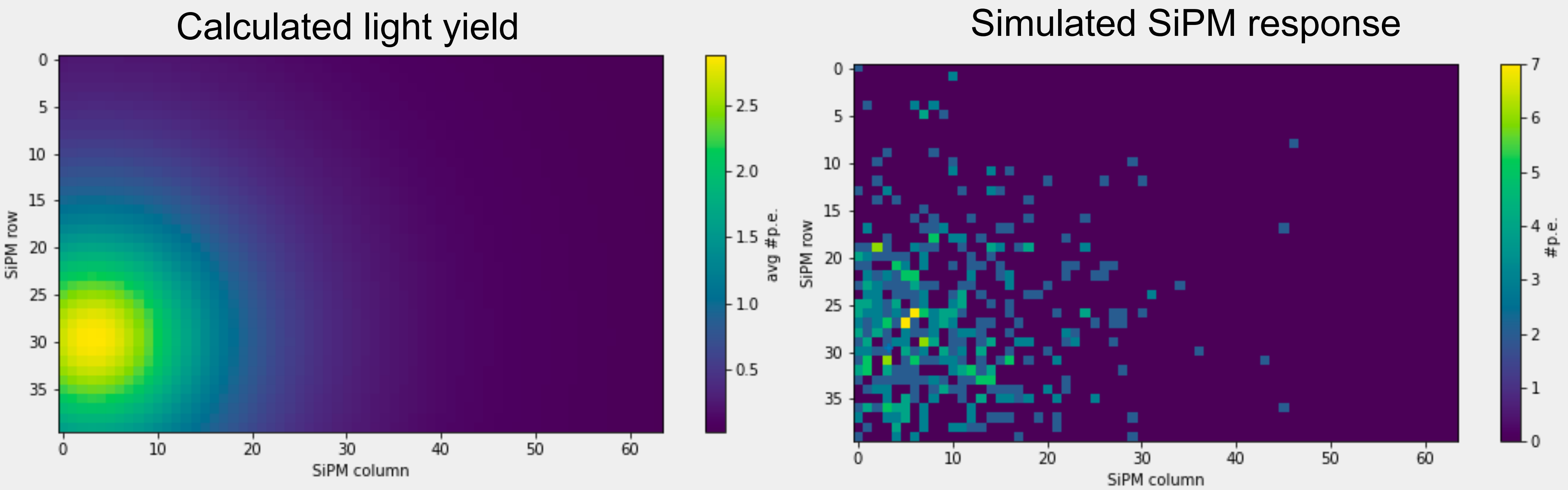
- Concept:
  - Place both charge pixels and SiPMs on anode plane
  - Direct light collection with VUV SiPMs
- Challenges:
  - Large number of SiPM readout channels
  - E-field shapping to maximise charge collection



Outlook: SoLAr

- Possibilities:
  - Very high spatial resolution on light readout
  - Online light emission point reconstruction for virtual detector voxelisation and “Level-1 trigger” like operation?

Toy simulation for 2500x1600x1000mm^3 TPC, random point like deposit:



Calculated light yield

Simulated SiPM response

Outlook: SoLAr

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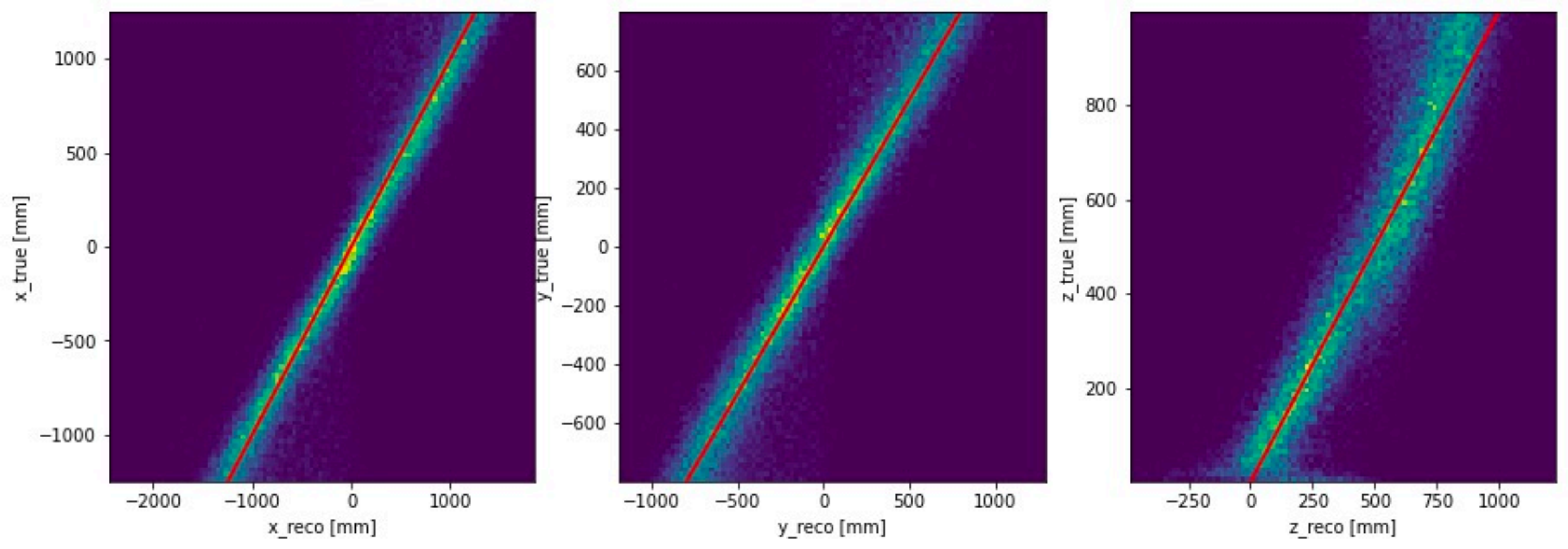
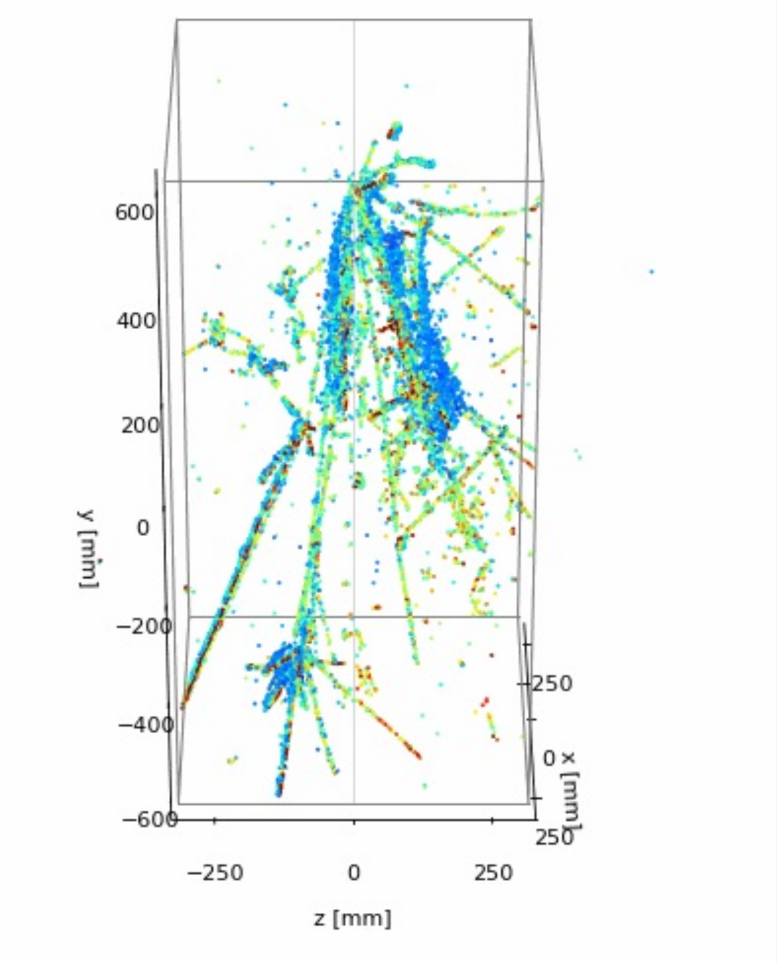
  - Very high spatial resolution on light readout
  - Online light emission point reconstruction for virtual detector voxelisation and “T1 trigger” like operation?

”First try” position reconstruction with light signal only:

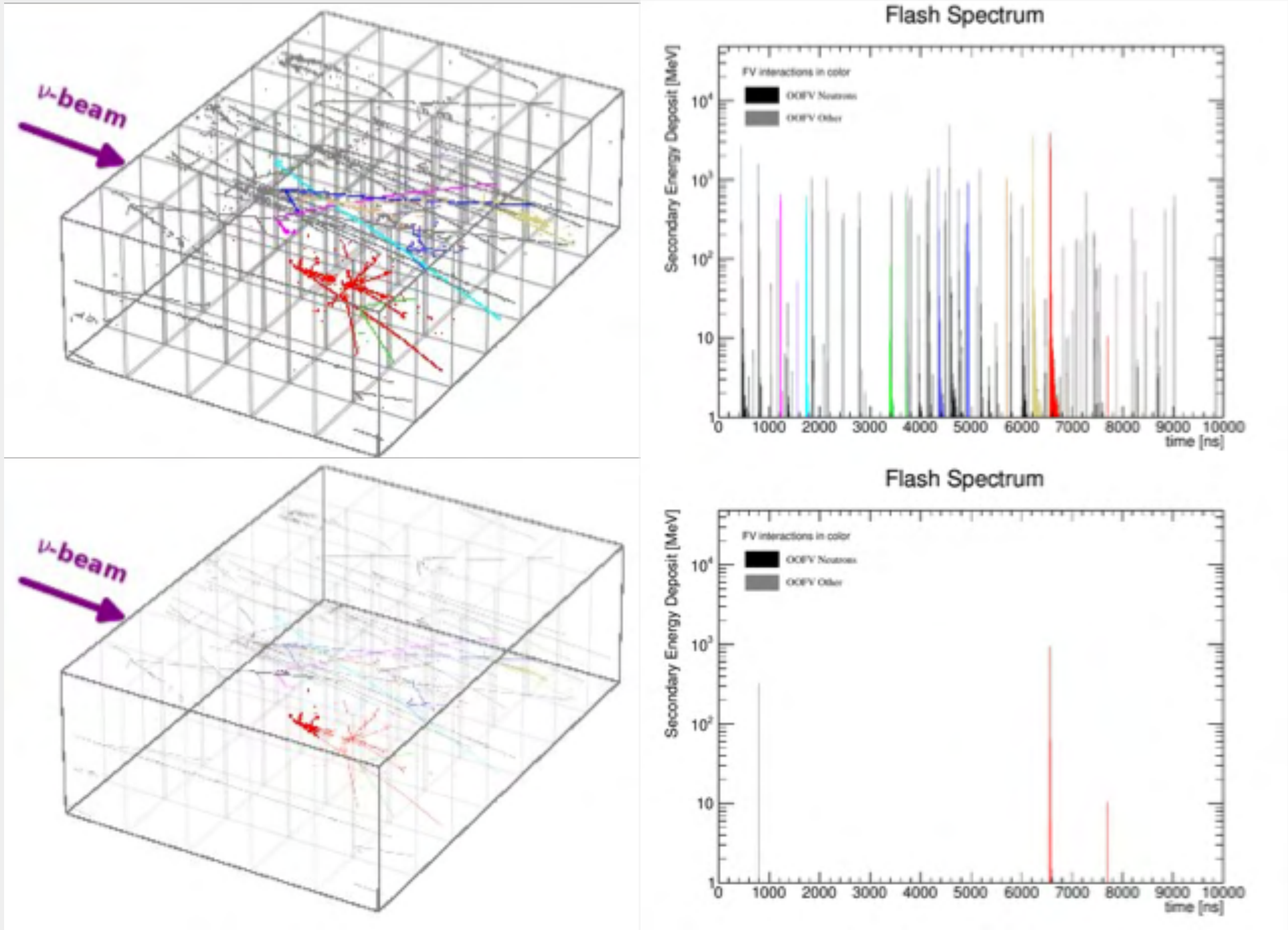


Summary

- Light detection in LAr TPCs can be a key component for resolving unprecedent pile up environments and allow new types of measurements
- New light detector technologies and reconstruction algorithms needed to achieve in-spill timing
- New technology developments open the door for future detectors with lower energy thresholds



Backup


ν-beam
Flash Spectrum
FV interactions in color
OOFV Neutrons
OOFV Other
Secondary Energy Deposit [MeV]
1
10
10^2
10^3
10^4
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
time [ns]
ν-beam
Flash Spectrum
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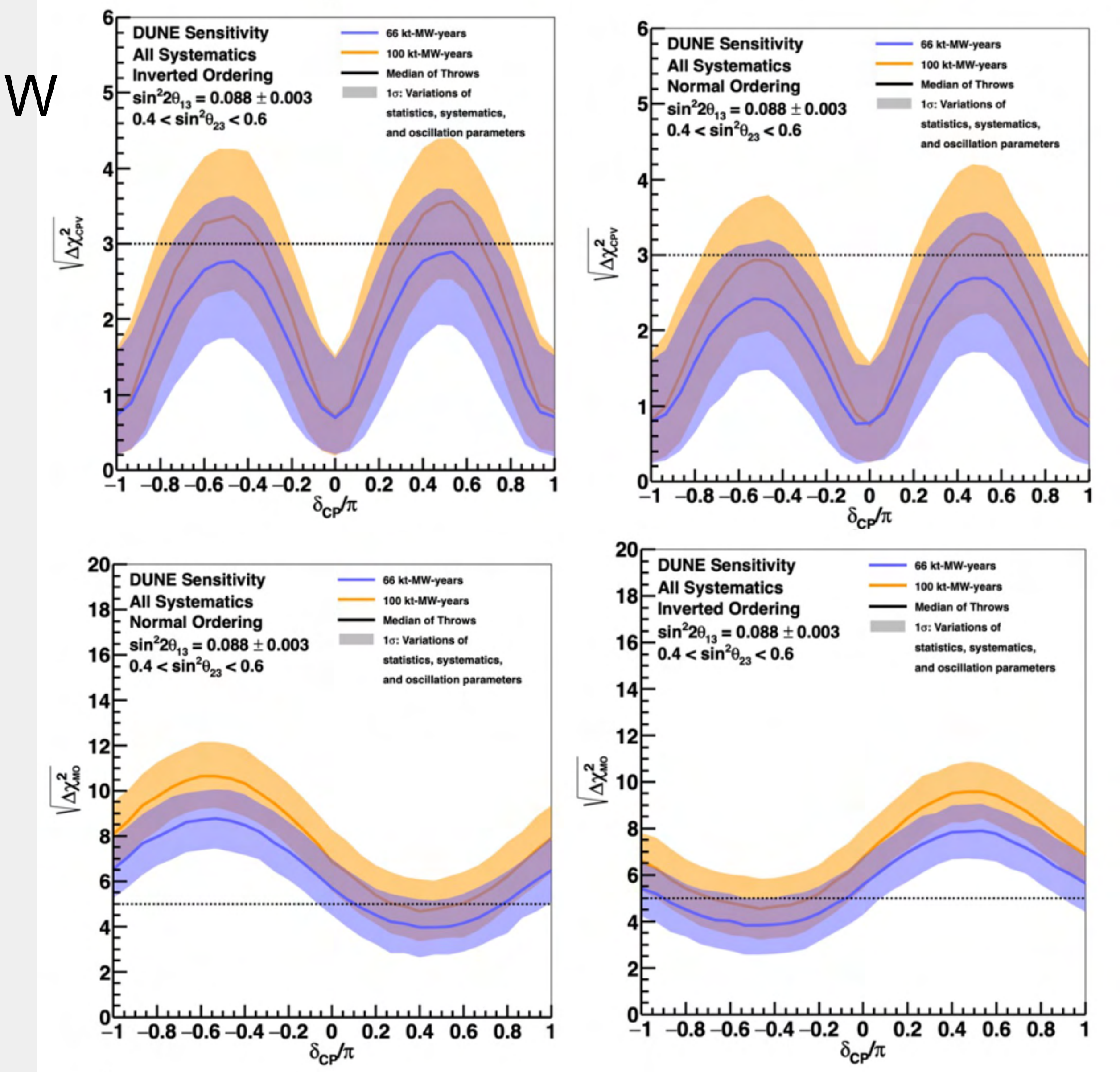
1
10
10^2
10^3
10^4
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
time [ns]

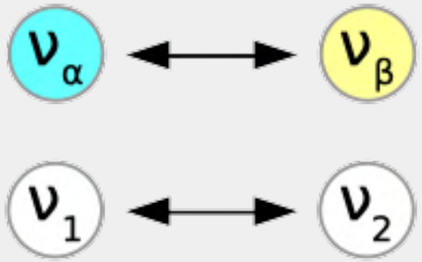
Sensitivity

- Nomial beam power: 1.2 (2.4) MW
- 10kT per FD module
- With full configuration:

  48kT-MW-year



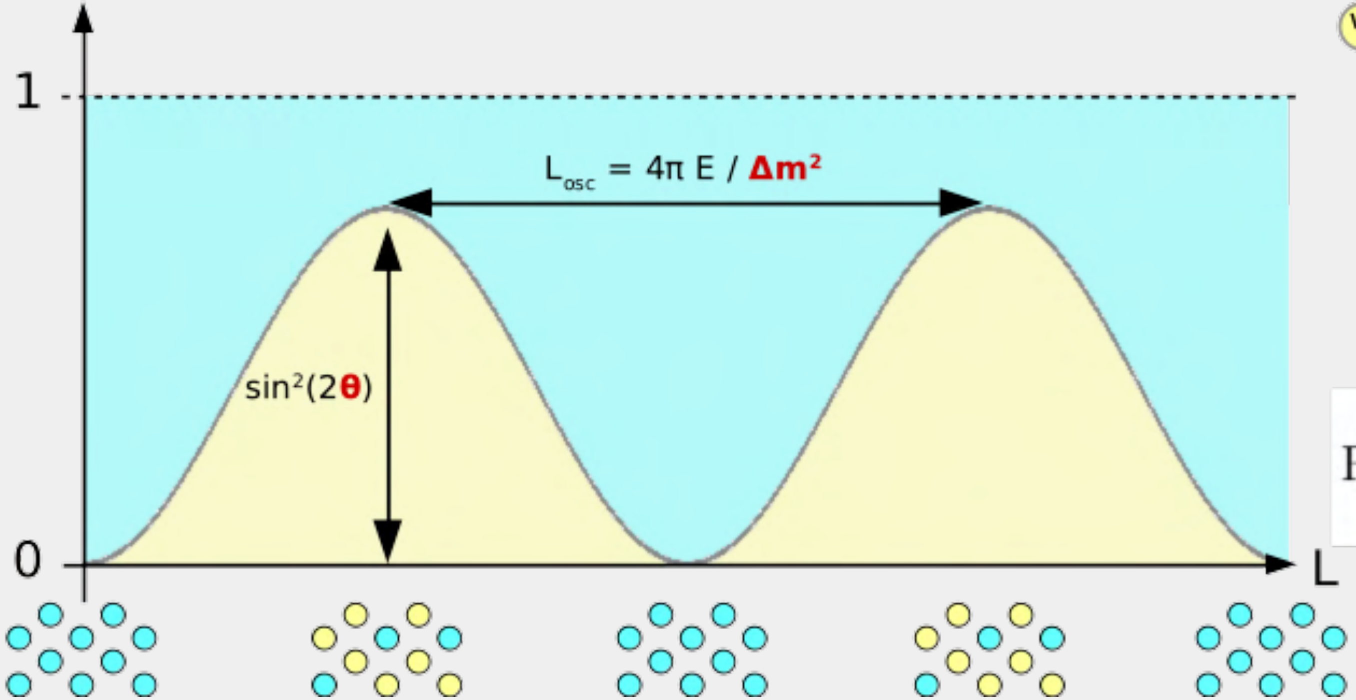
Oscillation

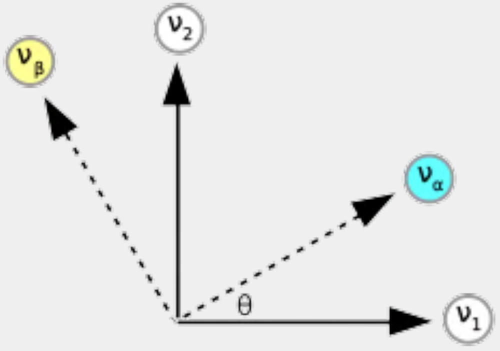


$$P_{\nu_\alpha \to \nu_\beta}(L, E) = \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$\Delta m^2 \equiv m_2^2 - m_1^2$$

E = const.

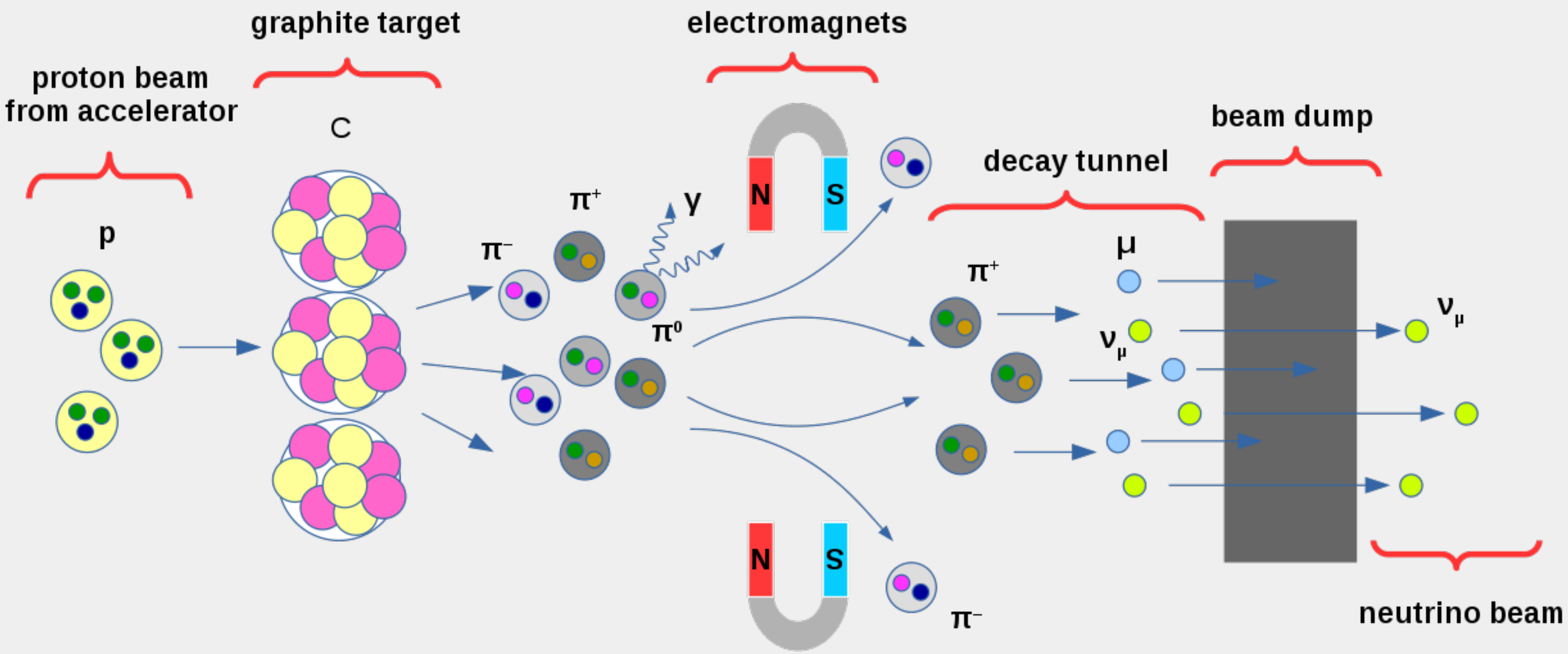




$$\mathrm{Rot} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

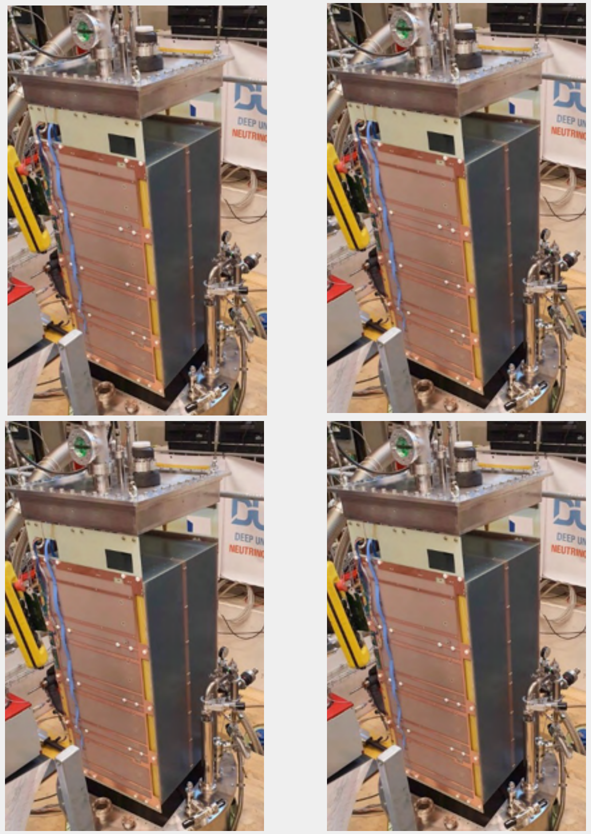
Beam production

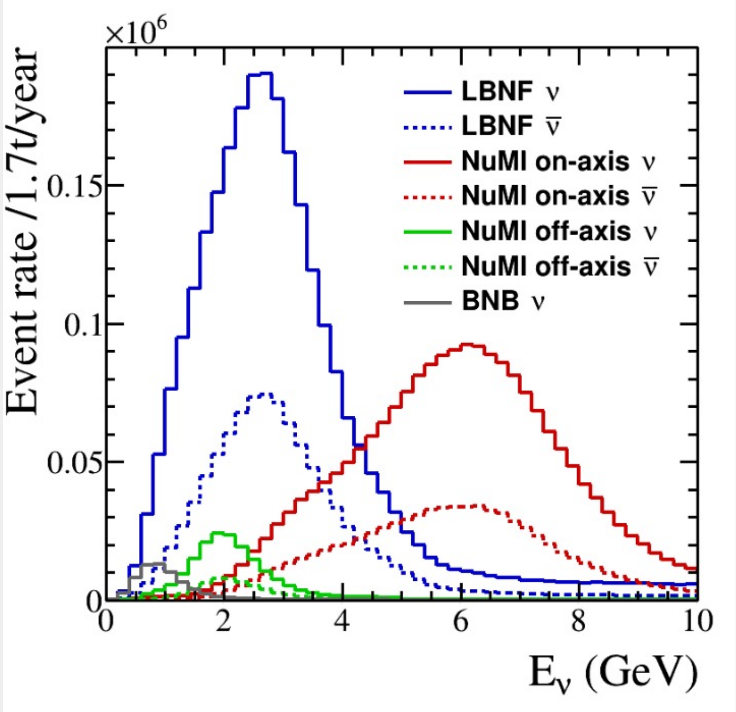
LABORATORIUM FÜR HOCHENERGIEPHYSIK
LHEP
UNIVERSITÄT BERN



2x2 Demonstrator

- Integraton of 2x2 prototype modules
- First test in neutrino beam (NuMI) @ Fermilab





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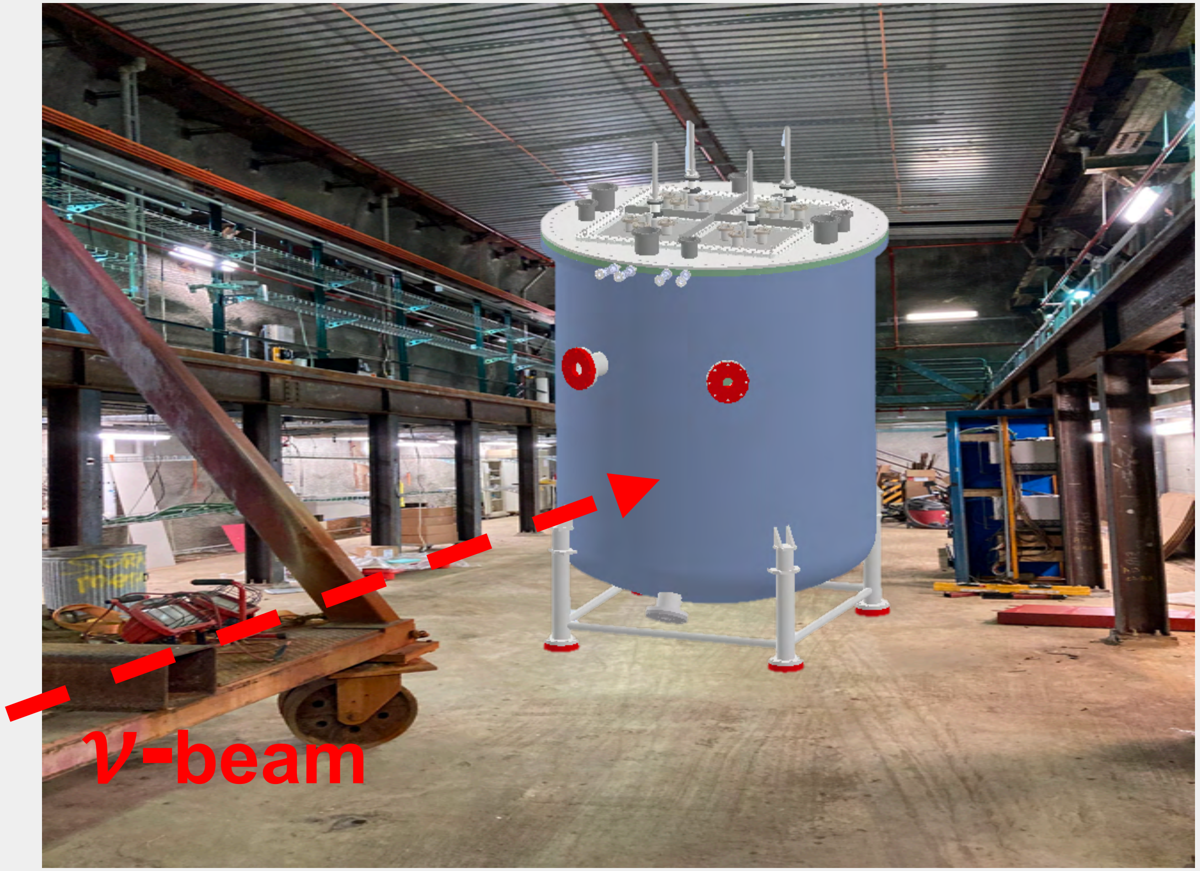
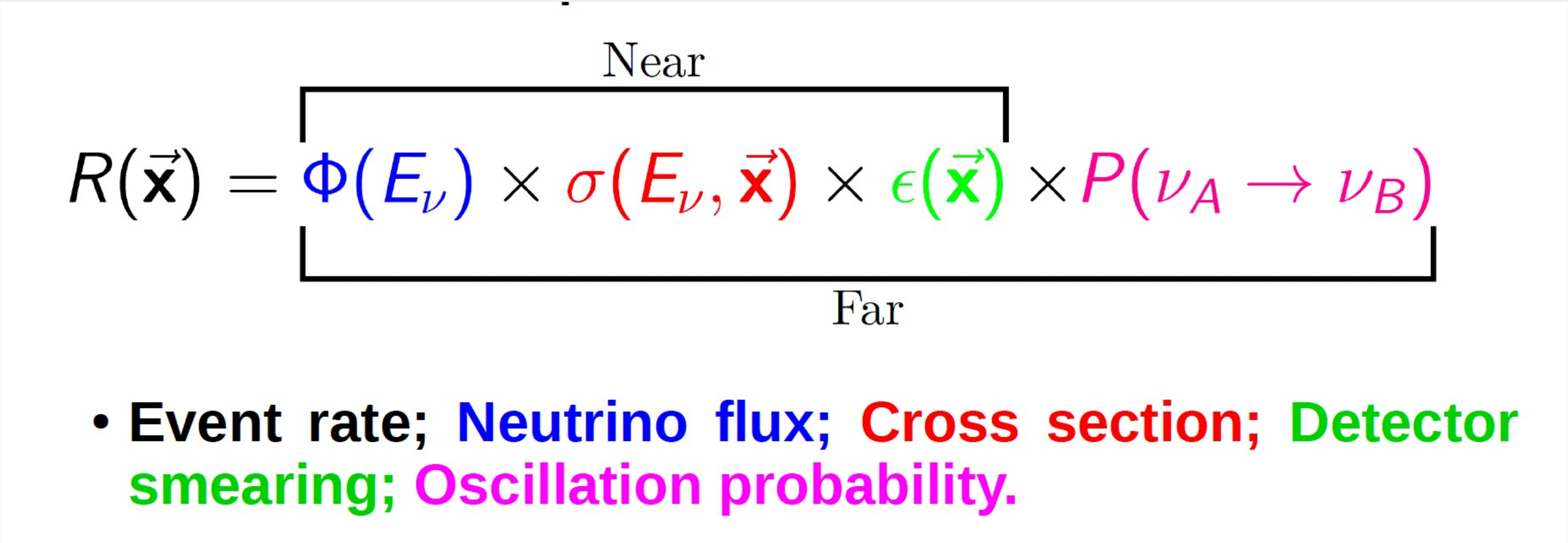


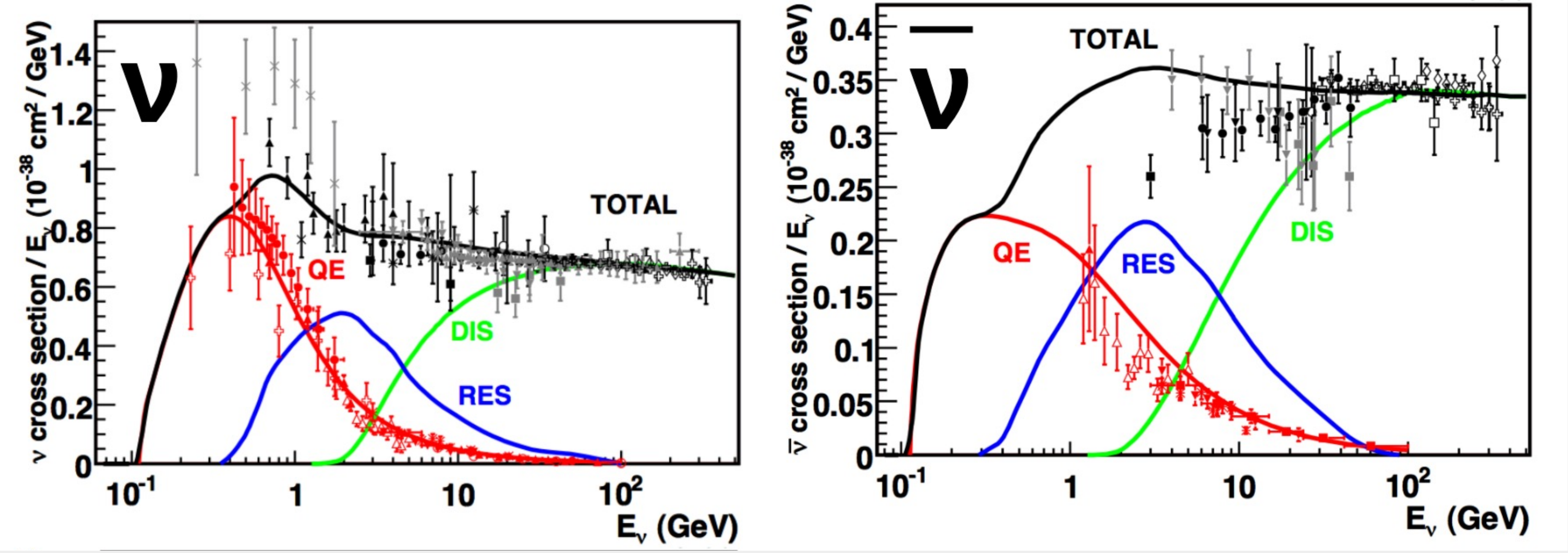
Interaction rate



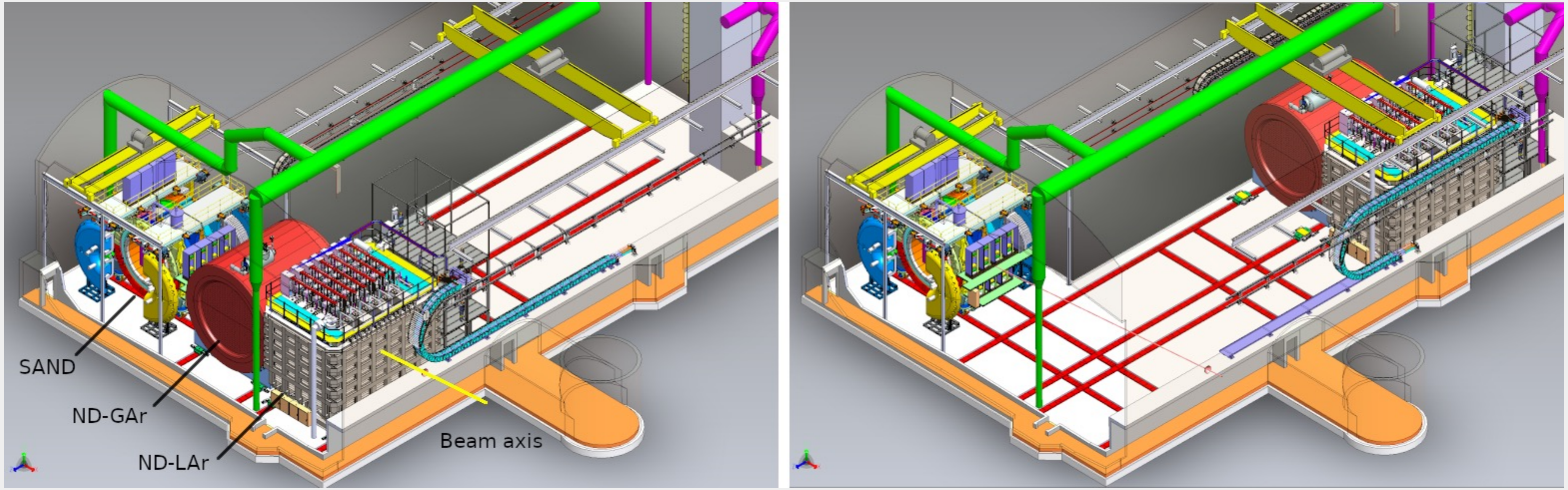
$$R(\vec{\mathbf{x}}) = \underbrace{\overbrace{\Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}})}^{\text{Near}} \times P(\nu_A \to \nu_B)}_{\text{Far}}$$

- **Event rate; Neutrino flux; Cross section; Detector smearing; Oscillation probability.**

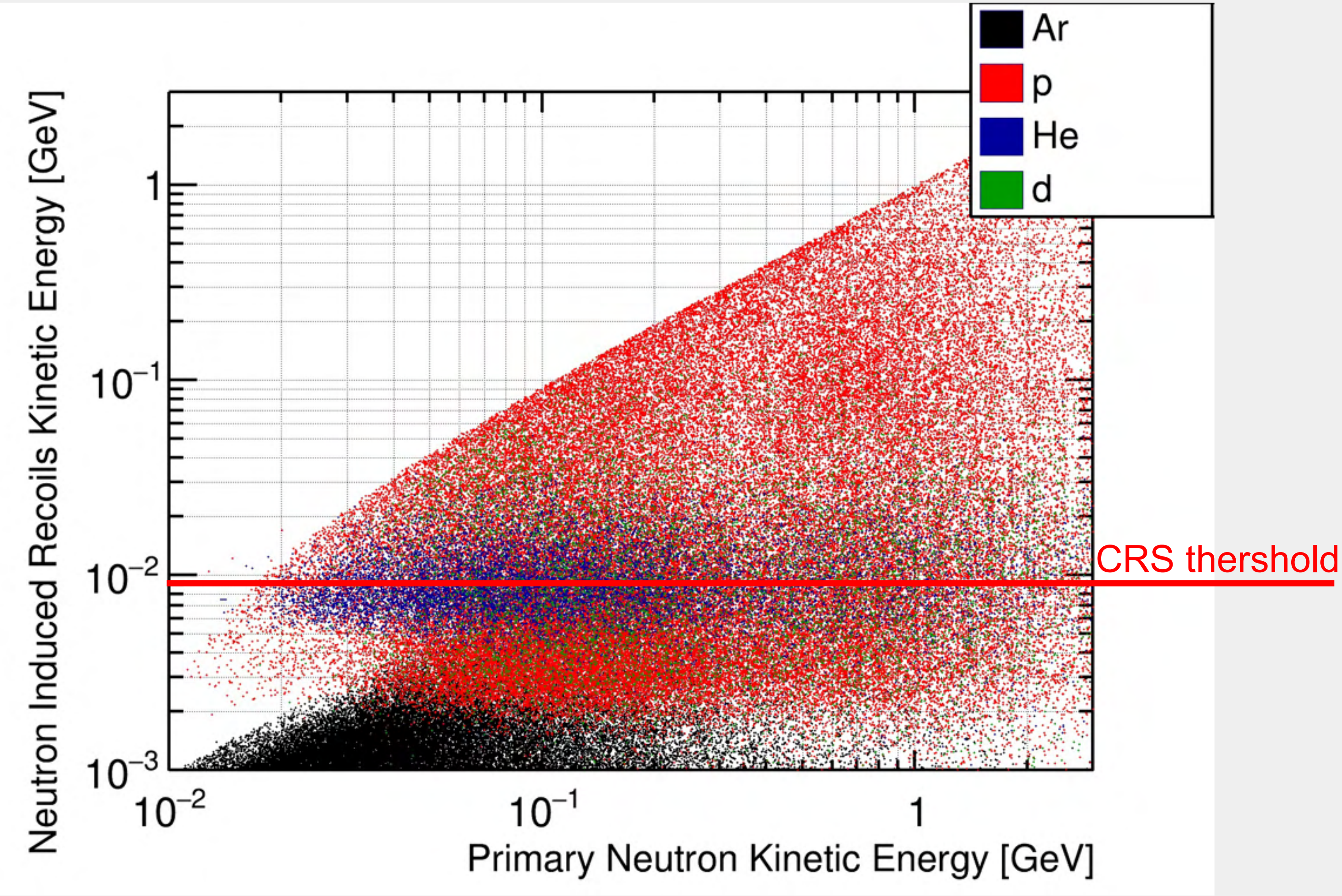
Cross section



DUNE ND



DUNE



CRS thershold