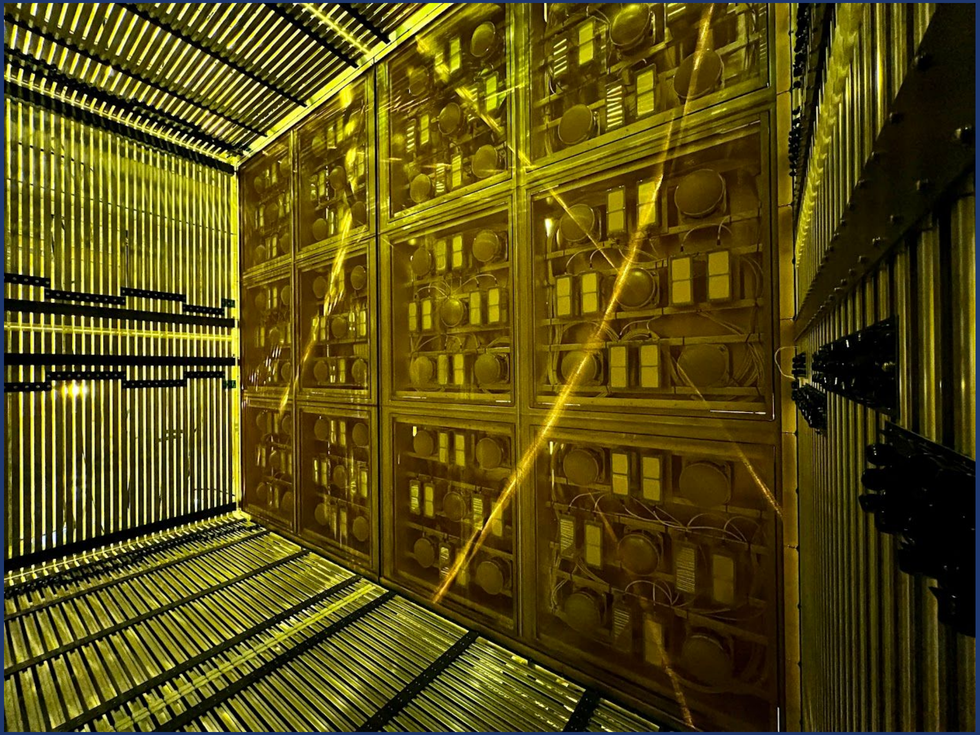
LArTPC light reconstruction

2nd Short-Baseline Experiment-Theory Workshop

Rodrigo Alvarez Garrote
on behalf of the SBND collaboration

*rodrigo.alvarez@ciemat.es



SBND Short-Baseline Near Detector

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

3 Years ago...

17:00 → 18:00 **Discussion**
Speakers: Animesh Chatterjee (Pittsburgh U.), Mark Ross-Lonergan (Columbia University)

Tuesday, 14 December

15:00 → 16:00 **EM showers**
Speakers: Andrzej Szelc (University of Edinburgh), David Caratelli (UCSB), Dominic Brailsford (Lancaster U.), Edward
EMShowers.pdf

16:00 → 16:30 **Proton reconstruction**
Speakers: Andy Furmanski (Rutgers U.), Gray Putnam (U. Chicago), Ornella Palamara (Fermilab)
Proton Reconstructi...

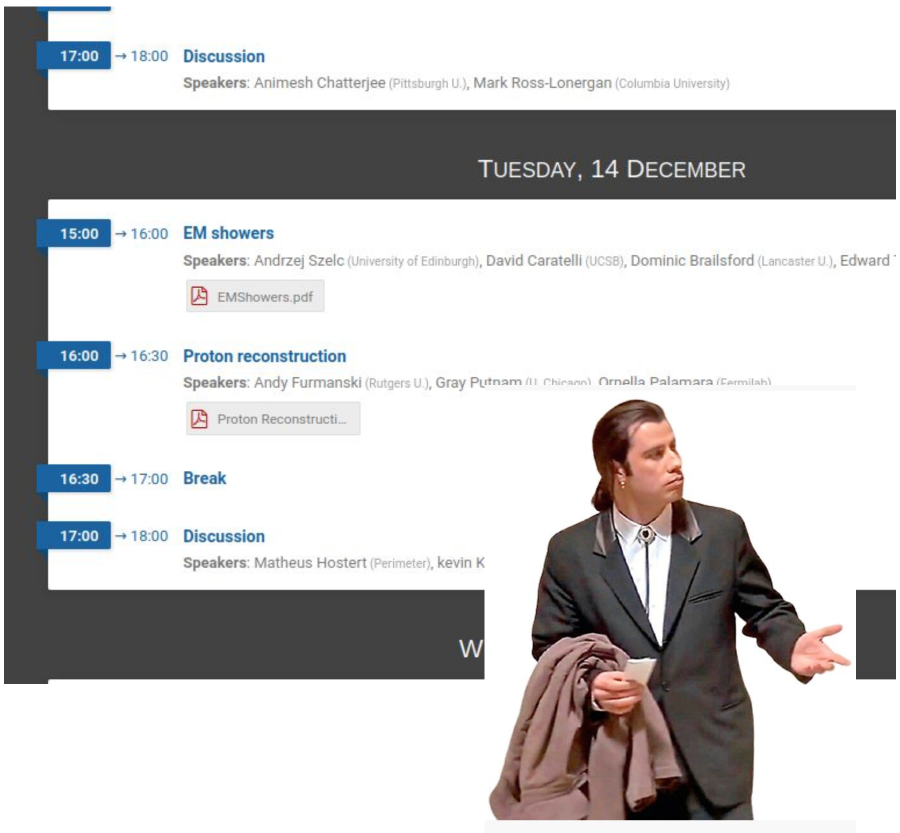
16:30 → 17:00 **Break**

17:00 → 18:00 **Discussion**
Speakers: Matheus Hostert (Perimeter), kevin Kelly (CERN)

Wednesday, 15 December

Where's the light?

3 Years ago…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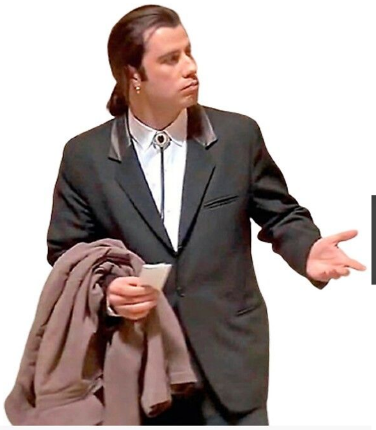


LArTPC light reconstruction	*Rodrigo Alvarez Garrote*	
Hotel Santa Fe, Santa Fe, NM	14:30 - 15:00	
LArTPC track Reconstruction	*Alice Campani*	
Hotel Santa Fe, Santa Fe, NM	15:00 - 15:30	
Coffee Break		
Hotel Santa Fe, Santa Fe, NM	15:30 - 16:00	
O(1 ns) timing resolution in LAr-TPCs, Based on a MicroBooNE analysis	*Dante Totani*	
Hotel Santa Fe, Santa Fe, NM	16:00 - 16:30	
LArTPC Electromagnetic Shower Reconstruction	*Xin Qian*	
Hotel Santa Fe, Santa Fe, NM	16:30 - 17:00	
Discussion Session		

Today!

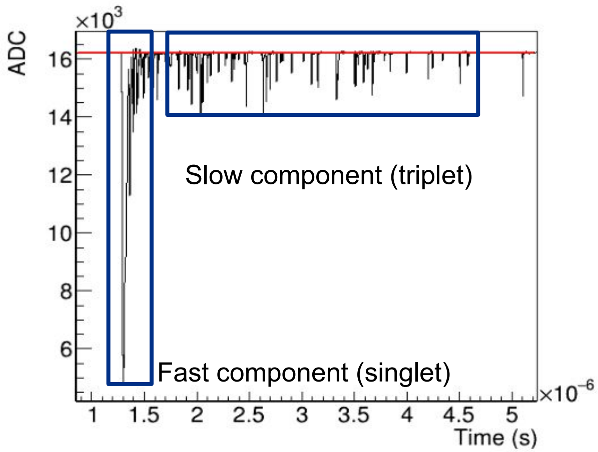
Outline

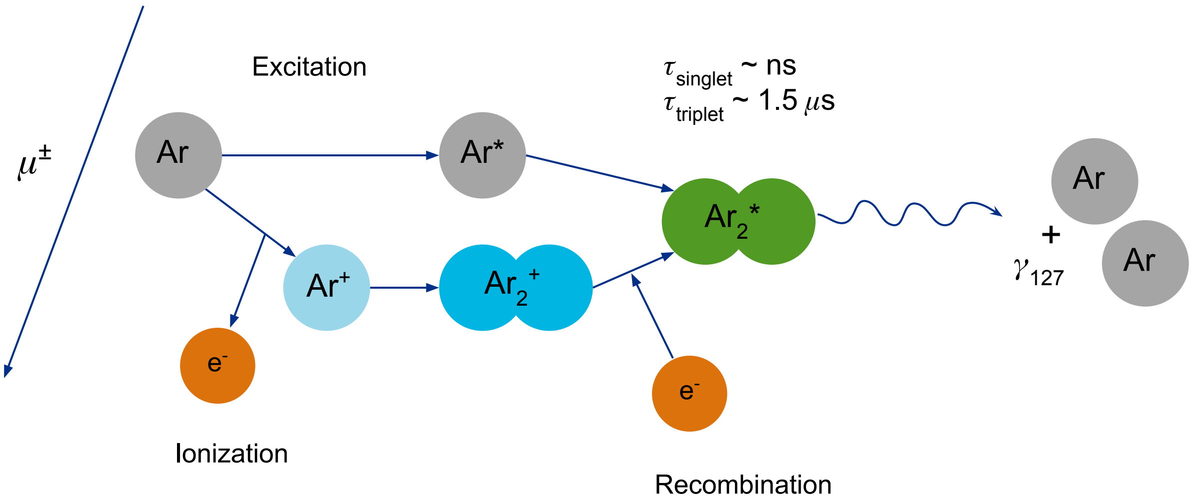
- **Brief introduction**
  - **Light production in LAr**
  - **Light propagation in LAr**
  - **What can we use light for?**
- SBN light reconstruction: current performance and next steps
  - SBND
  - ICARUS
  - MicroBooNE
- Conclusions

Light production in LAr

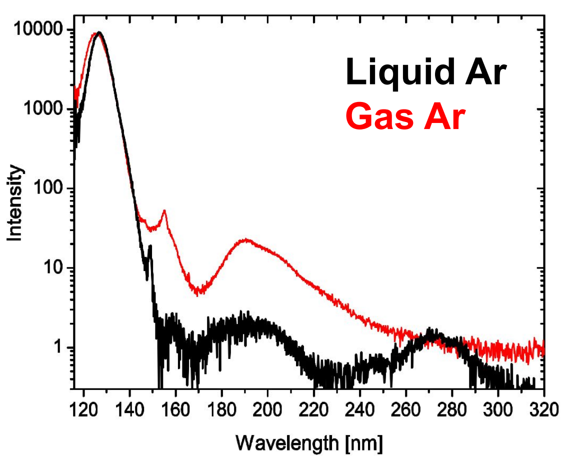
- ➔ LAr is a prolific scintillator (~40k photons/MeV in absence of E field)
- ➔ Argon dimers de-excitate from 2 states: singlet and triplet, commonly referred as the fast (prompt) and slow (late) light components.
- ➔ The emitted photons peak at 127 nm (VUV) region.

LAr scintillation light signal





Emission spectra of argon

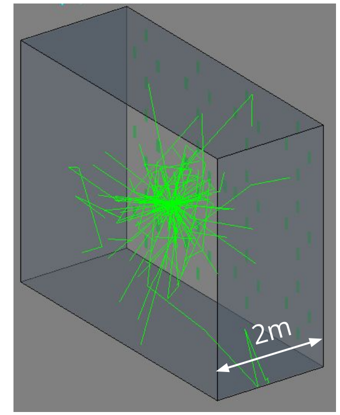


EPL (2010), *91*(6), 62002

Light propagation in LAr

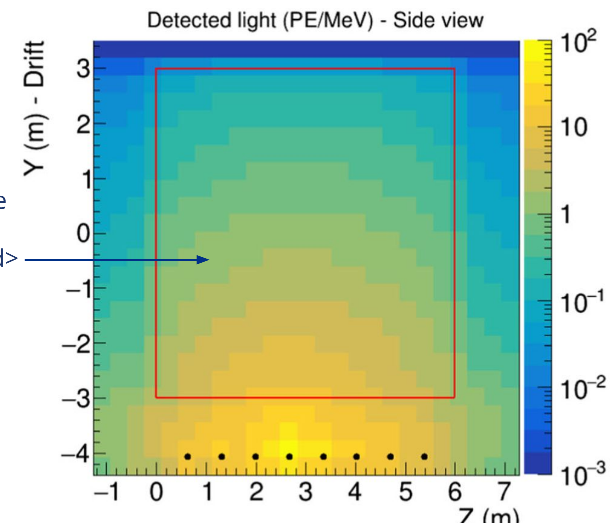
- ➔ Reported values on 127 nm Rayleigh length are ~1 m in LAr [1], and λ_{420nm}>10 m to visible light.
- ➔ Different approaches to compensate for the light dispersion:
  - Dope LAr with Xe, à la ProtoDUNE.
  - Use wavelength shifters at long distances from the light sensors (SBND TPB foils).
- ➔ Similar ideas: convert 127 nm light to a longer wavelength where scattering length is bigger.
- ➔ Light velocities in LAr ~ns/m:
  - Vis : 24 cm/ns - 4 ns/m
  - VUV: 13 cm/ns - 7.6 ns/m

VUV Light



Visible Light

G4 standalone simulation



Notice the light yield drop for d> 2/3m

ProtoDUNE DP, Eur. Phys. J. C (2022) 82:618

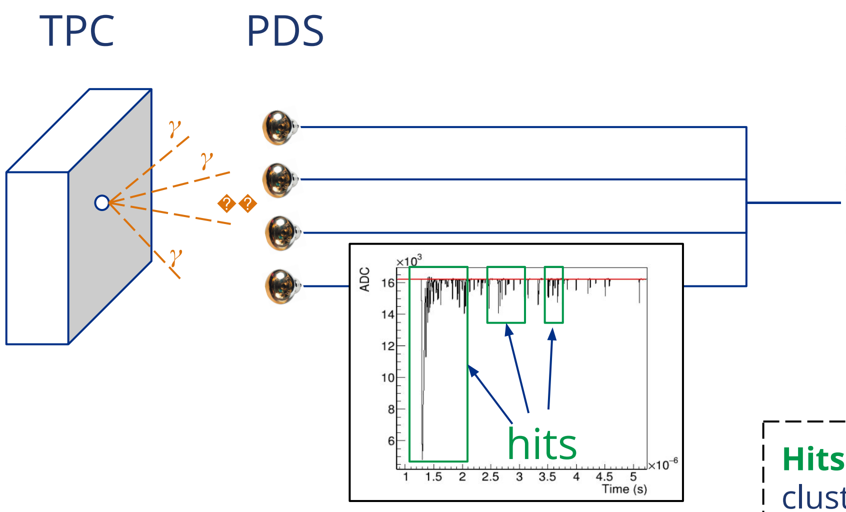
1. M. Babicz et al 2020 JINST 15 P09009

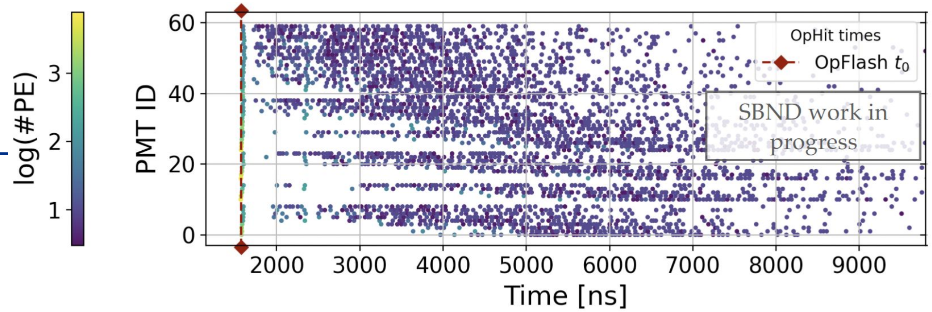
What can we use light for?

➔ Photon detection systems (PDS) have been used in LArTPCs mainly for triggering (thanks to the fast light propagation), but they can offer much more.

➔ After processing light signals, we end up with a list of "hits": charge depositions at specific times, for each PDS sensor.

➔ We can also use the sensor position to extract topology information of the interaction.

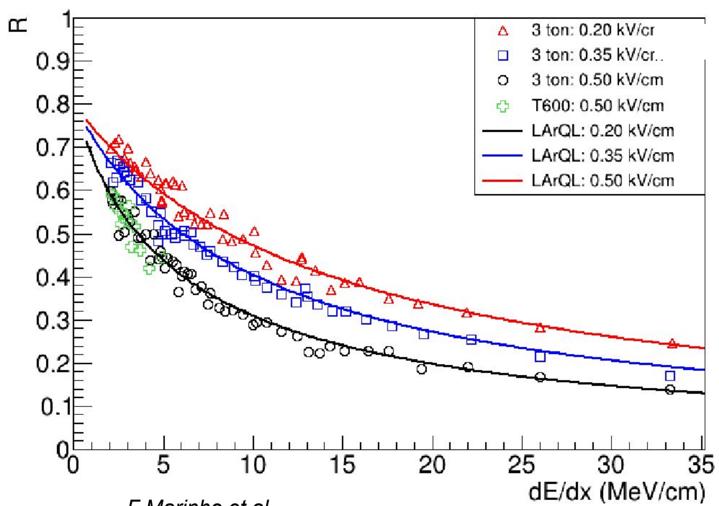




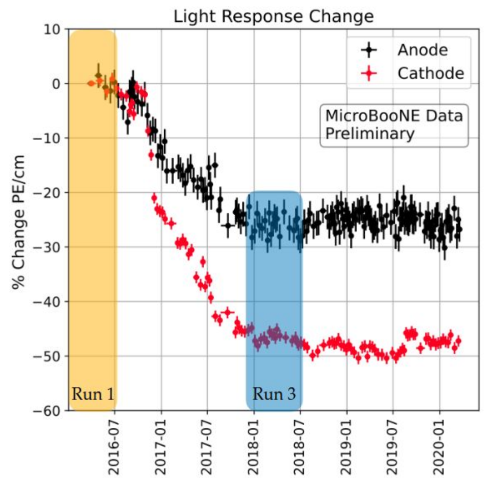
Hits from different PDS sensors are clustered in time and/or spatial coincidence to form **Flashes** (similar to tracks-showers)

Applications: calorimetry

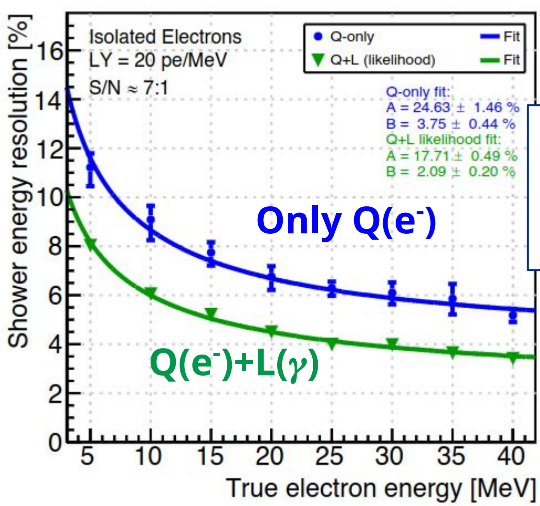
- ➔ Area of light **Hits** is related to the arriving #Photons.
- ➔ Light Yield (PEs/MeV) depends on the distance of the energy deposition to the sensor.
- ➔ It also depends on the amount of the deposited energy (dE/dx), due to Charge-Light anticorrelation.
- ➔ MicroBooNE has observed a reduction of LY over time not yet explained (degradation of wavelength-shifter materials, impurities …)



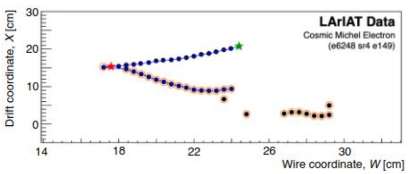
F Marinho et al, JINST, 17(07), C07009.



[MicroBooNE,NOTE-1119-PUB]

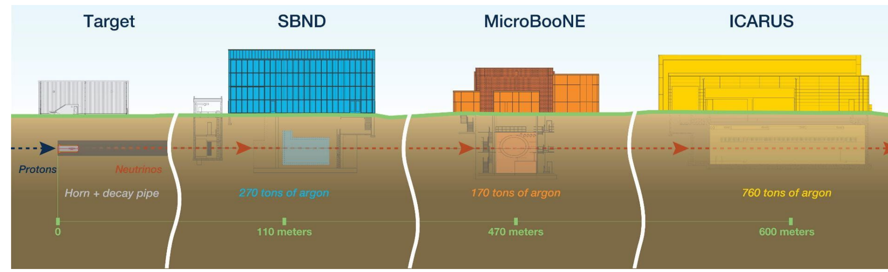


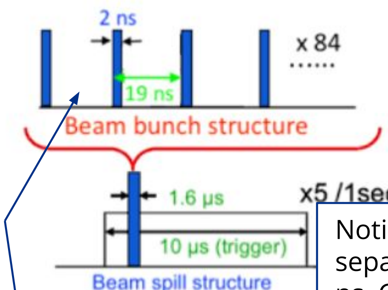
LArIAT showed how photon calorimetry enhances low energy shower reconstruction using Michelle Electrons [*Physical Review D, 101(1), 012010.*]



Applications: timing

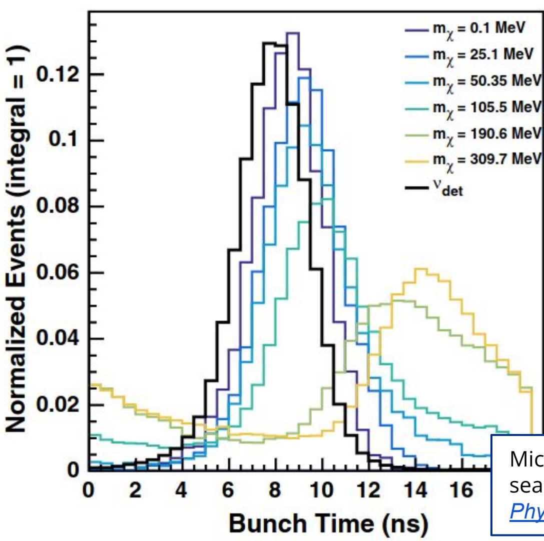
- ➔ Resolution of O(10ns) is sufficient to remove all out-of-time cosmics (muons crossing the TPC before-after the BNB window)
- ➔ Resolutions below 2-3 ns allow to resolve the BNB structure
  - ◆ Removes part of in-time cosmics
  - ◆ Powerful discriminant to search for long-lived BSM particles!
- ➔ Requires to properly correct propagation inside TPC, cable delays, electronics… and also precise event generators with O(ns) precision



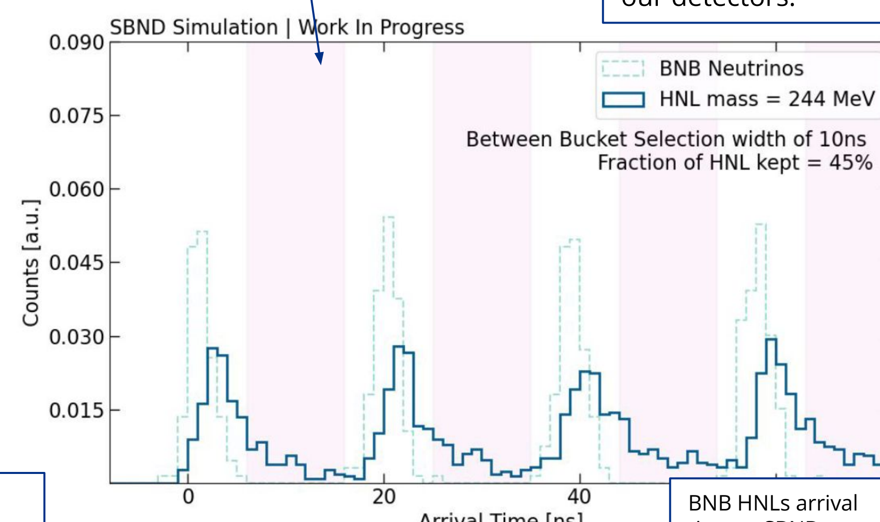


Windows for long lived particles (LLP) without SM BG

Notice BNB bunch separation is ~19 ns. Comparable to propagation inside our detectors.



MicroBooNE dark matter searches with bunch-timing
Physical Review D, 98(11), 112004

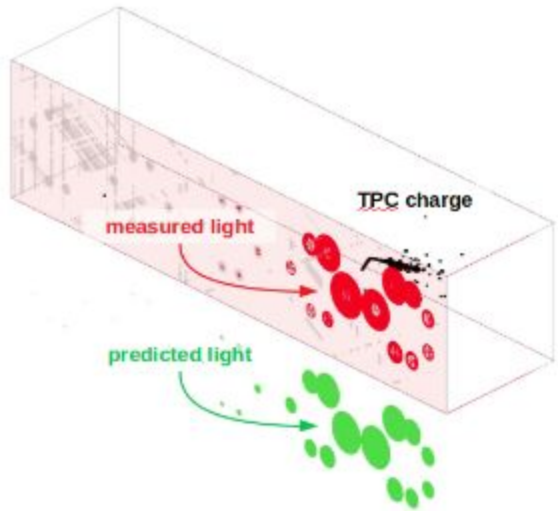


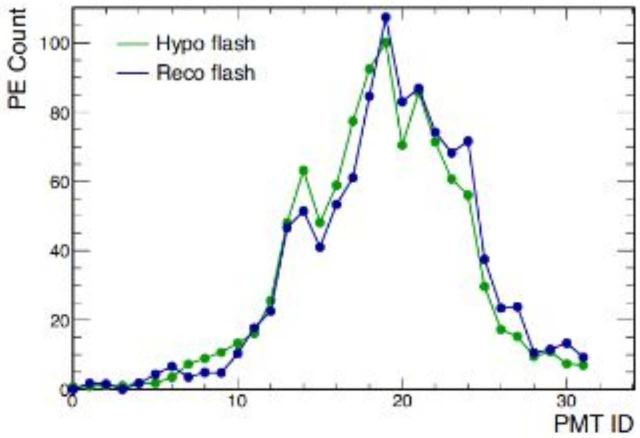
BNB HNLs arrival time at SBND

Combining information: Flash matching

- ➔ Requires good time, spatial and energy reconstruction.
- ➔ Make an hypothesis for a charge cluster (track/shower).
- ➔ Find the light cluster (Flash) that better matches the hypothesis.
- ➔ Many-to-many flash matching can be used to isolate interactions in large detectors (MicroBooNE, ICARUS, DUNE FD...)
- ➔ Matching needed to set the drift coordinate of the TPC track/shower (uncertainty due to long electron drift times).

$$\chi = \sum_{n=0}^{32} \frac{\left[\mathrm{PE}^{\mathrm{hypothesis}}(n) - \mathrm{PE}^{\mathrm{reconstructed}}(n)\right]^2}{\sigma_{\mathrm{PE}}}$$

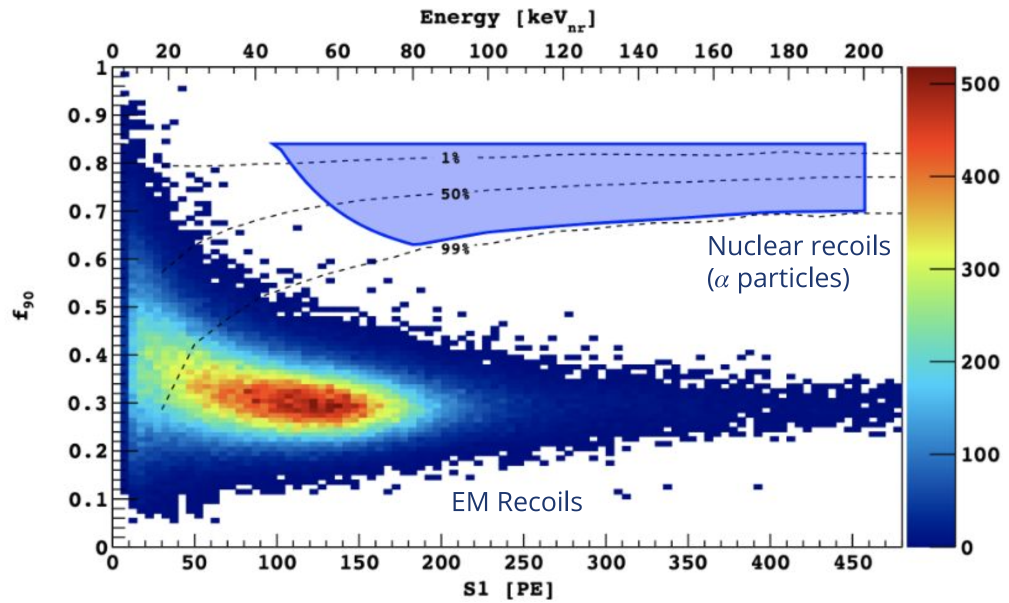




MicroBooNE, *JINST* 15.03 (2020): C03023

Applications: Particle ID

- Different particles in LAr have different fast/slow ratios.
- Main separation is between α particles and the rest.
- Dark matter experiments such as DarkSide, have used it to put constraints on WiMP searches.



DarkSide,
Physical Review D, 98(10), 102006

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  - Light production in LAr
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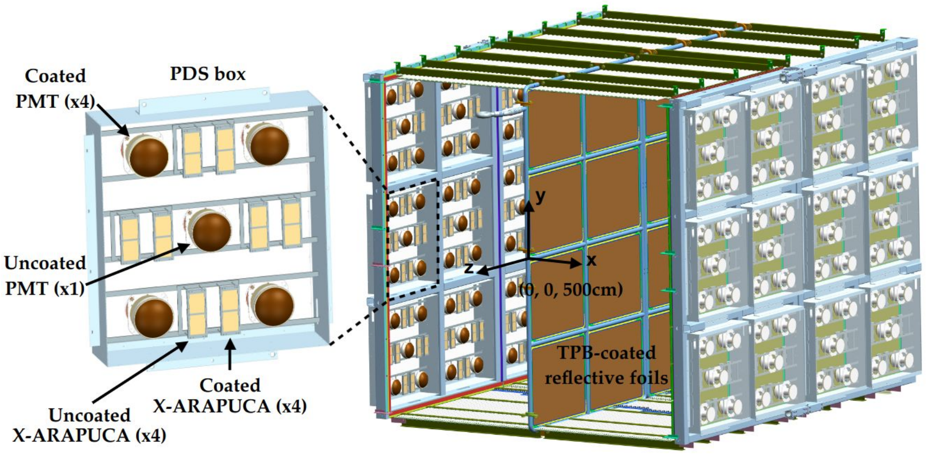
  - What can we use light for?
- **SBN light reconstruction: current performance and next steps**
  - **SBND**
  - **ICARUS**
  - **MicroBooNE**
- Conclusions

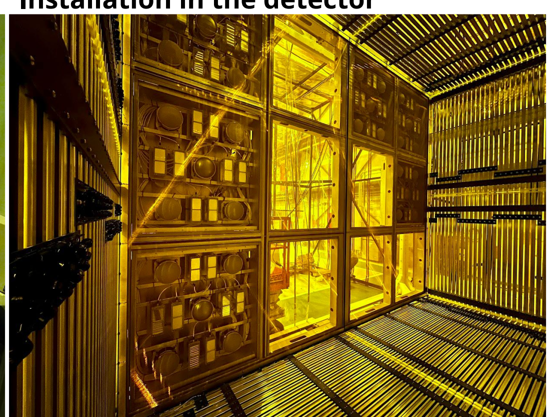
SBND PDS



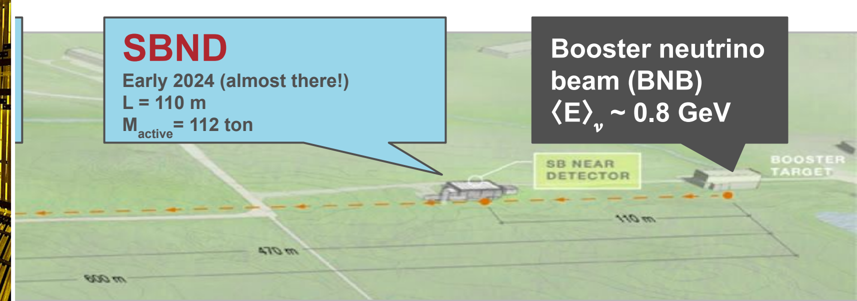
- ➔ 312 total sensors (half each TPC).
  - ◆ 120 PMTs
  - ◆ 192 X-ARAPUCAs [2]
- ➔ VUV light re-emitted as vis in the middle (TPB foils).
- ➔ Coated are sensible to VUV and vis light.
- ➔ Uncoated are sensible to vis light only.
- ➔ Thanks to both light components, we can estimate the drift direction as well using **only** light info.
- ➔ LAr filling completed past month, preparing to take data!

Single box

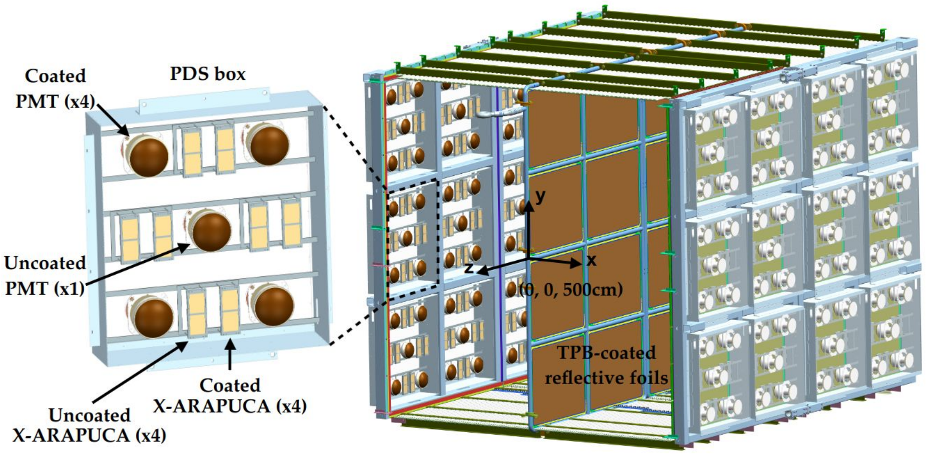
Installation in the detector



2. A.A. Machado et al, 2018 JINST 13 C04026



SBND PDS



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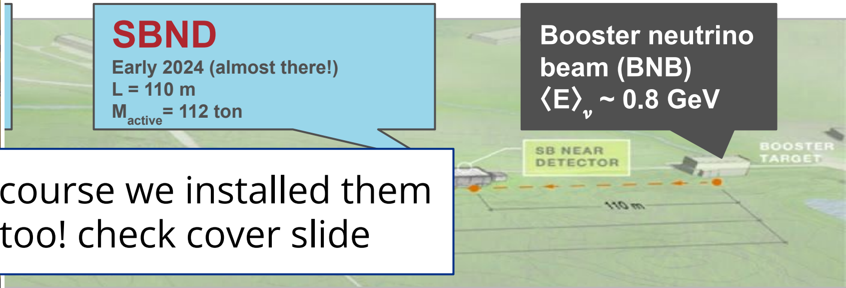
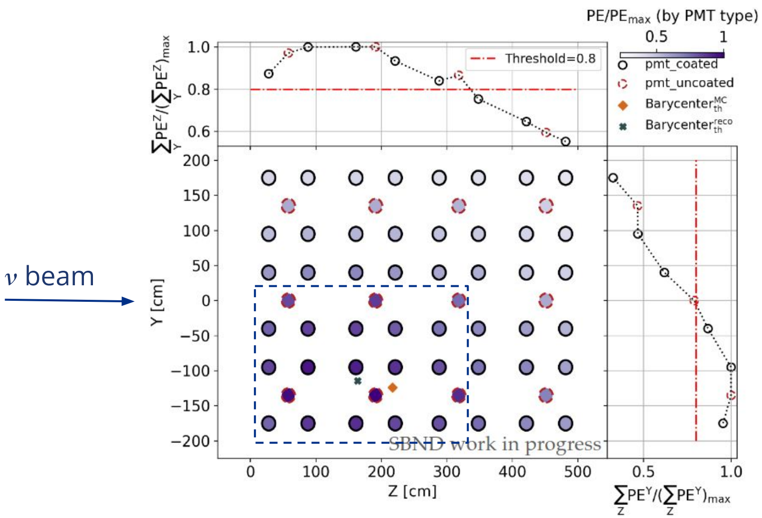
Of course we installed them too! check cover slide

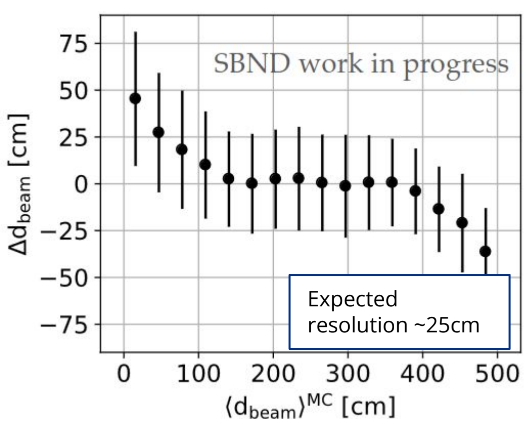
2. A.A. Machado et al, 2018 JINST 13 C04026

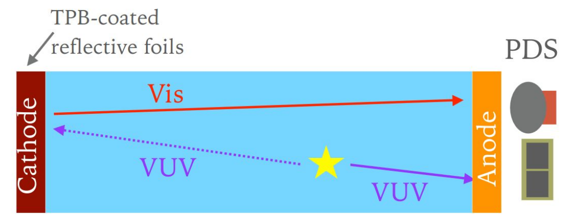


Light reconstruction: SBND

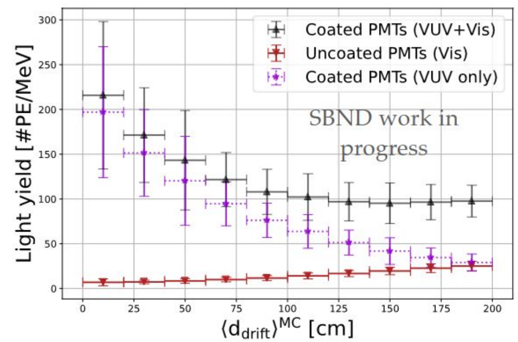
Non-drift coordinates can be reconstructed using the position of the hottest sensors ($Z = d_{beam}$)

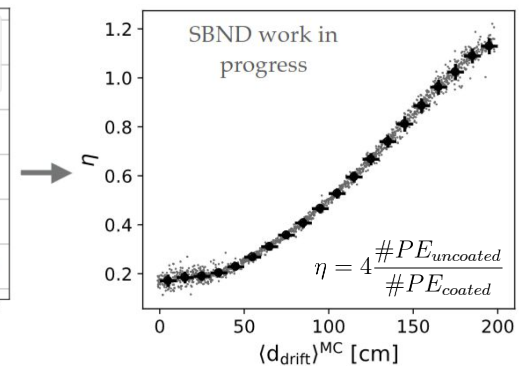


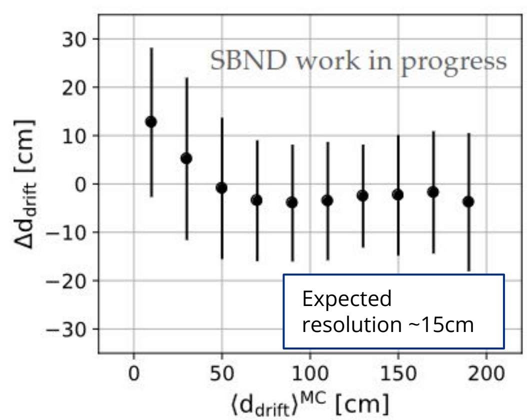




Drift coordinate can be estimated using the ratio of visible and VUV light (uncoated/coated).

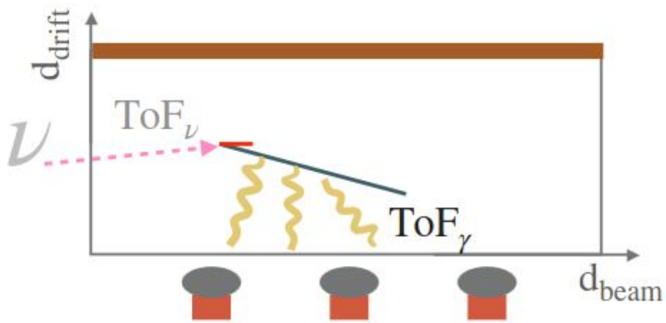




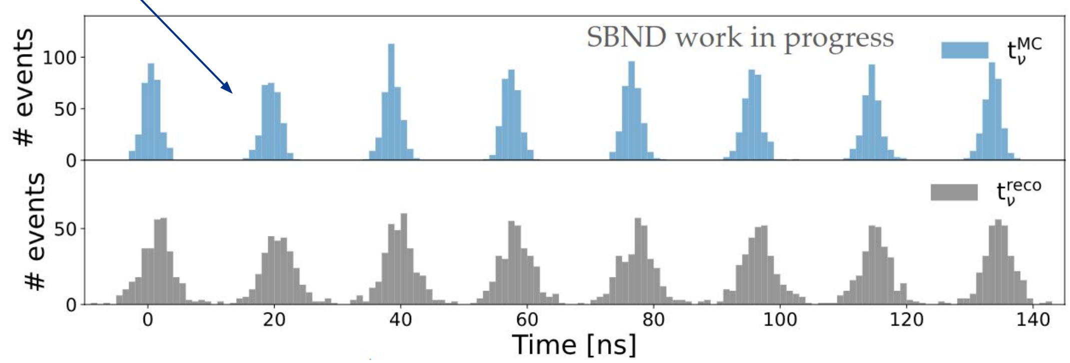


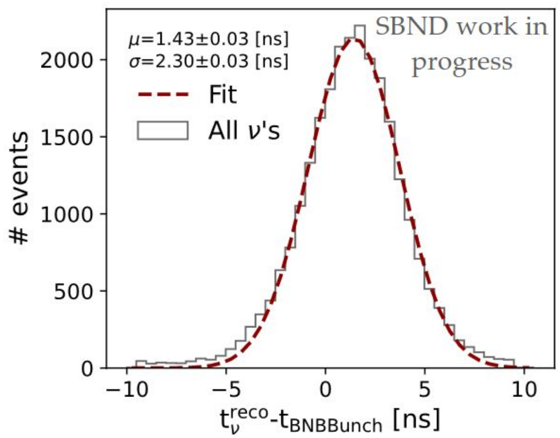
Light reconstruction: SBND II

- ➔ After correcting for the time of flight (ToF) of the neutrino inside the TPC and the ToF of the photons, SBND can recover the BNB structure using only light information.
- ➔ The expected time resolution is O(2ns), while only using light (TPC info will enhance the performance).



Neutrino arrival times at upstream wall





μBooNE PDS

➔ 32 PMTs with TPB coated plates

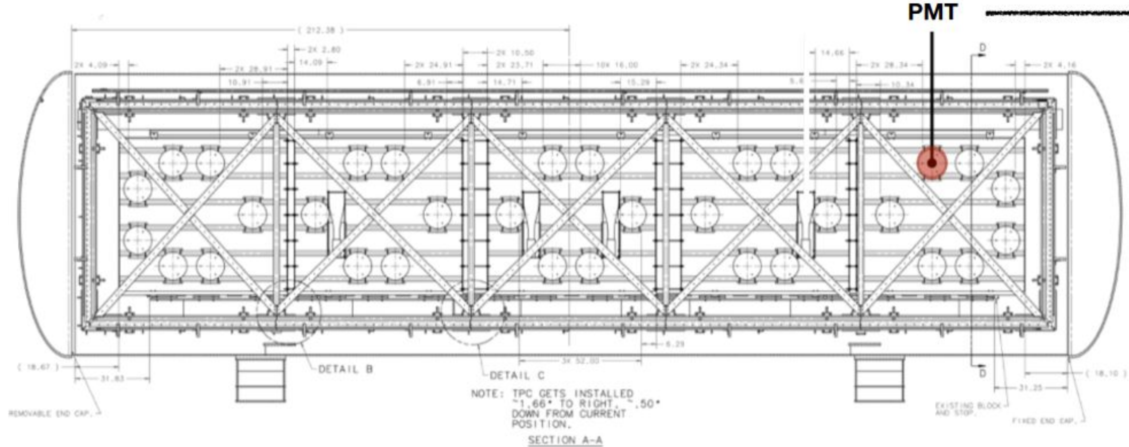
➔ Up to 2.6 m drift distante

➔ 10.3 m in beam direction

➔ Slow sampling frequency (15.6ns)
compensated using a electronic shaper (60ns)

ν beam

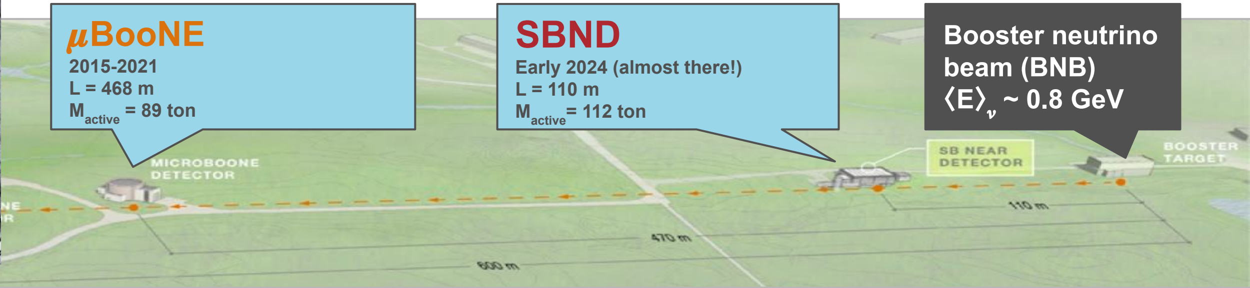
PMT



γ_{VUV}

γ_{VIS}

Frontal view



μBooNE
2015-2021
L = 468 m
M_{active} = 89 ton

SBND
Early 2024 (almost there!)
L = 110 m
M_{active} = 112 ton

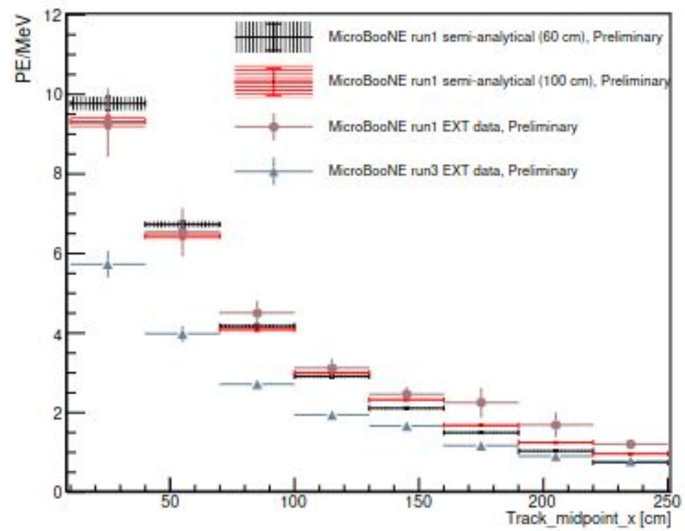
Booster neutrino beam (BNB)
$\langle E \rangle_\nu$ ~ 0.8 GeV

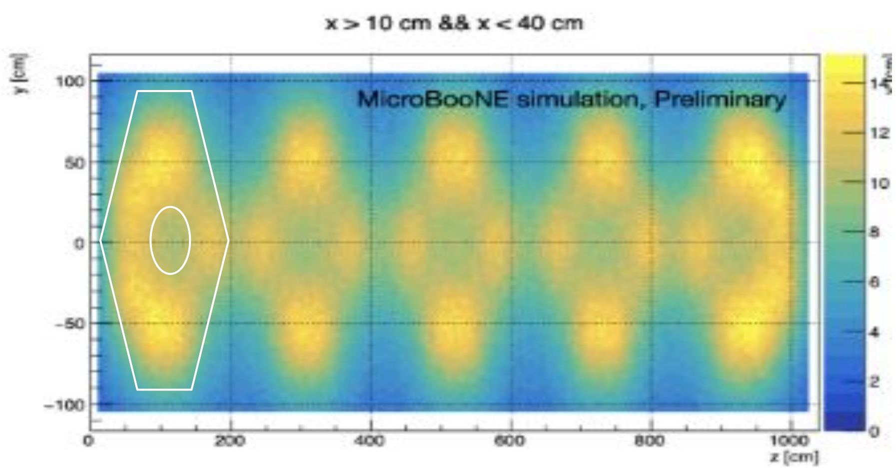
Light reconstruction: μBooNE

Analysis performed with point-like proton candidates aligned with PMTs. Different Rayleigh scattering lengths tested (60,100 cm), not finding huge differences between them.

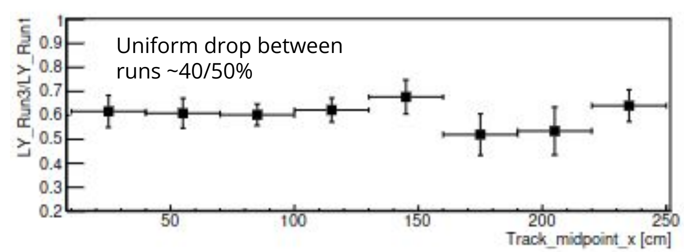
Factor of x5-6 light yield drop from anode to cathode (2.5 m propagation).

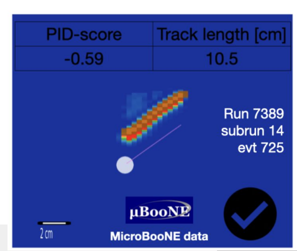
MICROBOONE-NOTE-1119-PUB





Hexagonal cut selecting hot areas only





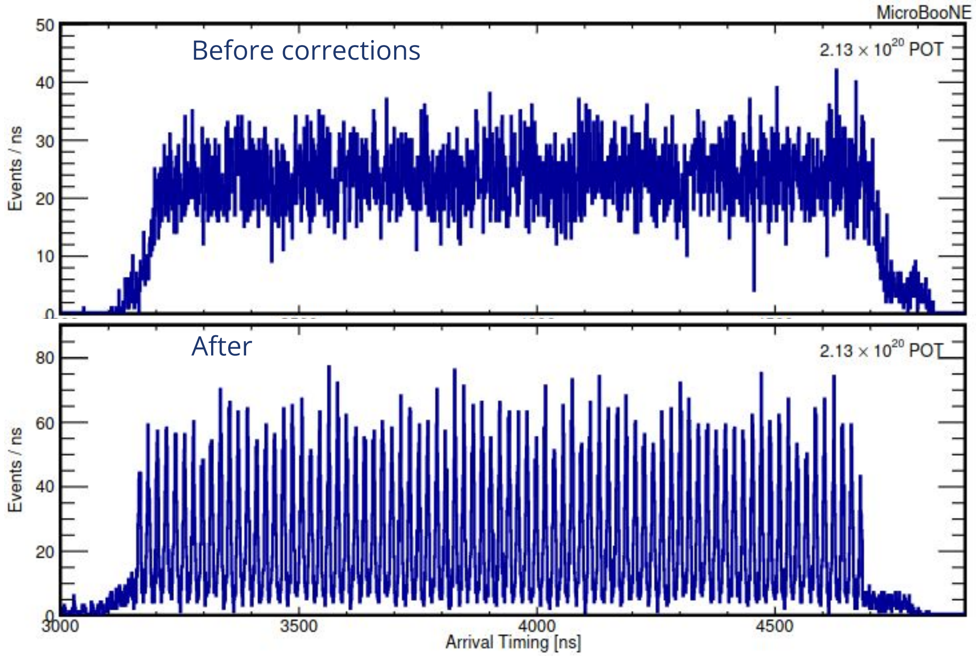
Proton candidate

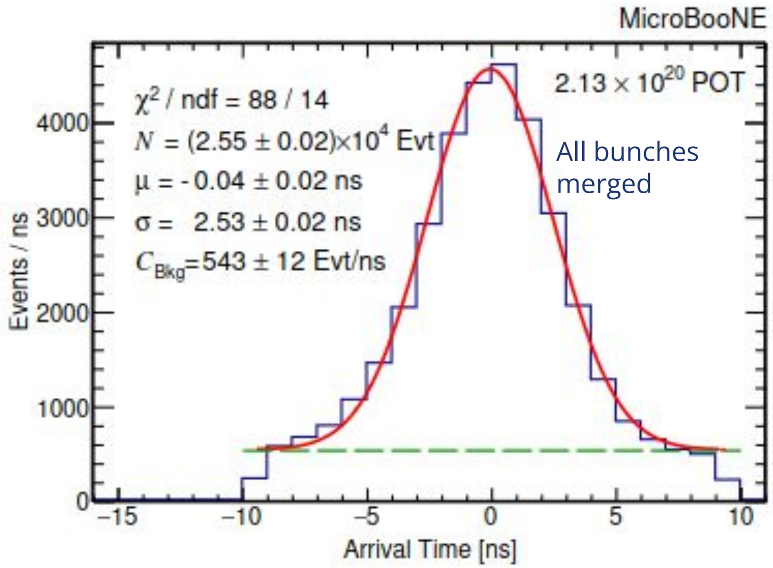
Light reconstruction: μBooNE II

Recently demonstrated O(ns) timing resolution!

[Phys. Rev. D 108, 052010](#)

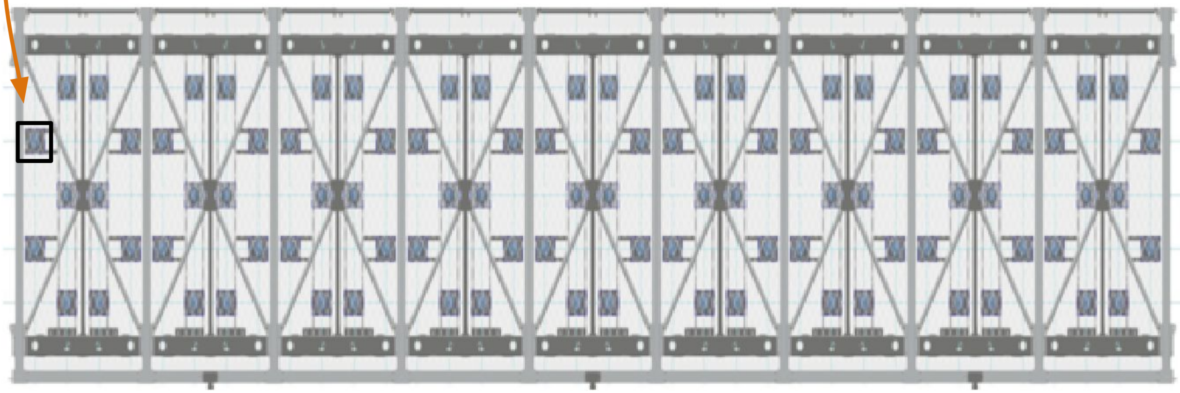
Check Dante's talk for all the details.



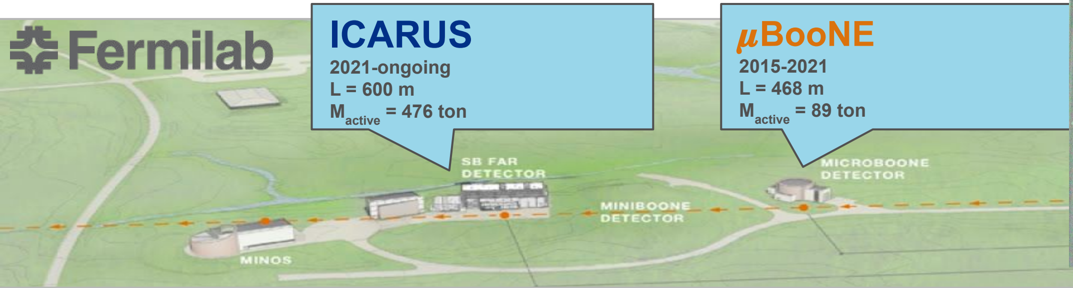


ICARUS PDS

- ➔ Up to 360 PMTs (90 on each TPC)
- ➔ 2 ns tick sampling (500 MHz)
- ➔ TPB coating evaporated on top of the PMTs surface



Frontal view

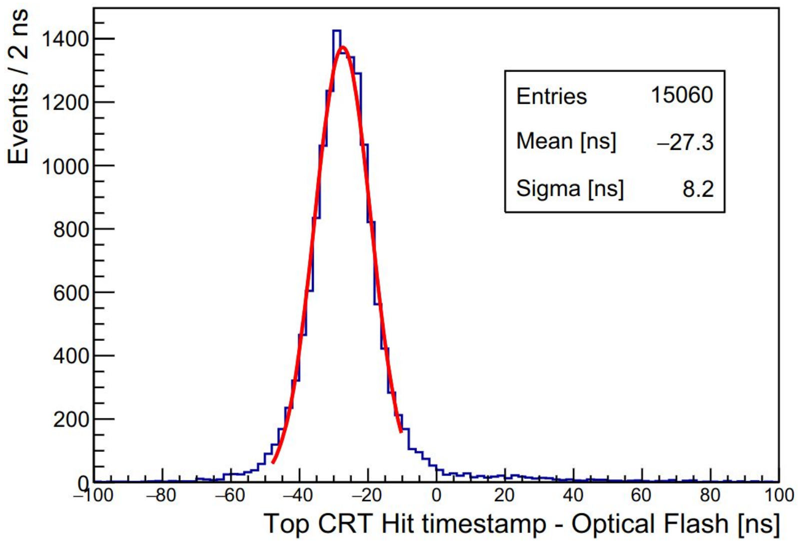


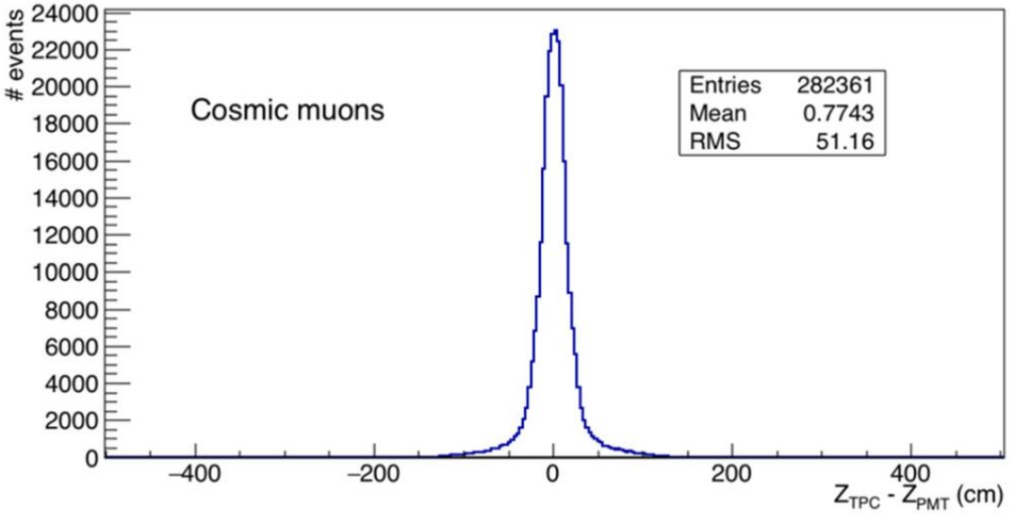
Light reconstruction: ICARUS

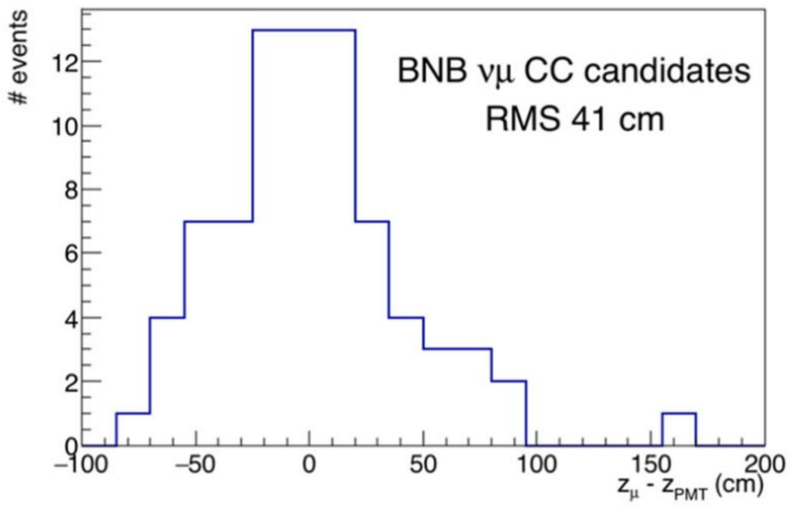
Good agreement between TPC and PDS barycenters (beam coordinate) using cosmic muons and scan selected BNB candidates (bottom)

EPJ C 83(6), 467, 2023

Also tested cosmics time of flight using CRT and PMTs (flash) time with good agreement.



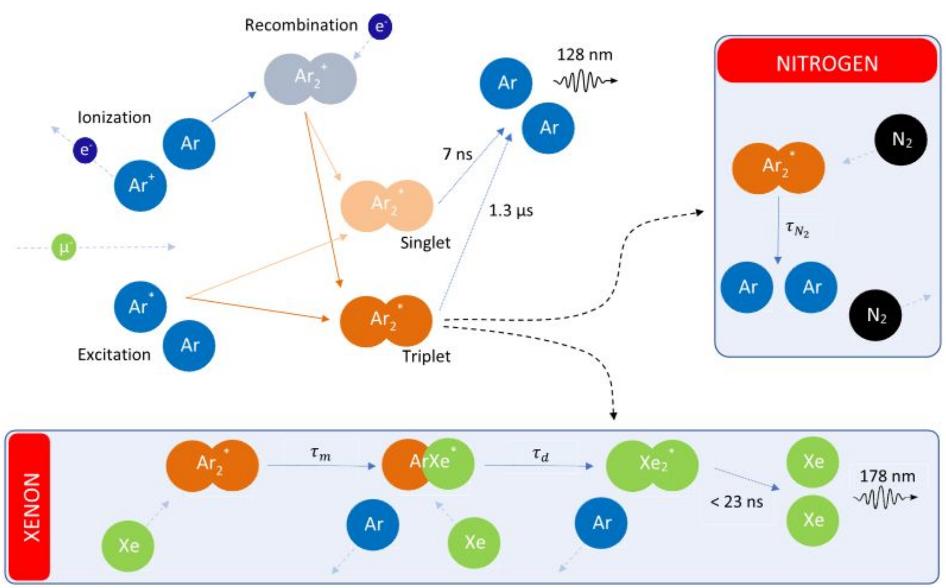


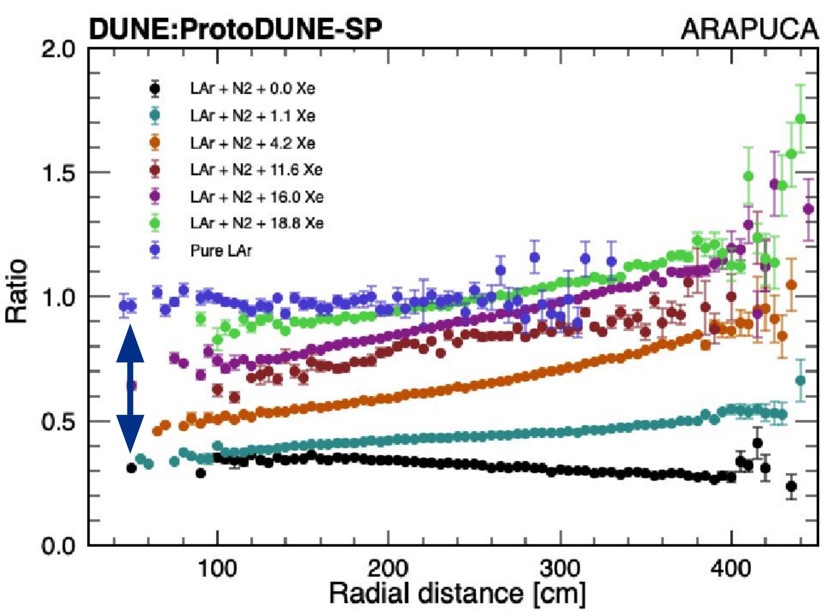


Caveats: impurities

Xenon doping can improve light yield, but other elements (N2), can de-excite the Argon dimers without producing light at all!

Needles to say, purity is key for good performance.



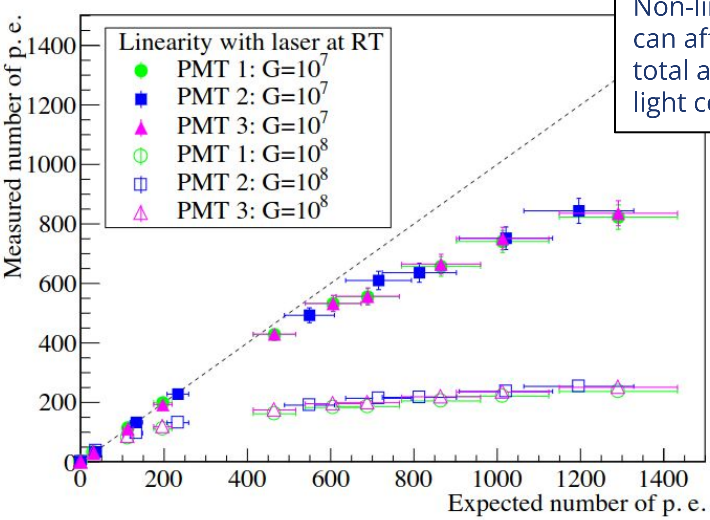


[Niccolò Gallice and the DUNE collaboration 2021 J. Phys.: Conf. Ser. 2156 012197]

Caveats: non-linearities

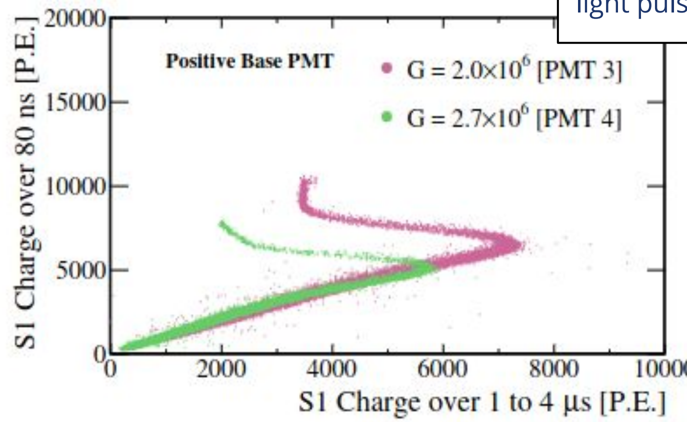
Real world detectors suffer from effects such as dark current, correlated noise, saturation… that will smear and bias our distributions. We better characterize them if we want our simulations to match our data!

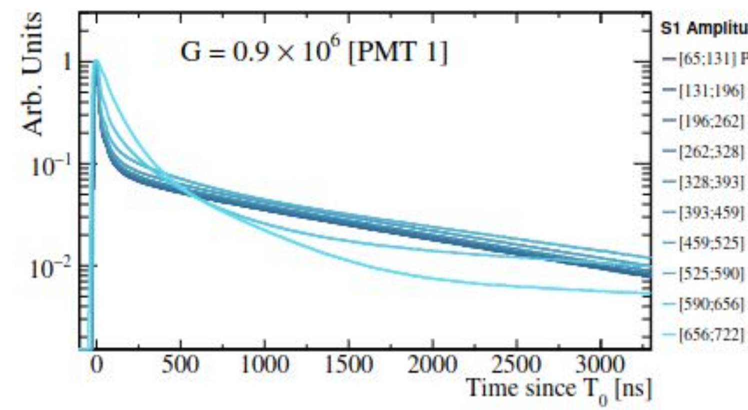
Non-linearities can affect the total amount of light collected….



ProtoDUNE DP,
J.A. Soto Oton Phd. Thesis

And even the shape of the light pulses!



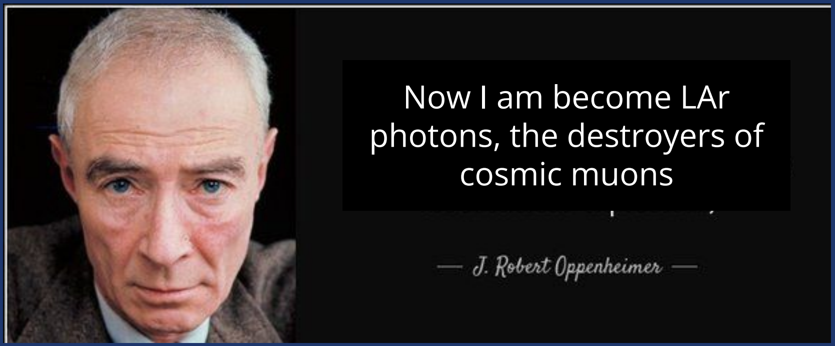


WA105,
C.F. Lastoria Phd.Thesis

Conclusions

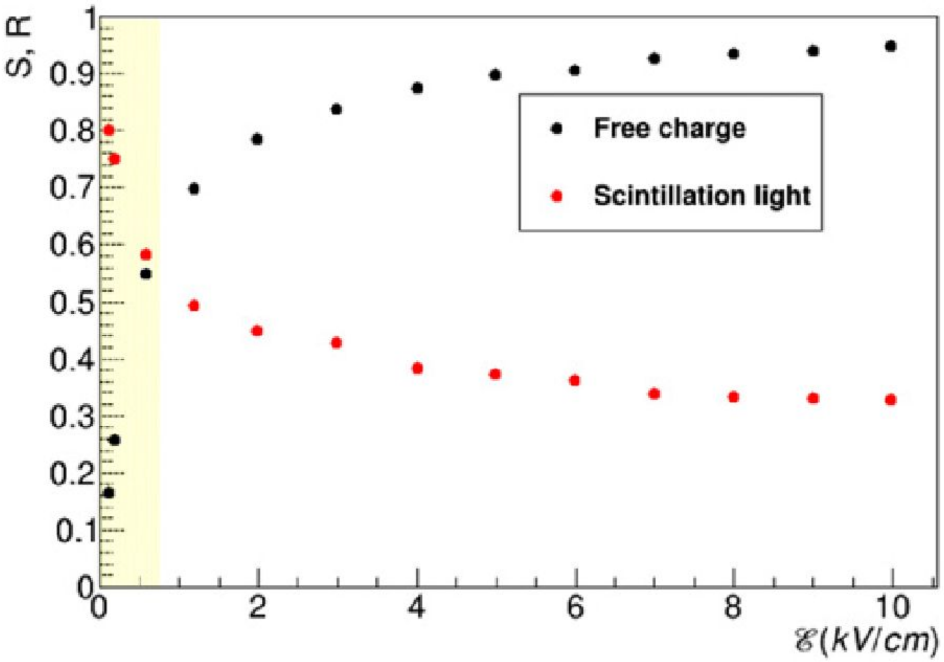
- ➔ Scintillation light provides many more capabilities beyond triggering.
- ➔ SBND design with 2 light components allows to also estimate the drift coordinate using purely light information.
- ➔ In combination with TPC and CRT information (well-known topology events). Provides complementary calorimetry, especially good for low-E events.
- ➔ Allows to measure many properties in LAr such as time of flight, Rayleigh scattering length, group velocity of photons, TPB efficiencies, ***your own idea*** …
- ➔ All SBN experiments will be capable of resolving interaction times with O(ns) precision. This opens the door for LLP BSM searches in BNB-background free regions.

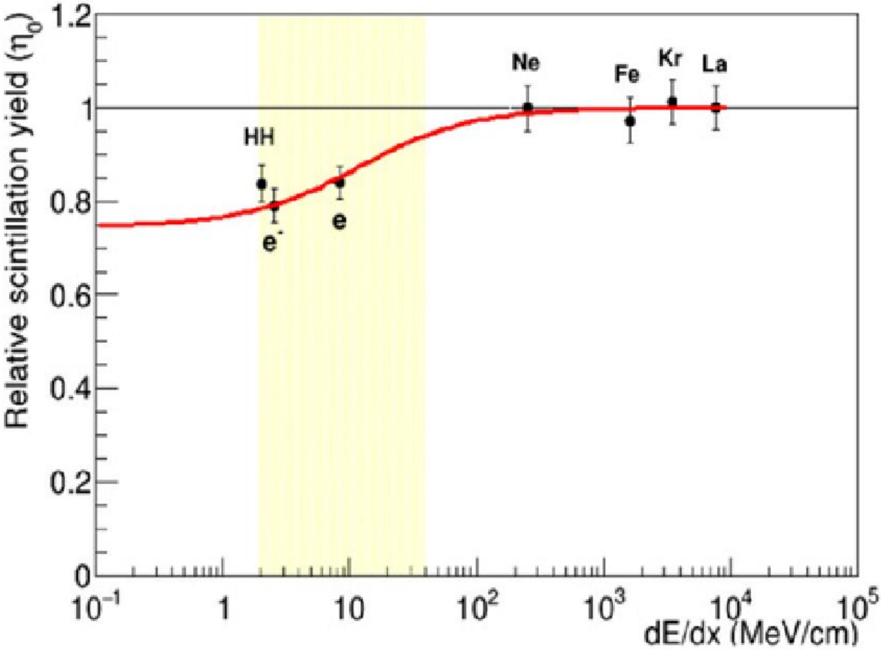
Thanks!


Now I am become LAr photons, the destroyers of cosmic muons
— J. Robert Oppenheimer —

Backup

Charge light anticorrelation





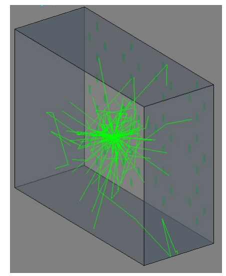
Light production in SBND

2 m drift

TPB coated foils

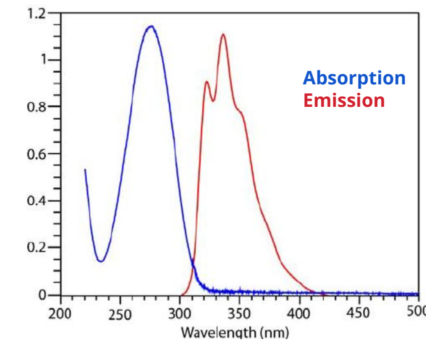
Photon Detection System

VUV Light



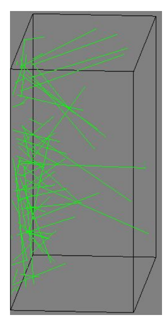
- **Directly produced in LAr volume**
- **Rayleigh scattering length ~1 m**
- **TPB & P-Terphenyl (pTP) coating of PDS sensors**

pTP absorption & emission spectra



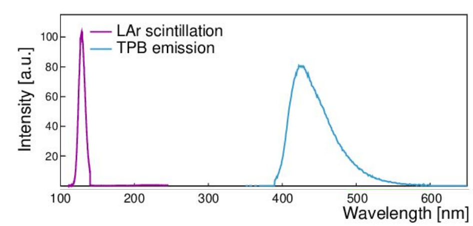
Nuclear Science Symposium (pp. 2228-2233), 2008

Visible Light



- **Re-emitted by TPB foils in the cathode plane**
- **Rayleigh scattering length ~20 m**

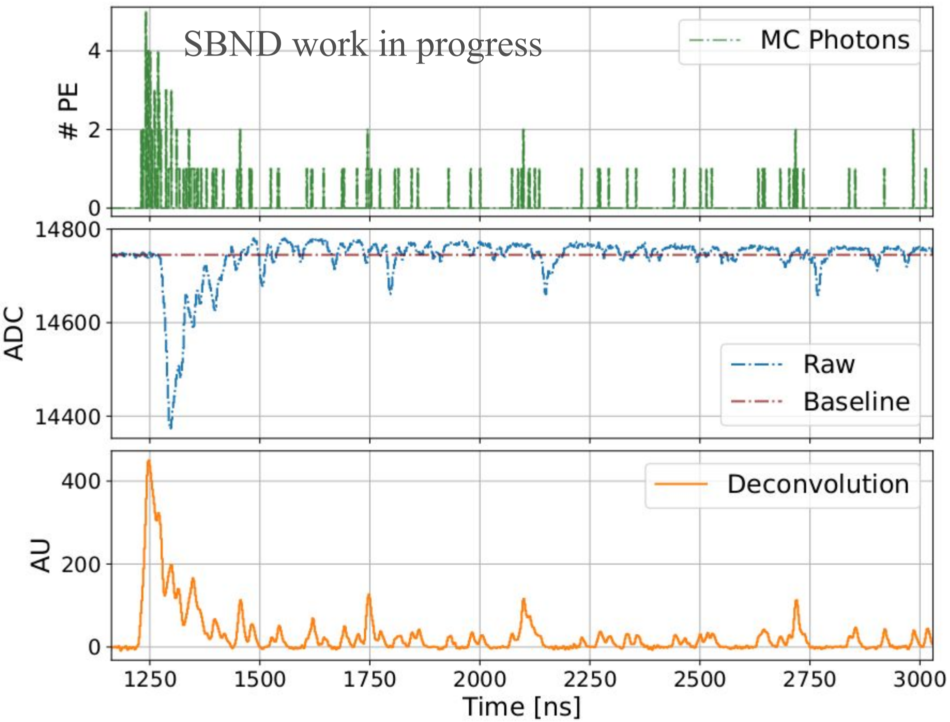
TPB emission spectra



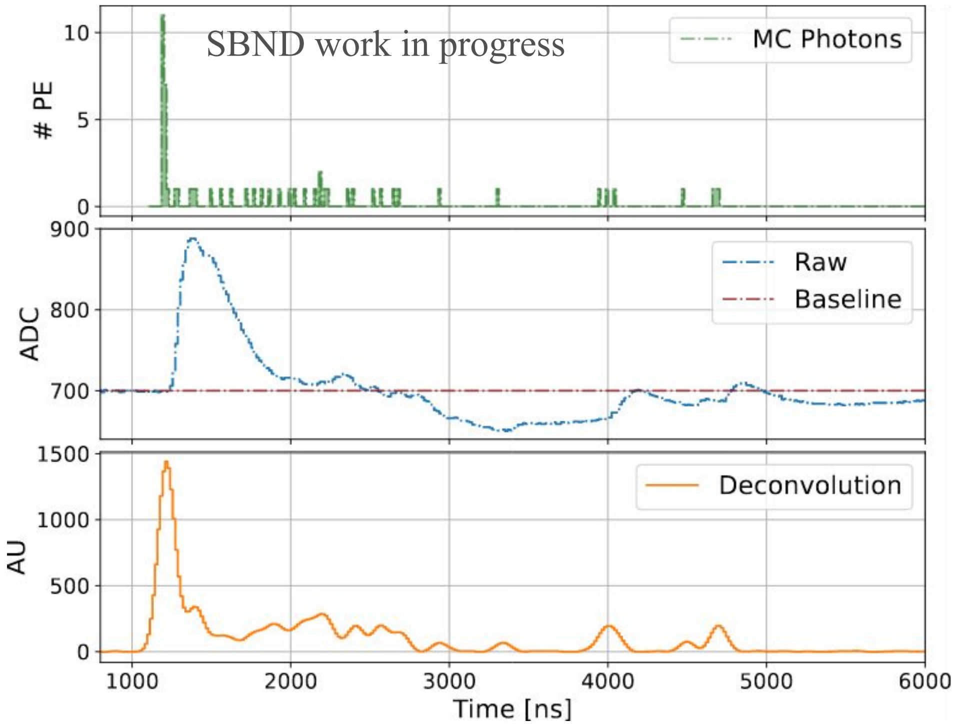
Eur.Phys.J.C 82 (2022) 5, 442

Light signals deconvolution

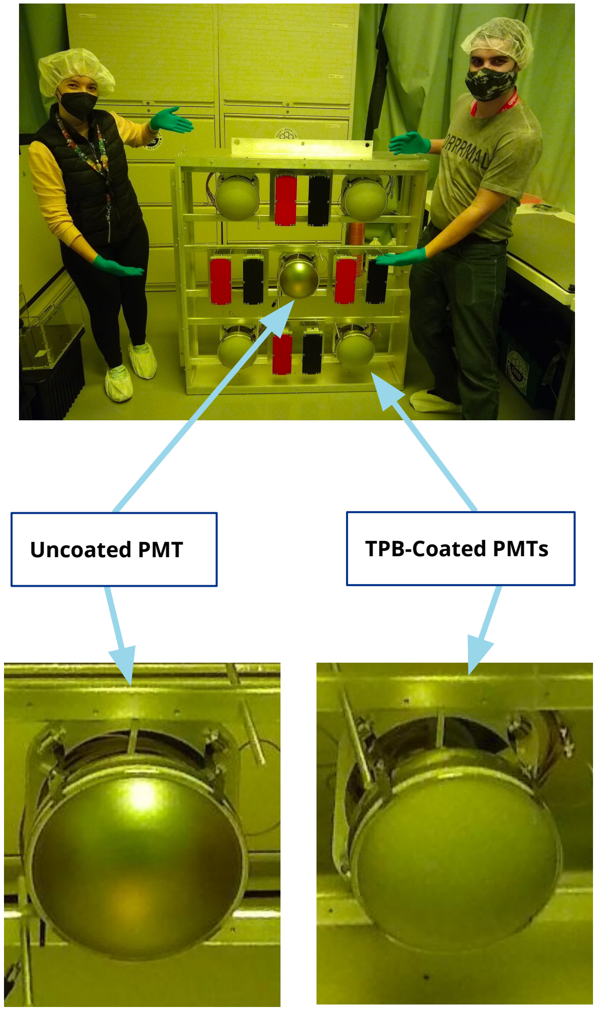
Simulated PMT Signal



Simulated X-ARAPUCA Signal



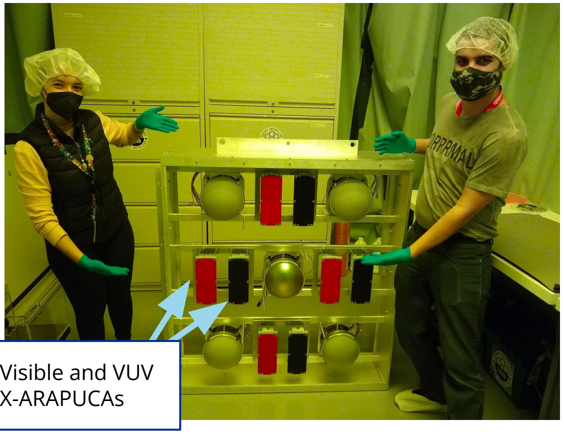
PDS: Photomultiplier Tubes



Left & right: uncoated and coated PMTs installed in PDS Box

- ➔ **120 total 8” Hamamatsu R5912 PMTs**
  - ◆ **96 TPB coated PMTs (VUV +visible light)**
  - ◆ **24 uncoated PMTs (visible only)**
- ➔ **500 MHz CAEN readout.**
- ➔ **PMT system already tested and characterized by CCM experiment**
- ➔ **Used for trigger building.**

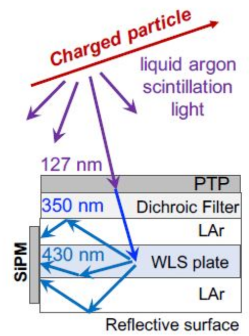
PDS: X-ARAPUCAs



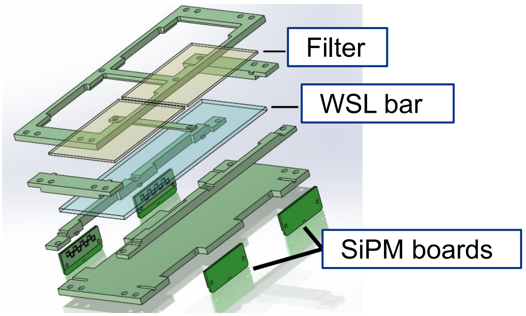
SiPMs	WLS Bar	Filter	Modules in SBND
SensL MICROFC-30050-SMT	**Eljen 286**	**pTP coated 400 nm cutoff**	**88**
SensL MICROFC-30050-SMT	**Eljen 280**	**450 nm cutoff**	**88**
HPK 6050-VE	**Glass to power B.**	**pTP coated 400 nm cutoff**	**6**
HPK-VE 6050-VE	**Glass to power G.**	**450 nm cutoff**	**6**
HPK 6050-HS (↓bias,↑PDE)	**Glass to power B.**	**pTP coated 400 nm cutoff**	**2**
HPK-HS 6050-HS (↓bias,↑PDE)	**Glass to power G.**	**450 nm cutoff**	**2**

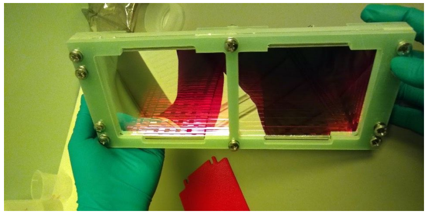
SBND X-ARAPAPUCA configurations

- ➔ **New scalable technology under development.**
- ➔ **Photons get trapped inside the module, increasing collection area. Side SiPMs collect the photons.**
- ➔ **Cut-offs allow for light source discrimination (450nm filter lets only visible light through)**
- ➔ **CAEN readouts: 14-bit 5 MHz and 12-bit 62.5 MHz**
- ➔ **Important R&D for future experiments (DUNE PDS is only X-ARAPUCA based).**



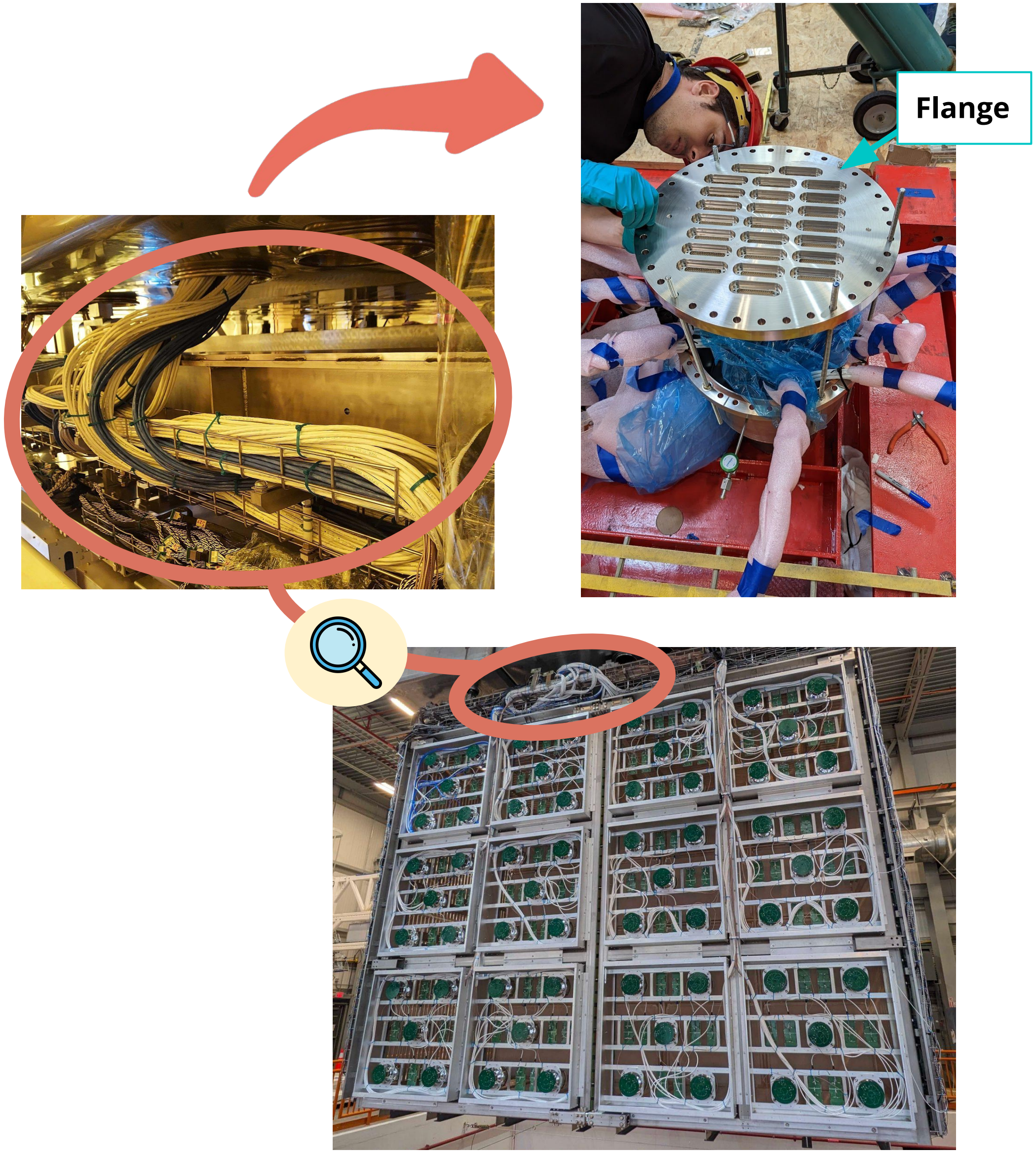
X-ARAPUCA operating principle. Nucl. Instrum. Meth. A, 985 (2021)





Left: SBND X-ARAPUCA mechanical scheme. Right: mounted module

PDS installation



- ➔ **PDS cabling of each box to the top side of the detector.**
- ➔ **Cold-warm connection through flanges at the top of the cryostat.**
- ➔ **QA/QC tests performed at different stages.**

LArTPCs working principle

- ➔ Charged particles produce ionization electrons and scintillation photons inside the TPC.
- ➔ Photon sensors measure the interaction time t_0 with ns precision.
- ➔ Electric field drifts e^- towards anode plane.
- ➔ Wire planes(or other readouts) detect the e^- producing 3D mm-level resolution images.