μBooNE

MicroBooNE as a supernova neutrino detector: using the SNEWS alert as delayed trigger

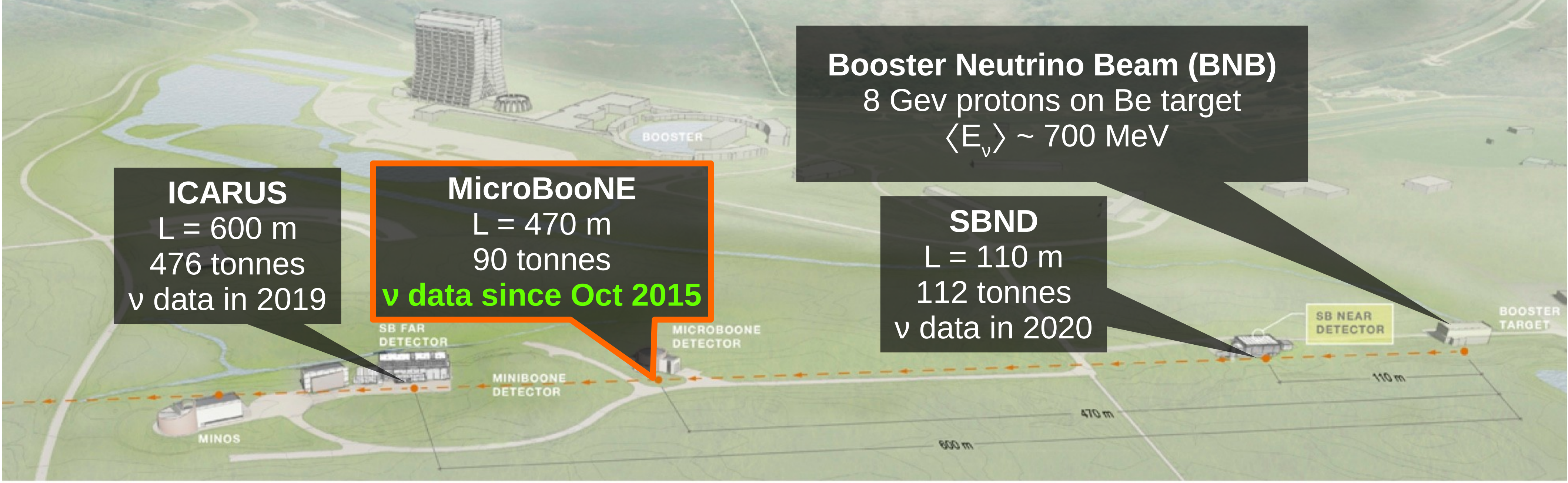
José I. Crespo-Anadón
Columbia University Nevis Laboratories
for the MicroBooNE Collaboration

06/16/2019 SNEWS 2.0: Supernova Neutrinos in the Multi-Messenger Era

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

NEVIS LABORATORIES

The Short-Baseline Neutrino Program at Fermilab



MicroBooNE physics goals:

1) **Investigate the excess of electron-like events observed in MiniBooNE.**

2) **Perform high-precision measurements of cross-sections of ν_μ and ν_e on Ar.**

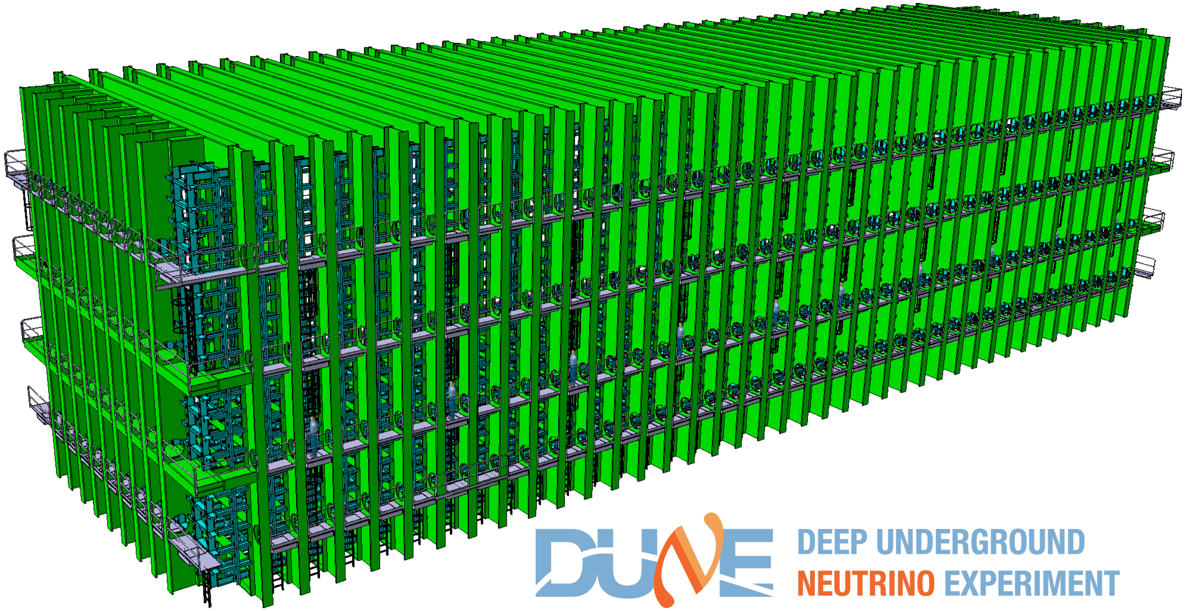
3) **Develop further the LArTPC detector technology.**

4) **Perform searches for astroparticles and exotic physics exploiting the LArTPC capabilities (on-beam & off-beam)**

The Short-Baseline Neutrino Program at Fermilab

μBooNE

90 tonnes
Near surface



DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

4 × 10 kton
1475 m underground

MicroBooNE physics goals:

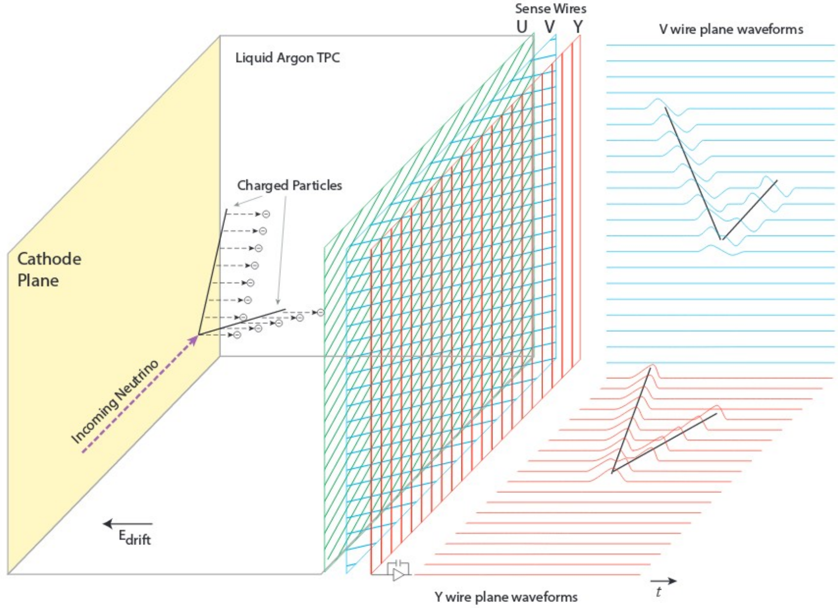
1) **Investigate the excess of electron-like events observed in MiniBooNE.**

2) **Perform high-precision measurements of cross-sections of ν_μ and ν_e on Ar.**

3) **Develop further the LArTPC detector technology.**

4) **Perform searches for astroparticles and exotic physics exploiting the LArTPC capabilities (on-beam & off-beam)**

MicroBooNE TPC

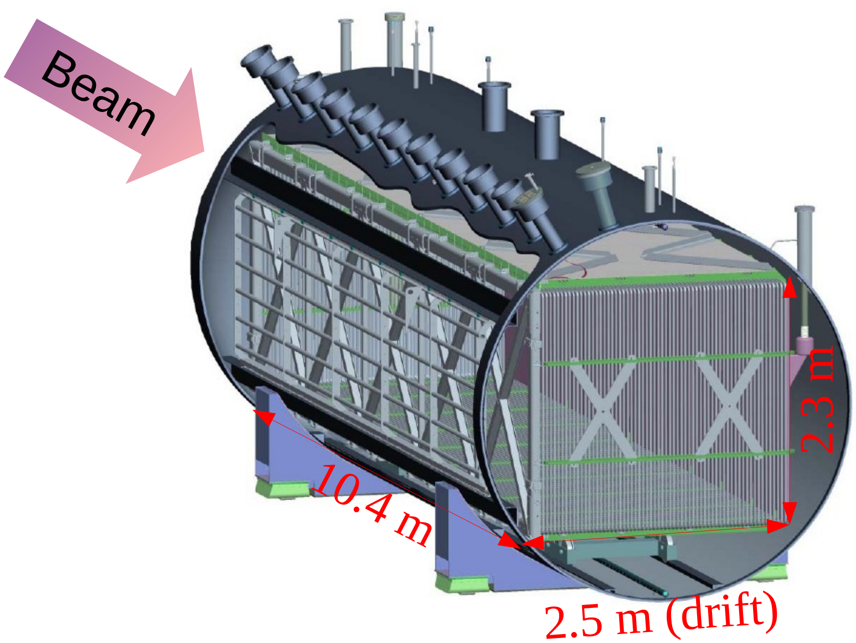


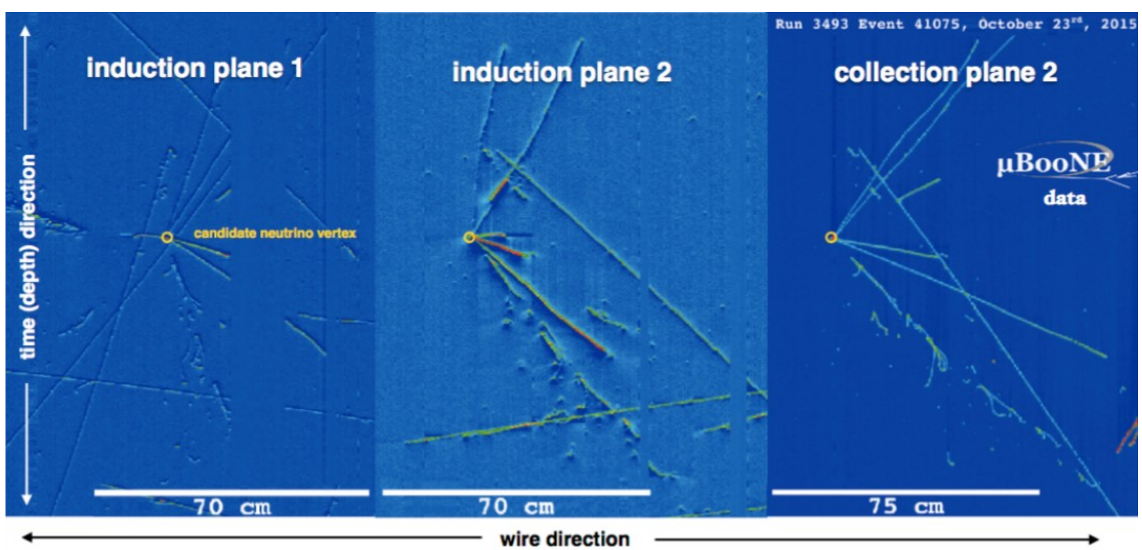
JINST 12 P02017 (2017)

- **90 tonnes of liquid argon (active).**
- **Slow detector.** Drift time: 2.3 ms.
- **Three wire planes** to reconstruct 3D interaction. **3 mm wire pitch**. **8256 channels.**

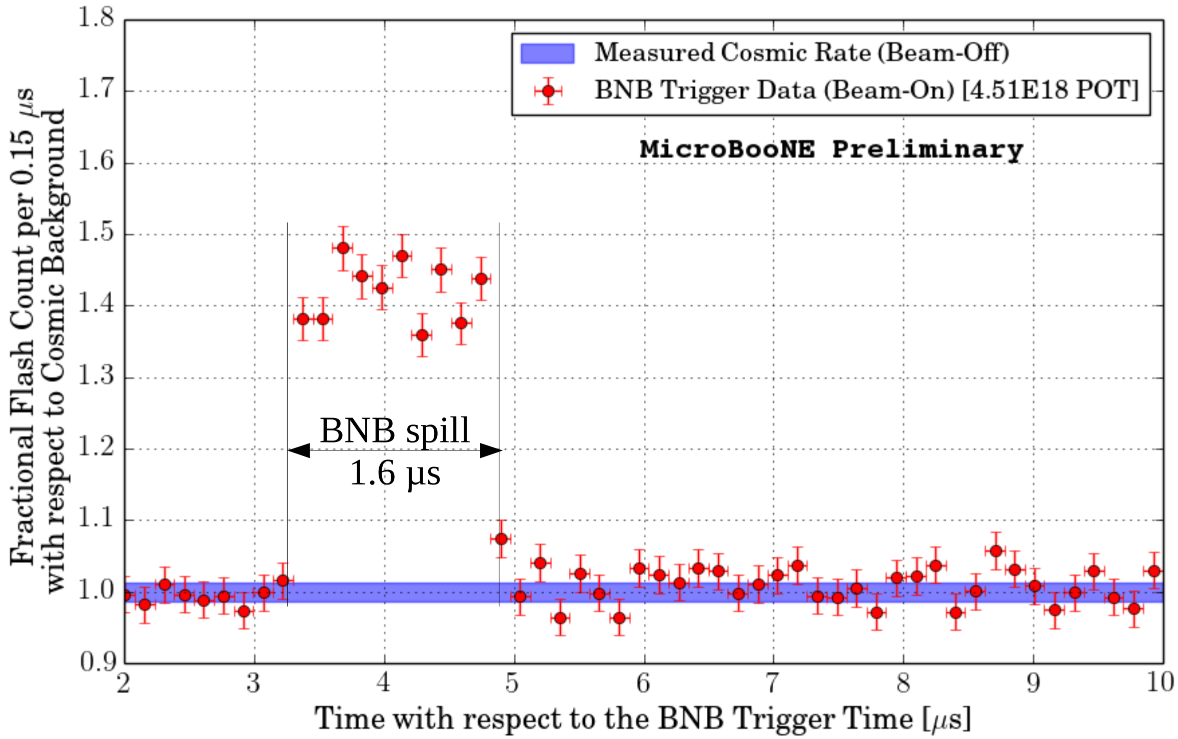
  2 **induction planes** with 2400 wires each at ± 60º from vertical.

  1 **collection plane** with 3456 vertical wires.





MicroBooNE PMT & trigger systems



Detect scintillation light: fast (6 ns)

32 8" Hamamatsu R5912 Cryogenic **PMTs** mounted behind the wire planes.

Custom (**64 MHz**) readout electronics.

- **Level-1 trigger** using accelerator gates (BNB and NuMI) and random triggers (for cosmics).
- **Level-2 trigger** in software using PMT information in the beam window.

SN neutrinos in MicroBooNE

- Expectation at MicroBooNE:
  - **~ O(10) events** for a SN at 10 kpc.

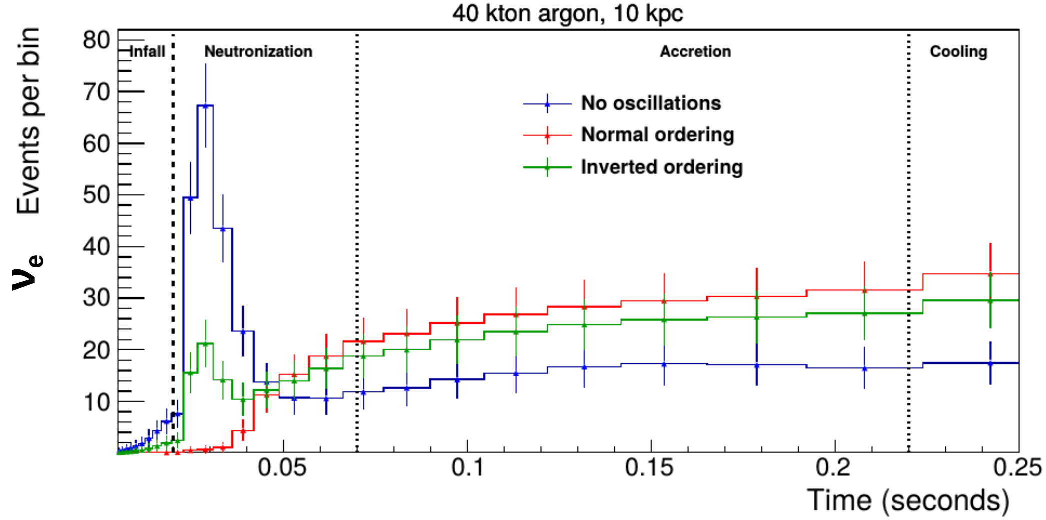
    Similar number for SBND
  - CC: ν_e + ^{40}Ar → e^- + $^{40}K^*$ (E_{th} ~ 5 MeV)

    LArTPC: unique **sensitivity to ν_e** flux.

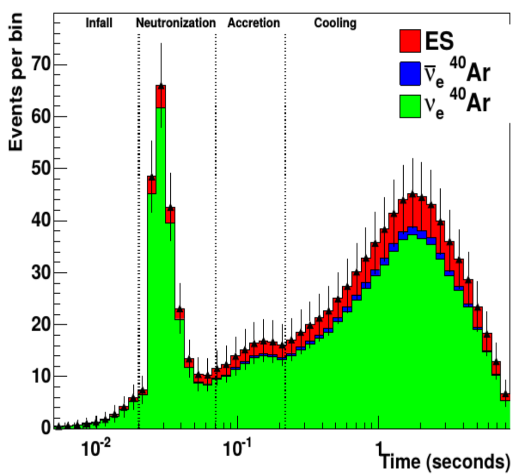
    Complementary to (mostly) $\bar{\nu}_e$ sensitivity of water Cherenkov and LS detectors.
- MicroBooNE challenges:
  - Near-surface detector.
  - Small number of events.
  - Low energy.

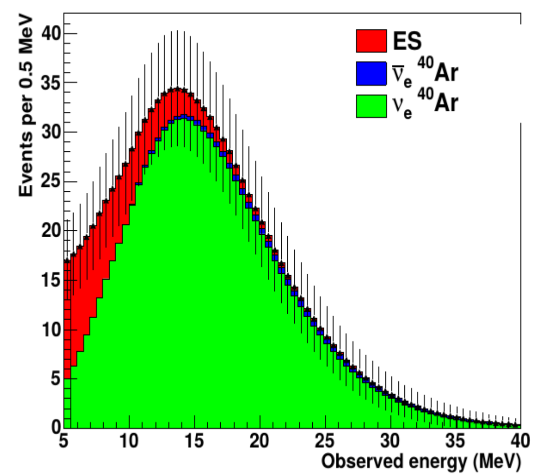
→ **No self-trigger**.

Prediction for DUNE [arXiv:1807.10334]



Prediction for DUNE (40 kt) [arXiv:1512.06148]





MicroBooNE continuous readout

- Instead, **read out detector continuously** and **rely on a delayed external trigger from SNEWS.**
  - Run Coordinators + Readout Experts subscribed to the SNEWS alert mailing list.
  - We are also subscribed to **KamLAND's pre-SN alert**. Used to increase DAQ uptime awareness for shifters and cancel non-Physics runs.

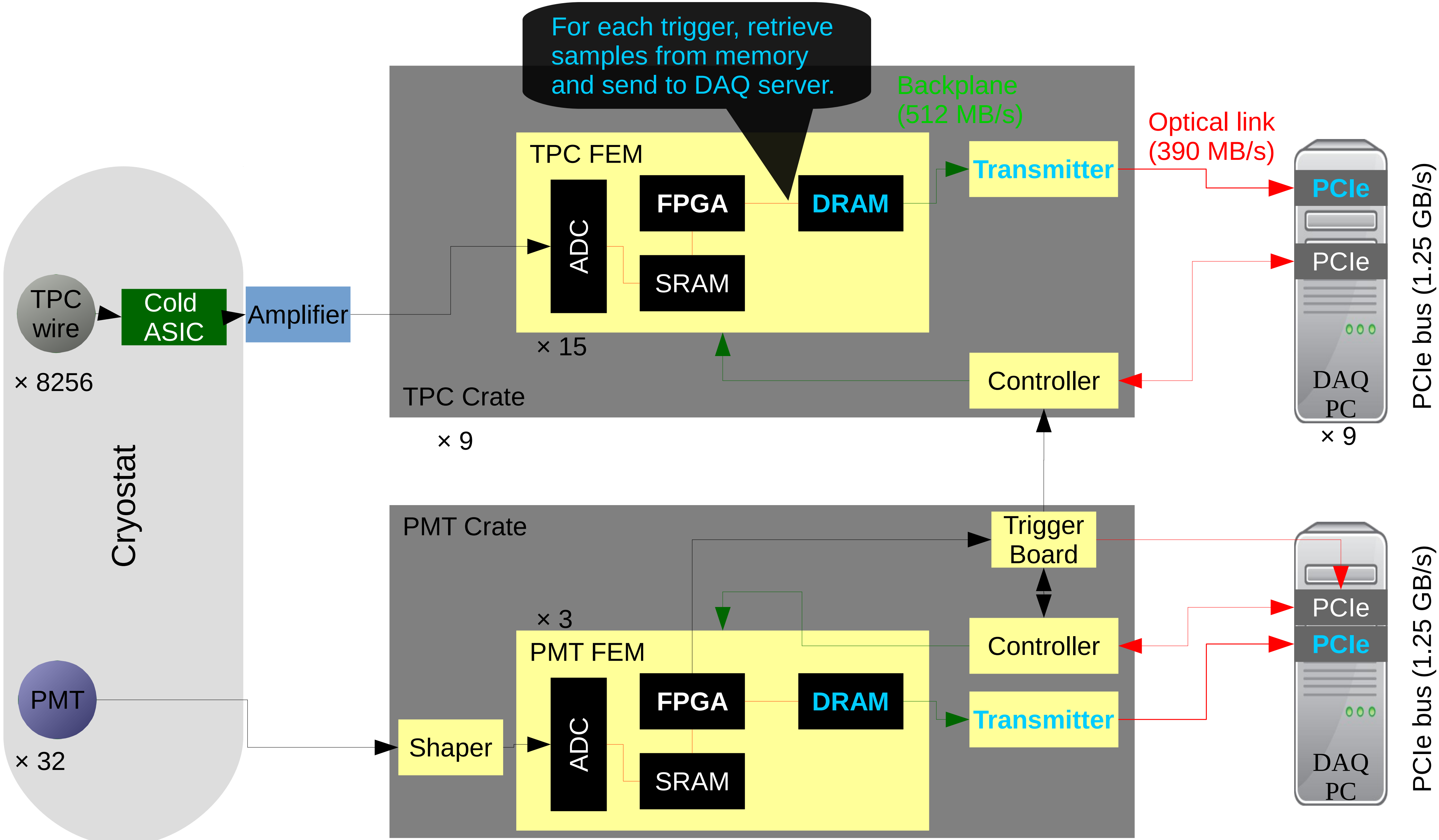
- Continuous readout of the detector also enables:
  - **R+D for non-beam beyond-Standard Model physics at DUNE (p decay, n-nbar oscillation...)**
    - Study backgrounds, prototype analyses...
  - **Continuous monitoring** of the detector for diagnosing.
  - **Demonstrate processing of TPC information in real time**.
    - Foundation for a TPC-based trigger for DUNE. Complementary to a PMT-based trigger.

The continuous readout stream of MicroBooNE

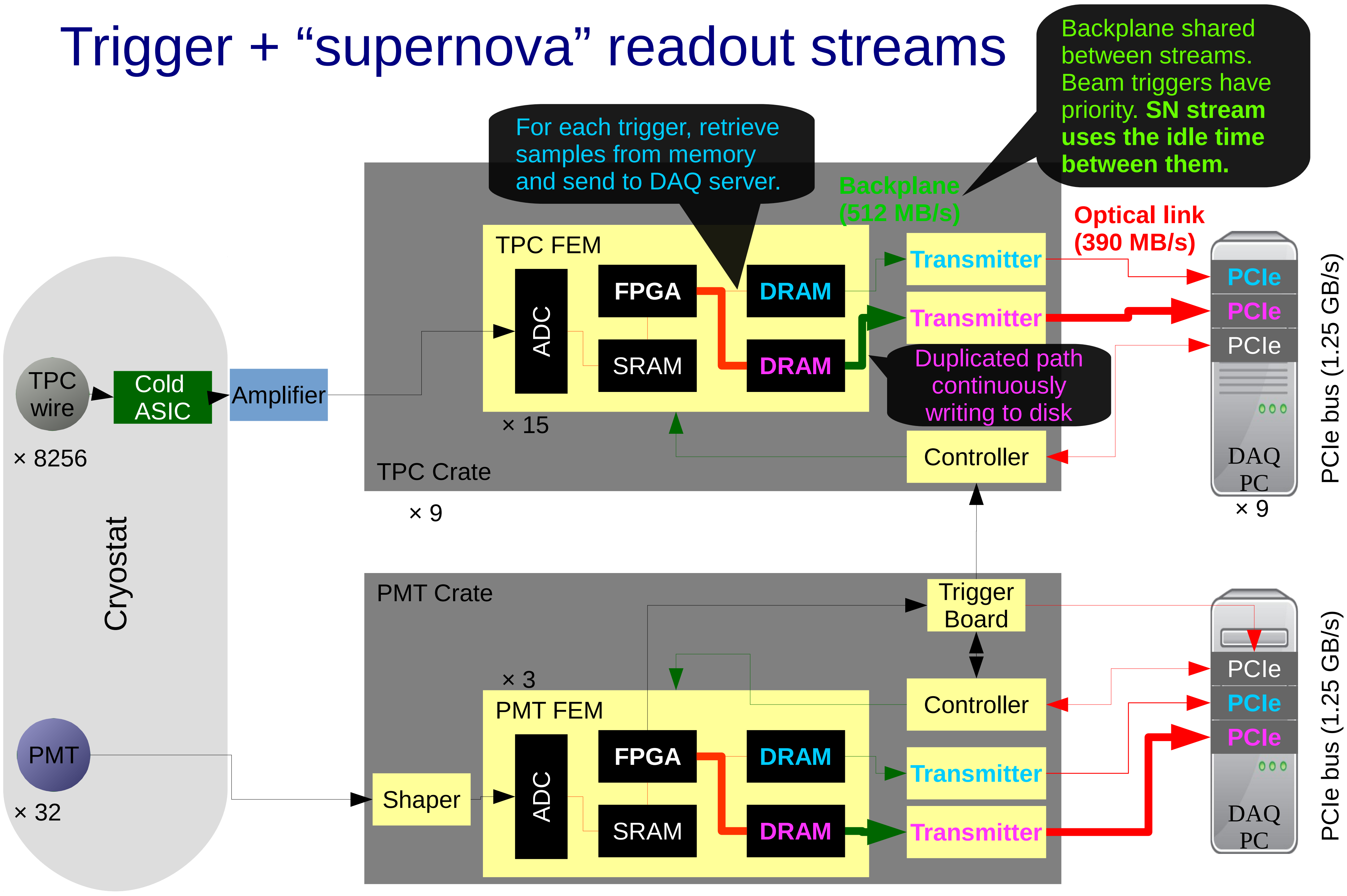
A *security camera* for supernova neutrinos

NASA, ESA, R. Kirshner (Harvard-Smithsonian Center for Astrophysics and Gordon and Betty Moore Foundation), and M. Mutchler and R. Avila (STScI)

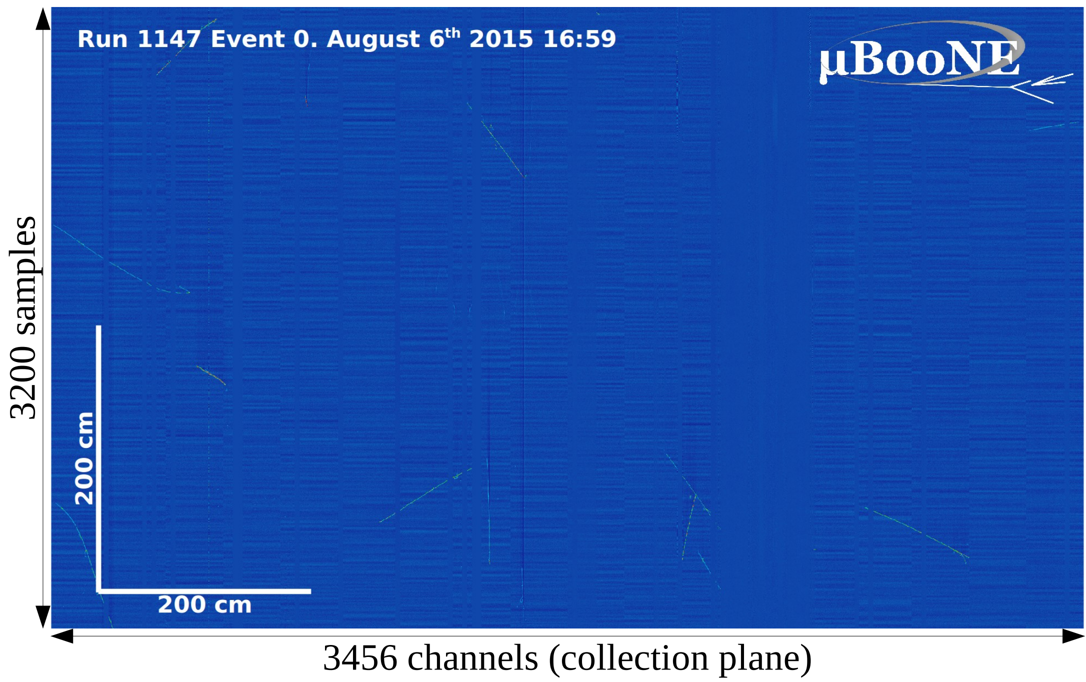
Trigger readout stream



Trigger + "supernova" readout streams



Data challenge



- **Data is stored temporarily** on a 13 TB HDD at each DAQ server, awaiting an **SNEWS alert** to be transferred to permanent storage (manually!).
- Continuous readout: **625 frames per second.**
- 1.6 ms frame at 2Ms/s. 8256 channels.

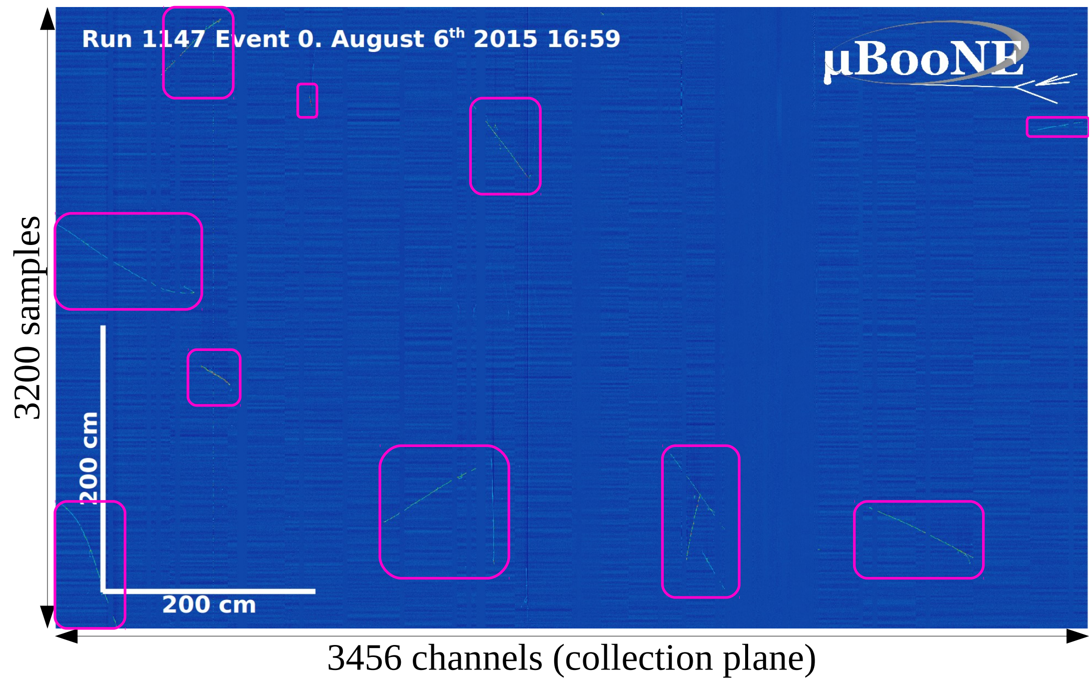
  → **26.4 Mpixels/frame**

- Total: **33 GB/s**

  → **Distributed between 9 servers: ~ 3.7 GB/s/server**

- **Bottleneck: disk writing speed** of the DAQ servers (conservatively **50 MB/s**).
- Need a **compression factor ~ 80**.
- Lossless compression (Huffman) gives factor ~ 5: not enough.
- Requires additional **lossy compression** **(***a "LArTPC.jpg"***)**. Feasible since images are **sparse**.
- Also: writing at 50 MB/s gives us a window of **> 48 h before data is deleted**.

Data challenge



- **Data is stored temporarily** on a 13 TB HDD at each DAQ server, awaiting an **SNEWS alert** to be transferred to permanent storage (manually!).
- Continuous readout: **625 frames per second.**
- 1.6 ms frame at 2Ms/s. 8256 channels.

  → **26.4 Mpixels/frame**
- Total: **33 GB/s**

  → **Distributed between 9 servers: ~ 3.7 GB/s/server**
- **Bottleneck: disk writing speed** of the DAQ servers (conservatively **50 MB/s**).
- Need a **compression factor ~ 80**.
- Lossless compression (Huffman) gives factor ~ 5: not enough.
- Requires additional **lossy compression** **(***a "LArTPC.jpg"***)**. Feasible since images are **sparse**.
- Also: writing at 50 MB/s gives us a window of **> 48 h before data is deleted**.

Zero suppression (TPC)

- **Implemented in the Front End Module FPGA (Altera Stratix III).**
- Only the **waveform** passing the **amplitude threshold (configurable per channel)** with respect to the channel baseline is saved

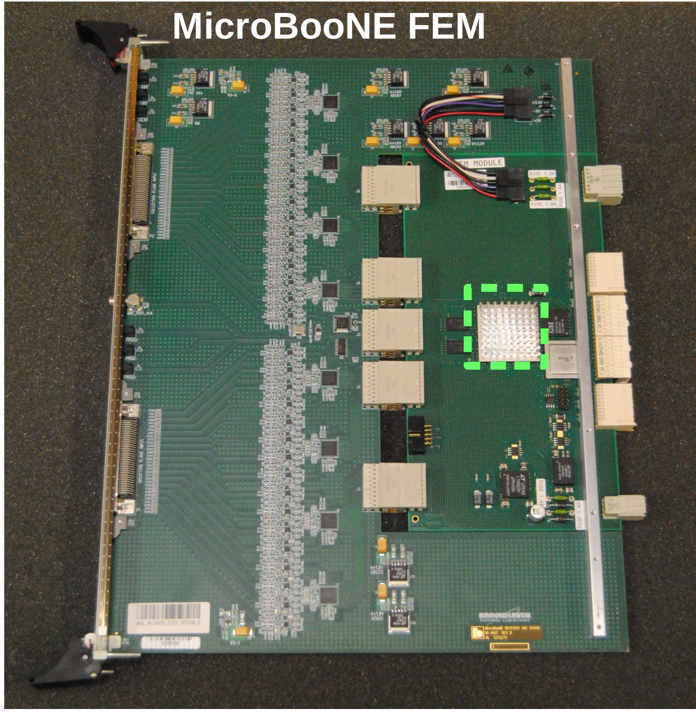
  plus **presamples** and **postsamples (configurable per FEM)**.
- The **baseline** can be

  dynamically computed using preceding samples (if within mean and RMS tolerances)

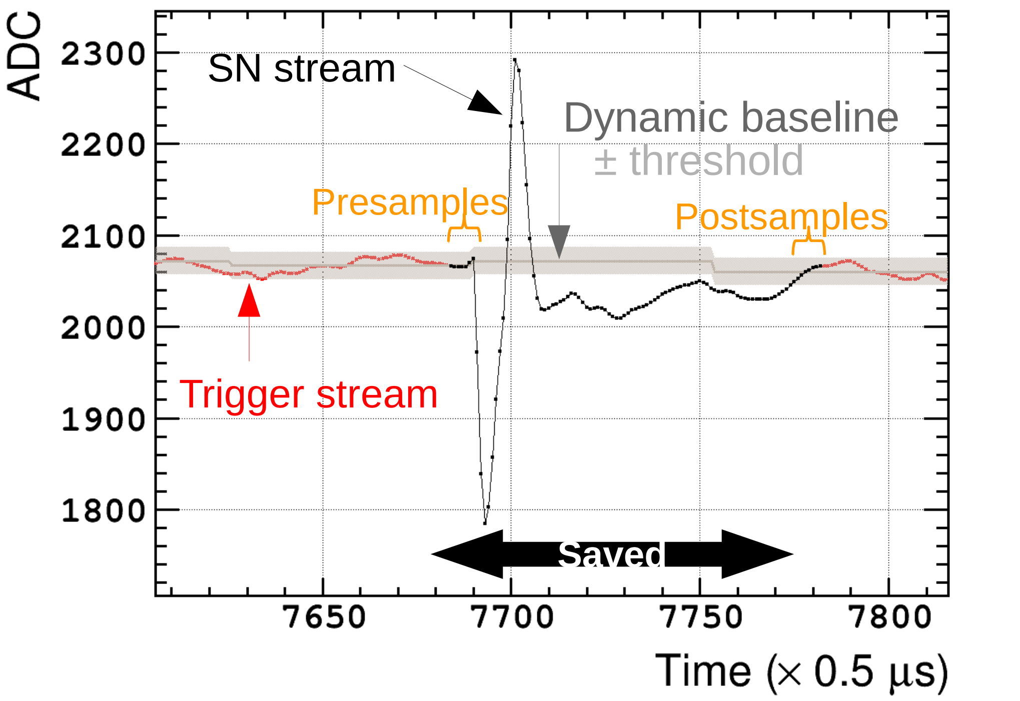
  or

  loaded as static value at the beginning of the run

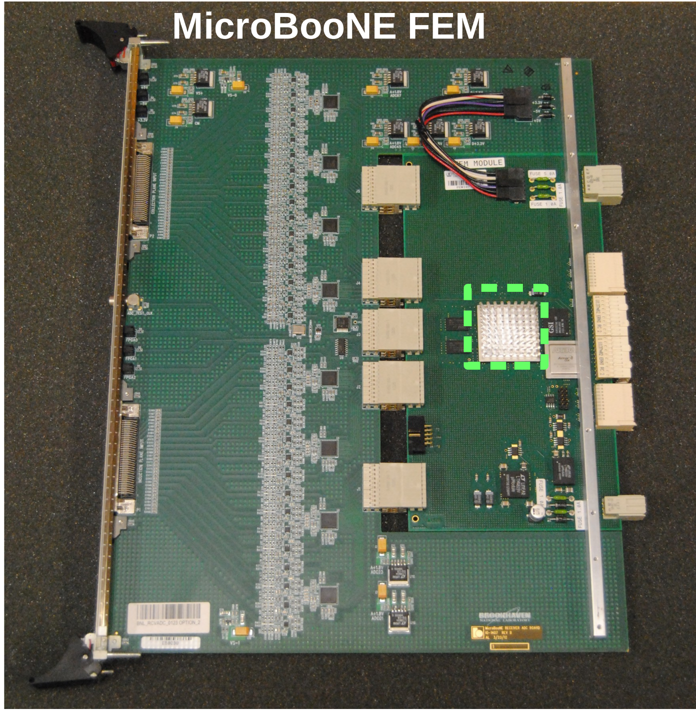
  (both have been commissioned and tested).



DATA from Nevis test stand



Zero suppression (TPC)



- **Implemented in the Front End Module FPGA (Altera Stratix III).**
- Only the **waveform** passing the **amplitude threshold (configurable per channel)** with respect to the channel baseline is saved

  plus **presamples** and **postsamples (configurable per FEM)**.
- The **baseline** can be

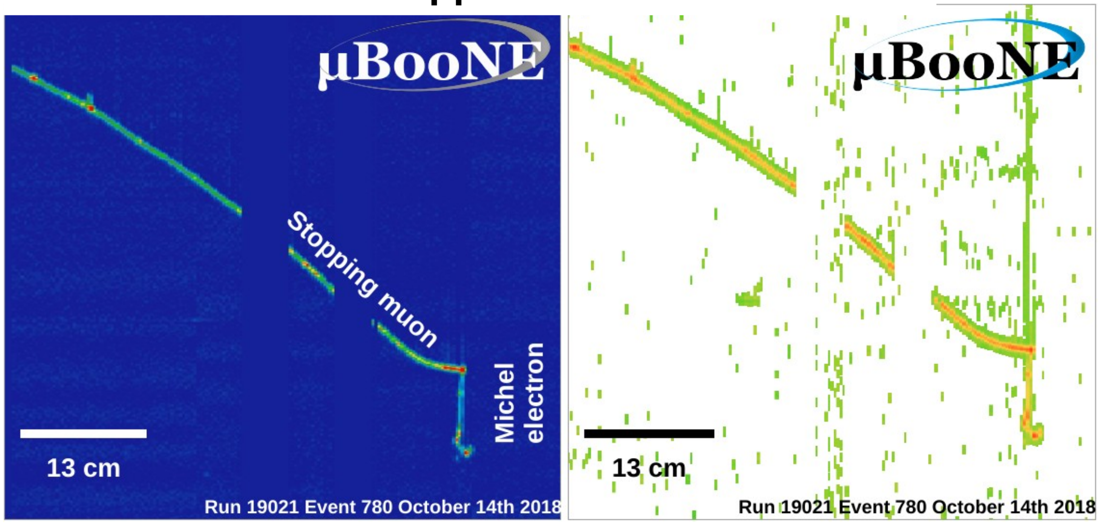
  dynamically computed using preceding samples (if within mean and RMS tolerances)

  or

  loaded as static value at the beginning of the run

  (both have been commissioned and tested).

Simulation of zero-suppression over real data



Continuous readout display

SN Run II
Channel thresholds
Dynamic baselines

5 fps gif → 125 times slower than actual readout

½ Frame N + 1

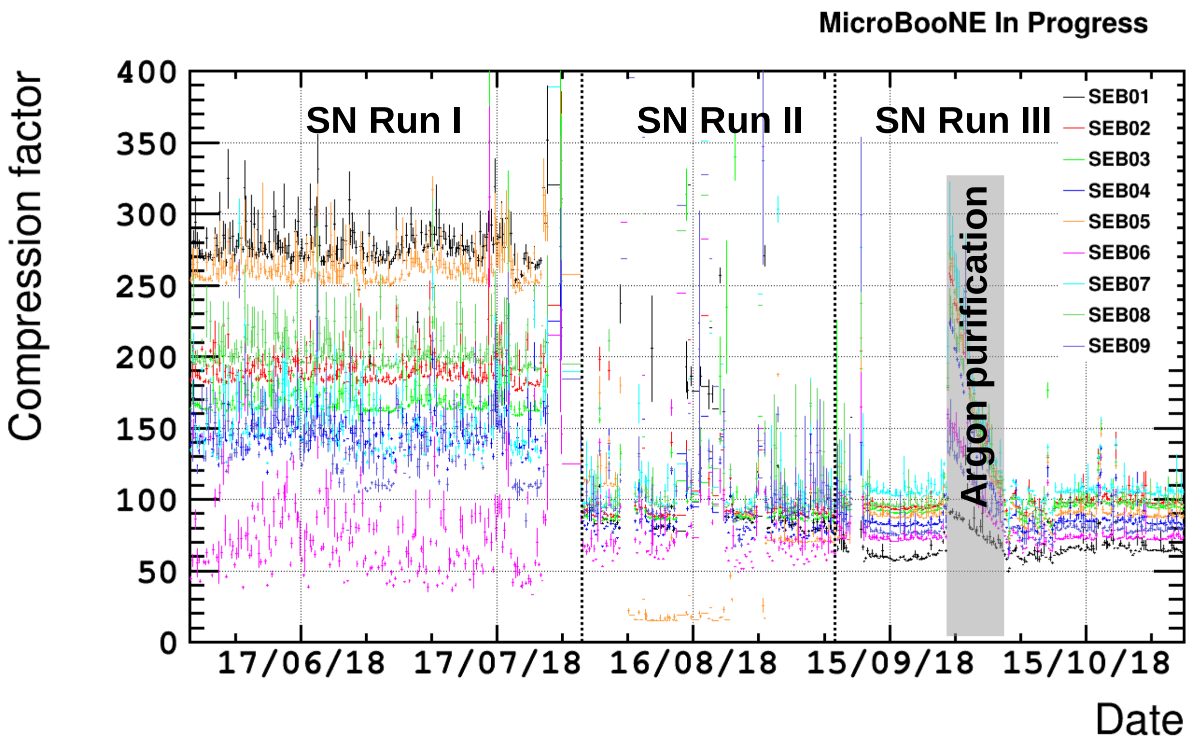
Frame N

½ Frame N - 1

Raw ADC (12-bit)

Results: Compression factor

$$\text{Compression factor} = \frac{\text{Expected rate w/o compression}}{\text{Measured rate}}$$



First SN Run used **single threshold** for all channels within one TPC plane.

Noisy channels affected dynamic baseline estimation, producing large variations.

Second SN Run used **individualized (lower) channel threshold** → Increased sensitivity to low-energy physics.

Still noisy channels affected dynamic baseline calculation.

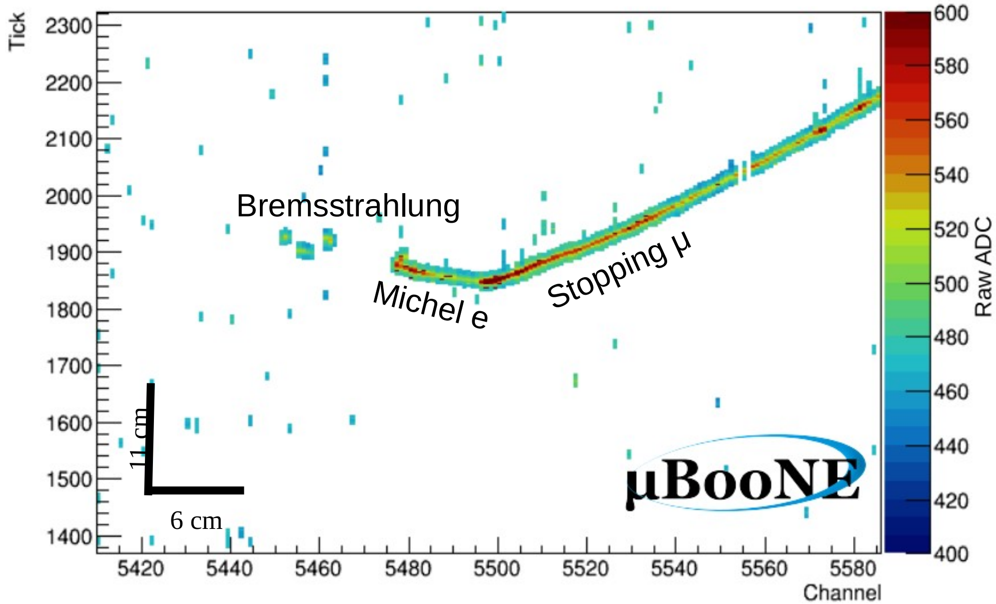
Third SN Run uses **individualized (lower) channel threshold** and **static baselines**.

Target compression factor achieved!

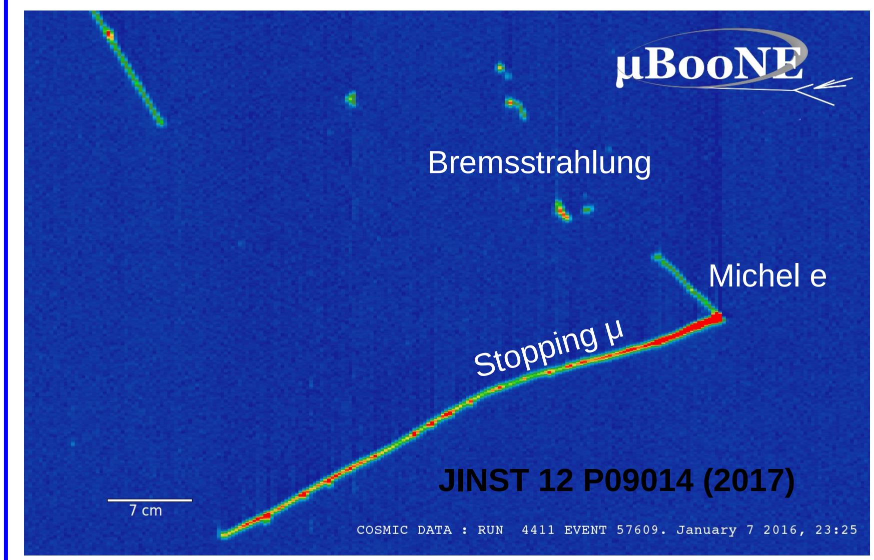
Lesson: MicroBooNE TPC channel baselines are stable for discrimination.

SN-like physics with continuous stream: Michel e candidates

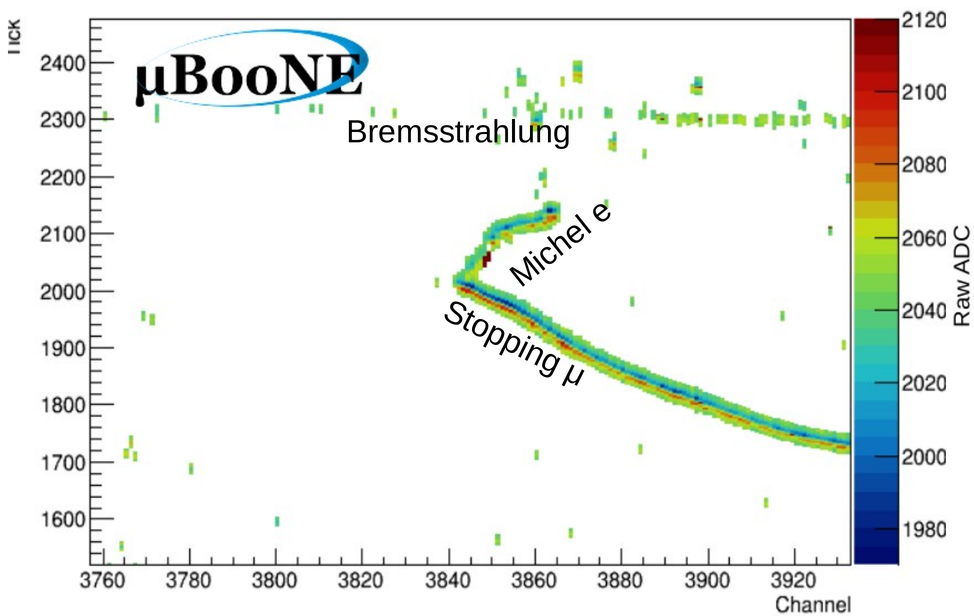
Collection plane



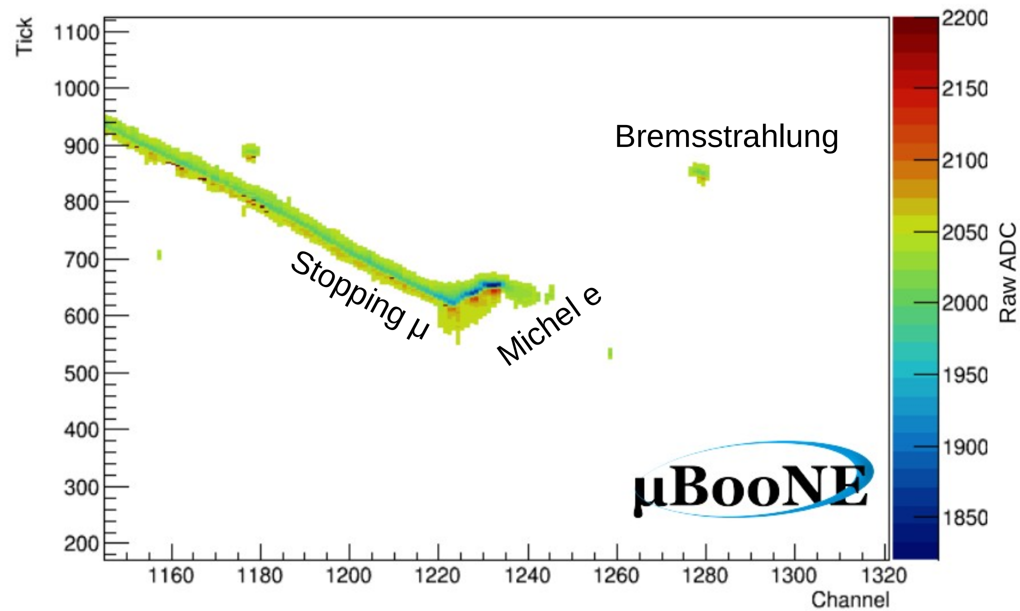
Trigger stream (for reference)



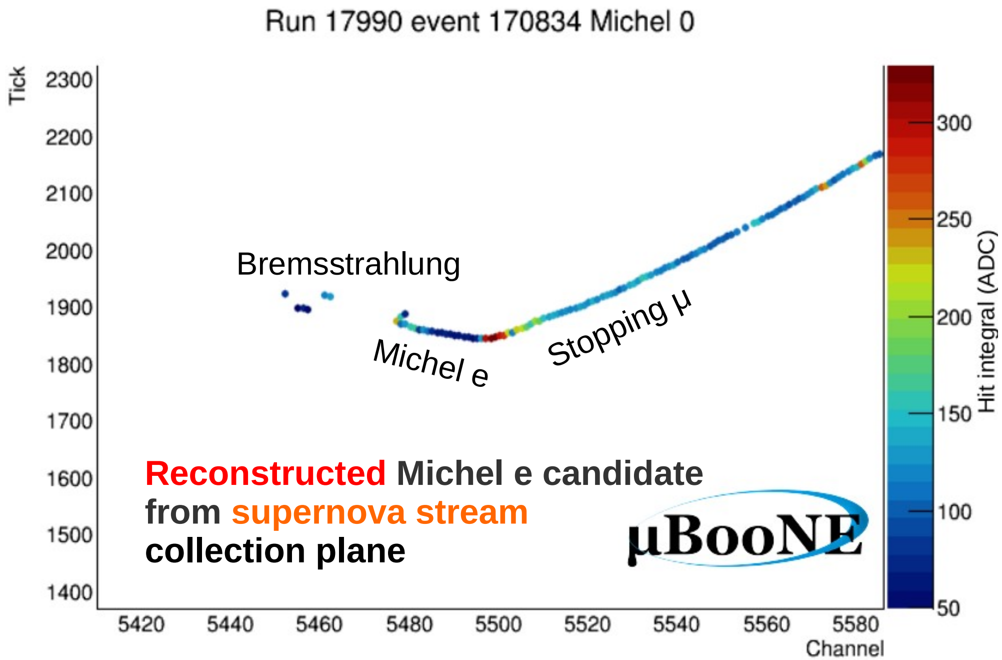
2nd induction plane

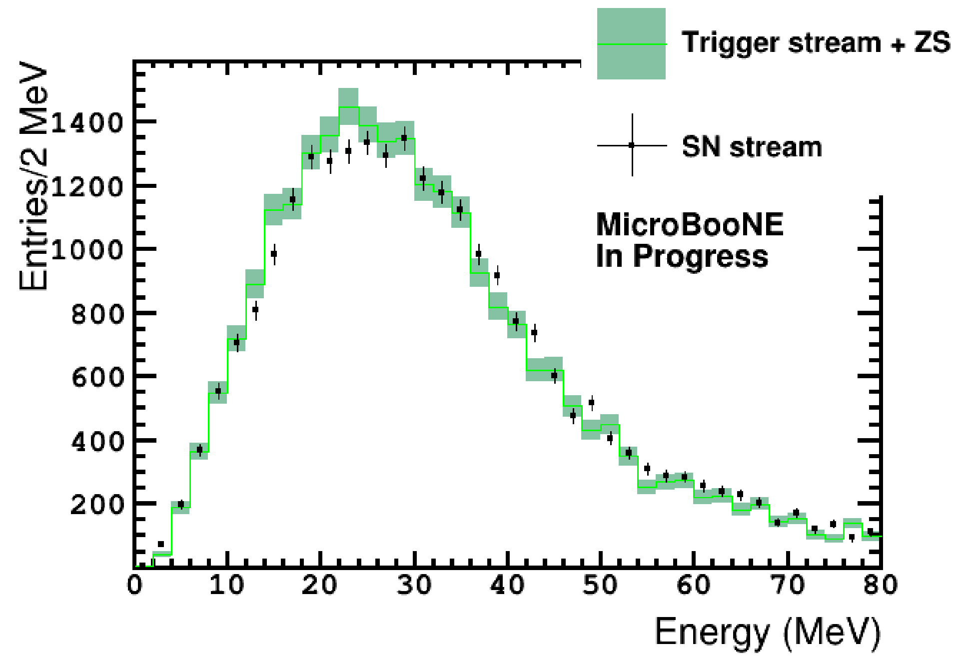


1st induction plane



SN-like physics with continuous stream: Michel e reconstruction





- **Lesson**: our bandwidth allowed us to **keep some noise** online to increase our efficiency to record low energy signals.

  Remaining noise is removed by off-line reconstruction.

- **> 20k Michel e candidates found in ~ 1h of the continuous readout stream using fully automated reconstruction.**

  Same reconstruction and selection as trigger stream JINST 12 P09014 (2017).

Good agreement between **SN stream data** and **trigger stream with simulated zero-suppression (ZS).** Well-understood detector response.

Conclusion

- MicroBooNE commissioned a **continuous readout stream for detection of supernova neutrinos using the SNEWS alert**.
  - Successful operation for over 1.5 years.
- **Zero suppression for LArTPC using FPGA**.
  - Settled to zero suppression with channel-wise thresholds and static baselines.
  - Stable ~ **× 80 compression factor** goal accomplished.
- >20k Michel electrons observed on three TPC planes → **Demonstration of low-energy (SN-like) capabilities.**
- **Publication in preparation.**
- The continuous readout can be repurposed as **trigger primitive generator for DUNE DAQ prototyping.**
  - SBND will serve as R&D platform, complementary to ProtoDUNE.


Thank you for your attention!

MicroBooNE Collaboration

October 2018

University of Bern, Switzerland: Y. Chen, A. Ereditato, D. Goeldi, I. Kreslo, D. Lorca, M. Lüethi, T. Mettler, J. Sinclair, M. Weber

Brookhaven: M. Bishai, H. Chen, W. Gu, X. Ji, J. Joshi, B. Kirby, Y. Li, X. Qian, B. Viren, H. Wei, C. Zhang

University of Cambridge: J. Anthony, L. Escudero Sanchez, J. Jan de Vries, A. Smith

University of Chicago: A. Mastbaum, K. Miller, D.W. Schmitz

University of Cincinnati: R.A. Johnson

Colorado State University: I. Caro Terrazas, R. LaZur, M. Mooney, H. Rogers

Columbia University: D. Cianci, J. Crespo, V. Genty, Y.-J. Jwa, G. Karagiorgi, M. Ross-Lonergan, W. Seligman, M. Shaevitz, K. Sutton

Davidson College: B. Eberly

Fermilab: B. Baller, S. Berkman, D. Caratelli, R. Castillo Fernandez, F. Cavanna, G. Cerati, K. Duffy, S. Gardiner, E. Gramellini, H. Greenlee, C. James, W. Ketchum, M. Kirby, T. Kobilarcik, S. Lockwitz, A. Marchionni, S. Marcocci, O. Palamara, Z. Pavlovic, J.L. Raaf, A. Schukraft, E. Snider, P. Spentzouris, M. Stancari, J. St. John, T. Strauss, M. Toups, S. Wolbers, M. Wospakrik, W. Wu, T. Yang, G.P. Zeller*, J, Zennamo

Harvard University: N. Foppiani, R. Guenette, J. Martin-Albo, S. Prince

Illinois Institute of Technology: R. An, I. Lepetic, B. Littlejohn, D. Martinez

Kansas State University: M. Alrashed, T. Bolton, G. Horton-Smith, K. Neely, V. Meddage. A. Paudel

Lancaster University: A. Blake, D. Devitt, A. Lister, J. Nowak

Los Alamos: G. Garvey, E-C. Huang, W.C. Louis, T. Thornton, R. Van de Water

University of Manchester: J. Evans, A. Furmanski, D. Gamez, O. Goodwin, P. Guzowski, C. Hill, K. Mistry, R. Murrells, D. Porzio, S. Söldner-Rembold, A.M. Szelc

MIT: A. Ashkenazi, J.M. Conrad, O. Hen, A. Hourlier, J. Moon, A. Papadopoulou, L. Yates

University of Michigan, Ann Arbor: C. Barnes, R. Fitzpatrick, J. Mousseau, J. Spitz

New Mexico State University: V. Papavassiliou, S.F. Pate, L. Ren, S. Sword-Fehlberg, K. Woodruff

Otterbein University: N. Tagg

University of Oxford: G. Barr, M. Del Tutto, R. Soleti, W. Van De Pontseele

University of Pittsburgh: S. Dytman, L. Jiang, D. Naples, V. Paolone, A. Wickremasinghe

Pacific Northwest National Laboratory: E. Church

Saint Mary's University of Minnesota: P. Nienaber

SLAC: M. Convery, L. Domine, R. Itay, L. Rochester, K. Terao, Y-T. Tsai, T. Usher

South Dakota School of Mines & Technology: D. Martinez

Syracuse University: A. Bhat, P. Hamilton, G. Pulliam, M. Soderberg

Tel Aviv University: E. Cohen, E. Piasetzky

University of Tennessee, Knoxville: S. Gollapinni, A. Mogan, W. Tang, G. Yarbrough

University of Texas at Arlington: J. Asaadi, Z. Williams

Tubitak Space Technologies Research Institute, Turkey: F. Bay

Tufts University: K. Mason, J. Mills, R. Sharankova, T. Wongjirad

Virginia Tech: L. Gu, C. Mariani, M. Murphy, V. Pandey

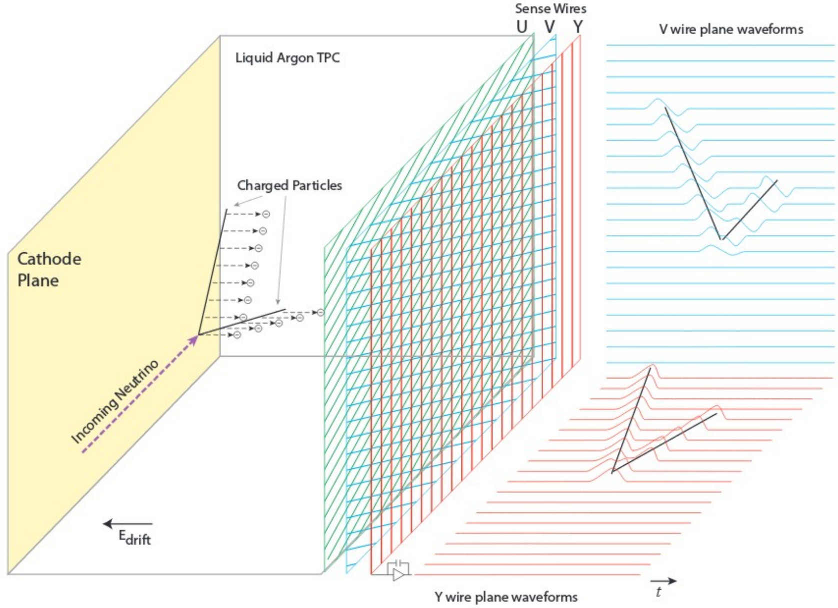
University of Warwick: J. Marshall

Yale University: S. Balasubramanian, L. Cooper-Troendle, B.T. Fleming*, D. Franco, J. Jo, . Luo, B. Russell, G. Scanavini, S. Tufanli

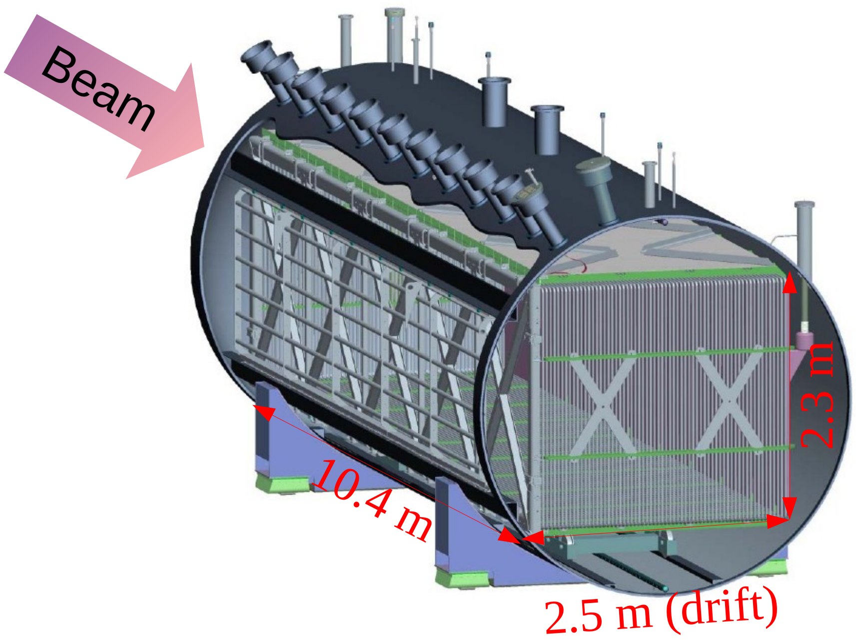
174 collaborators
34 institutions (7 non-U.S.)
44 postdocs
52 grad students

*spokespeople

Backup



JINST 12 P02017 (2017)

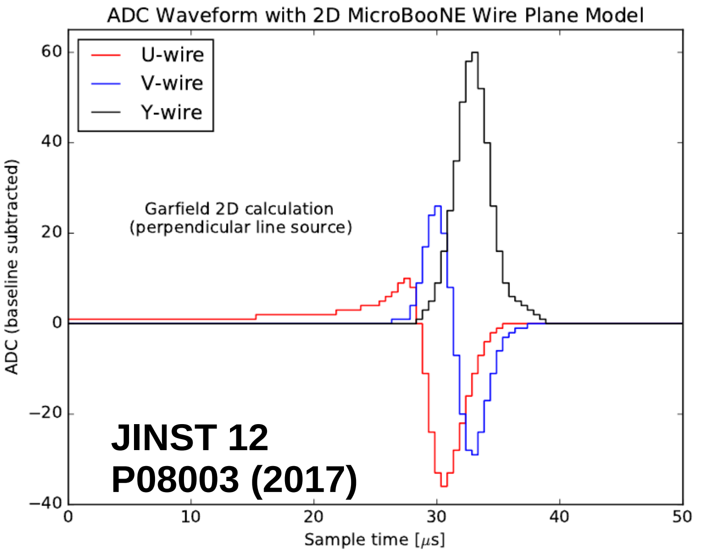


MicroBooNE TPC

- 170 tonnes of liquid argon (**90 tonnes active**).
- Cathode at -70 kV. E_{drift} ~ 273 V/cm.
- **Maximum drift length: 2.5 m.** Drift time: 2.3 ms.
- Three wire planes to reconstruct 3D interaction. 3 mm wire pitch. **8256 channels.**

  2 induction planes with 2400 wires each at ± 60º from vertical.

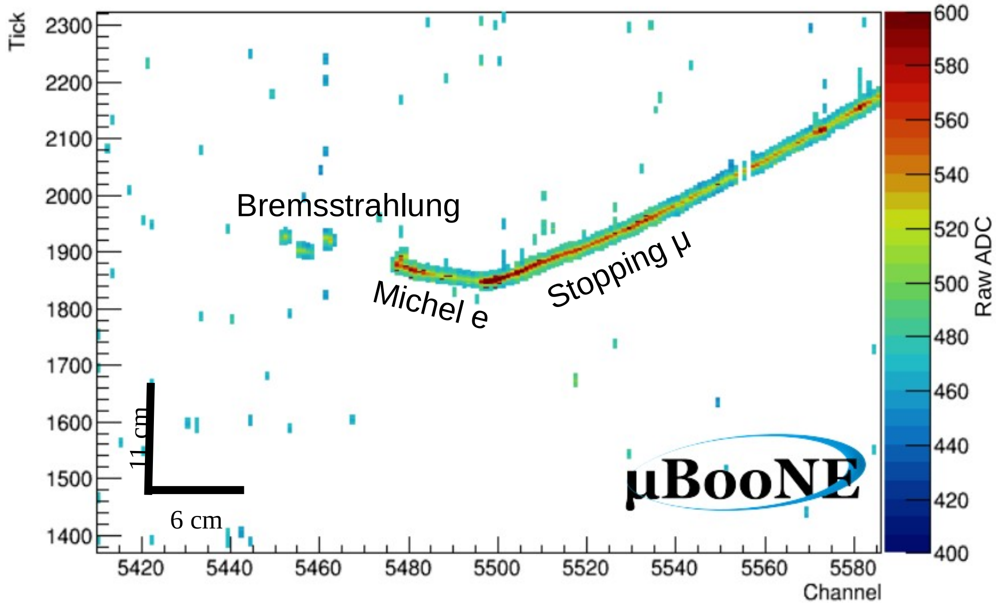
  1 collection plane with 3456 vertical wires.
- Cold front-end electronics.
- 2 MHz digitization with warm electronics.



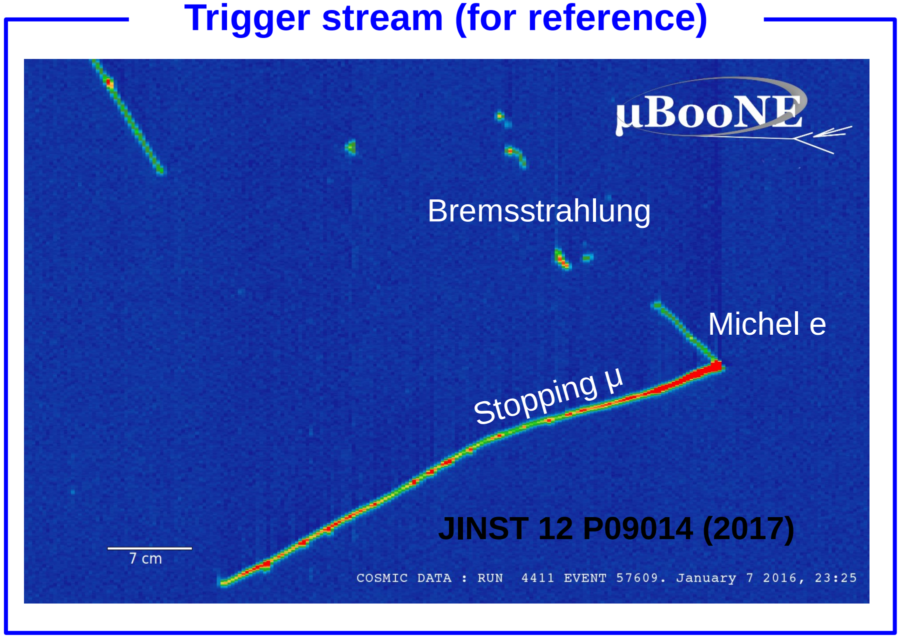
JINST 12 P08003 (2017)

SN-like physics with continuous stream: Michel e candidates

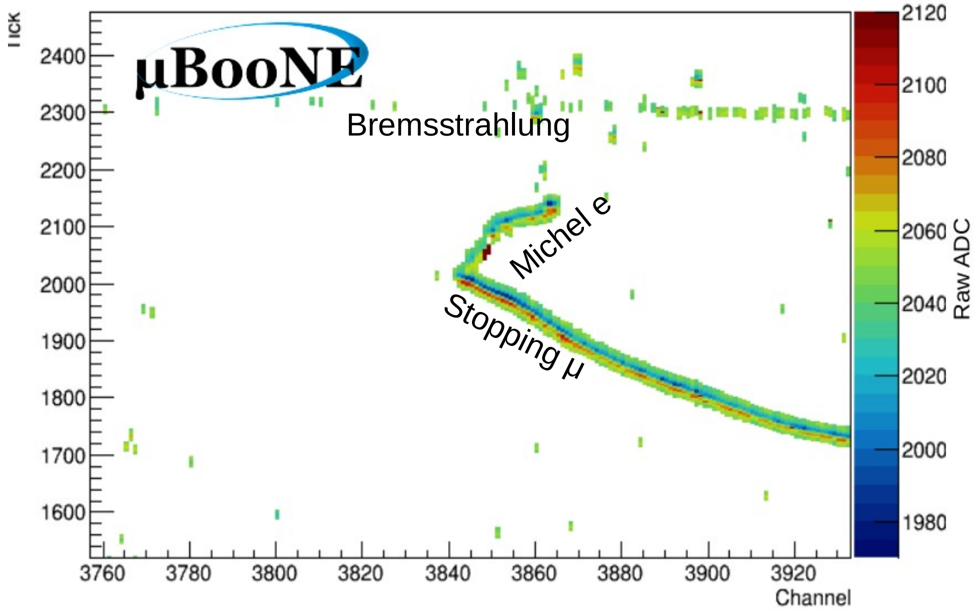
Collection plane



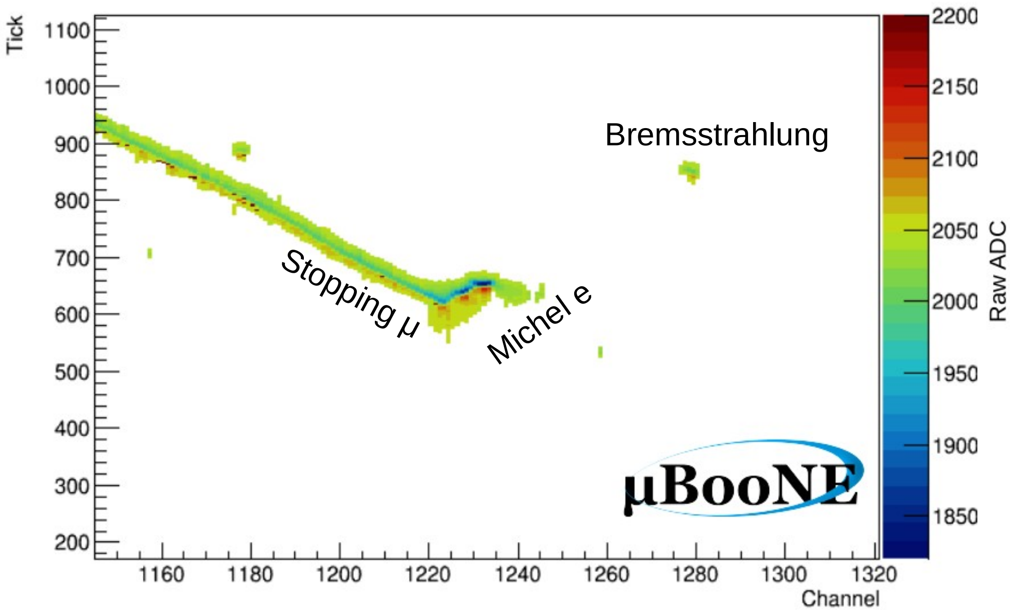
Trigger stream (for reference)



2nd induction plane

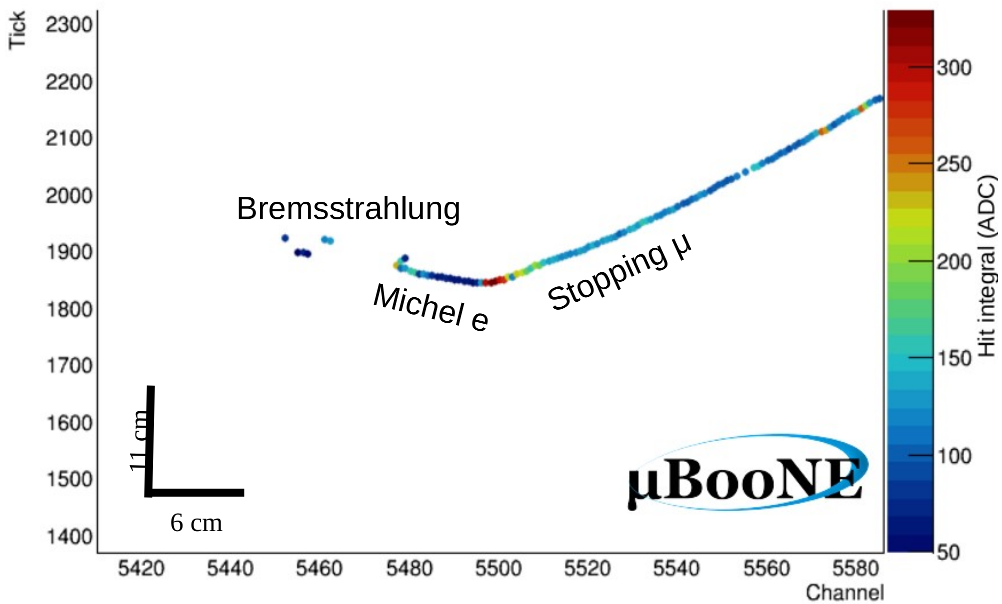


1st induction plane

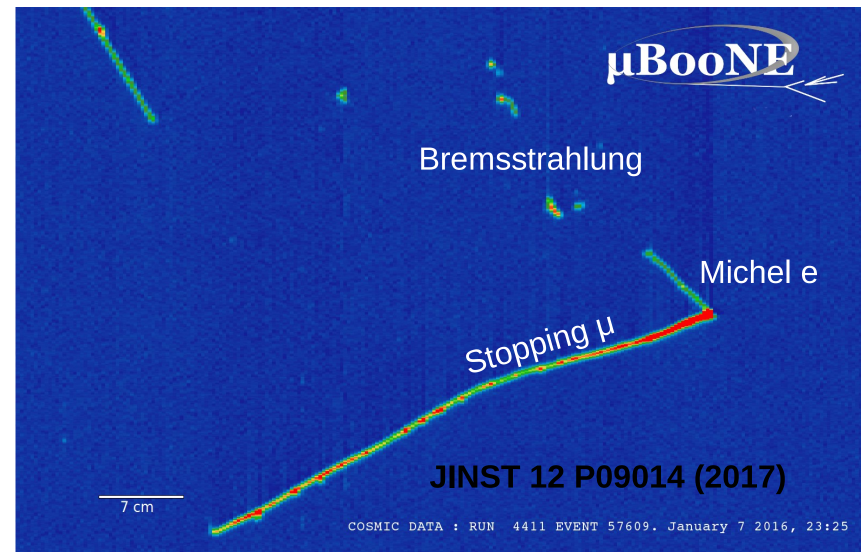


SN-like physics with continuous stream: Michel e candidates

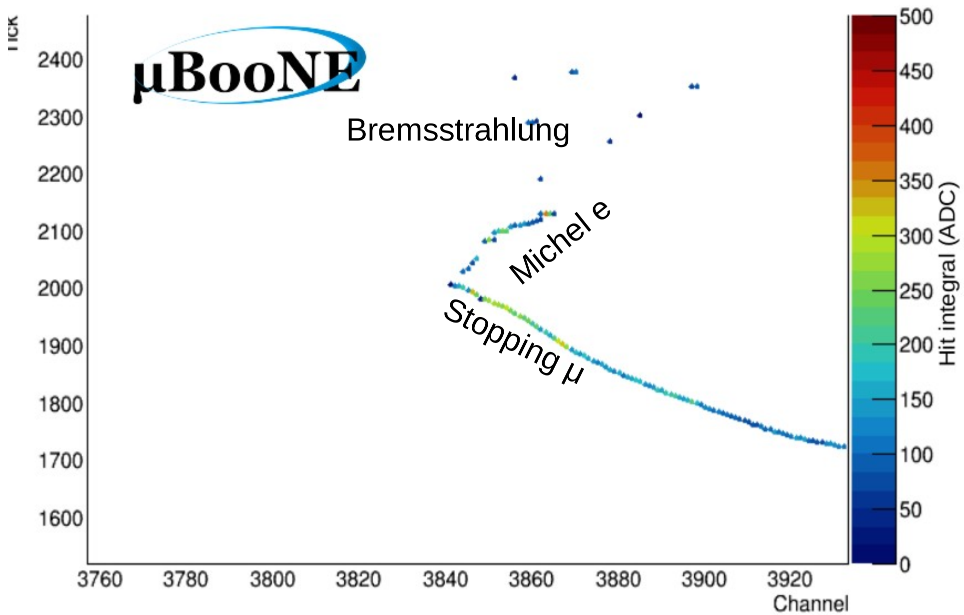
Collection plane



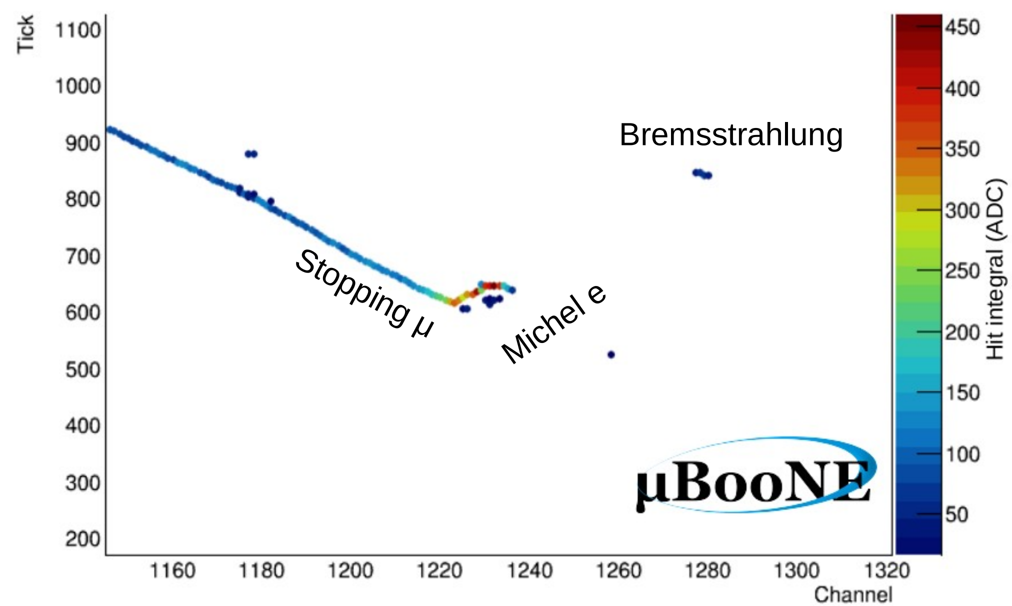
Trigger stream (for reference)



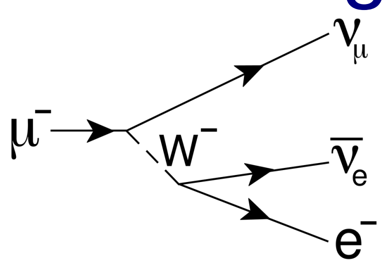
2[nd] induction plane

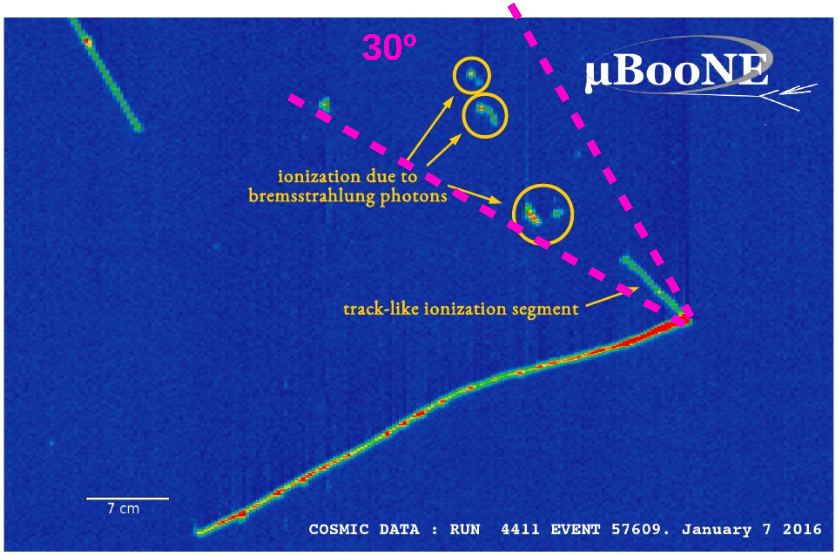


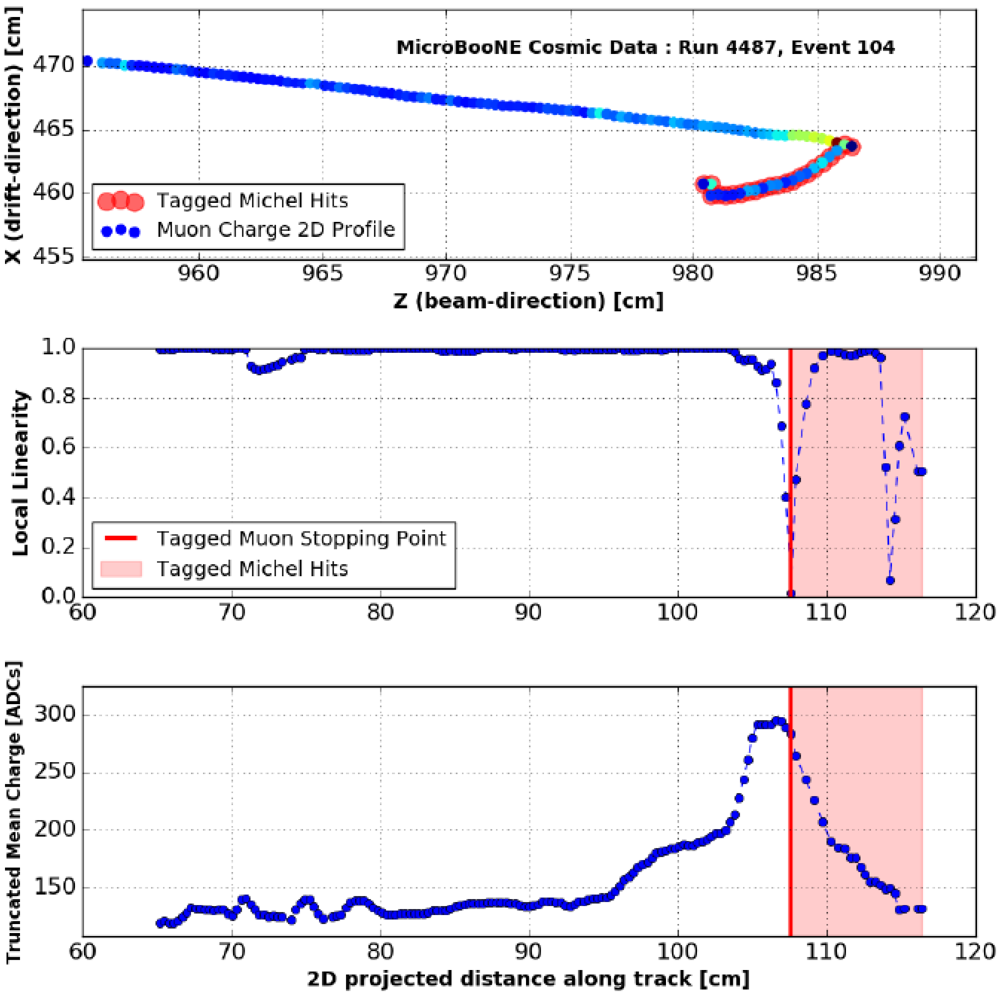
1[st] induction plane



Cosmogenic Michel electrons in MicroBooNE







JINST 12 P09014 (2017)

First fully automated electron reconstruction.

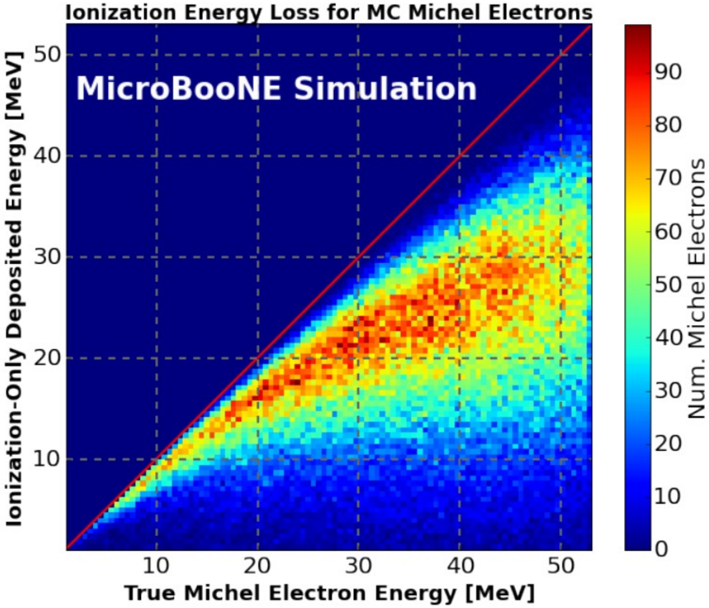
- Input from Pandora pattern recognition..

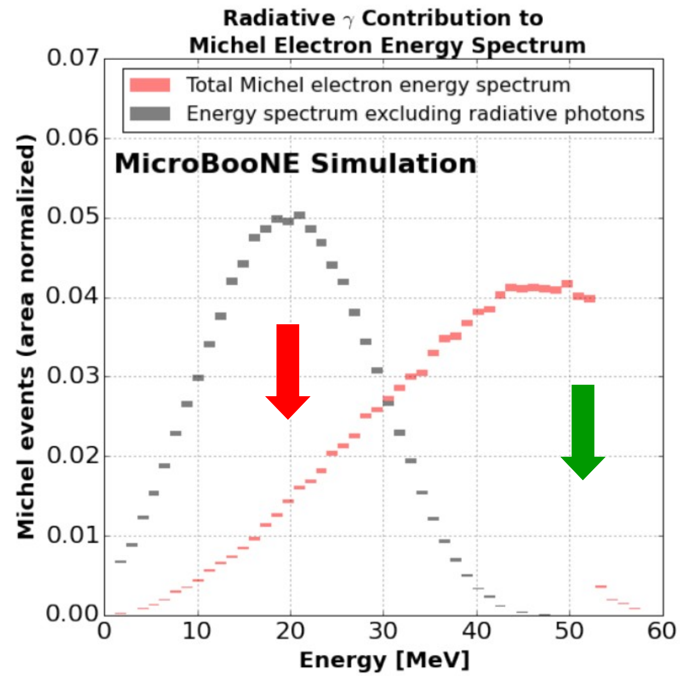
  Eur.Phys.J. C78 (2018) no.1, 82

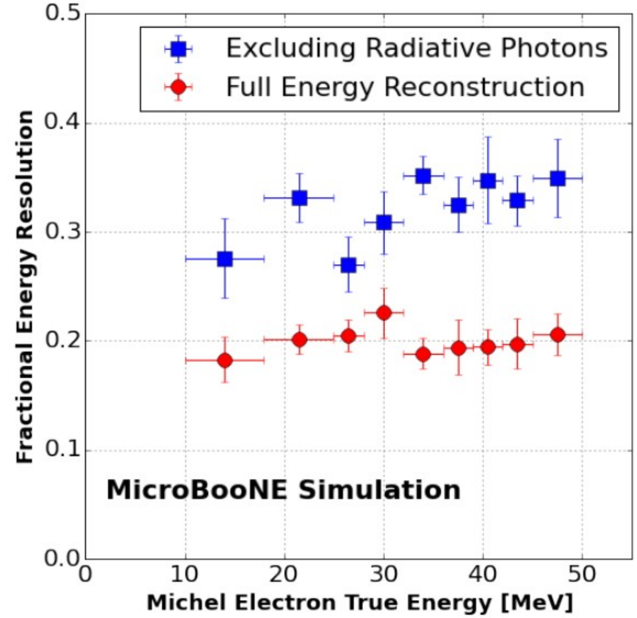
- Uses muon Bragg peak and decay kink to select events.

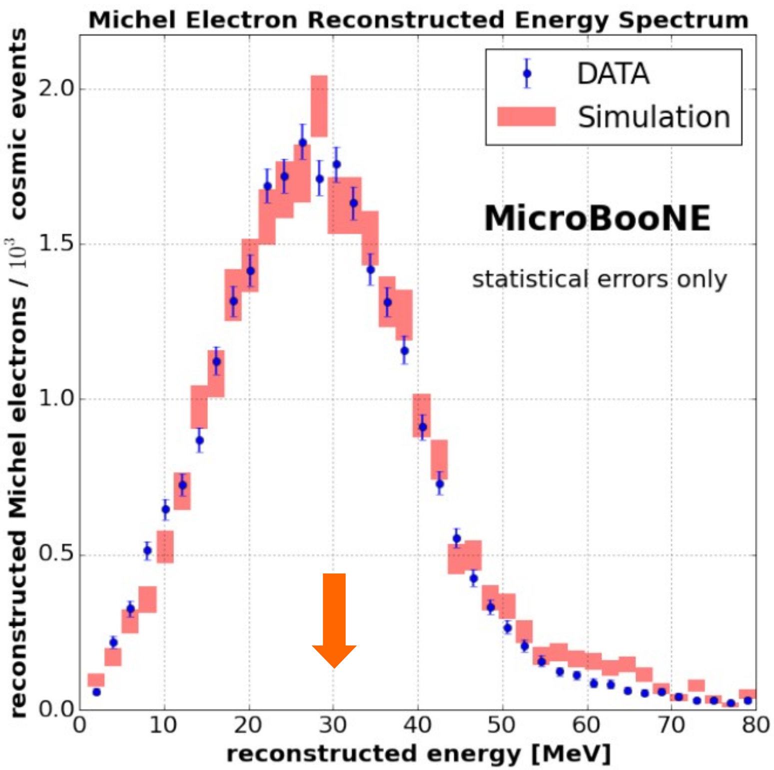
Michel electron reconstruction

JINST 12 P09014 (2017)



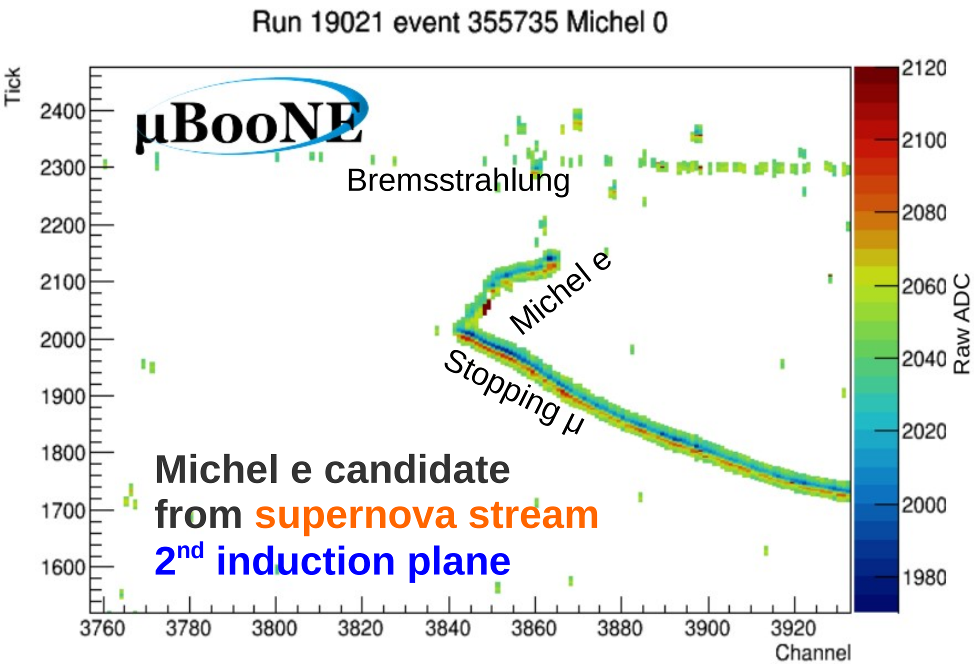


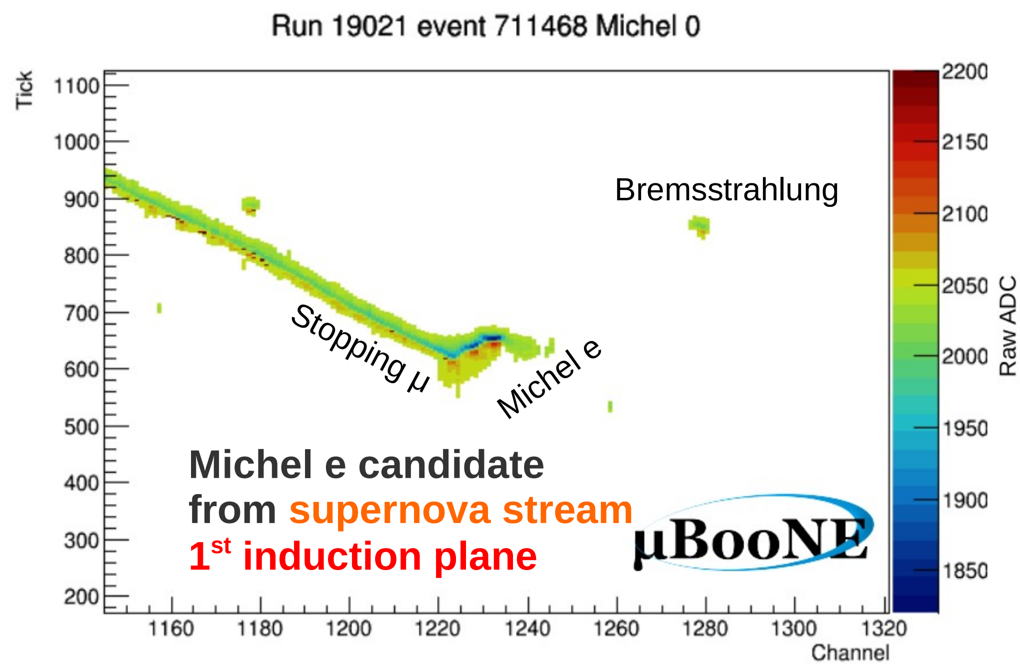


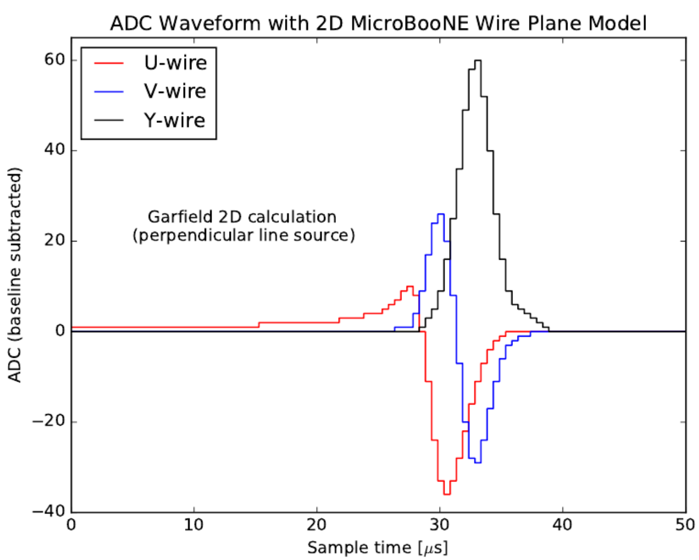


- Sample: ~ 14000 candidates.
- Recombination R = 0.62 from ArgoNeuT's modified box model, assuming constant dE/dx = 2.3 MeV/cm.
- **MC: 15% of radiated energy under reconstruction threshold.**

SN-like physics with continuous stream





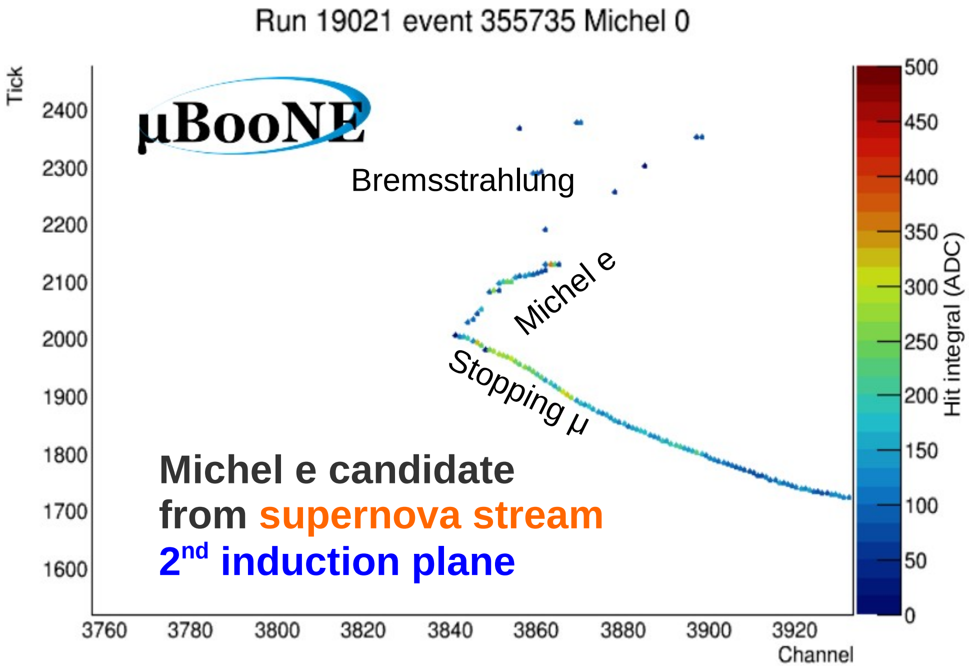


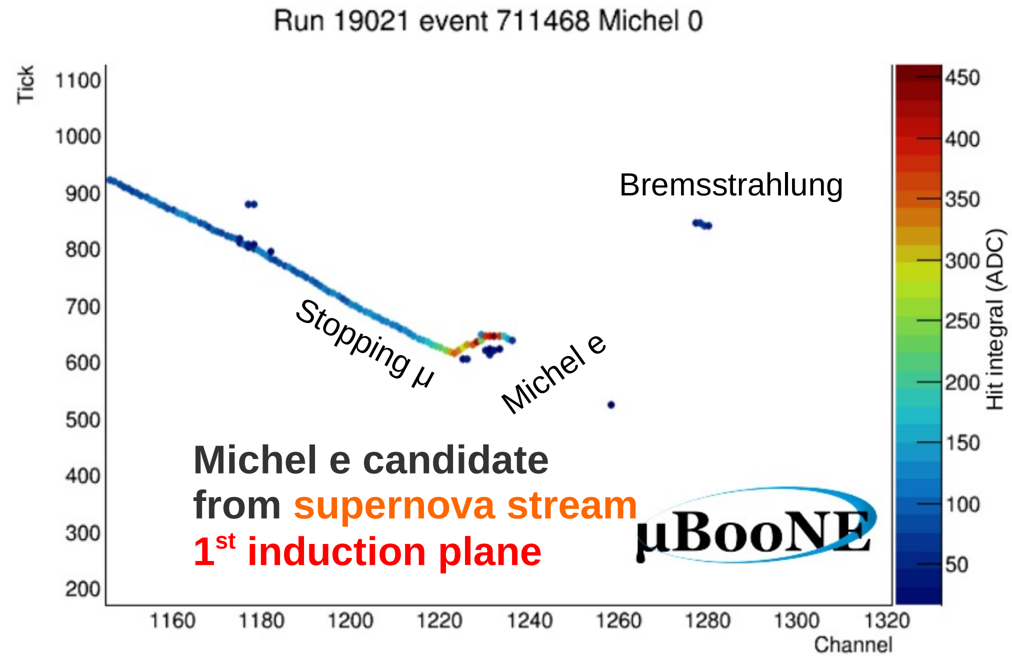
- Michel e candidates in the continuous readout stream **also found on the induction planes.**
- **Induction planes are especially challenging** due to the bipolar waveforms.

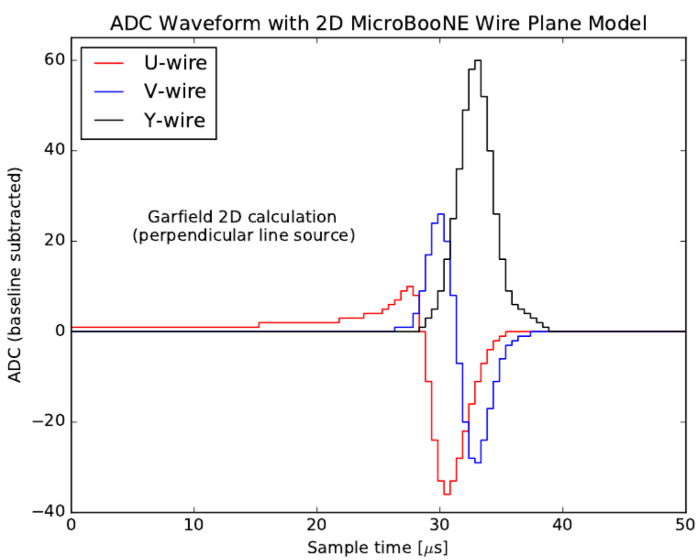
Worse peak signal-to-noise ratio:

U: 18.1; V: 13.1; Y: 33.4 **JINST 12 P08003 (2017)**

SN-like physics with continuous stream





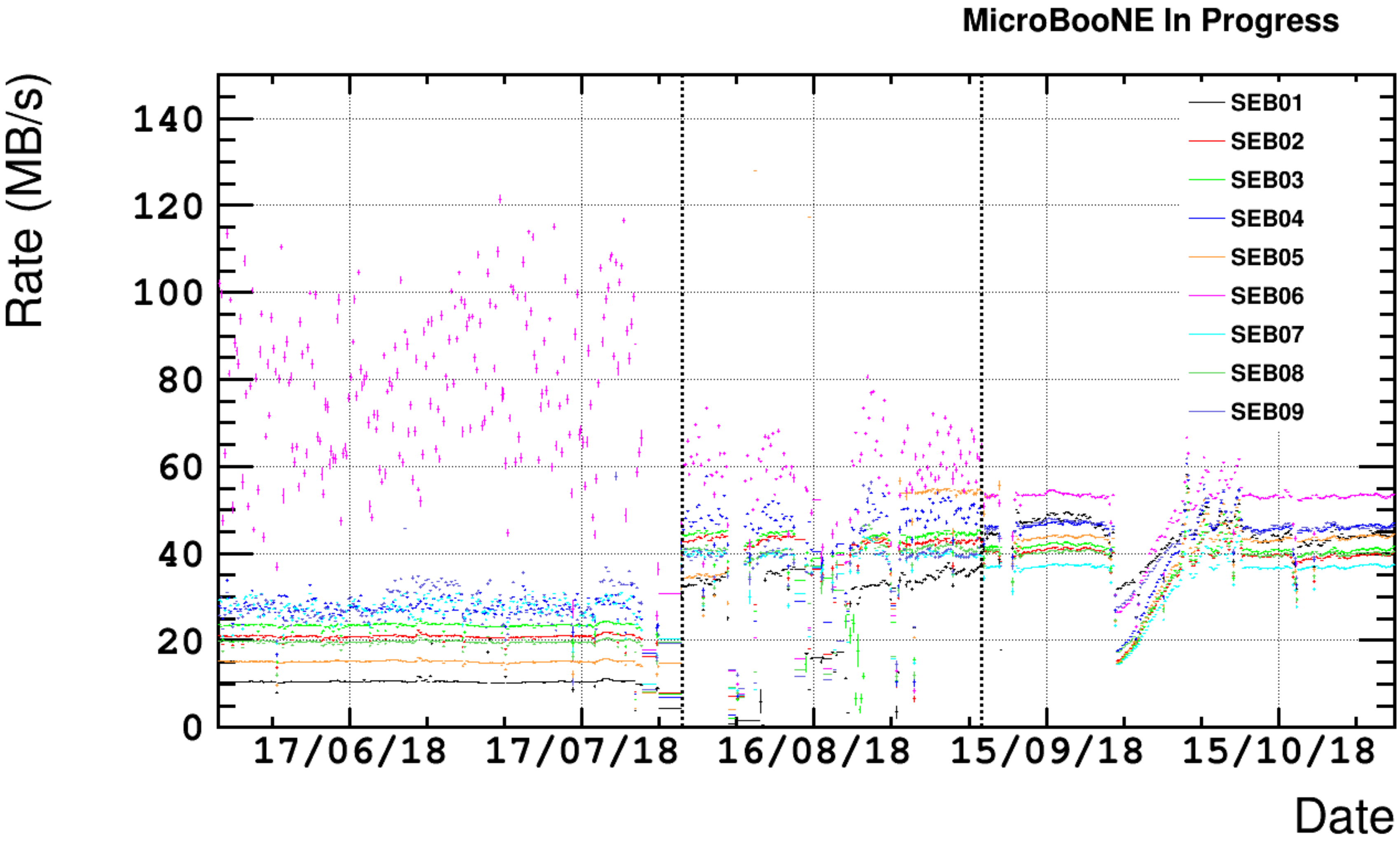


- Michel e candidates in the continuous readout stream **also found on the induction planes.**
- **Induction planes are especially challenging** due to the bipolar waveforms.

Worse peak signal-to-noise ratio:

U: 18.1; V: 13.1; Y: 33.4 **JINST 12 P08003 (2017)**

Data rates



MicroBooNE In Progress
Rate (MB/s)
140
120
100
80
60
40
20
0
17/06/18
17/07/18
16/08/18
15/09/18
15/10/18
Date
SEB01
SEB02
SEB03
SEB04
SEB05
SEB06
SEB07
SEB08
SEB09

MicroBooNE & SBND

Very similar designs.

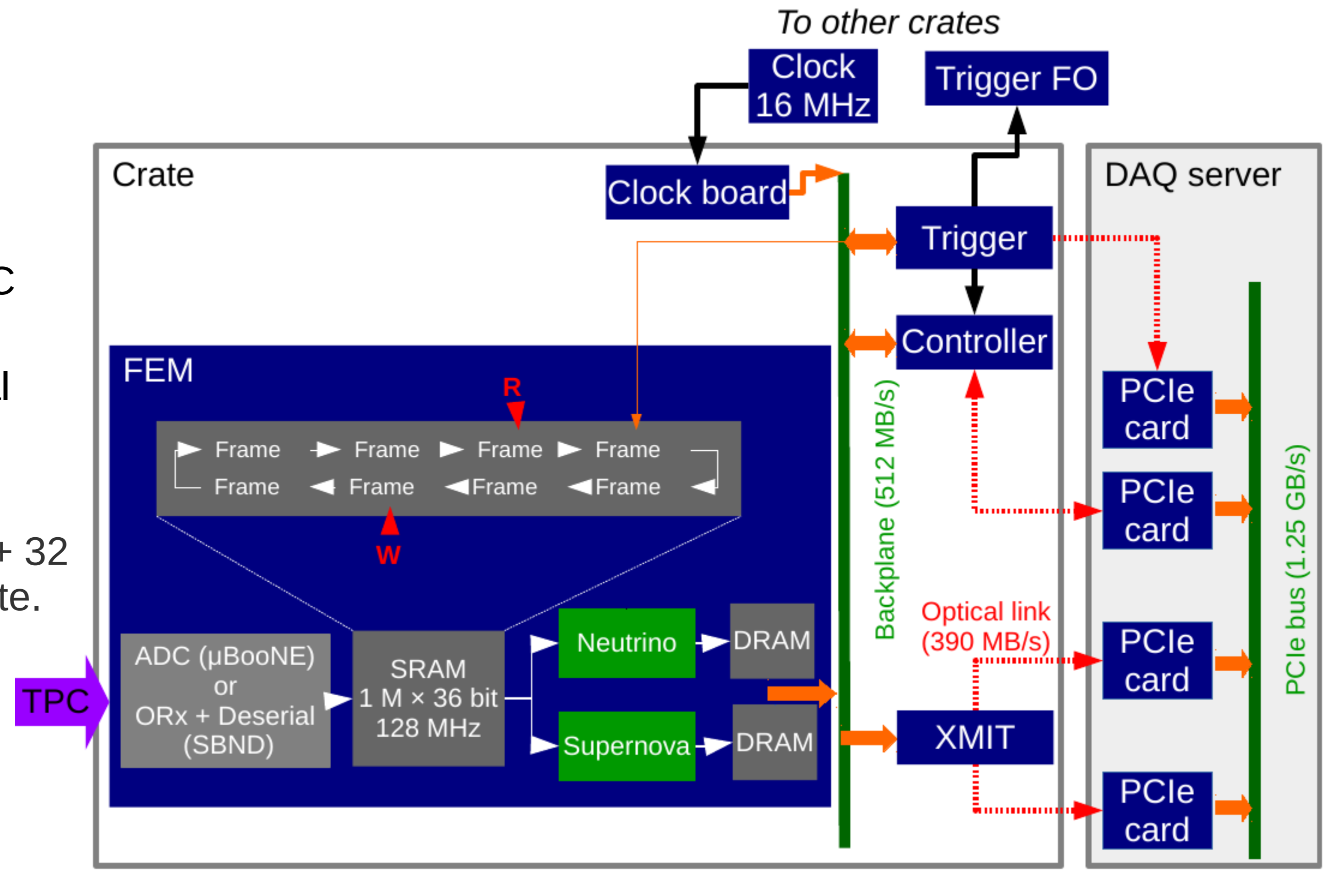
MicroBooNE: analog data sent to ADC attached to back-end electronics.

SBND: digital data sent through optical link to back-end electronics.

Front End Module (FEM).

64 ch/board (typically 32 induction ch + 32 collection ch). Up to 16 boards per crate.

- Data processing by FPGA
  (Altera Stratix III).

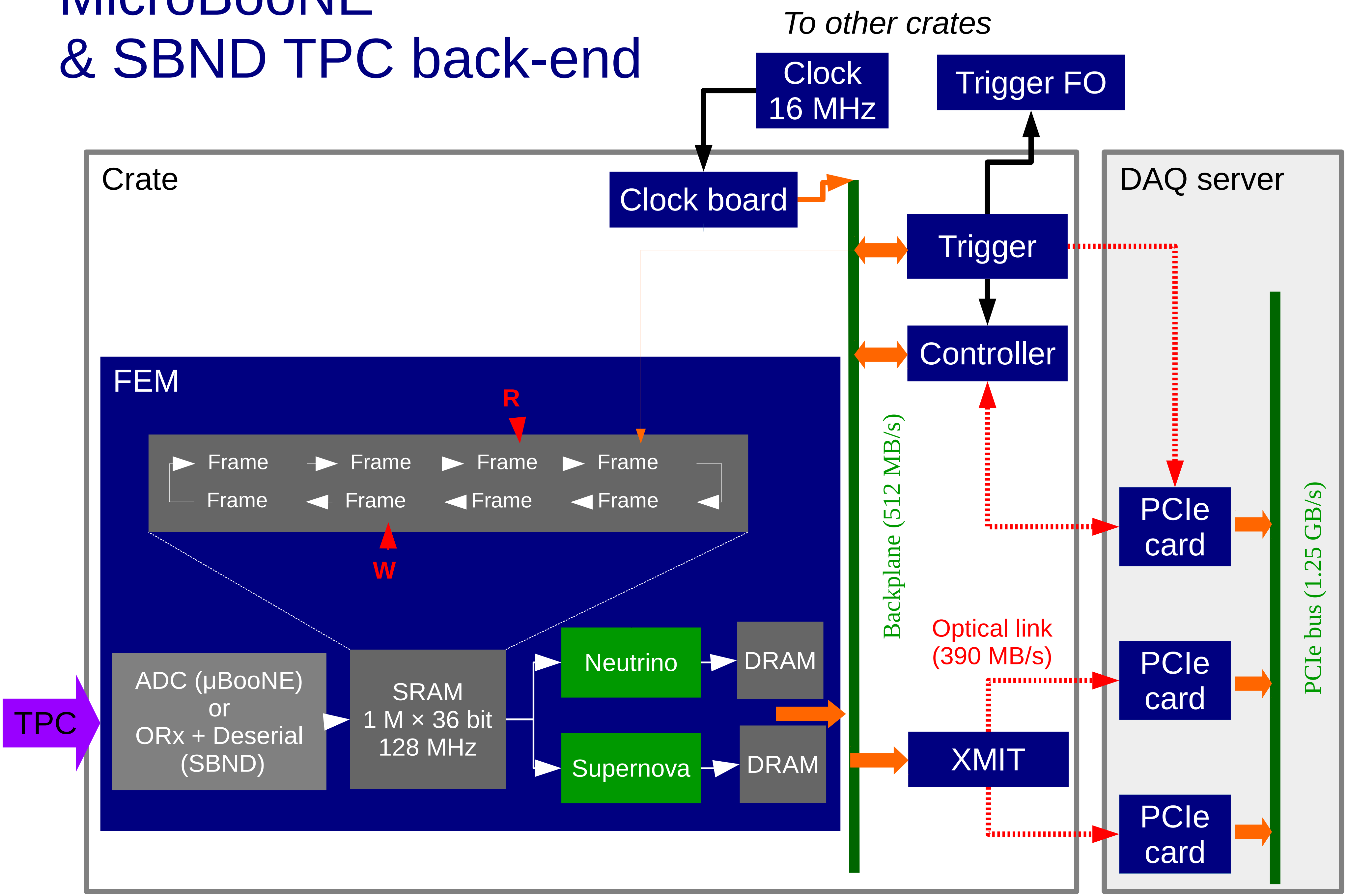


- 1 M × 36 bit 128 MHz SRAM
  as ring buffer. 8 frames in buffer (1.6 ms/frame × 8 frames = 12.8 ms).
- 64 MHz for writing in time-order. 64 MHz for reading by channel. **No deadtime.**
- Two data streams. **1) Triggered stream**: read out 1 frame before + 2 frames after trigger.
  3 × 1.6 ms window/ch × 2 MS/s × 2B/S = 19.2 kB/ch. But ~ × 5 lossless (Huffman) compression.
  2) “Supernova” stream: continuous readout.

Transmitter (XMIT) board. 1 board/crate reads up to 16 FEMs.

- Fetching data through backplane (512 MB/s). Data sent to PCIe card on DAQ server via optical links (390 MB/s).

MicroBooNE & SBND TPC back-end



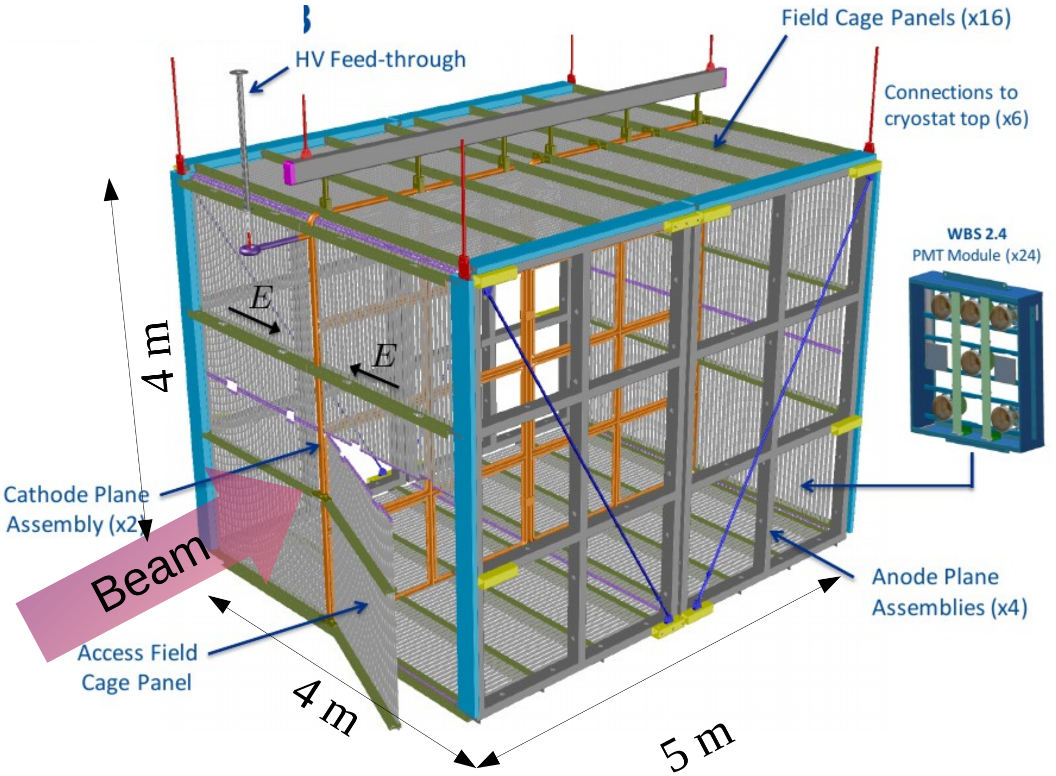
SBND detector

- **112 tonnes of liquid argon (active)**.
- Cathode Plane Assembly in the middle of the TPC at -100 kV. E_{drift} = 500 V/cm.
- **2 drift volumes.**

  Maximum drift length: 2 m.

  Maximum drift time: 1.28 ms.
- 3 wire planes. 3 mm wire pitch. **11264 channels.** Same orientation as MicroBooNE.
- Cold TPC front-end electronics by Brookhaven National Laboratory.

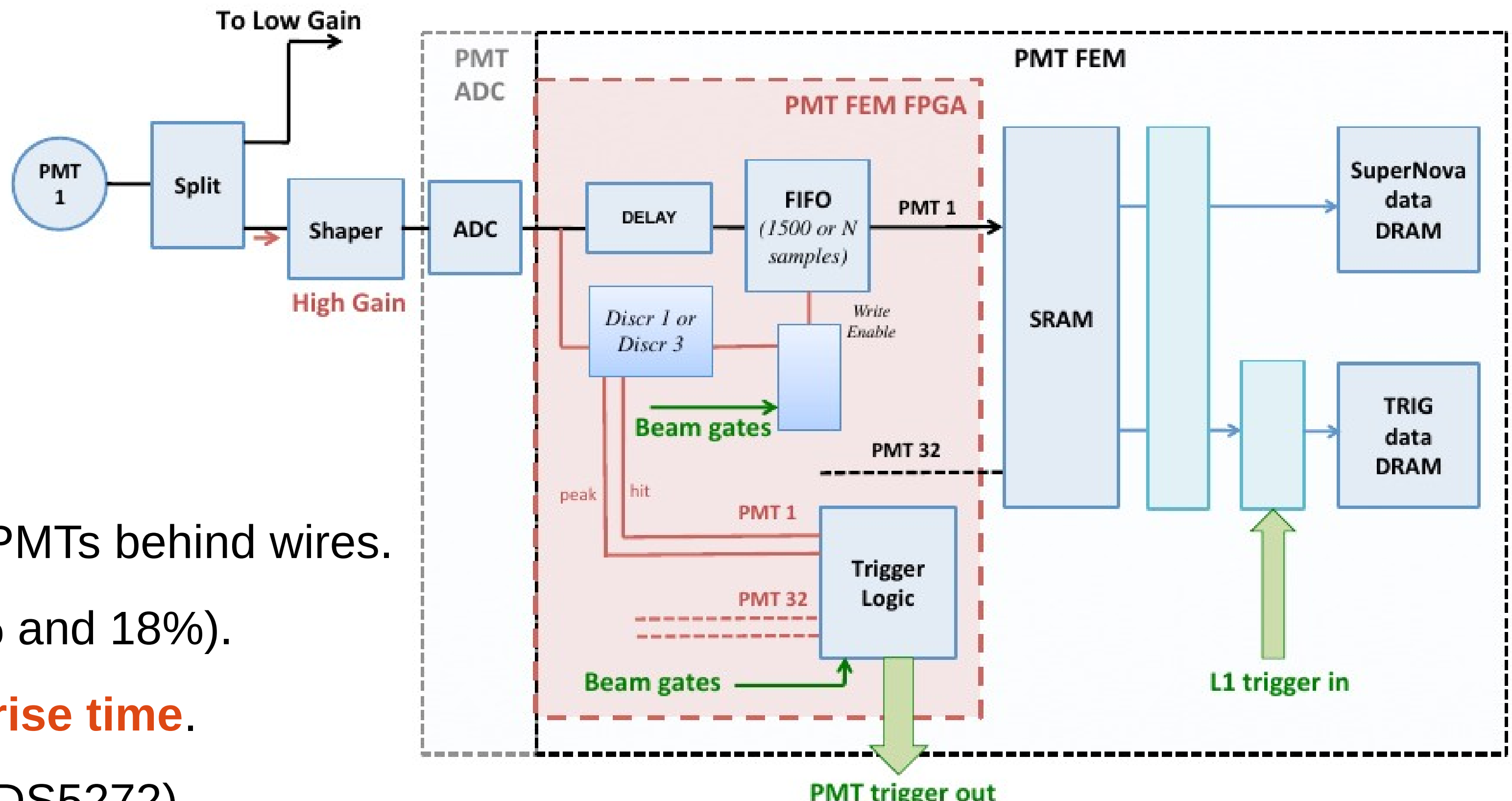
  2 MHz digitization. **Cold ADC electronics (commercial off-the-shelf).**
- **Custom TPC back-end electronics by Columbia University Nevis Laboratories.**



- **160 8"** Hamamatsu R5912 Cryogenic **PMTs** mounted behind the wire planes.

  (≥ 24 not TPB-coated to detect Cherenkov light).
- CAEN flash-ADC (500 MHz) PMT readout electronics.
- Additional photon detection systems: light guide bars and photon traps.

MicroBooNE PMT readout



- 32 TPB-coated PMTs behind wires.
- Two gains (1.8% and 18%).
- Shaping: **60 ns rise time**.
- **64 MHz ADC** (ADS5272).
  - Accurate determination of event t_0.
- Read 23.44 μs around beam (1500 samples).
- 0.31 μs (20 samples) for cosmics passing amplitude threshold.
- Back-end electronics similar to TPC design.

Zero suppression (PMT)

- The **bottleneck** of the stream is the **disk writing speed** at the DAQ PCs (assumed conservatively to be 50 MB/s).
- Neglecting header sizes:

  64 Msamples/s * 2 B/sample * 32 PMTs * 2 gains / 1 DAQ server = **8.2 GB/s/server**
- **Cannot write all data. Front End Module FPGA decides on the fly.**

Single-PMT ADC data

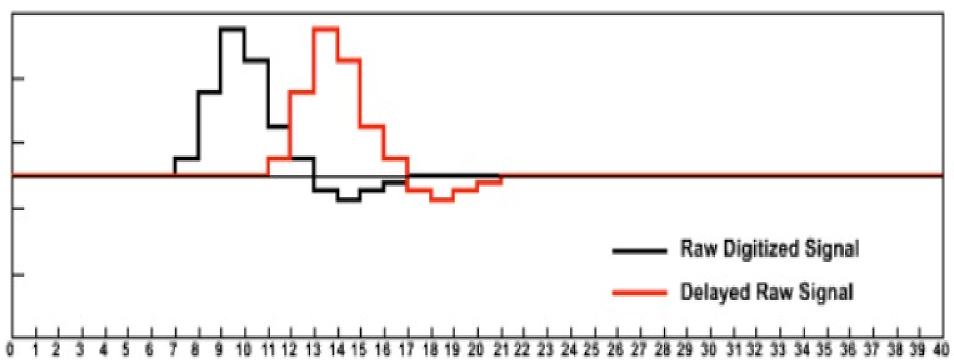
Same data delayed by 4 samples

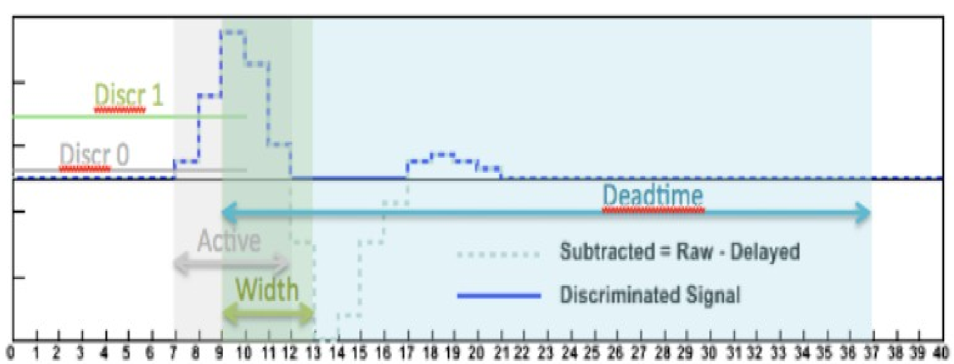
Subtracted pulse: original waveform – delayed one

Difference: only retain positive values from the subtracted pulse.

Apply two discriminators:

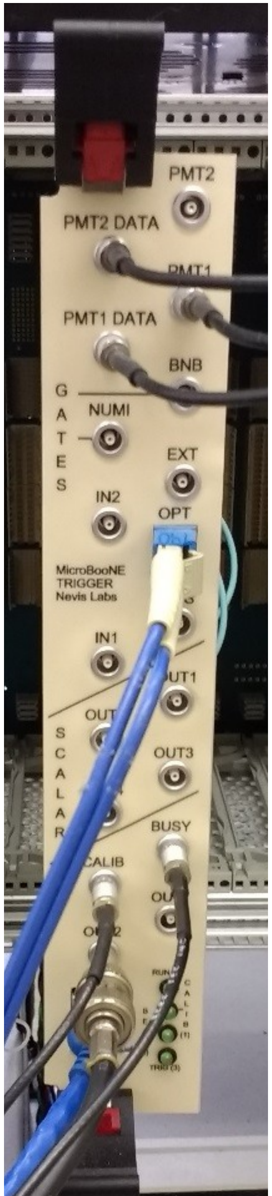
- Discr0 to open an active window.
- Discr1 to cut on amplitude.



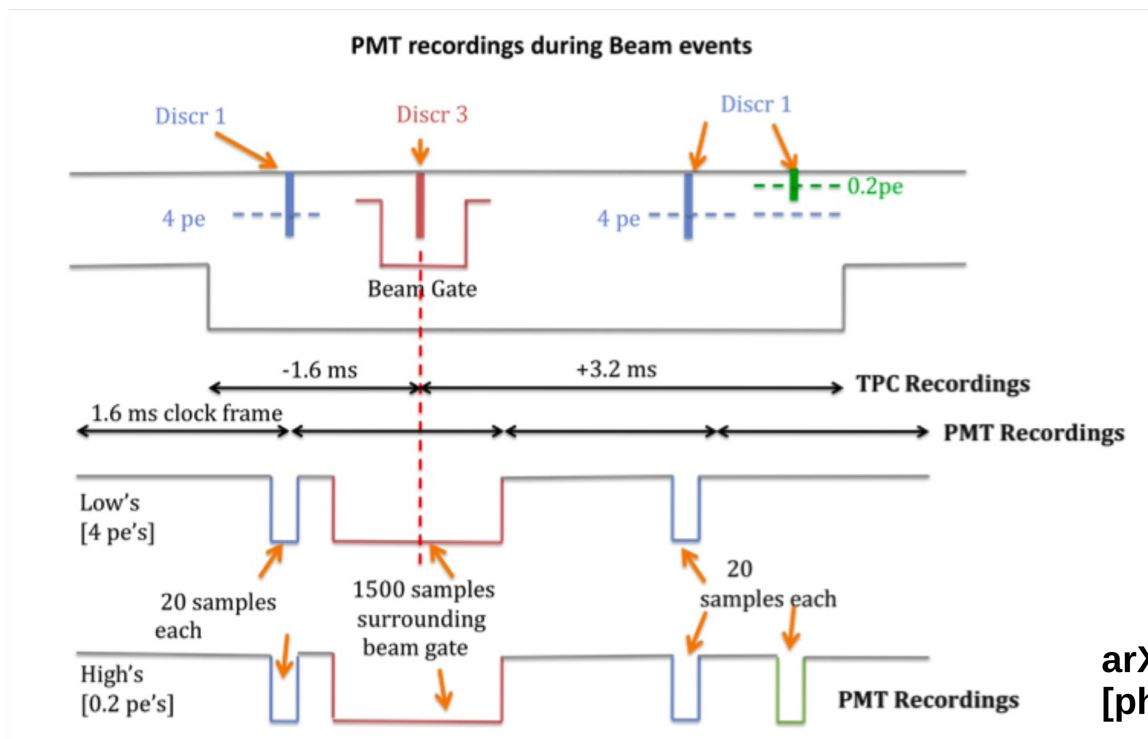


Instead, if **difference** passes threshold, **20 samples (312.5 ns)** are recorded (enough for prompt scintillation, $\tau \sim 6$ ns)

MicroBooNE trigger



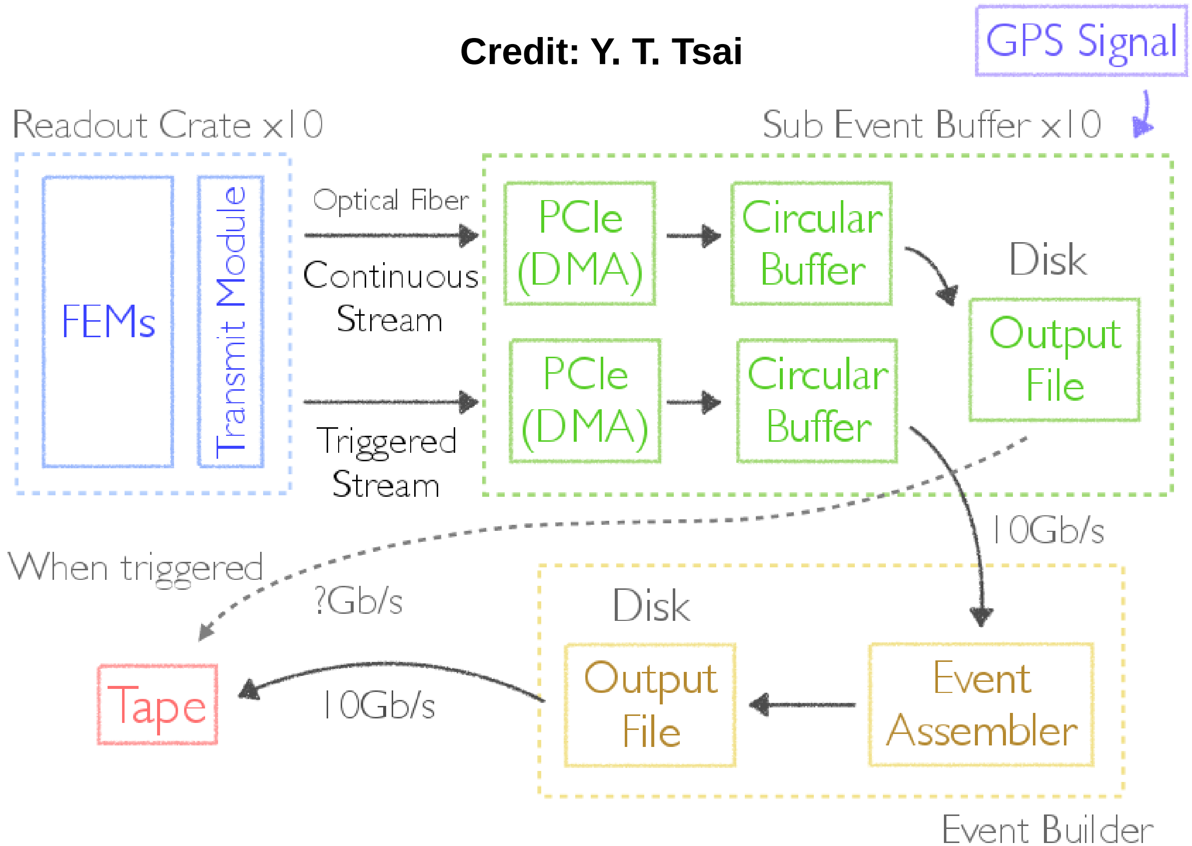
- Inputs for **PMT primitives**, **accelerator signals** (BNB and NuMI beam), **external trigger** and **calibration subsystems** (UV laser calibration, cosmic-ray tracker).
  - Configurable logic and prescaling.
- PMT trigger based on both multiplicity and pulse height provided by an FPGA. Currently disabled. Instead, **level-1 trigger on accelerator gates** and **software (level-2) trigger running an emulation of the FPGA** algorithm at the Event Builder stage.



arXiv:1308.3446 [physics.ins-det]

MicroBooNE DAQ

Credit: Y. T. Tsai



- Jungo Windriver to interface with PCIe card.
- TPC data distributed between 9 servers (Sub-event buffers).

  PMT + GPS data in 1 server.
- Triggered stream data sent over 10 Gbps network to Event Assembler.
- Continuous readout stream written locally on each server waiting for an SNEWS alert. After a few hours, it is deleted.
- Ganglia monitoring for DAQ servers. Slow Monitoring using EPICS.

Supernova neutrinos

[arXiv:1512.06148]