Low(er) Energy Neutrinos in DUNE

UC SANTA BARBARA

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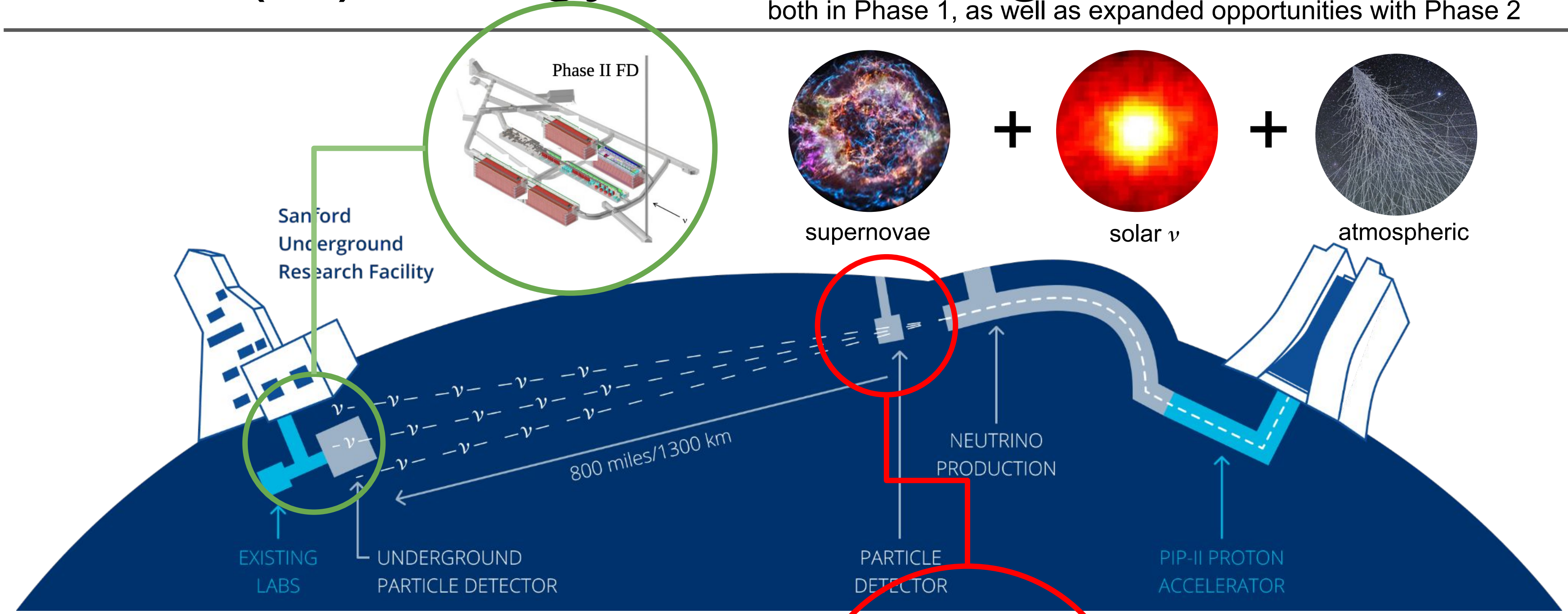
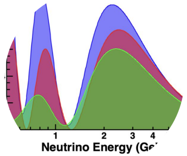
Snowmass Community Summer Study, Seattle, 07/20/22

Low(er) Energy ν have a big role in DUNE!

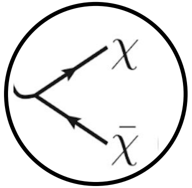
both in Phase 1, as well as expanded opportunities with Phase 2



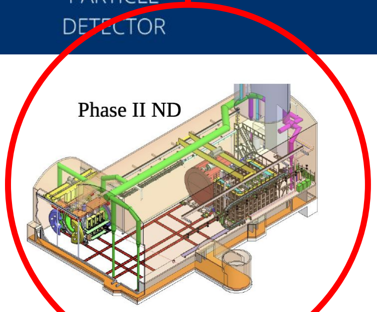


broad-band beam

+



sub-GeV BSM



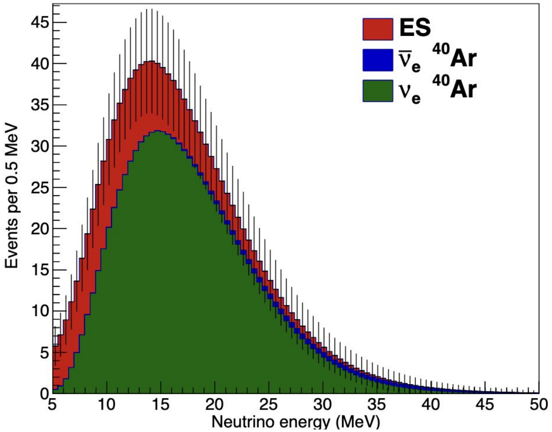
See talks by Gina and Chris for overview and “Phase I” vs. “Phase II” details.

Supernova and Solar Neutrinos

Supernova Burst

DUNE, Eur.Phys.J.C 81 (2021) 5, 423

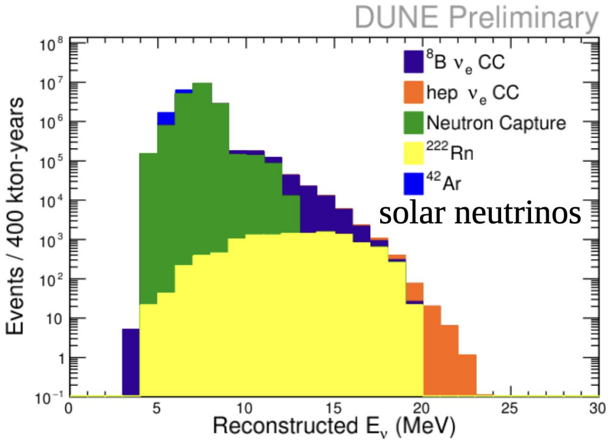
- Unique and rich astrophysics program.
- Neutrino properties (e.g. mass ordering)
- Few second burst w/ 10^2-10^3 @ 10 kpc



Solar Neutrinos

Capozzi, Li, Zhu, Beacom PRL 123 (2019) 13, 131803

- ^{8}B and potentially hep neutrino fluxes.
- Solar neutrino mixing
- continuous flux of neutrinos

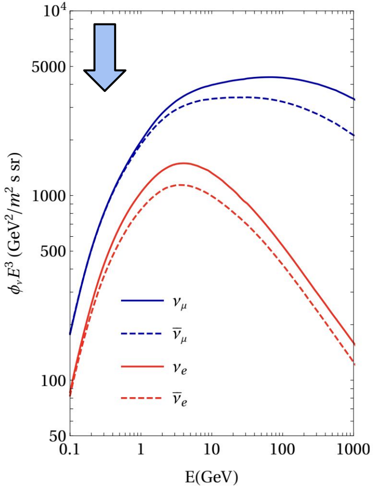


Refer to talk by Daniel Pershey for more details on this SNB and solar neutrinos

See also “Low Energy Physics in Liquid Argon” workshop summary / whitepaper

sub-GeV Neutrinos

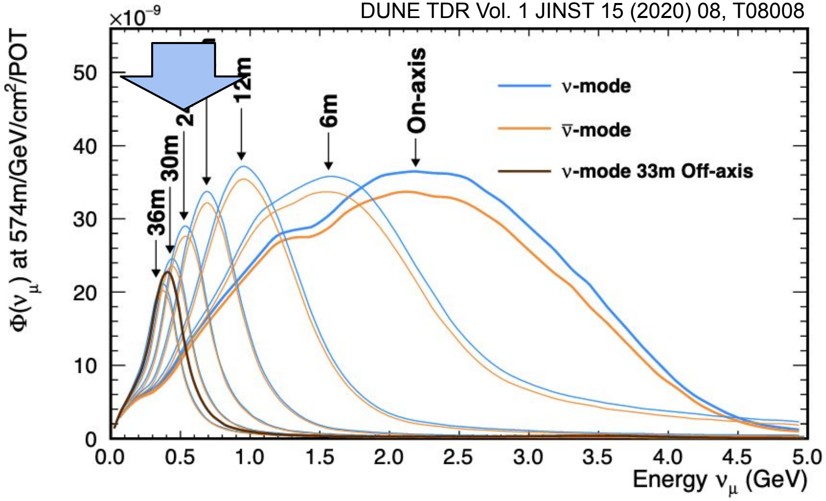
atmospheric



"[...] detailed event reconstruction capability of [LArTPCs]. This allows for studying the subGeV atmospheric neutrino component, which bears a rich oscillation phenomenology, strongly dependent on the matter potential sourced by the Earth."
JHEP 05 (2022) 187, Kelly, Machado, Martinez-Soler, Perez-Gonzalez

beam induced

DUNE TDR Vol. 1 JINST 15 (2020) 08, T08008



Lower energy beam neutrinos:
- 2nd oscillation maximum
- Oscillation and BSM physics @ Near Detector

BSM / Neutrinos as Backgrounds

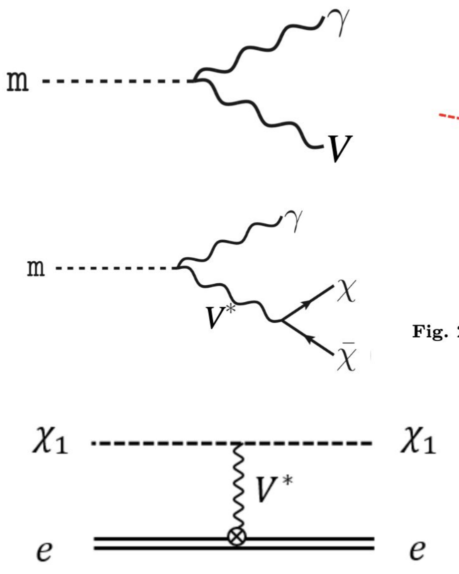


Fig. 18 Production of fermionic DM via two-body pseudoscalar meson decay $\mathfrak{m} \to \gamma V$, when $M_V < m_{\mathfrak{m}}$ (top) or via three-body decay $\mathfrak{m} \to \gamma\chi\overline{\chi}$ (center) and DM-electron elastic scattering (bottom).

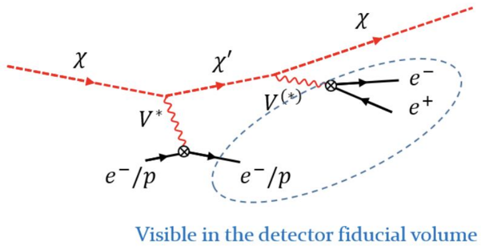


Fig. 20 The inelastic BDM signal under consideration.

DUNE provides a rich program for Beyond the Standard Model searches.

sub-GeV Dark Matter produced directly in the beam is a centerpiece of this program.

See Kevin's talk for more details on this.

Neutrino interactions are a background.

Uncertainty on their rate, at low energies in particular, impacts sensitivity and physics reach.

Talks by Pilar Coloma [link], Alex Sousa [link], and Jaehoon Yu [link] in Tuesday's session provide broad overview.

Many examples in literature. Taking some diagrams from DUNE's "Prospects for Beyond the Standard Model physics searches …" [Eur.Phys.J.C 81 (2021) 4, 322]

Potential New Directions in Phase II

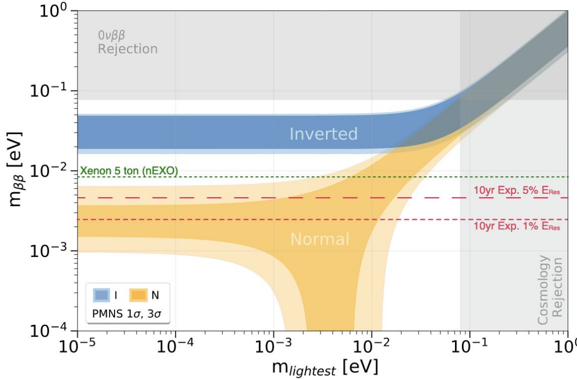
How can new technologies complement / expand existing program?

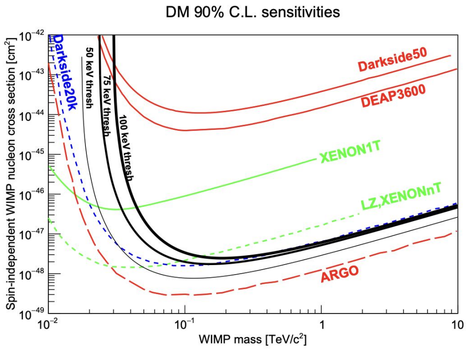
Many ideas aiming to leverage FD underground environment, as well as multi-detector and MW beam setup at the ND.

- $0\nu\beta\beta$
- CEνNS glow from a supernova
- Diffuse Supernova Neutrino Background
- Dark Matter searches

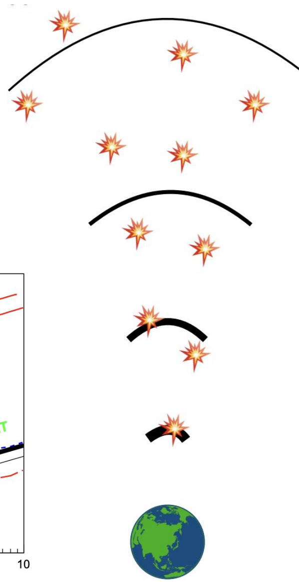
Low(er) energy νs play a key role here as well!

Mastbaum, Psihas, Zennamo, arXiv:2203.14700



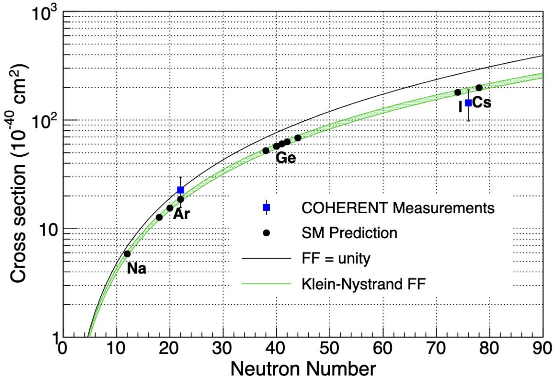


arXiv:2005.04824, Church, Jackson, Saldana

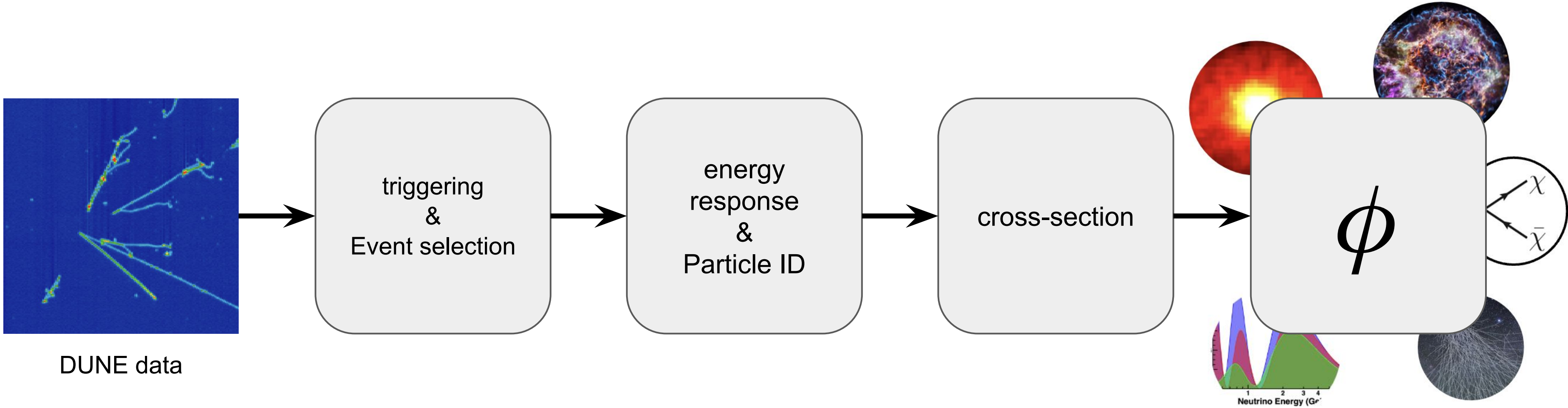


Cartoon from A. Mastbaum Neutrino '22 talk

COHERENT, PRL126 (2021) 1, 012002



Extracting Physics with Low(er) Energy νs

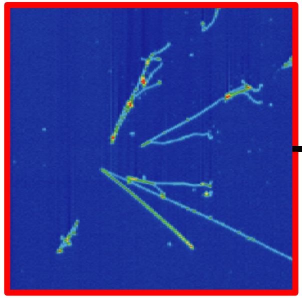


DUNE data

This is a chain that can be applied to most topics of interest, and to any detector technology, planned or conducting R&D.

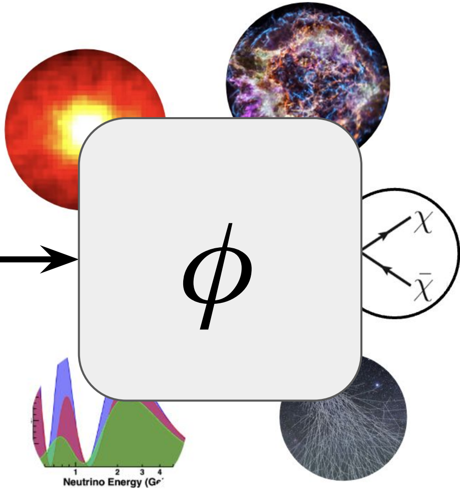
Will walk through this chart and attempt to make relevant considerations.

The Data at Low(er) Energies

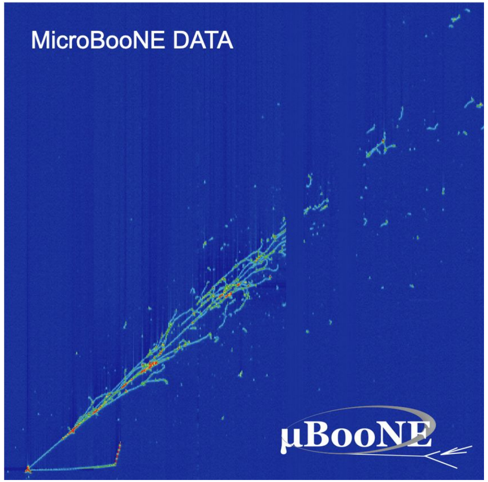


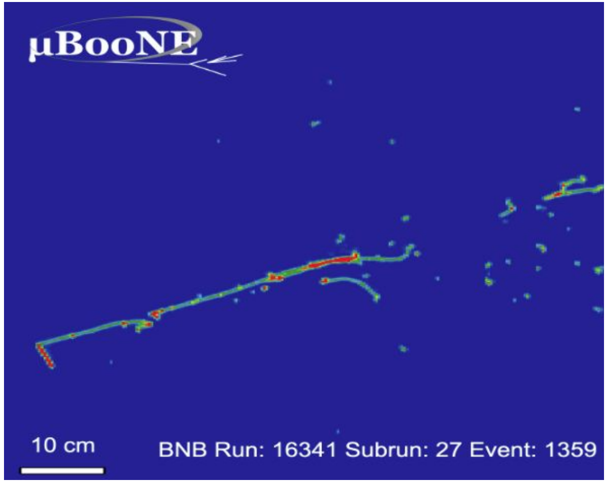
DUNE data

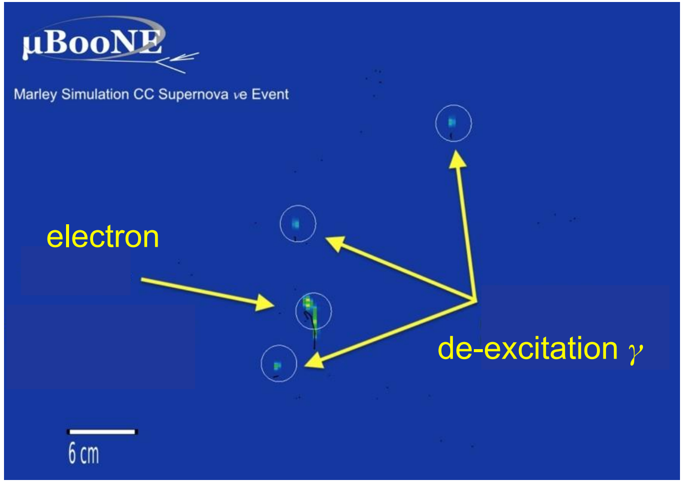
triggering & Event selection → energy response & Particle ID → cross-section →



What Neutrinos?







GeV-scale

100s of MeV

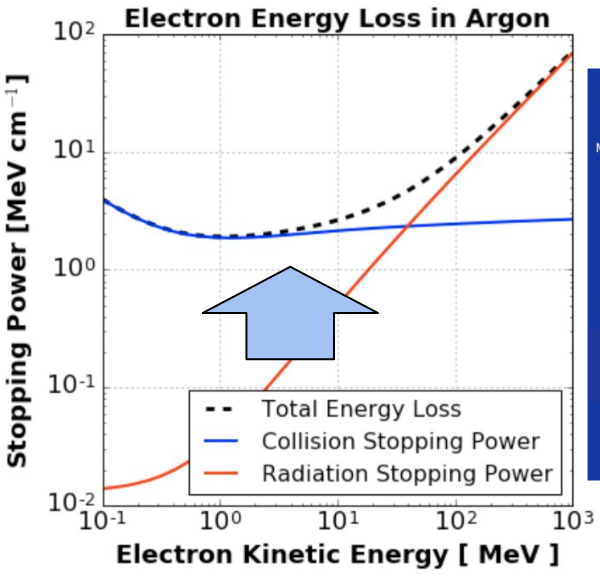
Few-10s of MeV

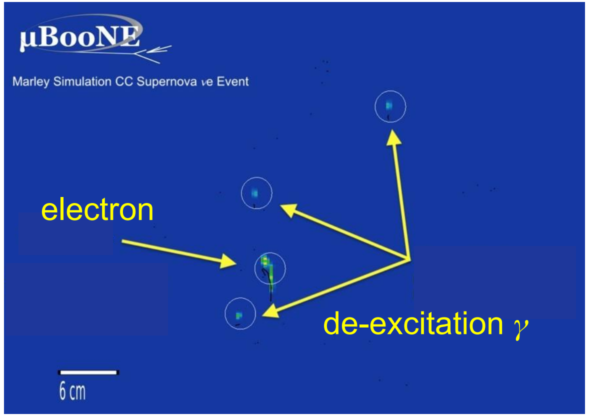
Examples of ν_e interactions in LAr. Final-state appearance varies significantly depending on the energy.

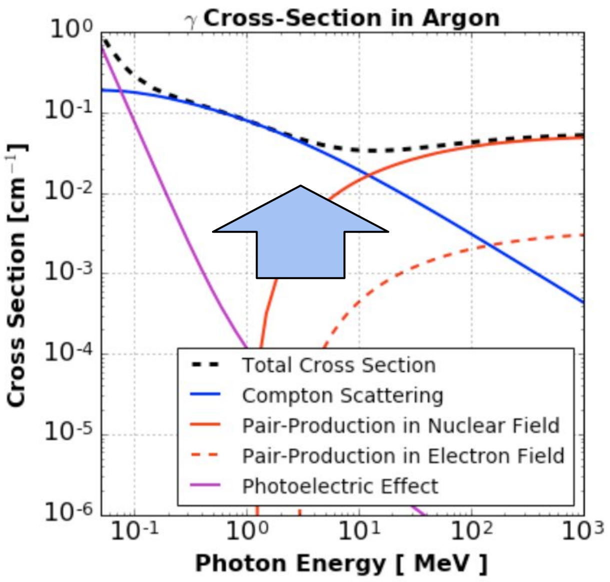
- Potentially different design and analysis considerations for different regimes.
- At the same time, MeV-scale performance improvements can benefit GeV-scale program.

[Friedland, Li Phys.Rev.D 99 (2019) 3, 036009] & [Castiglioni, et al. Phys.Rev.D 102 (2020) 9, 092010]

Detector response: electrons and γ





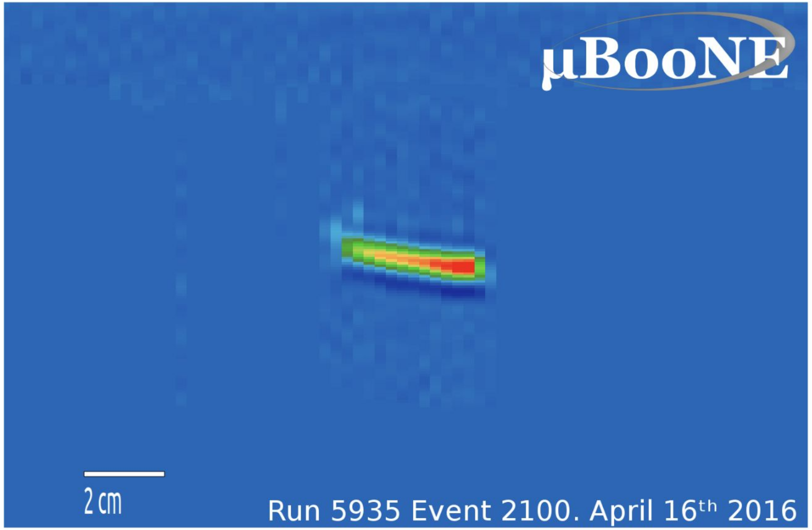


Radiative losses a lower fraction of total:

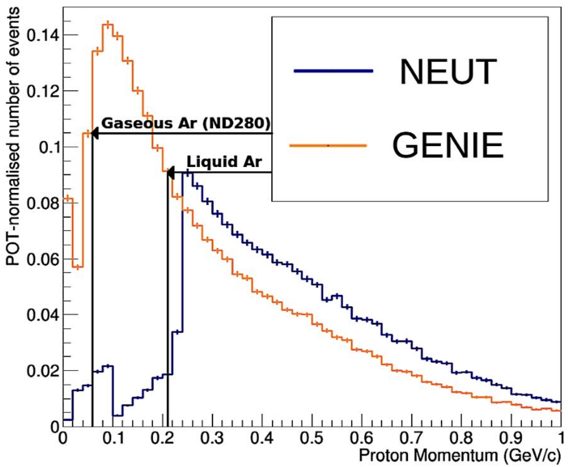
- "track-like" EM showers
- Stochastic photons, event-to-event variation in topology

Below 10 MeV photons Compton scatter, losing a small fraction of their energy in "blips".

Detector response: protons



Illustrative plot. Pip Hamilton's PhD [thesis] on T2K

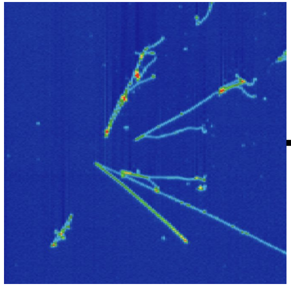


Protons range out quickly due to high dE/dx.

Gas detector like ND-GAr brings new capabilities in tracking and measuring kinematics of low-energy protons.

See talk by Jen Raaf [link] @ 10 AM Thursday session.

Triggering on Low(er) Energy νs

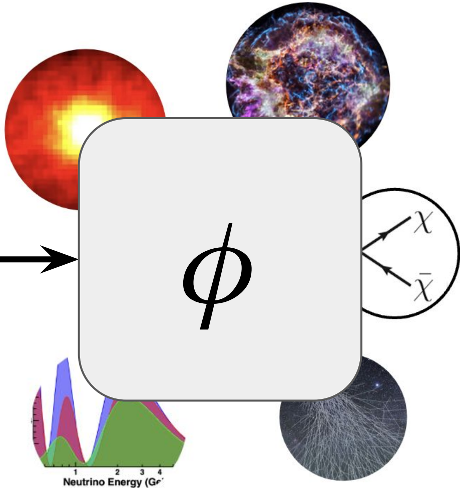


DUNE data

triggering & event selection

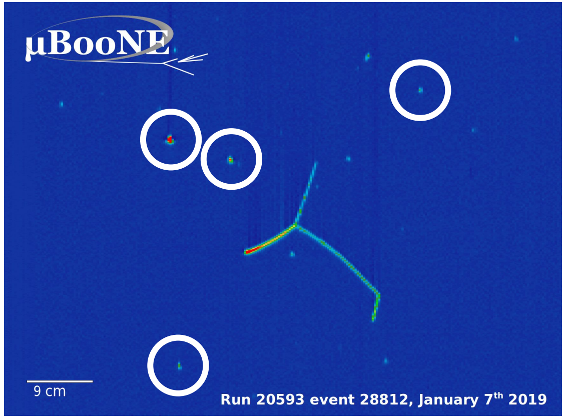
energy response & Particle ID

cross-section



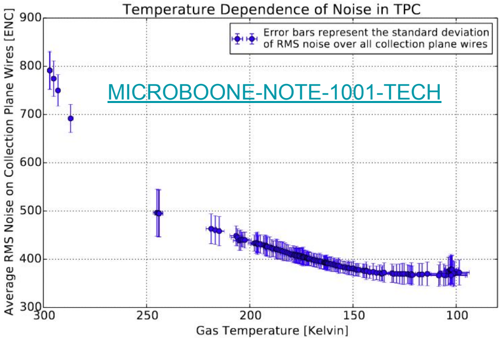
ϕ

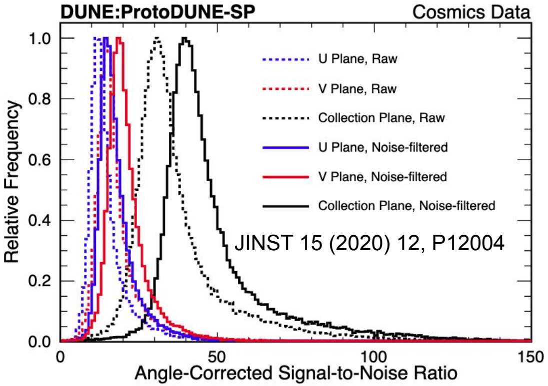
Low-Thresholds

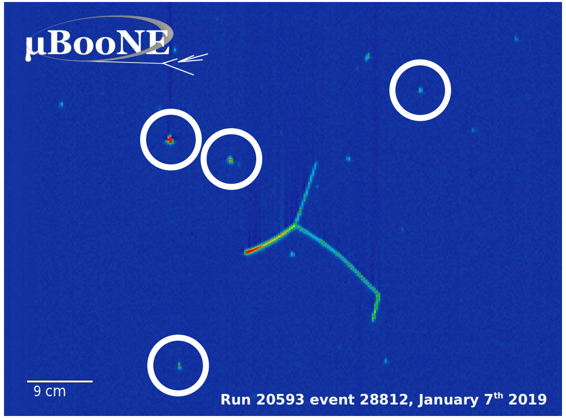


Low-Thresholds

Cold electronics have had a huge impact on the ability to reconstruct low-energy activity







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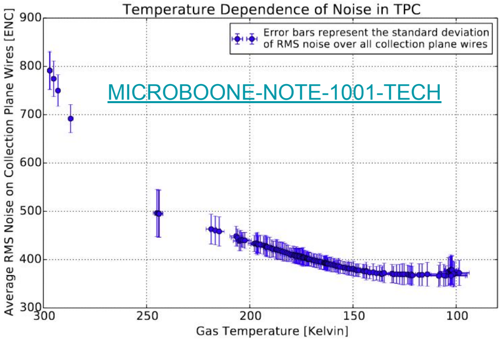
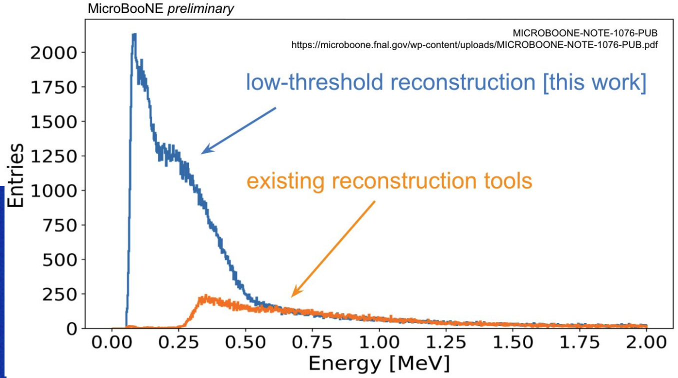
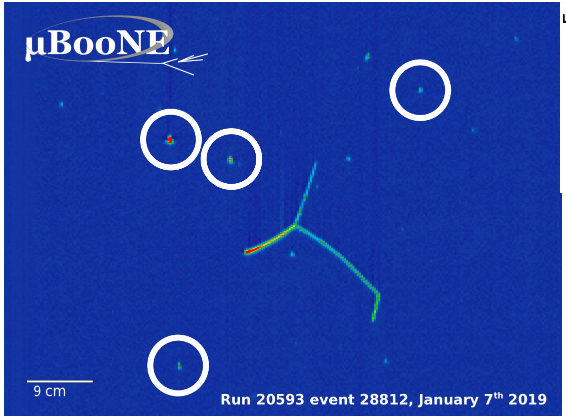
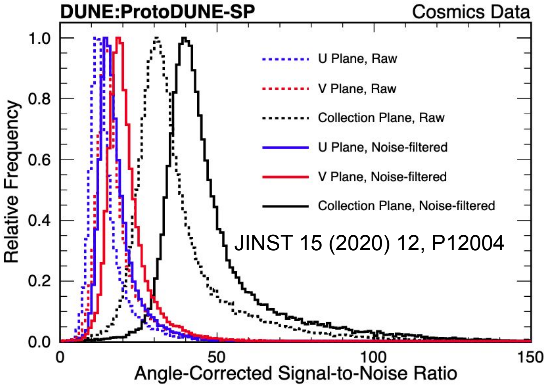
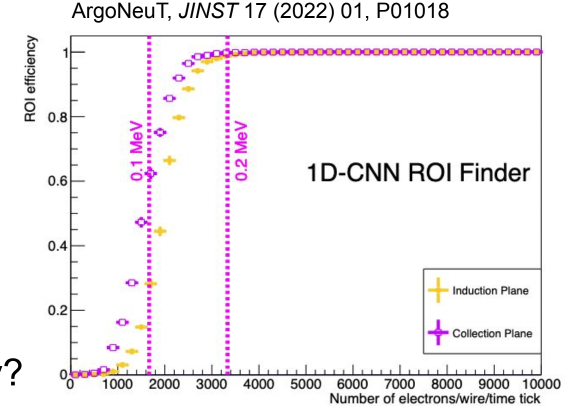






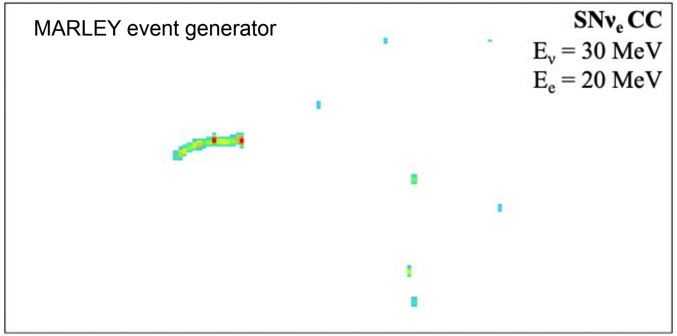


Can we outperform?
Where to go from here?
What complements this technology?



Triggering on MeV-scale Physics in DUNE

W. Castiglioni, et al., Phys. Rev. D, 102(9):092010, 2020

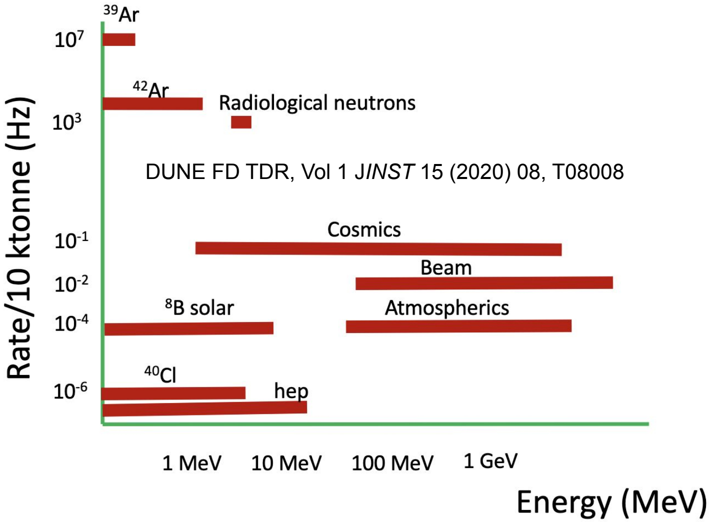


How to mitigate backgrounds:

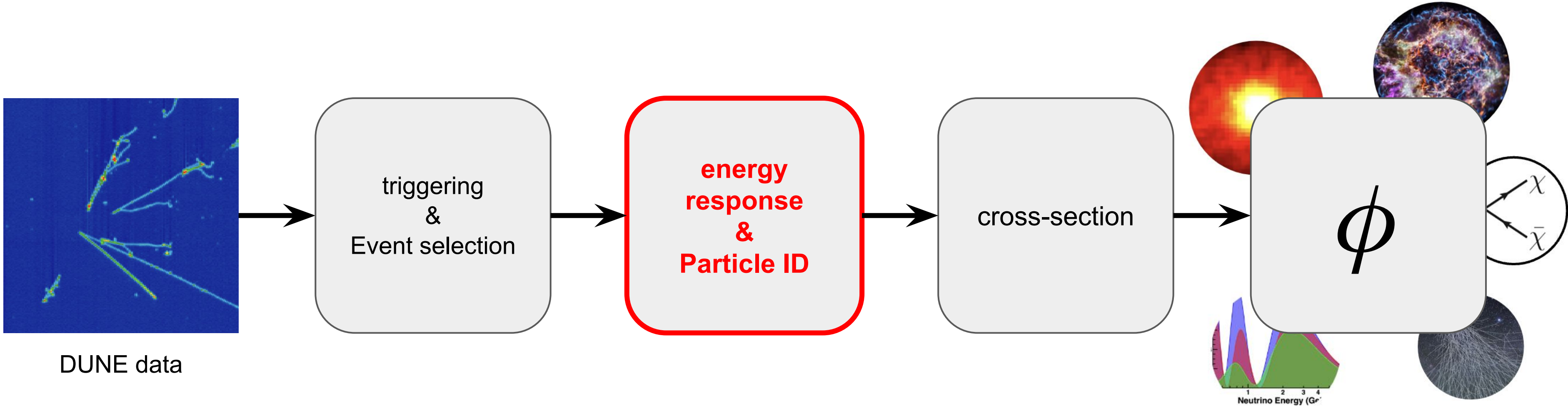
- Sophisticated Triggers
- Shielding (e.g. Capozzi, Li, Zhu, Beacom PRL 123 (2019) 13, 131803)
- Underground Ar [see next NF session]

Low-Energy Physics in Neutrino LArTPCs, arXiv:2203.00740

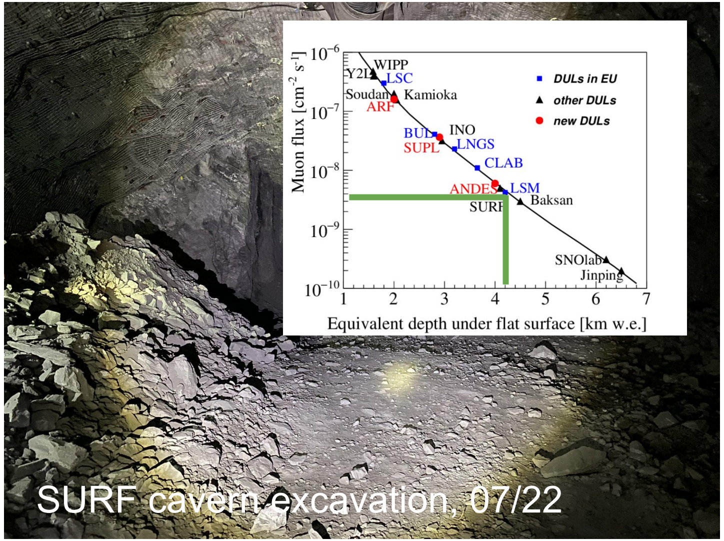
Event Type	Rate (1/s/10 kT)	Data Rate (PB/y)		
		Module	TPC	m^3 Box
Beam or Atmospheric ν	2×10^{-5}	10^{-3}	-	-
Cosmic Muons	4×10^{-2}	4	-	-
Solar ν	3×10^{-4}	0.03	2×10^{-4}	10^{-6}
n-Ar Captures	1	10^2	0.6	4×10^{-3}
^{42}Ar Decays	1000	10^5	700	4



Calibrations and Energy Measurements



Calibrations @ FD



Low energy physics program has particular calibration needs:

- Neutron and Compton scatters
- MeV-scale electrons vs. higher energy showers.
- particle-species dependent charge quenching and Light Yield.

Important for each module to have adequate calibration strategy (intrinsic + artificial) that can meet the needs of this physics program.

Underground environment is “quiet” by design. Fewer cosmogenic sources traditionally leveraged in LArTPCs thus far.

Value of existing detectors, both in designing calibration strategies, and providing constraints on detector physics parameters.

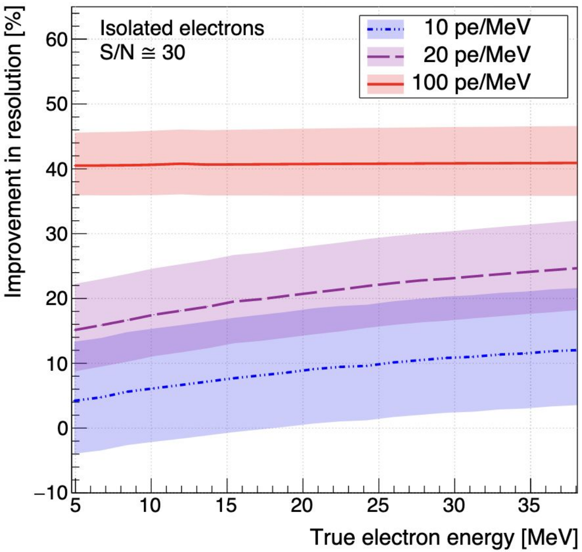
Light Collection

Scintillation light in LArTPCs key to extract full 3D position.

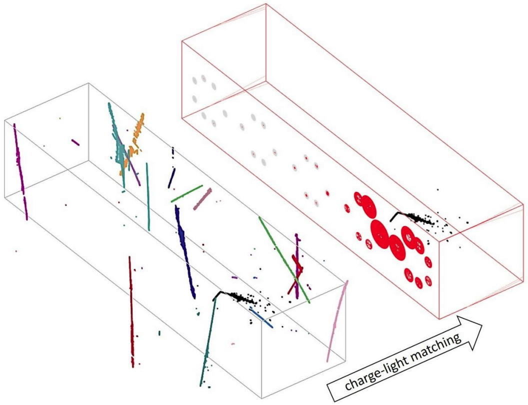
“Charge-to-light” matching used to “time” interaction.

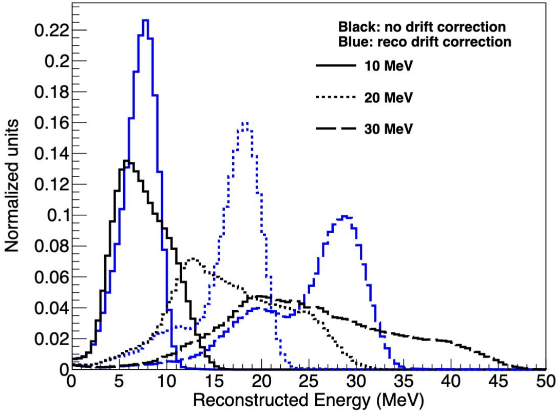
Enhancements to scintillation light collection can further expand reach and opportunities for event tagging.

LArIAT, Phys.Rev.D 101 (2020) 1, 012010



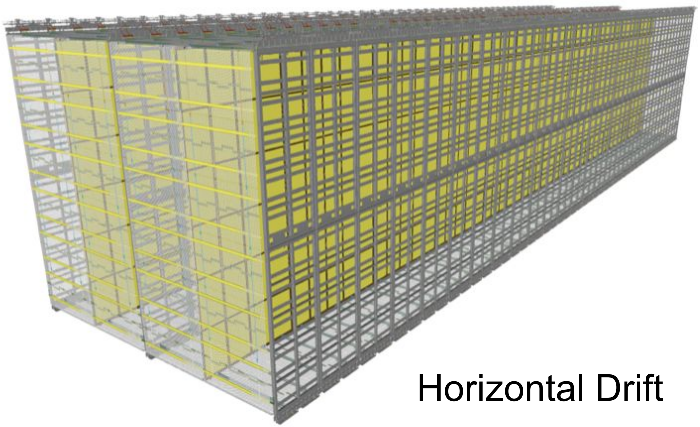
DUNE, Eur.Phys.J.C 81 (2021) 5, 423



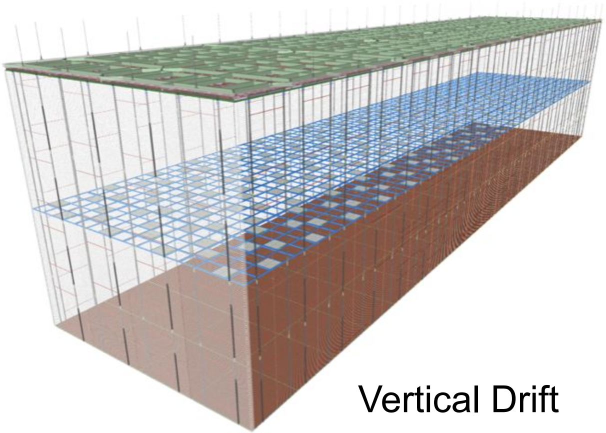


high Light Yield can further bring improvements to calorimetric energy reconstruction

Calibrations with Multiple FD Modules

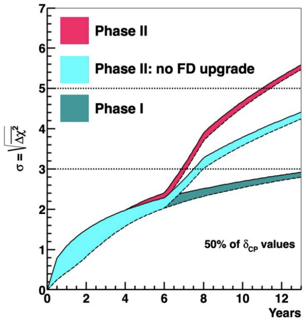


Horizontal Drift



Vertical Drift

+ ...

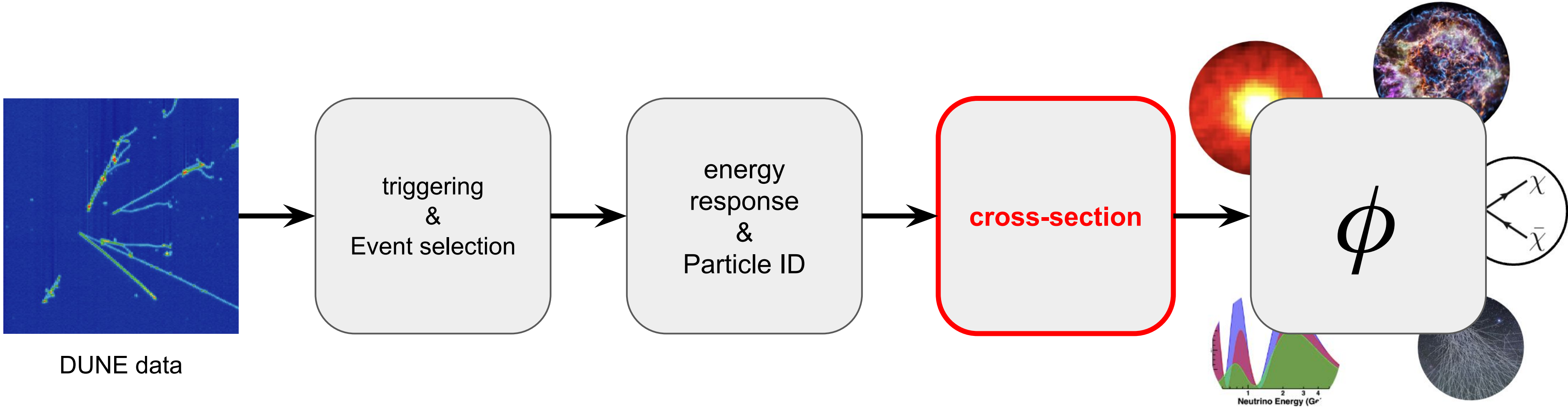


Precious statistics from all 4 FD modules for DUNE Phase II.

Important for modules to satisfy the needs of the beam oscillation program.

Ensure datasets from different detectors can be combined effectively.

Neutrino Interaction Modeling



DUNE data

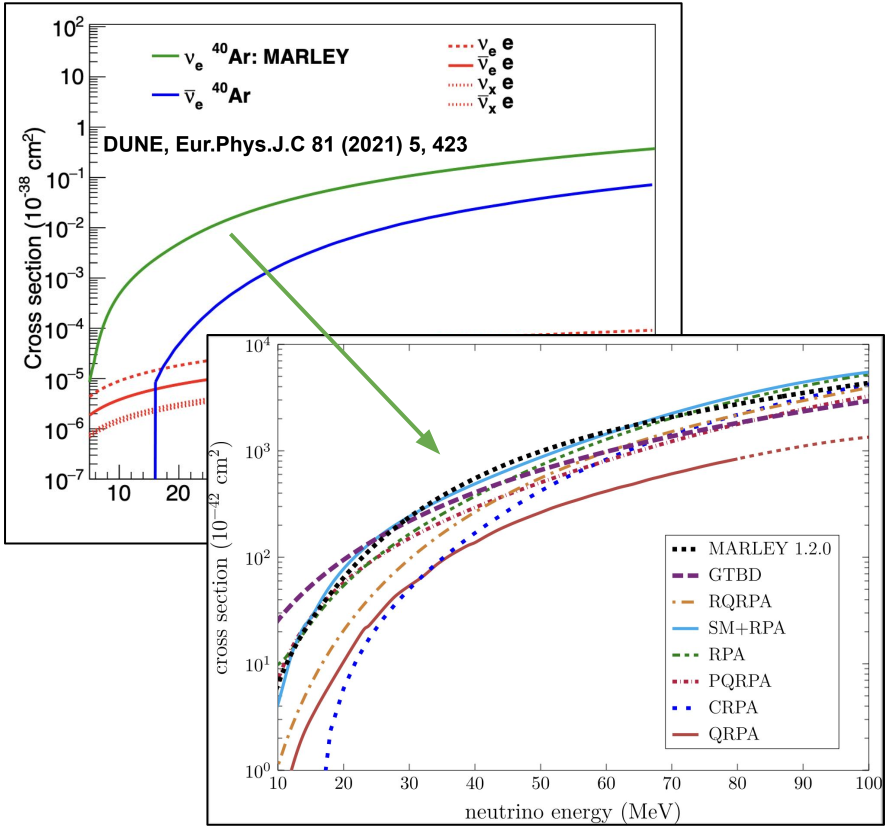
Interaction Cross-Sections

Modeling uncertainties on ^{40}Ar cross-section calculations impact ability to measure the flux of the sources we are interested in

- Calculations focus on inclusive channel
- MARLEY generator [Gardiner, Phys. Rev. C 103, 044604] recent development focusing on de-excitation modeling.
- Need for experimental data

Input can come from:

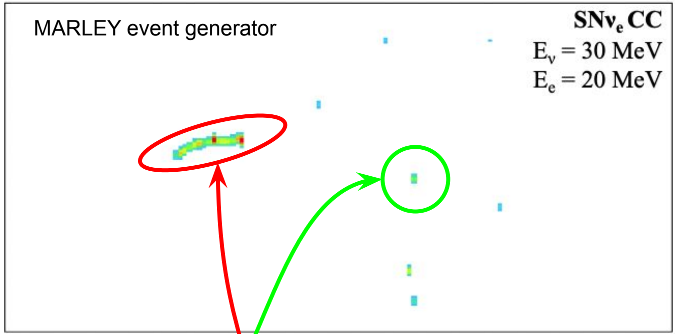
- Measurements of 10s of MeV ν-Ar interactions
- MeV activity in higher energy neutrinos
- Further theory / generator developments



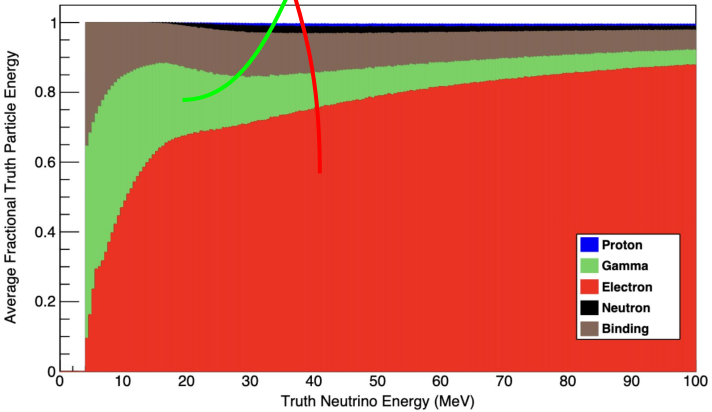
Discussion contained in “Low-Energy Physics in Neutrino LArTPCs” [arXiv:2203.00740] and references therein
Summary of LEPLAr workshops, prepared for Snowmass

Final States / ν Energy Reconstruction

W. Castiglioni, et al., Phys. Rev. D, 102(9):092010, 2020

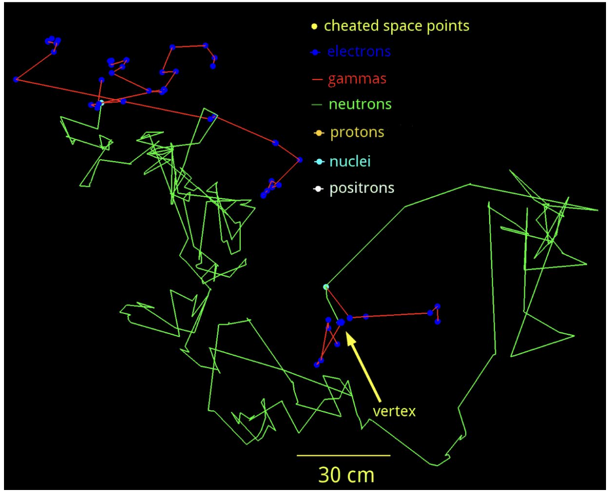


DUNE, Eur.Phys.J.C 81 (2021) 5, 423

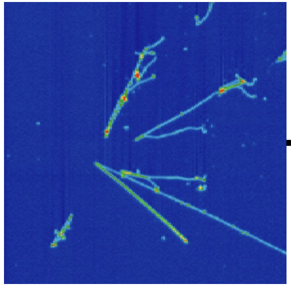


- Energy “budget” split amongst final-states
  - Important to model different contributions
  - Important to tag and reconstruct final-states

- Significant event-to-event variation.

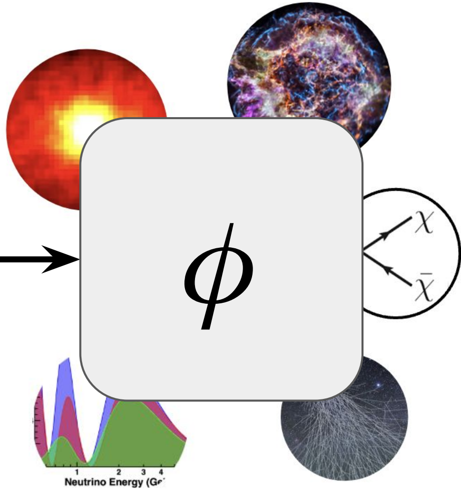


New Analysis Tools and Techniques



DUNE data

triggering & Event selection → energy response & Particle ID → cross-section → ϕ



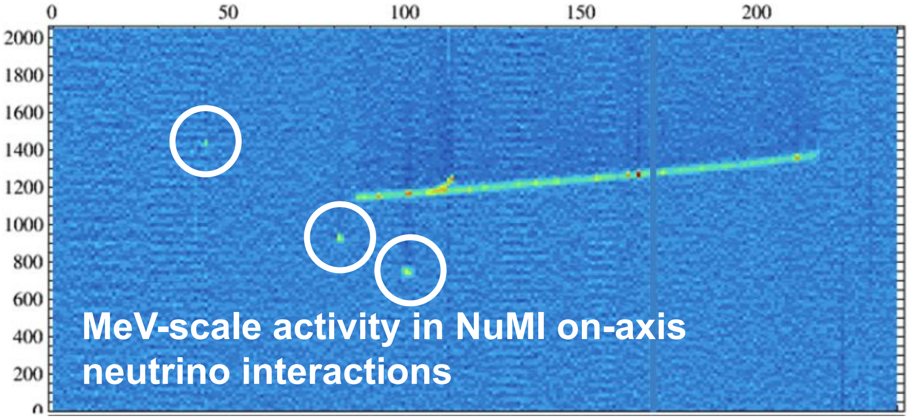
We are continuously devising new ways to analyze and extract more information from LArTPCs

R&D in analysis methods offers exciting opportunities for low-energy physics program in DUNE

- An investment in the future potential for DUNE

ArgoNeuT

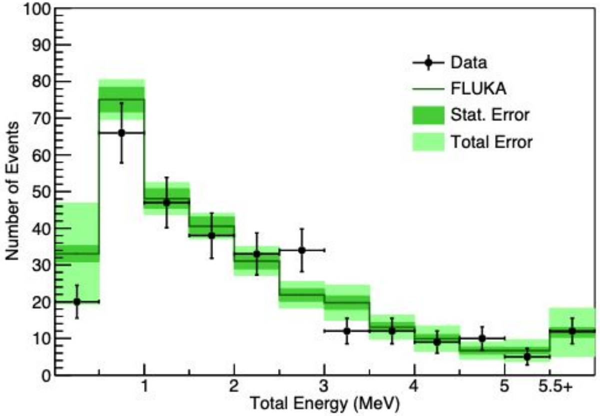
ArgoNeuT, *Phys.Rev.D* 99 (2019) 1, 012002



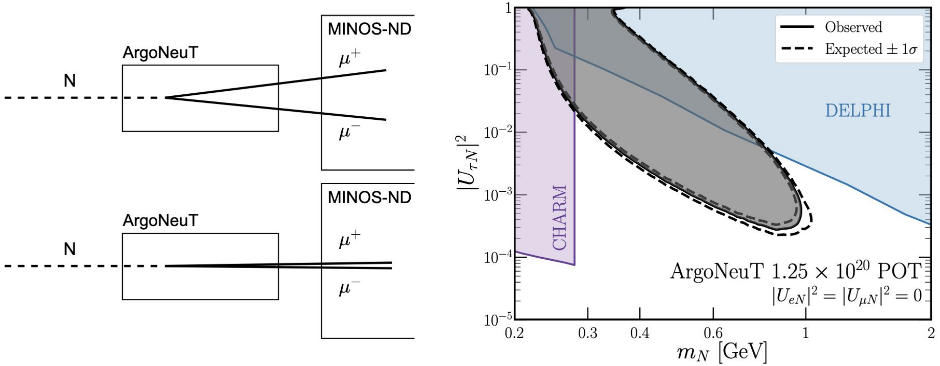
ν interaction modeling

Expanded BSM program

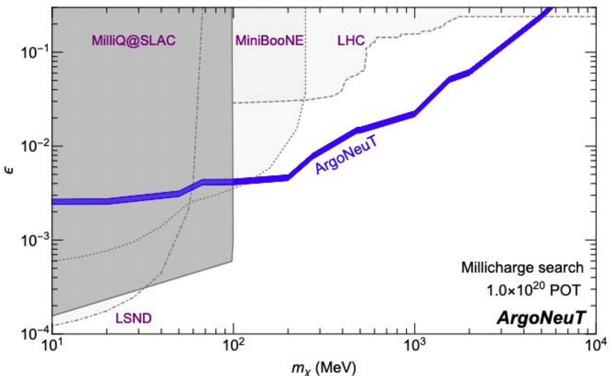
ArgoNeuT, *Phys.Rev.D* 99 (2019) 1, 012002



Phys.Rev.Lett. 127 (2021) 12, 121801



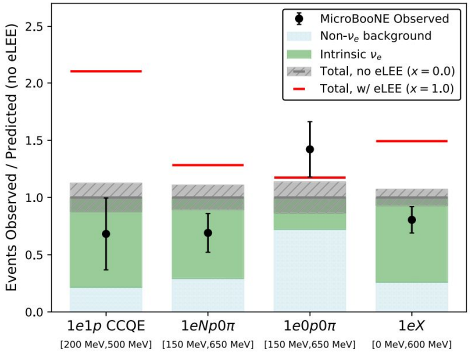
ArgoNeuT, *Phys.Rev.Lett.* 124 (2020) 13, 131801



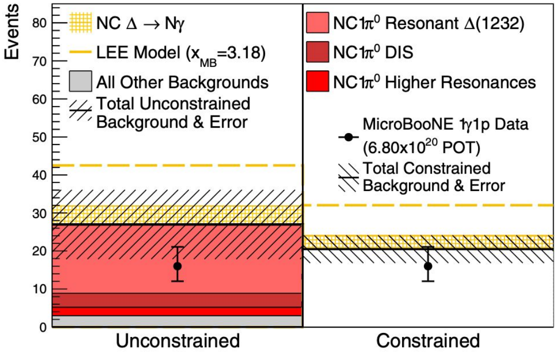
sub-GeV: MicroBooNE “LEE” Results

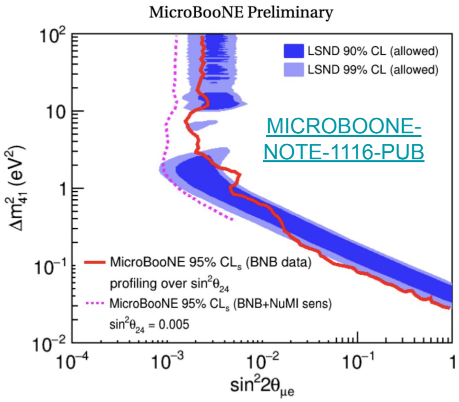
MicroBooNE released in 2021 its first results investigating the MiniBooNE “Low Energy Excess”

PRL 128 (2022) 24, 241801



PRL 128 (2022) 111801





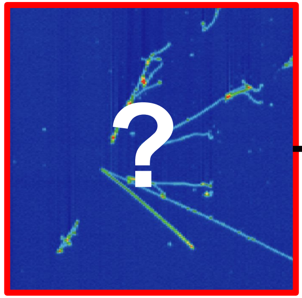
MICROBOONE-NOTE-1116-PUB

Major milestone for LArTPC technology, very much relevant to sub-GeV neutrino interactions.

Years of analysis R&D development in the making - even after demonstration of technology performance - on the tail of the Snomwass process.

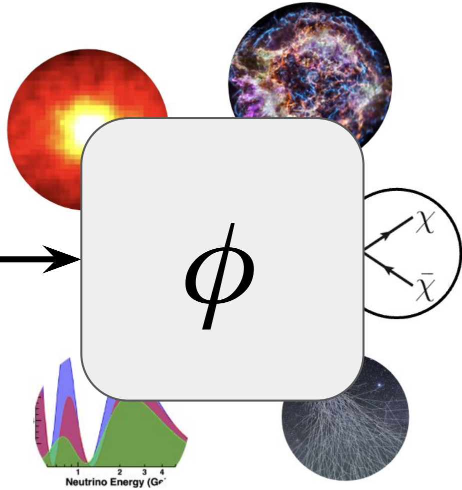
Contributing to broaden scope and reach of BSM searches in neutrino experiments.

Detector Technologies for Phase II



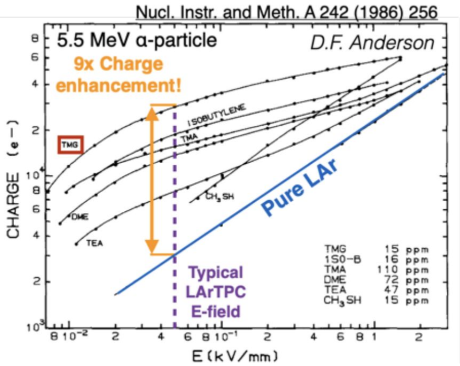
DUNE data

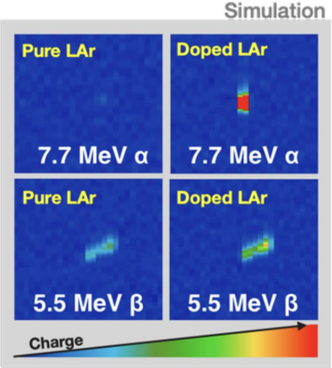
→ triggering & Event selection → energy response & Particle ID → cross-section →

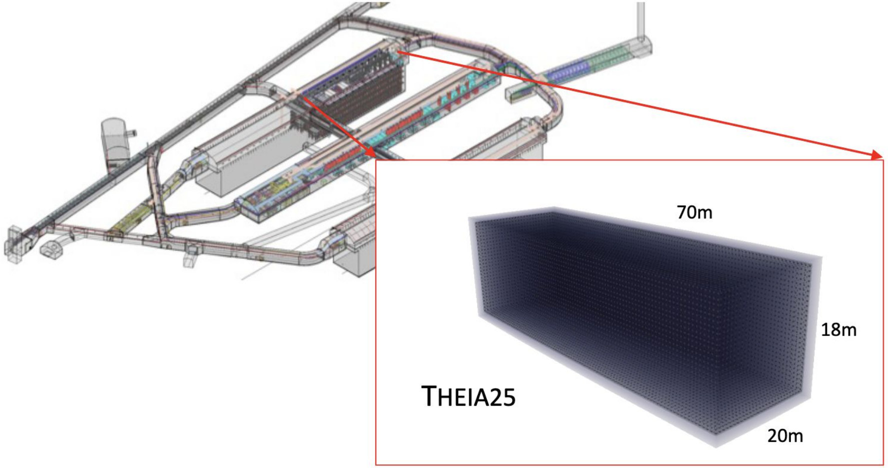


R&D Efforts Targeting Low-Energy

Talk by Fernanda Psihas [link] on dopants for increased charge yield

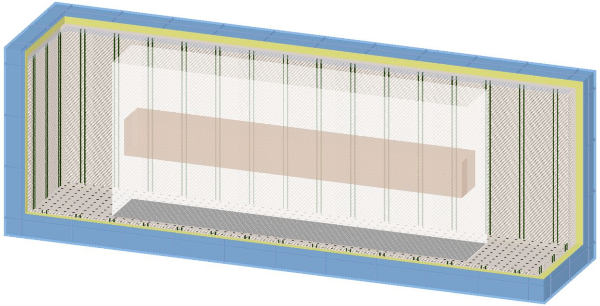






Talk by Chris Jackson [link] on Underground Argon solutions

Talk [link] by Gabriel Orebi Gann on THEIA module



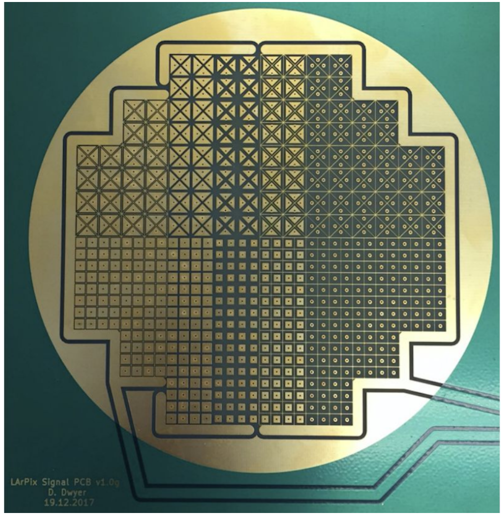
Many ideas: dope the argon…clean the argon…or get rid of the argon…

R&D Efforts Targeting Low-Energy

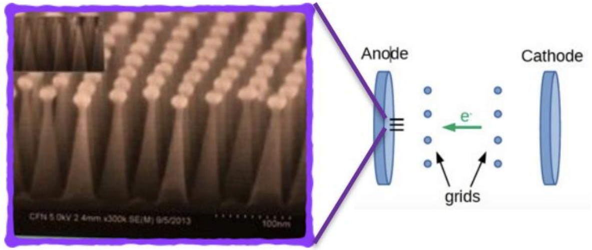
Broad landscape for R&D in LArTPCs that can build on and enhance existing detectors

[see Angela Fava's Neutrino '22 talk for a very nice overview]

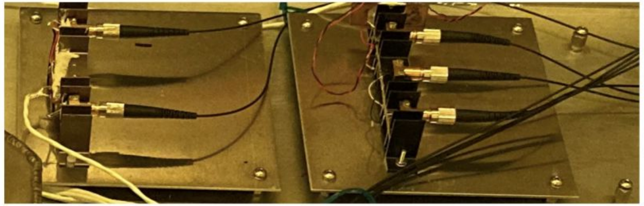
Pixel detectors, e.g. Q-Pix. Talk by Brooke Russell [link]



charge Amplification in LAr.



PoF - Power housing unit *(5 warm Transmitter laser diodes)*



LV-HC PoF supply board *(2 cold Receivers on heatsink)*

HV-LC PoF supply cold board *(3 cold Receivers on heatsink)*

Photodetectors for HV surfaces, and signal/power over fiber transport
Active and successful tests @ CERN

Conclusions

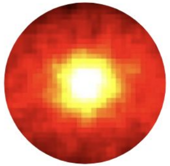
DUNE has an exciting road ahead with many clear scientific questions to address.

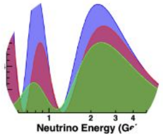
Excitement for the unknowns we may learn from a broad and diverse physics program.

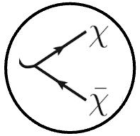
Achieving and expanding possibilities tied to Low(er) energy Neutrinos can support:

- Strong(er) astrophysics program in FD
- Exciting prospects for BSM searches and important role of sub-GeV neutrinos in ND
- Expanded physics scope with detector and analysis R&D

Coordinate strategically: achieve performance that is greater than the sum of the parts.







DEEP UNDERGROUND NEUTRINO EXPERIMENT