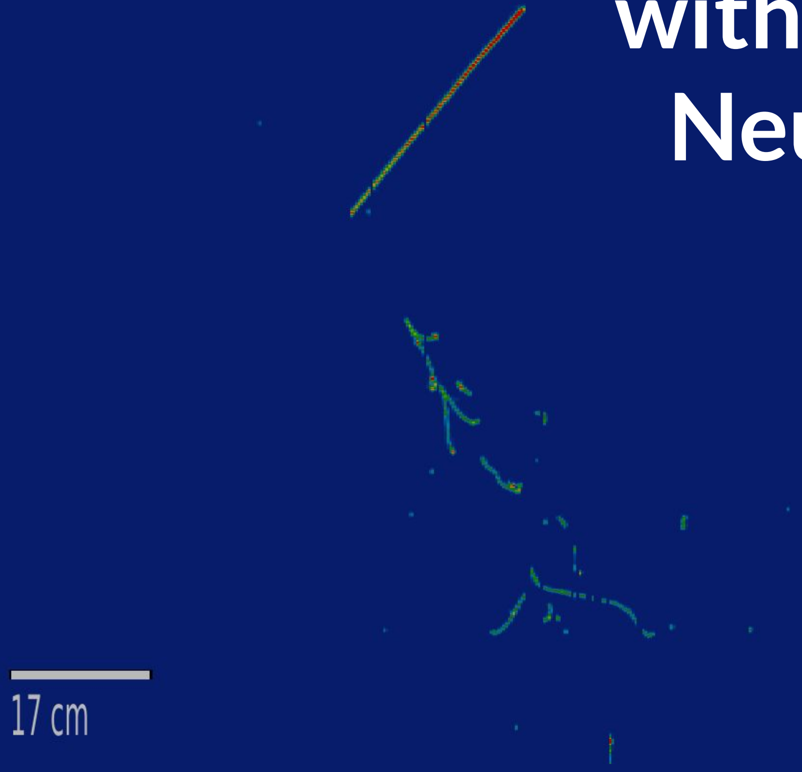
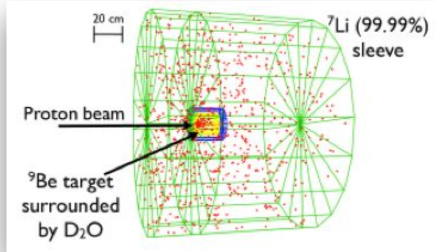
Searching for New Physics with Accelerator-based Neutrino Experiments



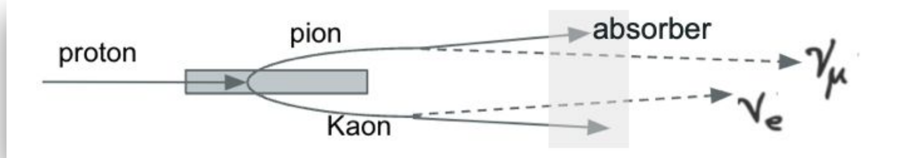
Georgia Karagiorgi, Columbia University

Symposium on Low Energy Experimental Particle Physics
Max Planck Institute of Physics
Munich, July 15, 2022

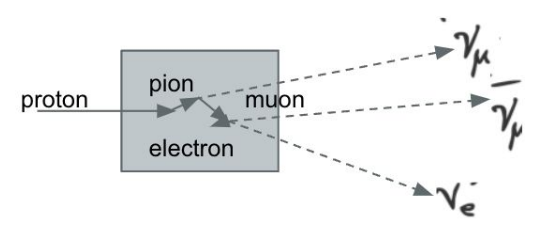
Accelerators as neutrino sources



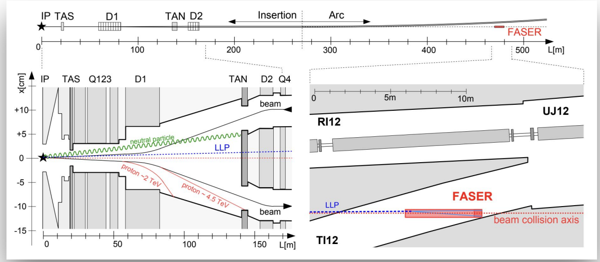
e.g., isotope Decay-At-Rest (DAR) sources



pion Decay-In-Flight (DIF) sources,



pion DAR sources,



proton-proton collisions

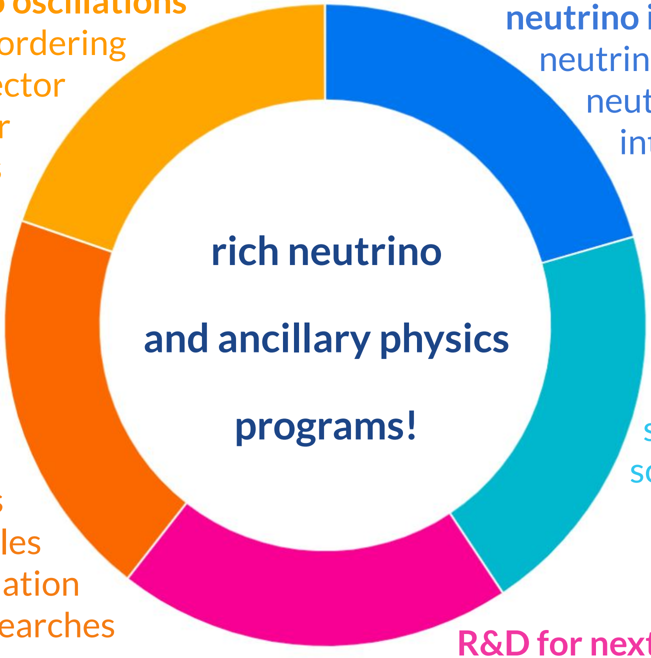
MeV

TeV

Accelerators as neutrino sources

neutrino oscillations
neutrino mass ordering
CP violation in the lepton sector
unitarity in the neutrino sector
light sterile neutrinos

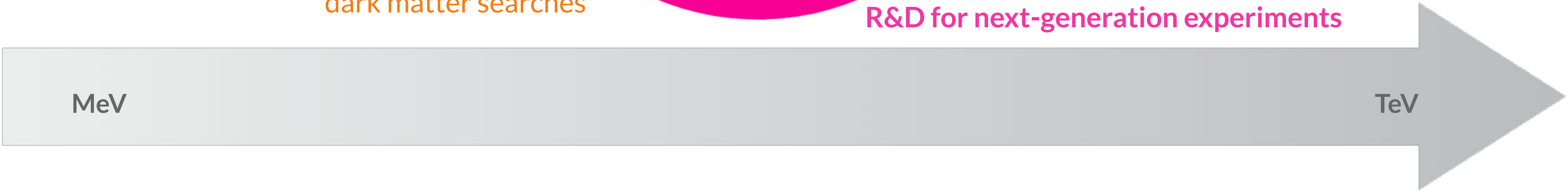
neutrino interactions
neutrino-electron scattering
neutrino-nucleus scattering
intra-nuclear effects (nucleon-nucleon correlations, …)



exotic/new physics
non-standard neutrino interactions
new neutrino species
CPT violation
extra dimensions
axion-like-particle searches
millicharged particles
baryon number violation
dark matter searches

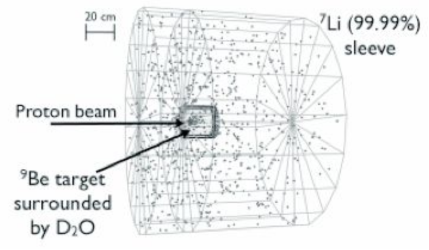
astro-particle
atmospheric neutrinos
supernova neutrinos
solar neutrinos

R&D for next-generation experiments

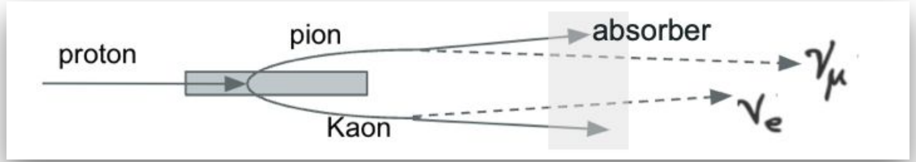


ALFRED P. SLOAN FOUNDATION

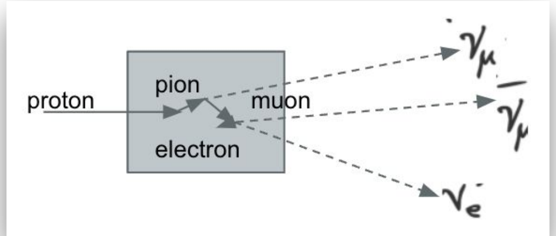
Accelerators as neutrino sources



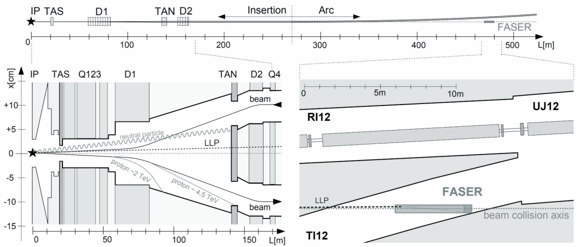
e.g., isotope Decay-At-Rest (DAR) sources



pion Decay-In-Flight (DIF) sources,



pion DAR sources,



proton-proton collisions

MeV

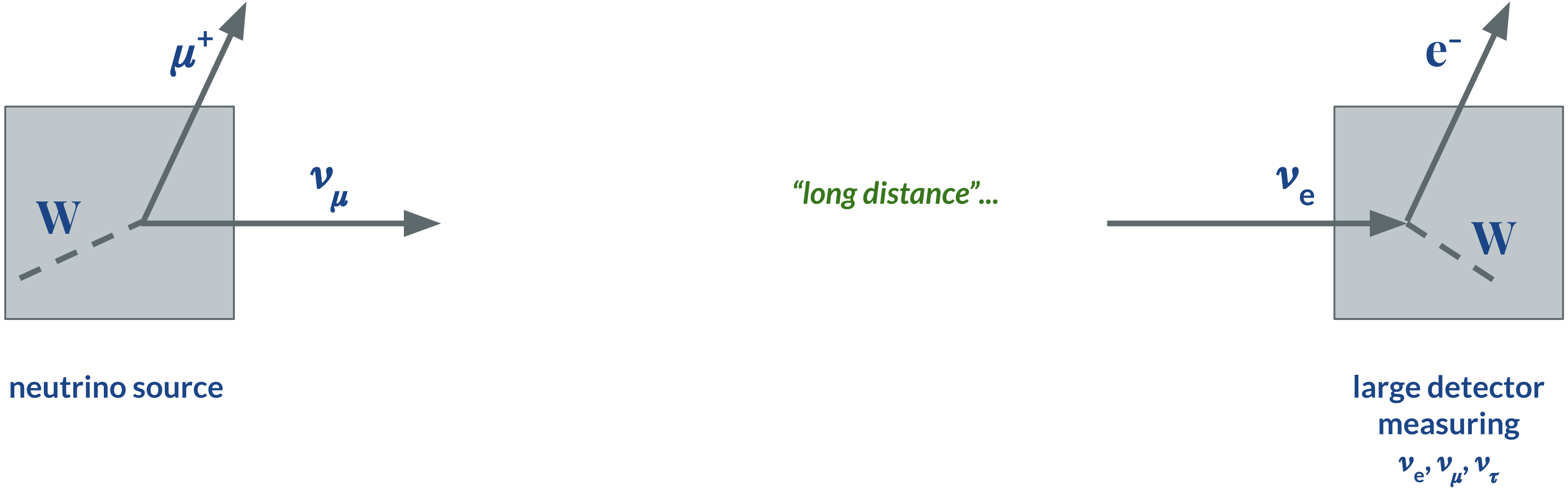
pion DAR and DIF source: "home" of experimental neutrino anomalies

TeV

ALFRED P. SLOAN FOUNDATION

Pion DAR and DIF experimental neutrino anomalies

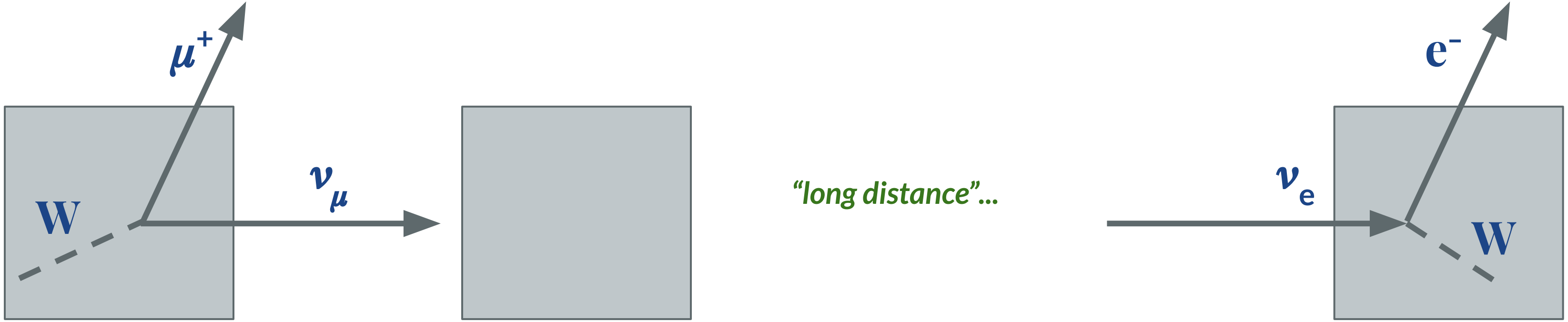
Your typical three-neutrino oscillation experiment…



ALFRED P. SLOAN FOUNDATION

Pion DAR and DIF experimental neutrino anomalies

Your typical three-neutrino oscillation experiment…



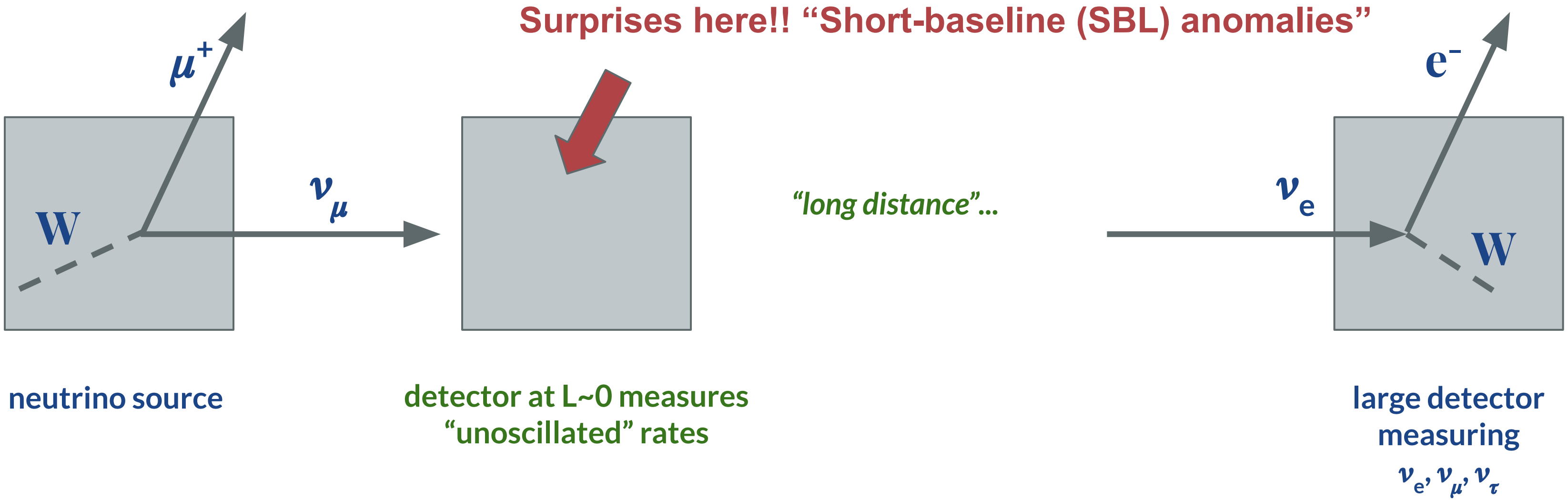
neutrino source

detector at L~0 measures "unoscillated" rates

large detector measuring ν_e, ν_μ, ν_τ

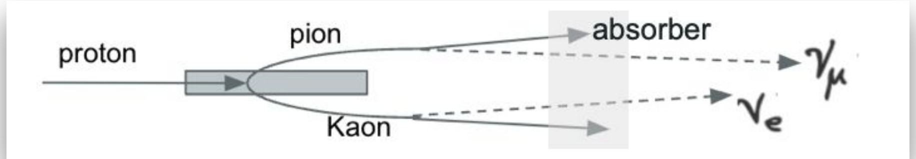
Pion DAR and DIF experimental neutrino anomalies

Your typical three-neutrino oscillation experiment…

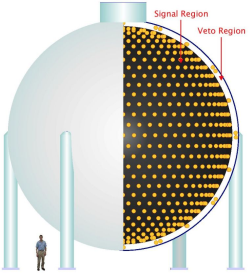


Pion DAR and DIF experimental neutrino anomalies

MiniBooNE



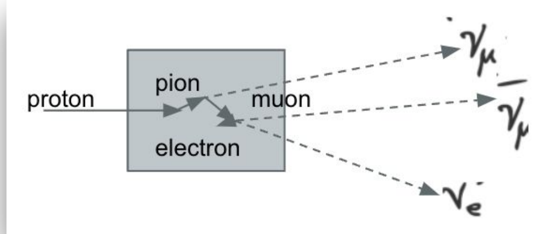
pion DIF source:
Booster Neutrino Beam (BNB) at Fermilab, US

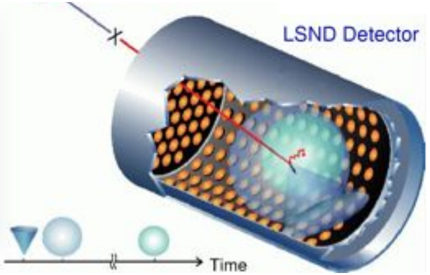


observed 4.8σ excess
of electron-anti/neutrinos
in muon-anti/neutrino beam

L_ν/E_ν ~ 500 m / 500 MeV

LSND





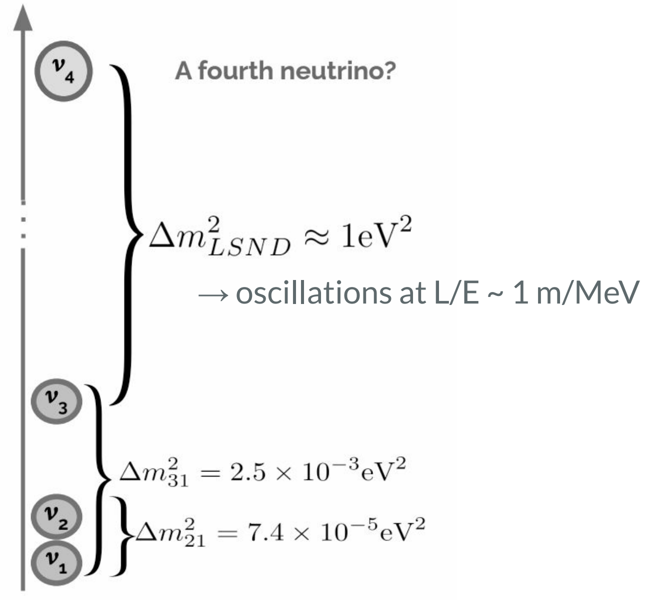
pion DAR source:
Los Alamos National Lab, US

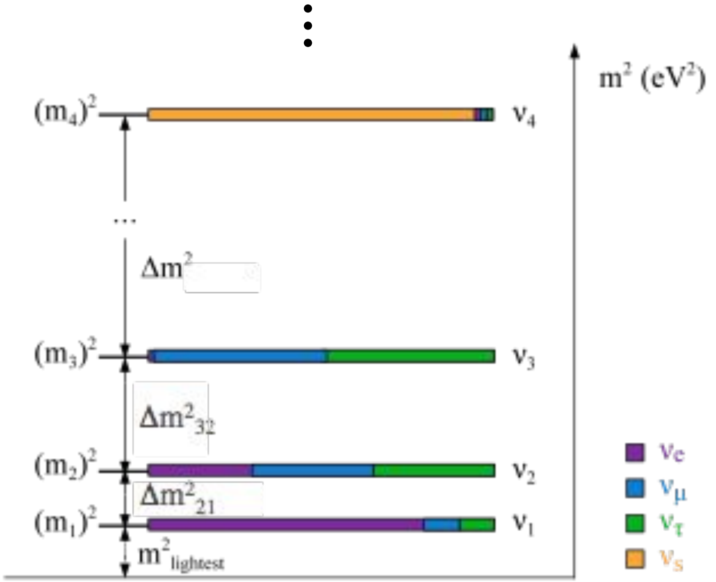
observed 3.8σ excess
of electron-antineutrinos
in muon-antineutrino beam

L_ν/E_ν ~ 30 m / 30 MeV

Most widely considered SBL anomaly interpretation

Beyond three neutrinos: Light (m ~ eV-scale) sterile neutrinos





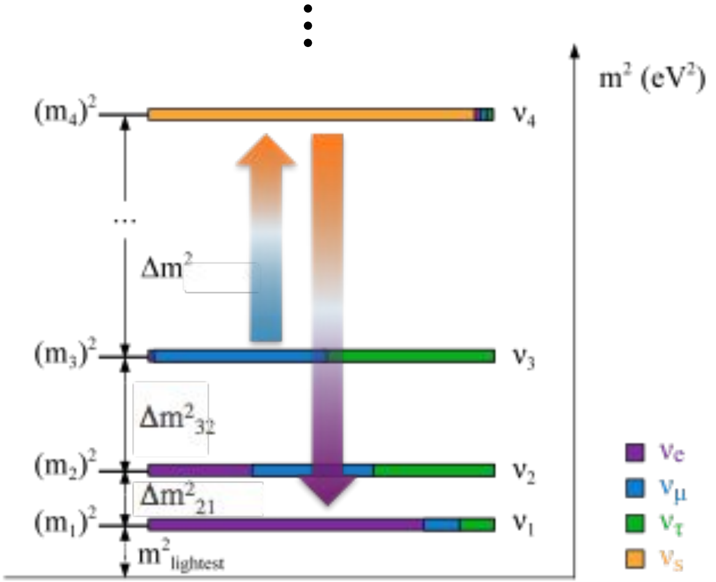
Most widely considered SBL anomaly interpretation

Beyond three neutrinos: Light (m ~ eV-scale) sterile neutrinos

$\nu_\mu \longrightarrow \nu_s \longrightarrow \nu_e$ oscillations

$$P(\nu_\alpha \to \nu_{\beta\neq\alpha}) = \sin^2 2\vartheta_{\alpha\beta} \sin^2(1.27\Delta m^2 L / E)$$

$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2$$

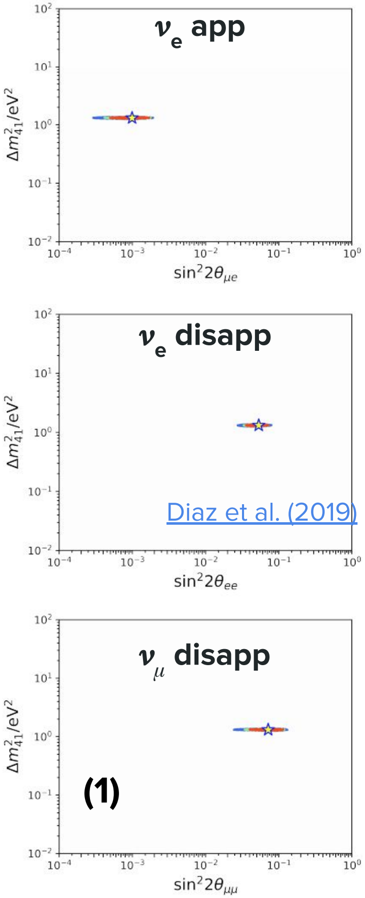


Predicts:
Small-amplitude **muon to electron neutrino appearance** ~O(1%)
Electron neutrino disappearance ~ O(10%)
Muon neutrino disappearance ~ O(10%)

Most widely considered SBL anomaly interpretation
… seems to fall short !

Sterile Neutrino Global Picture:
combining SBL anomalies
with other experimental data

1. The “3+1” scenario is much **more preferred than null**



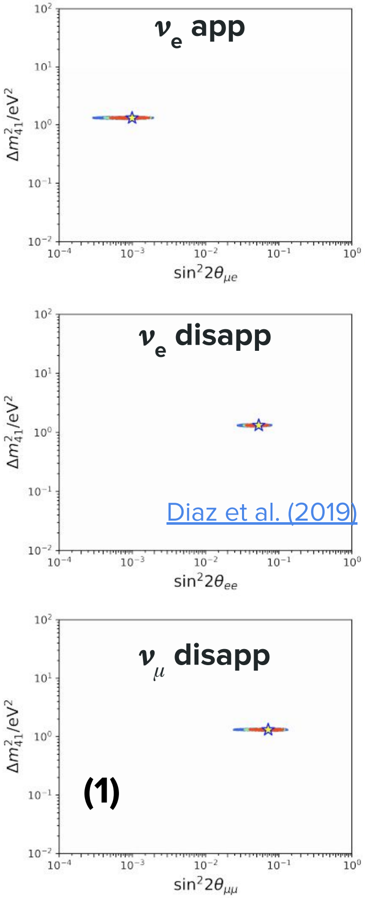
Most widely considered SBL anomaly interpretation

... seems to fall short !

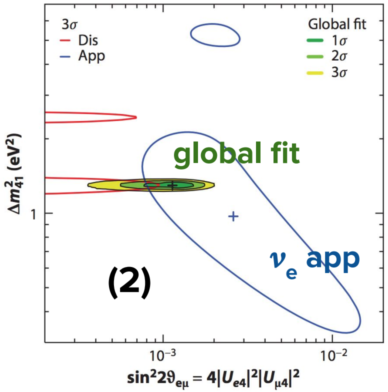
Sterile Neutrino Global Picture:
combining SBL anomalies
with other experimental data

1. The “3+1” scenario is much **more preferred than null**

2. There is a large **tension** between appearance and disappearance data sets, and incompatibility of parameters preferred by appearance vs. disappearance experiments



Diaz et al. (2019)



Giunti & Lasserre (2019)

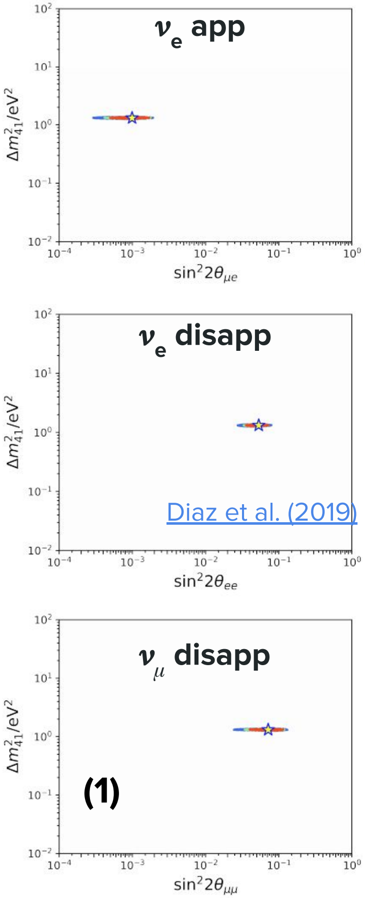
Most widely considered SBL anomaly interpretation ... seems to fall short !

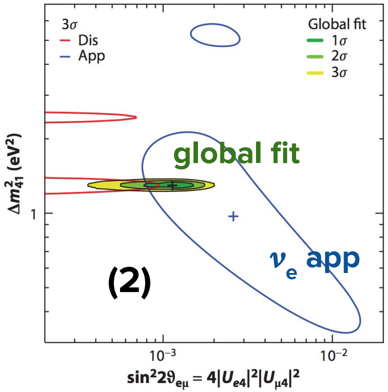
Sterile Neutrino Global Picture:
combining SBL anomalies
with other experimental data

1. The “3+1” scenario is much **more preferred than null**

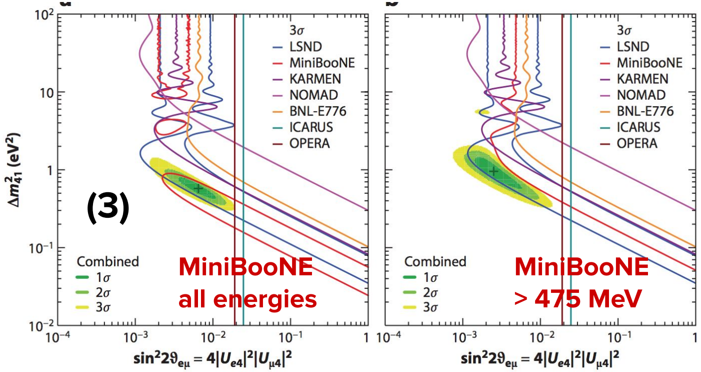
2. There is a large **tension** between appearance and disappearance data sets, and incompatibility of parameters preferred by appearance vs. disappearance experiments

3. Some of this tension can be relieved with omission of **MiniBooNE “low-energy excess”**



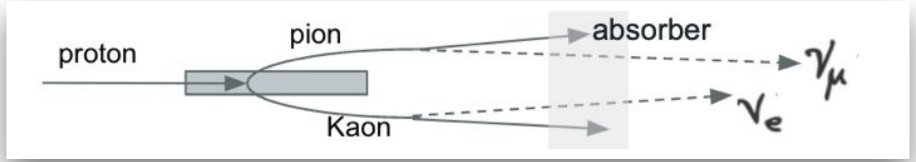


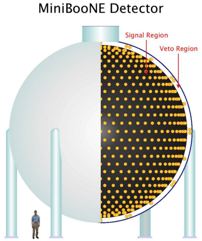
Giunti & Lasserre (2019)



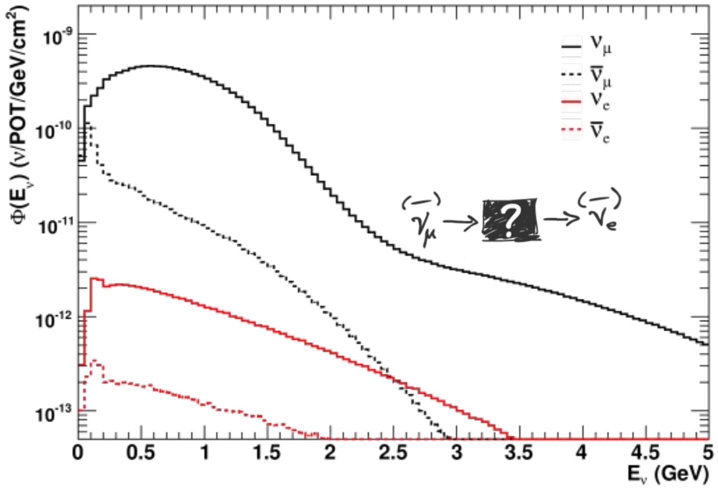
ALFRED P. SLOAN FOUNDATION

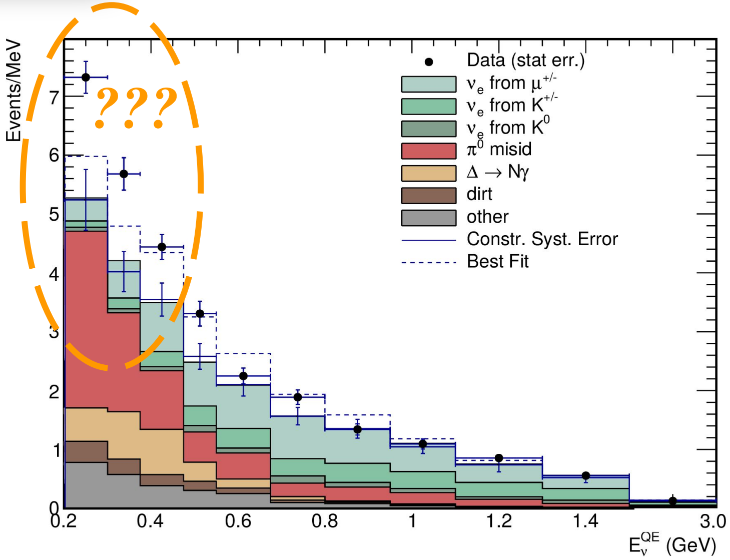
Re-examination of MiniBooNE "low-energy excess"





observed 4.8σ excess
of electron-anti/neutrinos
in muon-anti/neutrino beam





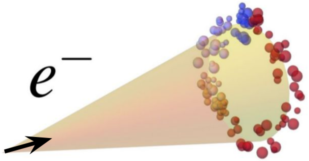
MiniBooNE Collaboration
Phys. Rev. D 103, 052002 (2021)
Electron neutrino spectrum
Neutrino mode only

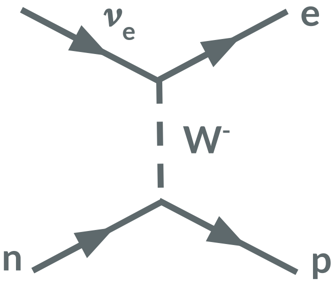
To this date, source of excess remains unexplained!

ALFRED P. SLOAN FOUNDATION

What could the source of the MiniBooNE excess be?

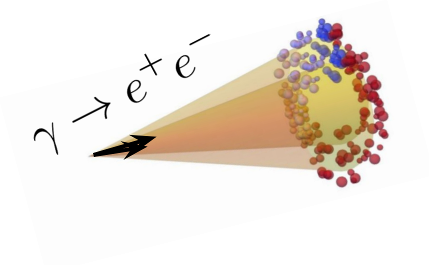
Key observation: **electromagnetic shower from ν_e CC interactions**

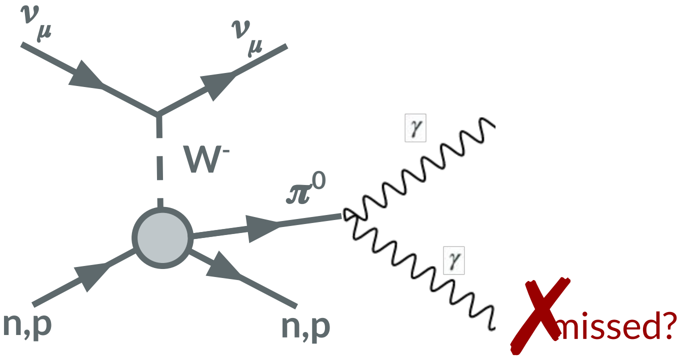




For a broad review of Standard Model and beyond-Standard Model interpretations, see the "Snowmass 2022 White Paper": [arXiv:2203.07323]

But, the same signature is shared by a **photon**, e.g. from ν_μ **NC interactions**

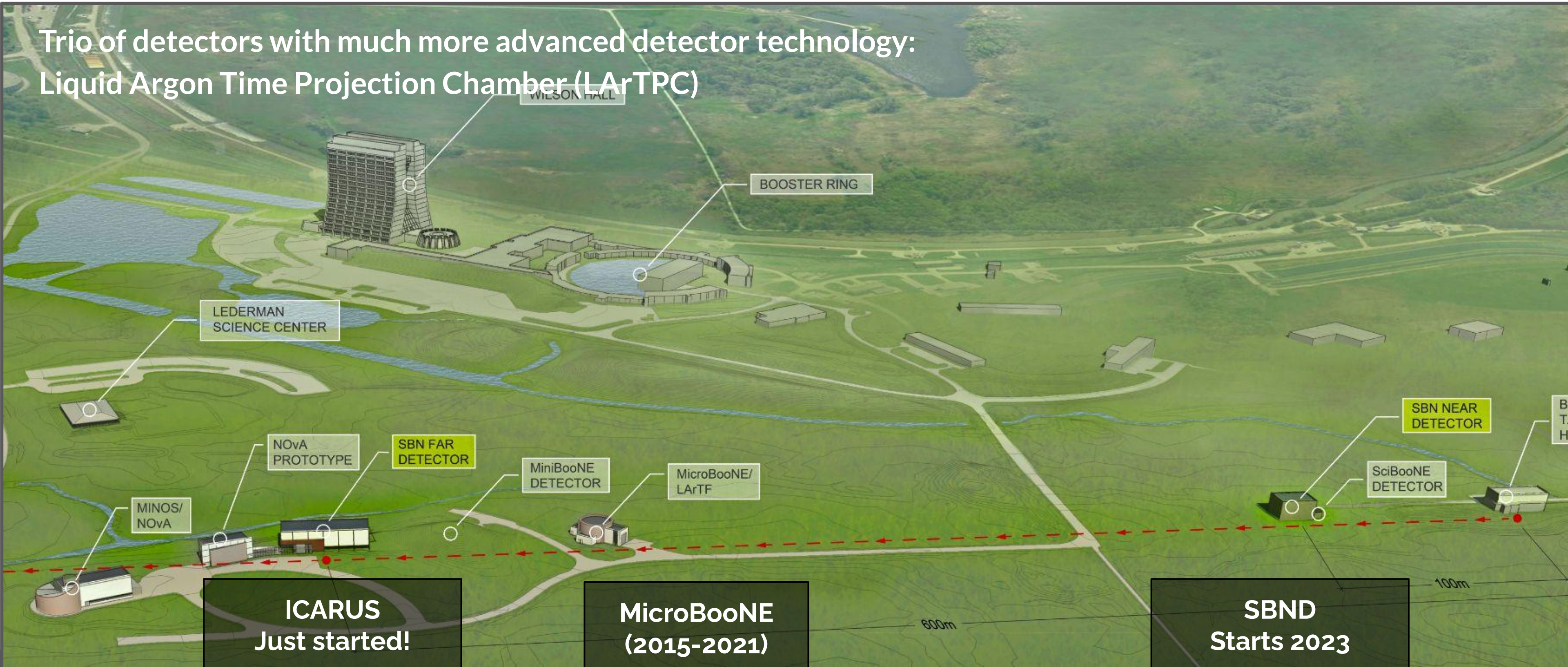




Could the MiniBooNE excess be a misunderstood SM photon background, or new physics?

Short Baseline Neutrino (SBN) Program at Fermilab

Trio of detectors with much more advanced detector technology:
Liquid Argon Time Projection Chamber (LArTPC)



ICARUS
Just started!

MicroBooNE
(2015-2021)

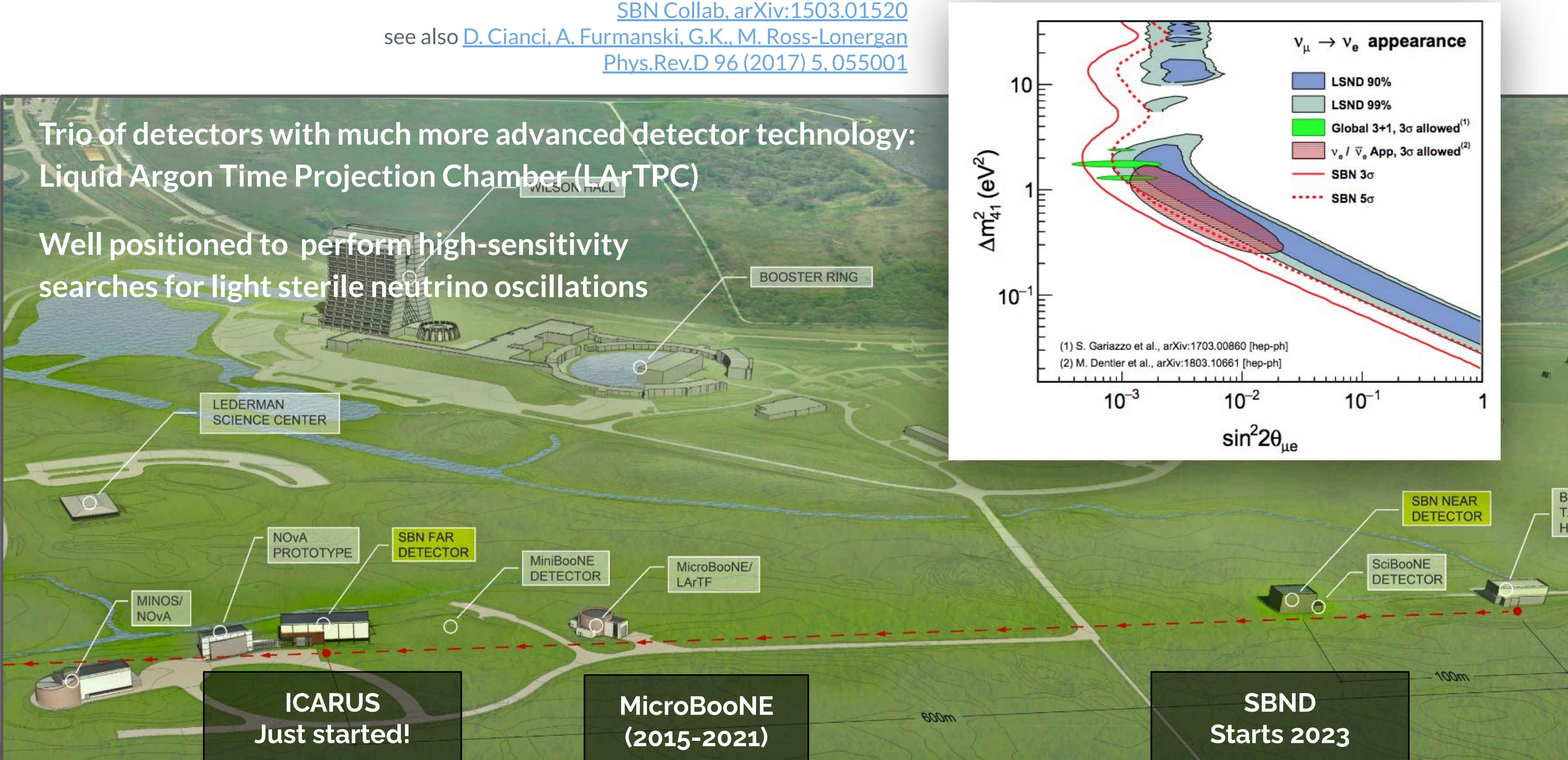
SBND
Starts 2023

Short Baseline Neutrino (SBN) Program at Fermilab

SBN Collab, arXiv:1503.01520
see also D. Cianci, A. Furmanski, G.K., M. Ross-Lonergan Phys.Rev.D 96 (2017) 5, 055001

Trio of detectors with much more advanced detector technology: Liquid Argon Time Projection Chamber (LArTPC)

Well positioned to perform high-sensitivity searches for light sterile neutrino oscillations



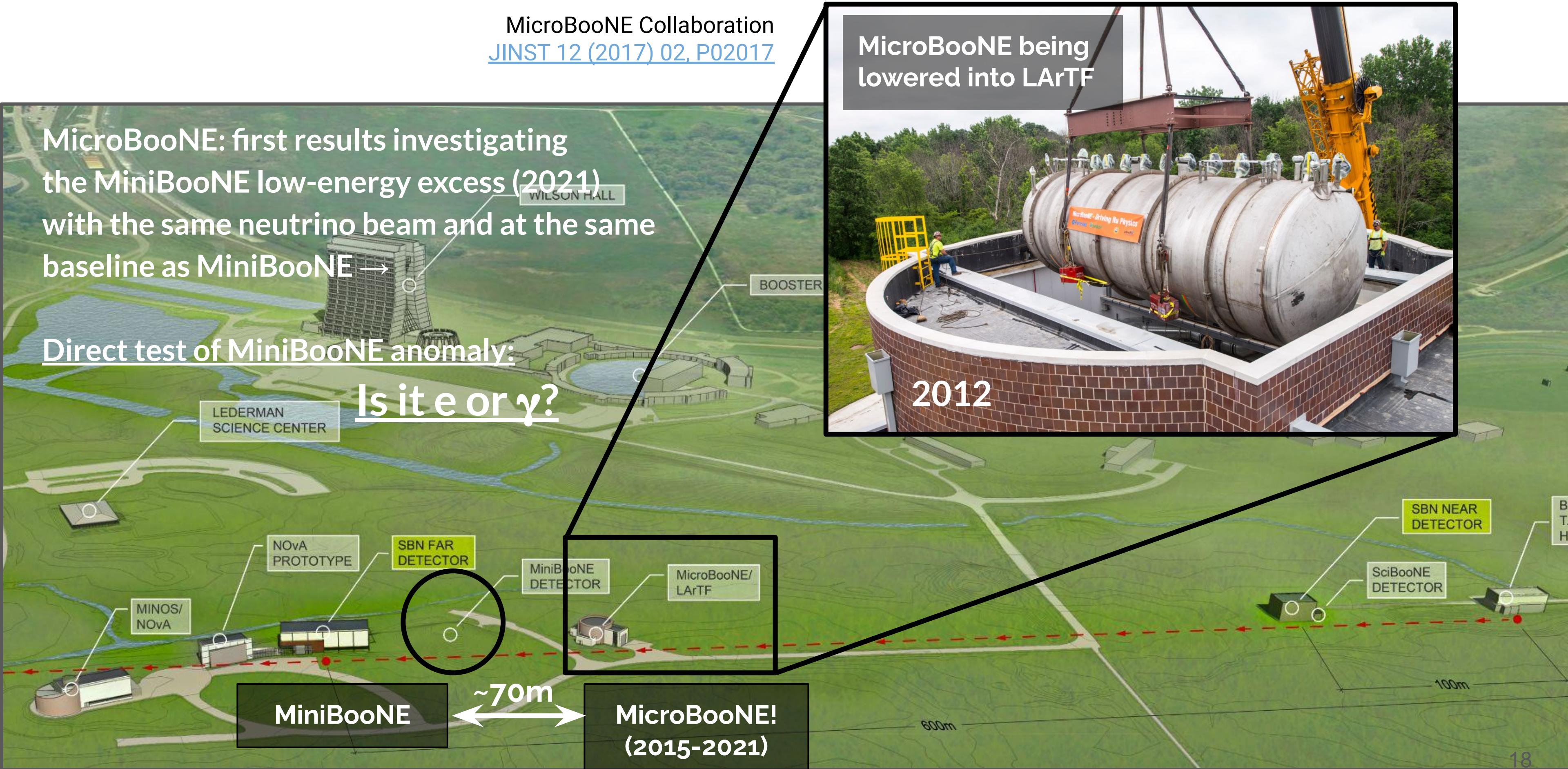
Short Baseline Neutrino (SBN) Program at Fermilab

MicroBooNE Collaboration
JINST 12 (2017) 02, P02017

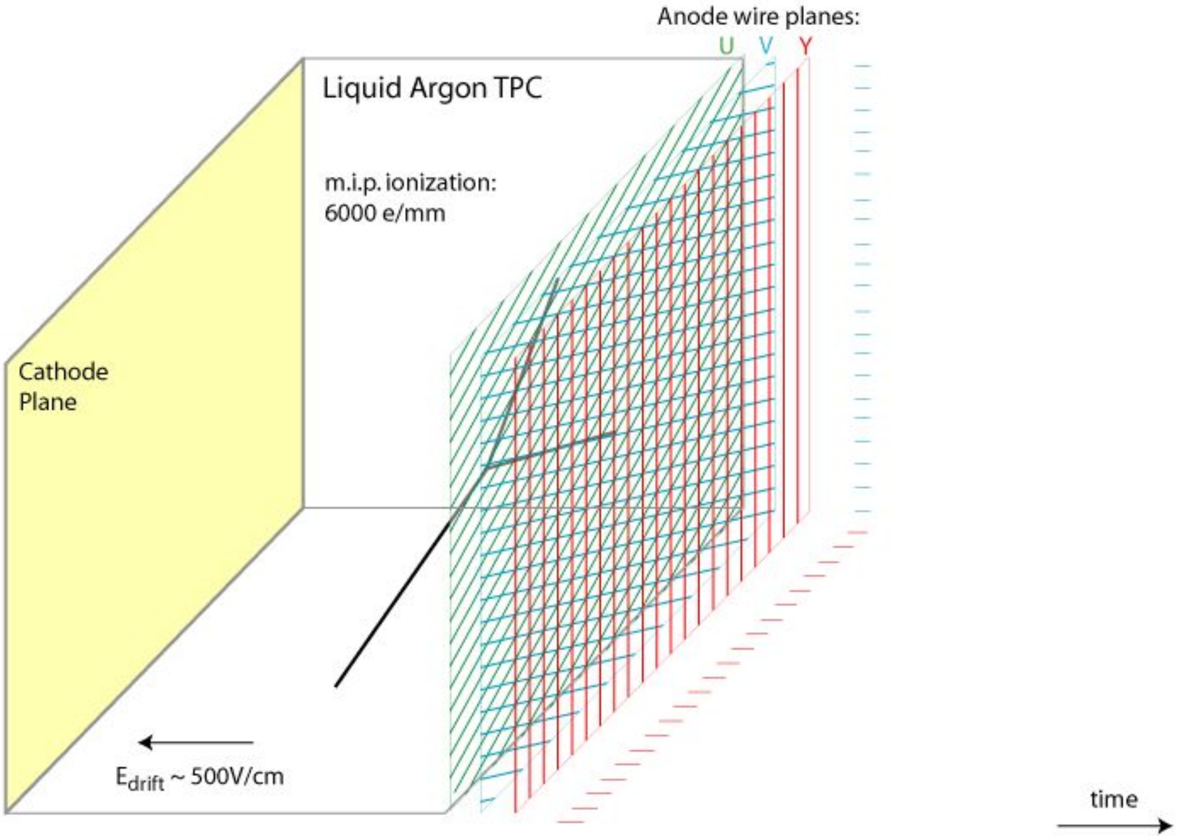
MicroBooNE: first results investigating the MiniBooNE low-energy excess (2021) with the same neutrino beam and at the same baseline as MiniBooNE →

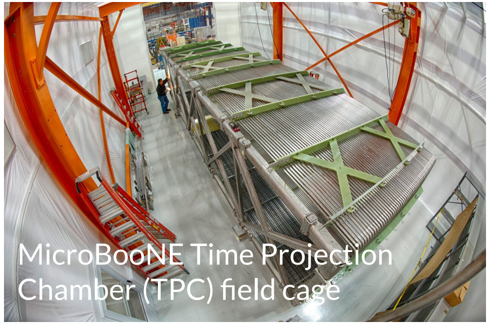
Direct test of MiniBooNE anomaly:

Is it e or γ?



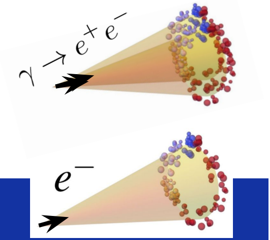
How a LArTPC works

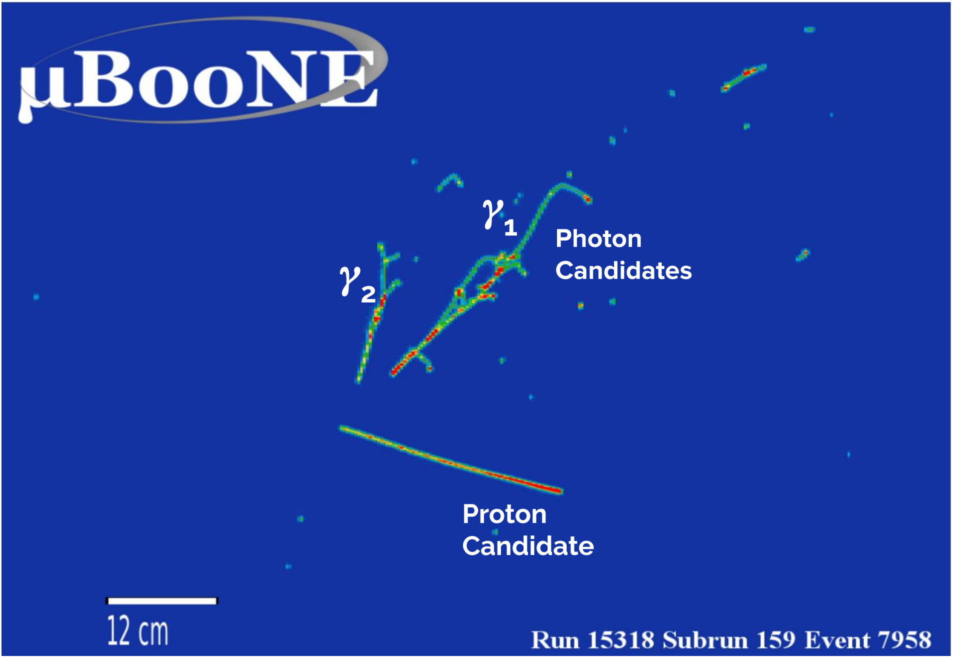




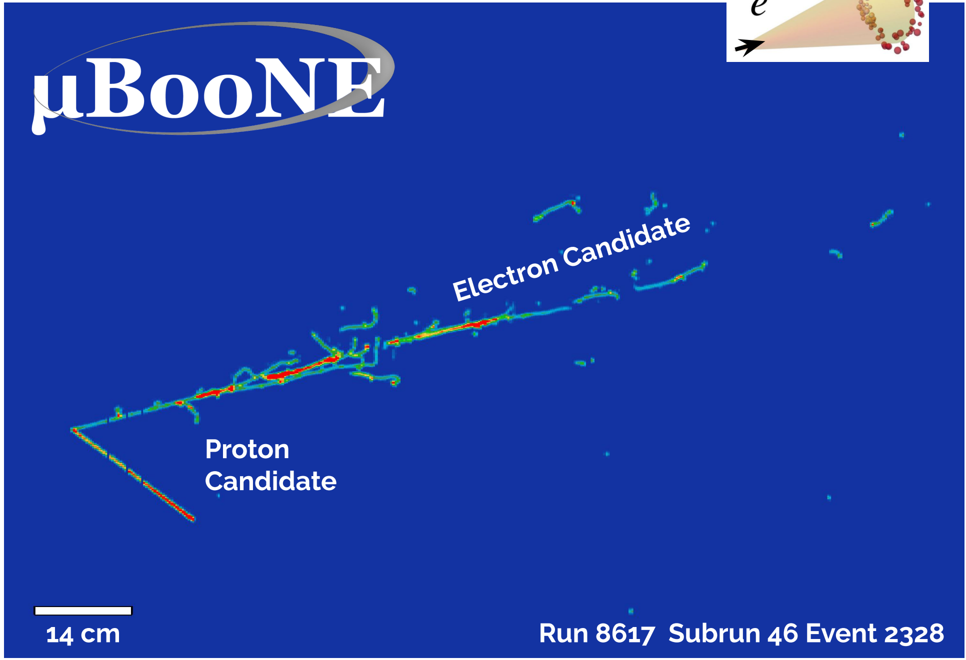
ALFRED P. SLOAN FOUNDATION

MicroBooNE can resolve electrons/photons!



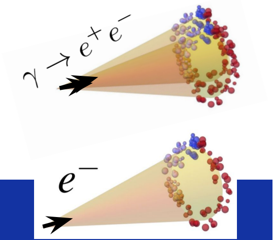


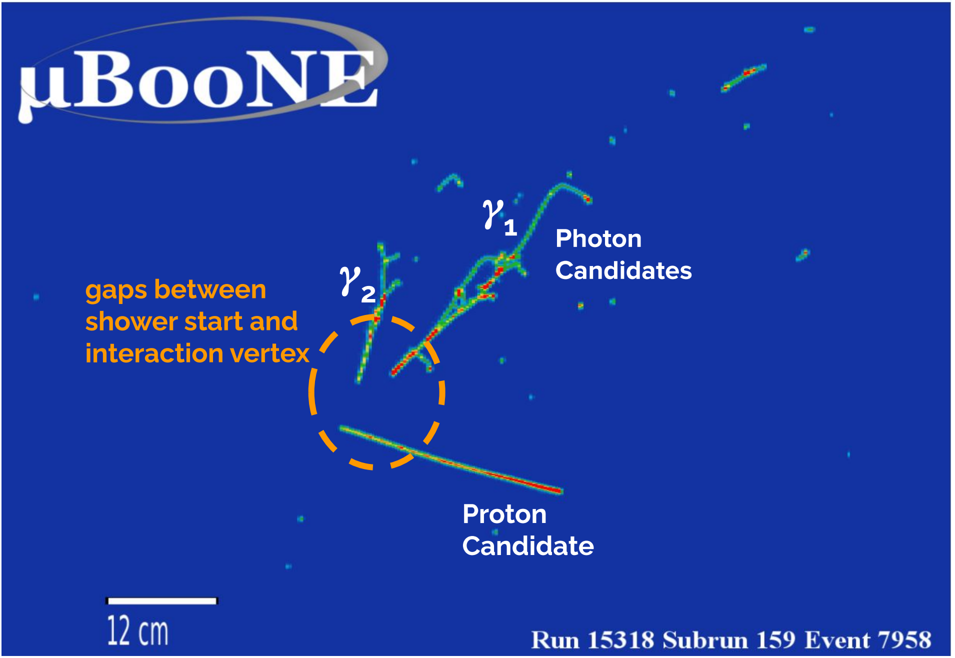
ν_μ NC π^0 candidate data event



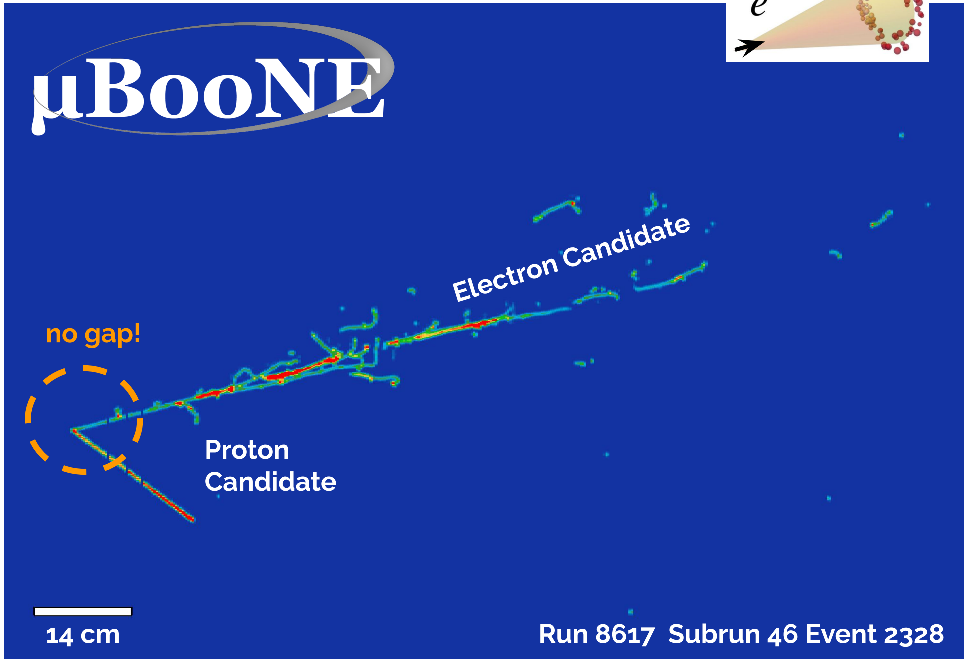
ν_e CC candidate data event

MicroBooNE can resolve electrons/photons!



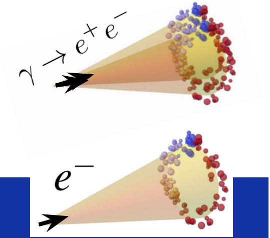


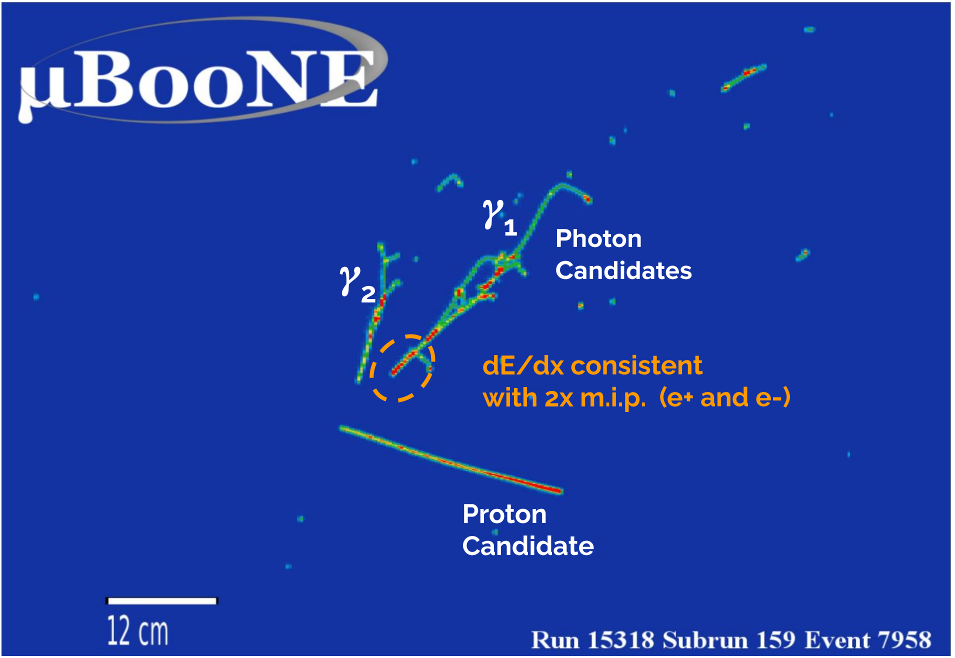
ν_μ NC π^0 candidate data event



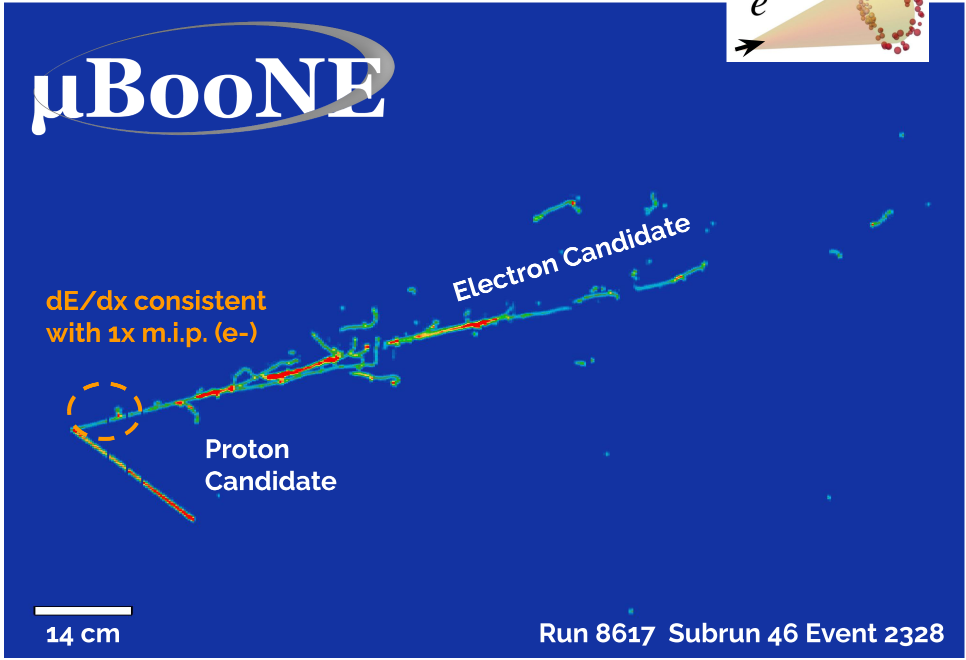
ν_e CC candidate data event

MicroBooNE can resolve electrons/photons!





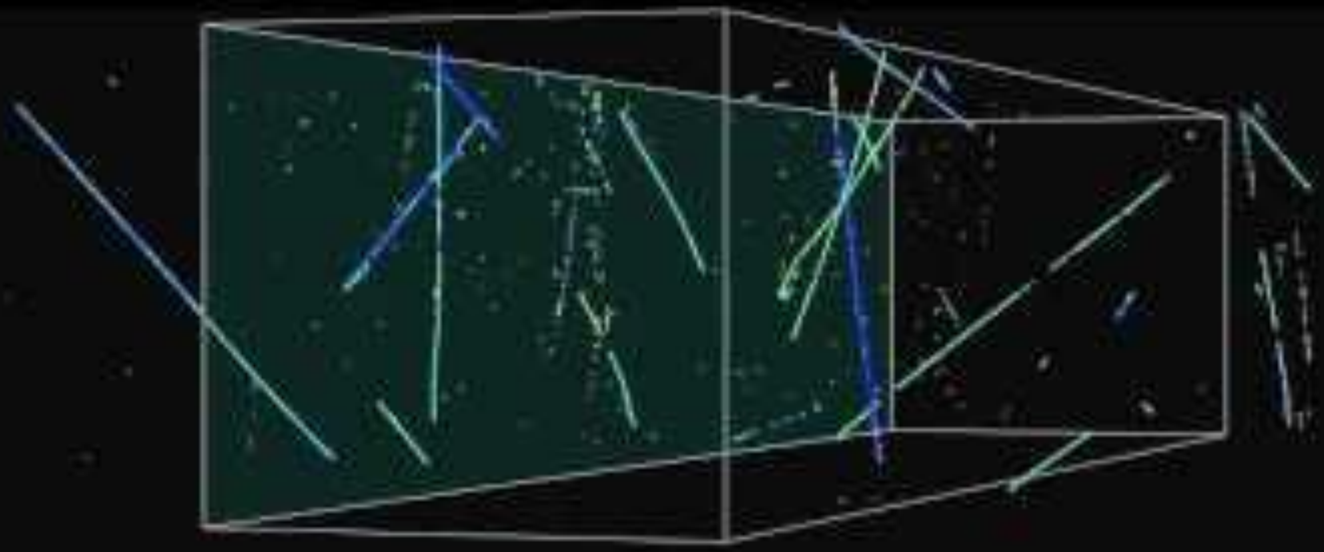
ν_μ NC π^0 candidate data event



ν_e CC candidate data event

ALFRED P. SLOAN FOUNDATION

A few milliseconds' worth of activity in the MicroBooNE detector



New detector technology, new challenges!

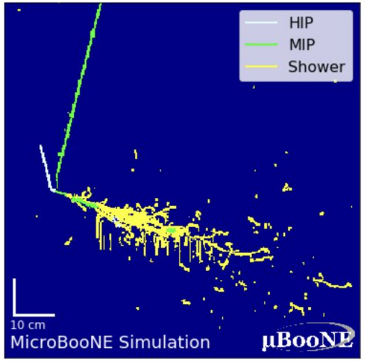
Led the construction, commissioning, and operation of MicroBooNE and SBND digital readout system, including a novel triggerless readout system for supernova neutrino detection!

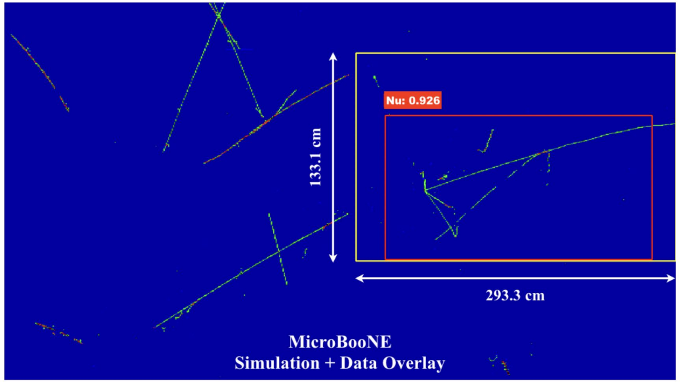
MicroBooNE Collab, 2017 JINST 12 P02017
MicroBooNE Collab, 2021 JINST 16 P02008

Detector generates **tens of GB/s, continuously**.
High data rate introduces challenges to the entire data pipeline (more so for future, much larger detectors!)

Potential neutrino events must be identified amongst a high multiplicity of cosmogenic interactions.

Advanced reconstruction techniques are employed offline; **computer vision** algorithms naturally lend themselves to **neutrino identification and reconstruction.**





MicroBooNE Collab, 2017 JINST 12 P03011
MicroBooNE Collab, Phys. Rev. D **99**, 092001 (2019)
MicroBooNE Collab, Phys. Rev. D **103**, 092003 (2021)

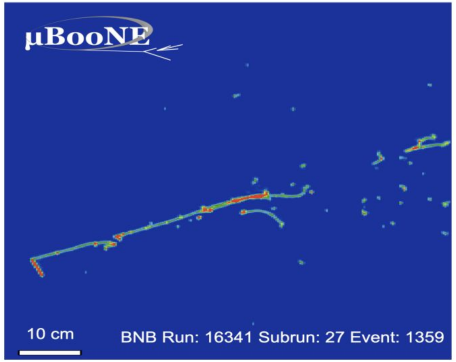
Unprecedented look at neutrino interaction final states!

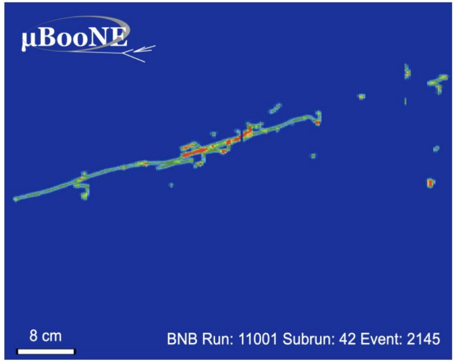
Neutrinos reveal themselves in multiple ways!

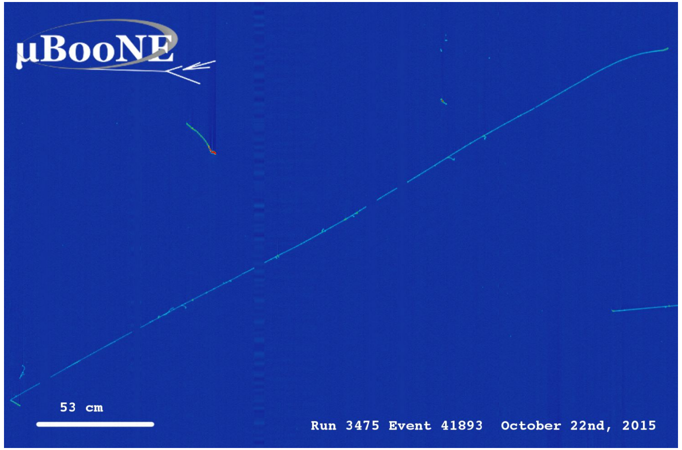
More/less violent (energetic) collisions with nucleus...

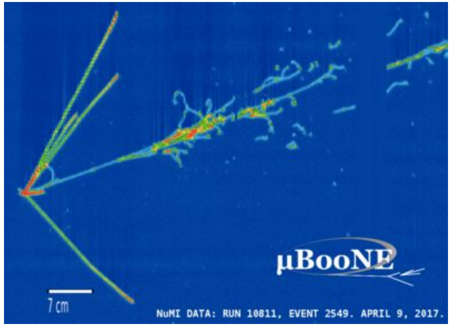
Resonantly, or coherently, leading to different (on average) kinematics...

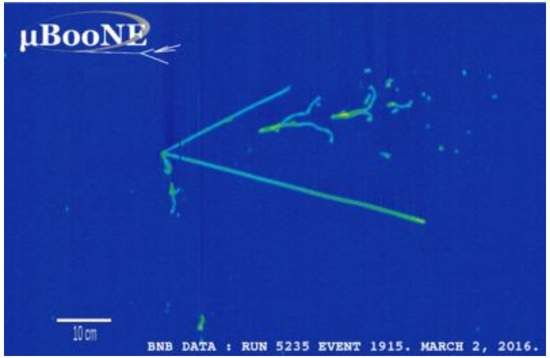
Unique strength of LArTPC detector technology:
Ability to identify explicitly the way each ν_e or ν_μ interacts!







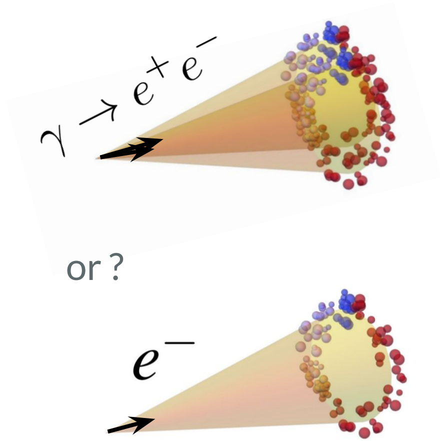


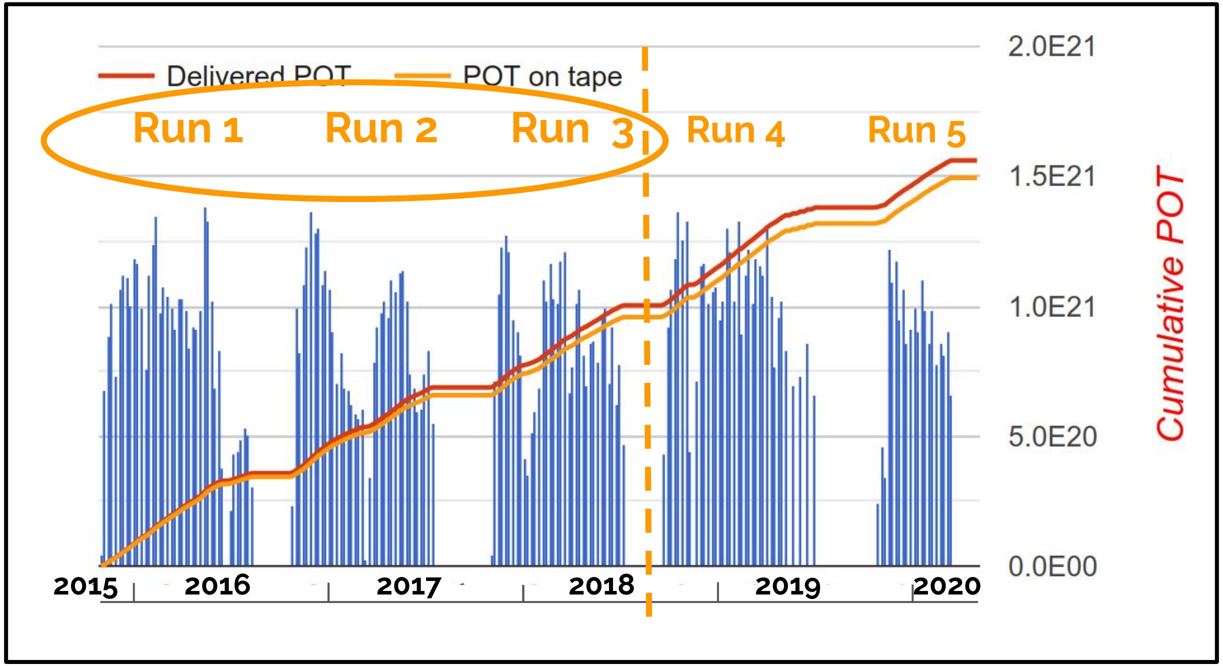


ALFRED P. SLOAN FOUNDATION

First low-energy excess search results in October 2021!

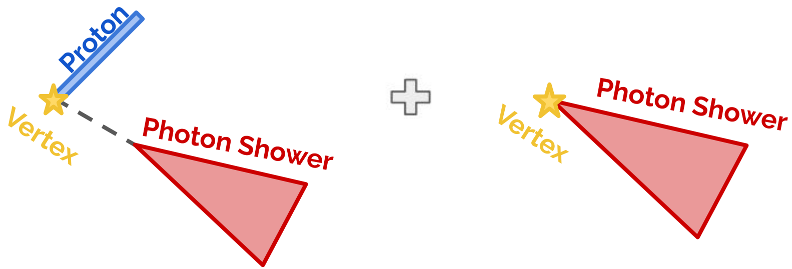
Making use of **only half of the total dataset** collected by MicroBooNE during its entire operations timeline



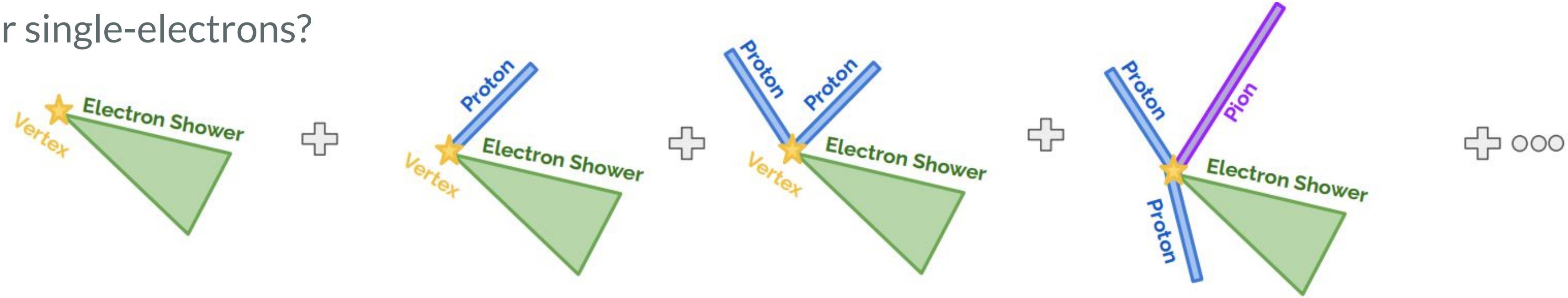


Two main searches in MicroBooNE

Is the MiniBooNE excess single-photons?

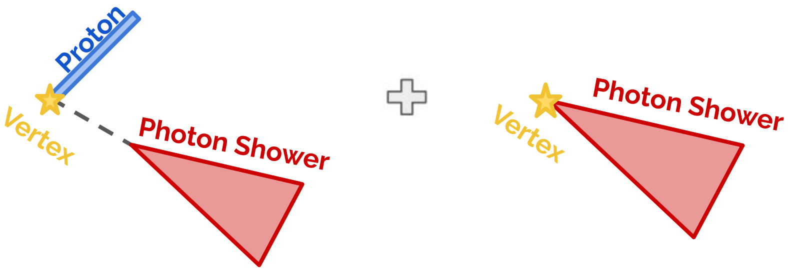


or single-electrons?



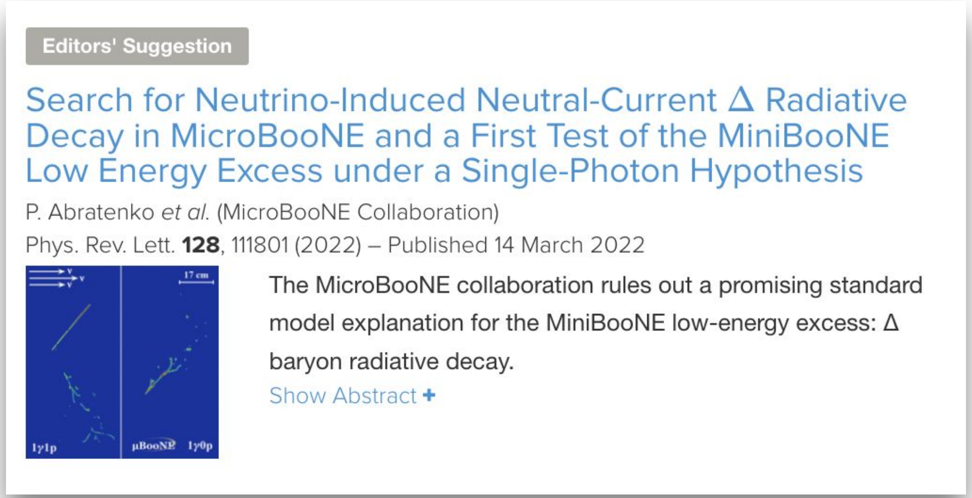
MicroBooNE photon search

Is the MiniBooNE excess single-photons?



[MicroBooNE Collab, Phys. Rev. Lett. 128, 111801 (2022)]

Led by my group at Columbia


Editors' Suggestion

Search for Neutrino-Induced Neutral-Current Δ Radiative Decay in MicroBooNE and a First Test of the MiniBooNE Low Energy Excess under a Single-Photon Hypothesis

P. Abratenko *et al.* (MicroBooNE Collaboration)

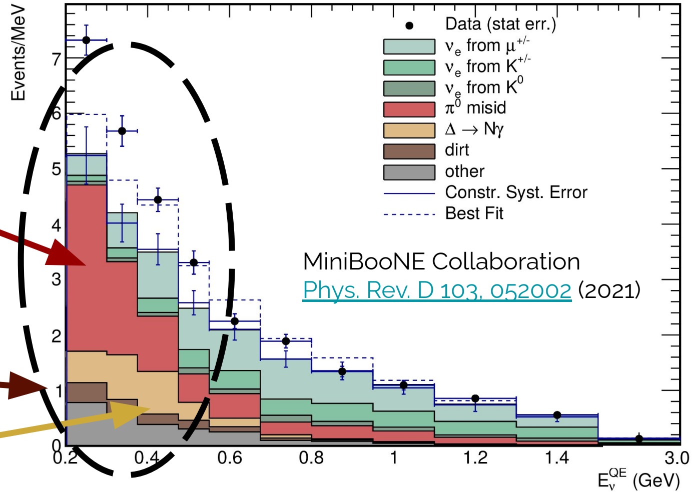
Phys. Rev. Lett. **128**, 111801 (2022) – Published 14 March 2022

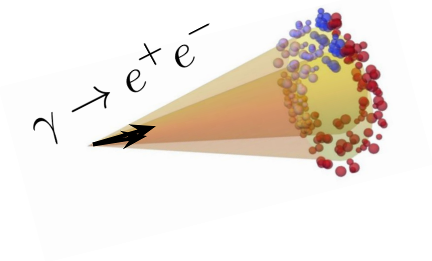
The MicroBooNE collaboration rules out a promising standard model explanation for the MiniBooNE low-energy excess: Δ baryon radiative decay.

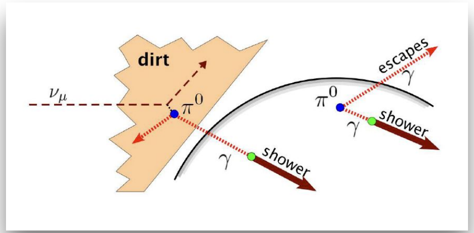
Show Abstract +

Is the MiniBooNE excess a misunderstood γ background?

- **Neutral Current (NC) π^0 production** followed by $\pi^0 \rightarrow \gamma\gamma$ decay and mis-identification
  - **Constrained in situ**
- **"Dirt"** (mostly π^0 events with γ's scattering in from outside the detector)
  - **Constrained in situ**
- A Standard Model-expected, rare process: **NC $\Delta \rightarrow N\gamma$**
  - **A factor of x3.18 increase could explain the MiniBooNE low-energy excess!**
  - **Needed a direct check!**



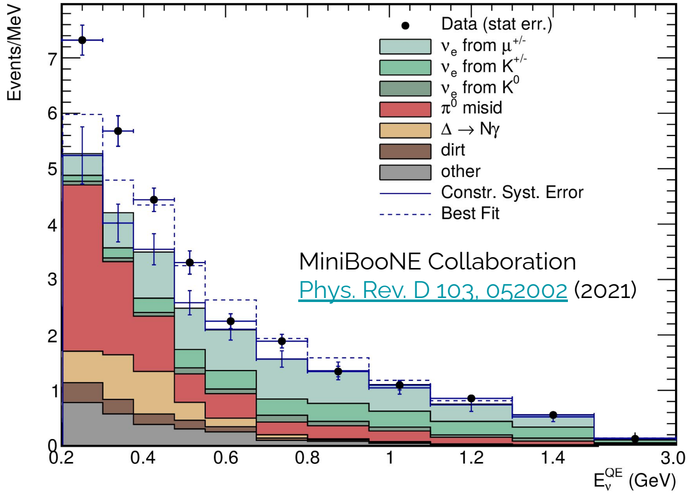


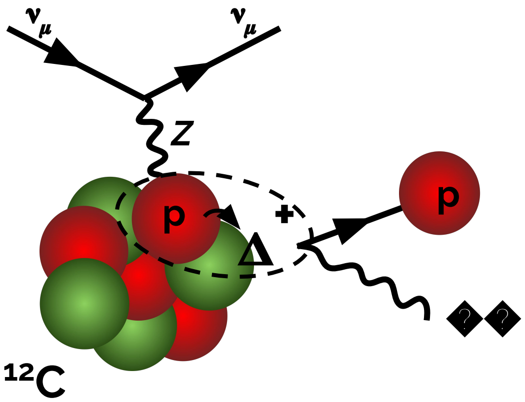


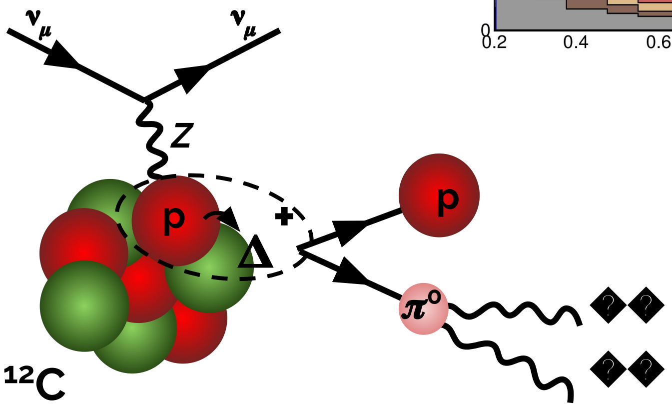
MicroBooNE photon search

Is the MiniBooNE excess mis-estimated NC $\Delta \rightarrow N\gamma$?

- Dominant source of Standard-Model-expected single-photon processes at MiniBooNE beam energies
- Never been directly measured in neutrinos before
- Only indirectly constrained in the MiniBooNE analysis





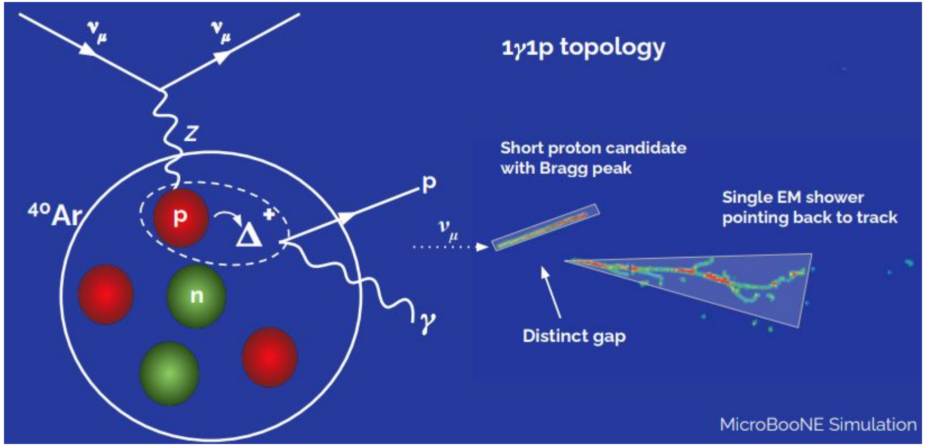


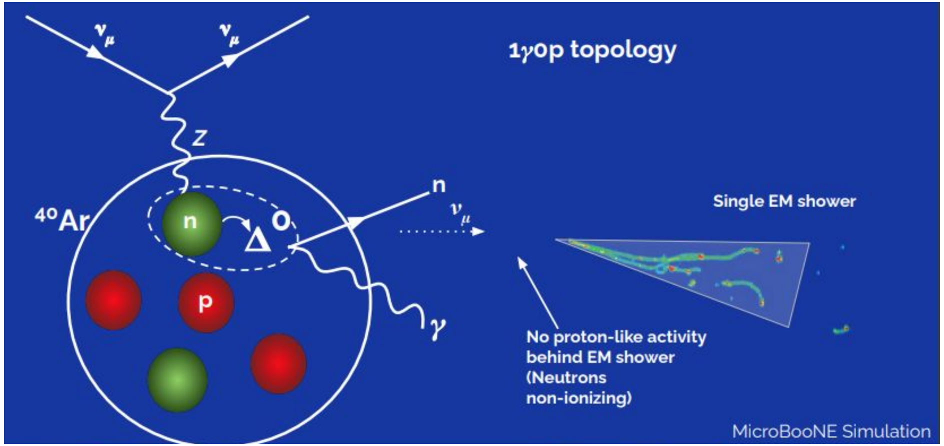
NC $\Delta \rightarrow N\gamma$ and
NC $\Delta \rightarrow N\pi^0$ rates
are correlated

MicroBooNE photon search

MicroBooNE Collab, Phys. Rev. Lett. 128, 111801 (2022)

NC $\Delta \rightarrow N\gamma$: Delta (1232MeV) baryon resonance production, followed by radiative decay:





A rare Standard Model-expected process!

We expect only 124.1 such events in Run 1-3 data!

MicroBooNE photon search

MicroBooNE Collab, Phys. Rev. Lett. 128, 111801 (2022)

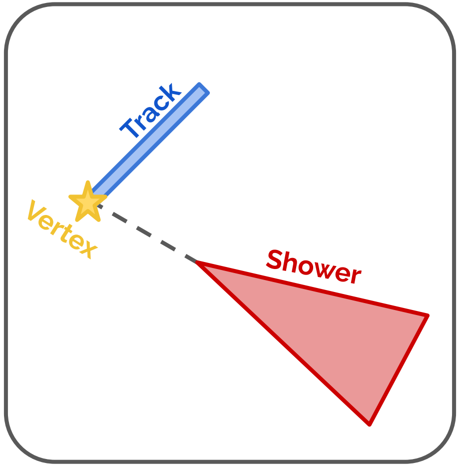
Data or MC → Pandora Reco → Flash matching → Topological Selection → Pre-Selection Cuts → BDT Selection → Final Selections

At this selection stage, >100,000 single-shower background events!

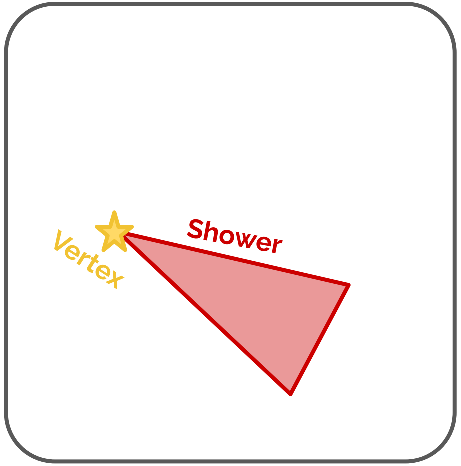
Additional machine learning algorithms target the key back-grounds to the NC $\Delta \rightarrow N\gamma$ signal.

Leverage the known kinematics of the $\Delta \rightarrow N\gamma$ decay products, particularly for the $1\gamma 1p$ selection.

$1\gamma 1p$

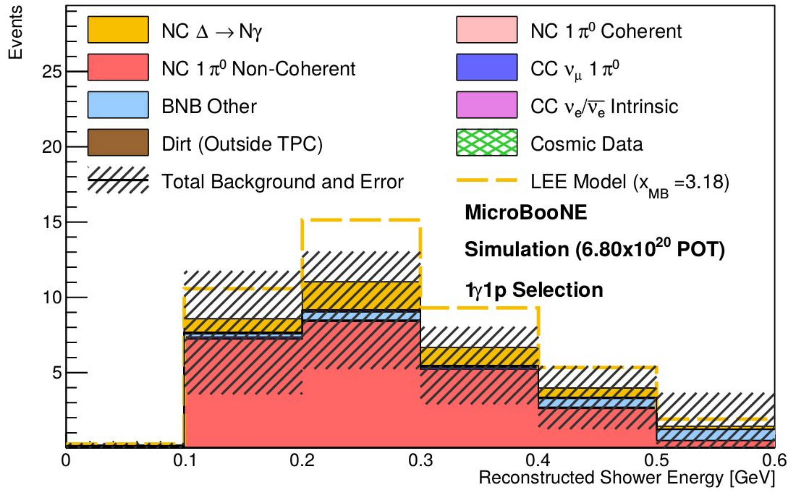


$1\gamma 0p$



Two mutually exclusive NC $\Delta \rightarrow N\gamma$ rich **single-photon** selections

MicroBooNE photon search

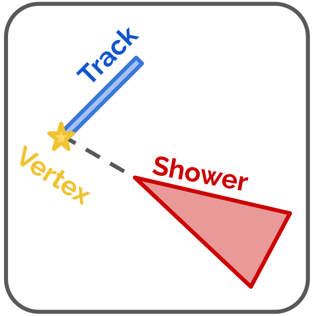


1γ1p

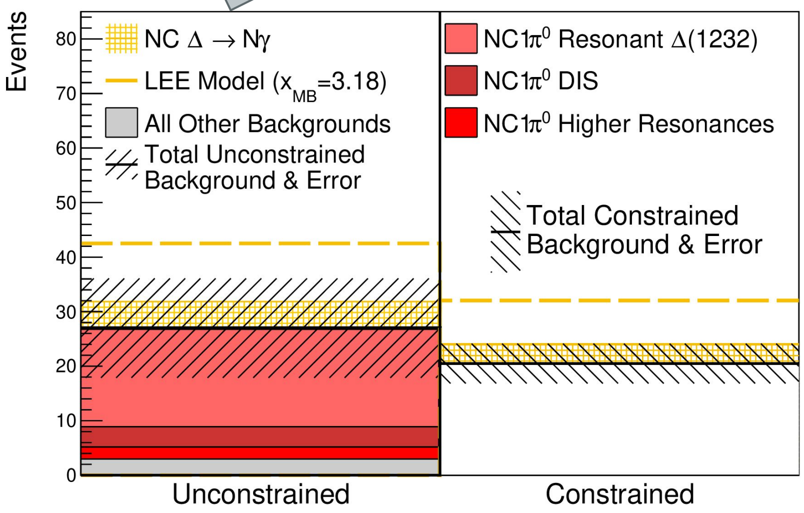
Unconstr. bkgd.	27.0 ± 8.1
Constr. bkgd.	20.5 ± 3.6
NC $\Delta \to N\gamma$	+ 4.88
LEE ($x_{\rm MB} = 3.18$)	+ 15.5

$1\gamma 1p$

final selection



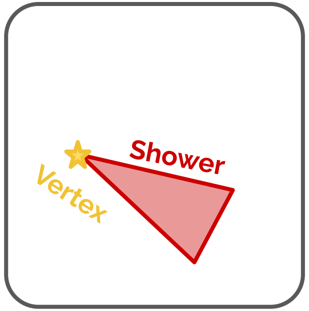
MicroBooNE Collab, Phys. Rev. Lett. 128, 111801 (2022)



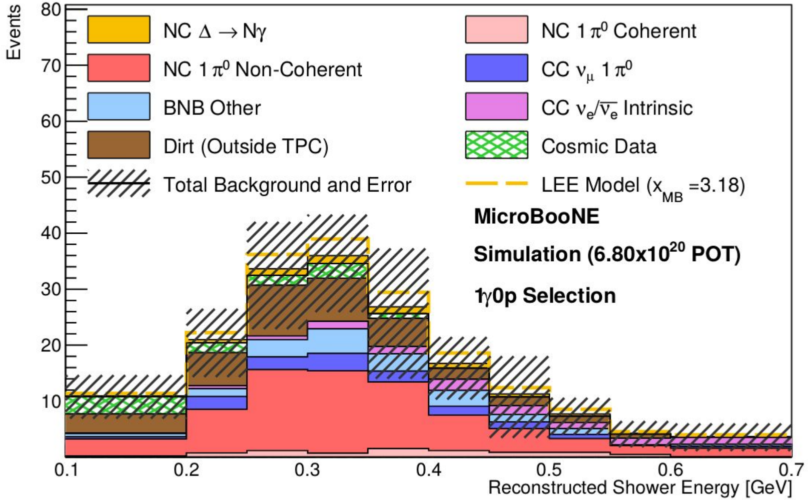
MicroBooNE photon search

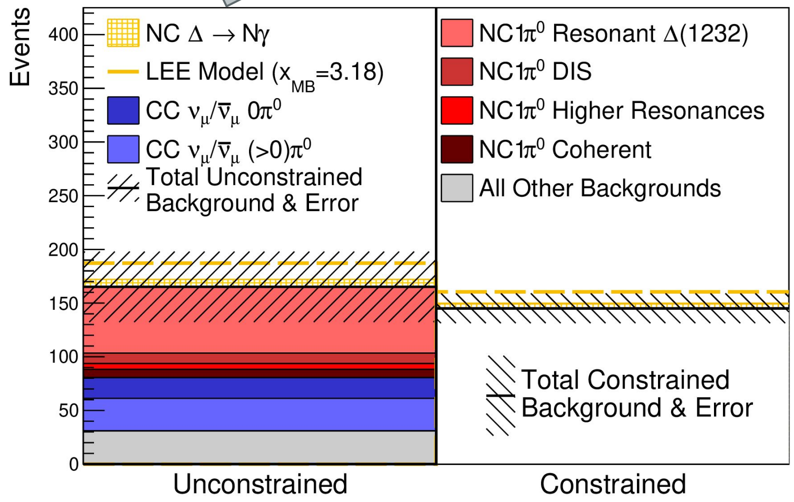
$1\gamma 0p$

final selection



[MicroBooNE Collab, Phys. Rev. Lett. 128, 111801 (2022)](#)





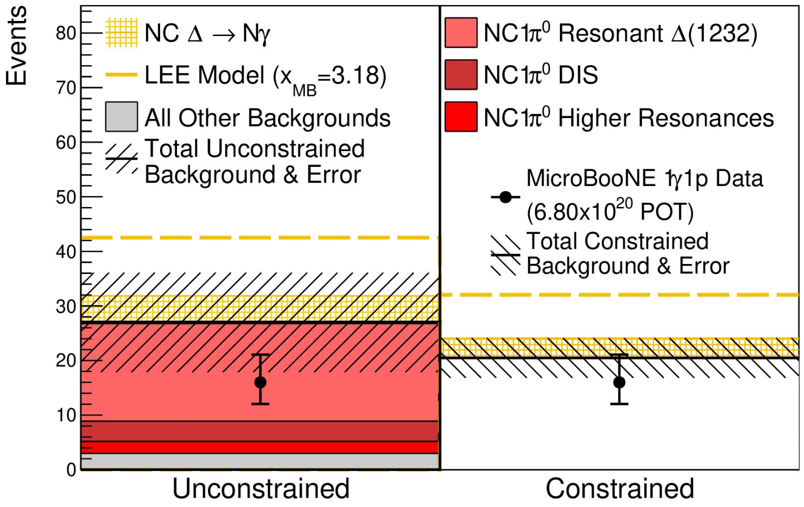
$1\gamma 0p$

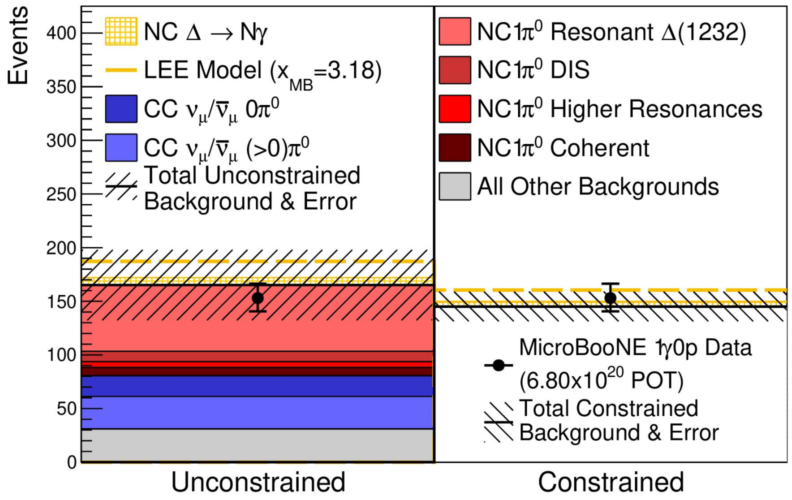
Unconstr. bkgd.	165.4 ± 31.7
Constr. bkgd.	145.1 ± 13.8
NC $\Delta \to N\gamma$	+ 6.55
LEE ($x_{\mathrm{MB}} = 3.18$)	+ 20.1

ALFRED P. SLOAN FOUNDATION

Photon search results

MicroBooNE Collab, Phys. Rev. Lett. 128, 111801 (2022)





1γ1p

Unconstr. bkgd.	27.0 ± 8.1
Constr. bkgd.	20.5 ± 3.6
NC $\Delta \to N\gamma$	+ 4.88
LEE ($x_{\mathrm{MB}} = 3.18$)	+ 15.5

16
Data Events Observed

1γ0p

Unconstr. bkgd.	165.4 ± 31.7
Constr. bkgd.	145.1 ± 13.8
NC $\Delta \to N\gamma$	+ 6.55
LEE ($x_{\mathrm{MB}} = 3.18$)	+ 20.1

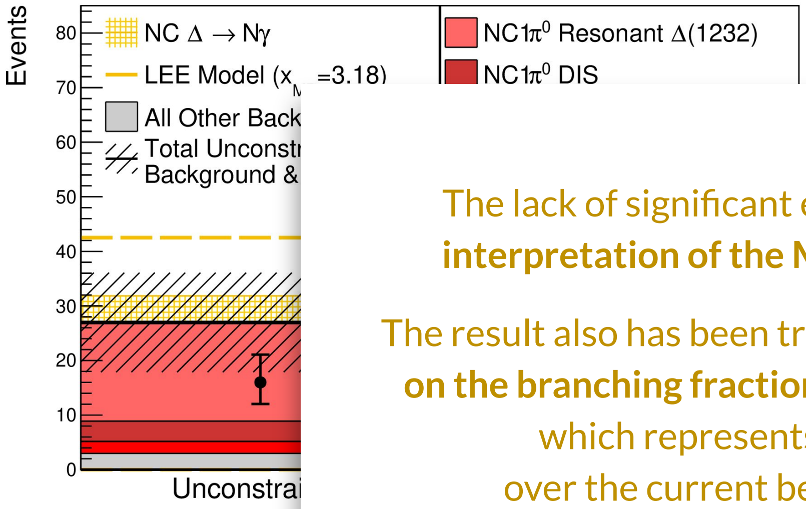
153
Data Events Observed

ALFRED P. SLOAN FOUNDATION

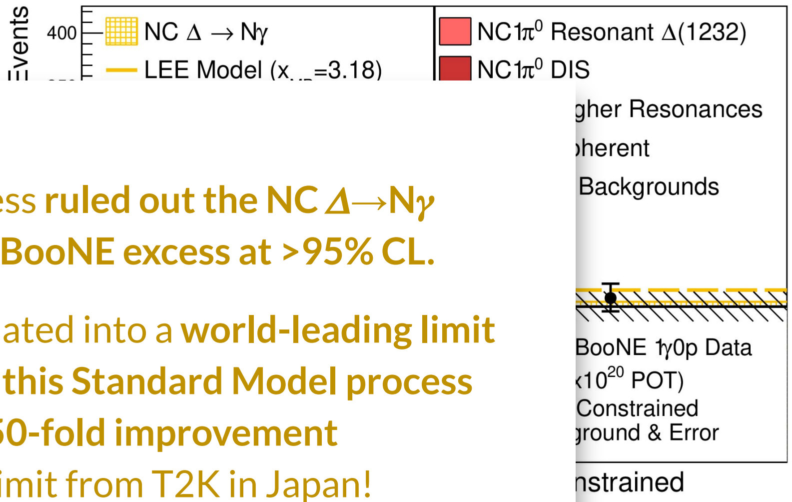
Photon search results

MicroBooNE Collab, Phys. Rev. Lett. 128, 111801 (2022)

1γ1p



1γ0p



The lack of significant excess **ruled out the NC Δ→Nγ interpretation of the MiniBooNE excess at >95% CL.**

The result also has been translated into a **world-leading limit on the branching fraction of this Standard Model process** which represents a **50-fold improvement** over the current best limit from T2K in Japan!

1γ1p

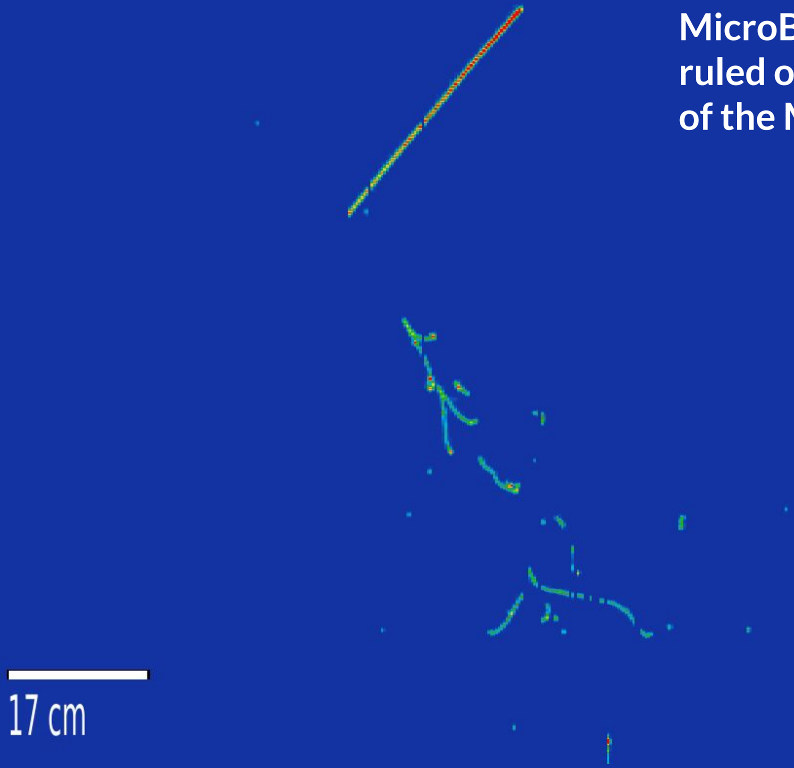
Unconstr. bkgd.	
Constr. bkgd.	20.5 ± 3.6
NC Δ → $N\gamma$	+ 4.88
LEE ($x_{MB} = 3.18$)	+ 15.5

16
Data Events Observed

Constr. bkgd.	145.1 ± 13.8
NC Δ → $N\gamma$	+ 6.55
LEE ($x_{MB} = 3.18$)	+ 20.1

153
Data Events Observed

ALFRED P. SLOAN FOUNDATION



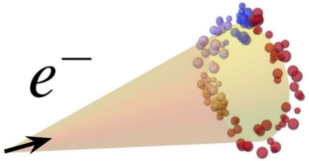
MicroBooNE's single-photon measurement has ruled out the leading background interpretation of the MiniBooNE anomaly

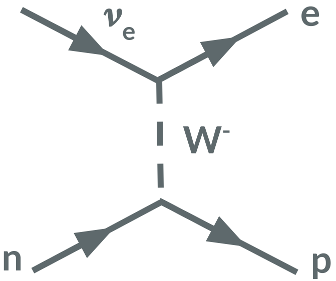
*"…the watershed moment where **neutrino analyses reached the same sophistication as LHC analyses**; this, **made possible by the LArTPC technology** …"*

Joseph Lykken, Fermilab Deputy Director
Oct. 2, 2021

MicroBooNE electron search

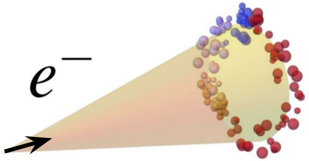
Is the MiniBooNE excess electrons?

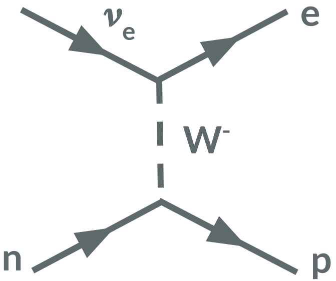




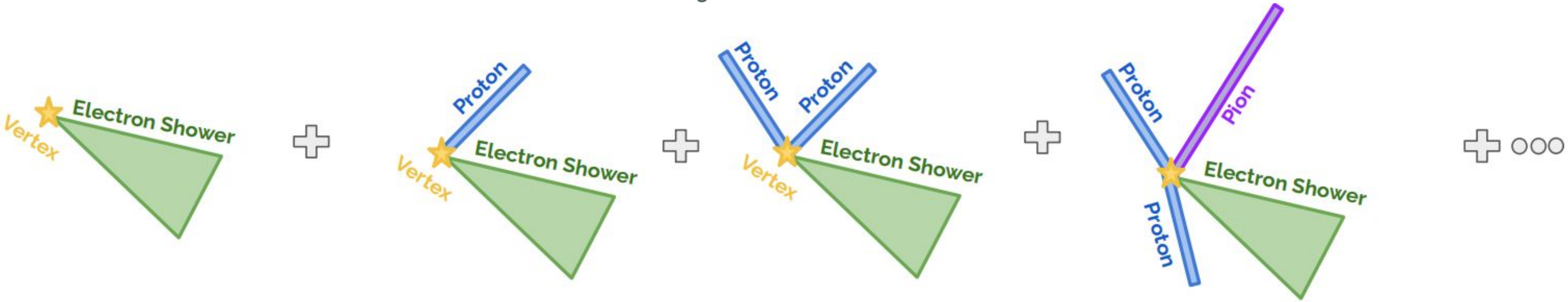
MicroBooNE electron search

Is the MiniBooNE excess electrons?

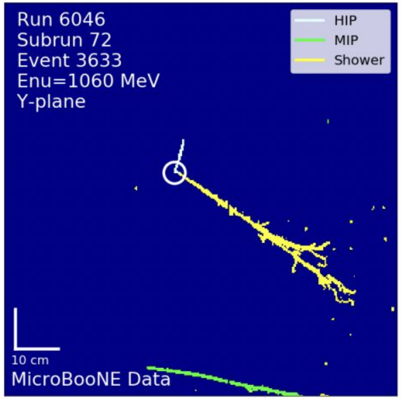




Three independent analyses: All searching for a ν_e excess at low energy



MicroBooNE electron search

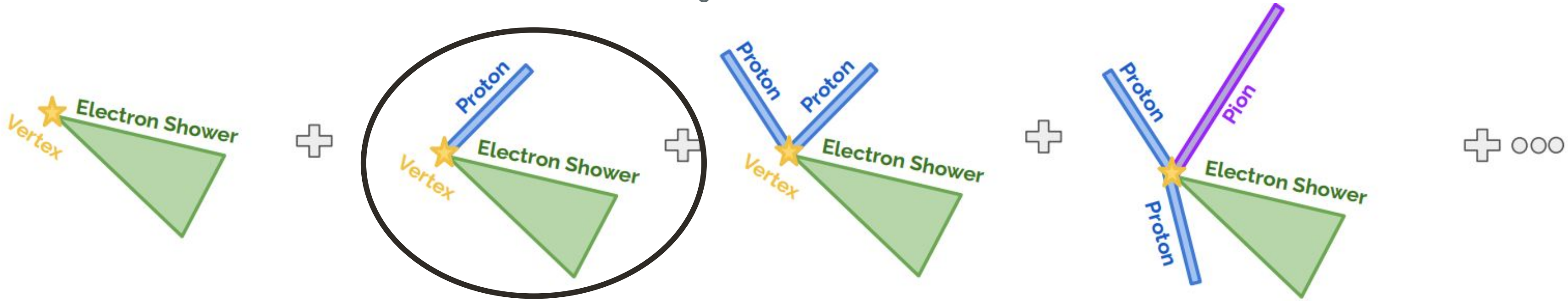


Analysis 1:

Very ν_e-pure (charged-current quasi-elastic kinematics)
Deep Learning-based reconstruction

MicroBooNE Collab, Phys.Rev.D 105 (2022) 11, 11
MicroBooNE Collab, Phys.Rev.Lett. 128 (2022) 24, 241801

Three independent analyses: All searching for a ν_e excess at low energy



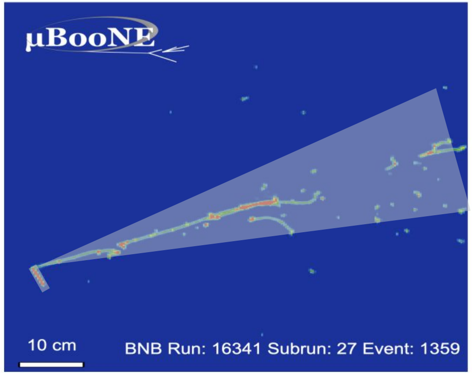
ALFRED P. SLOAN FOUNDATION

MicroBooNE electron search

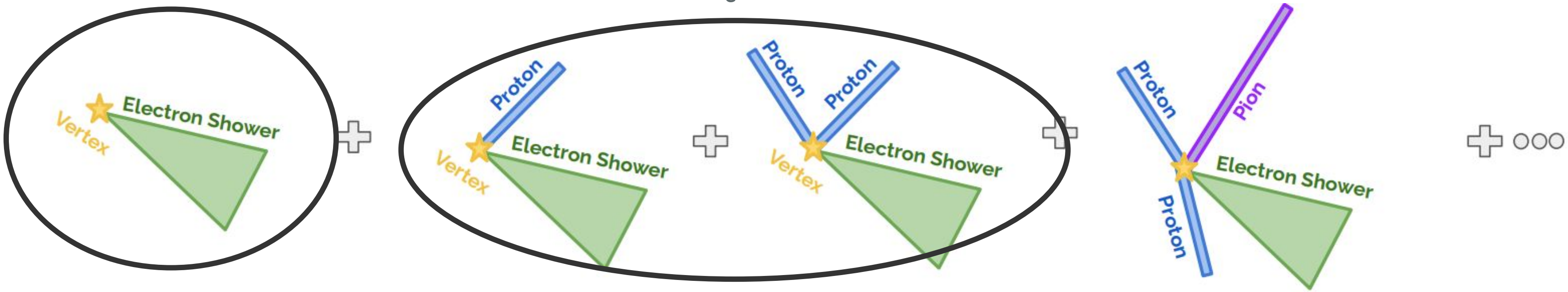
Analysis 2:

MiniBooNE-like final states
"Traditional" reconstruction

MicroBooNE Collab, [Phys.Rev.D 105 (2022) 11, 112004]
MicroBooNE Collab, [Phys.Rev.Lett. 128 (2022) 24, 241801]



Three independent analyses: All searching for a ν_e excess at low energy

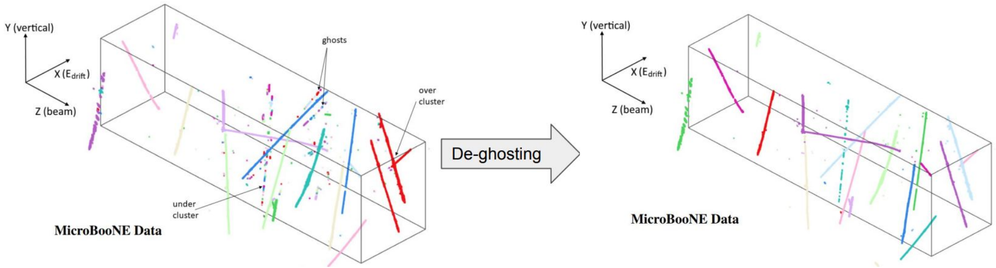


MicroBooNE electron search

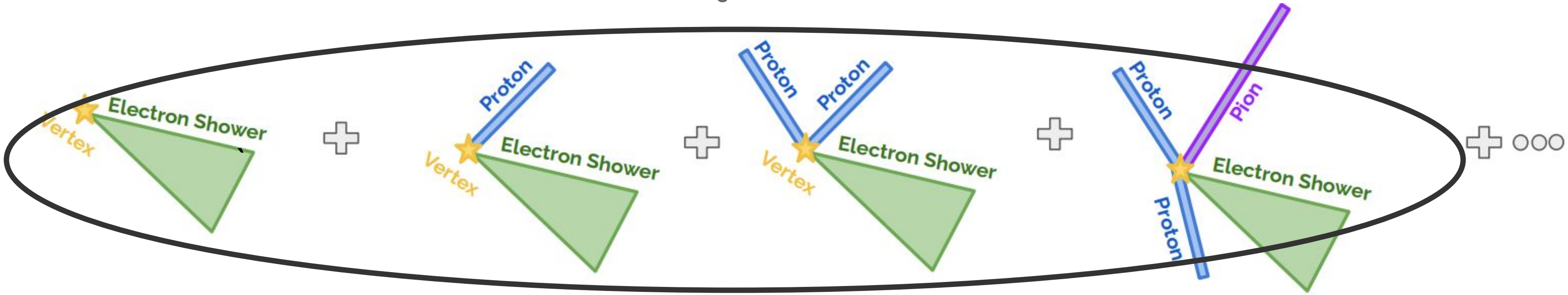
Analysis 3:

All-inclusive final states, **high statistics**
Tomographic reconstruction techniques

MicroBooNE Collab, [Phys.Rev.D 105 (2022) 11, 112005]
MicroBooNE Collab, [Phys.Rev.Lett. 128 (2022) 24, 241801]



Three independent analyses: All searching for a ν_e excess at low energy

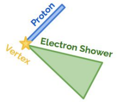


MicroBooNE electron search

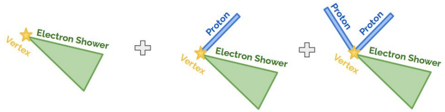
No significant ν_e excess observed!

Conclusion: MiniBooNE anomalous excess cannot be all ν_e

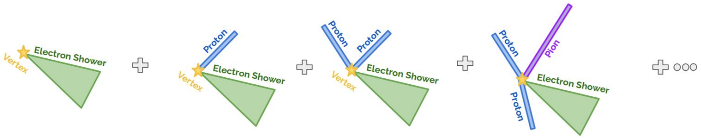
Analysis 1

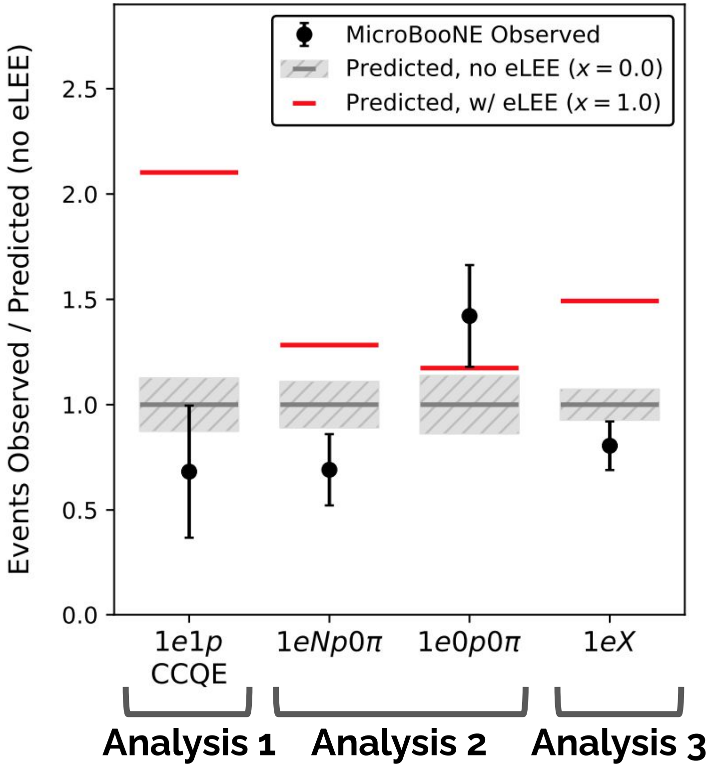


Analysis 2



Analysis 3



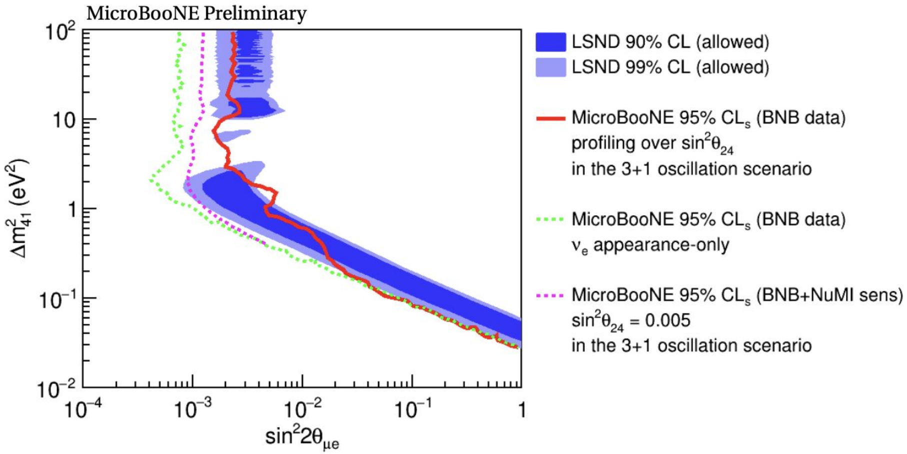


ALFRED P. SLOAN FOUNDATION

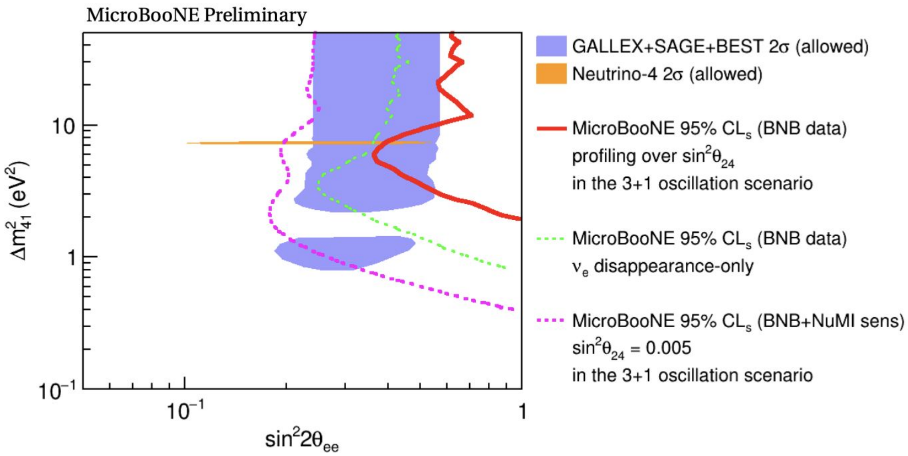
What does this imply about sterile neutrinos?

Preliminary results from MicroBooNE explicitly testing sterile neutrino hypothesis: MICROBOONE-NOTE-1116

ν_e appearance



ν_e disappearance



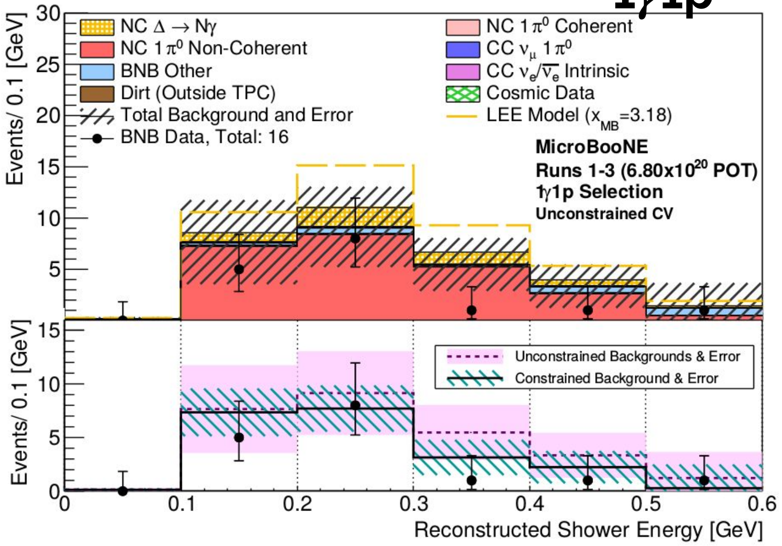
Results so far consistent with three-neutrinos.
LArTPC high-purity ν_e measurements pave the way toward future, more sensitive sterile neutrino oscillation searches with MicroBooNE and SBN

ALFRED P. SLOAN FOUNDATION

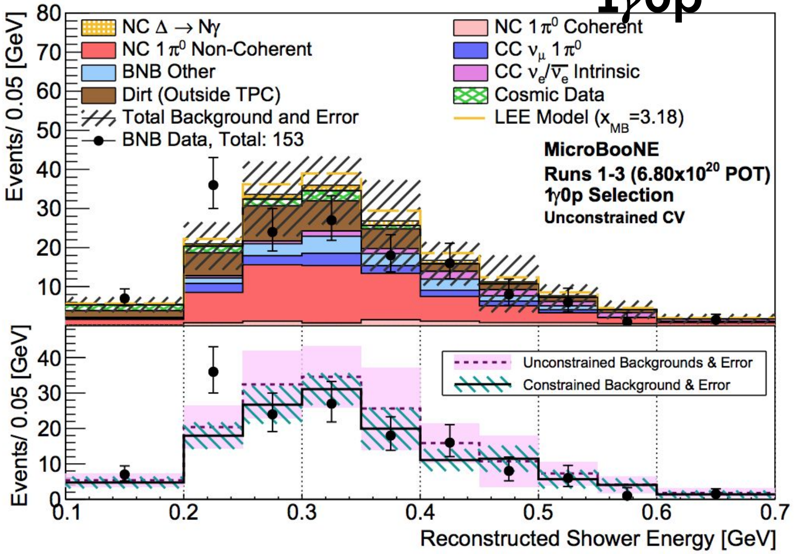
In the near future

More MicroBooNE data at hand (Runs 4 and 5)! **What more can we learn** from studying **single-photon** event rates with enhanced statistics, and as a function of different kinematic variables?

1γ1p



1γ0p

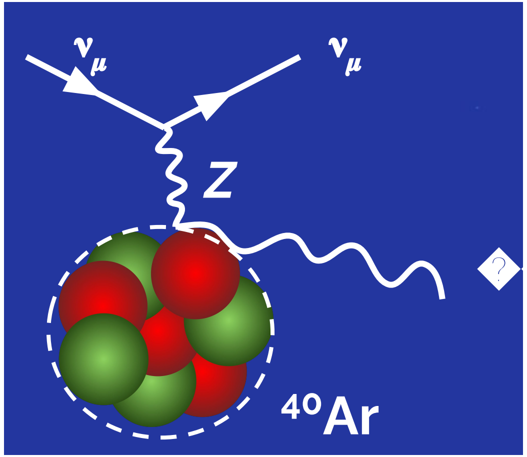


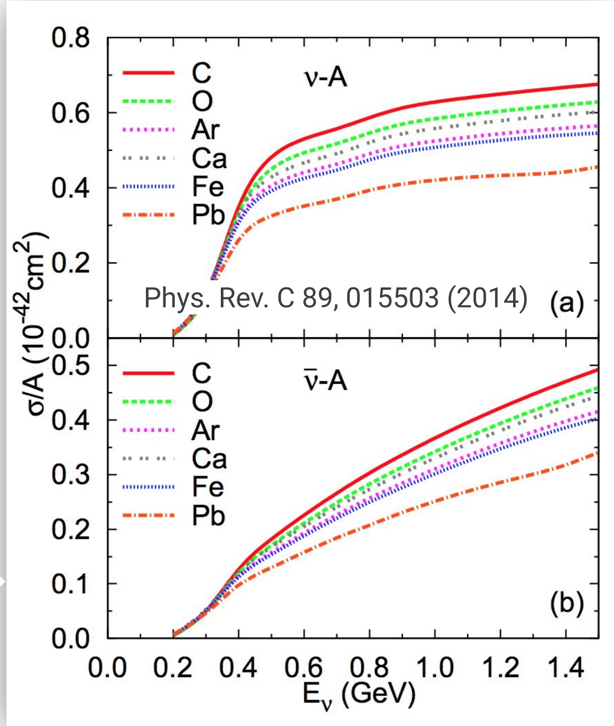
ALFRED P. SLOAN FOUNDATION

In the near future

MicroBooNE is searching for **other rare, never-before-measured, Standard Model-expected single-photon processes**, e.g. coherent single-photon production, production and radiative decays of higher-mass resonances, …

Expect **significantly enhanced sensitivity with SBND** (x15-20 higher neutrino flux!)

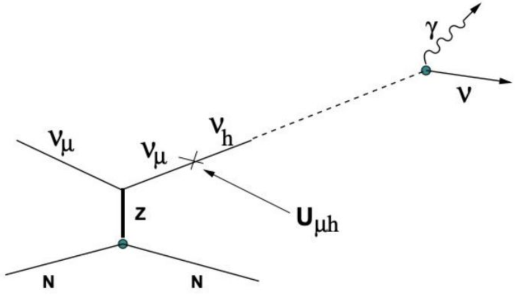


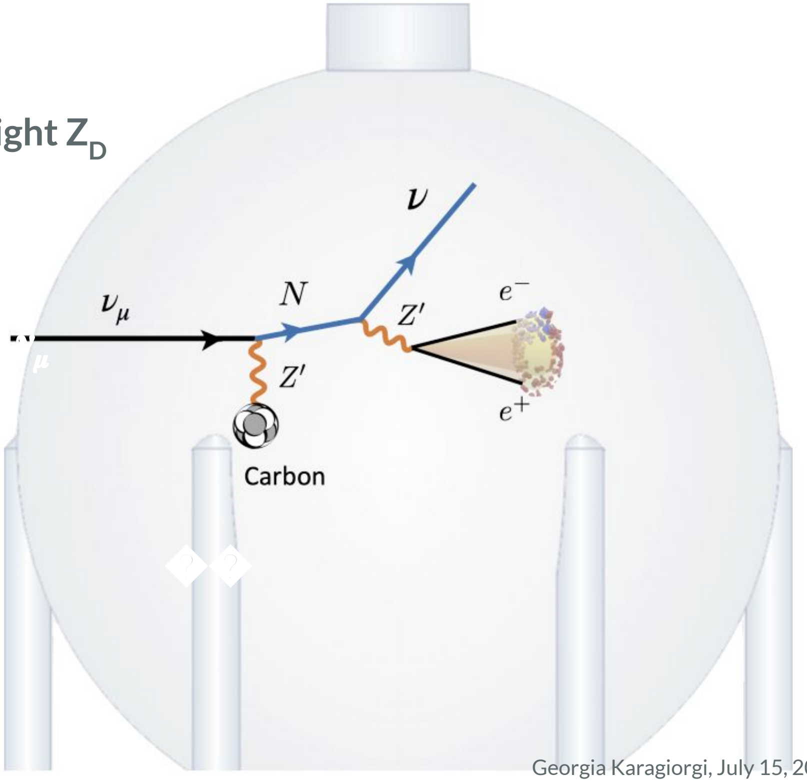


In the near future

MicroBooNE is also searching for **other rare, BSM "single-photon" processes**, e.g. anomalously large **neutrino magnetic moment**

or "single-photon-like" processes,
e.g. boosted e+e- pairs, e.g. due to **"dark neutrinos" and a light Z_D**

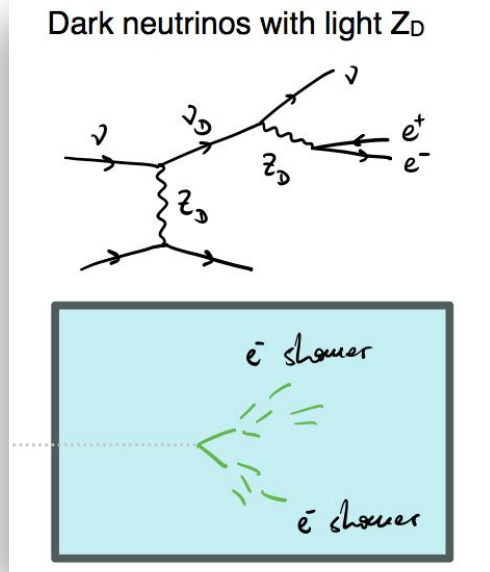




Expect **enhanced sensitivity with SBND**
(x15-20 higher neutrino flux!)

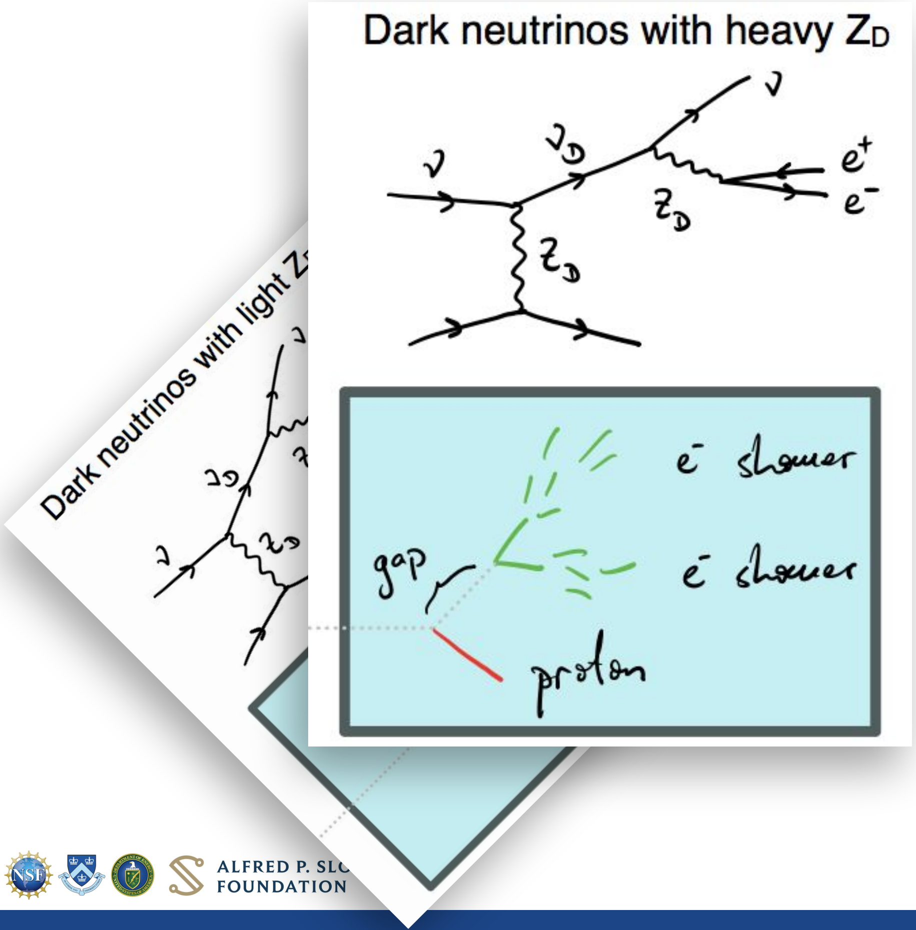
A plethora of new physics, testable at MicroBooNE and SBN!

The promise of the LArTPC technology has motivated exciting leaps into the dark/beyond-Standard Model sector by many within the theory community:



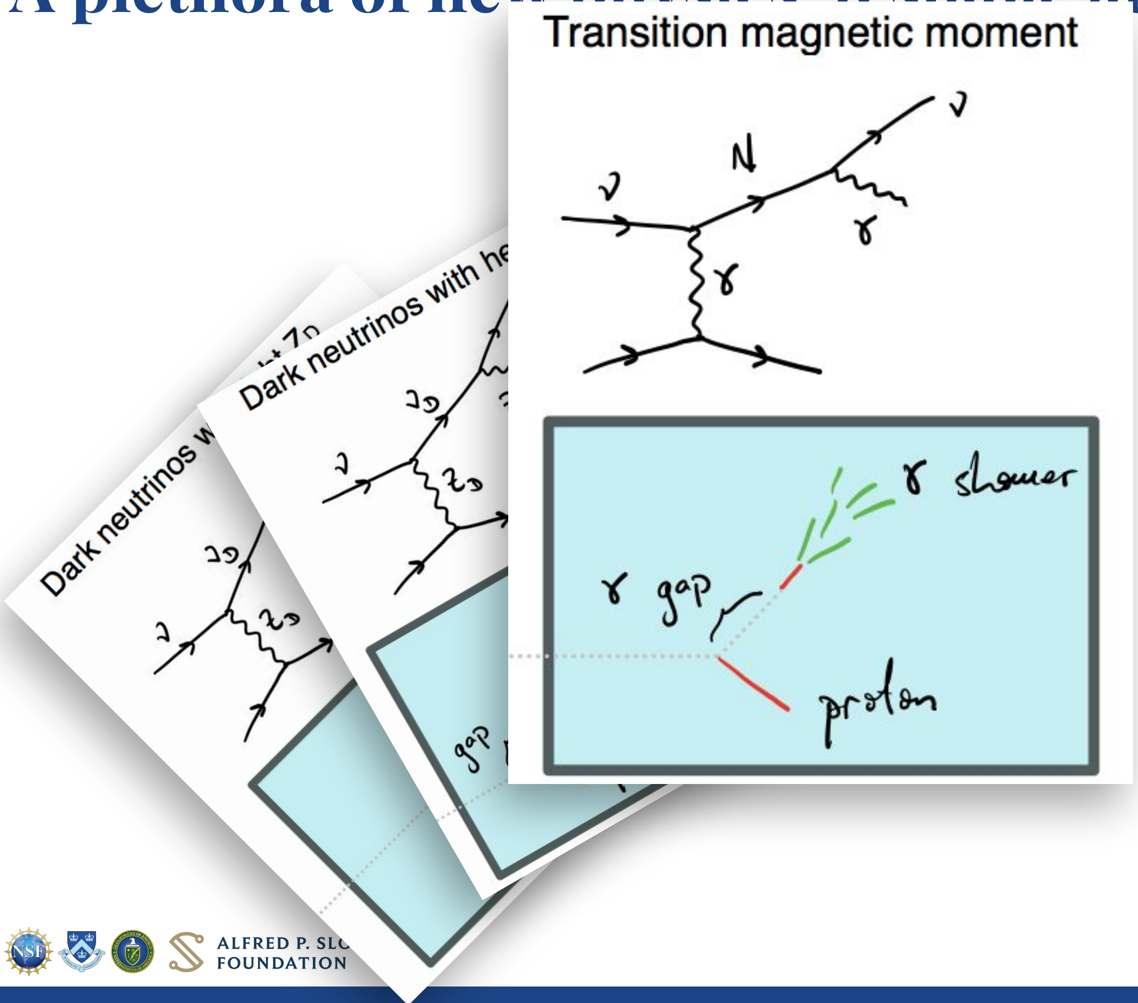
Bertuzzo Jana Machado Zukanovich PRL 2018
Bertuzzo Jana Machado Zukanovich PLB 2019
Arguelles Hostert Tsai PRL 2019

A plethora of new physics, testable at MicroBooNE and SBN!



Ballett Pascoli Ross-Lonergan PRD 2019
Ballett Hostert Pascoli PRD 2020

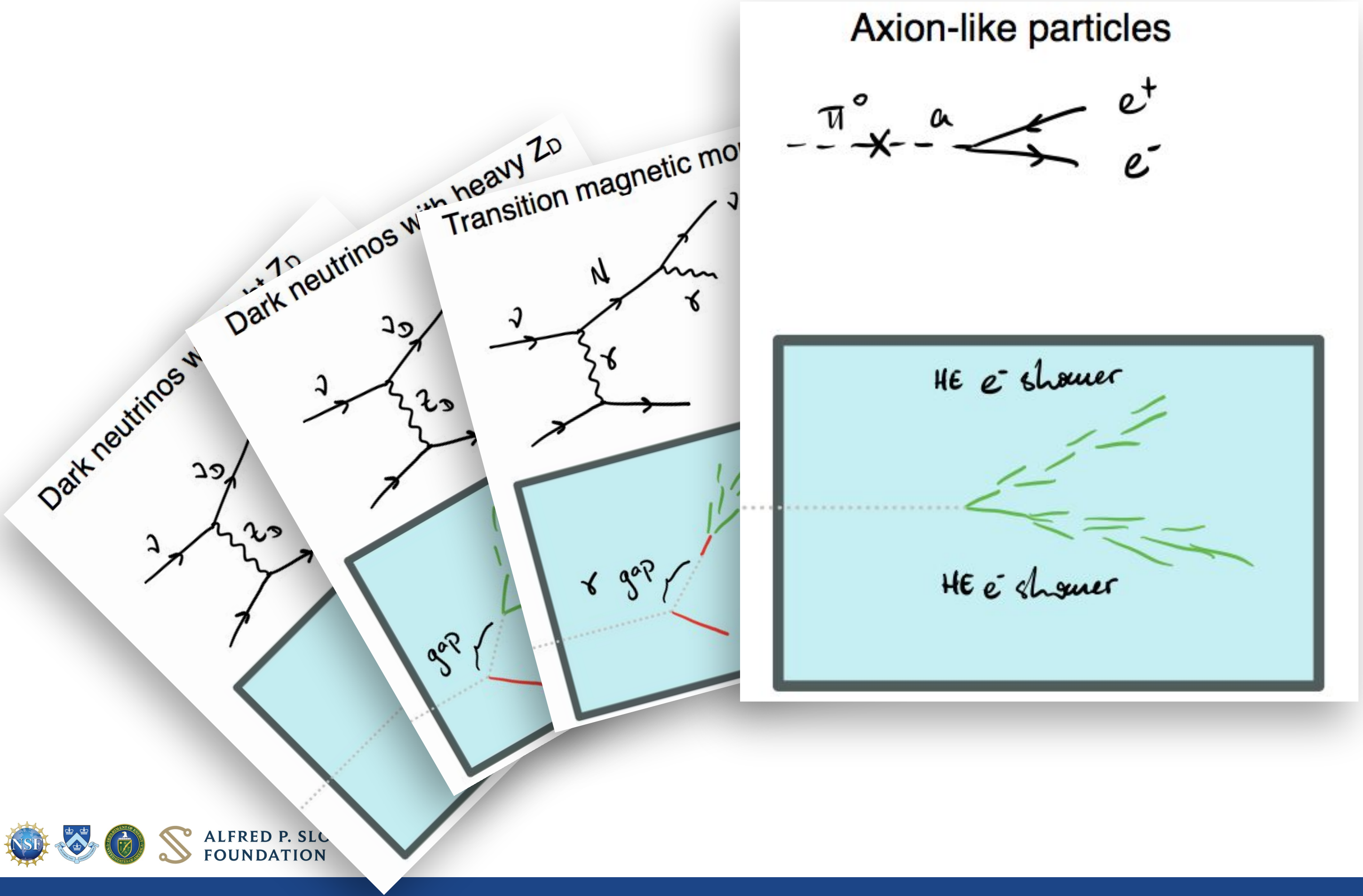
A plethora of new physics, testable at MicroBooNE and SBN!



Gninenko PRL 2009
Coloma Machado Soler Shoemaker PRL 2017
Atkinson et al 2021
Vergani et al 2021

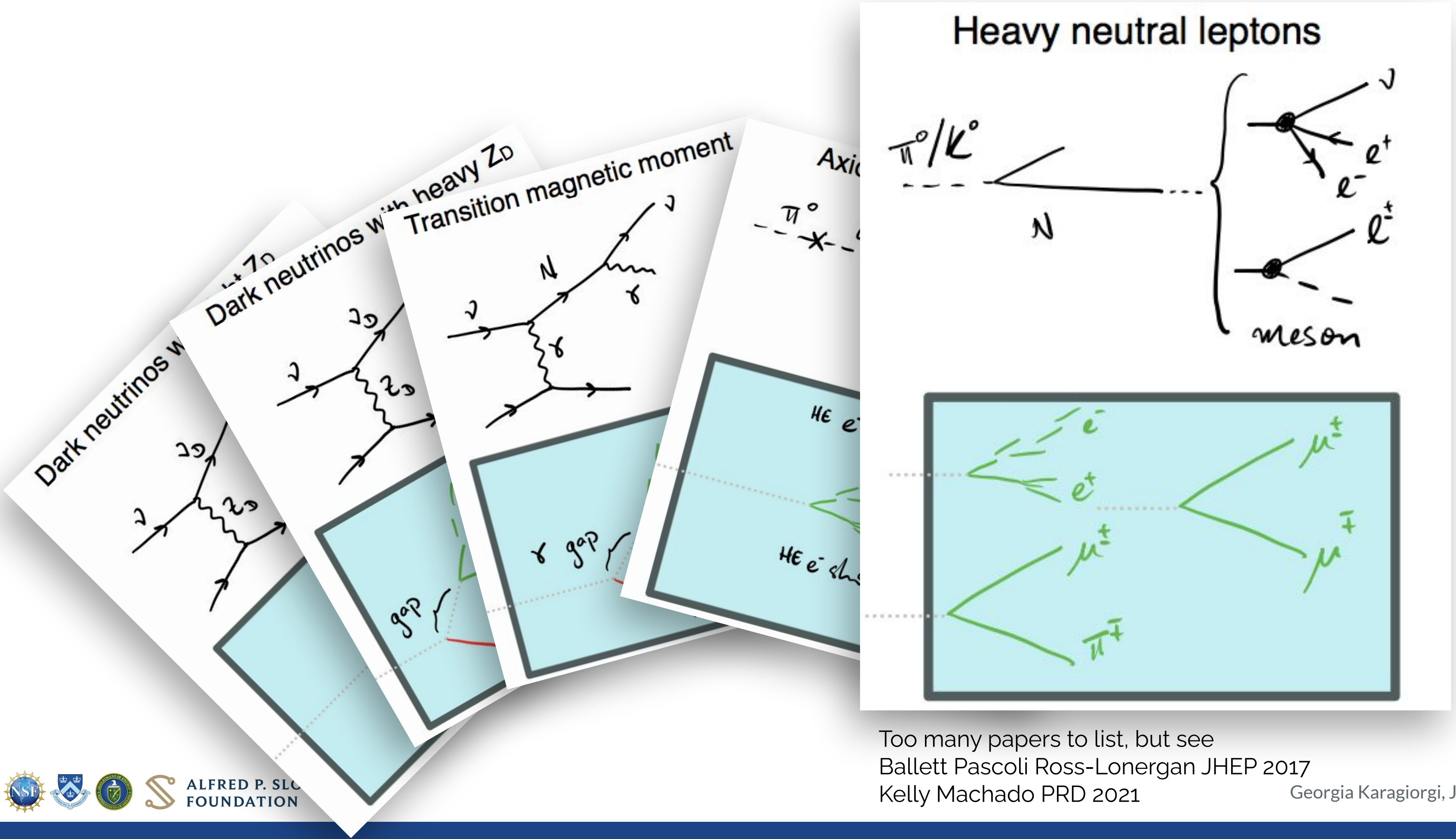
ALFRED P. SLO
FOUNDATION

A plethora of new physics, testable at MicroBooNE and SBN!



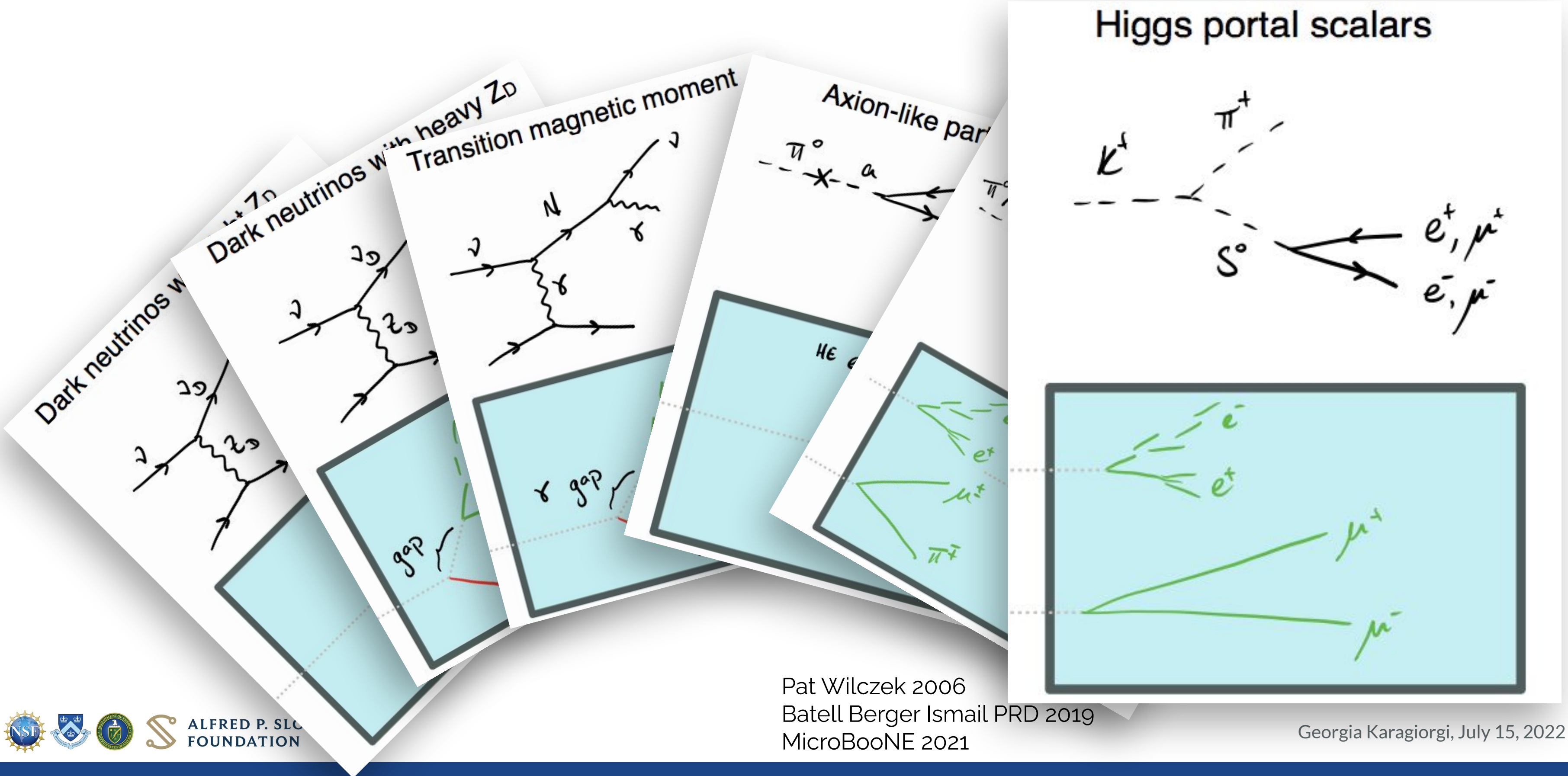
Kelly Kumar Liu PRD 2021
Brdar et al PRL 2021

A plethora of new physics, testable at MicroBooNE and SBN!



Too many papers to list, but see
Ballett Pascoli Ross-Lonergan JHEP 2017
Kelly Machado PRD 2021

A plethora of new physics, testable at MicroBooNE and SBN!

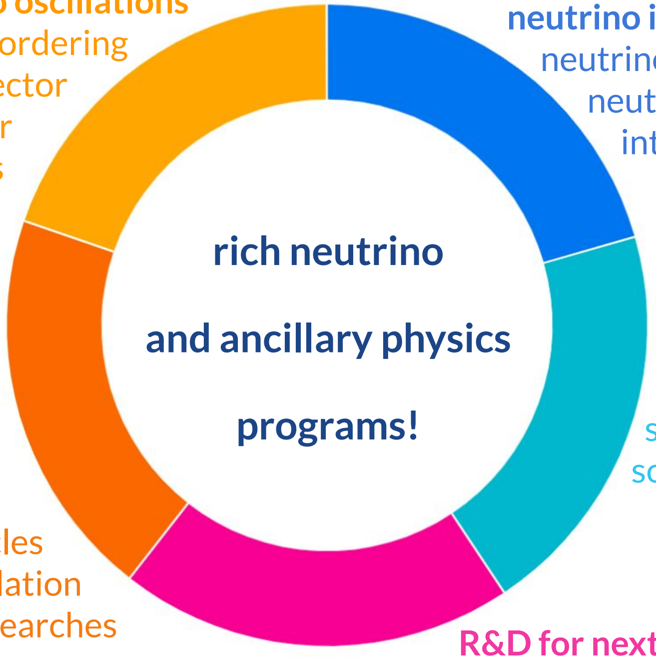


Pat Wilczek 2006
Batell Berger Ismail PRD 2019
MicroBooNE 2021

Accelerators as neutrino sources

neutrino oscillations
neutrino mass ordering
CP violation in the lepton sector
unitarity in the neutrino sector
light sterile neutrinos

neutrino interactions
neutrino-electron scattering
neutrino-nucleus scattering
intra-nuclear effects (nucleon-nucleon correlations, …)



exotic/new physics
non-standard neutrino interactions
new neutrino species
CPT violation
extra dimensions
axion-like-particle searches
millicharged particles
baryon number violation
dark matter searches

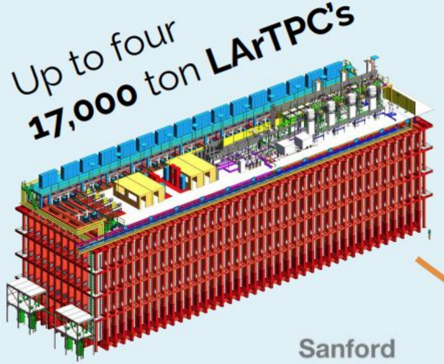
astro-particle
atmospheric neutrinos
supernova neutrinos
solar neutrinos

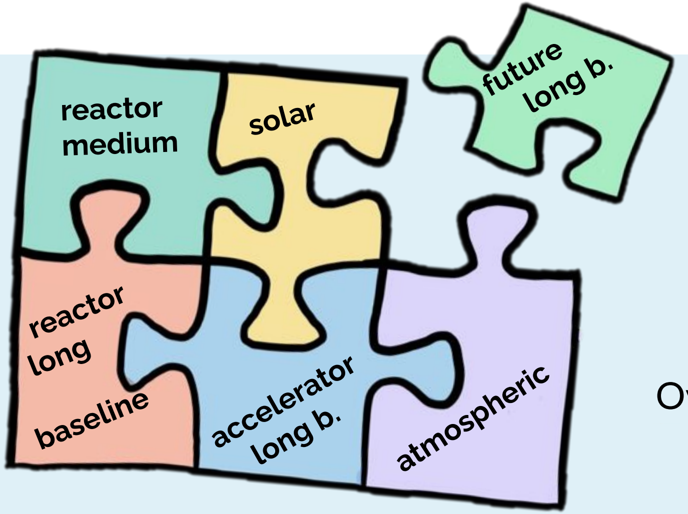
R&D for next-generation experiments

MeV → TeV

ALFRED P. SLOAN FOUNDATION

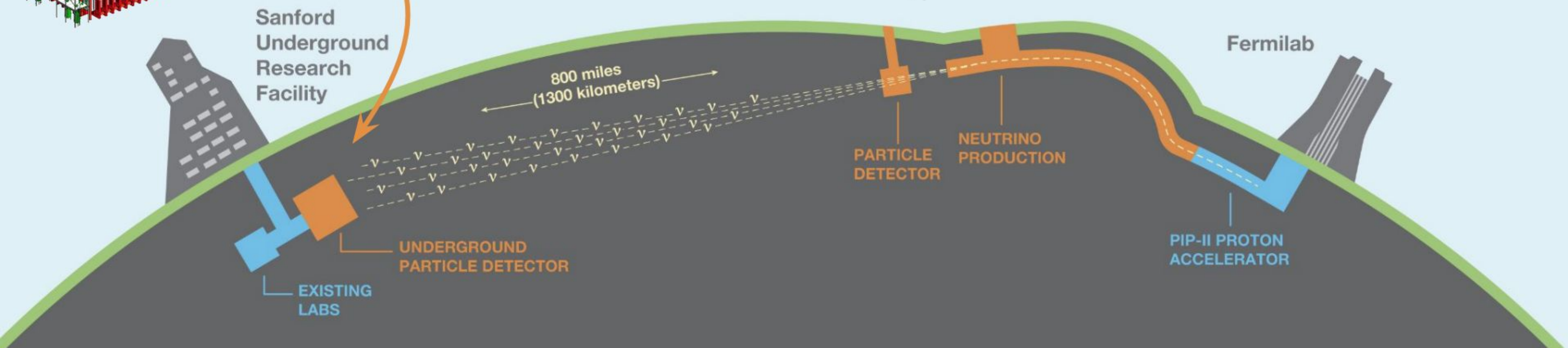
Beyond MicroBooNE and SBN: DUNE





DEEP UNDERGROUND NEUTRINO EXPERIMENT

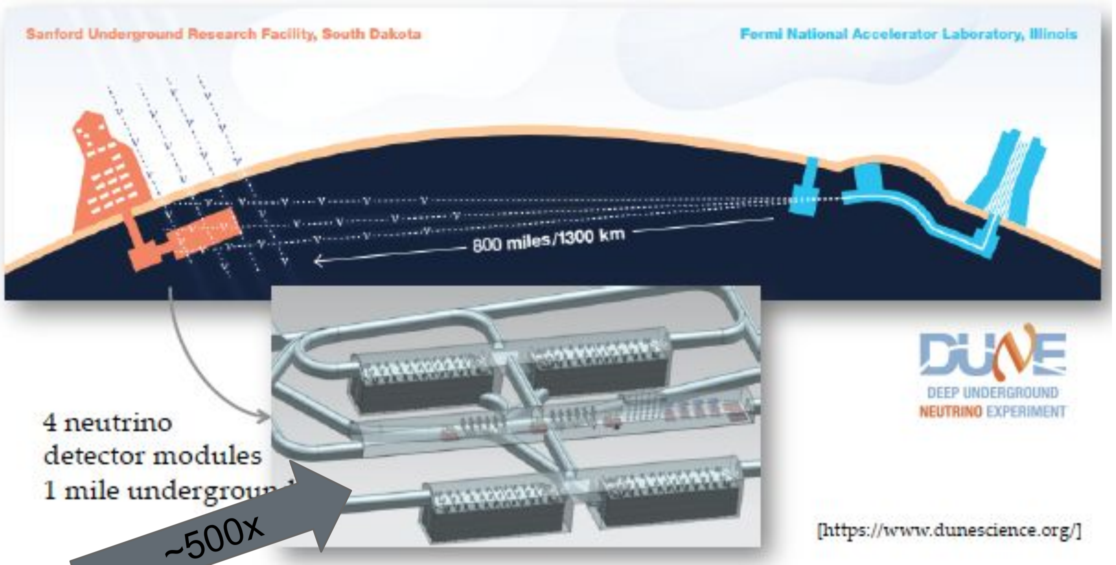
Over-constraining three-neutrino sector:
CP violation?
neutrino mass hierarchy?



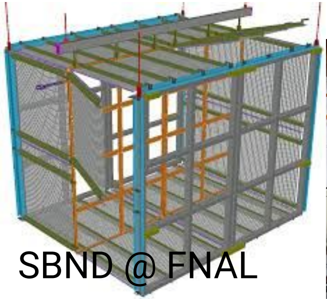
DUNE scalability challenge

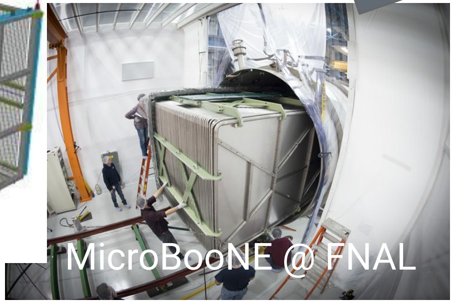

ProtoDUNE-SP @ CERN

~100x



~500x


SBND @ FNAL


MicroBooNE @ FNAL

DUNE: up to >1 million readout channels
2 MHz x 12 bit ADC digitization
>5 TB/s data rate!

ALFRED P. SLOAN FOUNDATION

Off-beam, rare event searches in DUNE

For rare event searches, future LArTPCs will require **efficient data processing systems** to parse increasingly large amounts of data through data-informed data selection!

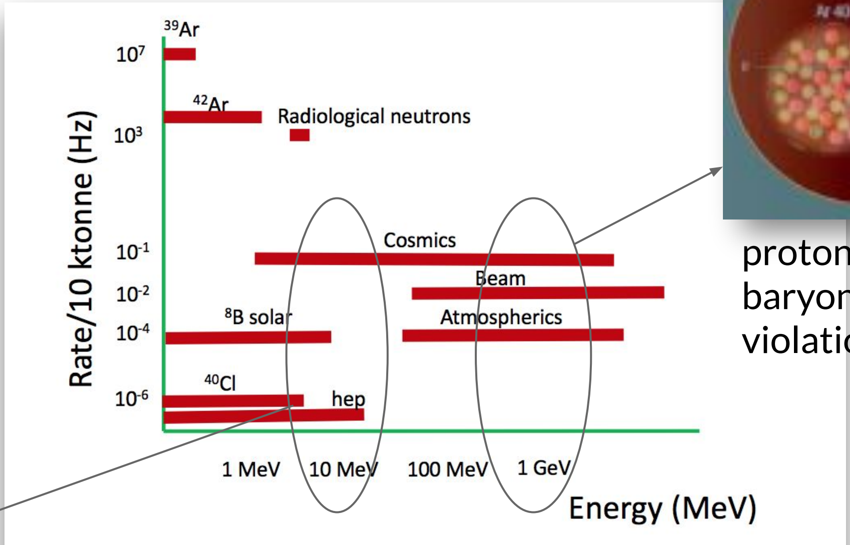
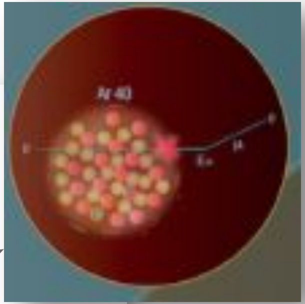


Figure 1.2: Expected physics-related activity rates in a single 10 kt module.

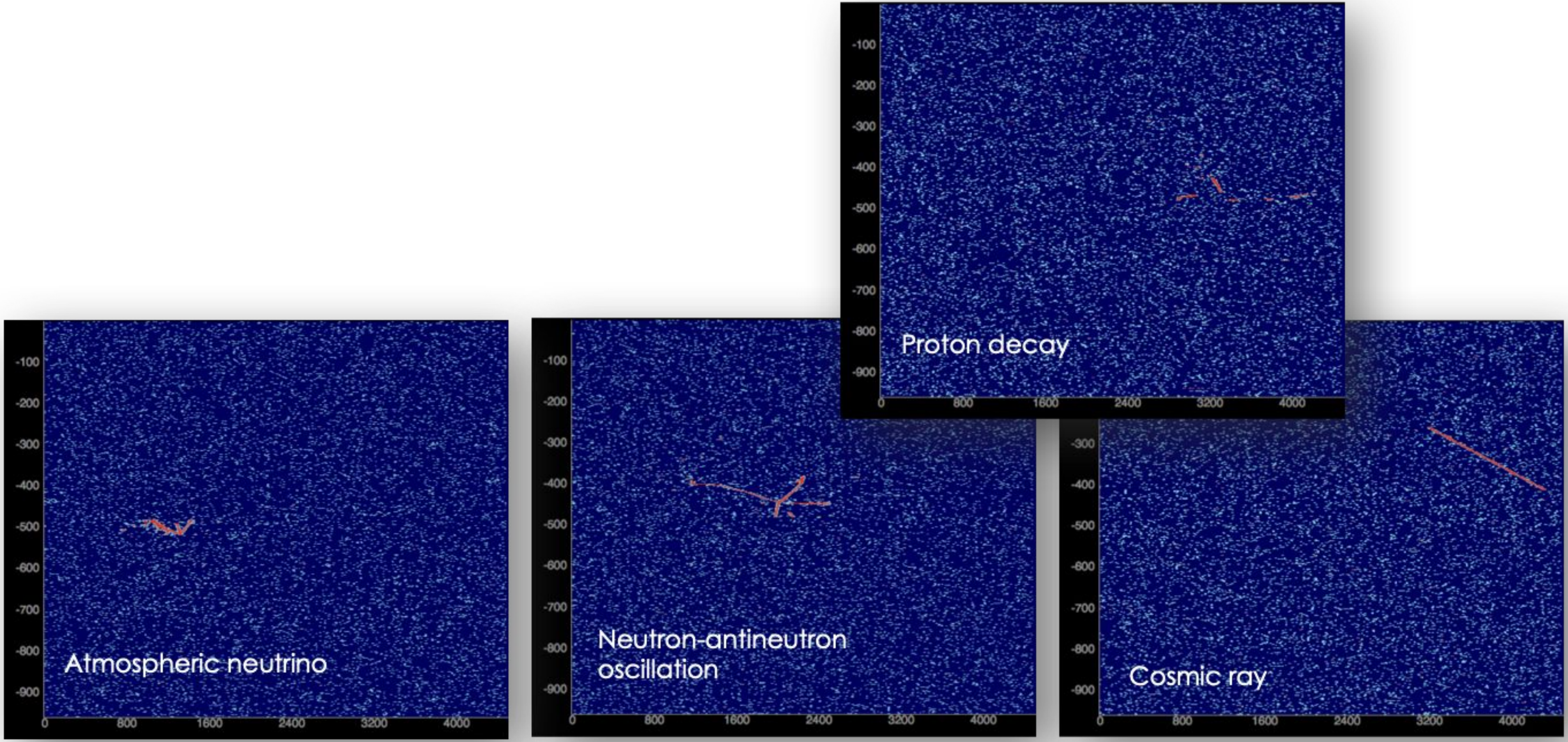
[DUNE TDR]



proton decay, baryon number violation

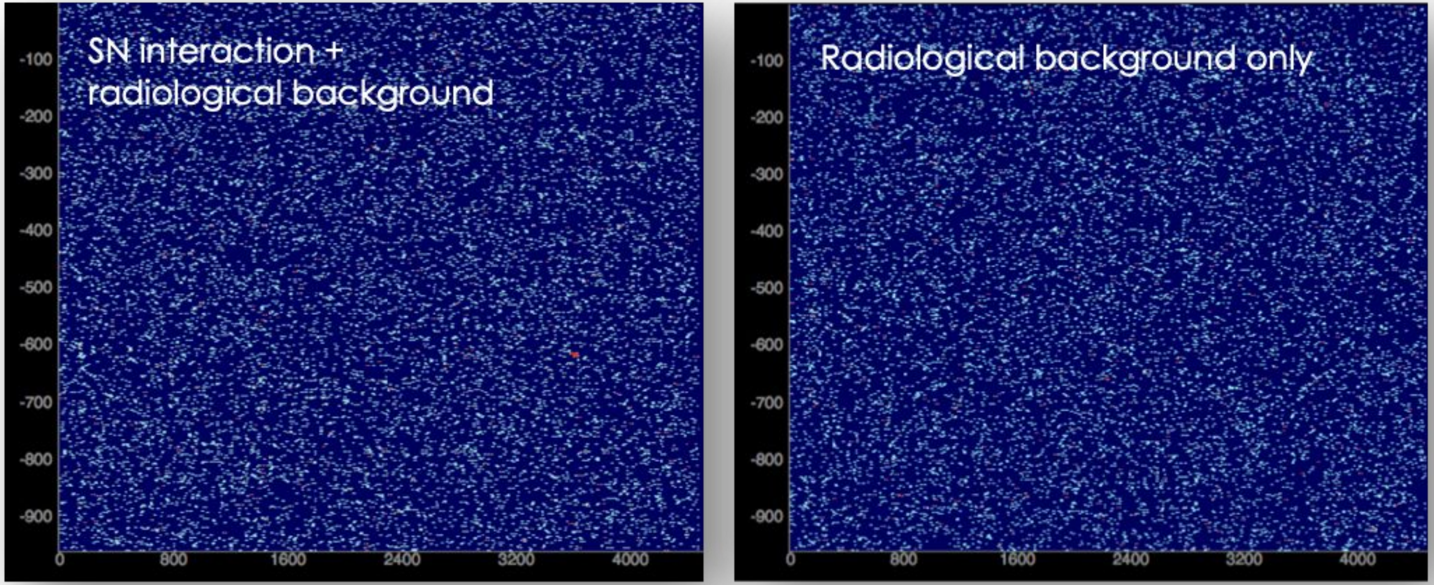
neutrinos from nearby supernova bursts

Off-beam interactions of interest in DUNE



The challenge of supernova neutrino detection

Supernova neutrino interactions:
Very low energy and small (in extent) topology, similar to radiological background activity in the detector
Need $O(10^4)$ background suppression, while maintaining high efficiency to individual supernova interactions

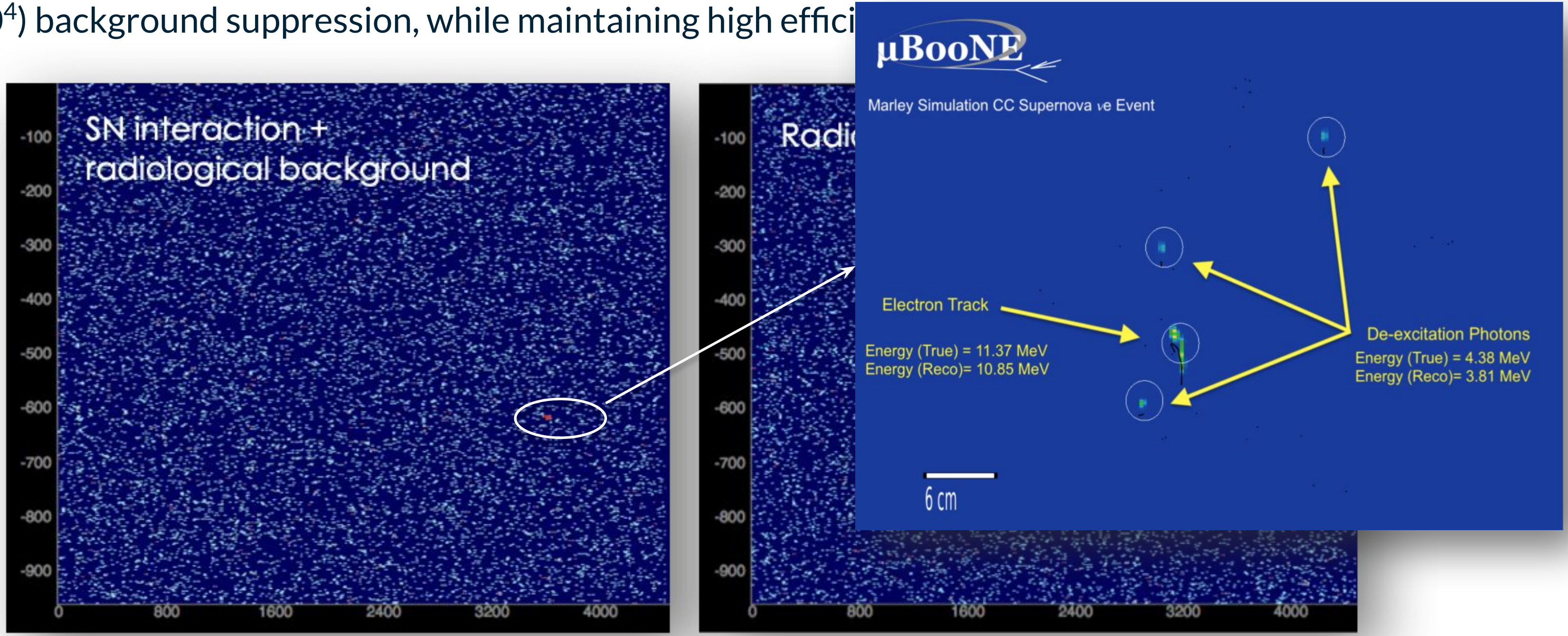


The challenge of supernova neutrino detection

Supernova neutrino interactions:

Very low energy and small (in extent) topology, similar to radiological background activity in the detector

Need O(10^4) background suppression, while maintaining high effici



Real-time AI for data selection/triggering

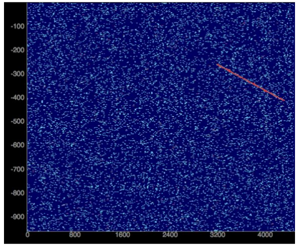
New technology and tools enable the possibility of **hardware acceleration of machine learning algorithms for low-latency, real-time applications in high-rate data streaming:**

hls 4 ml

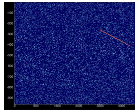
Increasingly more powerful COTS FPGA

Real-time inference in DUNE is possible with a small CNN, downsized and further optimized to reduce computational footprint, and trained with "quantization awareness"

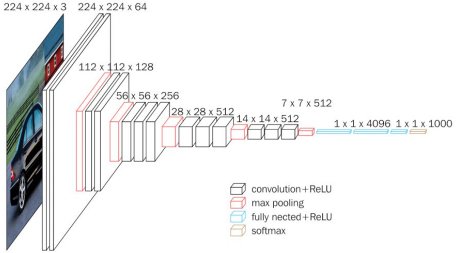
[Y. Jwa *et al.* arXiv:2201.04740]



raw image input (4450x960)



down-sampling, resizing (600x600)

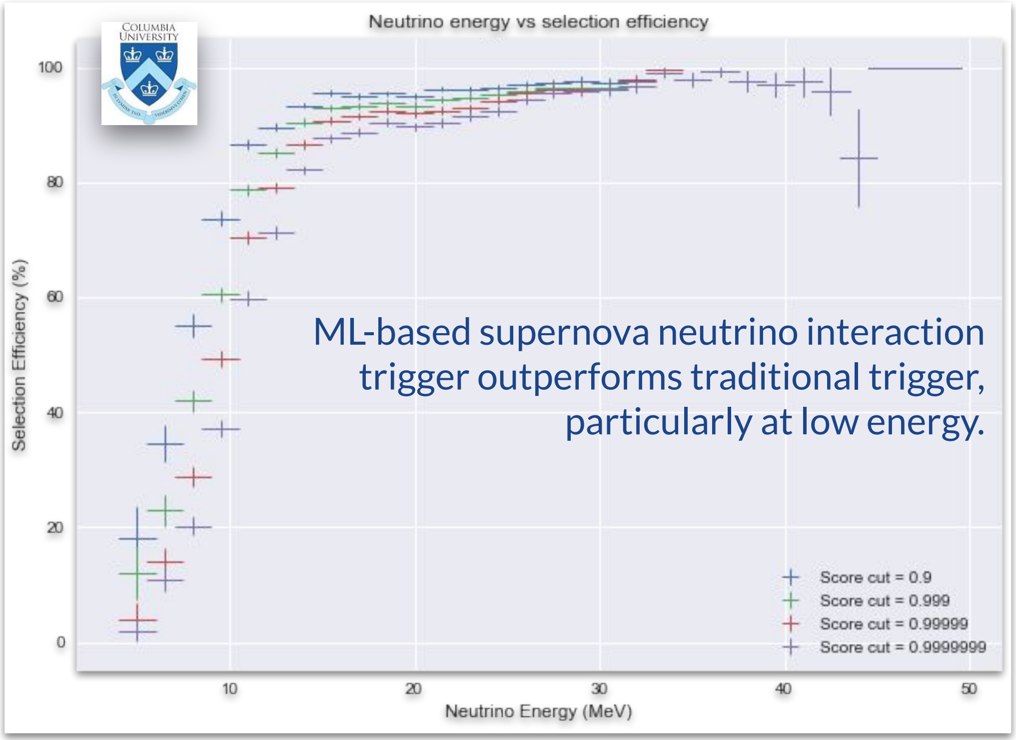


CNN classification

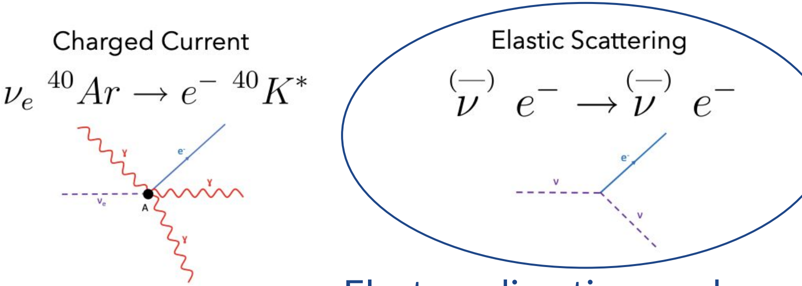
- Background
- Supernova neutrino
- Other interaction

selection (e.g., lowest background class score)

Pushing the (low-energy) limit of LArTPC's



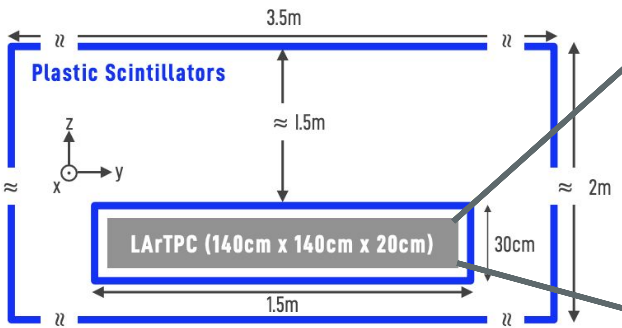
With large sample of supernova neutrino candidates in real time prompt studies of directionality are possible → DUNE could become an important player in multi-messenger astrophysics!

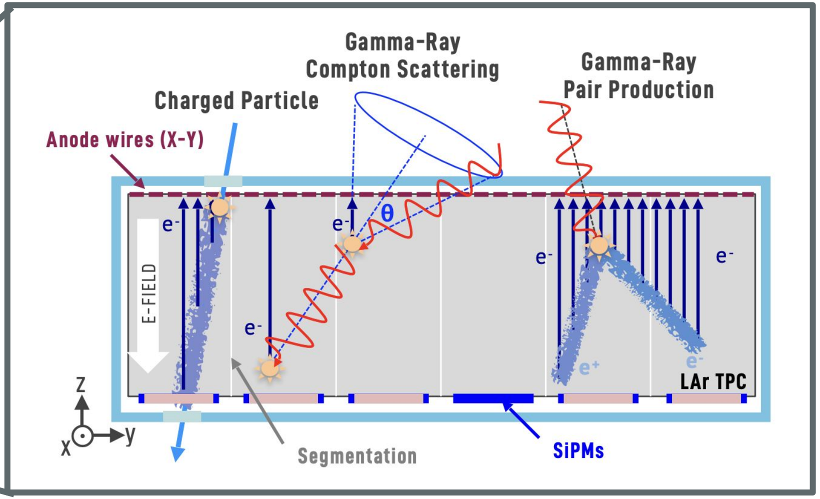


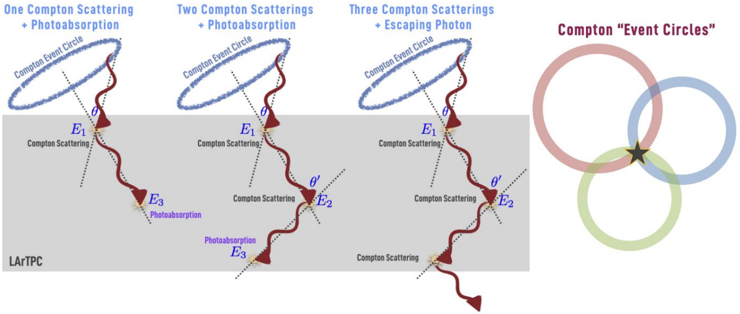
Electron direction much more correlated with incoming neutrino direction.

Pushing the (low-energy) limit of LArTPC's

LArTPC as a "Compton telescope":



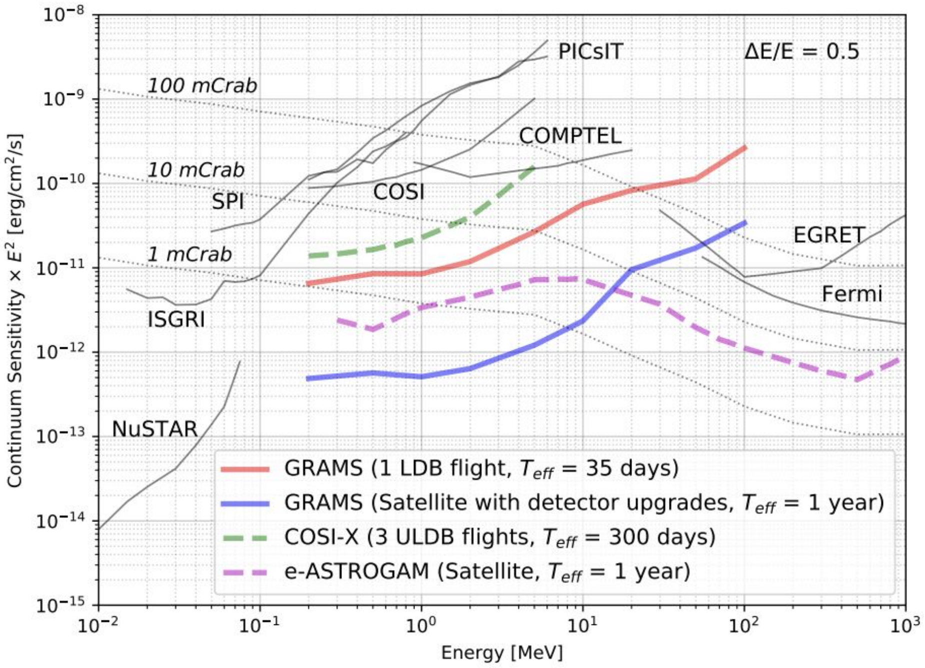


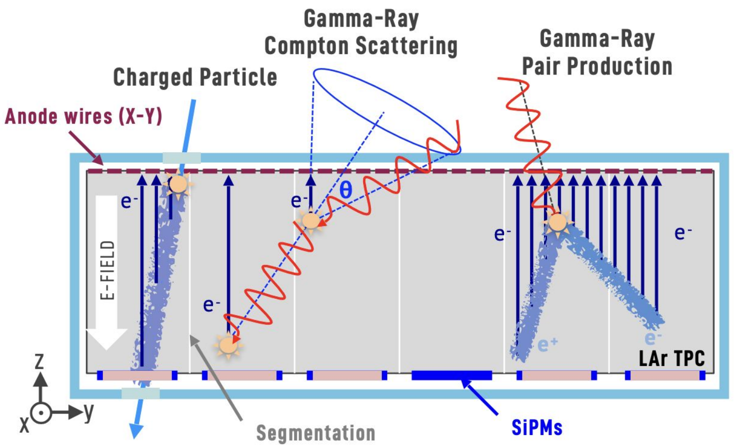


Target angular and energy resolutions of 2 degrees and 1% (2.5 MeV), respectively.

Pushing the (low-energy) limit of LArTPC's

LArTPC as a "Compton telescope":





Gamma Ray and AntiMatter Survey (GRAMS) experiment

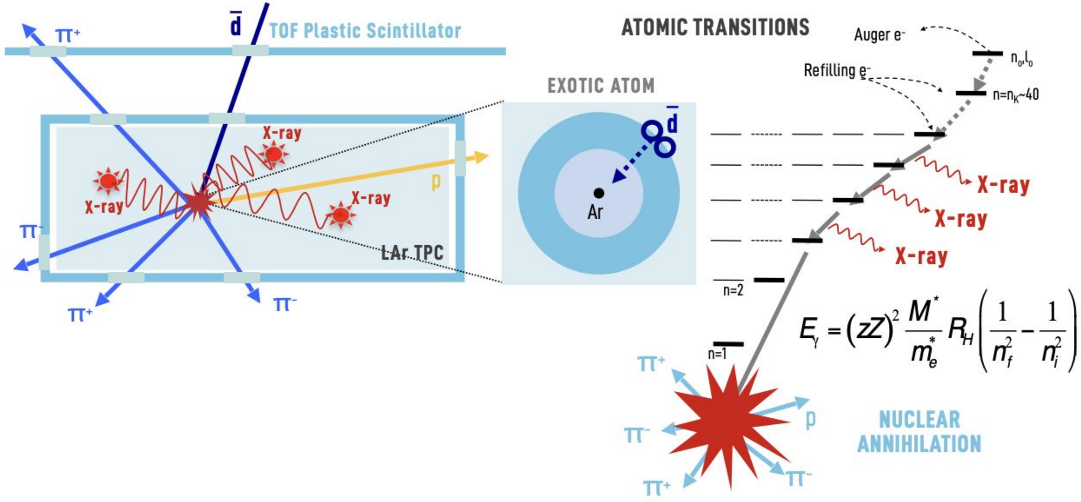
T. Aramaki, P. Hannson Adrien, GK, H. Odaka,
Astropart.Phys. 114 (2020) 107-114

Pushing the (low-energy) limit of LArTPC's

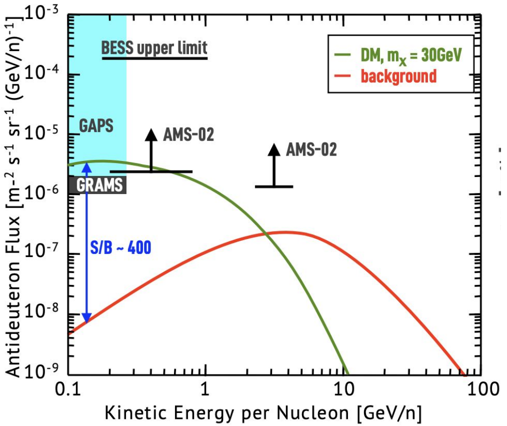
GRAMS as an indirect dark matter detector:

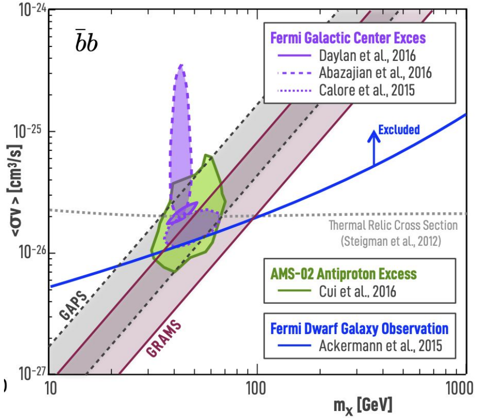
T. Aramaki, P. Hannson Adrien, GK, H. Odaka,
Astropart.Phys. 114 (2020) 107-114

antimatter from galactic
dark matter annihilation



$$E_\gamma = (zZ)^2 \frac{M^*}{m_e^*} R_H \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right)$$



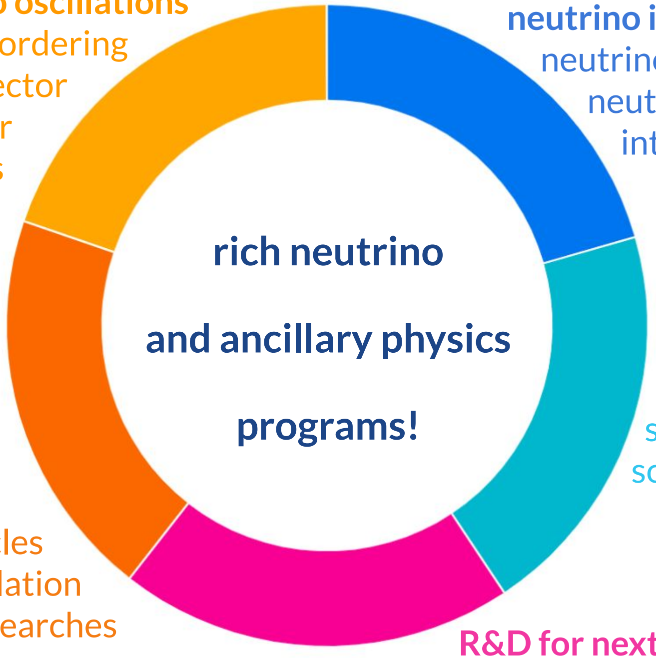


ALFRED P. SLOAN FOUNDATION

Exciting path ahead, in search for new physics!

neutrino oscillations
neutrino mass ordering
CP violation in the lepton sector
unitarity in the neutrino sector
light sterile neutrinos

exotic/new physics
non-standard neutrino interactions
new neutrino species
CPT violation
extra dimensions
axion-like-particle searches
millicharged particles
baryon number violation
dark matter searches



neutrino interactions
neutrino-electron scattering
neutrino-nucleus scattering
intra-nuclear effects (nucleon-nucleon correlations, …)

astro-particle
atmospheric neutrinos
supernova neutrinos
solar neutrinos

R&D for next-generation experiments

ALFRED P. SLOAN FOUNDATION

Exciting path ahead, in search for new physics!

Charted by accelerator-based neutrino experiments, and new LArTPC technology developments.

MicroBooNE's mastering of the LArTPC detector technology has enabled **unprecedented studies of neutrino interactions**, which are only **beginning to scratch the surface** of rich physics accessible through neutrino experiments.

MicroBooNE (and, in the near future, SBN) is bringing to test leading interpretations of compelling, **long-standing experimental anomalies**, and providing **new opportunities to search for BSM physics**.

Their technological success is **enabling future particle and astro-particle physics experiments.**

ALFRED P. SLOAN FOUNDATION

Thank you!