Short-Baseline Oscillations

Current and Future Efforts

NuTheories Workshop

University of Pittsburgh, November 7, 2018

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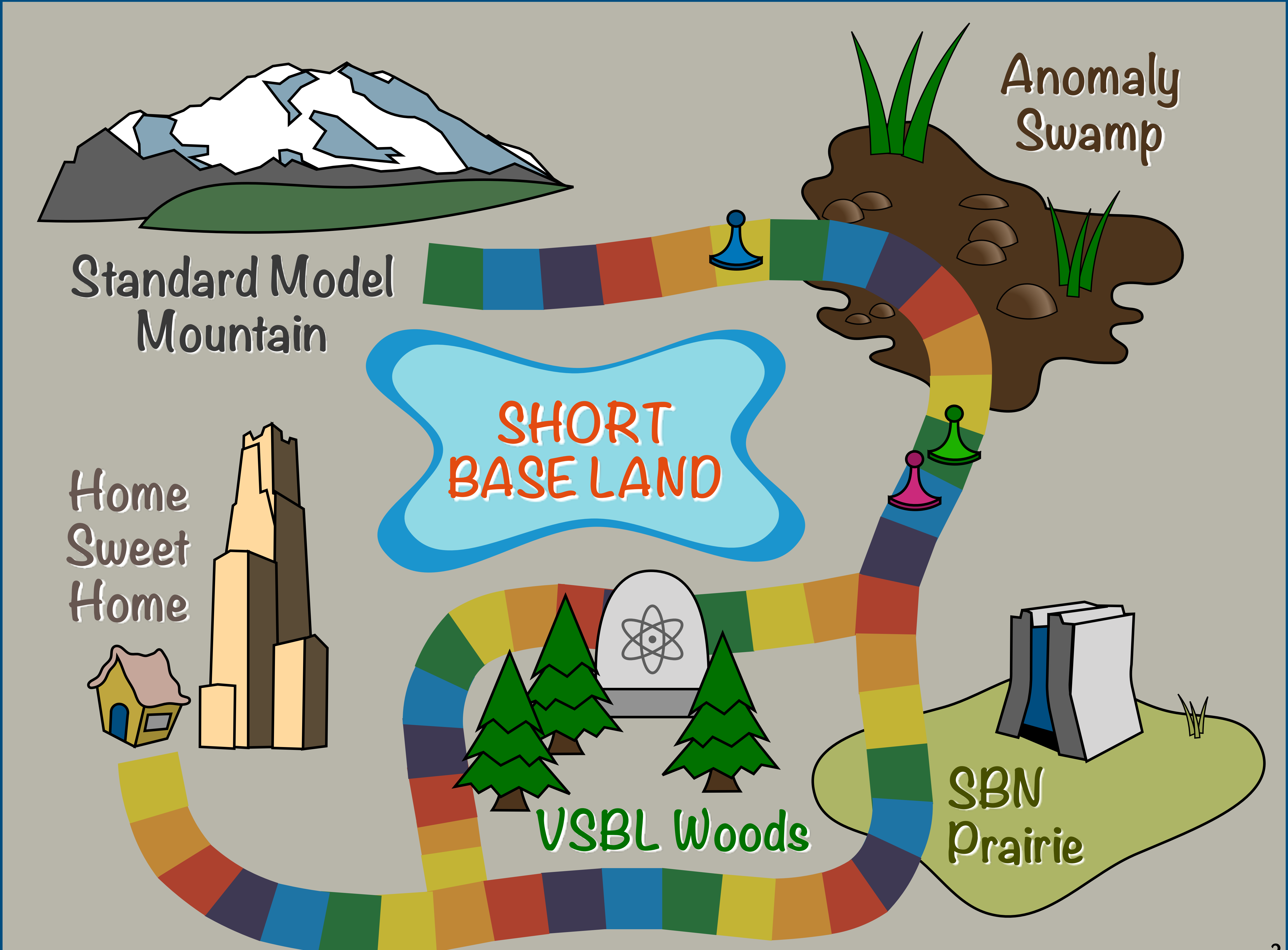
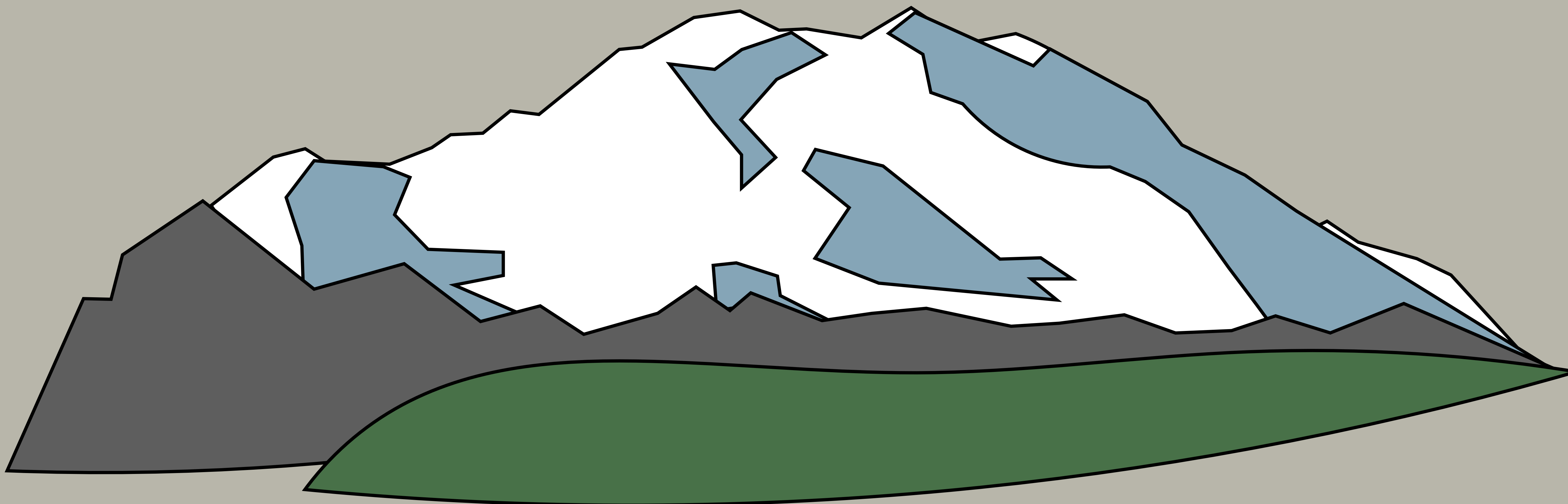
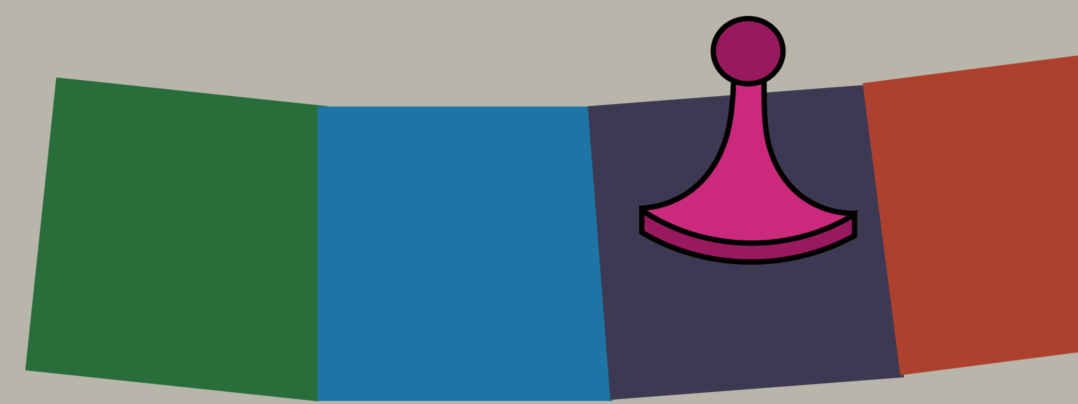

Standard Model Mountain
Anomaly Swamp
SHORT BASE LAND
Home Sweet Home
VSBL Woods
SBN Prairie

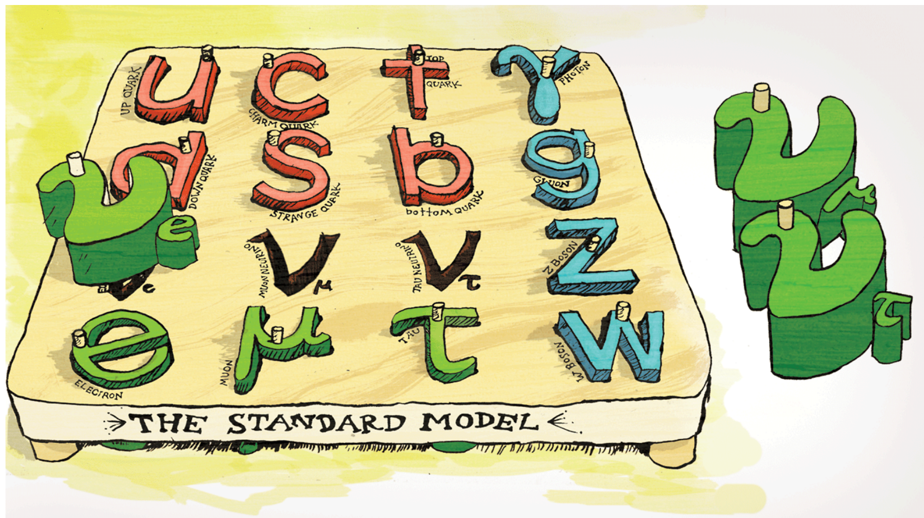


Standard Model Mountain



Standard Model

Three-Neutrino Oscillations



Symmetry Magazine, 2/2013

With massive neutrinos, **flavor** eigenstates of the weak interaction are related to **mass** eigenstates of the free-particle Hamiltonian:

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

Atmospheric & Accelerator

Reactor

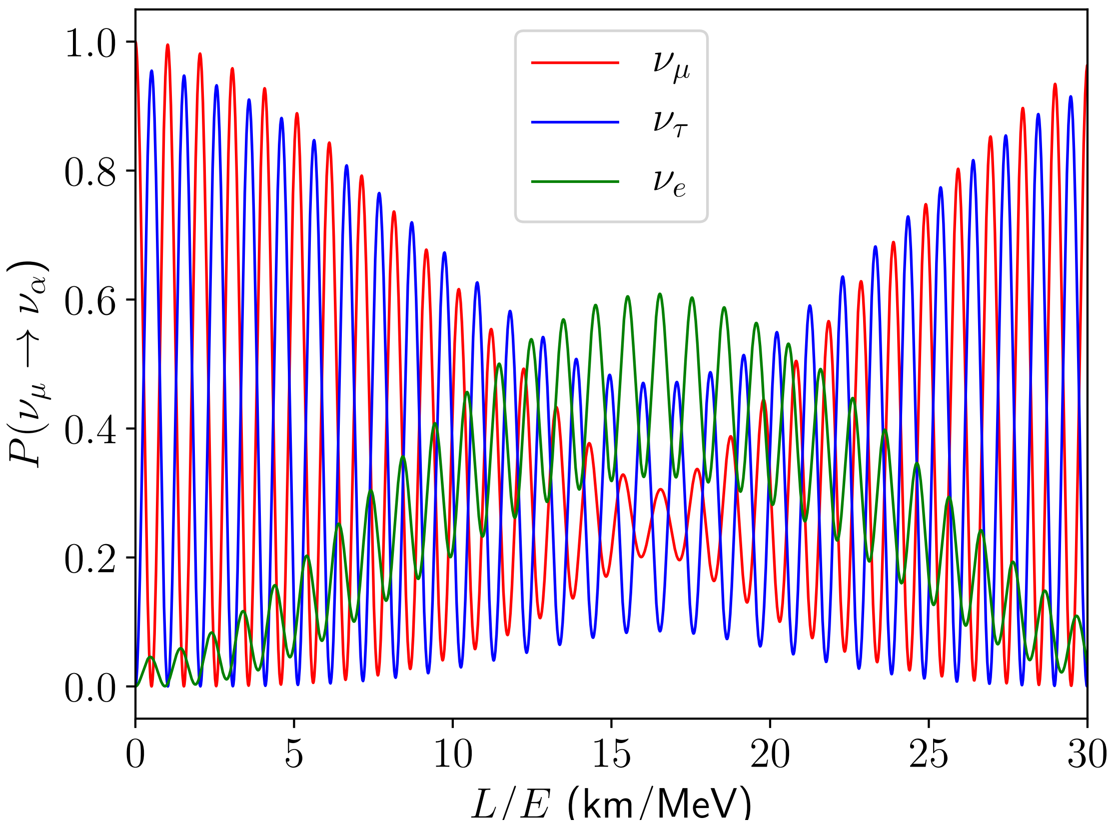
Solar & KamLAND

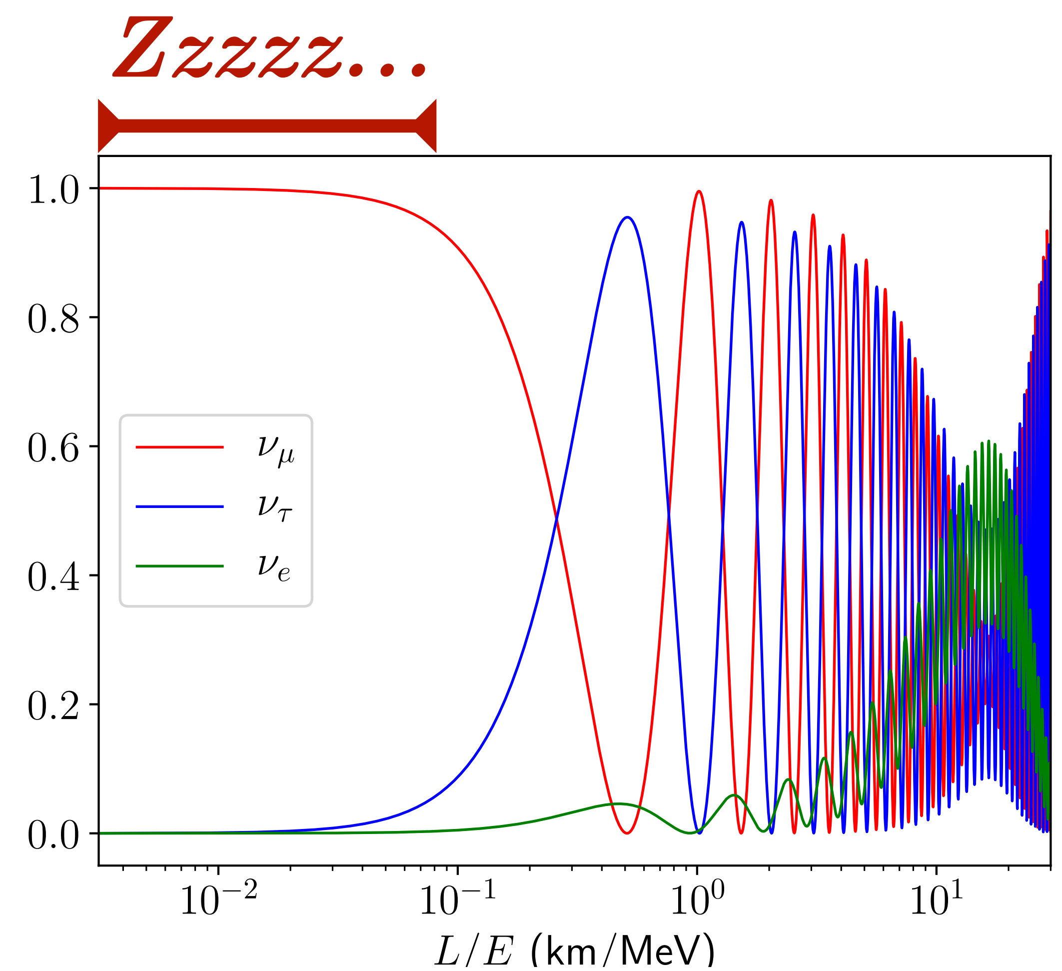
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

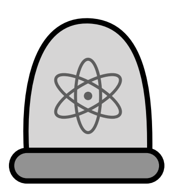
$$|\nu_\alpha\rangle \to |\nu(L \sim t)\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle e^{-i(m_i^2 L/2E)}$$

Standard Model

Three-Neutrino Oscillations

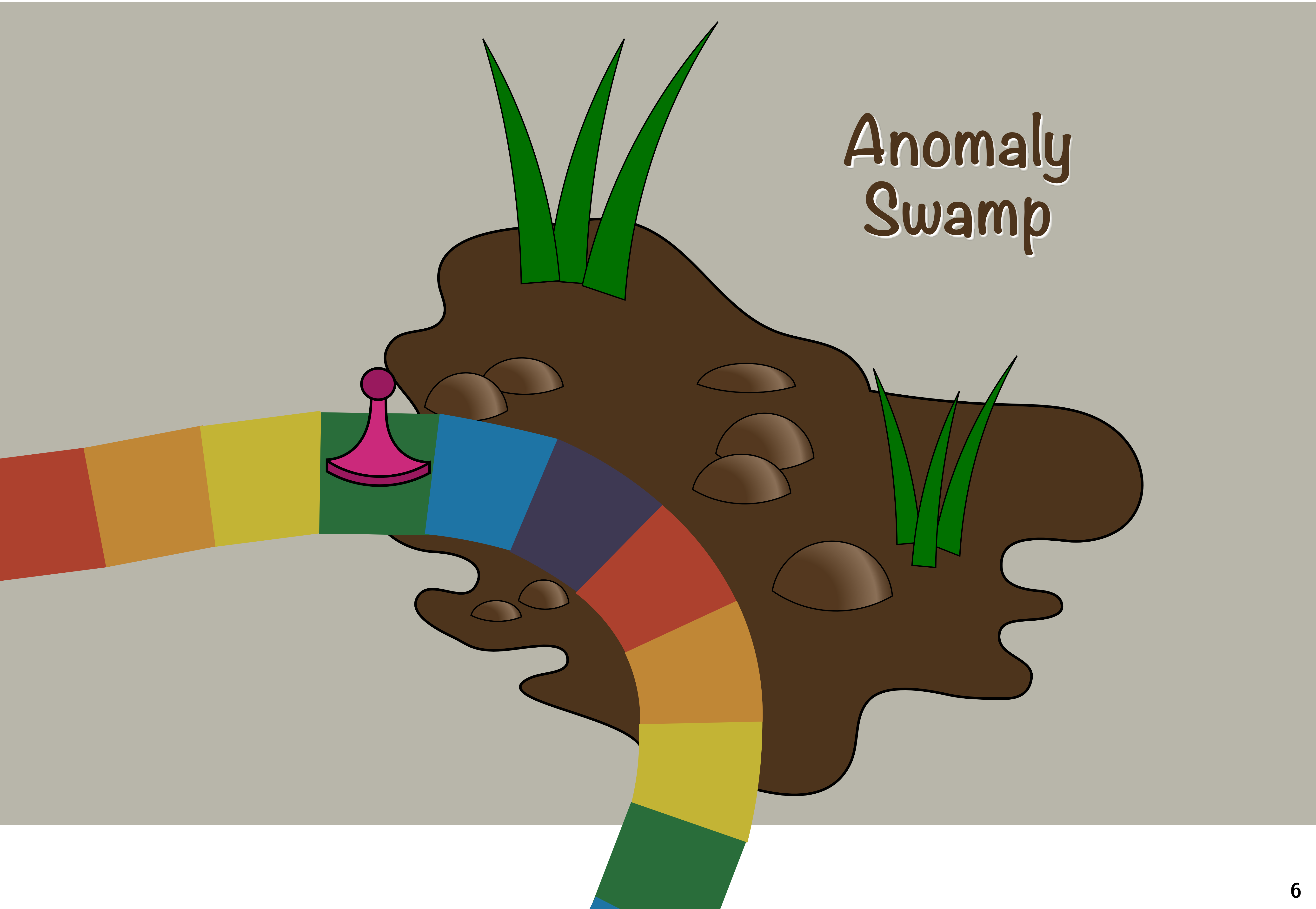






L ~ meters

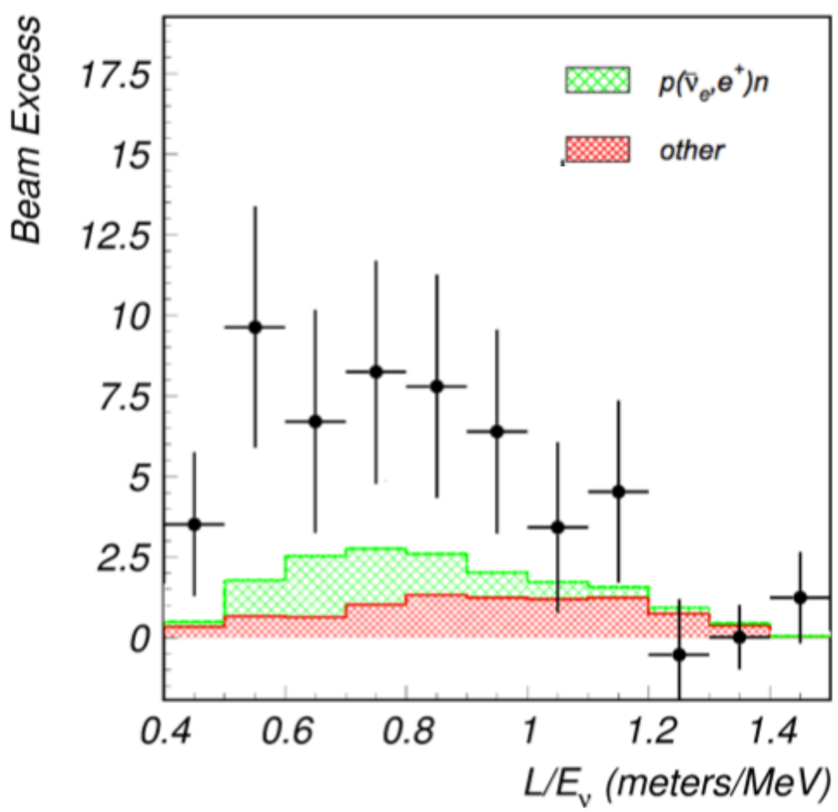
L ~ km


Anomaly
Swamp

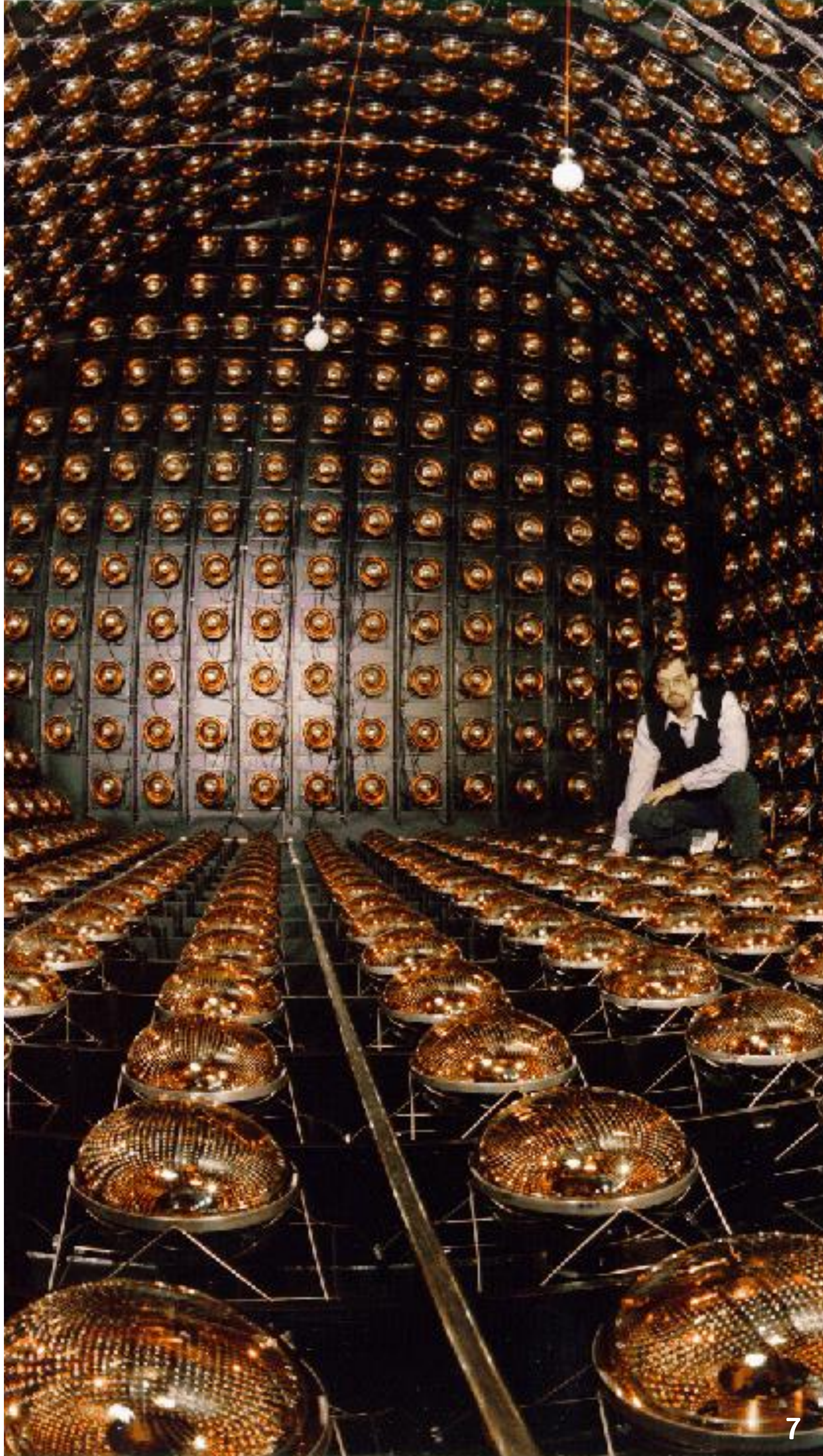
LSND

Liquid Scintillator Neutrino Detector

- LANL (LAMPF) Beam, 1993 - 1998
- $\overline{\nu}_\mu$ from μ^+ DAR, $L \sim 30$ m
- 3.8σ excess consistent with $\overline{\nu}_e$ appearance at small $L/E \sim 1$ m/MeV
  - $\Delta m^2 \sim 1$ eV^2, $\sin^2 2\theta_{\mu e} \sim 0.26\%$



See Phys. Rev. D 64, 112007 (2001)



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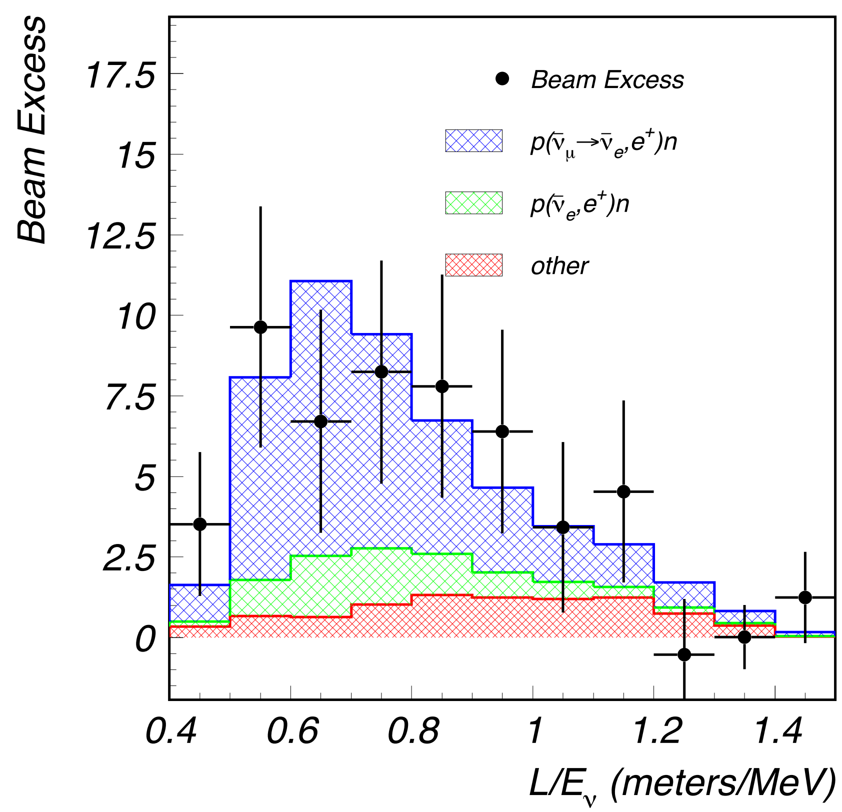

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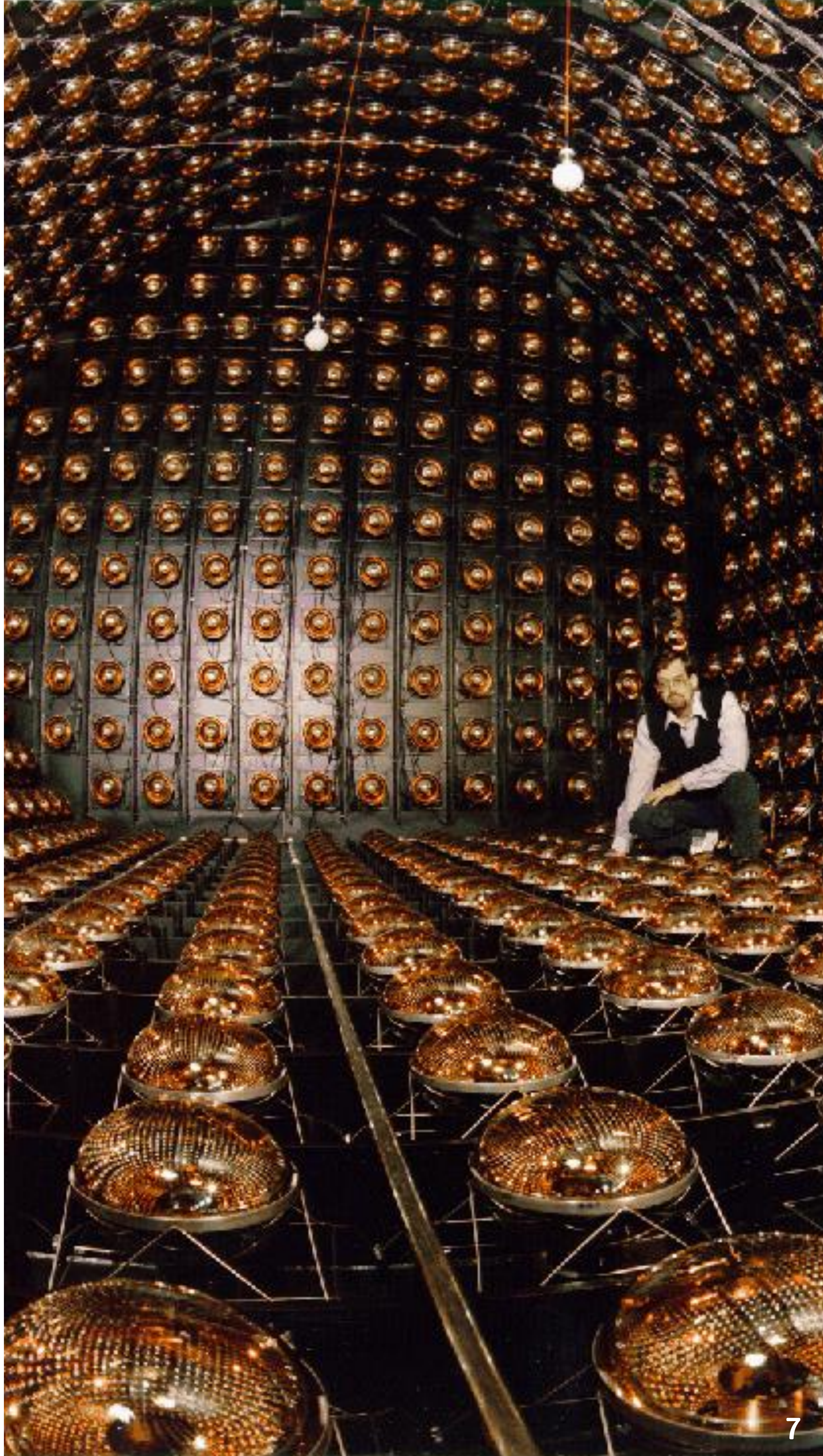
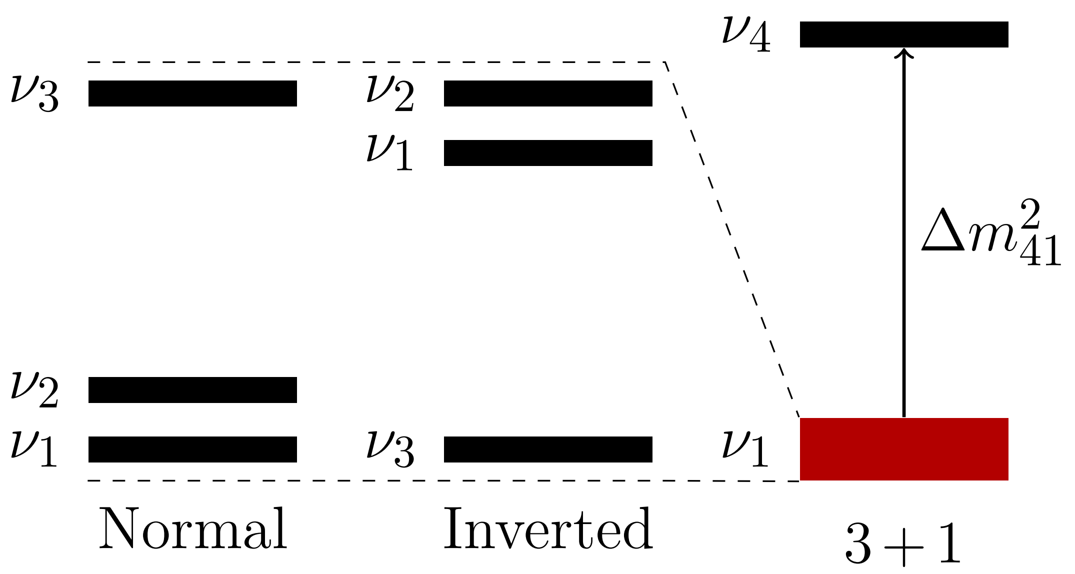


Sterile Neutrinos

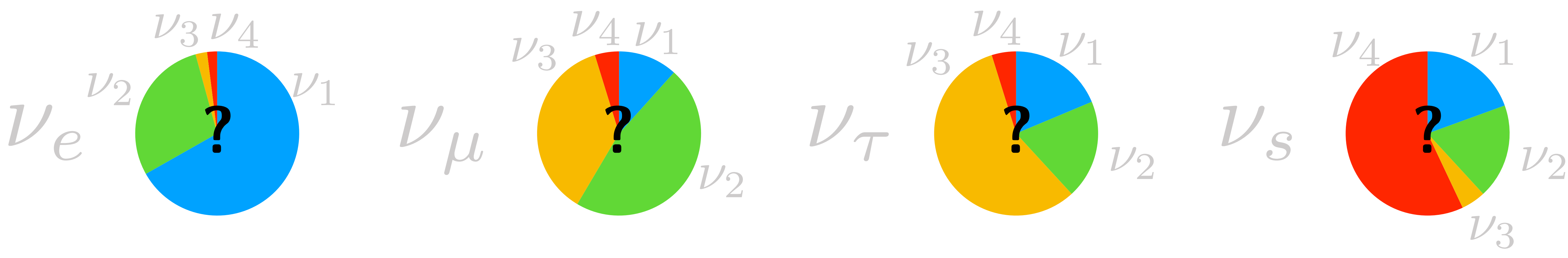
Extending the Three-Neutrino Paradigm

- Number of active neutrino flavors is fixed to three by Z width (LEP)
- Additional non-interacting neutrino states, detectable through impact on oscillations
- PMNS matrix expands to $N \times N$
- New mixing angles, mass splittings, and possibly CP-violating phases
- 3+1, 3+N, 1+3+1, ...



An effective two-neutrino model

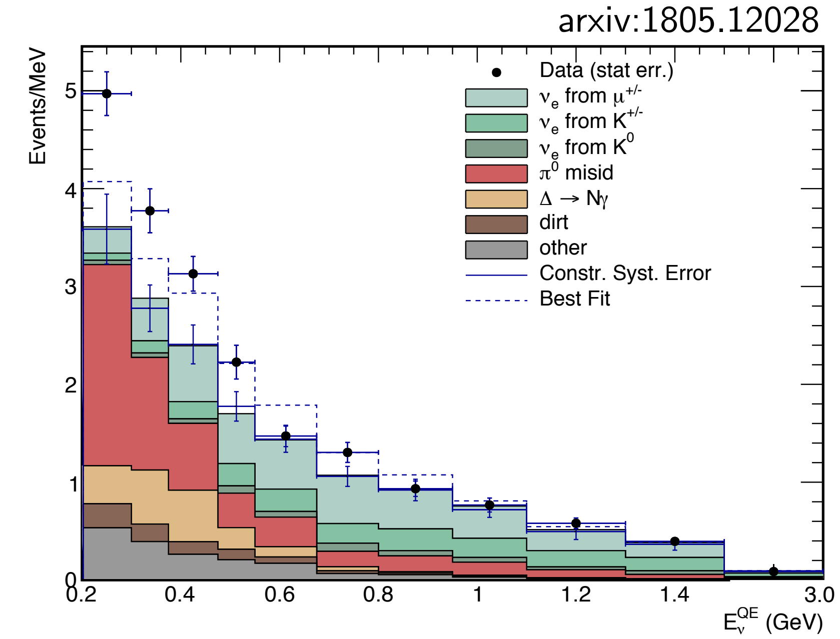
$$P_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2\left(1.27 \frac{\Delta m^2_{41} L}{E}\right)$$

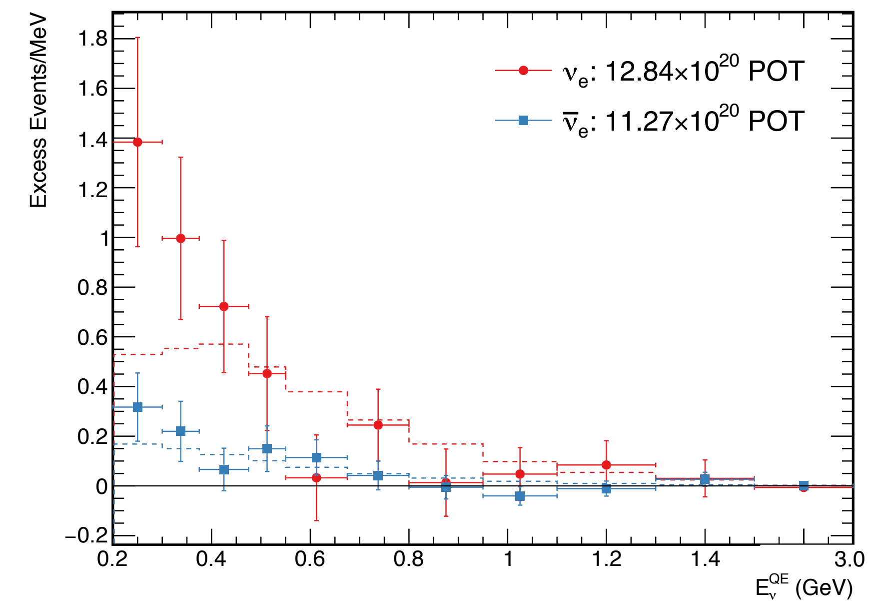


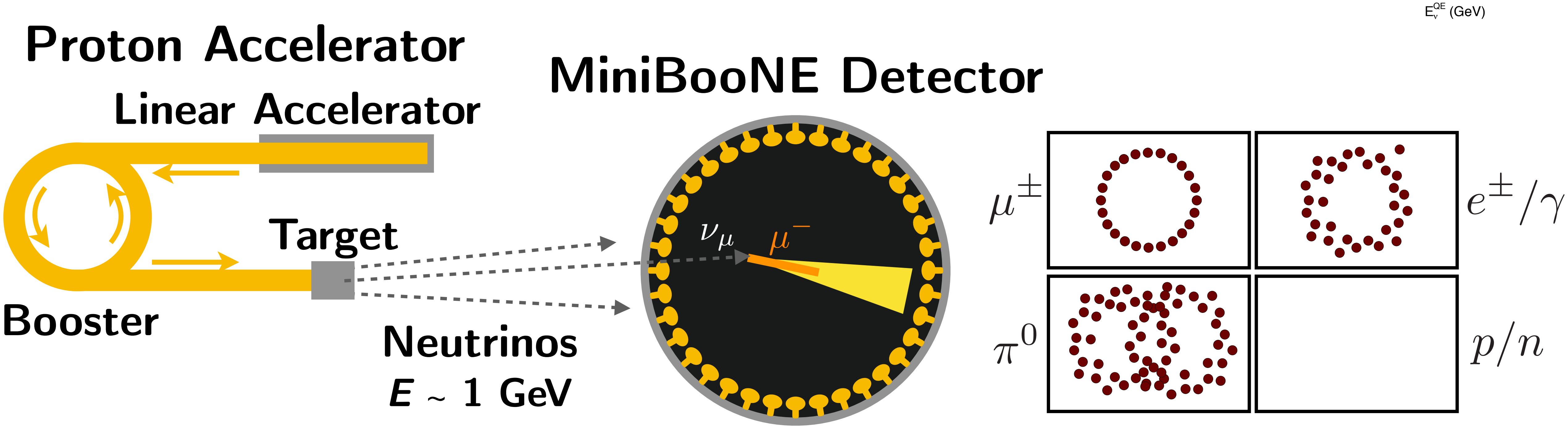
MiniBooNE

The Low-Energy Excess

- Fermilab Booster Neutrino Beam, 2002 - ∞
- Oil Cherenkov detector
- $L/E \sim$ LSND (1 m/MeV)
- EM-like excess at low energies
  - Doubled statistics in Fall 2018
  - Consistent with LSND
  - See arxiv:1805.12028







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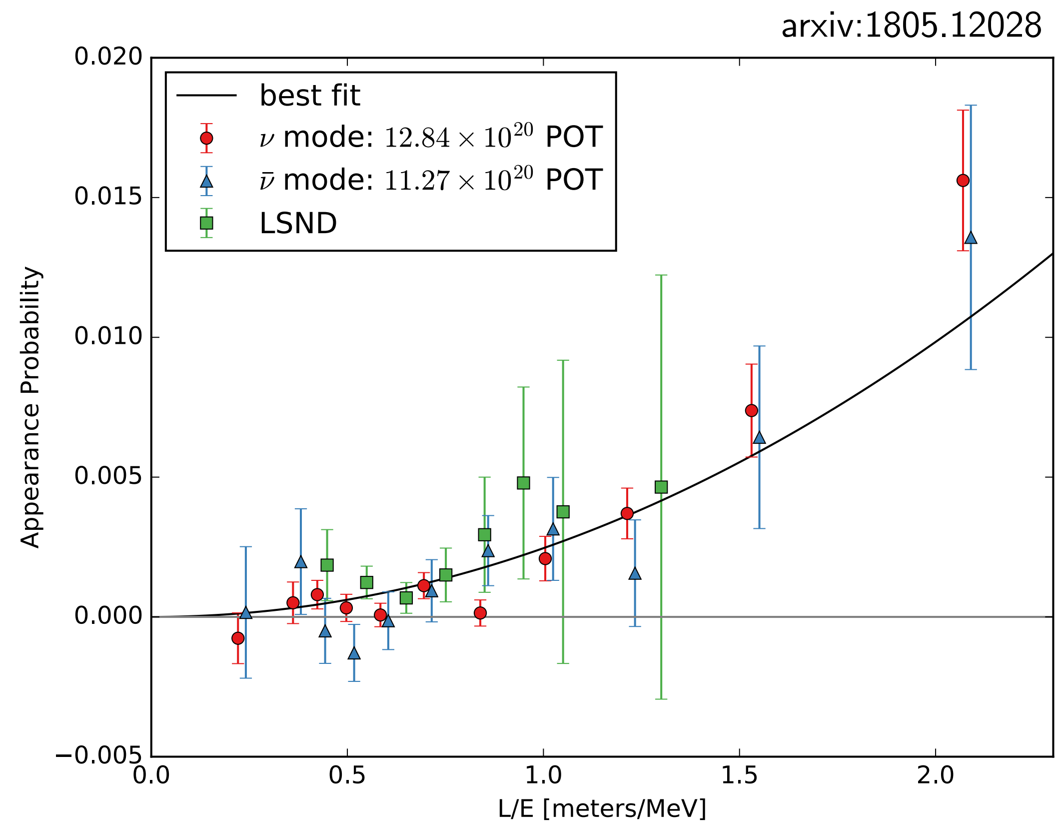
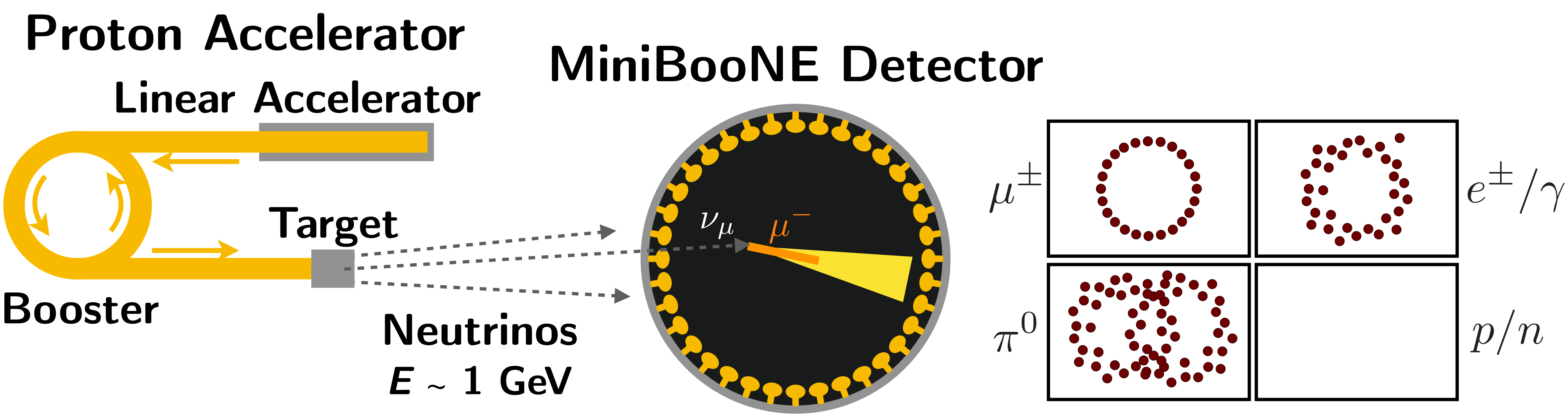
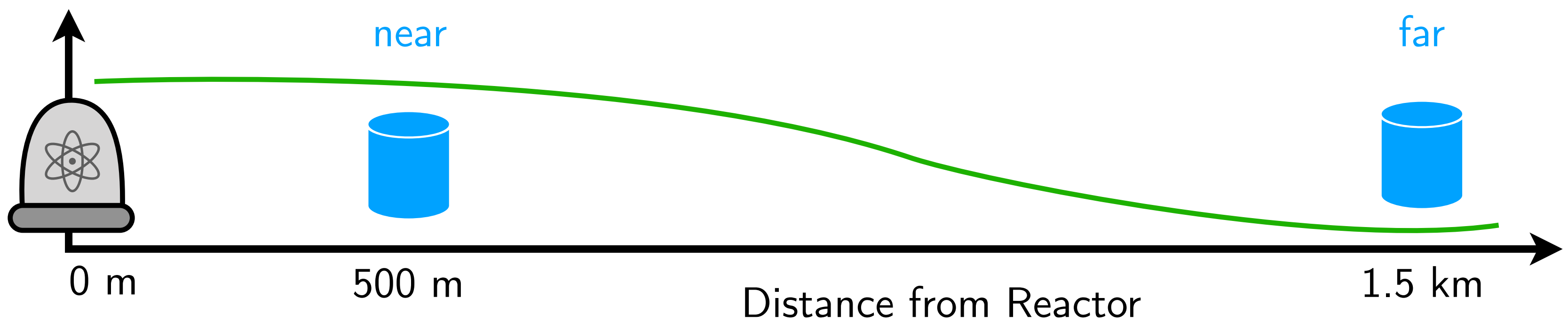
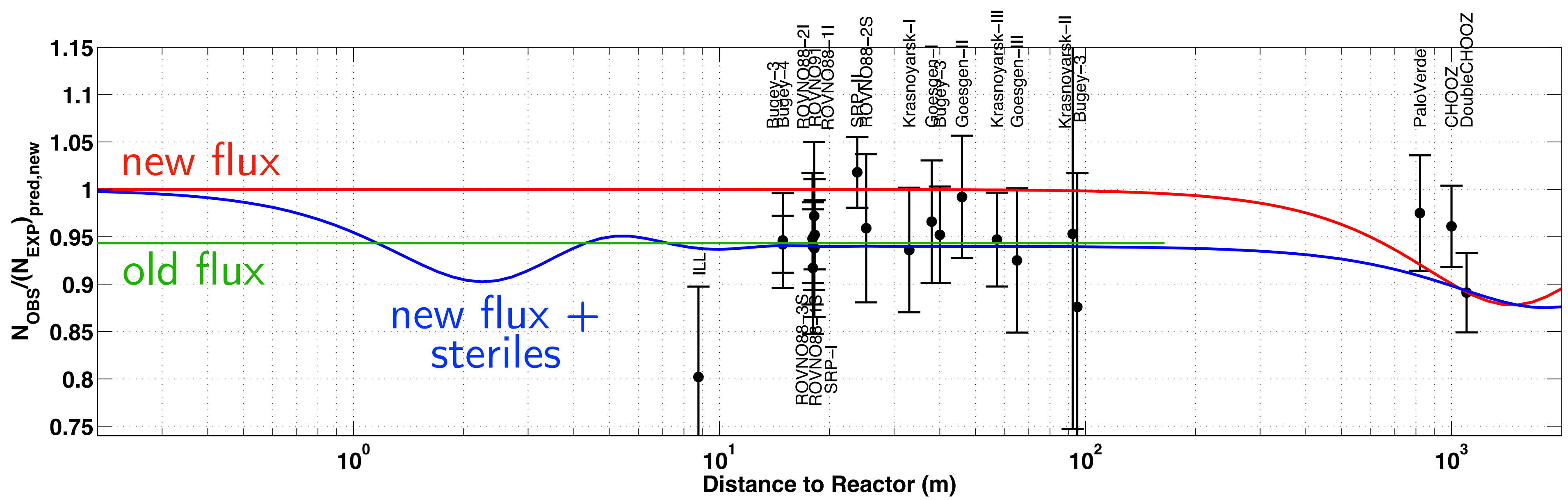




The Reactor Anomaly

- New flux calculations create/reveal a deficit in reactor neutrino measurements
- Uncertainties remain large, plus unaccounted-for structure in energy



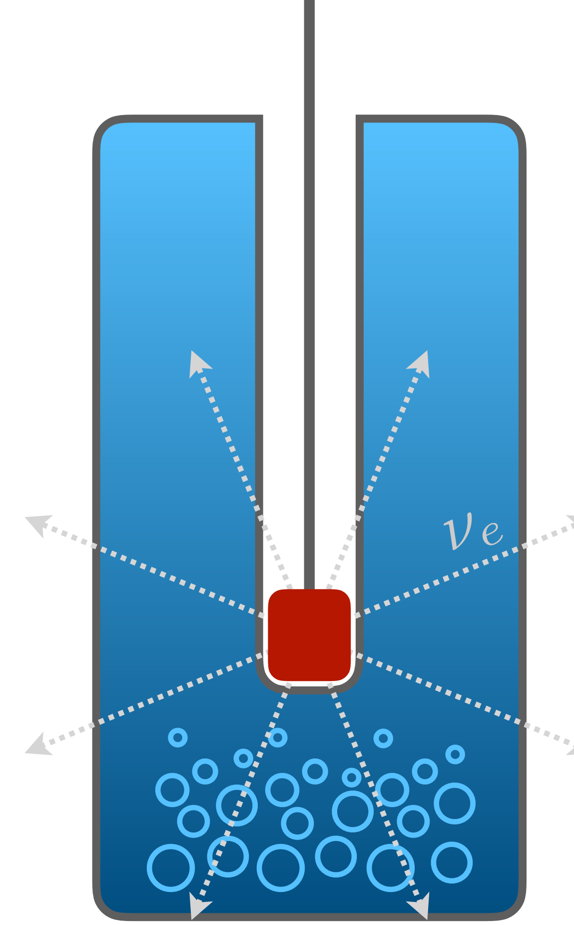


arxiv:1204.5379 (2012), annotations added

Gallium

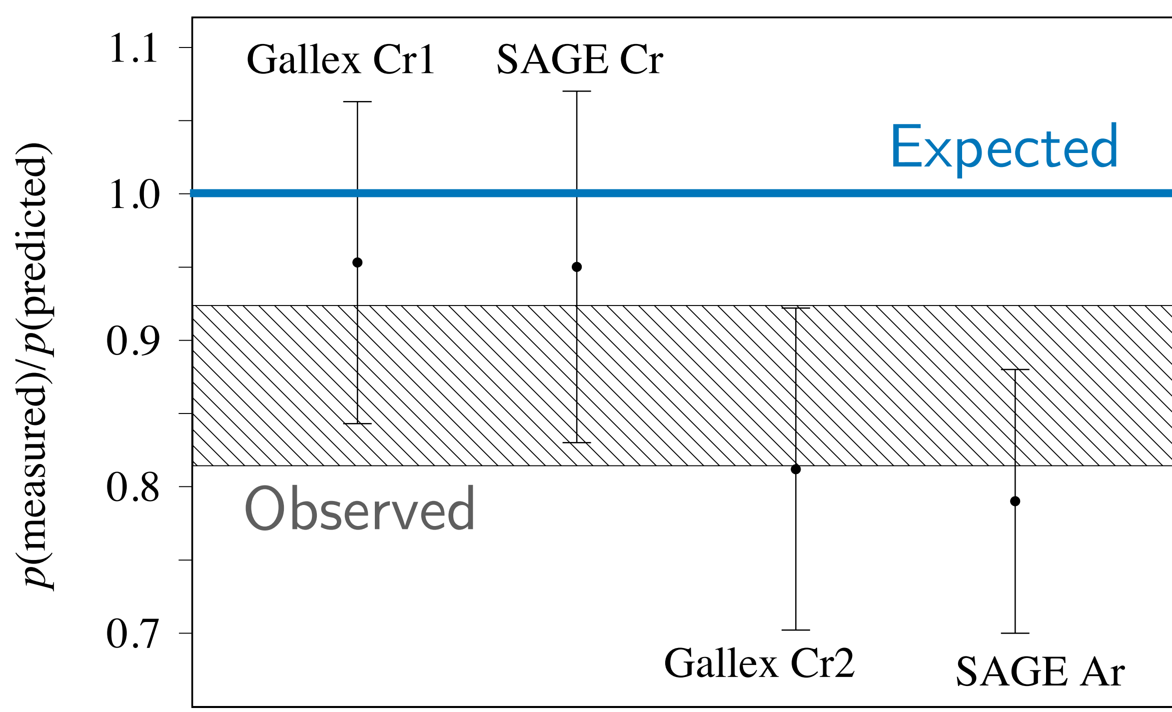
GALLEX/GNO and SAGE

- Radiochemical solar neutrino detectors
  - $\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$
- Efficiency measurements with MCi ^{51}Cr ν_e source
- Both observe a deficit: short-baseline ν_e oscillations with $L/E \sim 1$ m/MeV?



GALLEX/GNO
Gran Sasso, Italy

T. Kirsten, MPI Heidelberg



Phys. Rev. D 64, 112007 (2001)

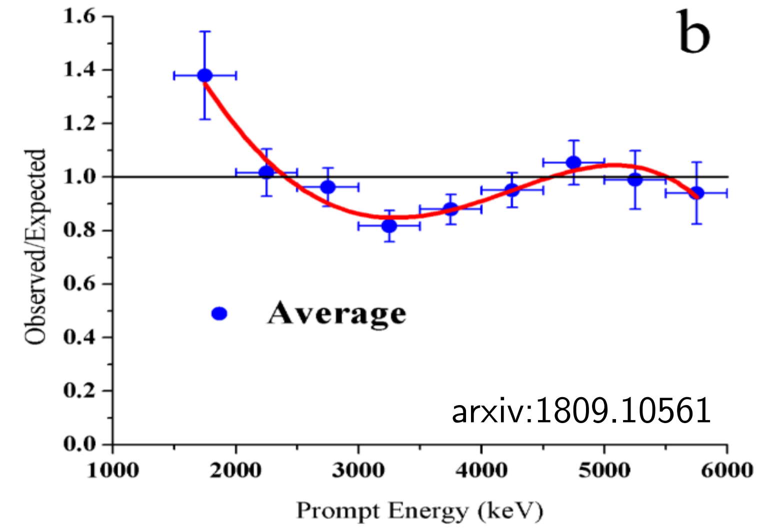
SAGE
Baksan, Russia

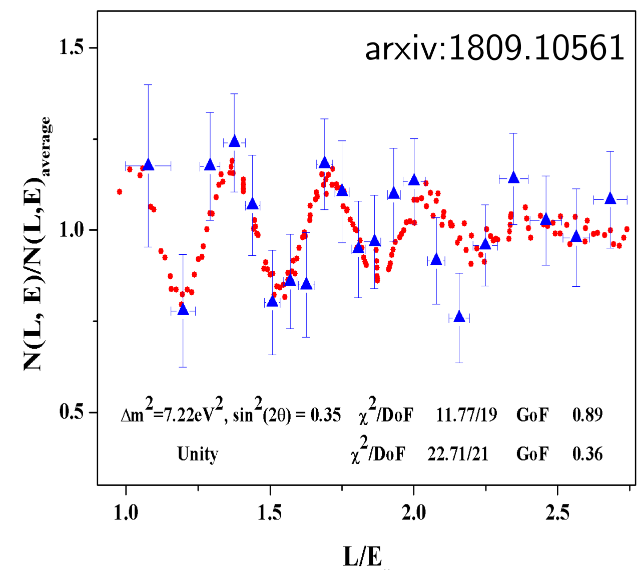
http://cerncourier.com/cws/article/cern/68795

Neutrino-4

New Action at High Δm^2

- Reactor antineutrino detector
- Movable, 6-12 m from the compact core of the SM-3 research reactor
- New results from September 2018
  - Excludes reactor, Ga at $>3\sigma$ CL
  - Oscillation at 7 eV^2, also $>3\sigma$ CL





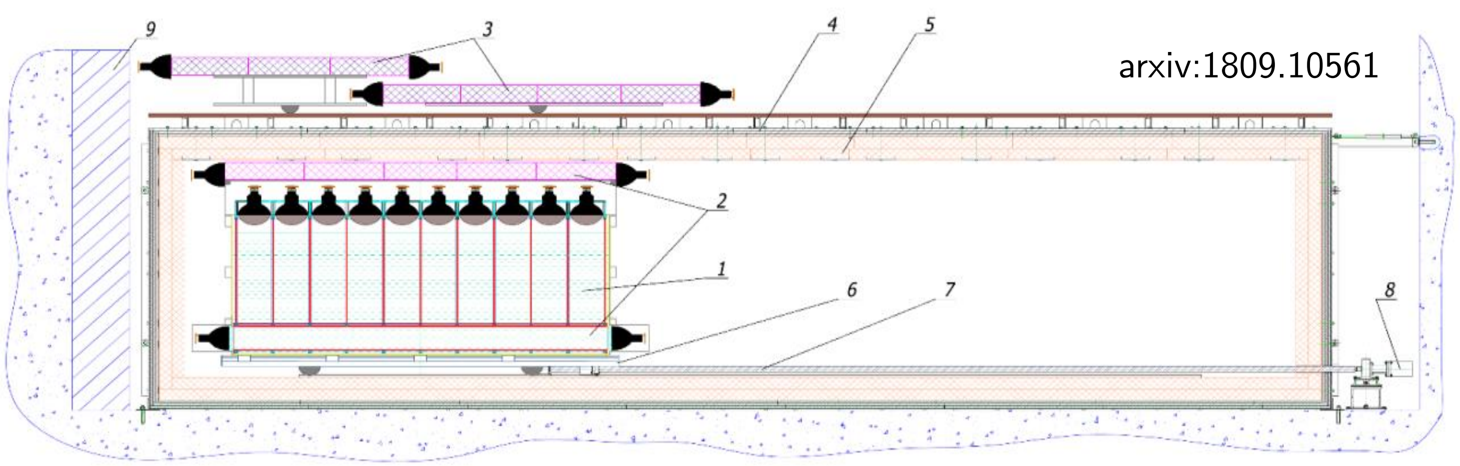
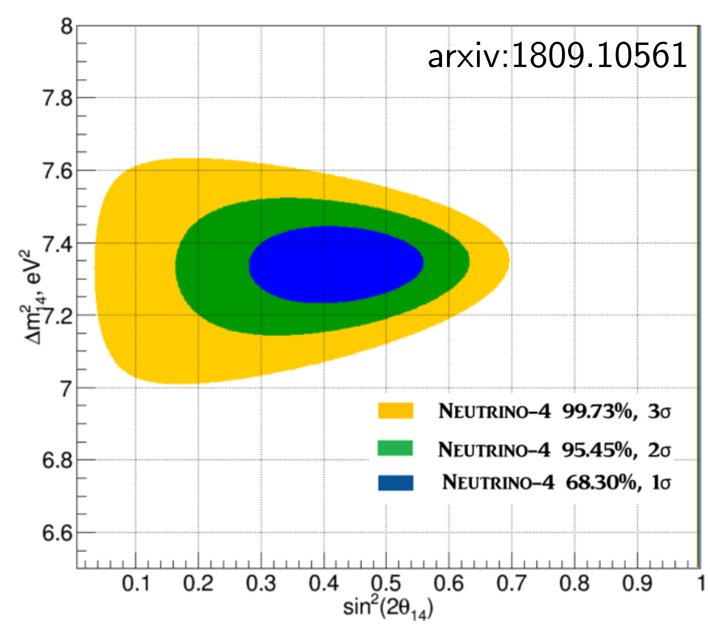


Fig. 1. General scheme of an experimental setup. 1 – detector of reactor antineutrino, 2 – internal active shielding, 3 – external active shielding (umbrella), 4 – steel and lead passive shielding, 5 – borated polyethylene passive shielding, 6 – moveable platform, 7 – feed screw, 8 – step motor, 9 –shielding against fast neutrons from iron shot.



Disappearance

Tension in Measurements

- Meanwhile, no evidence in disappearance (and other appearance) searches:

ν_e Appearance

- KARMEN (Karlsruhe, $\bar{\nu}_e$) $\rightarrow$ limit
- ICARUS (CNGS) $\rightarrow$ limit
- NOMAD (CERN SPS) $\rightarrow$ limit

ν_e Disappearance

- KARMEN + LSND $\nu_e - C$ $\rightarrow$ limit

ν_μ Disappearance

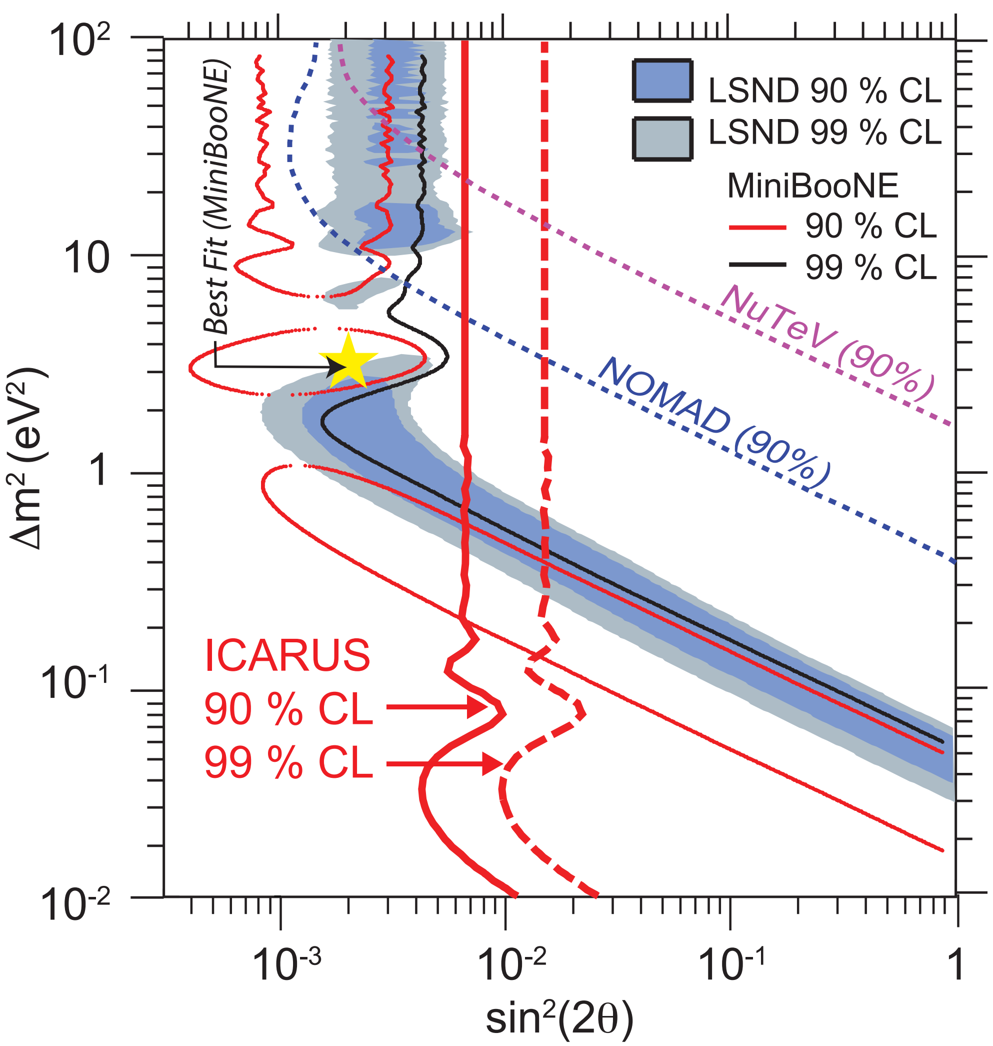
- MiniBooNE + SciBooNE ($\nu_\mu, \bar{\nu}_\mu$) $\rightarrow$ limit
- MINOS (FNAL NuMI) $\rightarrow$ limit
- CCFR (FNAL, 1985), CDHS (CERN, 1984) $\rightarrow$ limit
- IceCube (latest 2016) $\rightarrow$ limit

Based on arxiv:1609.07803

Signals & Limits

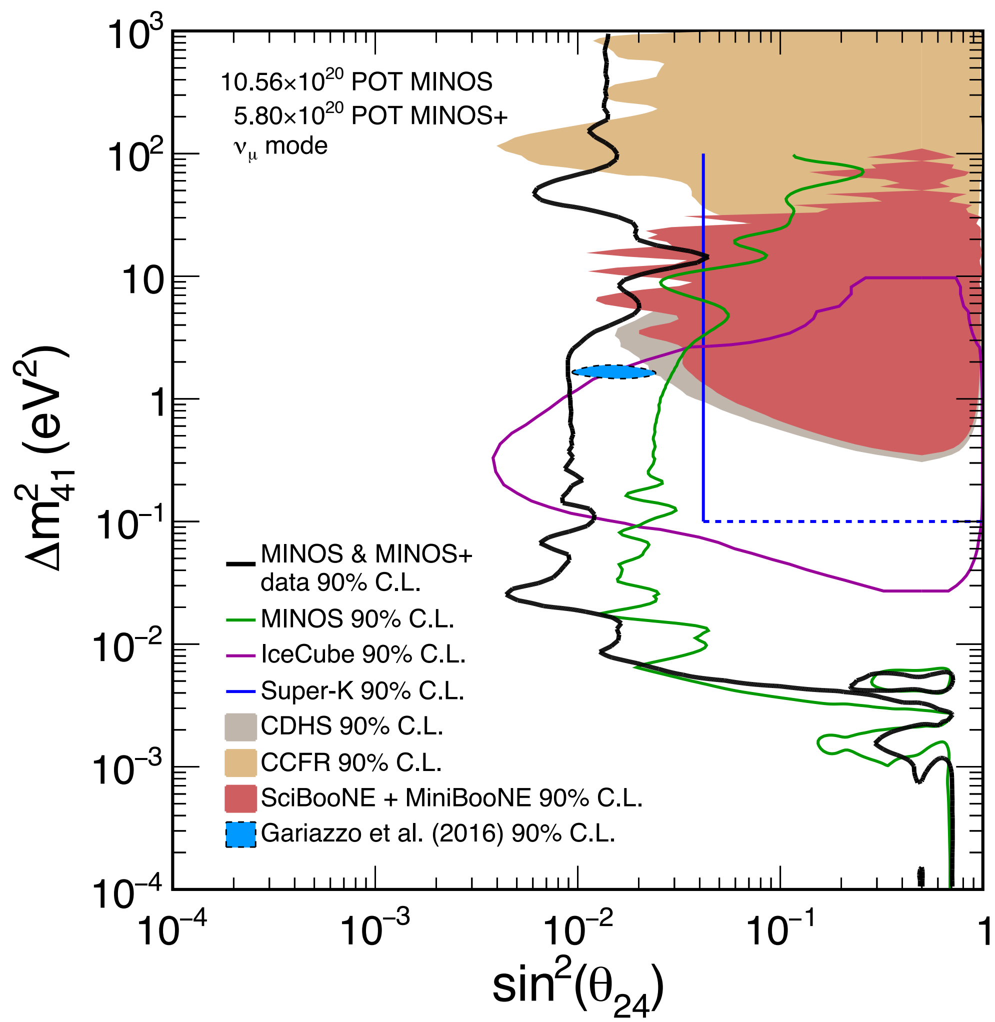
Tension in Measurements

ν_e Appearance



arxiv:1503.10520 (2015)

ν_μ Disappearance



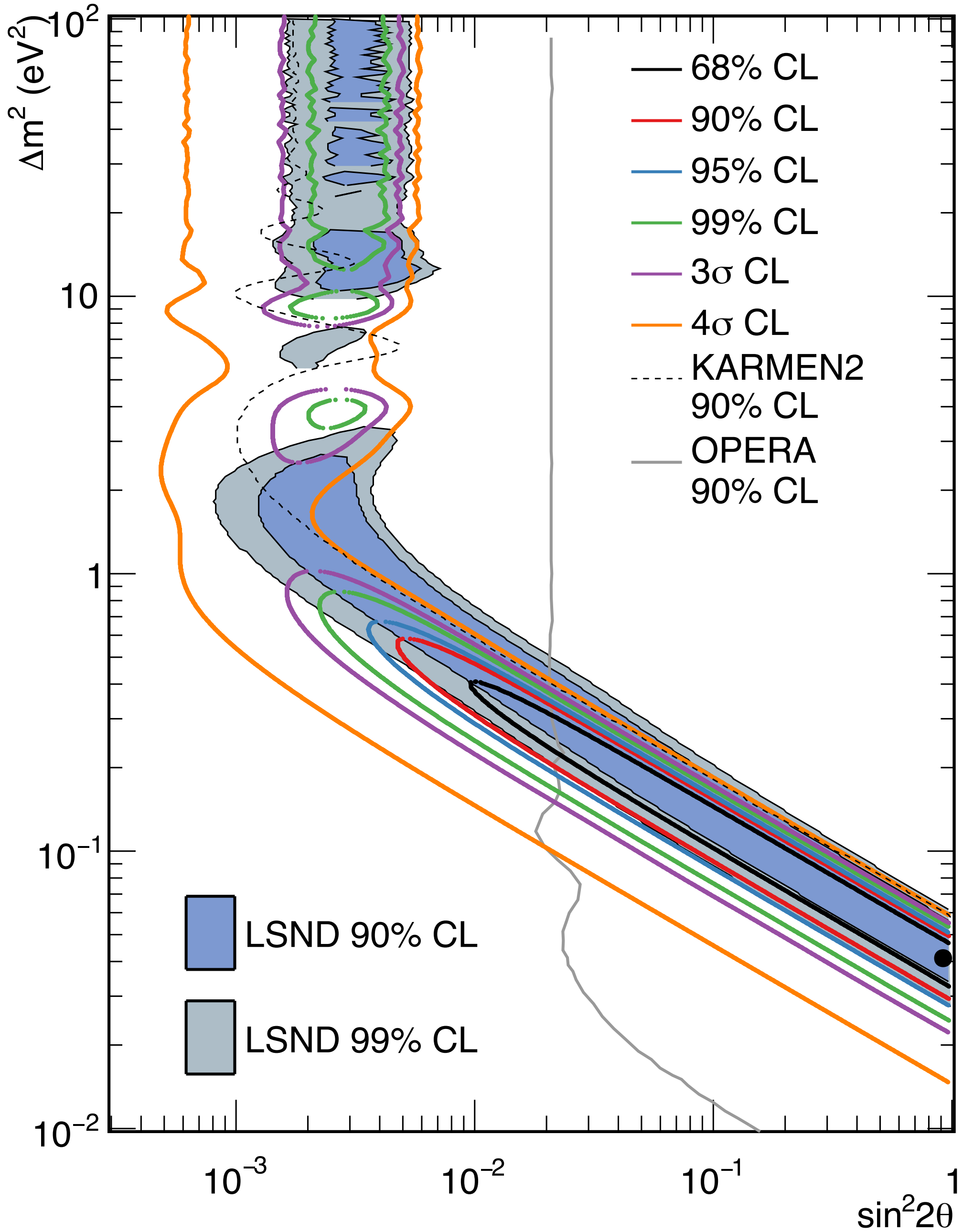
arxiv:1710.06488 (2017)

(All Exclusions)

Signals & Limits

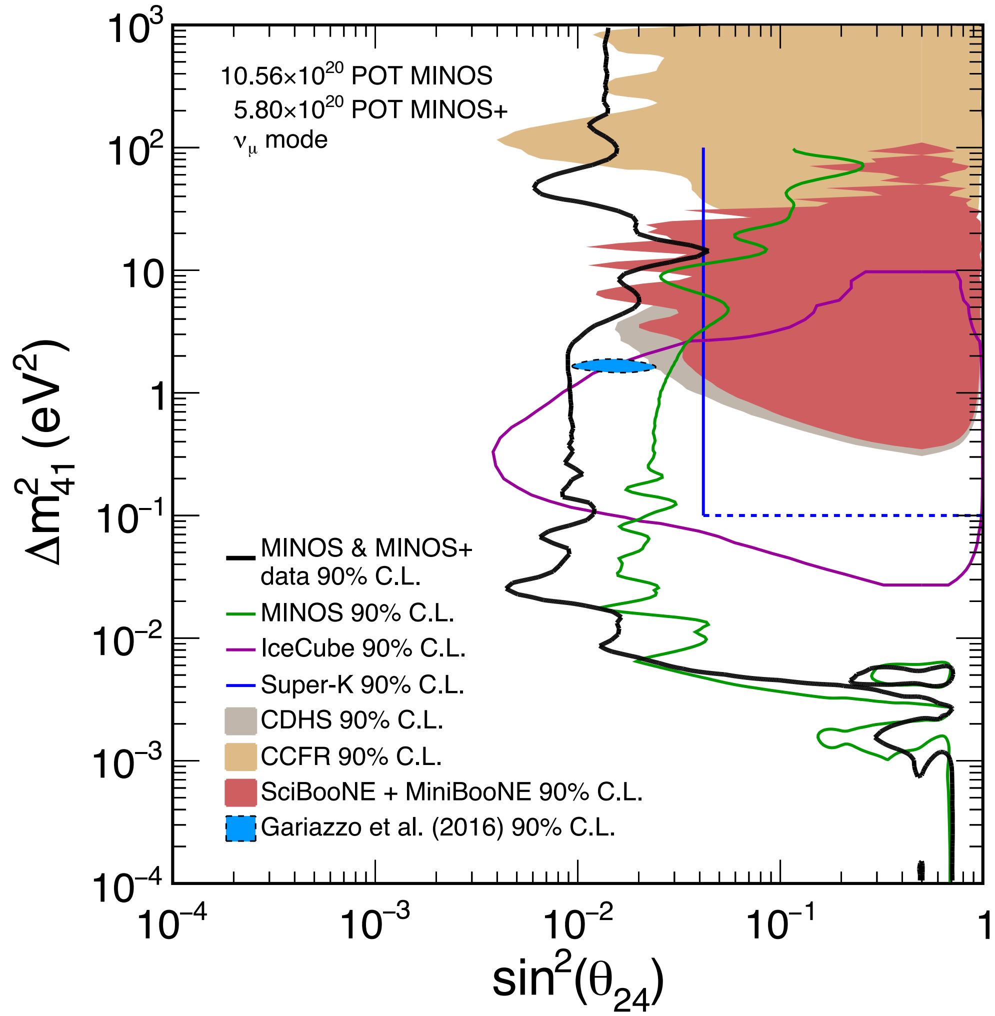
Tension in Measurements

ν_e Appearance



MiniBooNE 2018 results, arxiv:1805.12028

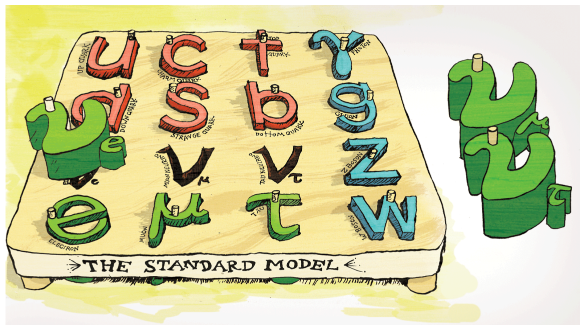
ν_μ Disappearance



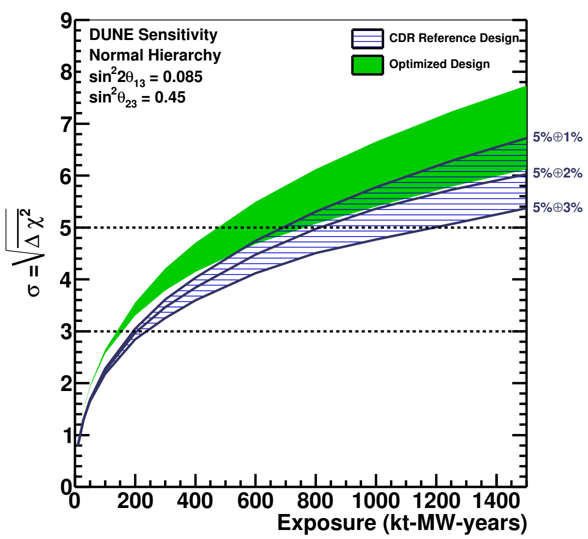
arxiv:1710.06488 (2017)

(All Exclusions)

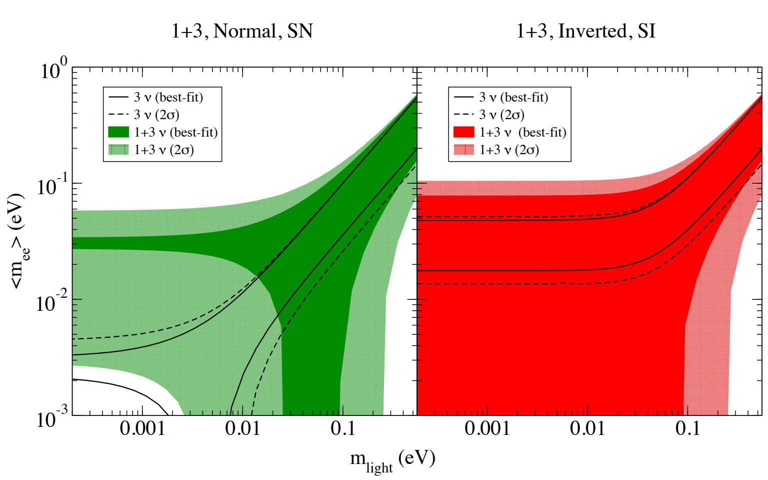
So What?



Symmetry Magazine, February 2013



E. Worchester, NuInt 2015



Int. J. Mod. Phys E20, 1833-1930 (2011)

Case 0: Moral Imperative

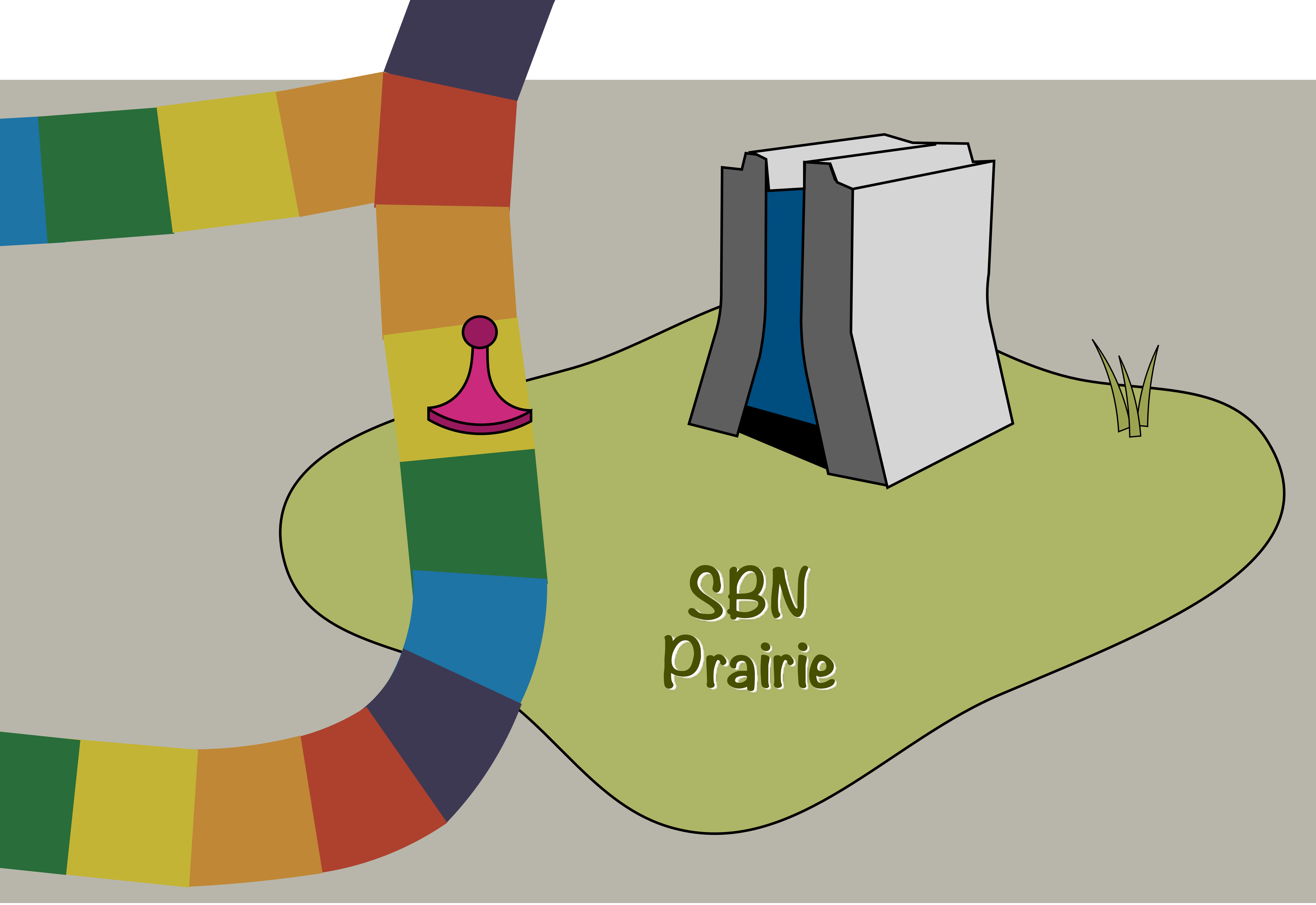
- Hints of BSM physics in several experiments, significant tension in data

Case 1: Long-Baseline Neutrino Physics

- *New Physics:* Modified survival probabilities, maybe more CP phases
- *Systematic:* e.g. Low-E background production modeling is poor

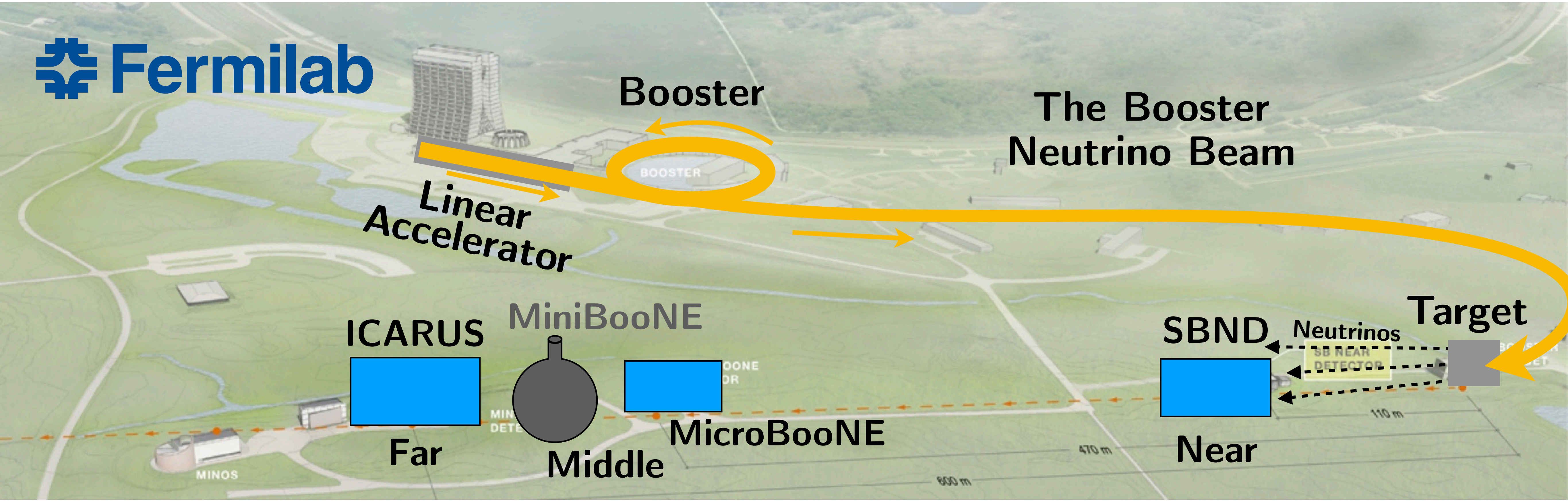
Case 2: Neutrinoless Double-Beta Decay, e.g.

- Searches for lepton number violation to determine Dirac/Majorana nature of the neutrino
- Sensitive to $\Gamma^{0\nu} \propto |\Sigma_i U_{ei}{}^2 m_i|^2$


SBN
Prairie

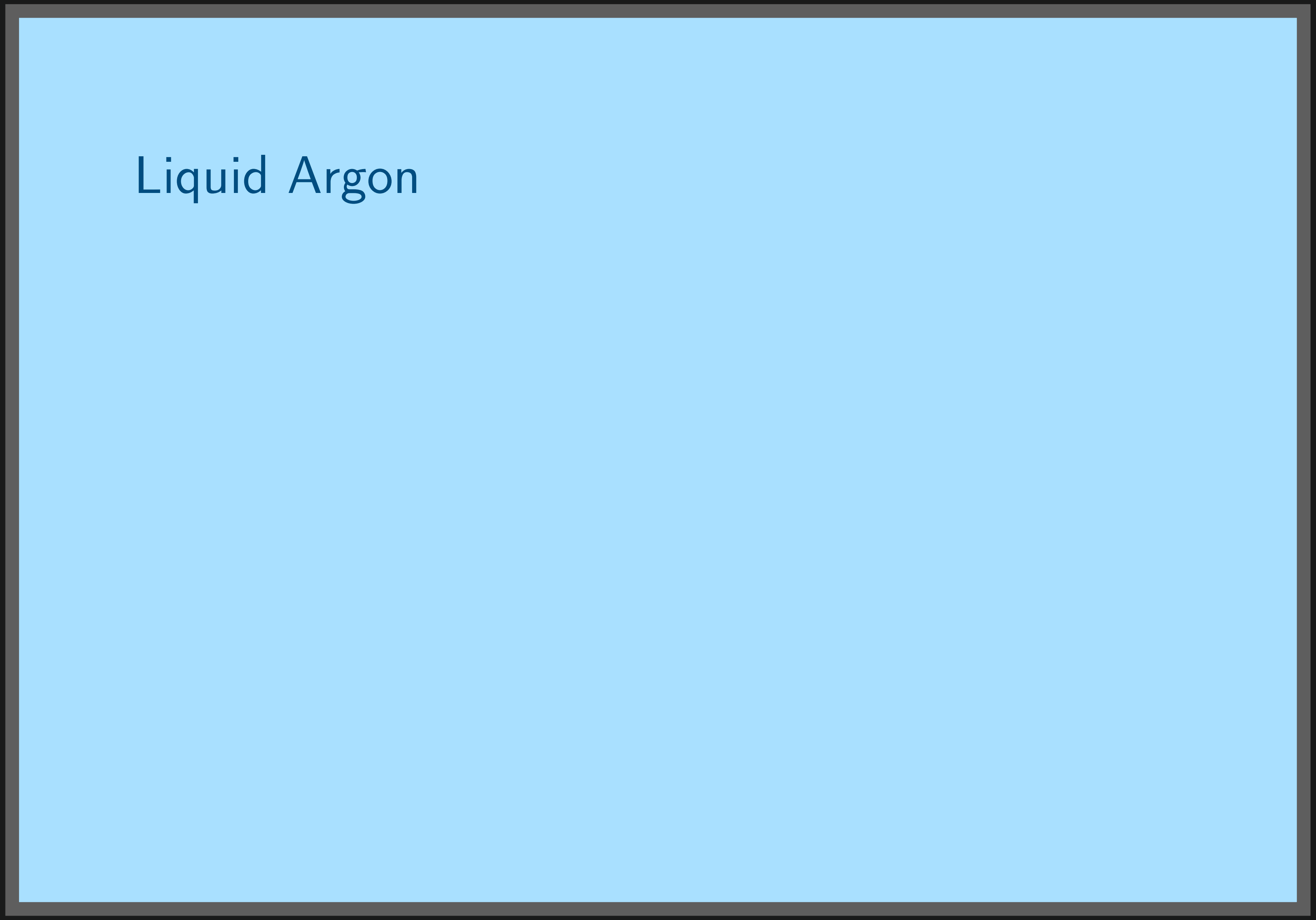
The Short-Baseline Neutrino Program

A Definitive Test of Short-Baseline Oscillations

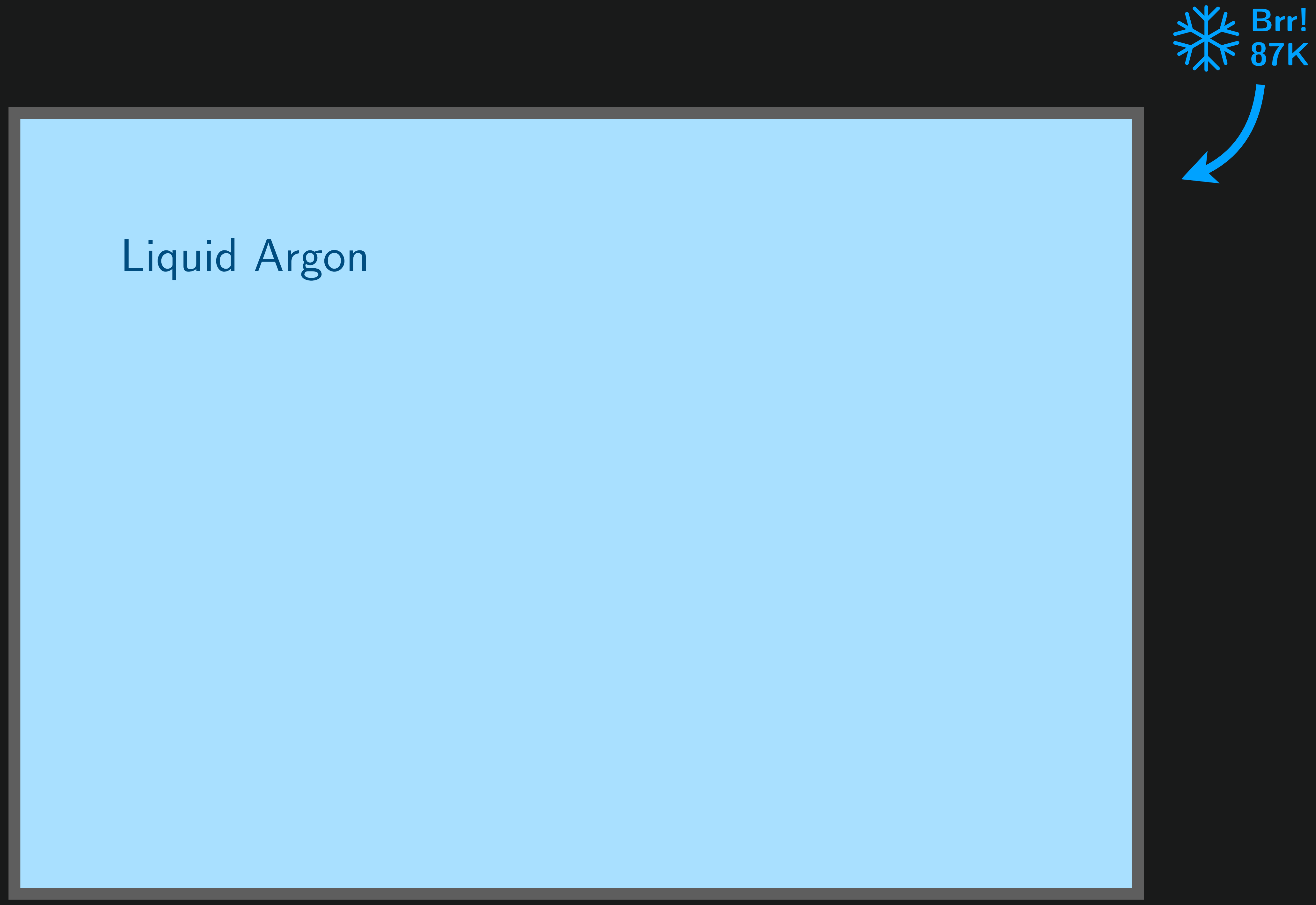


- Three liquid argon TPCs in the Fermilab Booster Neutrino Beam
  - Same argon target, functionally similar detectors
- Definitive test of LSND oscillations using three baselines
- Simultaneous ν_μ disappearance and ν_e appearance searches

Liquid Argon TPCs



Liquid Argon TPCs



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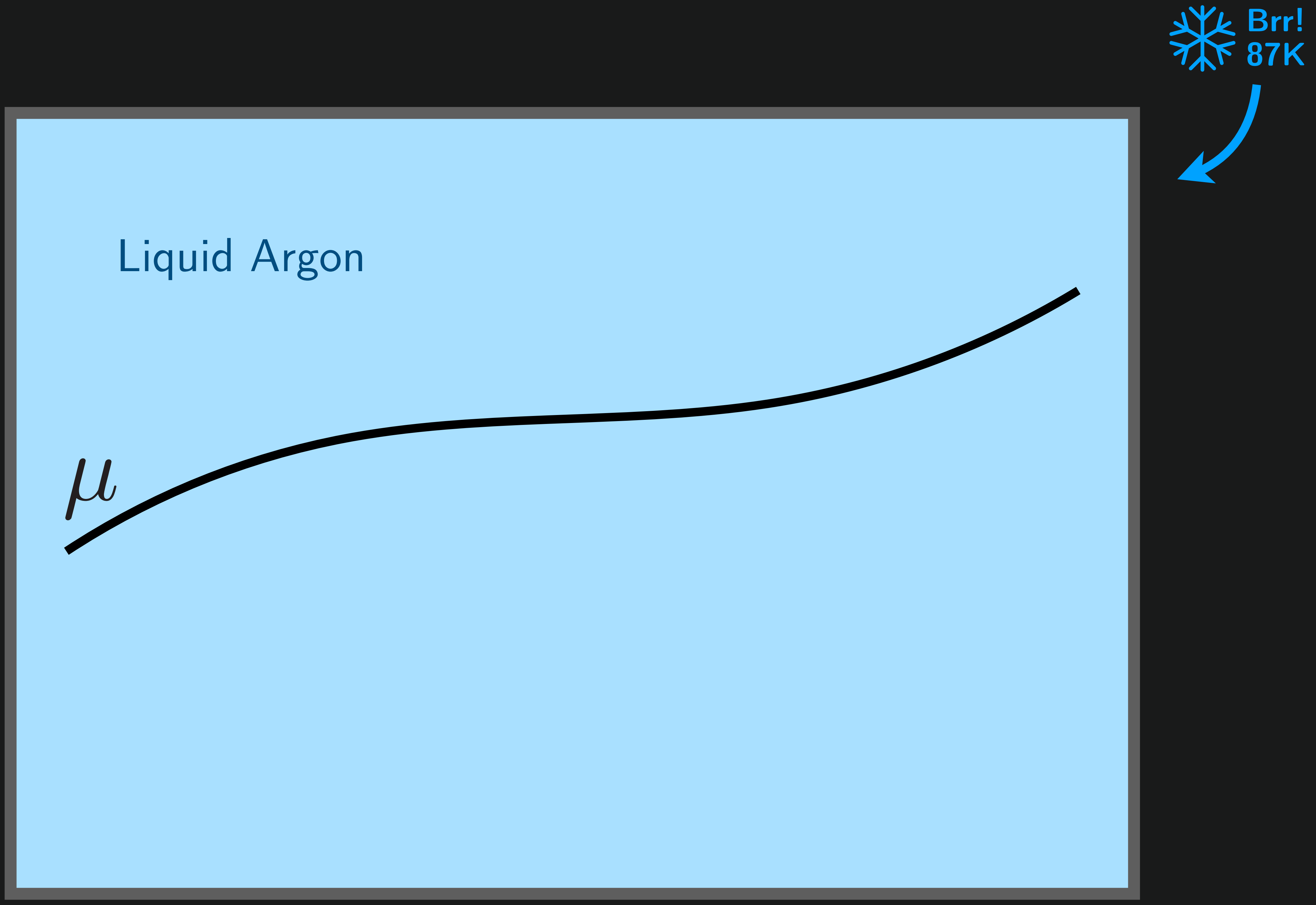

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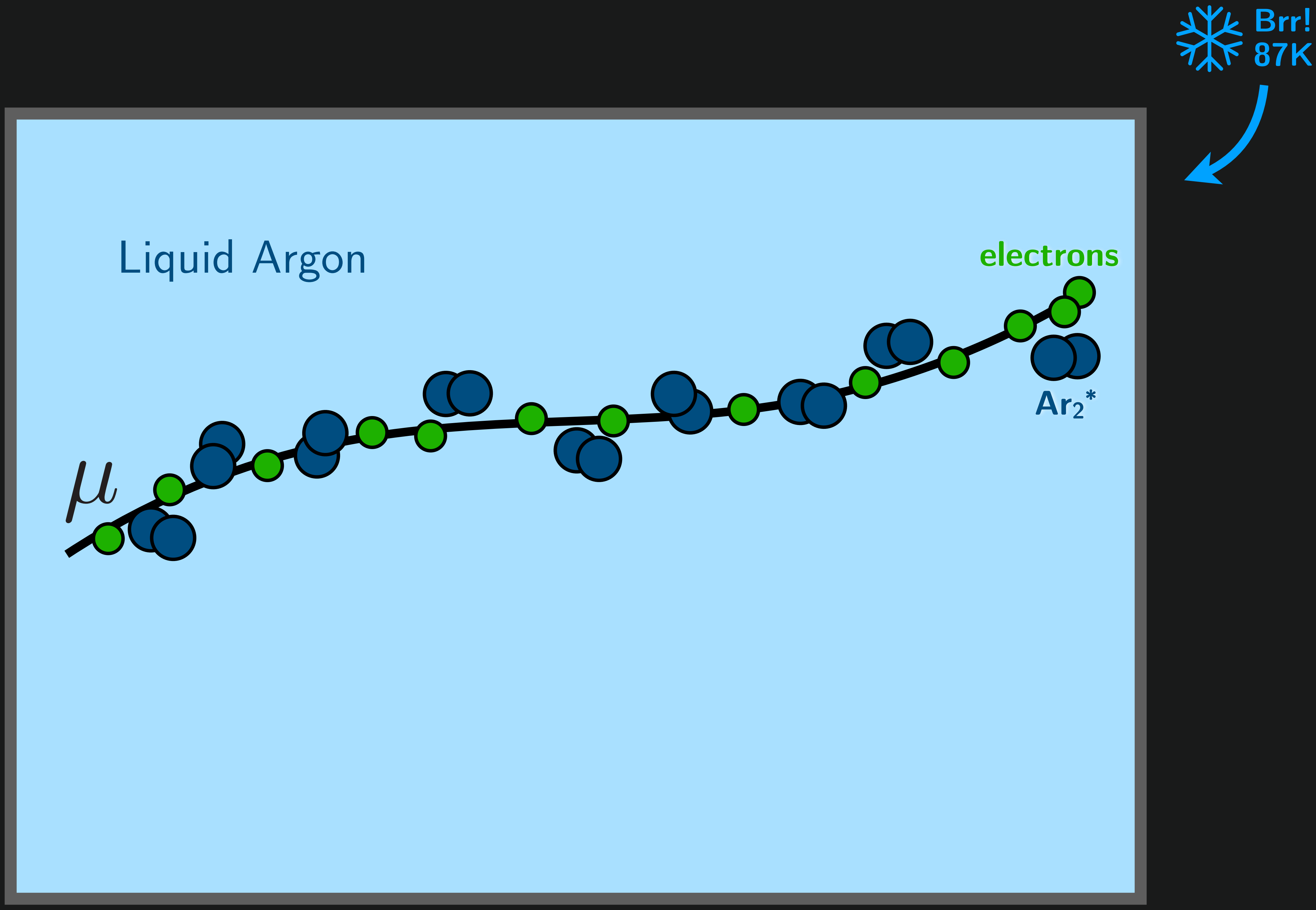

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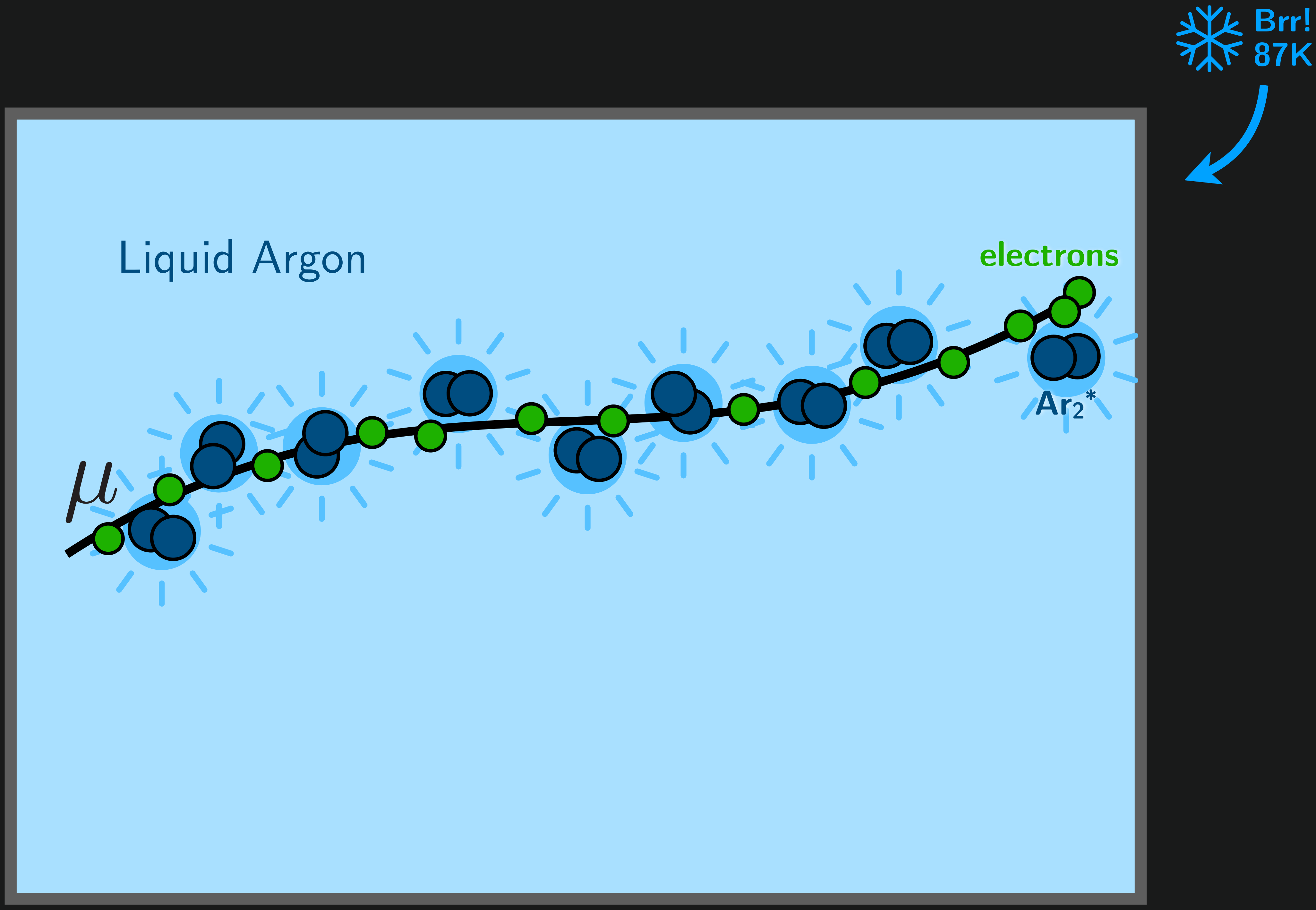

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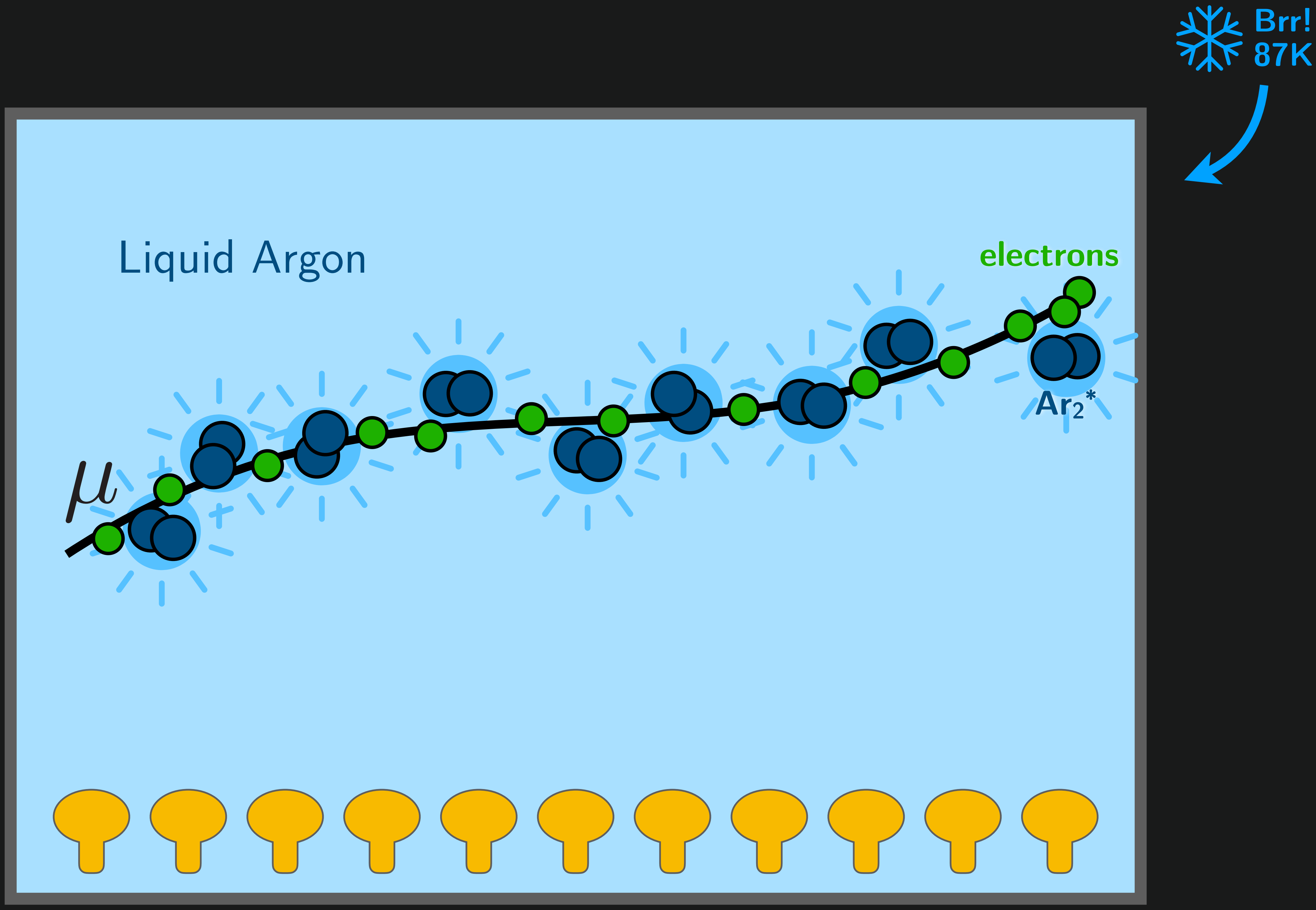
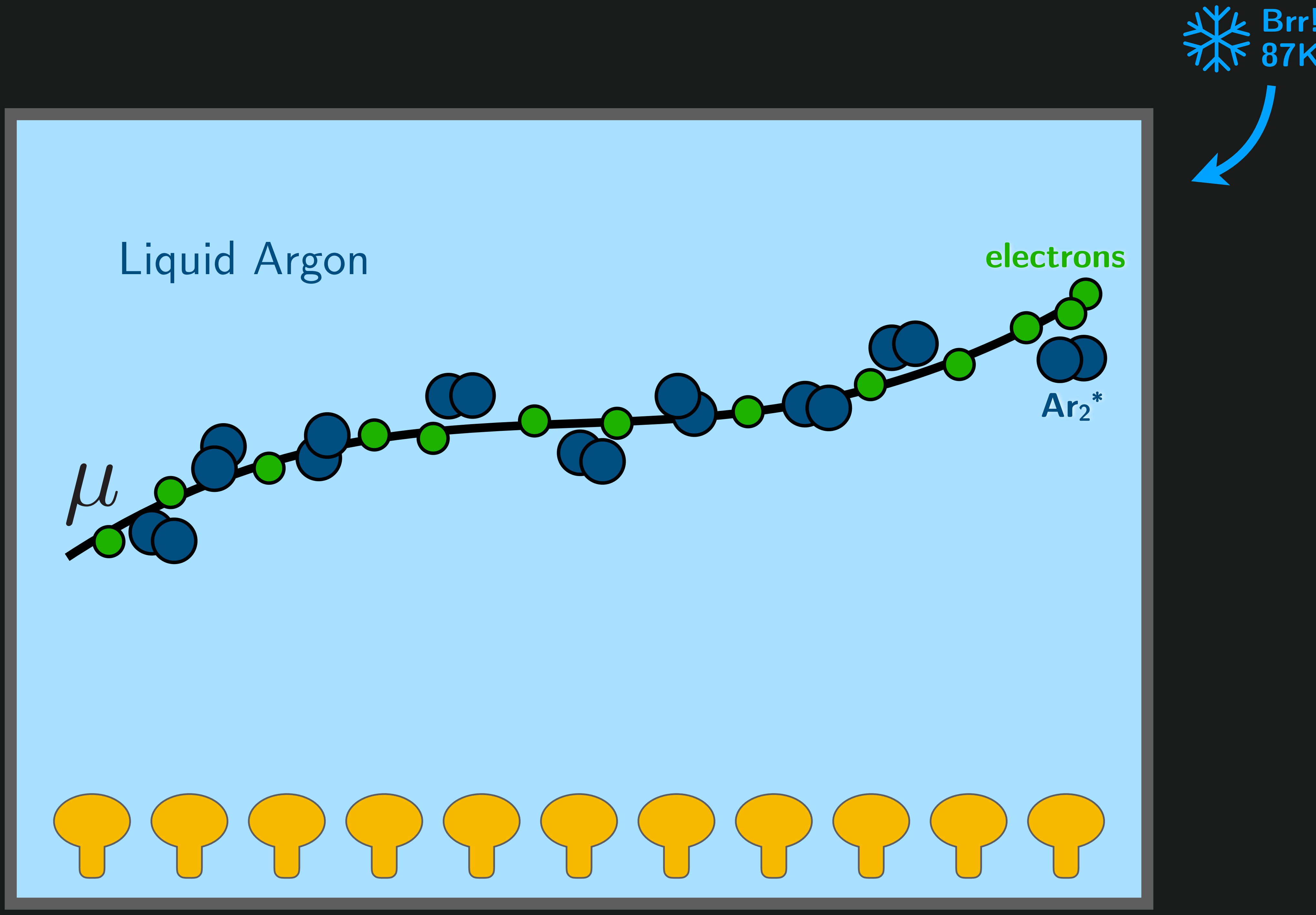


Liquid Argon TPCs



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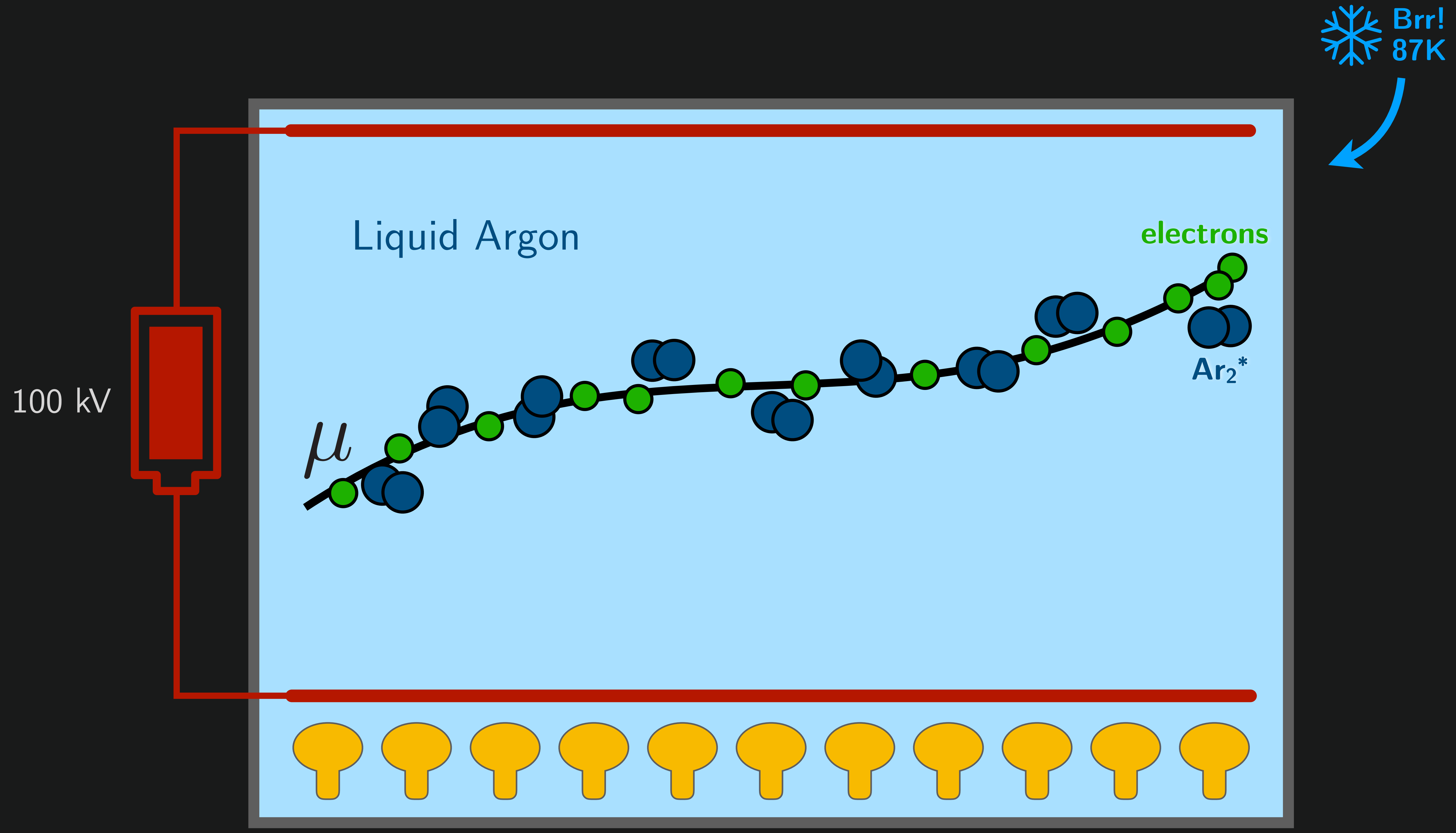

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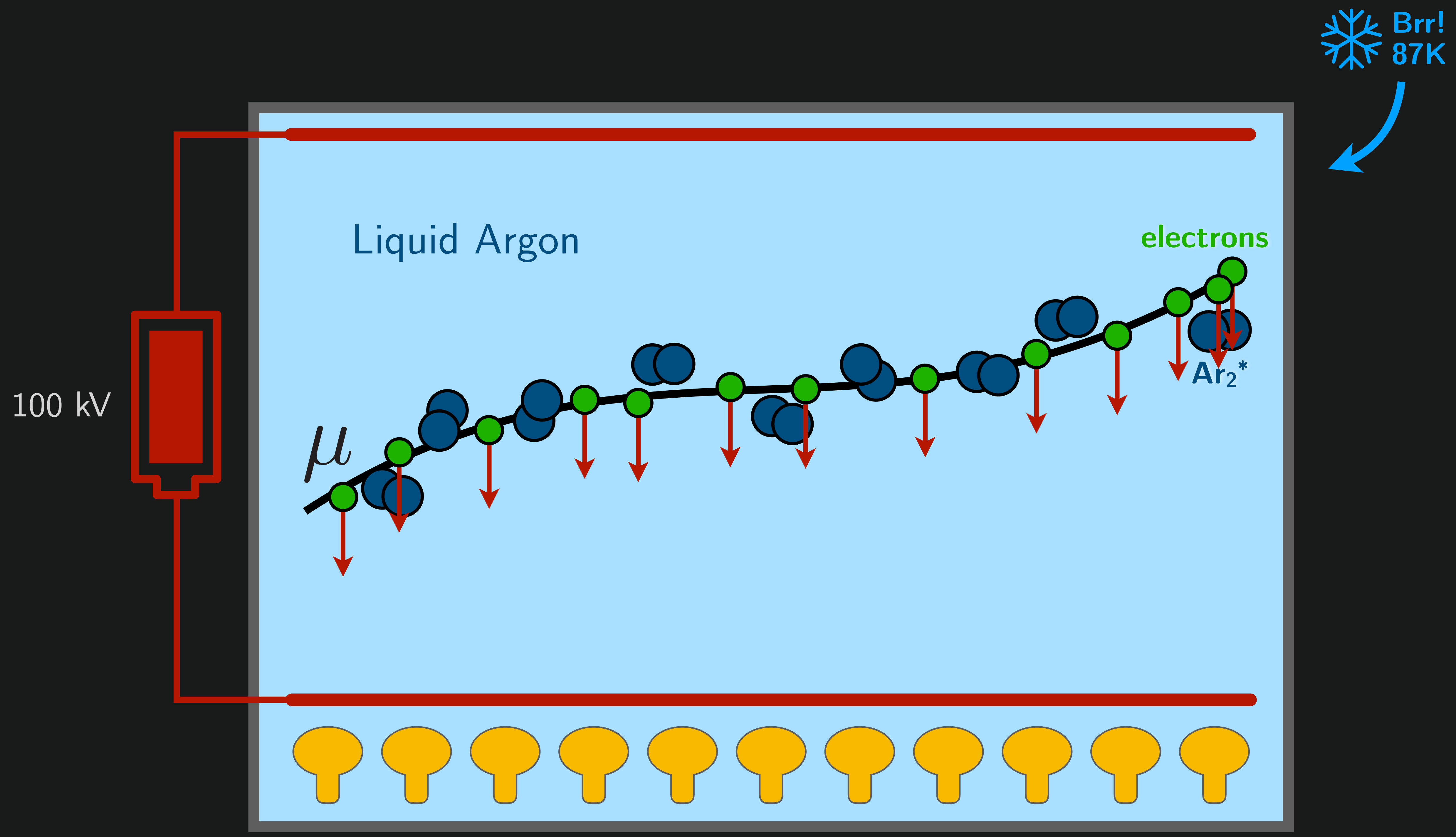

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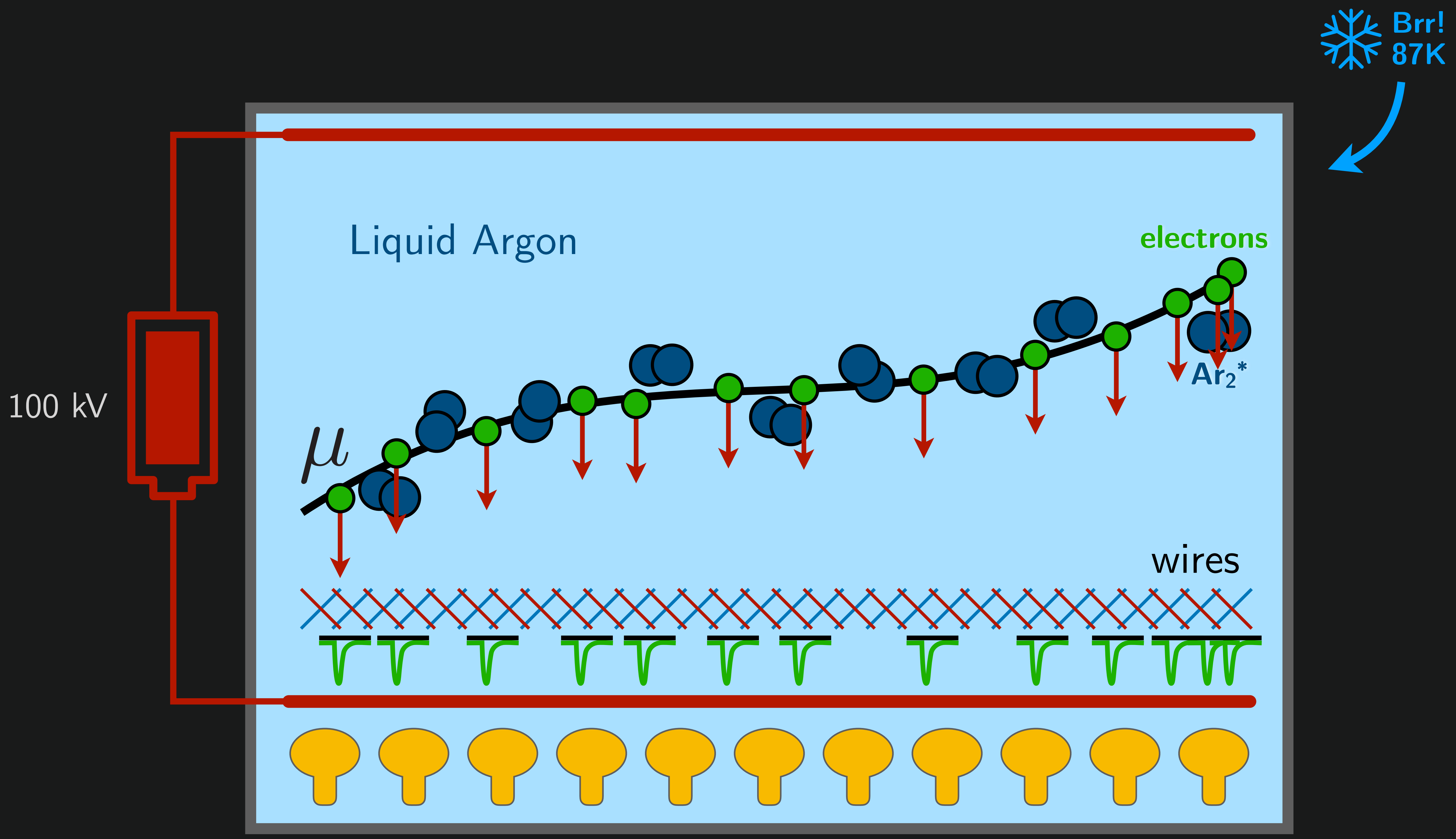

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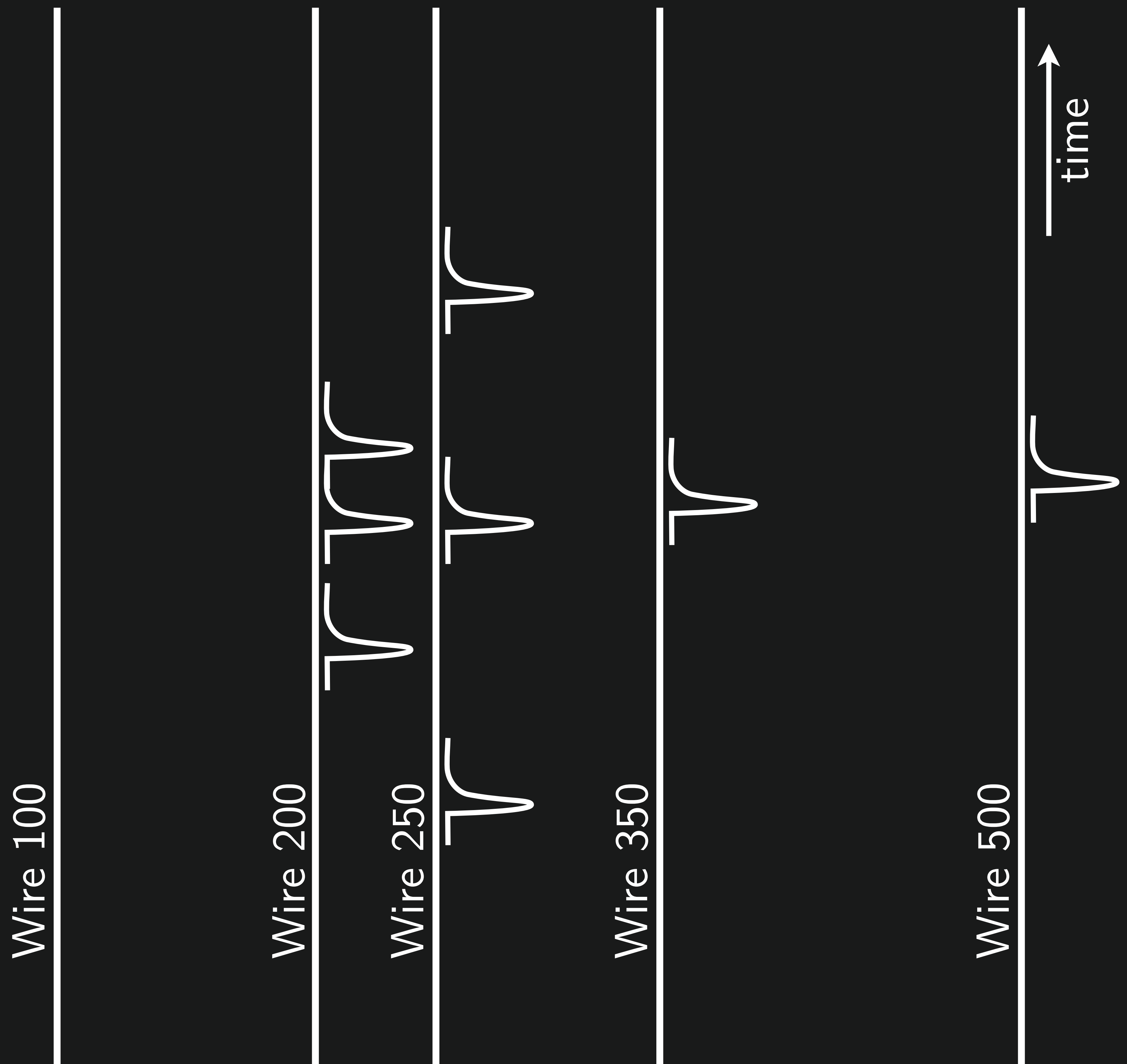

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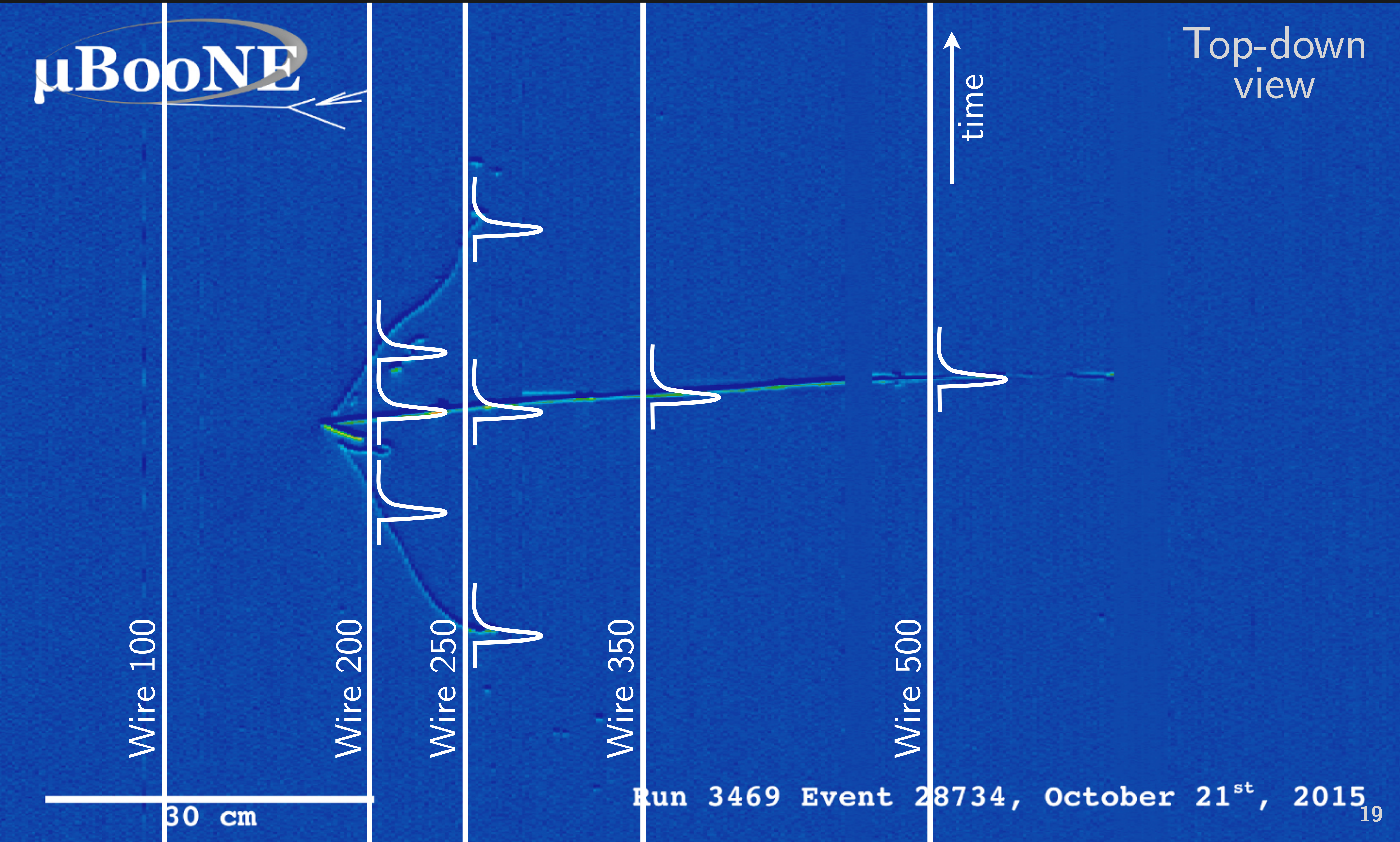

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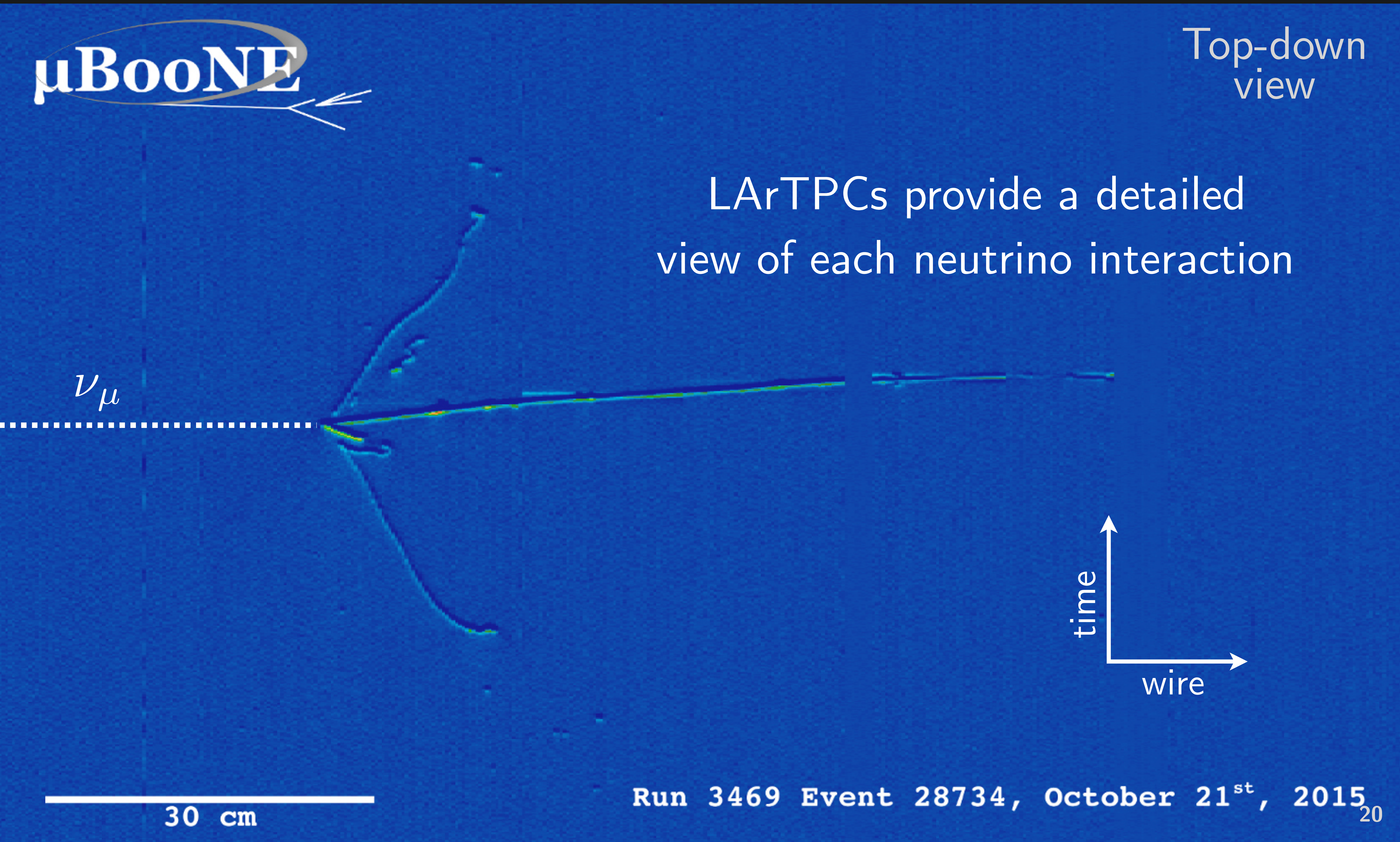
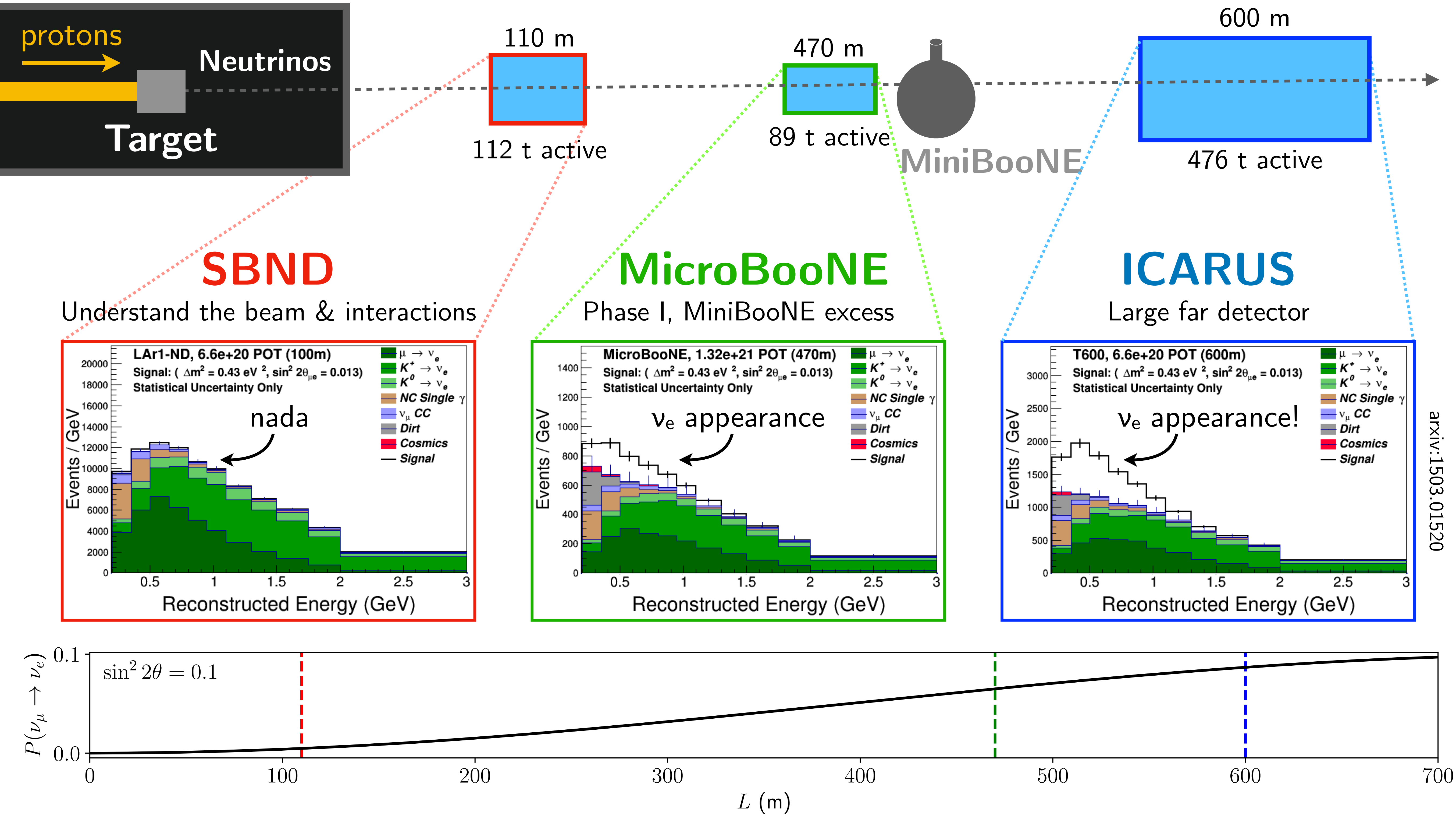


LArTPCs provide a detailed view of each neutrino interaction

The Short-Baseline Neutrino Program

A Definitive Test of Short-Baseline Oscillations



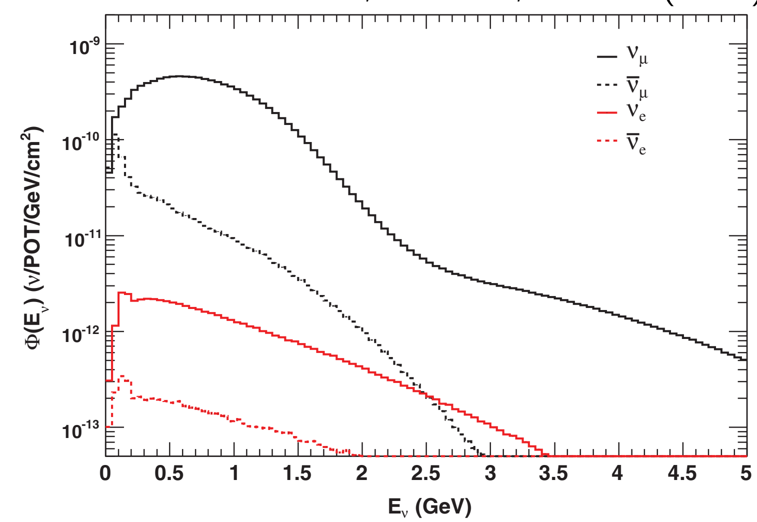
A Three-Detector Experiment

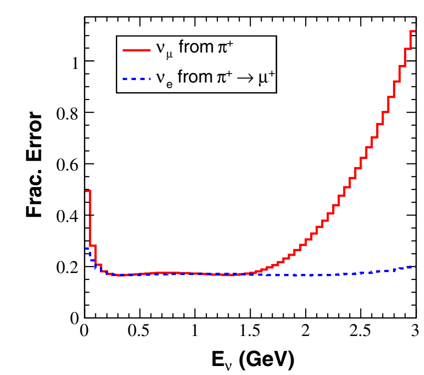
Leveraging Correlations to Minimize Systematics

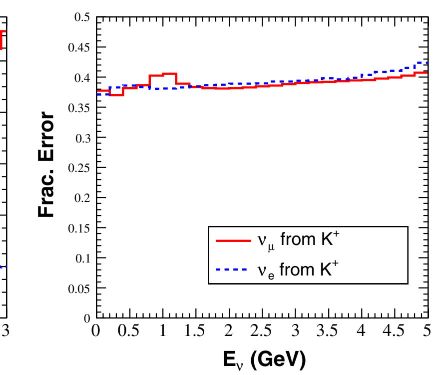
Flux Modeling & Uncertainties

- Fermilab Booster Neutrino Beam
  - 8 GeV protons on a Be target
  - Primarily ν_μ beam, with 0.5% ν_e
- MiniBooNE-based flux uncertainties
  - Conductor: horn current, skin depth
  - π, K production
  - π, nucleon interactions
- Highly correlated across detectors
  - Near detector provides a strong constraint

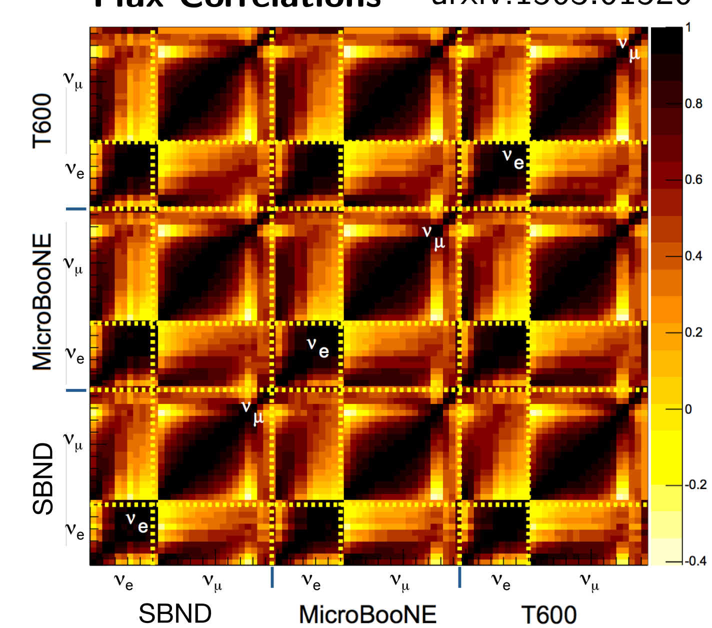
MiniBooNE, PRD **79**, 072002 (2009)

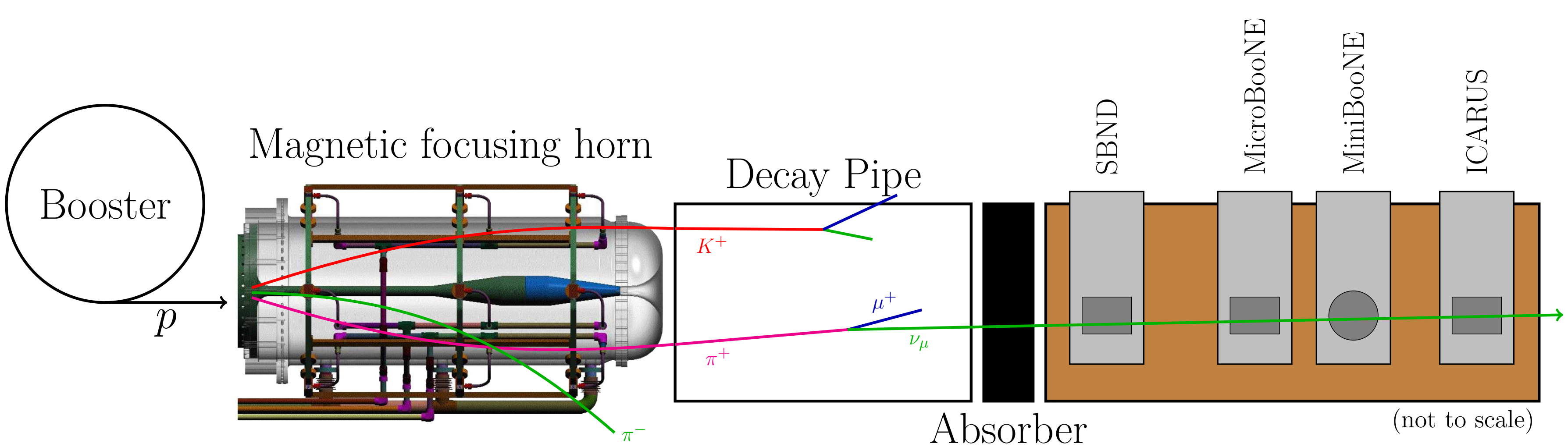






Flux Correlations arxiv:1503.01520





A Three-Detector Experiment

Leveraging Correlations to Minimize Systematics

Detector Modeling & Uncertainties

- **Particle propagation** (Geant4)
- **Electron drift** (space charge, diffusion, recombination, electronics response)
- **Photon propagation** (scintillation yield, detector response, triggering)

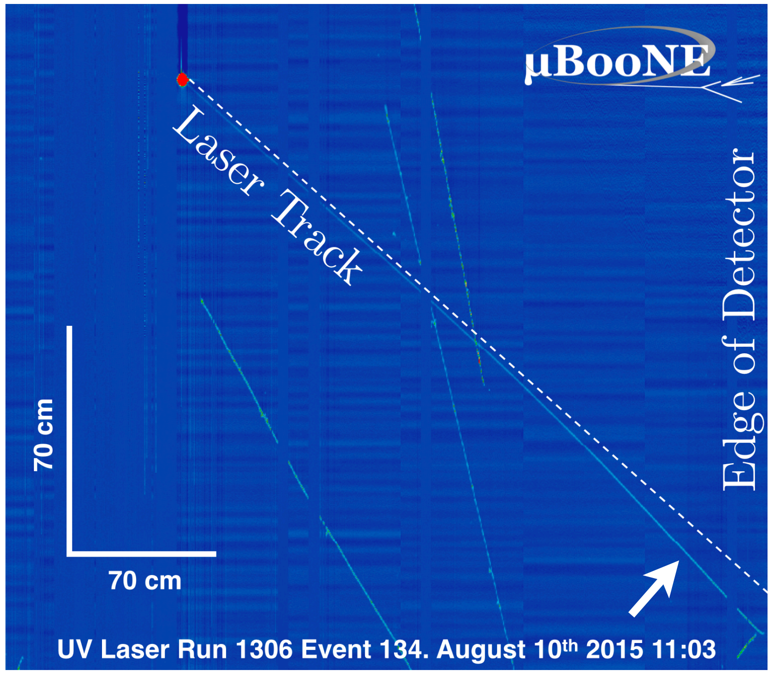
Challenges:

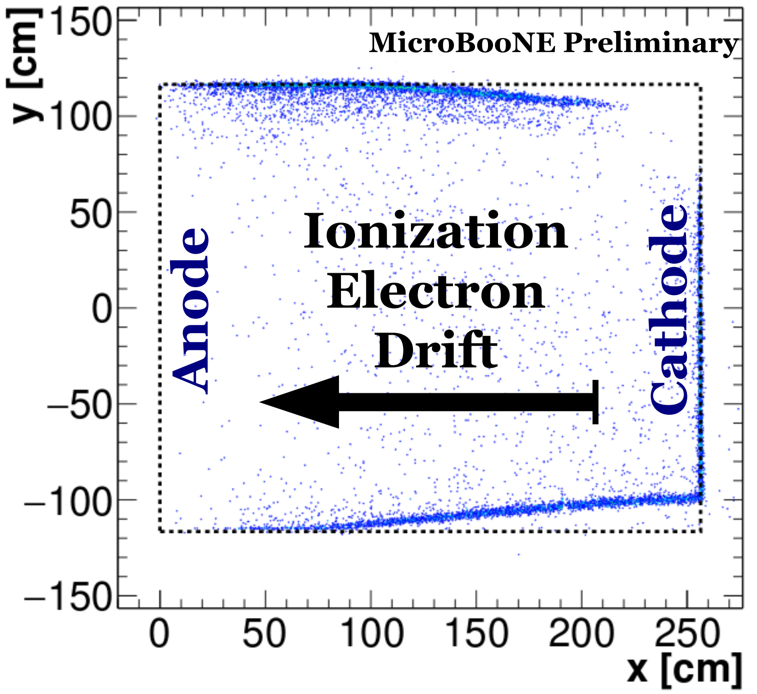
- Differences in geometry/acceptance
- Different wire angles × angle-dependent reconstruction efficiencies

Strategies:

- MC samples with detector variations
- Apply full chain to study analysis impact
- Parameterize calibration uncertainties

Space Charge Effect





MICROBOONE-NOTE-1018-PUB

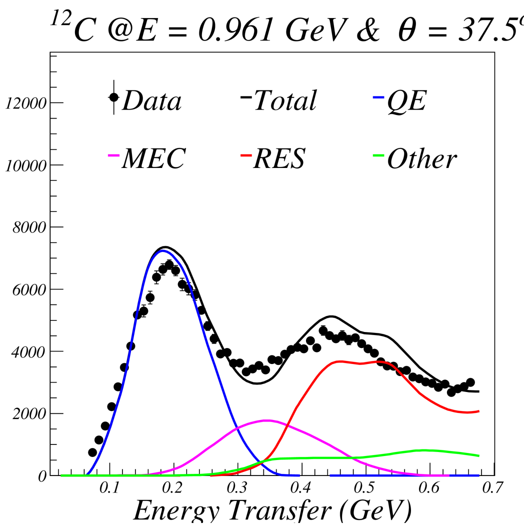
A Three-Detector Experiment

Leveraging Correlations to Minimize Systematics

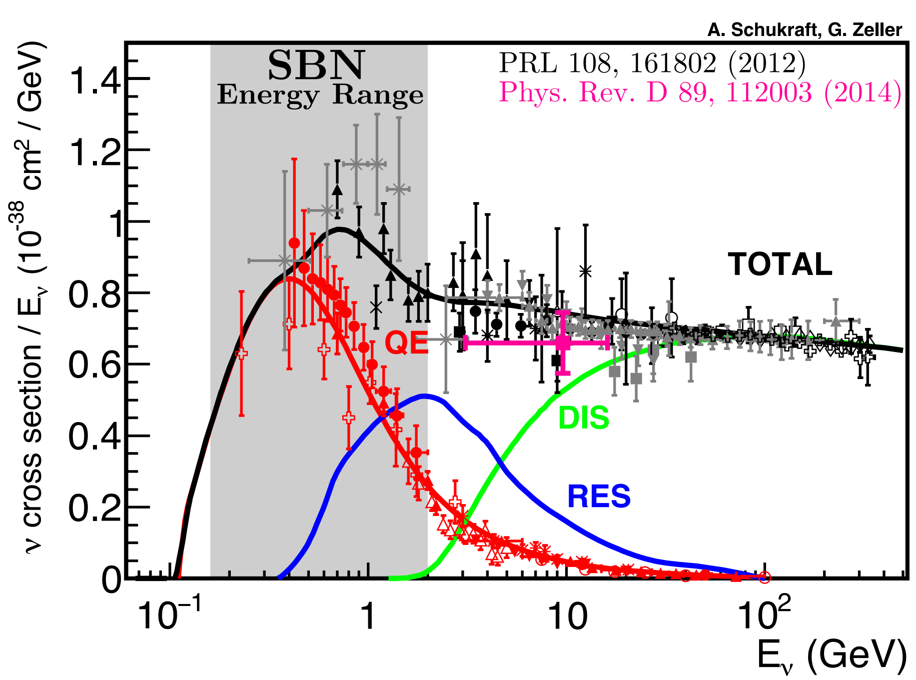
Interaction Modeling & Uncertainties

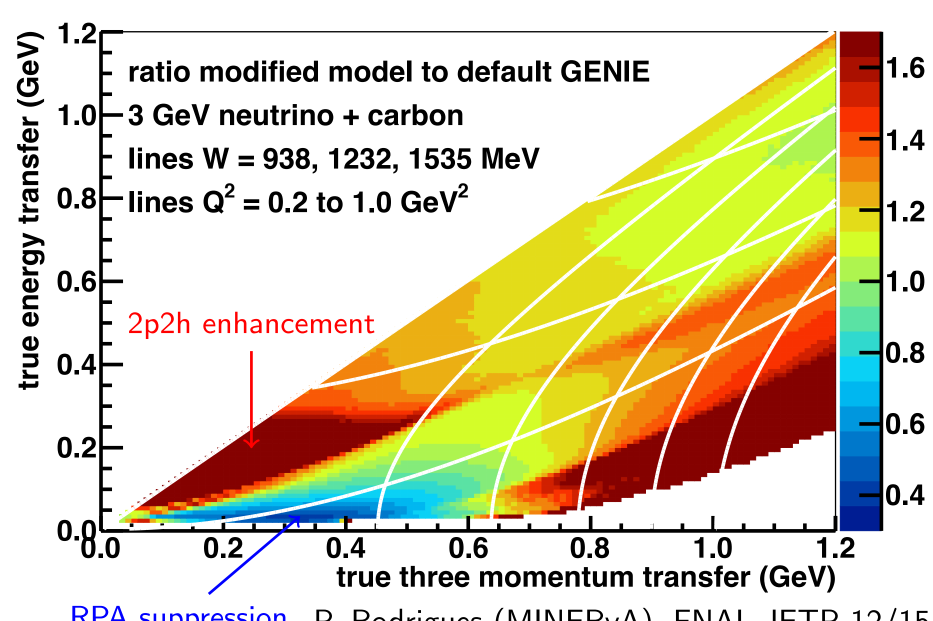
- Ongoing efforts to include state-of-the art models, multiple generators
- Updated tunes for deuterium bubble chamber reanalyses
- Integrating Ar cross section measurements into oscillation analysis

- GENIE cross section, hadronization, resonance decay, FSI uncertainties
- RPA and Valencia MEC uncertainties (cf. MINERvA, NOvA)
- Alternate FSI models (full vs. effective nuclear cascade)
- Alternate MEC models (Valencia vs. empirical tuned on e scattering)
- Second class currents, radiative corrections, ${}^{12}\mathrm{C}/{}^{40}\mathrm{Ar}$, ν_μ/ν_e



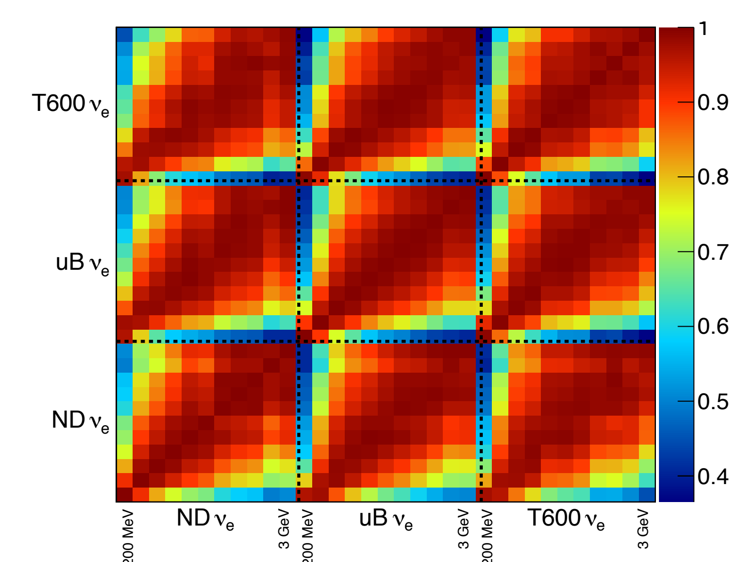
A. Papadopoulou (e4v), NuInt18



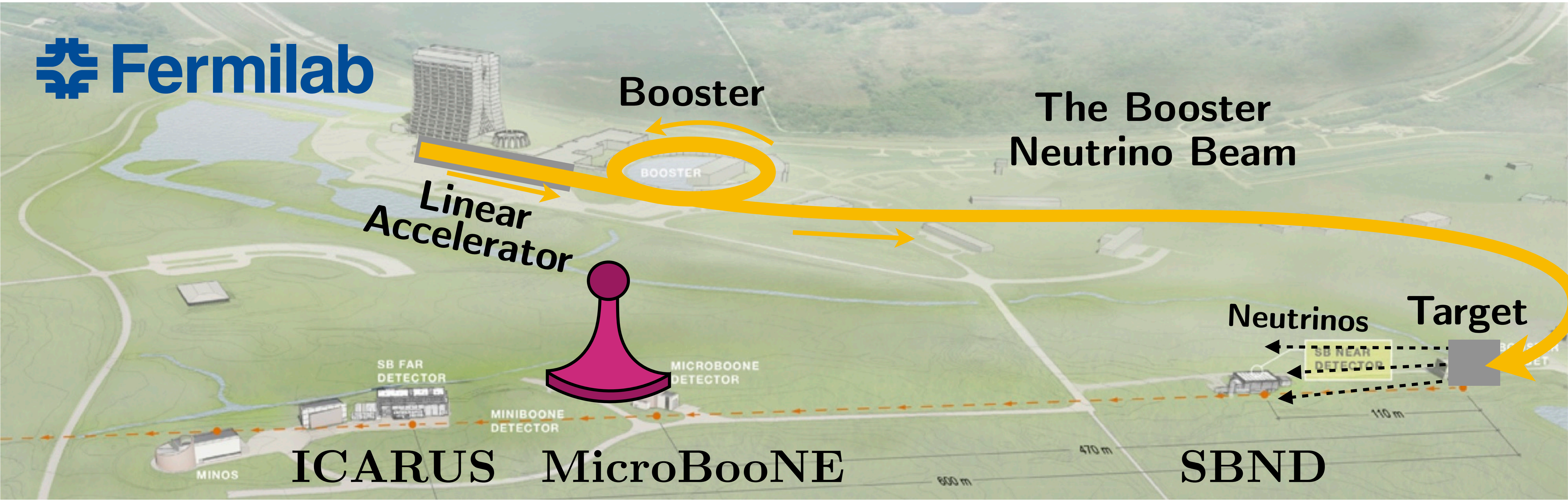


P. Rodrigues (MINERvA), FNAL JETP 12/15

GENIE Correlations arxiv:1503.01520



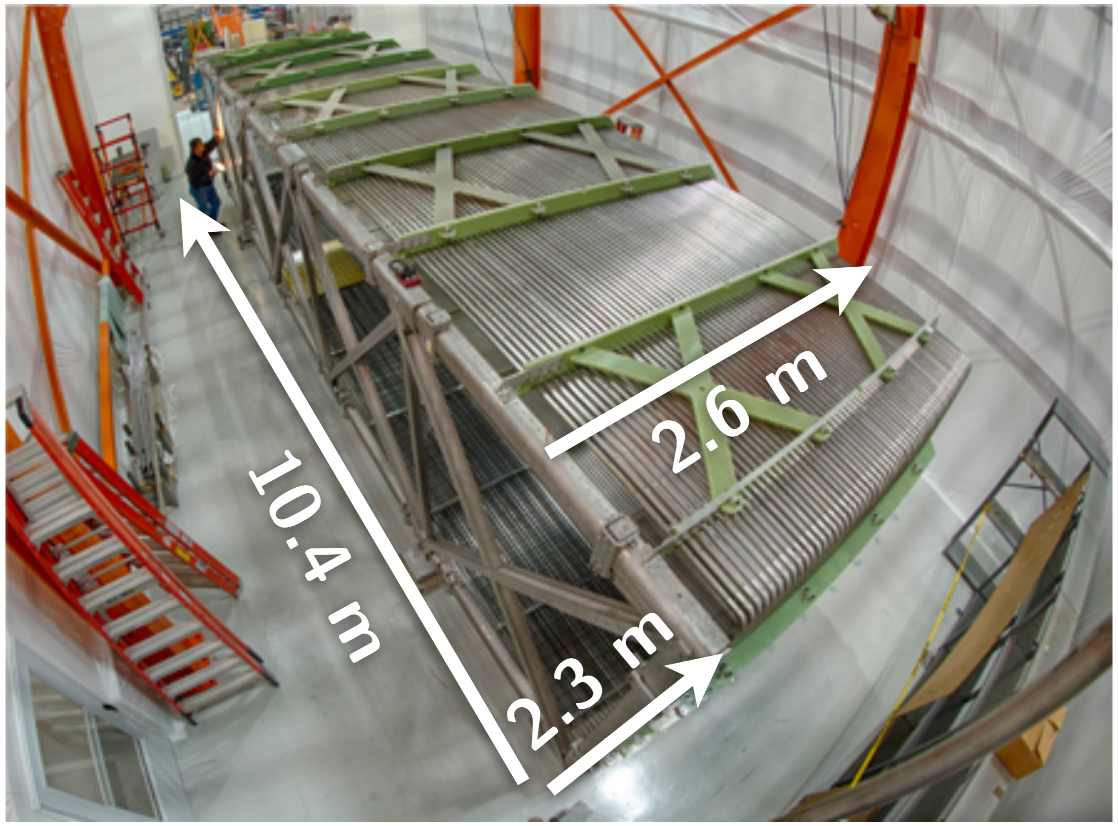
MicroBooNE


Fermilab
Booster
BOOSTER
The Booster
Neutrino Beam
Linear
Accelerator
Neutrinos
Target
SB NEAR
DETECTOR
SB FAR
DETECTOR
MICROBOONE
DETECTOR
MINIBOONE
DETECTOR
MINOS
110 m
470 m
600 m
ICARUS
MicroBooNE
SBND

MicroBooNE

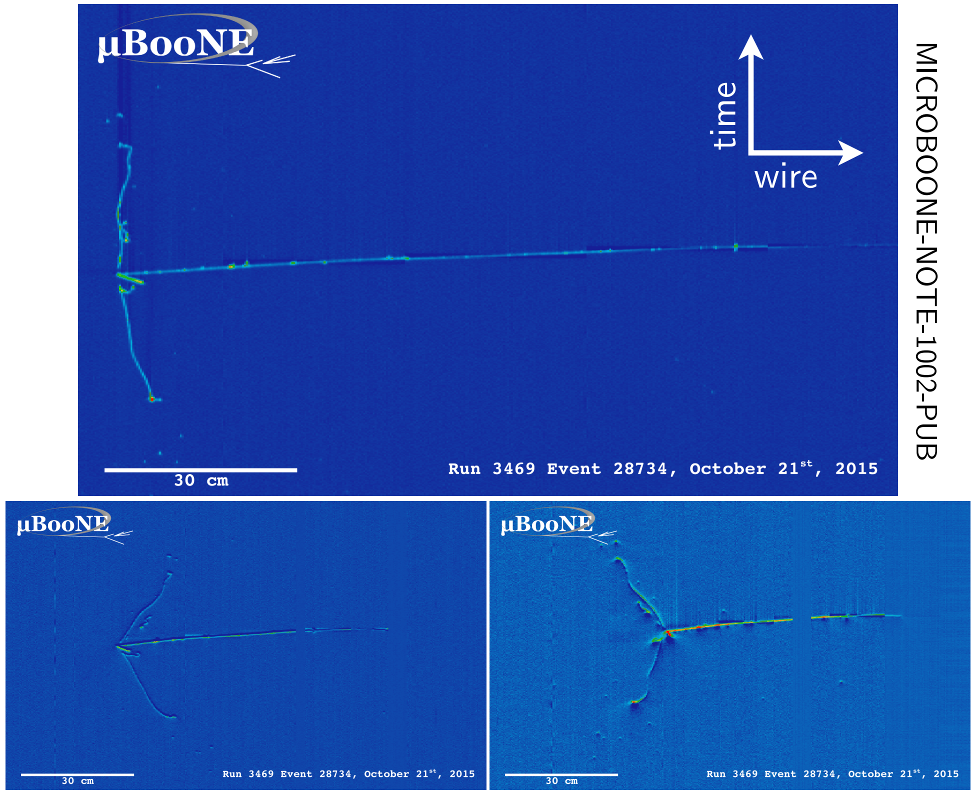
Addressing the MiniBooNE Excess

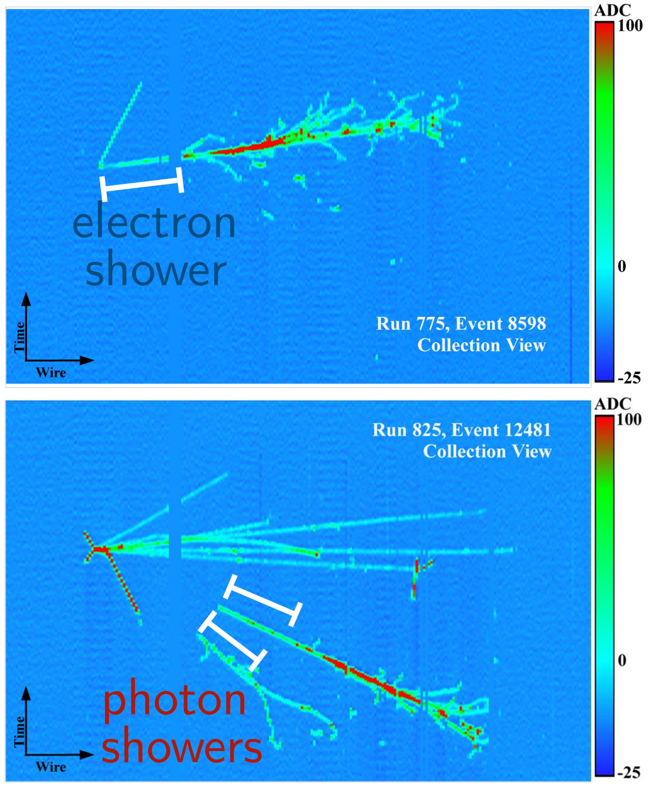
- Similar baseline to MiniBooNE (470 m)
- 89 tons active LAr mass
- Taking beam data since October 2015
- Cosmic ray tagger added in 2016



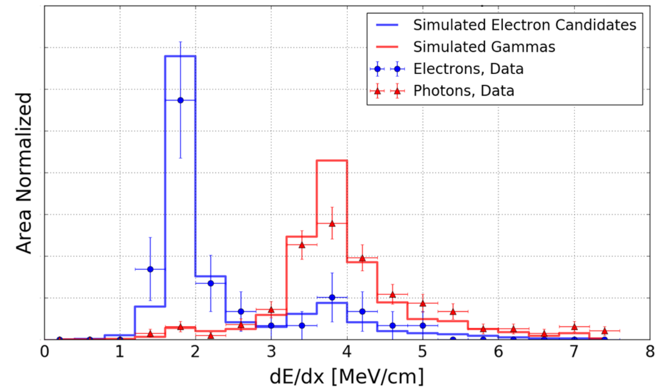
Key Advantages of LAr:

- Detailed imaging of neutrino interactions
- Electron/photon discrimination





dE/dx e/γ in ArgoNeut

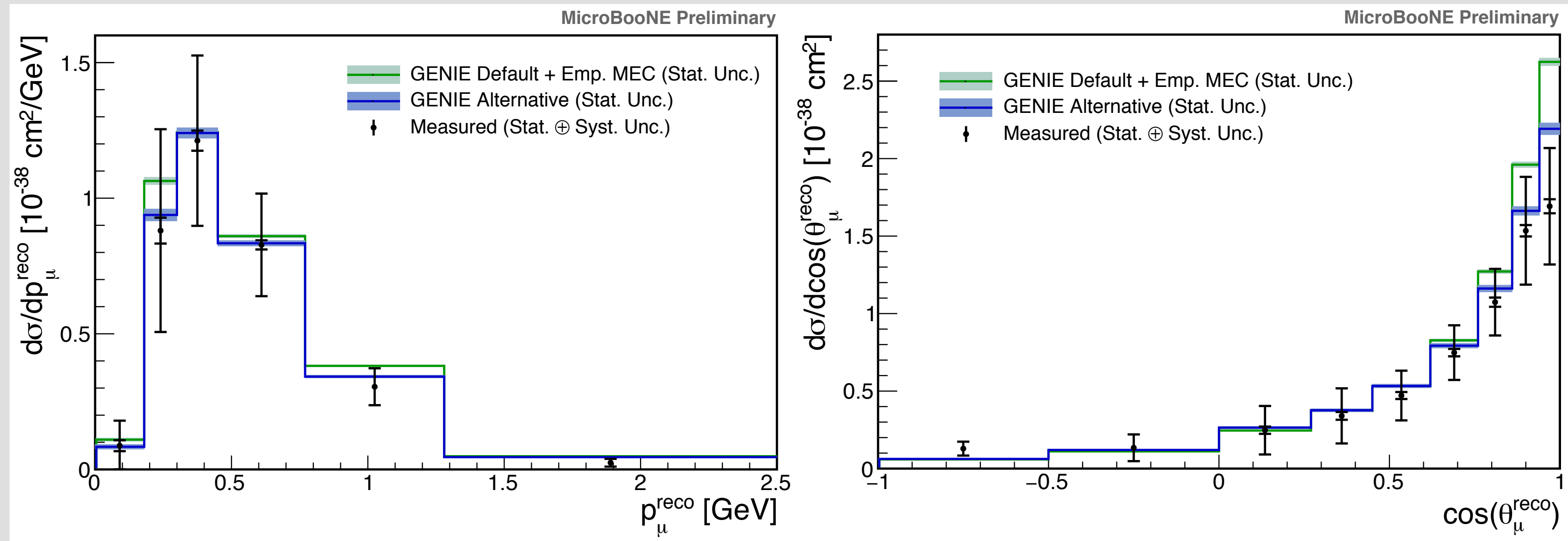


PRD 95, 072005 (2017)

MicroBooNE Recent Physics Results

CC Inclusive Cross Section

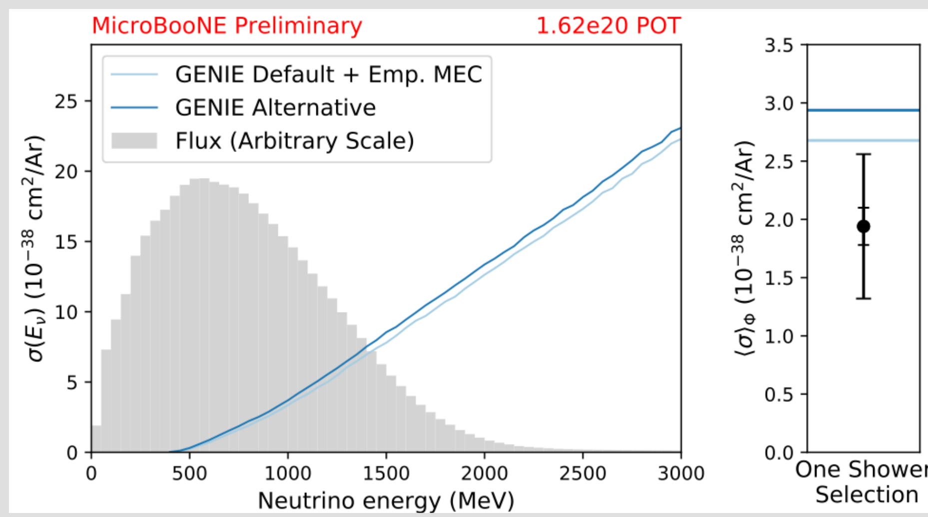
- High efficiency & purity
- Insensitive to hadrons
- Constrains ν_e rate
- Exclusive pre-selection

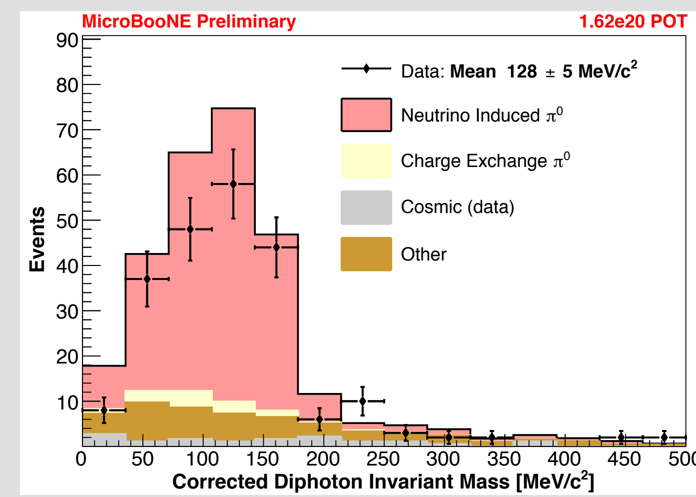


MICROBOONE-NOTE-1045-PUB

CC π^0 Cross Section

- First measurement on Ar
- Test shower reconstruction
- LEE photon backgrounds

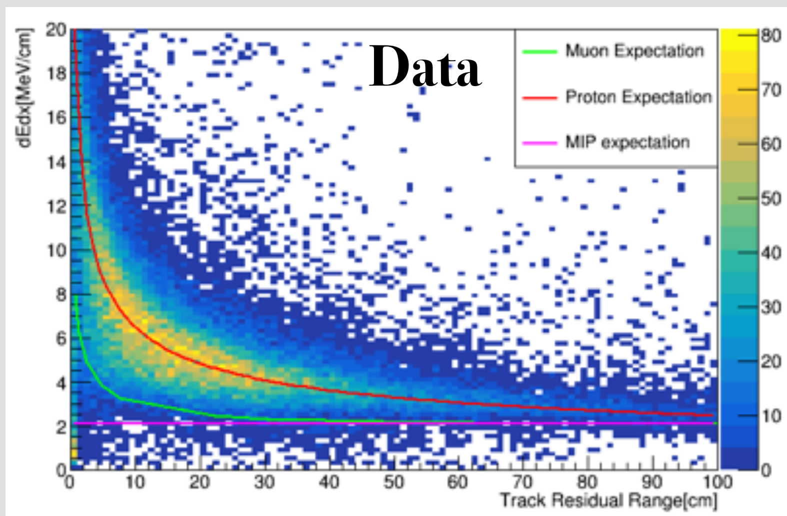




MICROBOONE-NOTE-1032-PUB

CC $1\mu Np$ Cross Section

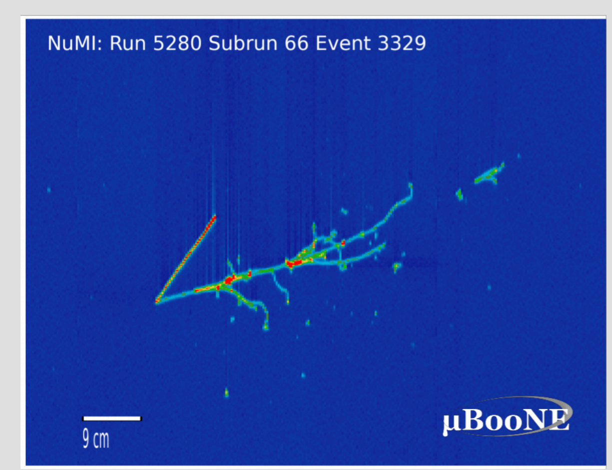
Proton production and kinematics



R. Castillo-Fernandez, NuInt 2018

NuMI ν_e Cross Section

Larger ν_e event sample in off axis NuMI



C. Hill, NuInt 2018

MicroBooNE

Addressing the MiniBooNE Excess

The MiniBooNE Excess

- Extra electrons?
  - Sterile neutrino oscillations?
  - Something else?
- Extra photons?
  - $\Delta \rightarrow N\gamma$? π^0 mis-ID? ...?

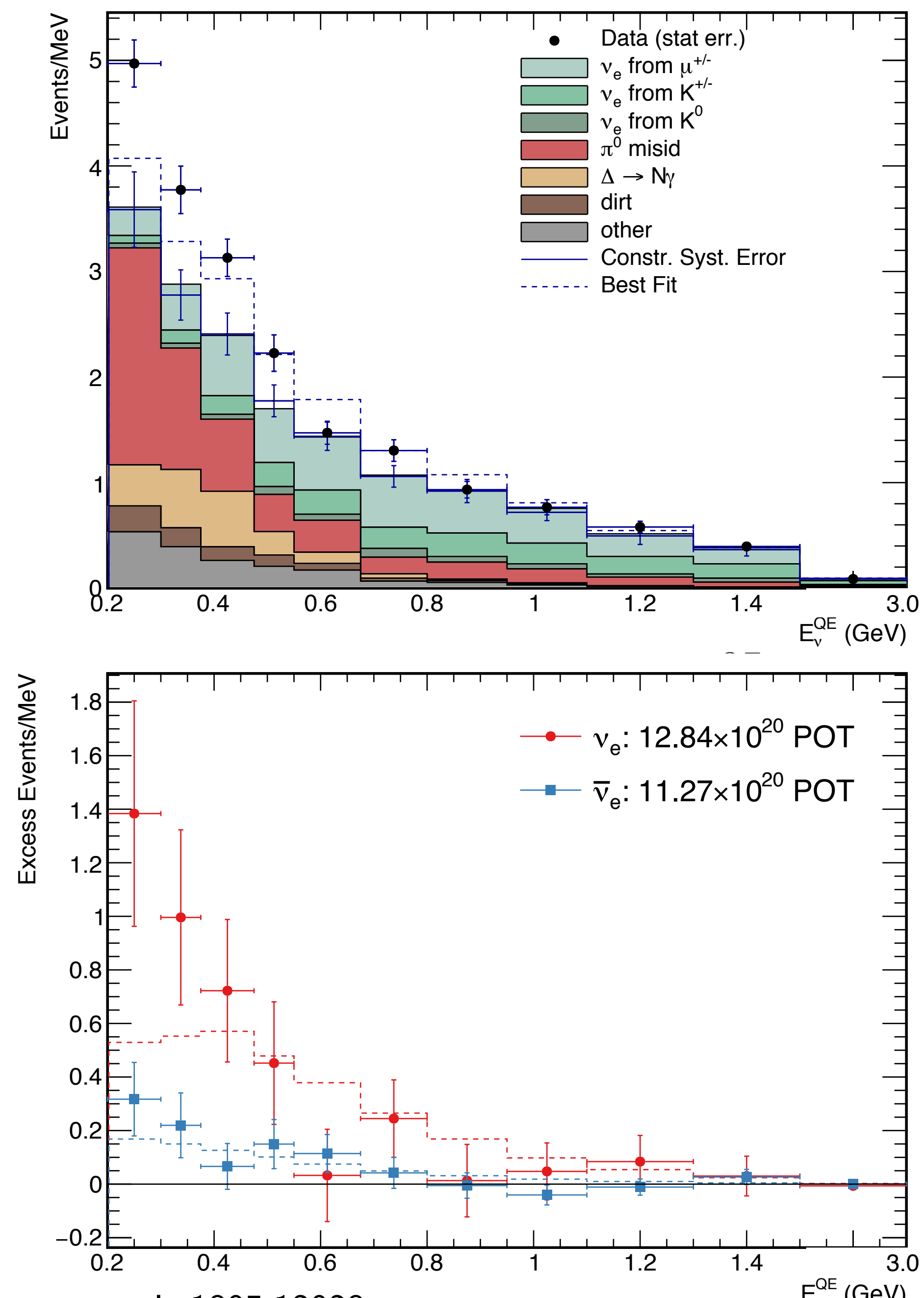
Q: Data consistent with...

- Models (generator MC)?
- Short-baseline oscillations?
- Extrapolated LEE signal?

Targeting sensitivity to signals extrapolated from MiniBooNE's excess

(See MICROBOONE-NOTE-1043-PUB)

MiniBooNE 2018



arxiv:1805.12028

MicroBooNE

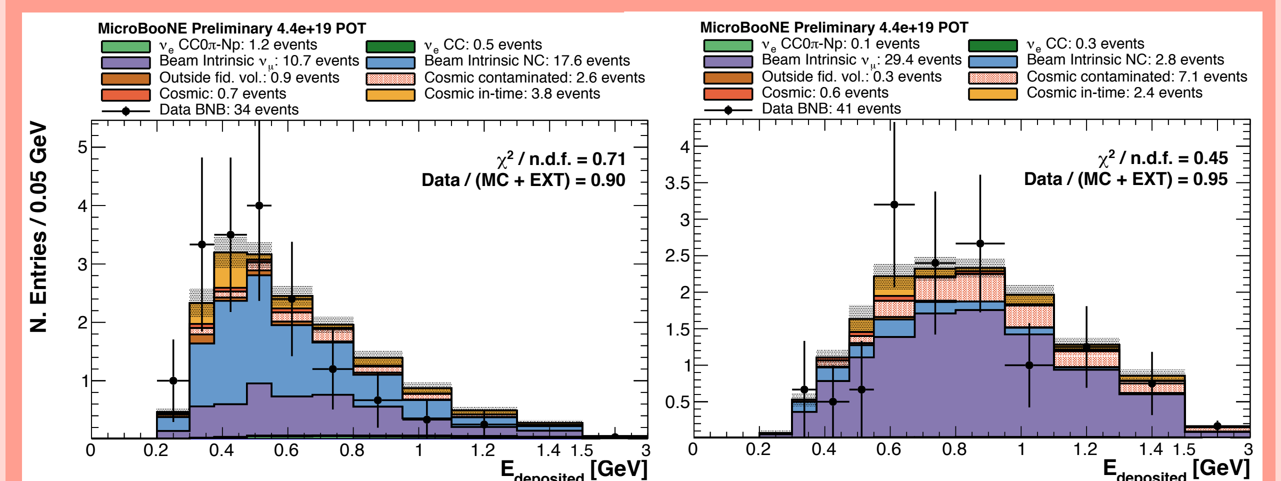
Addressing the MiniBooNE Excess

Parallel *e*-like Excess Analysis Efforts:

- Multiple reconstruction and selection techniques

Pandora-Based CC0π*Np* Selection

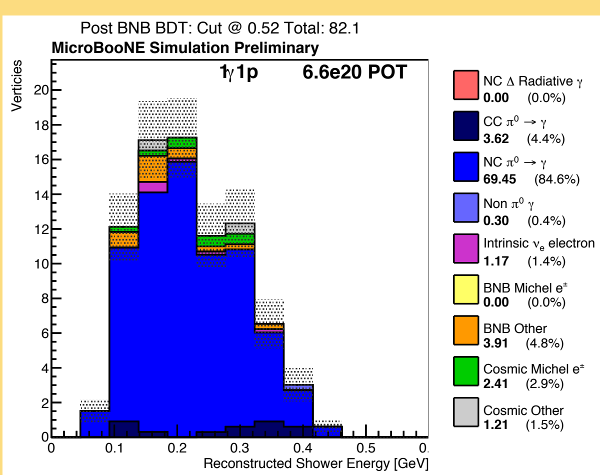
MICROBOONE-NOTE-1038-PUB

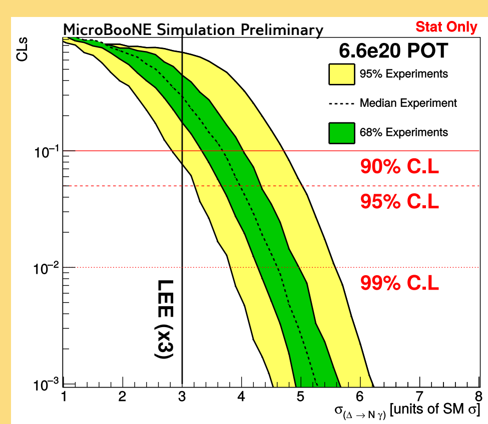


NC-enhanced sideband | Muon-enhanced sideband

Single Photon 1γ1*p* Selection

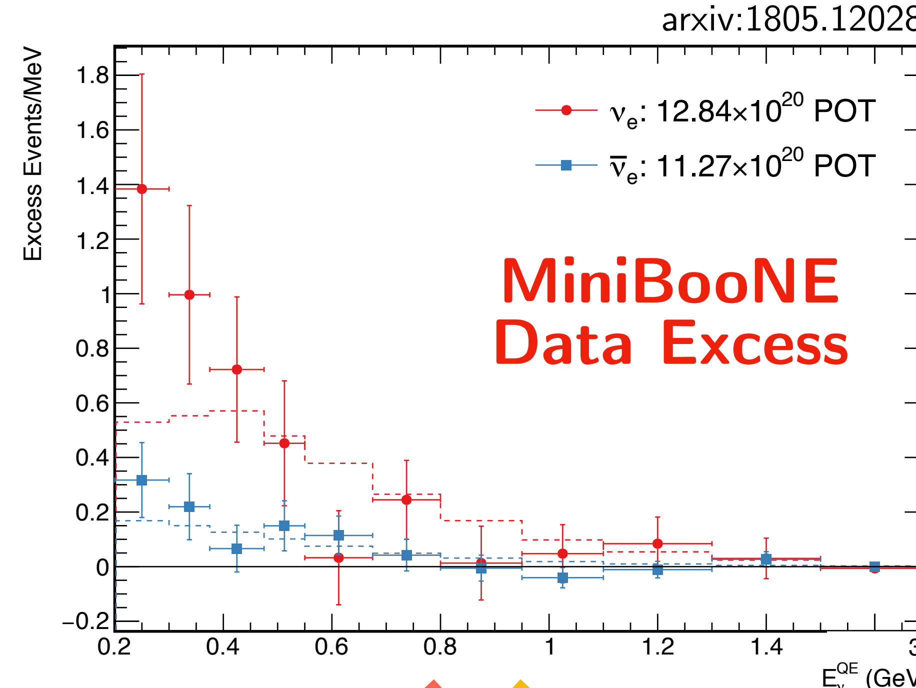
MICROBOONE-NOTE-1041-PUB





Also 1γ0*p*, 2γ1*p* (NCπ^0, CCπ^0) channels

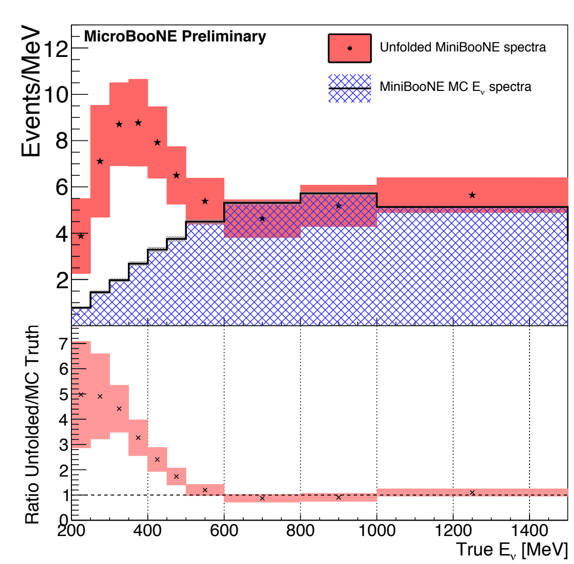
arxiv:1805.12028

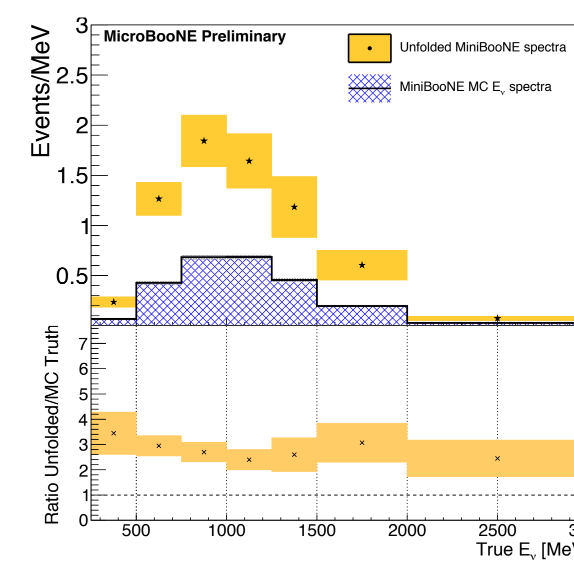


ν_e CC Hypothesis

MC Unfolding

NC Δ Radiative Hypothesis



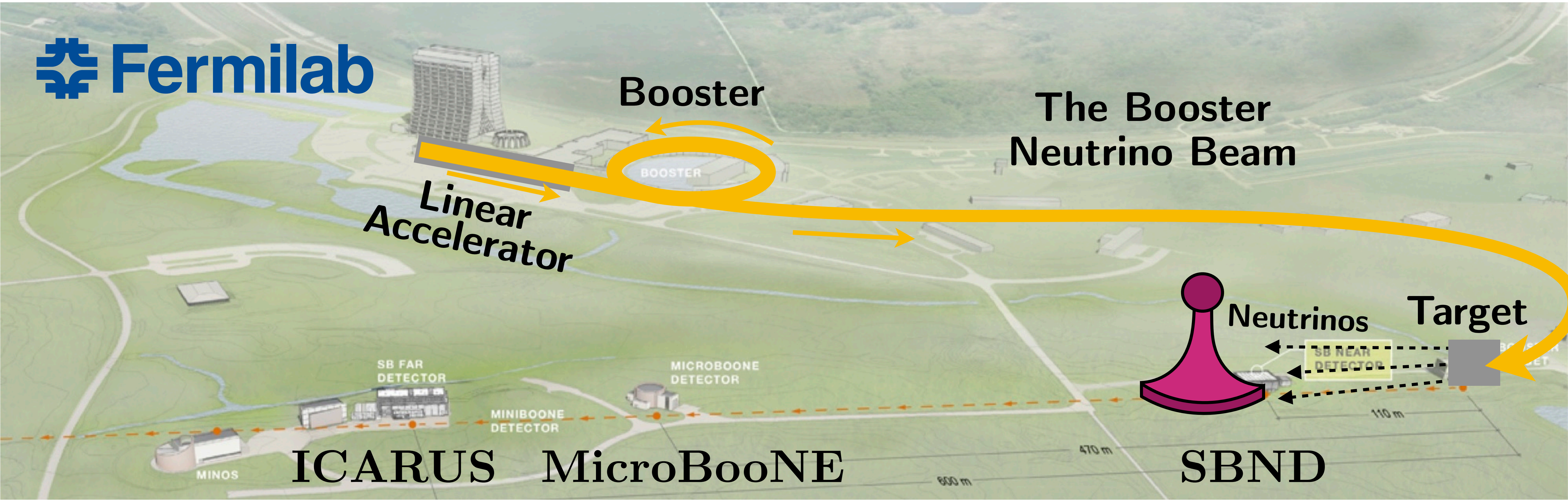


MICROBOONE-NOTE-1043-PUB

(N.B. using previous MiniBooNE results)

SBND

The Short-Baseline Near Detector



SBND

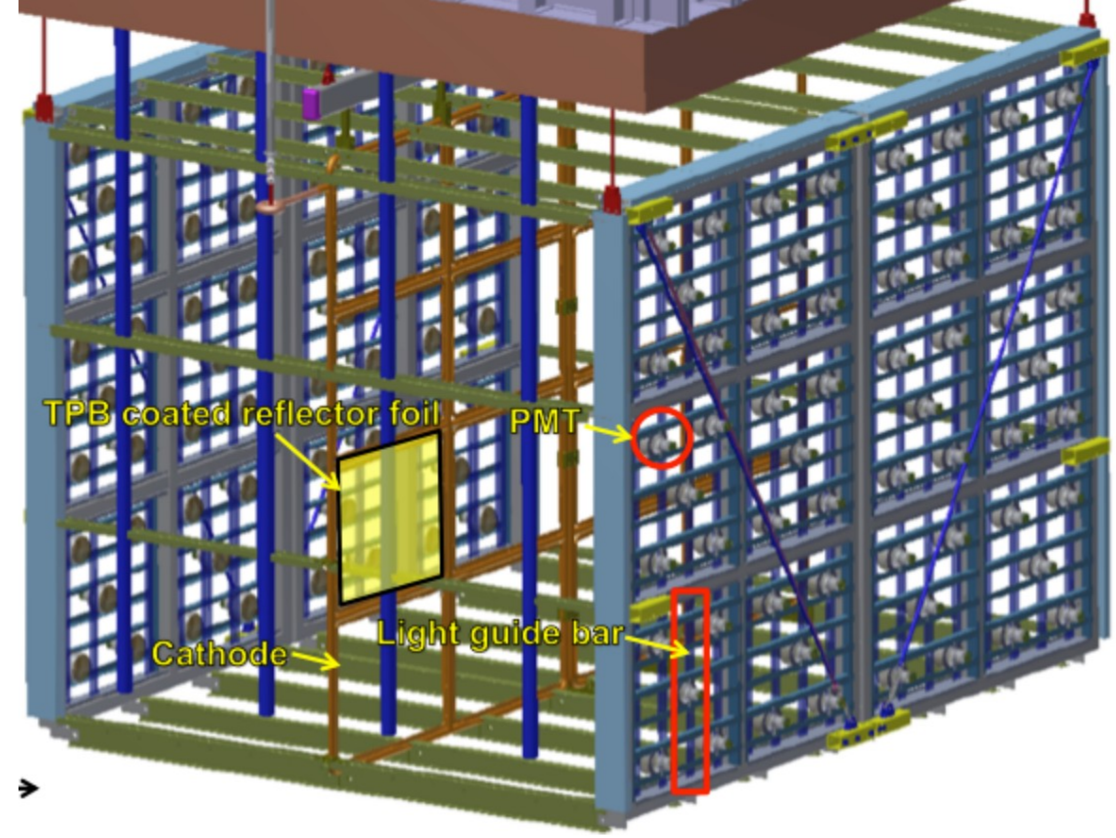
The Short-Baseline Near Detector

Detector:

- 110 m from the BNB target
  - No oscillation signal expected
- 112 tons active LAr mass
- Two TPCs sharing a central cathode

Physics Program:

- High statistics BNB event sample
  - Constrains flux and interactions
  - Differential cross sections, many exclusive final states
- Reconstruction and detector development



arxiv:1503.01520

Process		No. Events
	ν_μ *Events (By Final State Topology)*	
CC Inclusive		5,212,690
CC 0 π	$\nu_\mu N \to \mu + Np$	3,551,830
	· $\nu_\mu N \to \mu + 0p$	793,153
	· $\nu_\mu N \to \mu + 1p$	2,027,830
	· $\nu_\mu N \to \mu + 2p$	359,496
	· $\nu_\mu N \to \mu + \geq 3p$	371,347
CC 1 $\pi^\pm$	$\nu_\mu N \to \mu +$ nucleons $+ 1\pi^\pm$	1,161,610
CC $\geq 2\pi^\pm$	$\nu_\mu N \to \mu +$ nucleons $+ \geq 2\pi^\pm$	97,929
CC $\geq 1\pi^0$	$\nu_\mu N \to \mu +$ nucleons $+ \geq 1\pi^0$	497,963
NC Inclusive		1,988,110
NC 0 π	$\nu_\mu N \to$ nucleons	1,371,070
NC 1 $\pi^\pm$	$\nu_\mu N \to$ nucleons $+ 1\pi^\pm$	260,924
NC $\geq 2\pi^\pm$	$\nu_\mu N \to$ nucleons $+ \geq 2\pi^\pm$	31,940
NC $\geq 1\pi^0$	$\nu_\mu N \to$ nucleons $+ \geq 1\pi^0$	358,443
	ν_e *Events*	
CC Inclusive		36798
NC Inclusive		14351
Total ν_μ and ν_e Events		7,251,948

SBND

The Short-Baseline Near Detector

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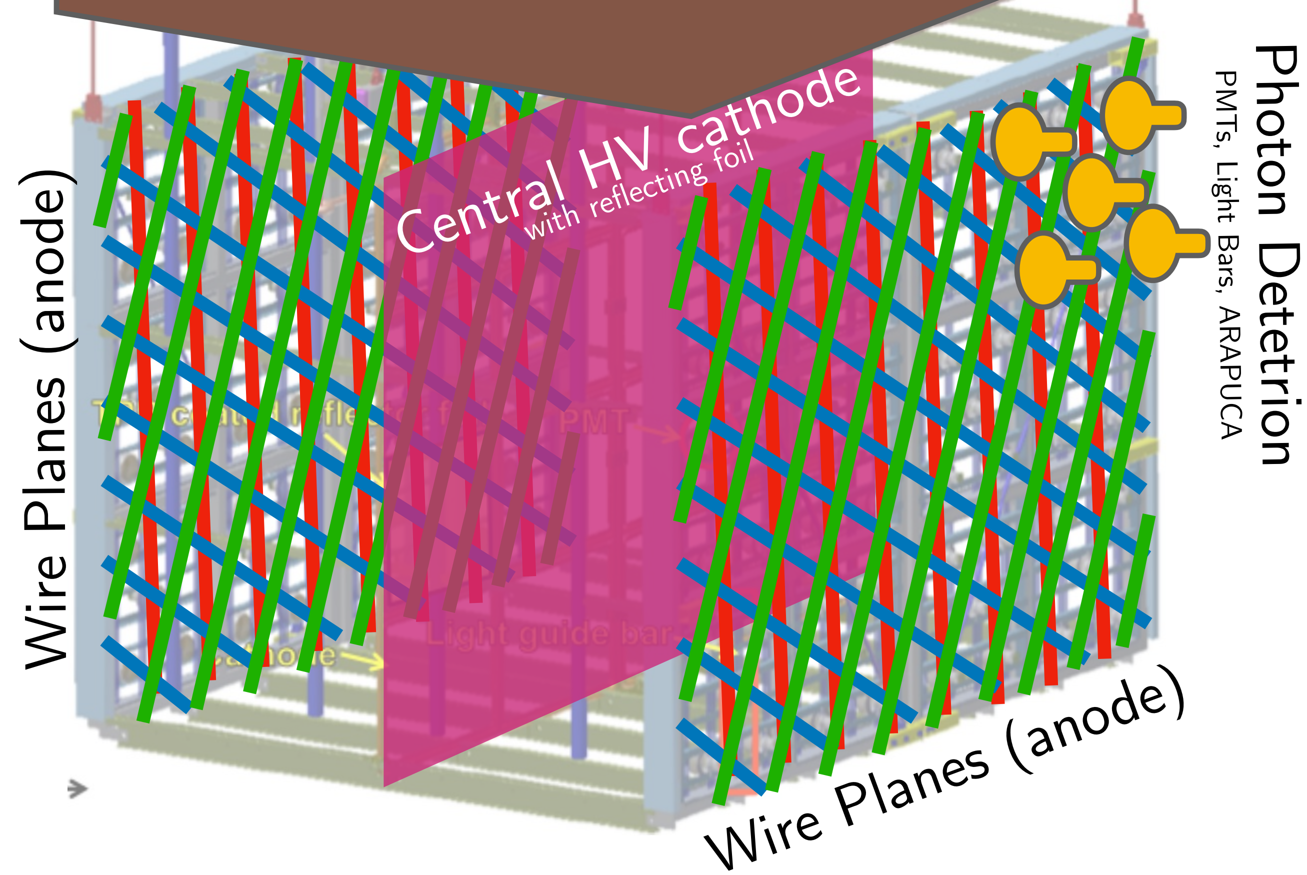

arxiv:1503.01520

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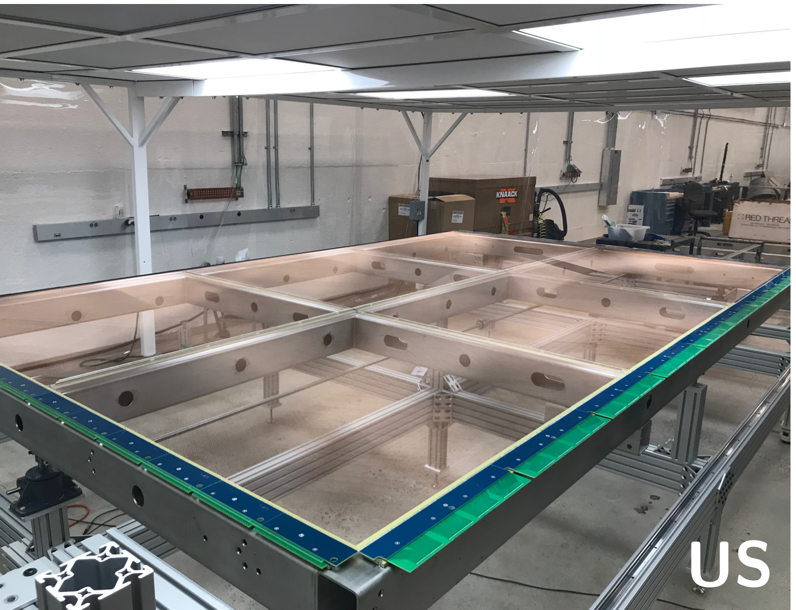
	ν_e *Events*	
CC Inclusive		36798
NC Inclusive		14351
Total ν_μ and ν_e Events		7,251,948

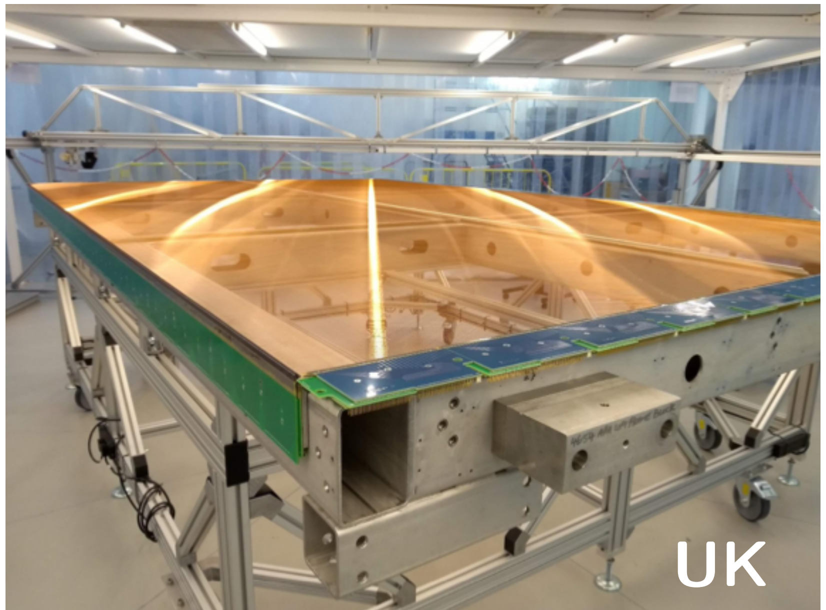
SBND

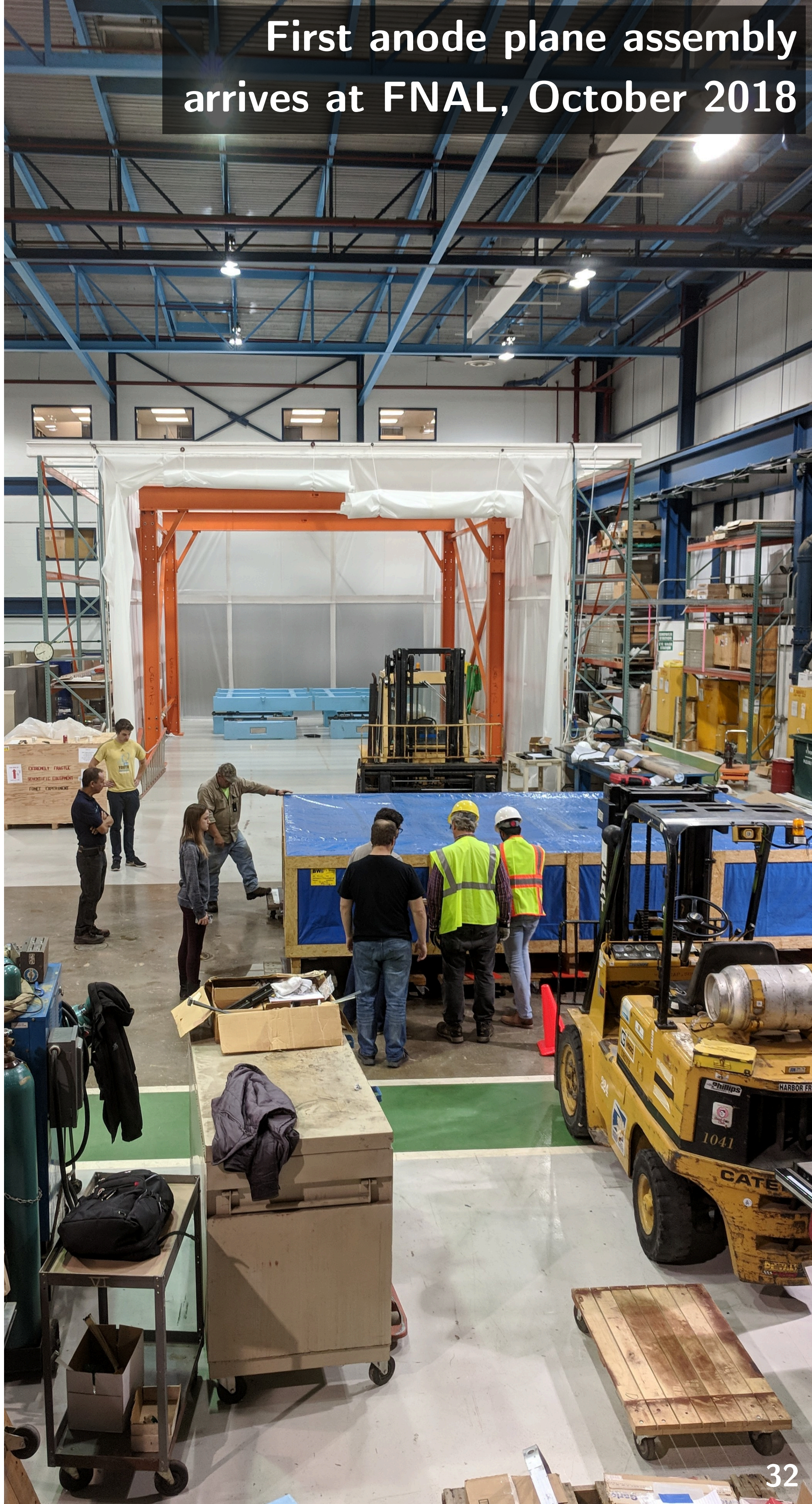
Project Status

- Components arriving at FNAL for assembly
  - Anode (wire) planes and cathode
  - Built at US & UK facilities
- Full TPC electronics & DAQ integration test completed using the LArIAT TPC
- Full PMT system test at LANL soon

- **Q1 2019:** TPC Assembly
- **Q3 2019:** Cryogenics installation
- **Q1 2020:** Detector commissioning
- **Q3 2020:** Physics data taking





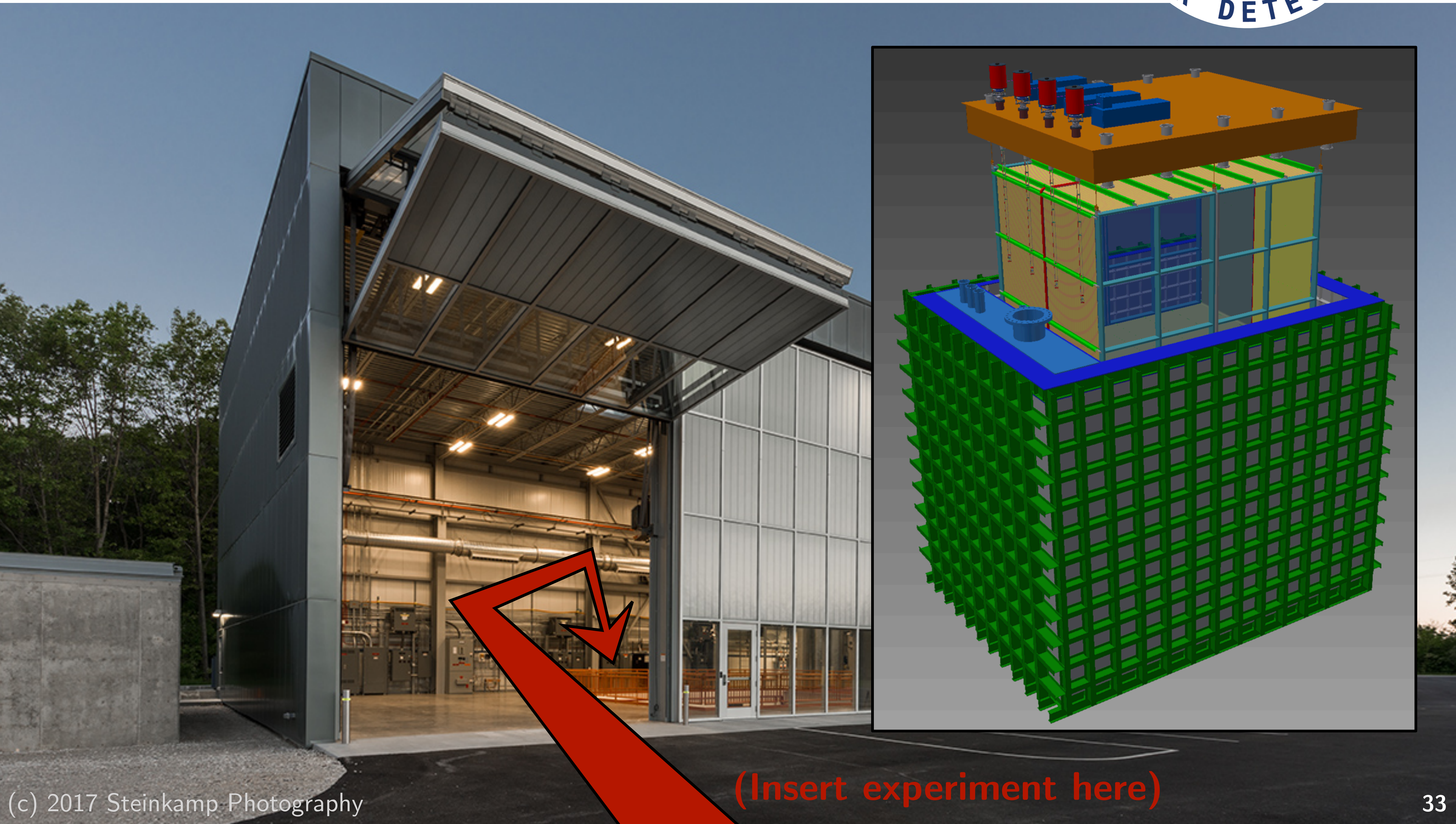


SBND

The Short-Baseline Near Detector

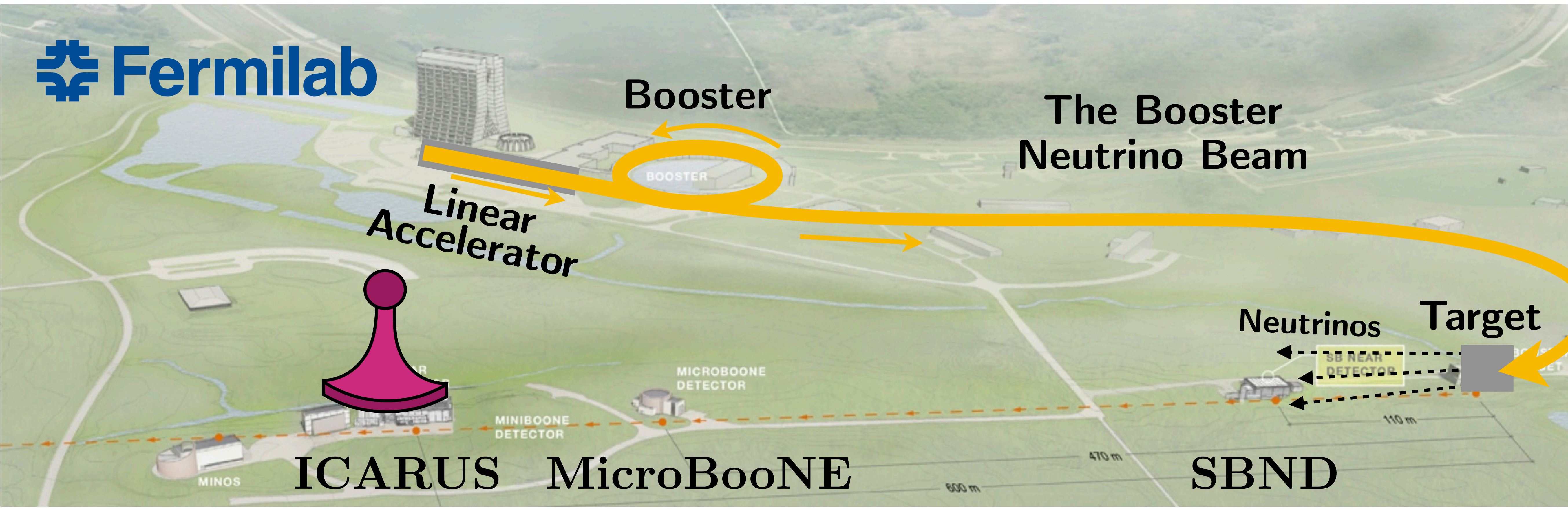
SBND

The Short-Baseline Near Detector



ICARUS

The Short-Baseline Far Detector



ICARUS T600

The Short-Baseline Far Detector

- Far detector for the SBN program
- 600 m baseline, 476 tons active LAr
- Ran at LNGS 2010 - 2013
- Refurbished, upgraded at CERN
- Now being installed at FNAL

Photo: CERN

(c) 2017 Steinkamp Photography

ICARUS LArTPC experience

- 1988: ICARUS Liquid Argon Imaging Chamber: A Novel Detector Technology
- 1994: Study of electron-ion recombination in liquid argon
- 1995: TPC signal processing using artificial neural networks
- 2004: Design, construction and tests of the ICARUS T600 detector
- 2006: Measurement of through-going particle momentum by means of multiple scattering with the ICARUS T600 TPC
- 2013: Experimental search for the LSND anomaly with the ICARUS detector in the CNGS neutrino beam

and many more! *(icarus.lngs.infn.it/publications.php)*


LNGS
Photo: CERN, icarustrip.fnal.gov


#icarustrip
Lake Geneva
Photo: CERN, icarustrip.fnal.gov

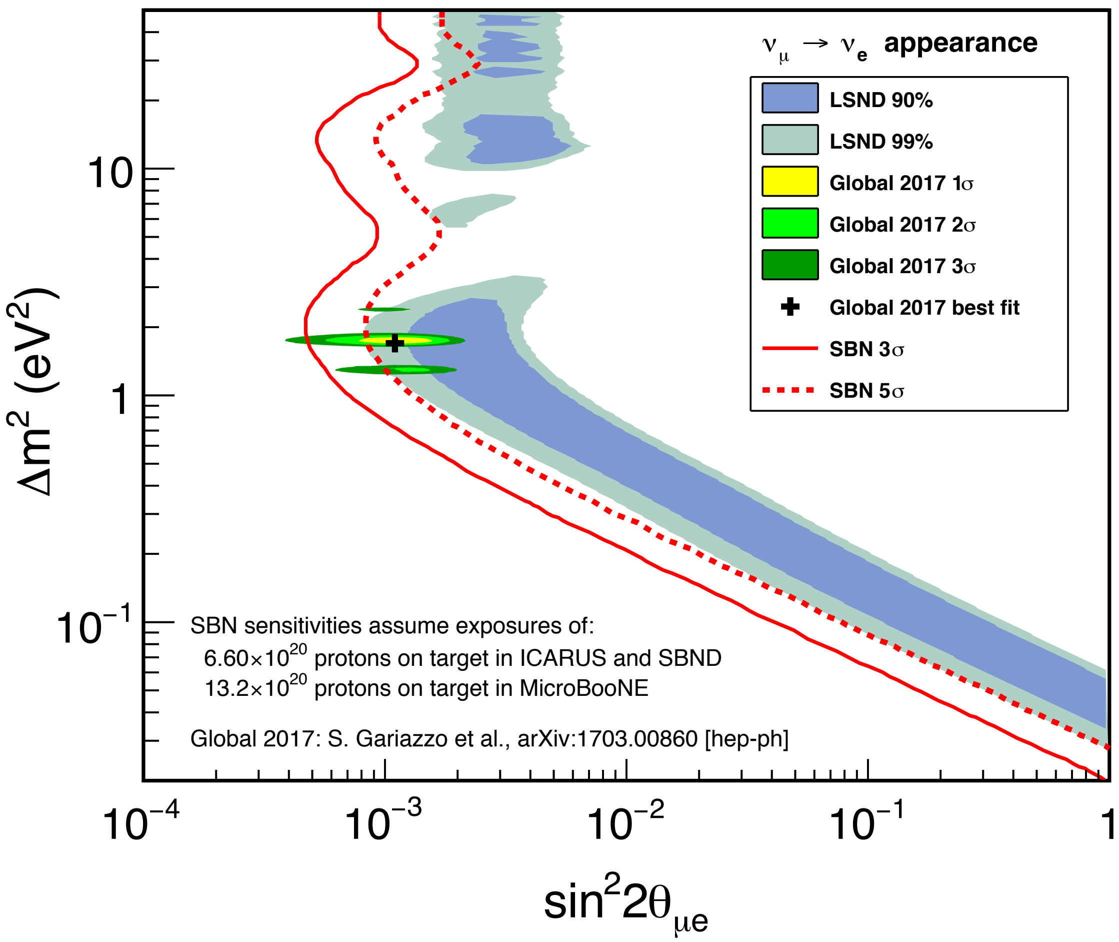

Indiana
Photo: Rich Allen, Ports of Indiana, , icarustrip.fnal.gov


Fermilab
OVERSIZE LO

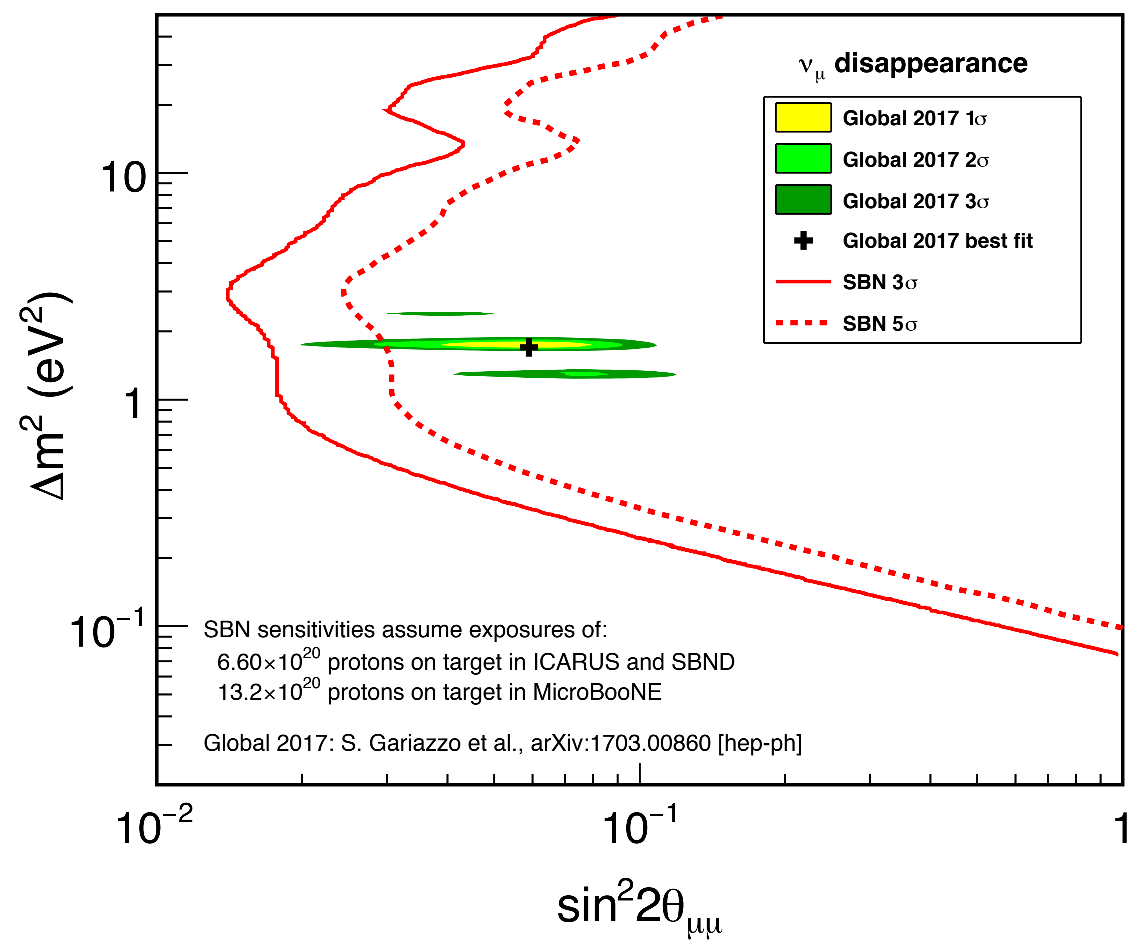
SBN Sensitivity

SBN Program

ν_e Appearance



ν_μ Disappearance



$$P_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2 2\theta_{\mu e} \sin^2(1.27\Delta m^2_{41} L/E)$$

$$P_{\mu\mu} = 1 - 4(1 - |U_{\mu 4}|^2)|U_{\mu 4}|^2 \sin^2(1.27\Delta m^2_{41} L/E)$$

Cover the LSND allowed region at 5σ...

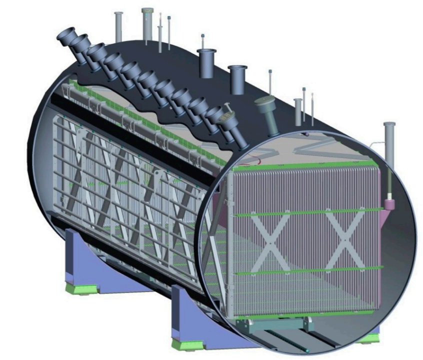
...and search for ν_μ disappearance which ν_e appearance implies

SBN Program

Status & Prospects

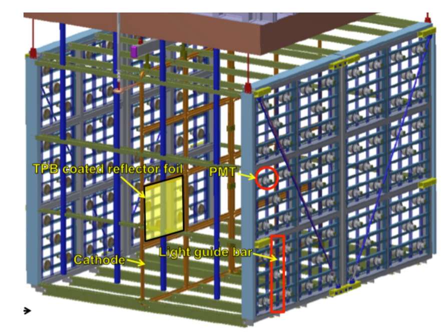
MicroBooNE

- MiniBooNE low-energy excess, cross sections
- Running since 2015, leading the way



SBND

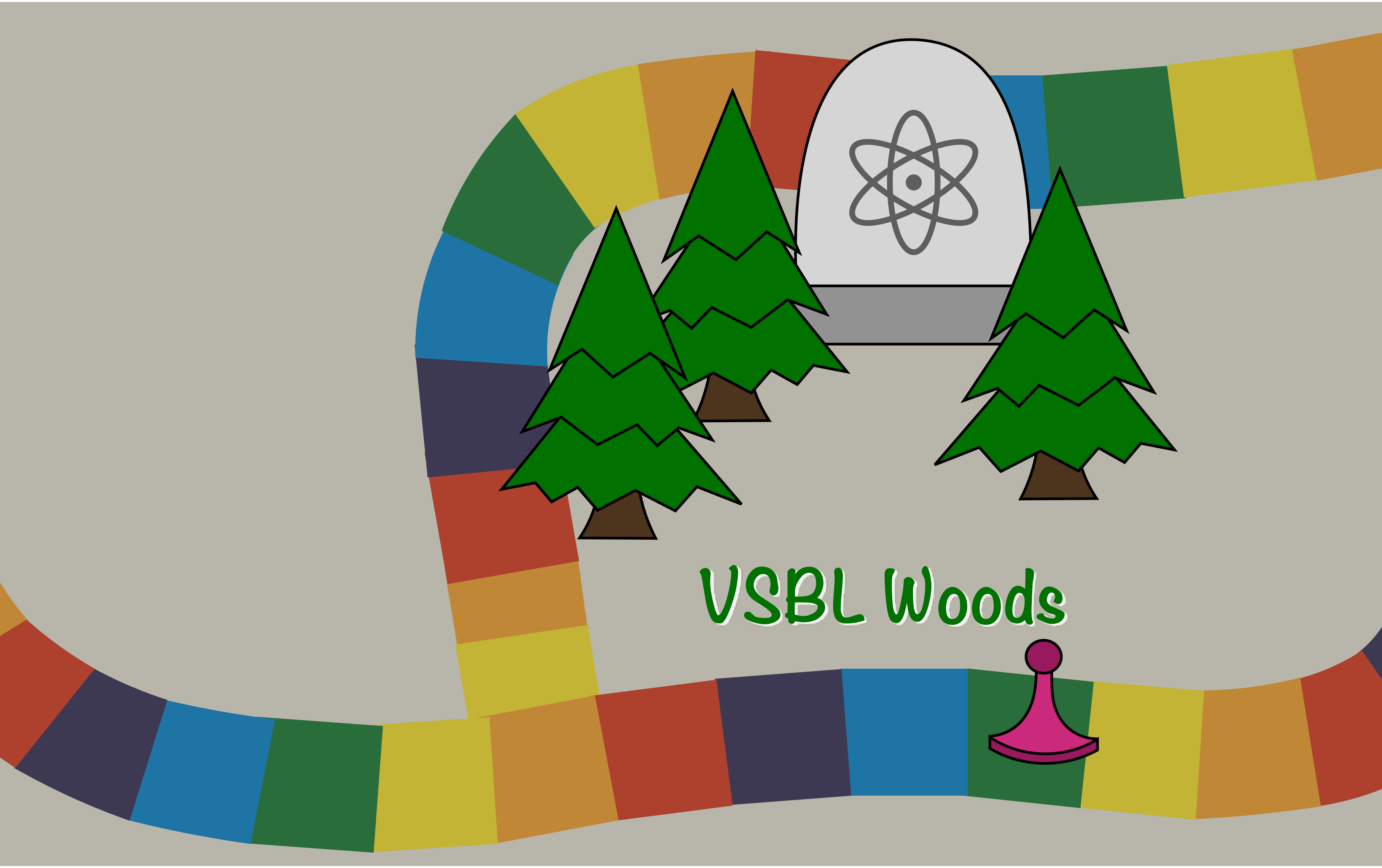
- Near detector, precision cross sections
- Construction phase



ICARUS-T600

- Far detector from far away
- Installation phase

The full SBN Program is coming soon, and will definitively address the eV-scale sterile neutrino anomalies, provide unprecedented precision on ν-nucleus interactions, and provide key inputs to the DUNE long-baseline program.


VSBL Woods

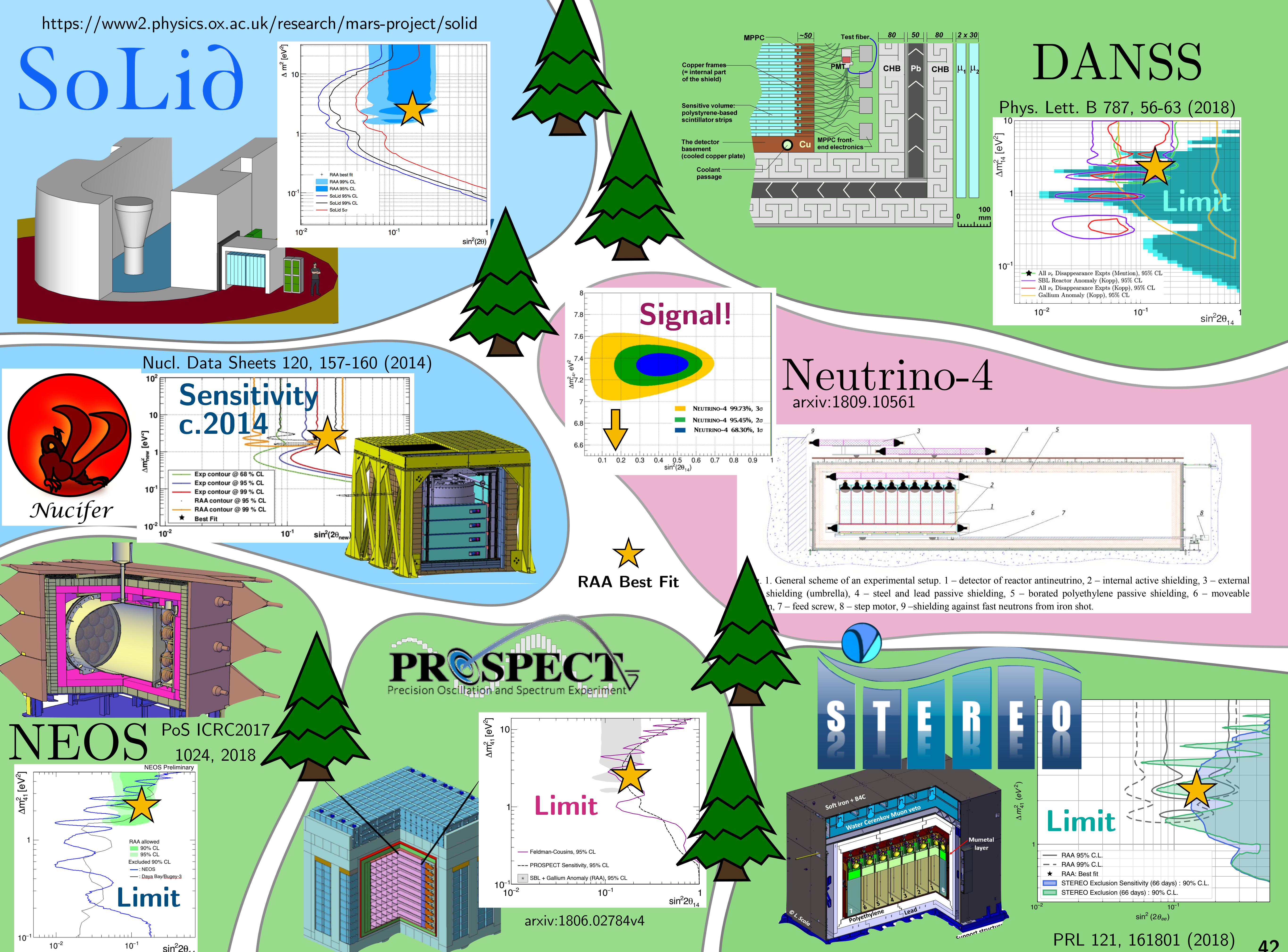
VSBL Oscillation Searches

Physics at Very Short Baselines

- Reactor anomaly can be interpreted as a ν_e disappearance effect
- $L/E \sim 1$ m/MeV anomalies
  - Reactor antineutrinos at a few MeV $\rightarrow$ oscillations baselines of a few meters

Strategies:

- IBD detectors
- Very close to a compact source
  - Research reactors, DAR sources
- Pure sources (e.g. ^{235}U)
  - Disentangle spectral anomalies
- Good spatial & energy resolution



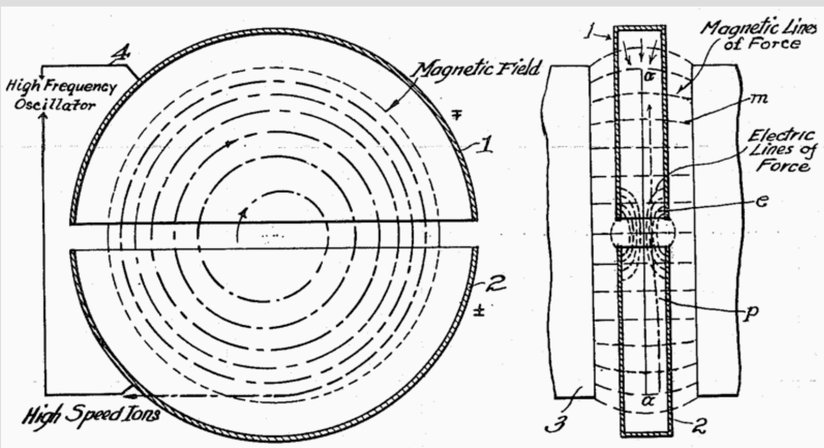
https://www2.physics.ox.ac.uk/research/mars-project/solid
SoLid
DANSS
Phys. Lett. B 787, 56-63 (2018)
Limit
MPPC
Test fiber
PMT
CHB
Pb
Copper frames (= internal part of the shield)
Sensitive volume: polystyrene-based scintillator strips
The detector basement (cooled copper plate)
Coolant passage
Cu
MPPC front-end electronics
Signal!
Neutrino-4
arxiv:1809.10561
RAA Best Fit
Nucl. Data Sheets 120, 157-160 (2014)
Sensitivity c.2014
Nucifer
NEOS
PoS ICRC2017 1024, 2018
NEOS Preliminary
Limit
PROSPECT
Precision Oscillation and Spectrum Experiment
Limit
arxiv:1806.02784v4
STEREO
Limit
PRL 121, 161801 (2018)

Isotope Decay at Rest

Physics at Very Short Baselines

DAEδALUS
IsoDAR

Cyclotron + KamLAND = Wiggles

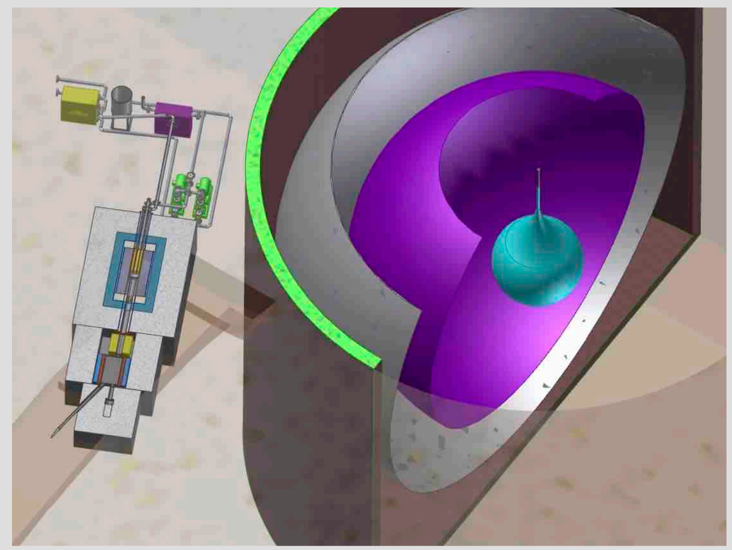


Lawrence's 1934 patent drawing for the cyclotron (Wikipedia)

H_2^+ source feeds a 60 MeV/amu cyclotron, stripped into proton beam on ^{9}Be target.

n captures on ^{7}Li create ^{8}Li

^{8}Li β decay $\rightarrow$ lots of $\overline{\nu}_e$

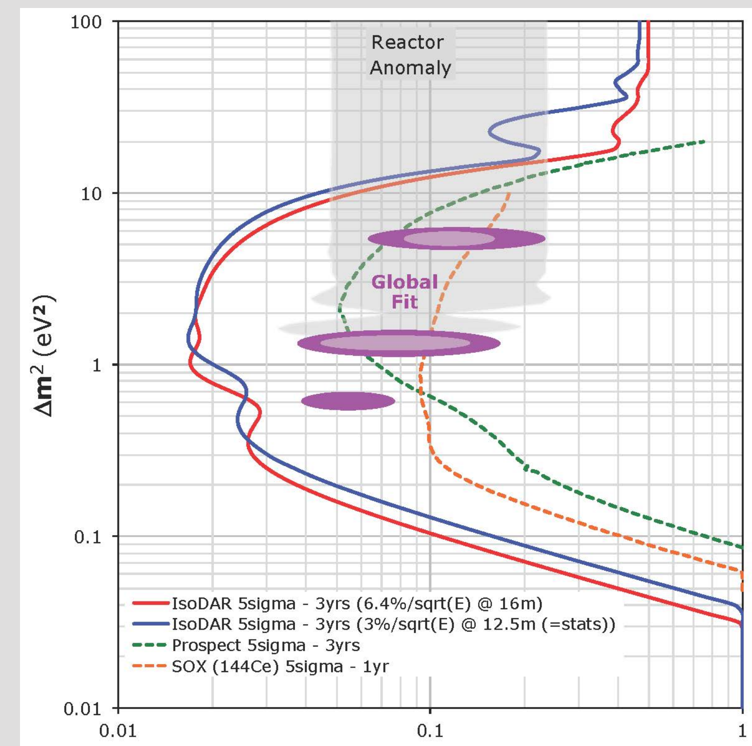


arxiv:1710.09325

Ultra high purity liquid scintillator detector

$\sigma_E \sim 3\%/\sqrt{E}$ (planned)

IBD $\overline{\nu}_e(p,n)e^+$ and ν_e-e elastic scattering



arxiv:1710.09325

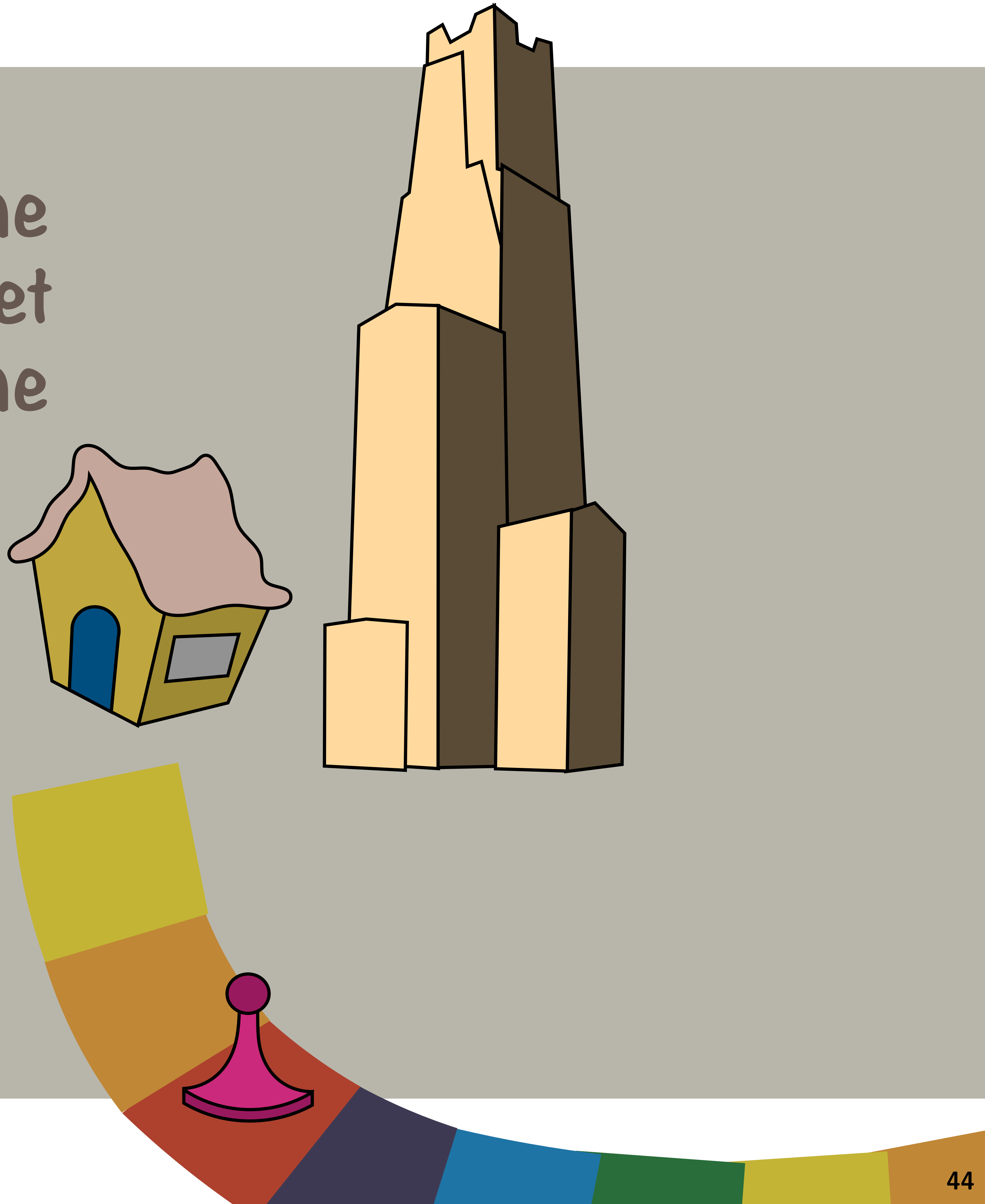
Reconstruct events in position and energy

Look for oscillations in L/E

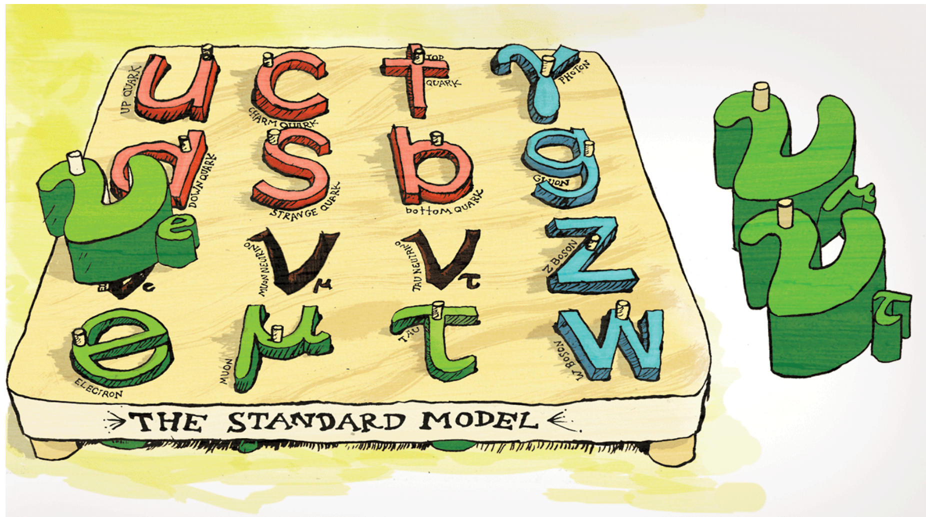
DAEdALUS is a future higher-intensity multi-baseline system, to search for CPV at short baselines

See www.nevis.columbia.edu/daedalus

Home
Sweet
Home



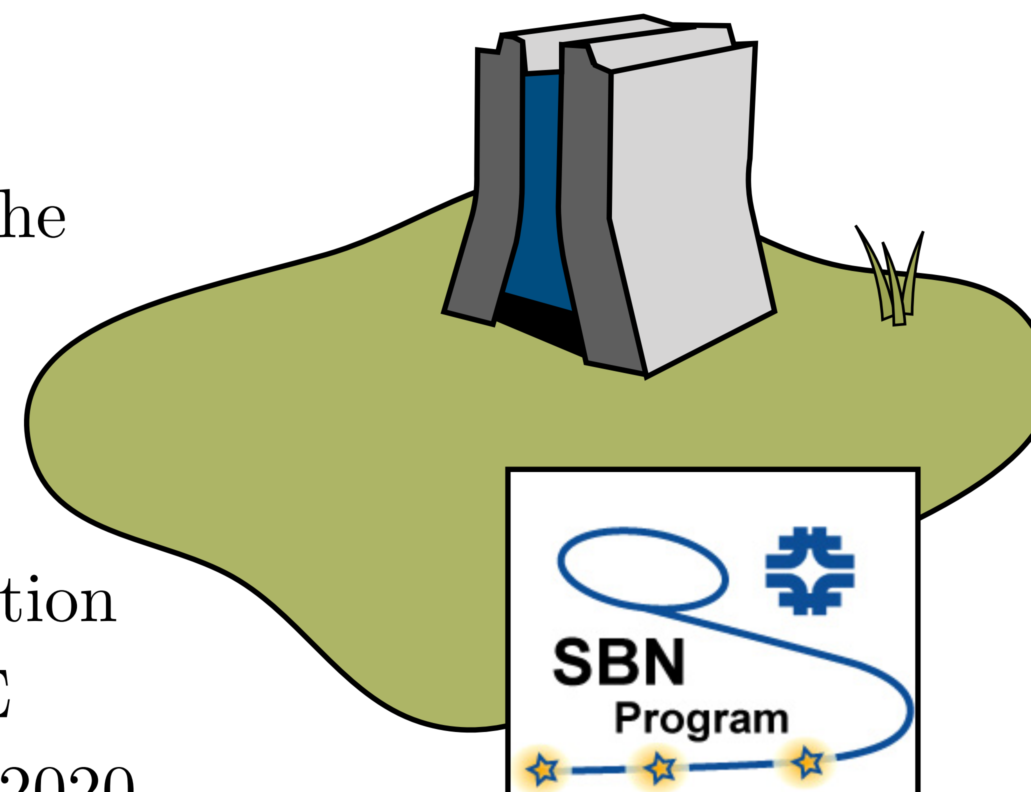
Conclusions

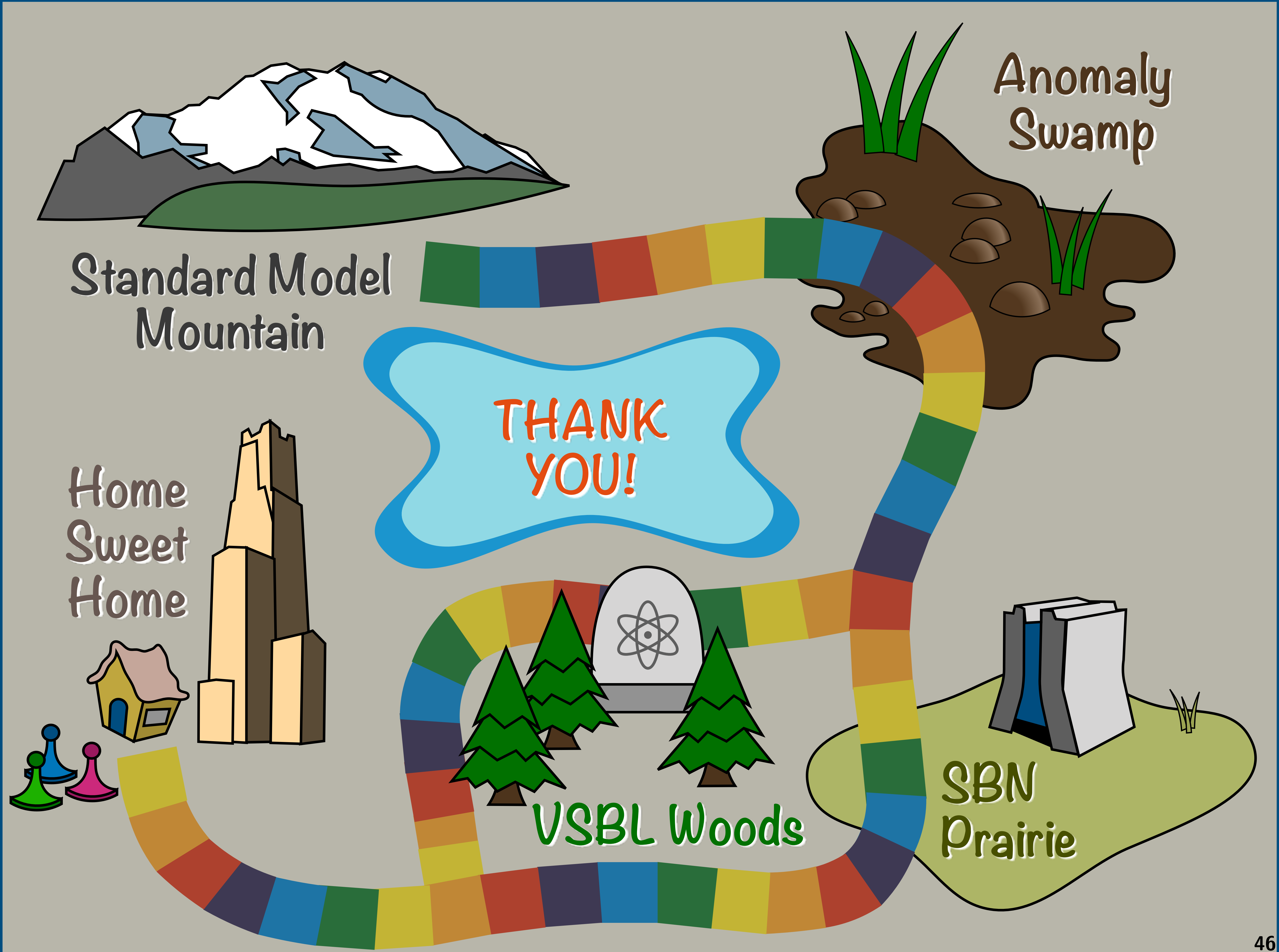


Symmetry Magazine, 2/2013

- Several anomalies, significant tension in the data
- There is *something* we're missing, sterile neutrinos or neutrino interactions, need to sort it out to move the field forward

- The SBN program will make a definitive test of the LSND-like anomalies
  - Three imaging LArTPCs at three baselines
  - Intense neutrino beam at Fermilab BNB
- MicroBooNE is running now, producing cross section measurements and studying the MiniBooNE LEE
- SBND and ICARUS are coming, full program in 2020
- Complementary VSBL experiments are meanwhile probing the sterile landscape



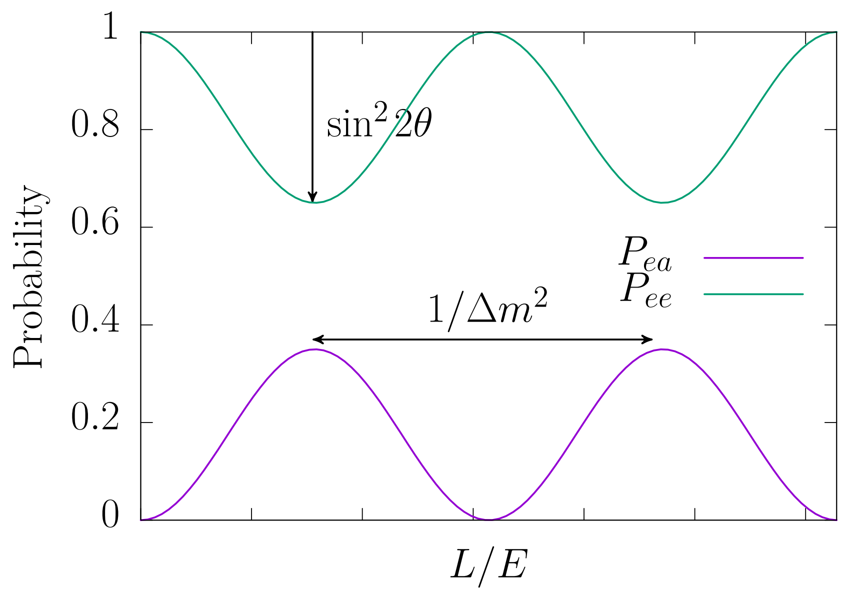


Standard Model Mountain
Anomaly Swamp
THANK YOU!
Home Sweet Home
VSBL Woods
SBN Prairie

Backup Slides

Standard Model

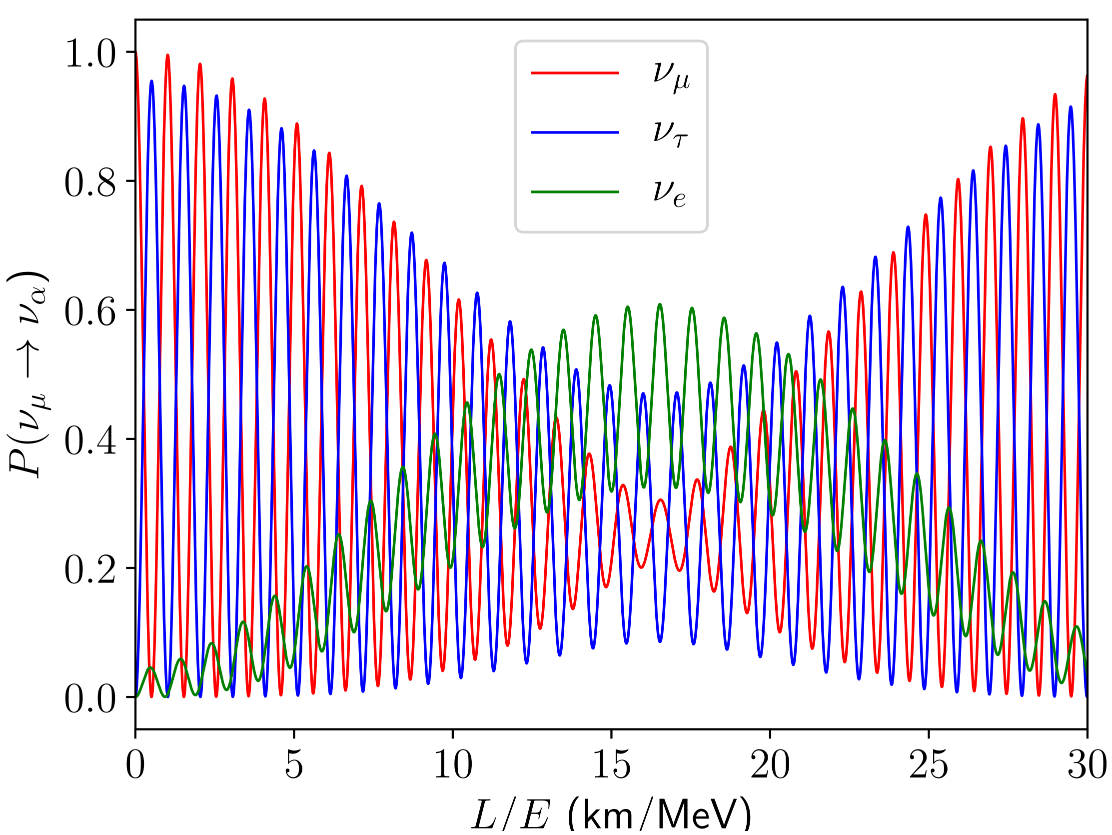
Three-Neutrino Oscillations

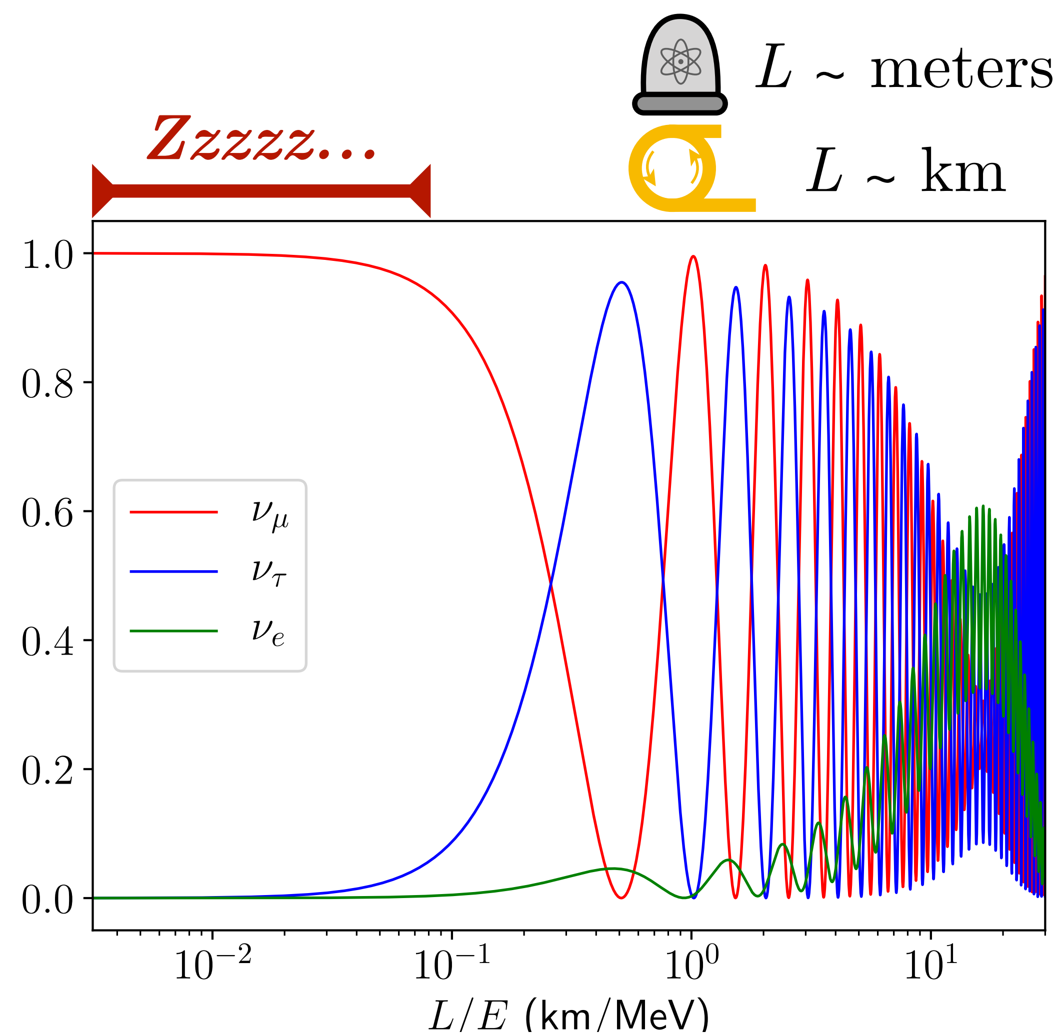


In a two-neutrino approximation, the *survival probability*

$$P_{ee} = 1 - P_{ea} = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2\ [\mathrm{eV}^2]\ L\ [\mathrm{km}]}{E_\nu\ [\mathrm{GeV}]}\right)$$

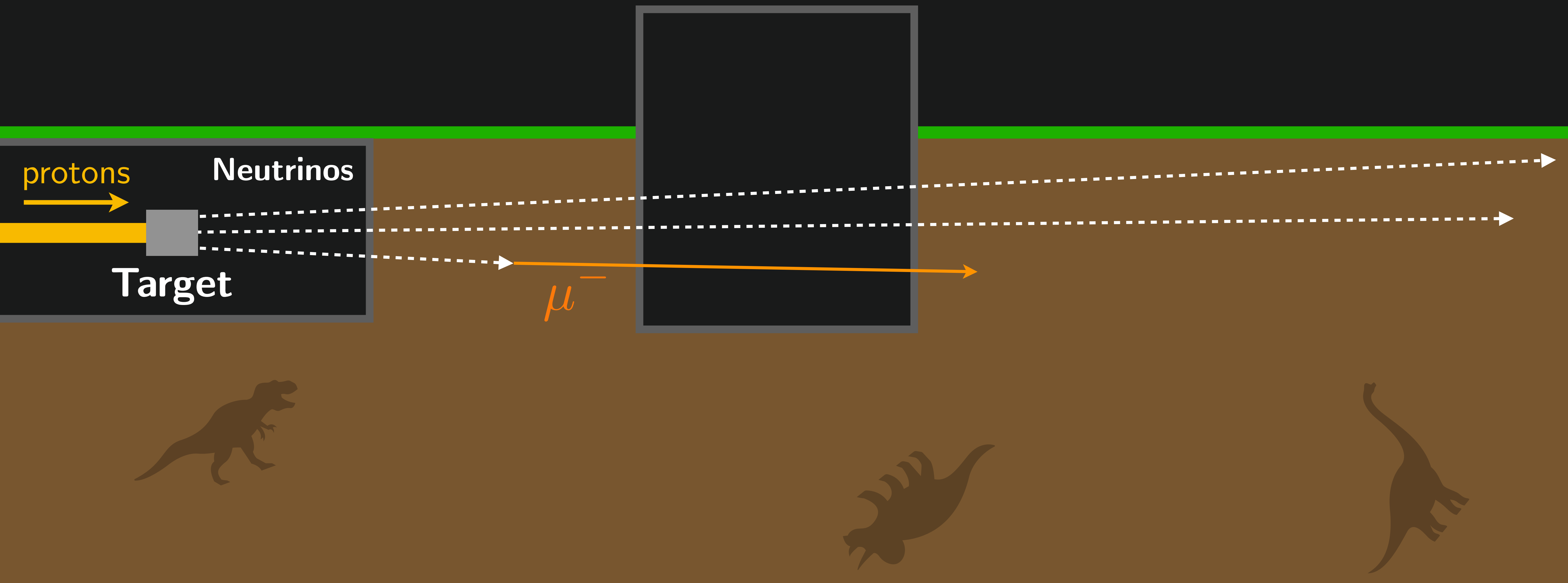
Where $\Delta m^2 \equiv m_2^2 - m_1^2$ and θ are constants of nature, and we control L and E_ν.

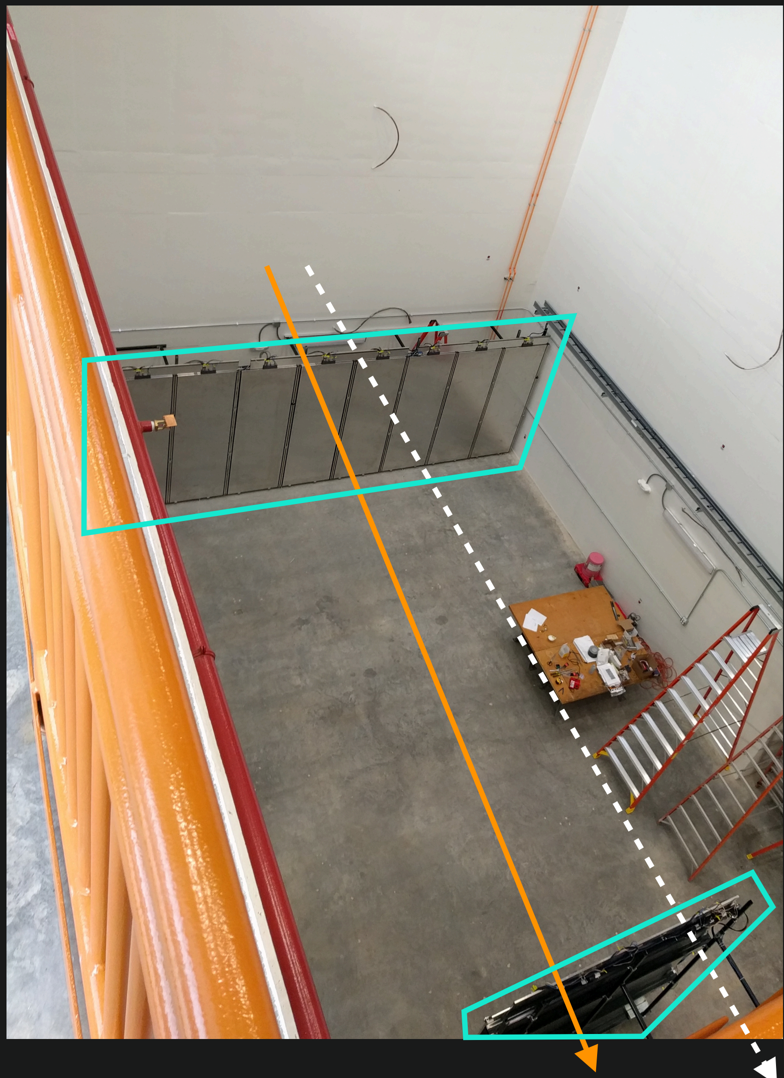




SBND

The Short-Baseline Near Detector



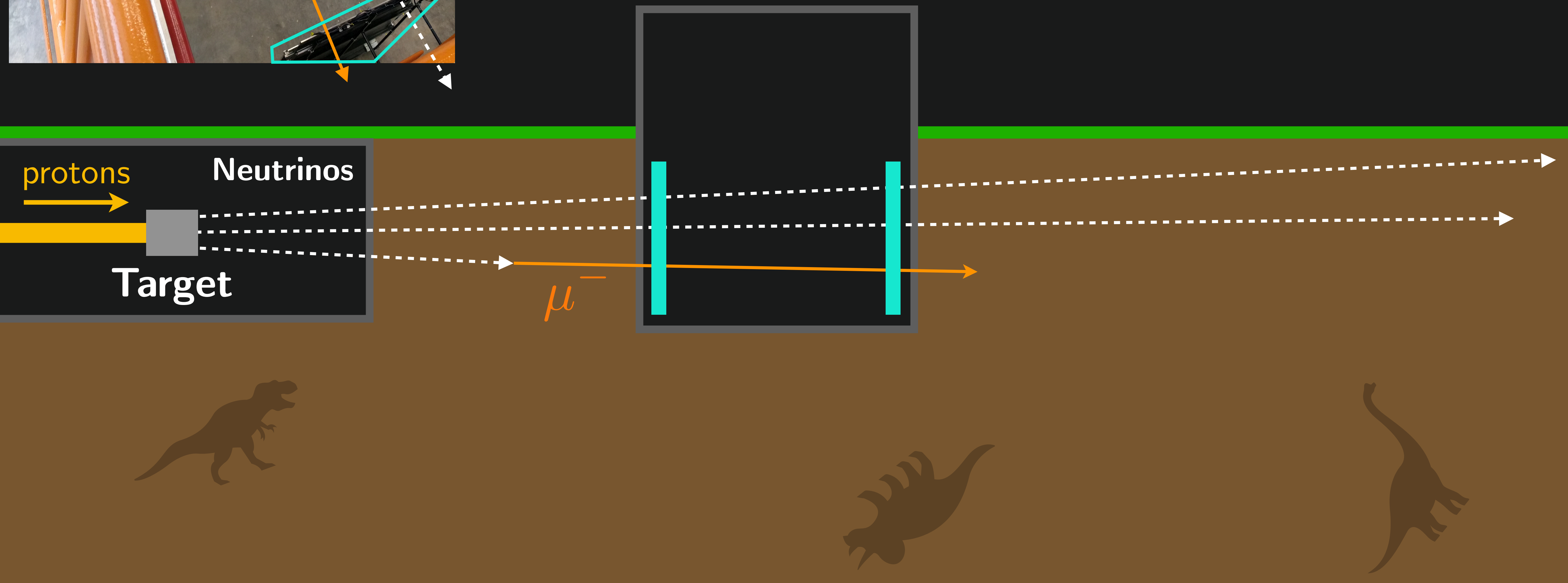


SBND

The Short-Baseline Near Detector

Outfitted the pit with scintillator detectors to look at muons from the dirt

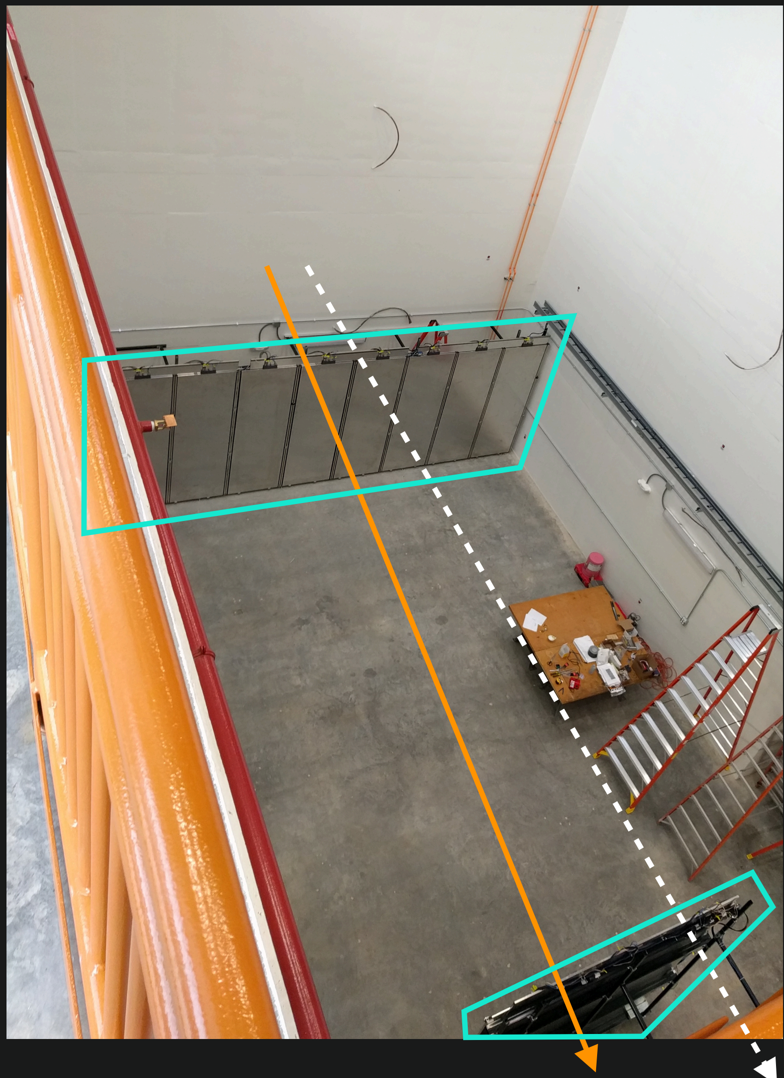
A first look at the neutrino beam



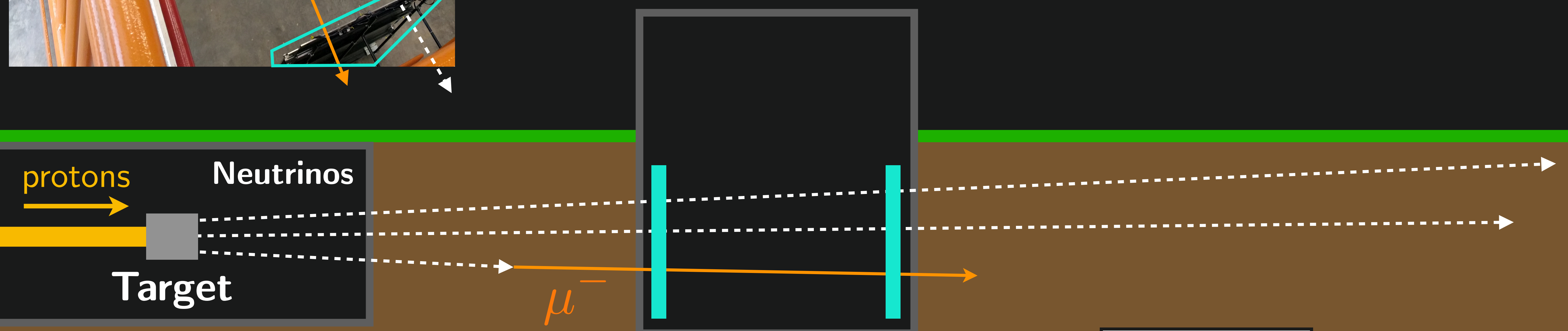
SBND

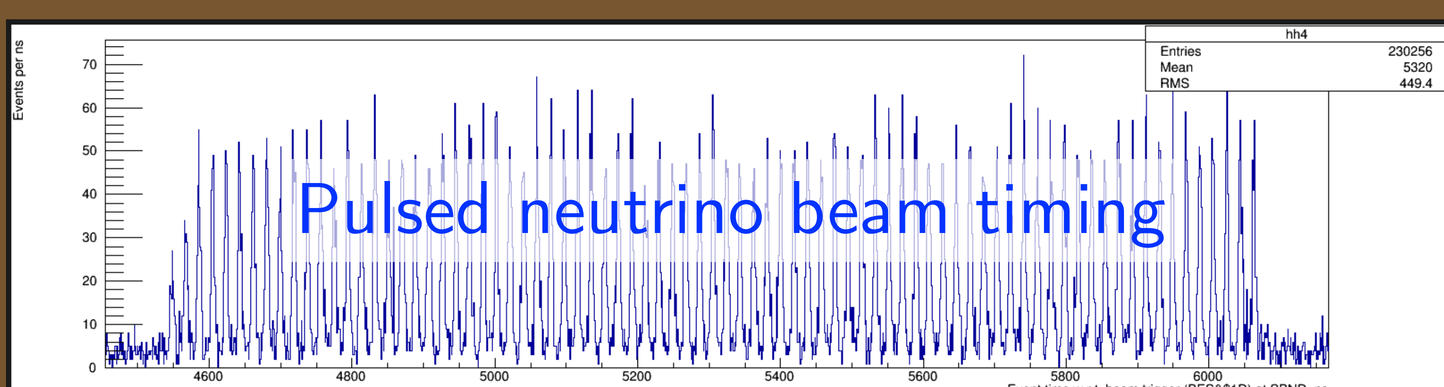
The Short-Baseline Near Detector

Outfitted the pit with scintillator detectors to look at muons from the dirt

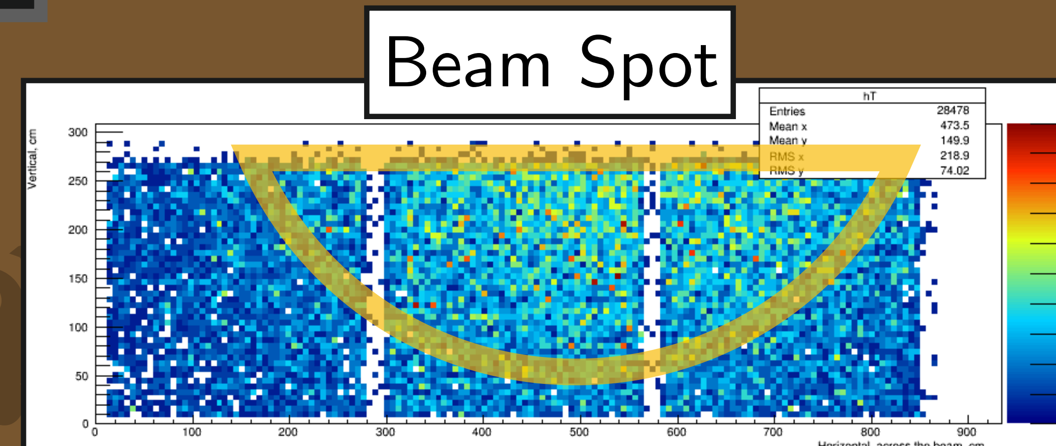


A first look at the neutrino beam





Igor Kreslo, Bern



Igor Kreslo, Bern

Fermi National Accelerator Laboratory
Batavia, IL

Photo: Google Maps


ICARUS
MicroBooNE
SBND
Wilson Hall
Ramsey Auditorium
Pine St
Kautz Rd
Giese Rd
Schwahn Rd
Indian Creek Rd
Outer Ring Rd
Google
Photo: Google Maps
Fermi National
Accelerator Laboratory
Batavia, IL

VSBL Experiments

Physics at Very Short Baselines

Experiment	P_{th} [MW]	L [m]	depth [mwe]	m [t]	technique	S/B
Nucifer	70	7	12	0.8	Gd-LS	<1
Neos	2700	25	20	1	Gd-LS	22
DANSS	3000	9–12	50	0.9	Gd-PS	~ 20
Neutrino-4	100	6–11	5–10	1.5	Gd-LS	<1
Stereo	57	9–11	10	1.7	Gd-LS	>1
Solid	100	6–11	10	1.6	^{6}Li-PS	~ 3
Prospect	85	7–12	~ 5	3	^{6}Li-LS	>1

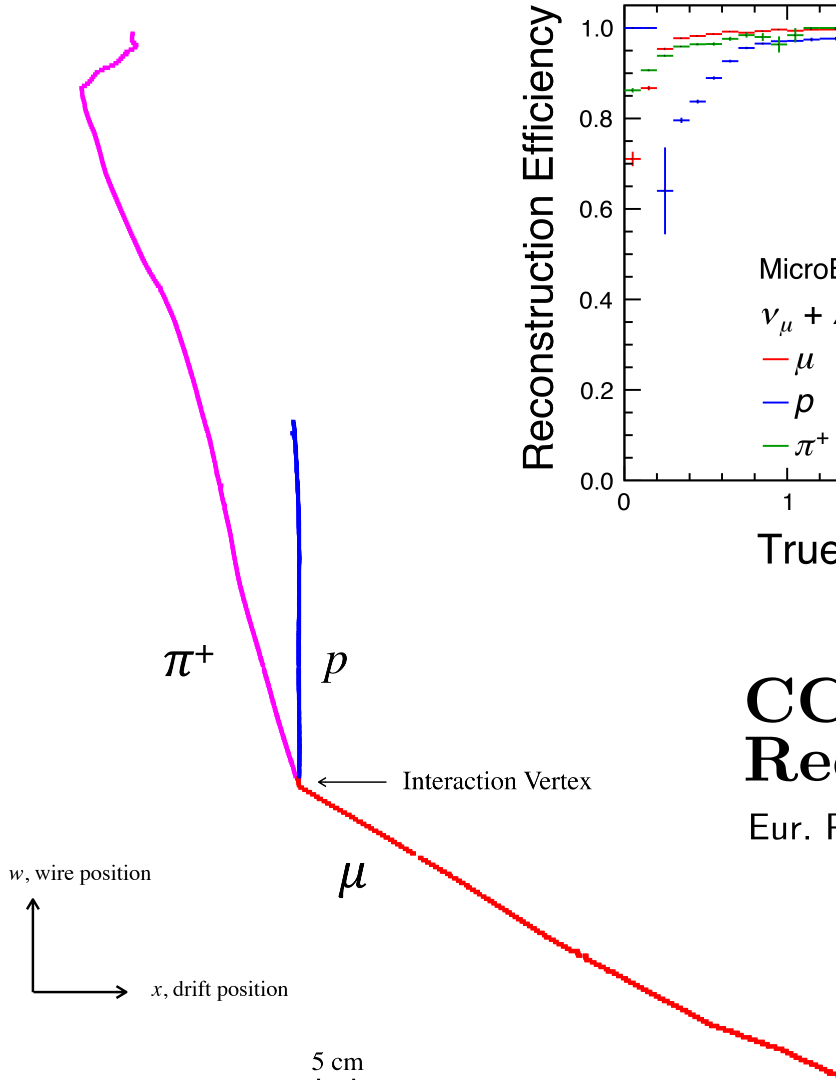
C. Buck, NuPhys2016, arxiv:1704.08885

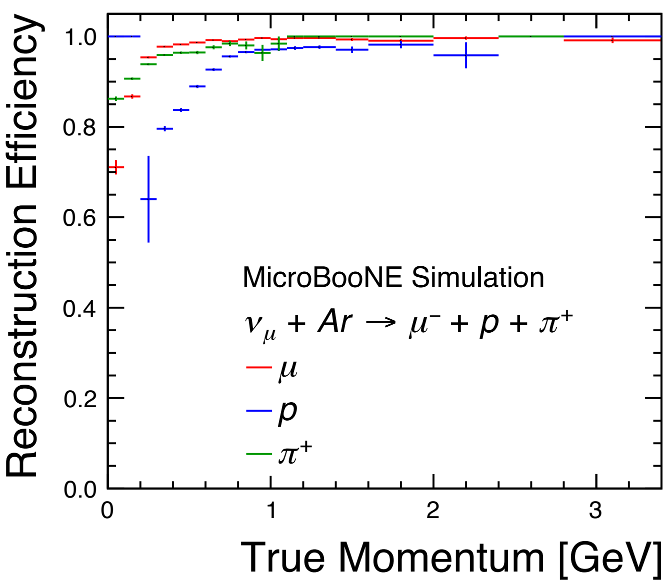
MicroBooNE

Event Reconstruction in LArTPCs

Pandora Path

- Pattern recognition using particle flow
- Pandora development toolkit
  - Eur. Phys. J C 75, 439 (2015)



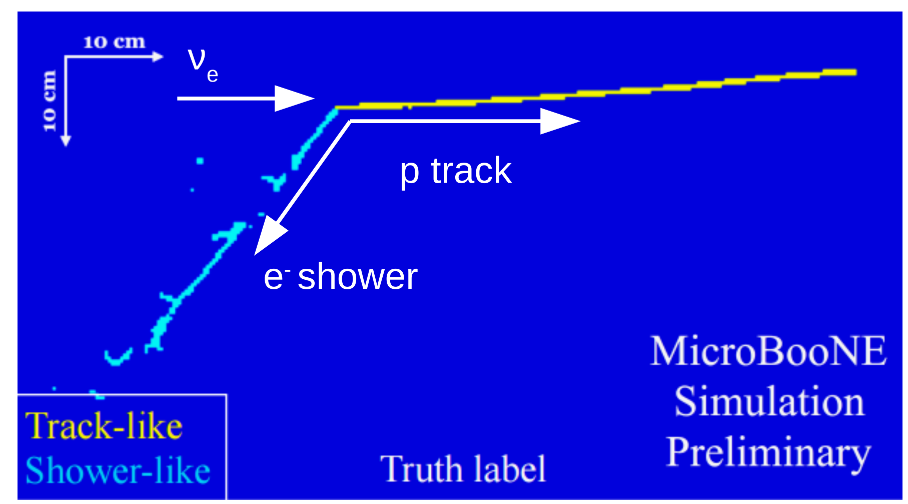


CC Event Reconstruction

Eur. Phys. J. C78, 1, 82 (2018)

Deep Learning Path

- Novel image classification approaches
- Focused on $1\ell 1p$ final states
- arxiv:1808.07269, JINST 12, P03011 (2017)

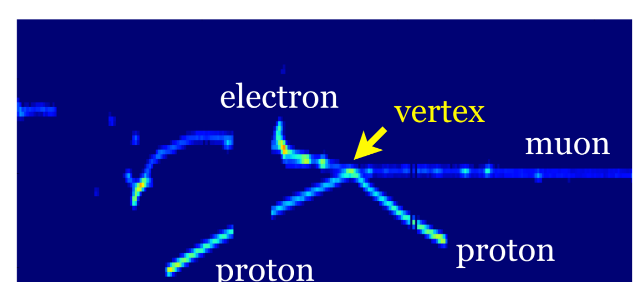


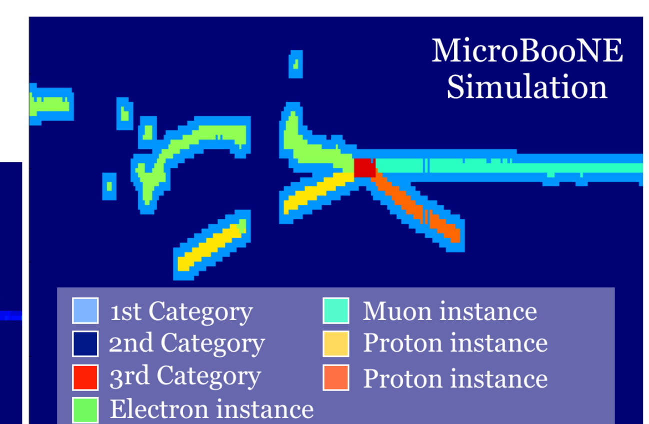
Track and Shower Pixel Labeling

JINST 12, P03011 (2017)

Particle ID

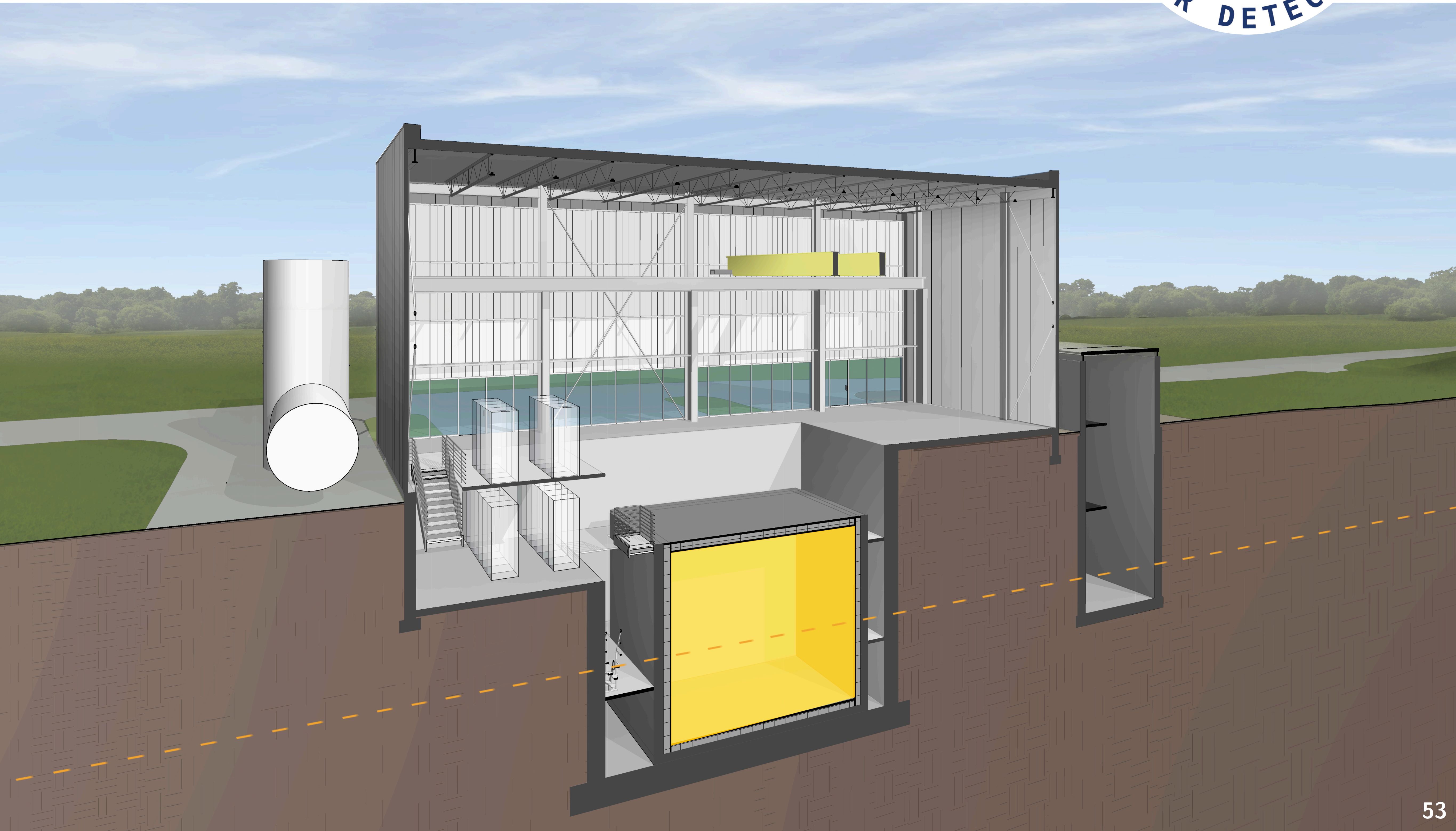
arxiv:1808.07269





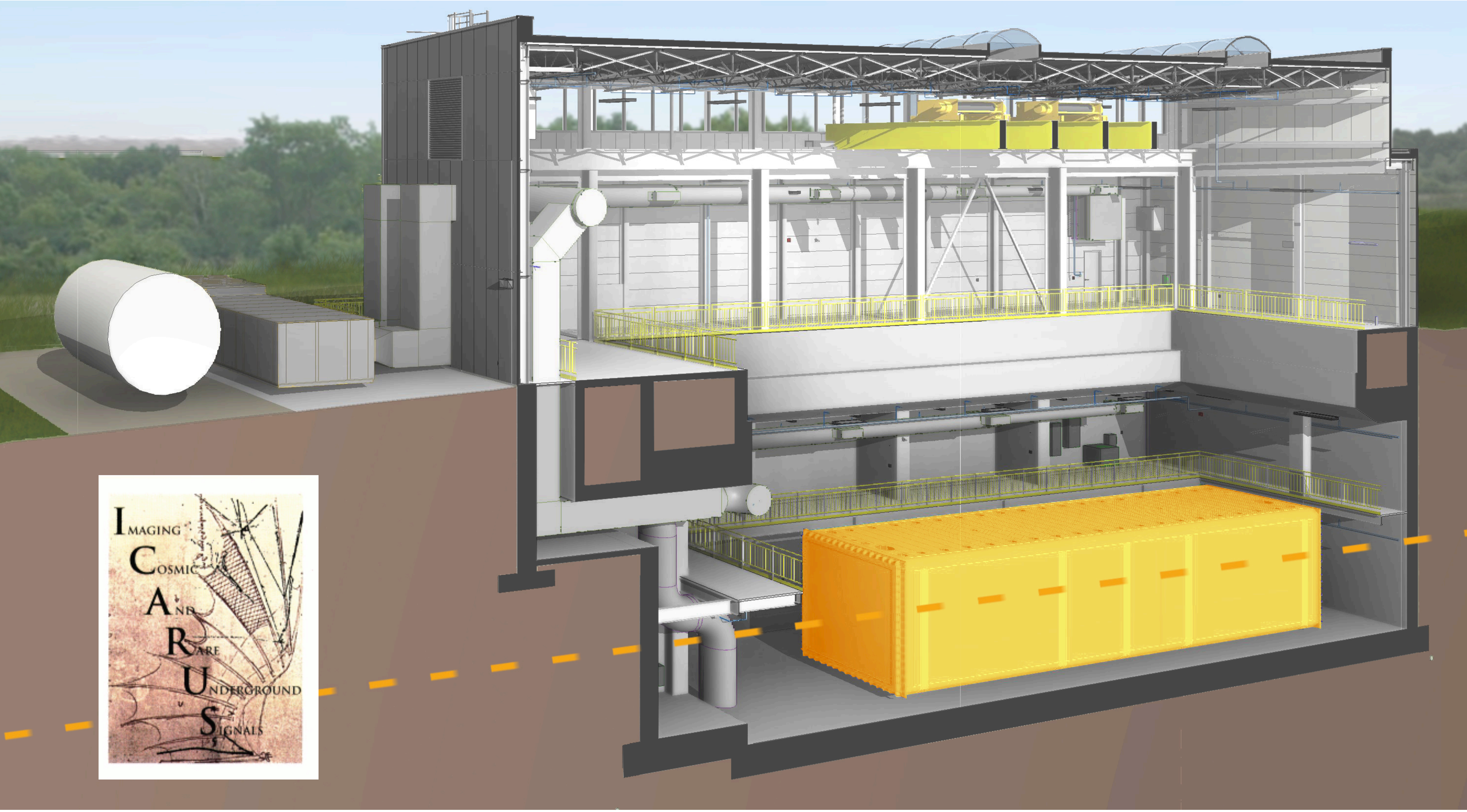
SBND

The Short-Baseline Near Detector



ICARUS

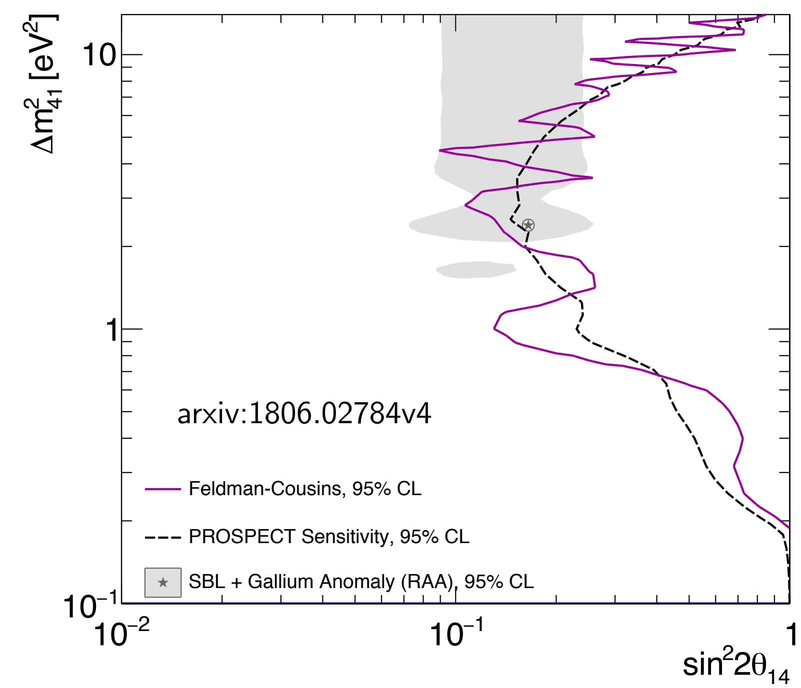
The Short-Baseline Far Detector

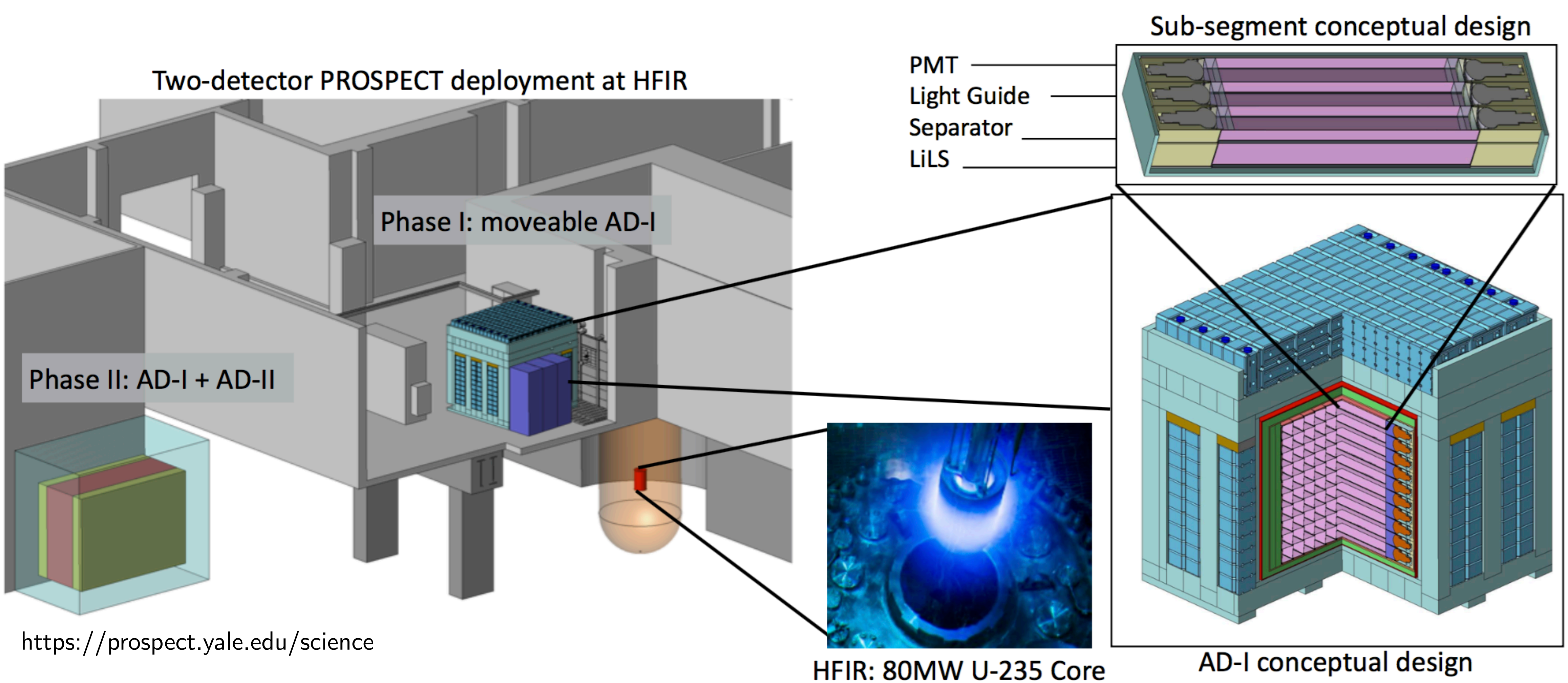


PROSPECT

A VSBL Example

- Detector close to a 99% ^{235}U research reactor (HFIR at ORNL)
- Baselines of 7-12 m and 16-20 m
- Segmented ^{6}Li doped liquid scintillator
- Addresses reactor flux anomaly and sterile neutrino oscillations





https://prospect.yale.edu/science