LABORATORIUM FÜR HOCHENERGIEPHYSIK
LHEP
UNIVERSITÄT BERN

Sterile Neutrinos

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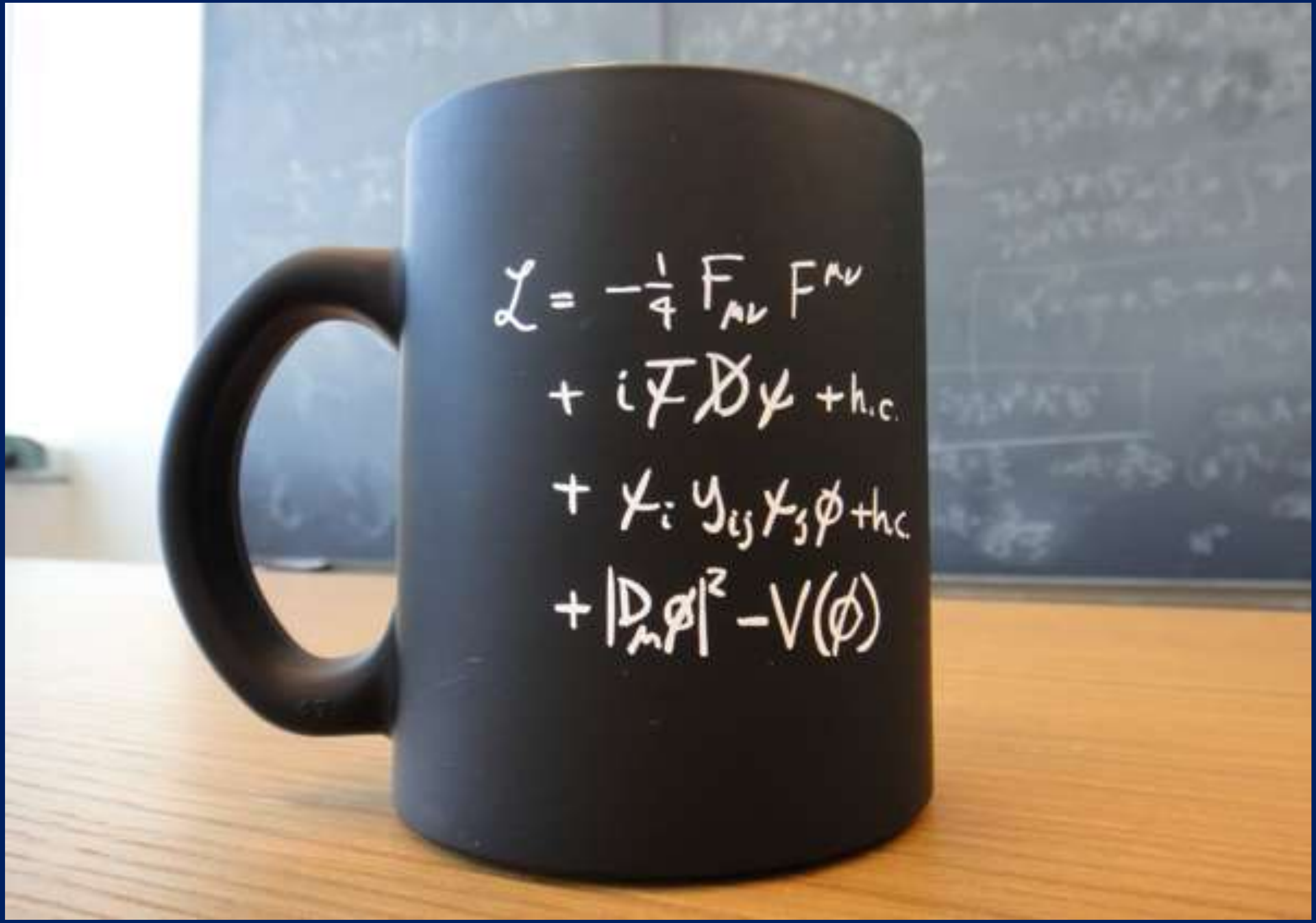
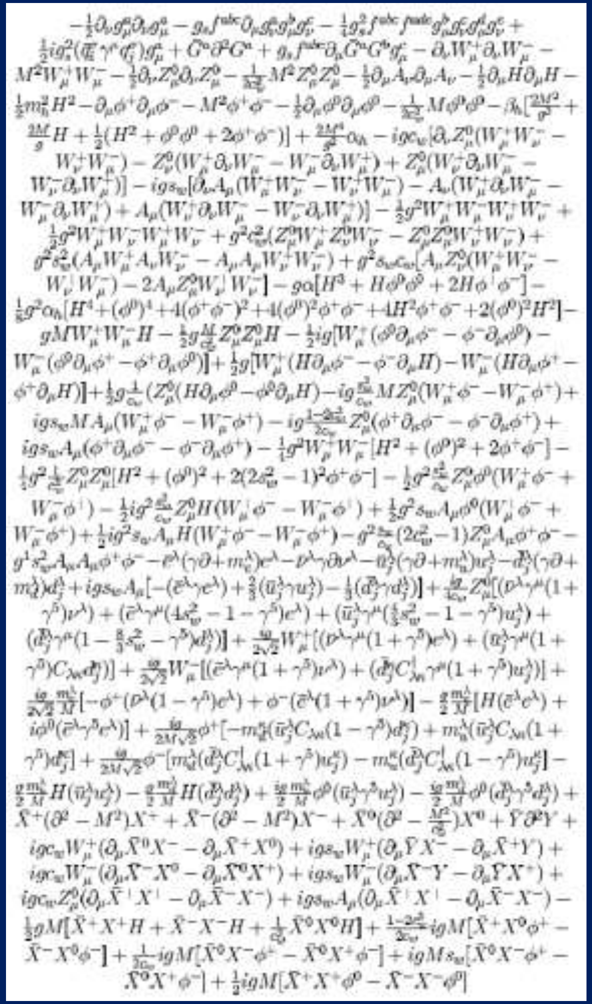
ATLAS EXPERIMENT

Seminar, Freiburg (D), June 2019

Standard Model of particle physics





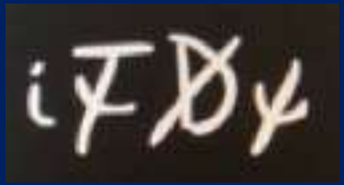
Are we done? No !

- Gravity is not included
- Matter-antimatter asymmetry?
- Large tuning needed to obtain the measured low Higgs mass (natural ?)
- Unification of electroweak and strong forces?
- Dark matter and dark energy?
- Origin of neutrino masses?
- Additional neutrino states ?
- …

Many scientists and projects addressing these questions

I will discuss neutrinos today, focusing on sterile neutrinos

Wolfgang Pauli



$$\frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda)$$

Coupling = small

Enrico Fermi

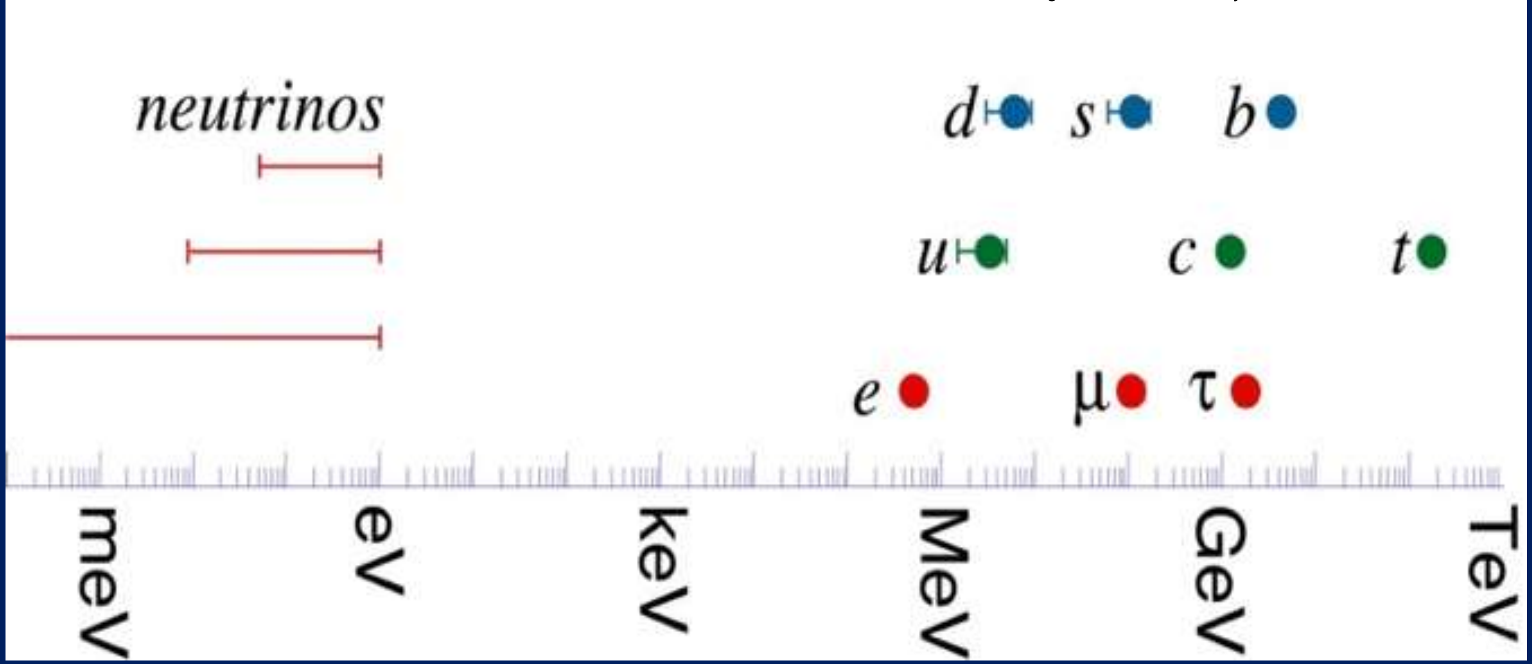
Neutrino Energy few MeV

$\sigma = 10^{-44}$ cm^2

Interaction Probability $= 10^{-11}$

10^{-39} cm^2 = 1 fb

Image credit Hitoshi Murayama



W und Z Bosons

Photon

Gluons

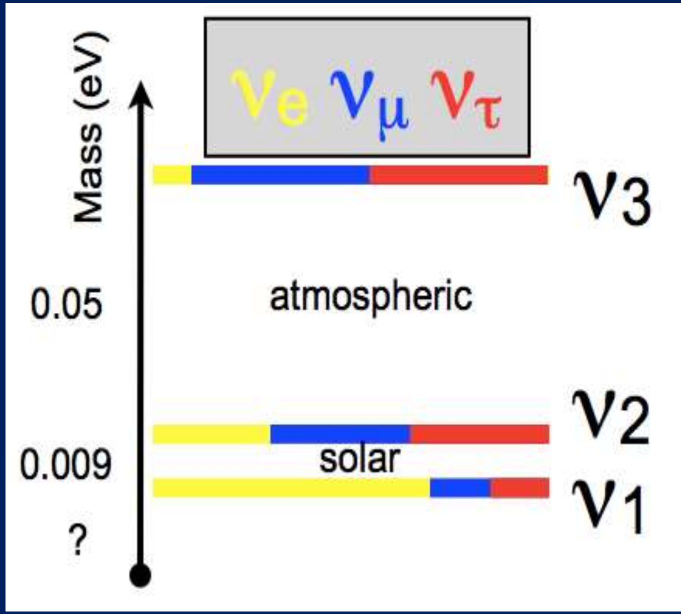
Higgs Boson

Neutrino oscillations

flavor		atmospheric	cross-mixing	solar	mass

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

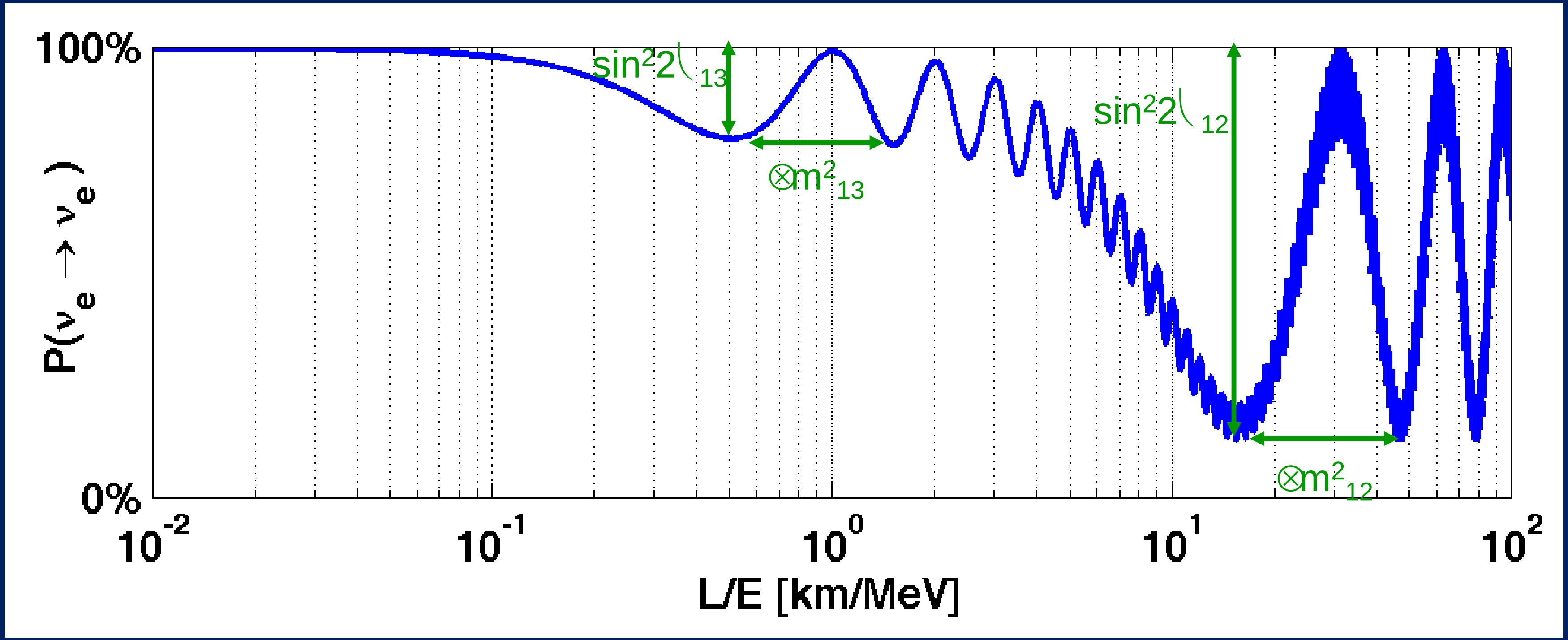
The PMNS matrix



Two-neutrino approximation

$$P(n_a \rightarrow n_b) = \sin^2 2q_{ij} \cdot \sin^2\left(1.27\,\mathrm{D}m_{ij}^2 \frac{L}{E}\right)$$

- Three angles θ_{12}, θ_{23} and θ_{13}
- One phase δ_{CP}
- Two mass-squared differences Δm^2_{21} and Δm^2_{23}



$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{13} L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{12} L}{4E}\right),$$

A global experimental effort

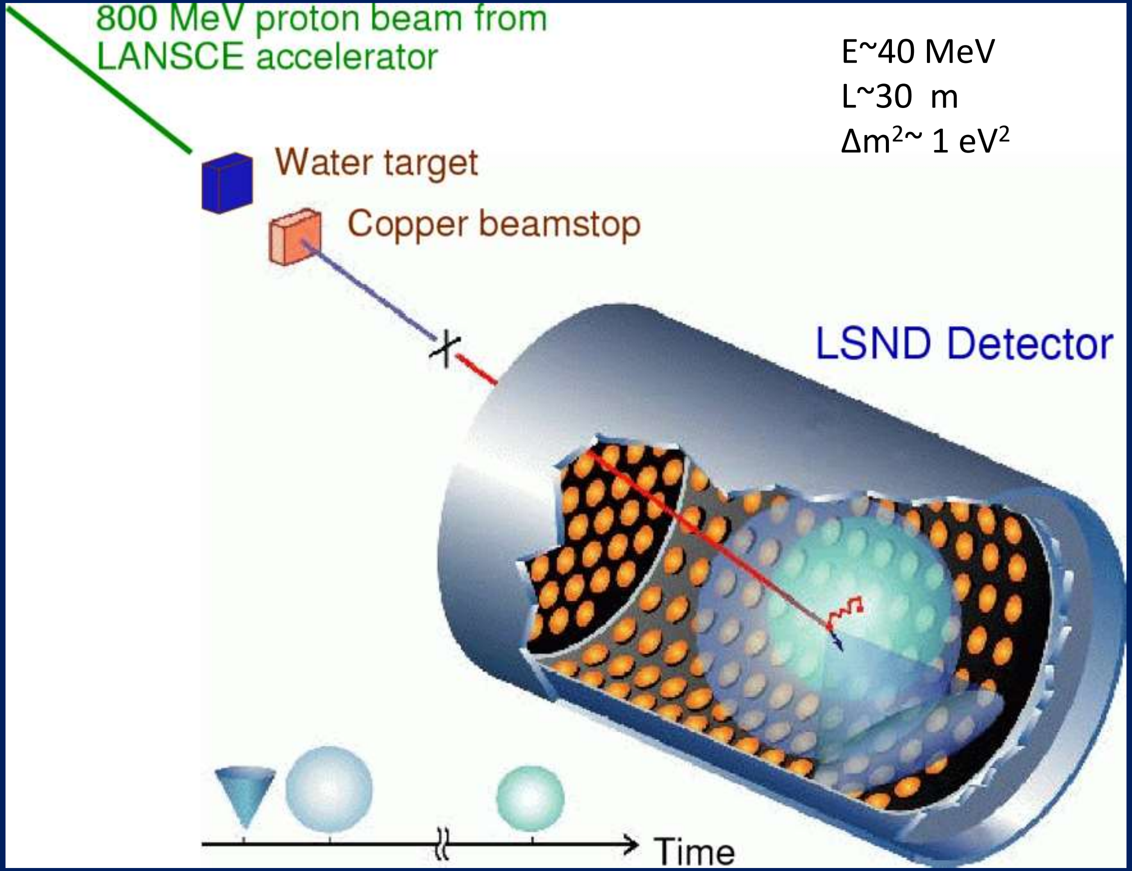
KamLAND, Double Chooz, Daya Bay, RENO, Gösgen, SNO, SK, T2K, MINOS, NOvA, OPERA, ICARUS, IceCube, ANTARES, …

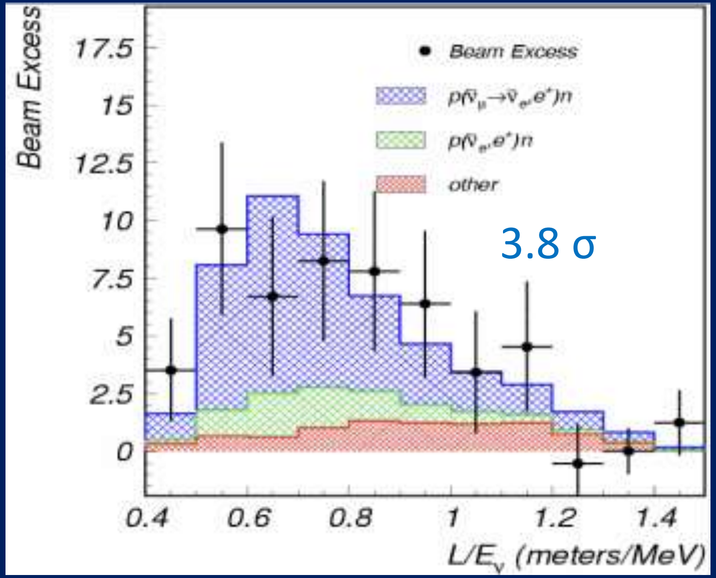
Parameter	best-fit	3σ
Δm^2_{21} [10^{-5} eV ^{2}]	7.37	6.93 – 7.96
$\Delta m^2_{31(23)}$ [10^{-3} eV ^{2}]	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	0.381 – 0.615
$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	0.384 – 0.636
$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	0.0190 – 0.0240
$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	0.0190 – 0.0242
δ/π	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))

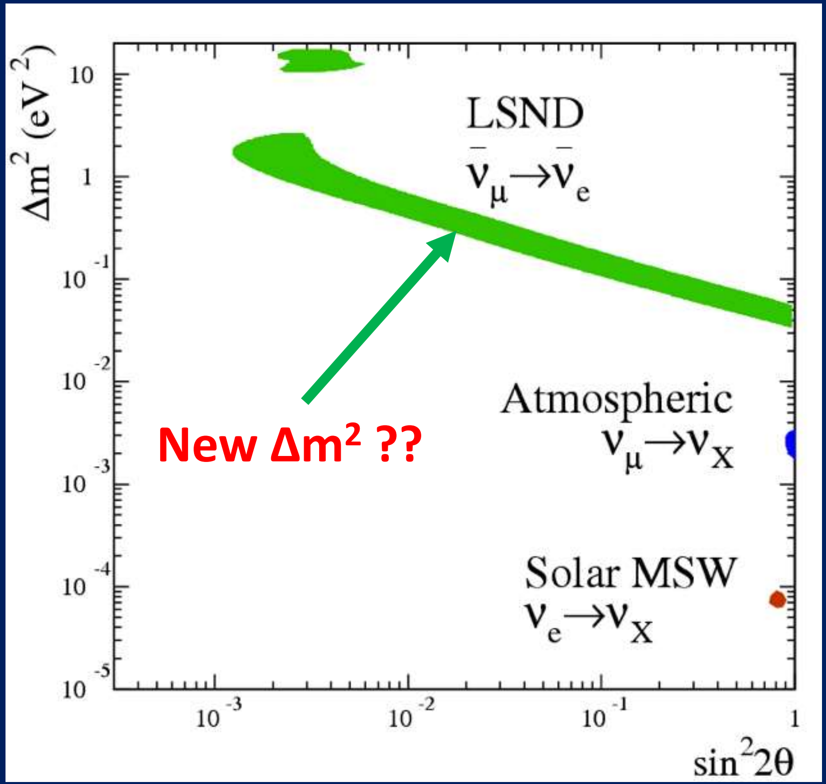
PDG update Dec 2017

LSND

The **L**iquid **S**cintillator **N**eutrino **D**etector
at Los Alamos National Lab
1993 -- 1998



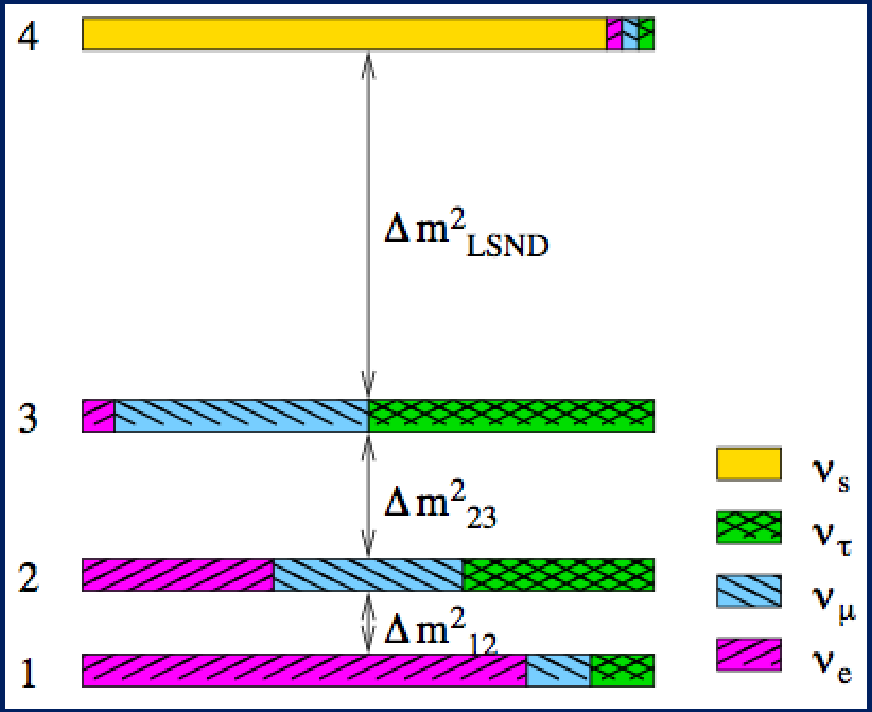




Two-neutrino approximation

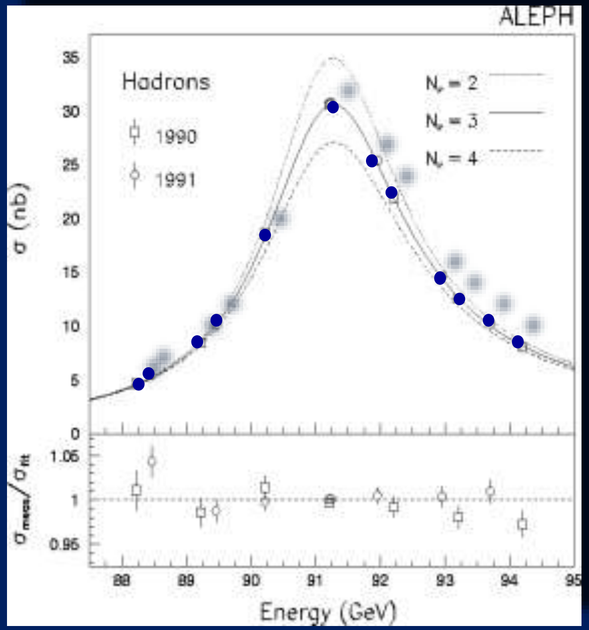
$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta_{ij} \cdot \sin^2\left(1.27\,\Delta m^2_{ij}\,\frac{L}{E}\right)$$

4^{th} neutrino mass state



Constraints

N_ν=3 from LEP



Cosmology

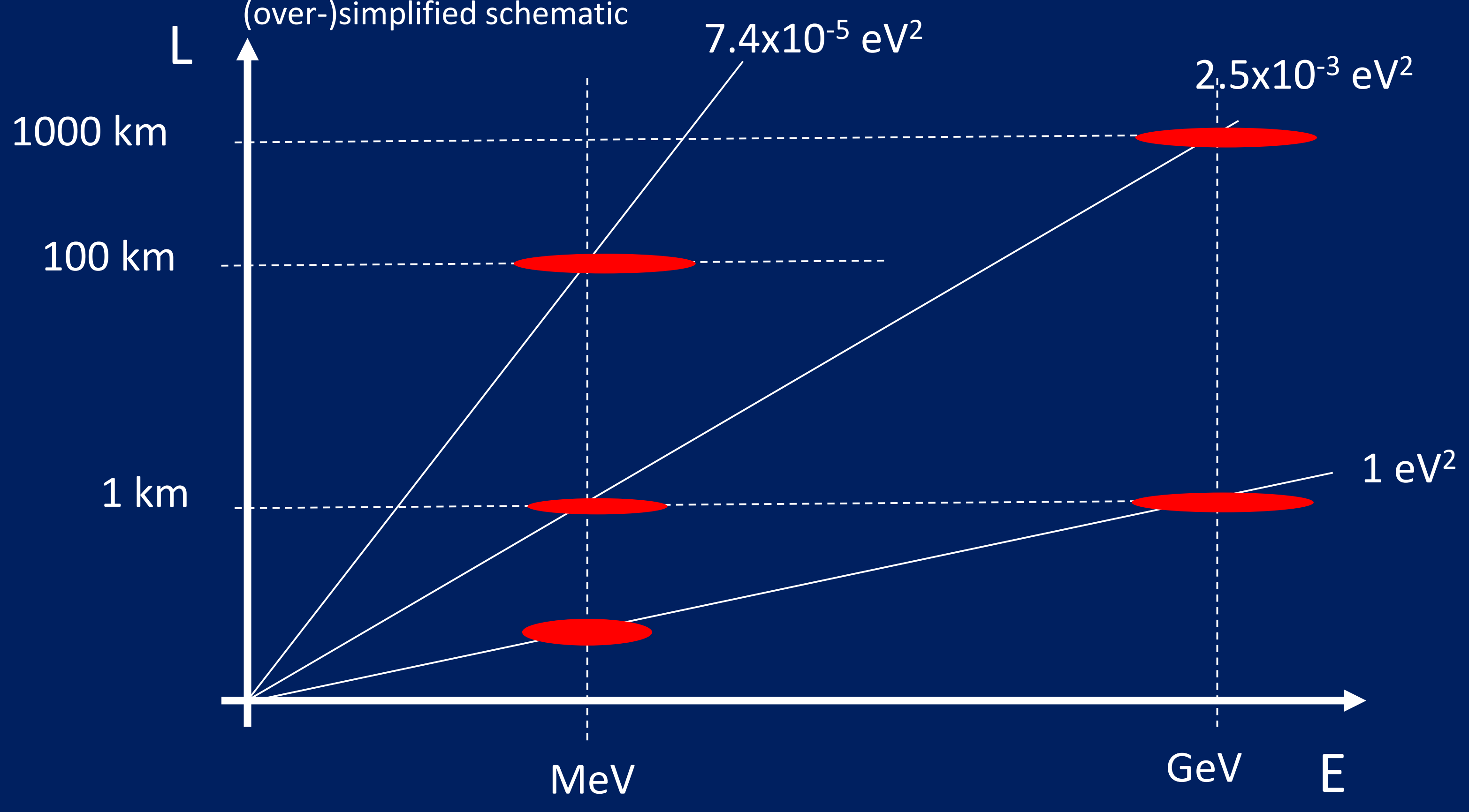
ΛCDM is sensitive to **N_ν**

(Large scale structures (BAO) and light nuclei abundance.)

Best fit is also consistent with **N_ν =3** active neutrinos.

➔ **Sterile**

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij} \cdot \sin^2\left(1.27\Delta m_{ij}^2 \frac{L}{E}\right)$$



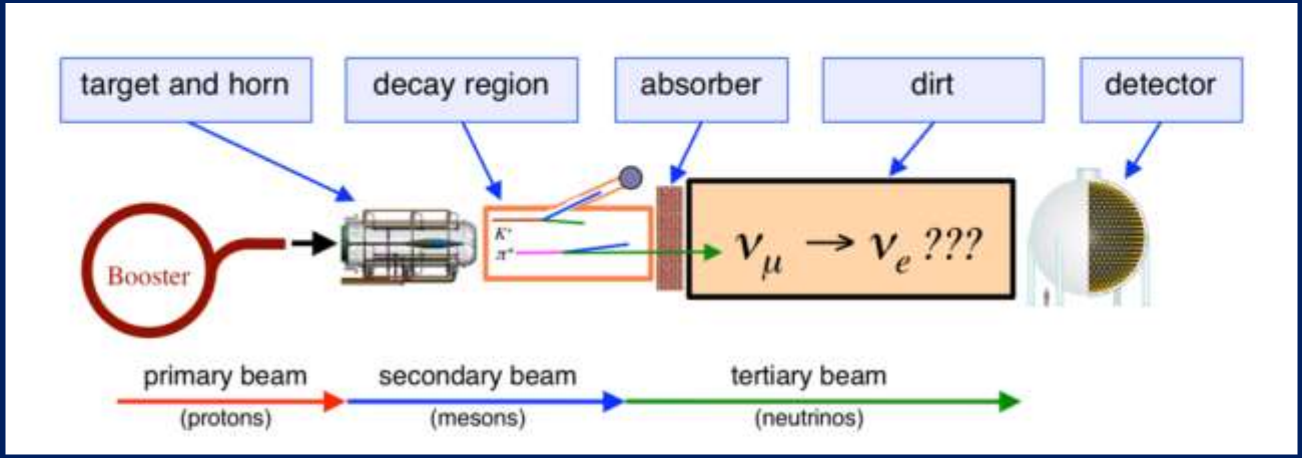
Rate goes with $1/L^2$

- Three (four) neutrinos
- Neutrino and Antineutrino
- Appearance and disappearance
- Mixing angles

- Short Base-Line:
  - Sensitivity to high Δm^2
  - High rates, statistics to measure cross sections

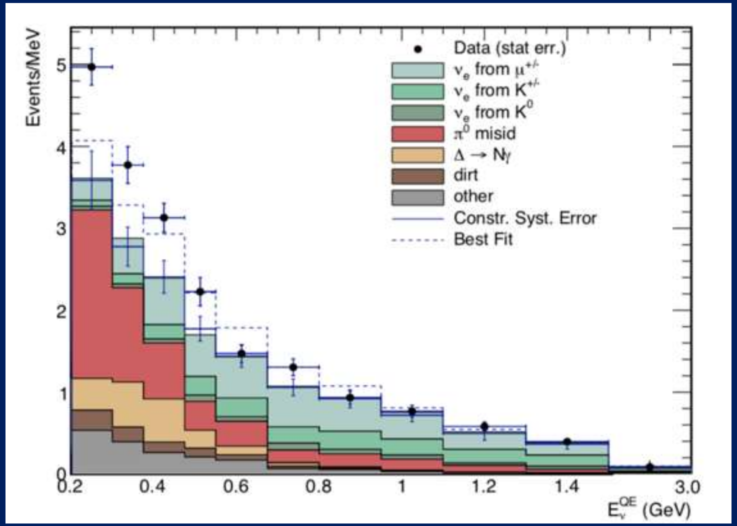
MiniBooNE

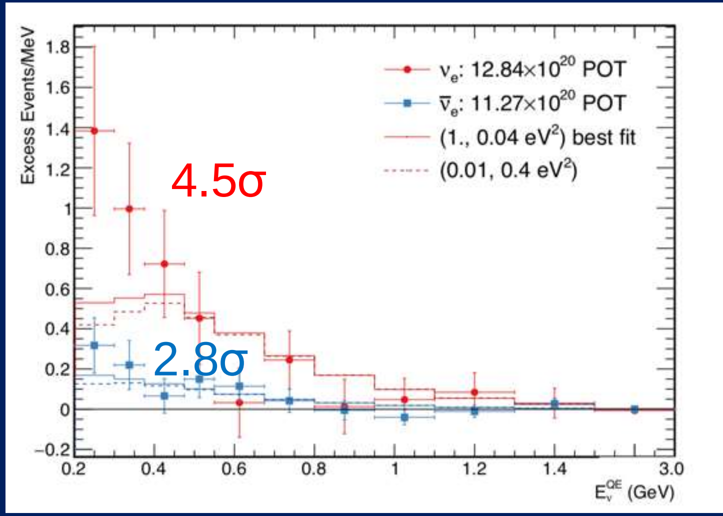
@Fermilab (2002--)

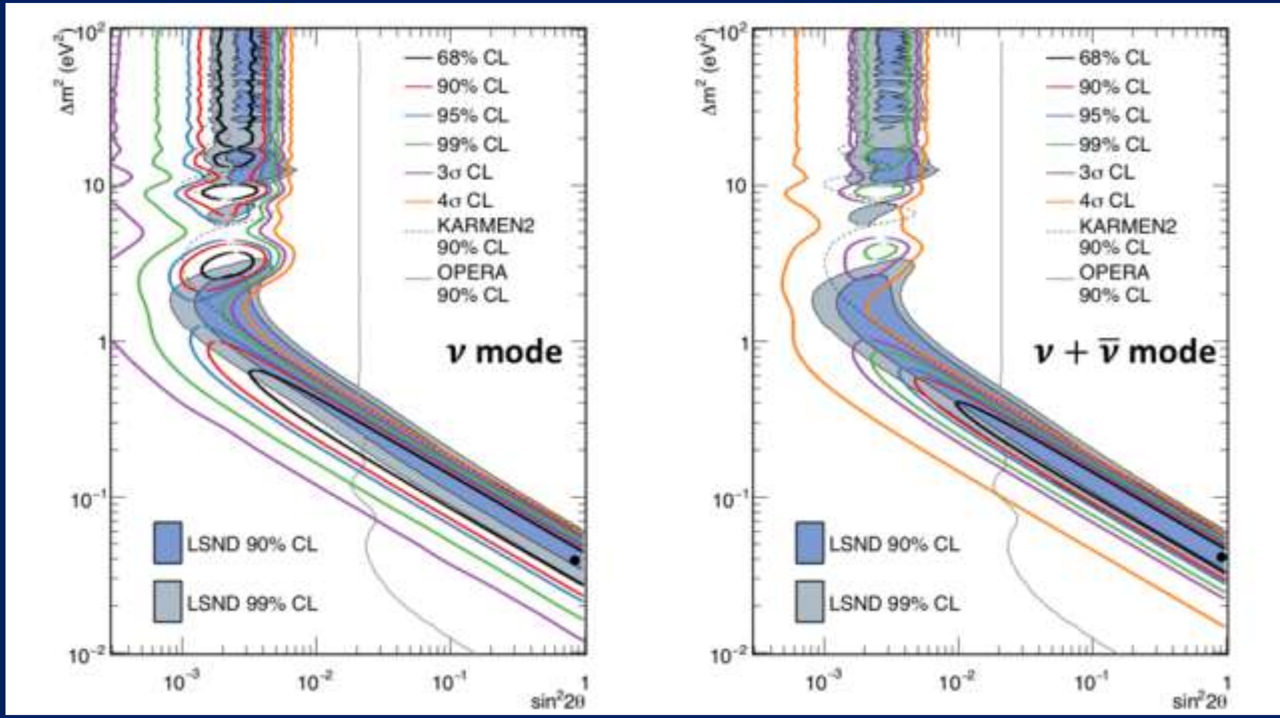


L/E ~ 1 MeV/m
E~800 MeV
L~600 m

Δm^2~ 1 eV^2





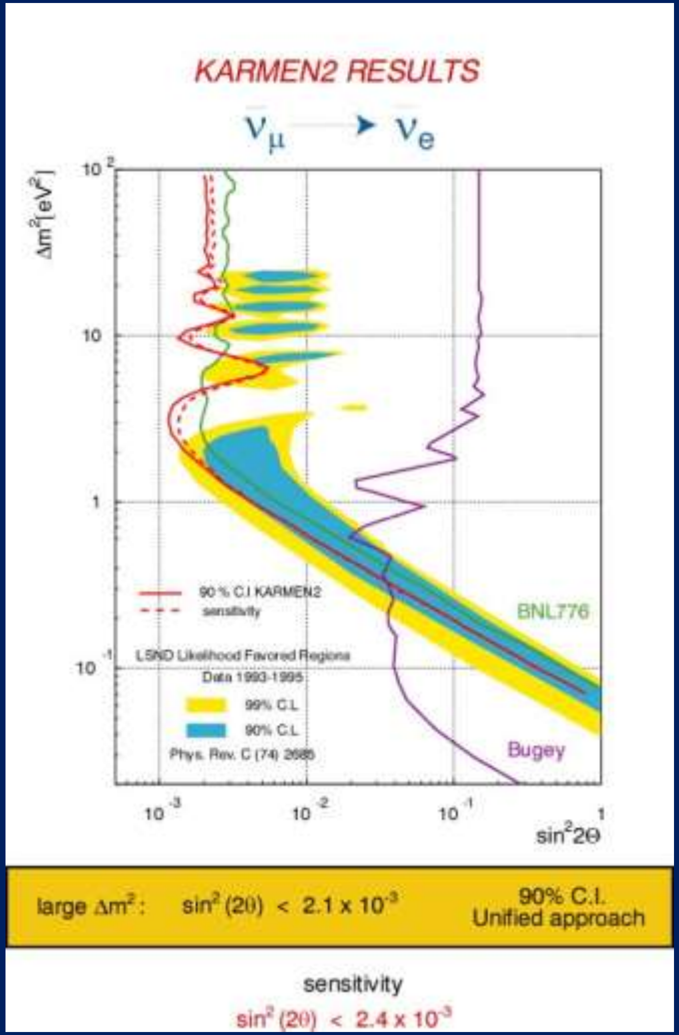


A.A. Aguilar-Arevalo et al. [MiniBooNE Collaboration], arXiv:1805.12028

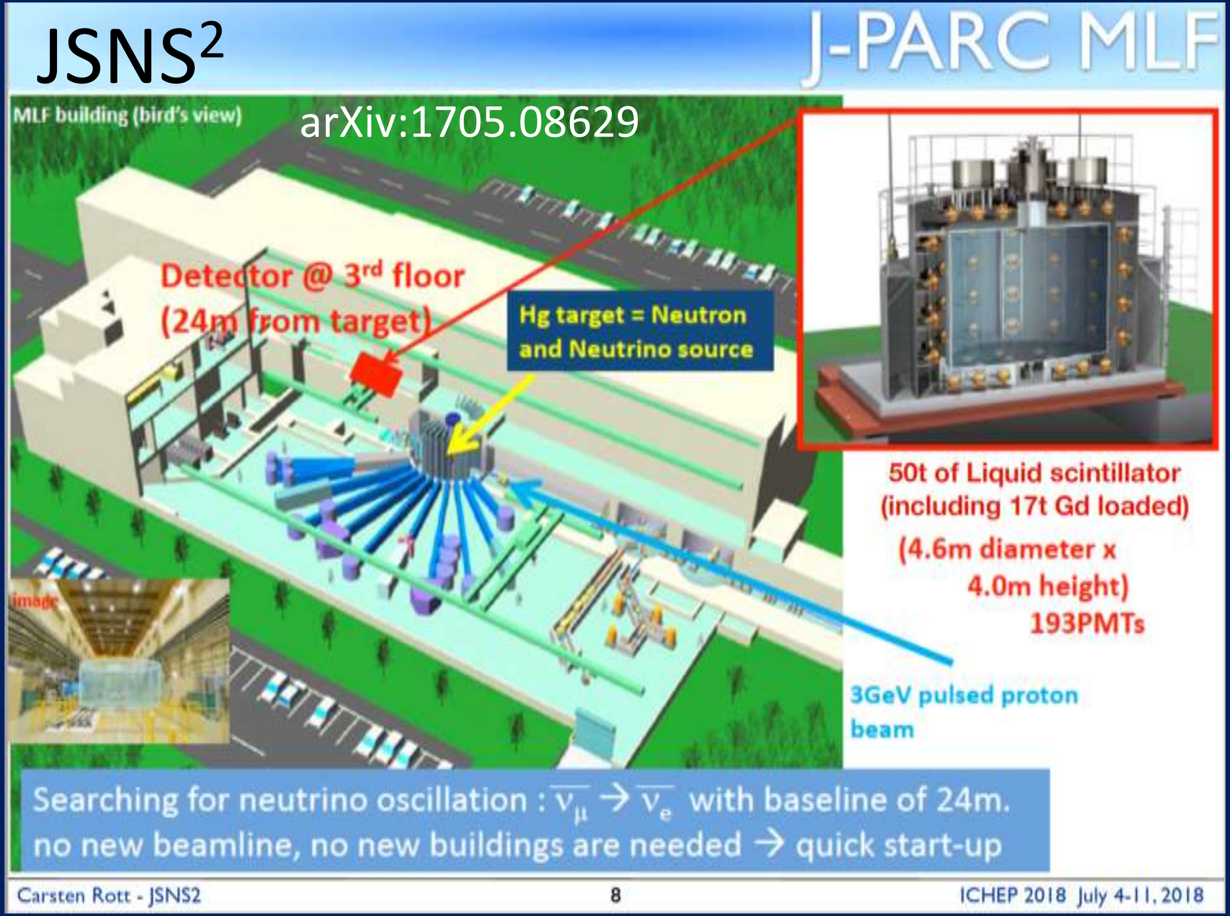
More hints, experiments, searches

- Investigations, also with new technologies (liquid argon TPC)
- "Reactor anomaly"
- Source experiments
- Disappearance analyses at long baseline experiments
- Dedicated reactors neutrino experiments

Investigating LSND



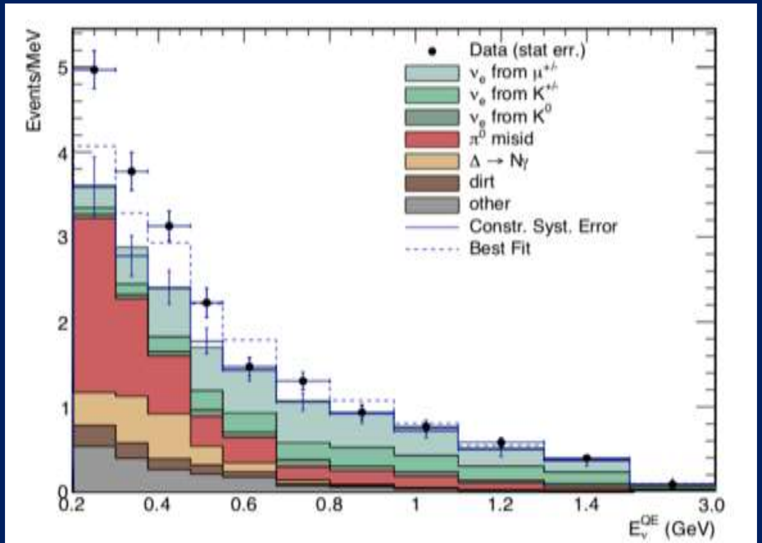
(Antineutrino, Pion Decay At Rest DAR)



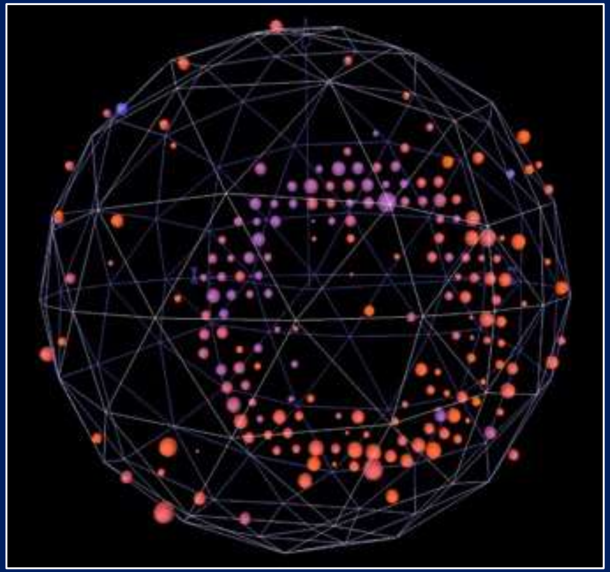
Operation start in 2019

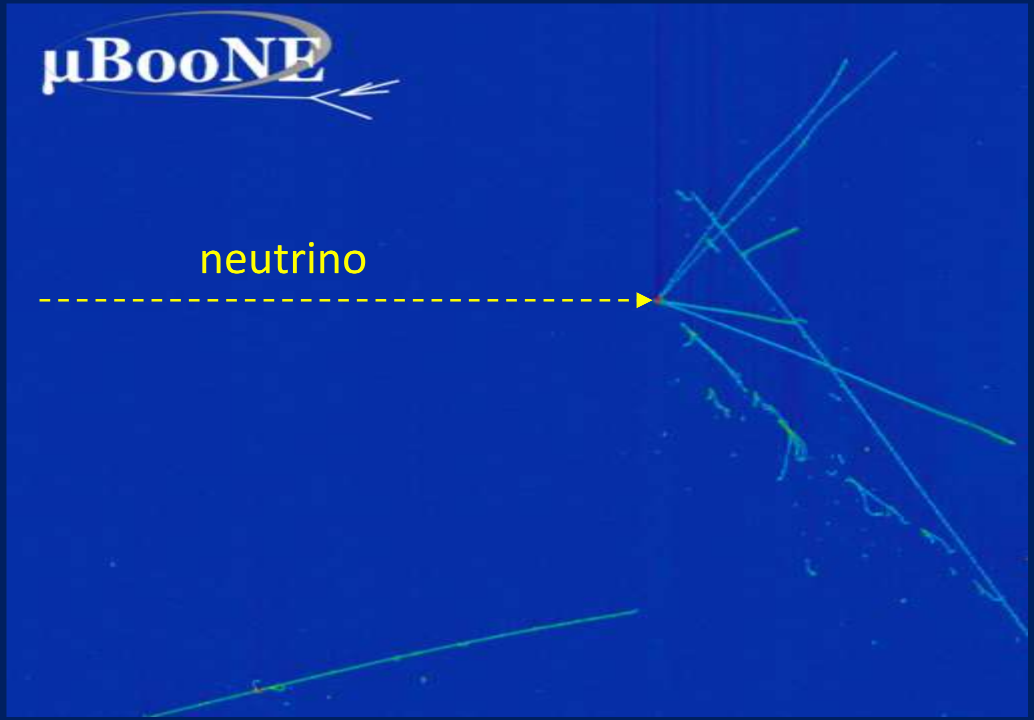
Also DAEδALUS and IsoDAR

Explore the MiniBooNE excess of events with a high resolution liquid Argon TPC

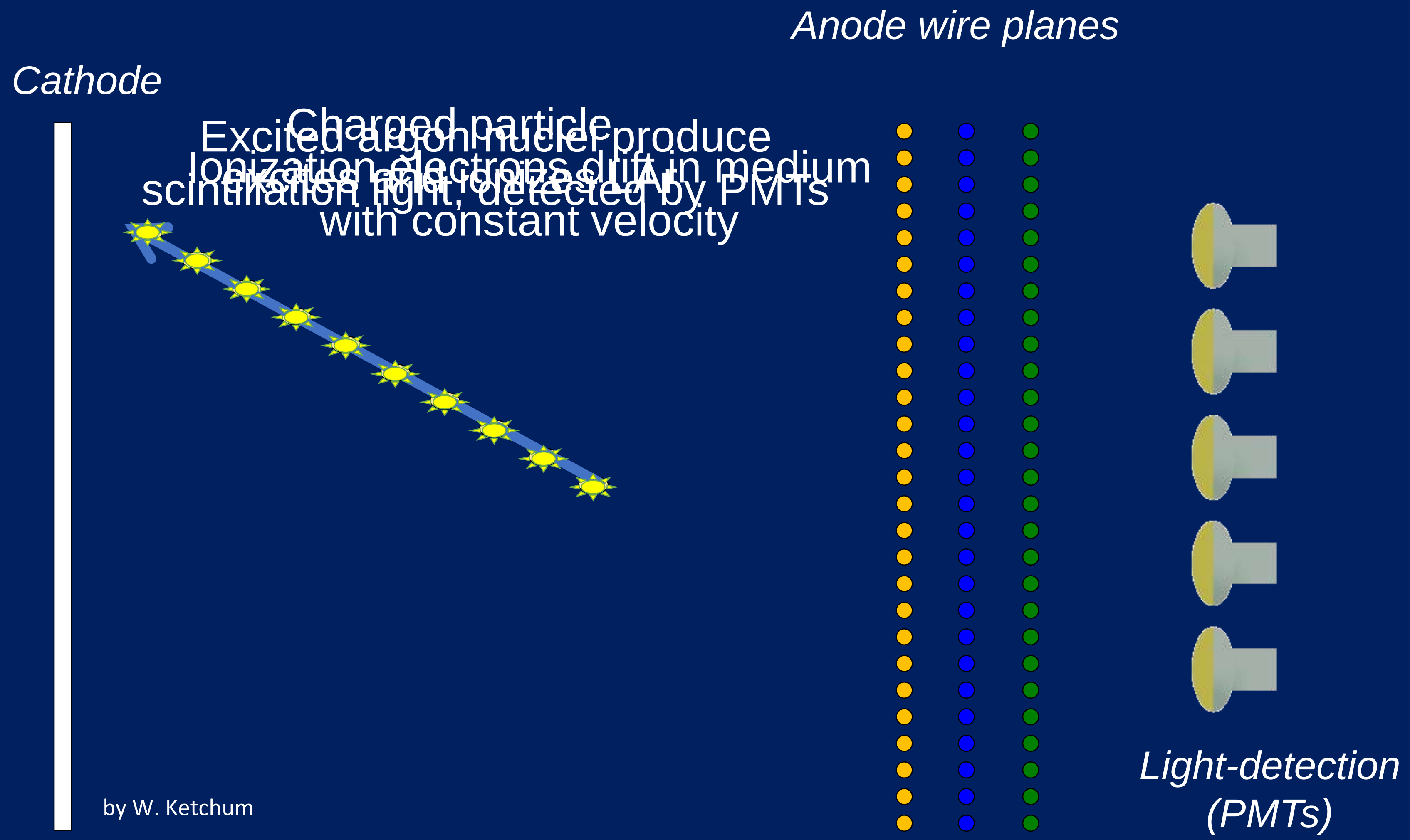


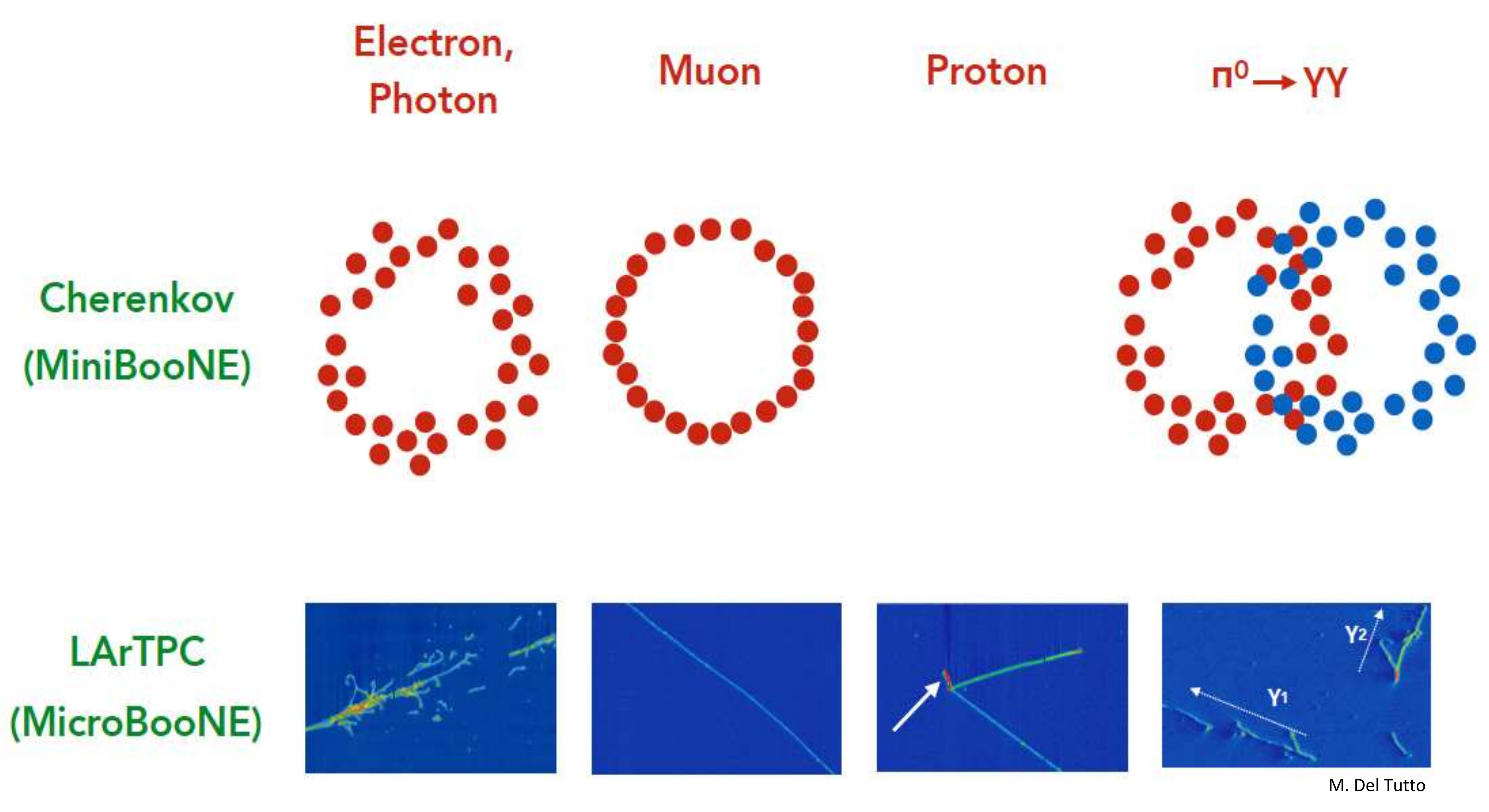
MiniBooNE event



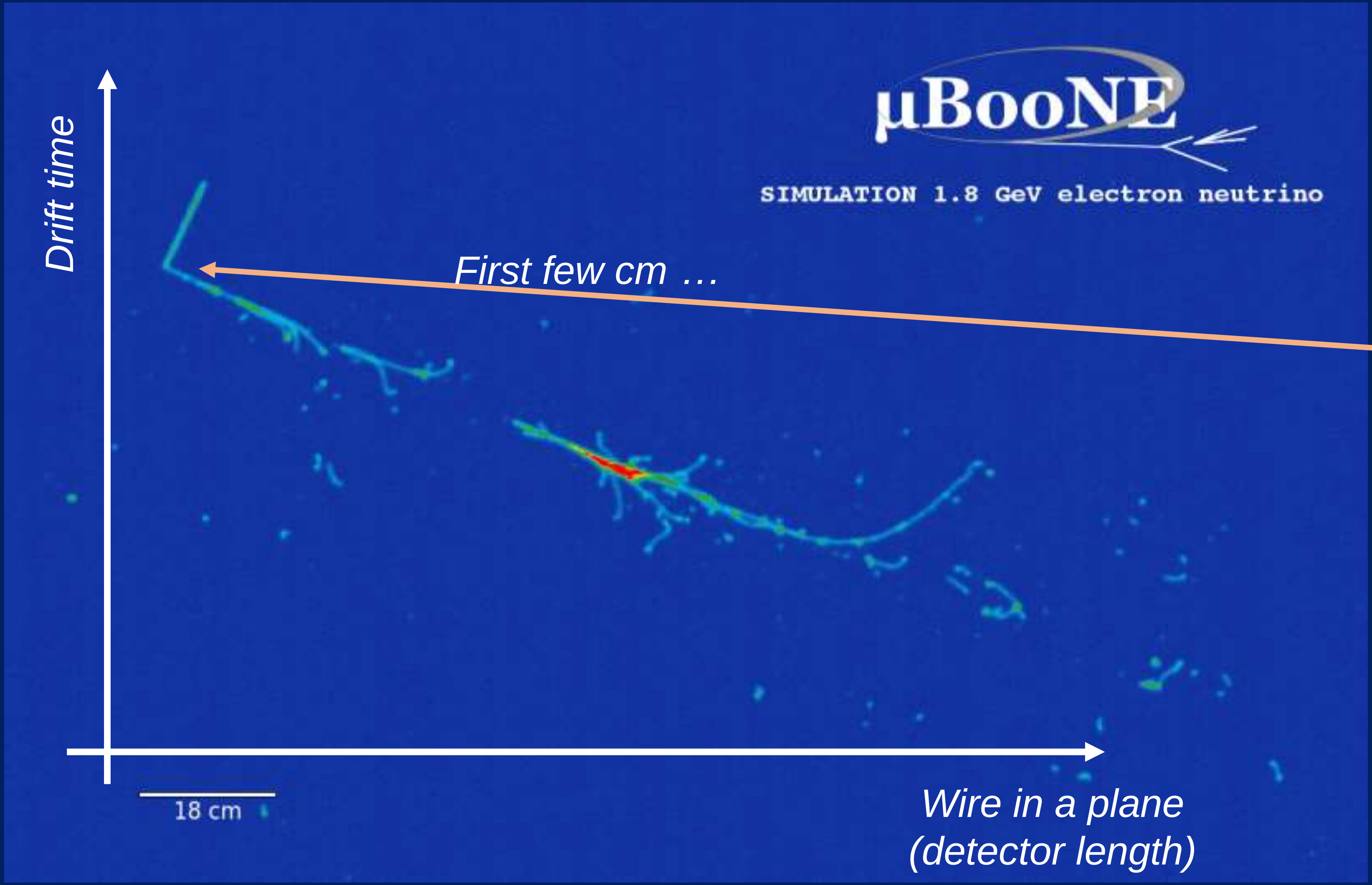


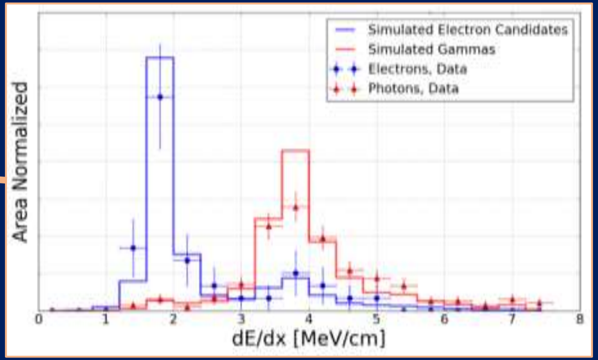
LArTPC


Anode wire planes
Cathode
Charged particle
excites and ionizes LAr
Excited argon nuclei produce
scintillation light, detected by PMTs
Ionization electrons drift in medium
with constant velocity
Light-detection
(PMTs)
by W. Ketchum

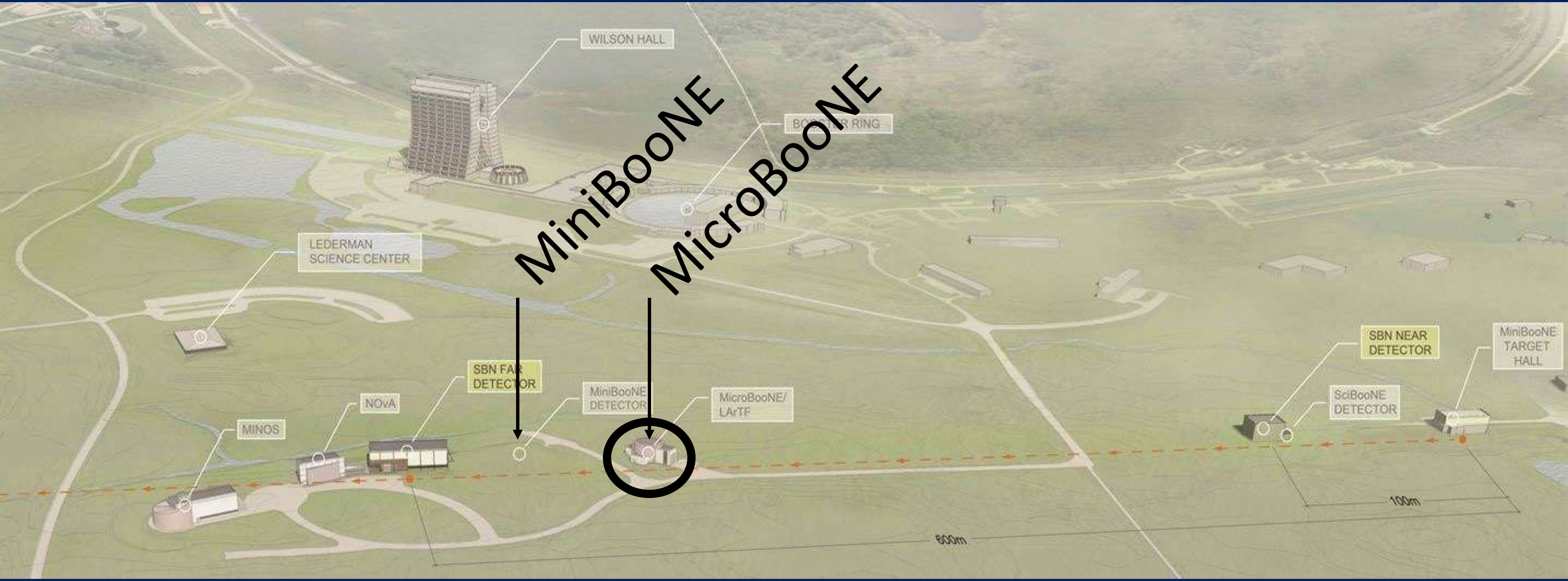

Electron,
Photon
Muon
Proton
$\pi^0 \rightarrow \gamma\gamma$
Cherenkov
(MiniBooNE)
LArTPC
(MicroBooNE)
γ_2
γ_1
M. Del Tutto

High-Definition 3D imaging detector and calorimeter

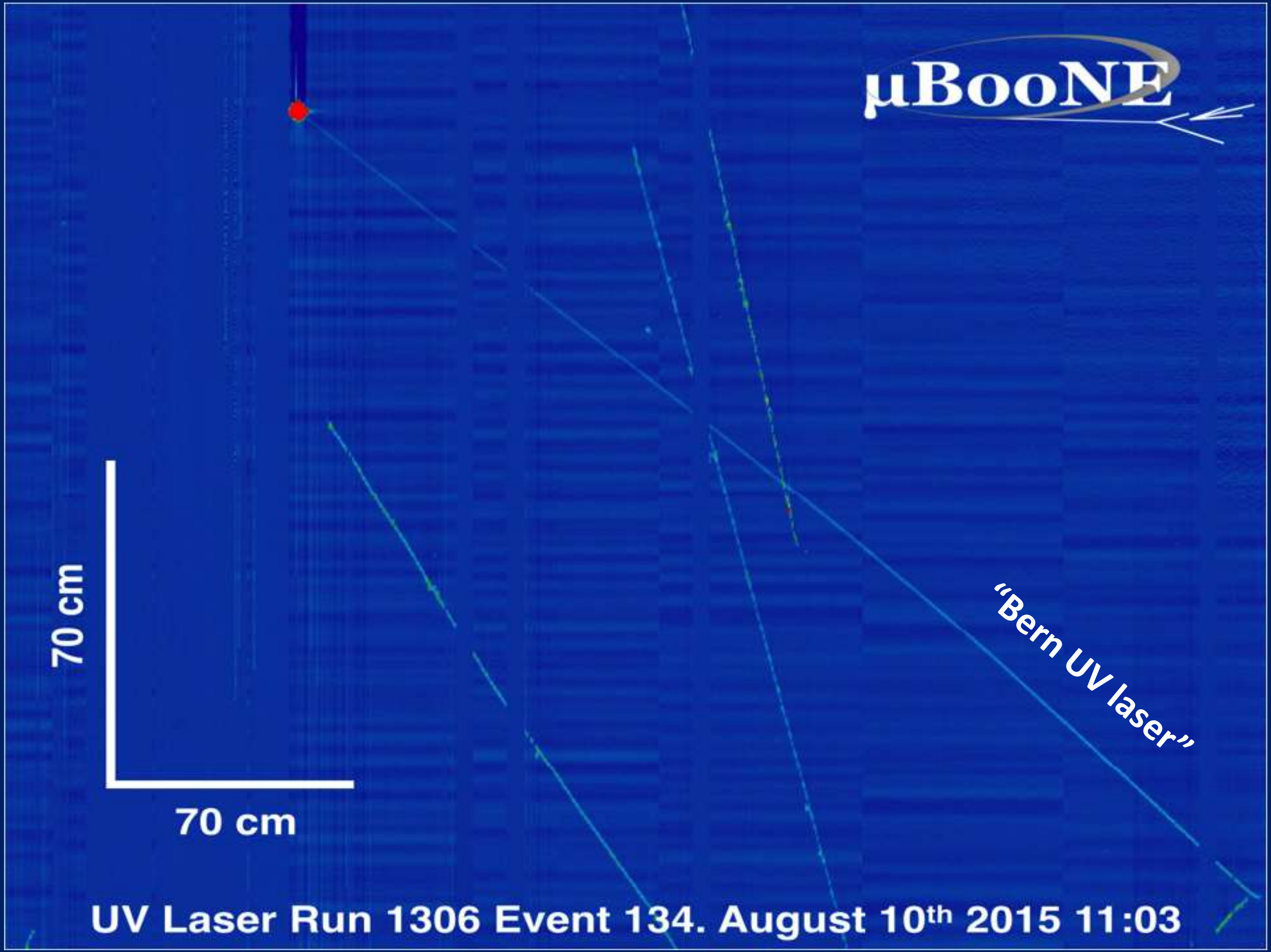


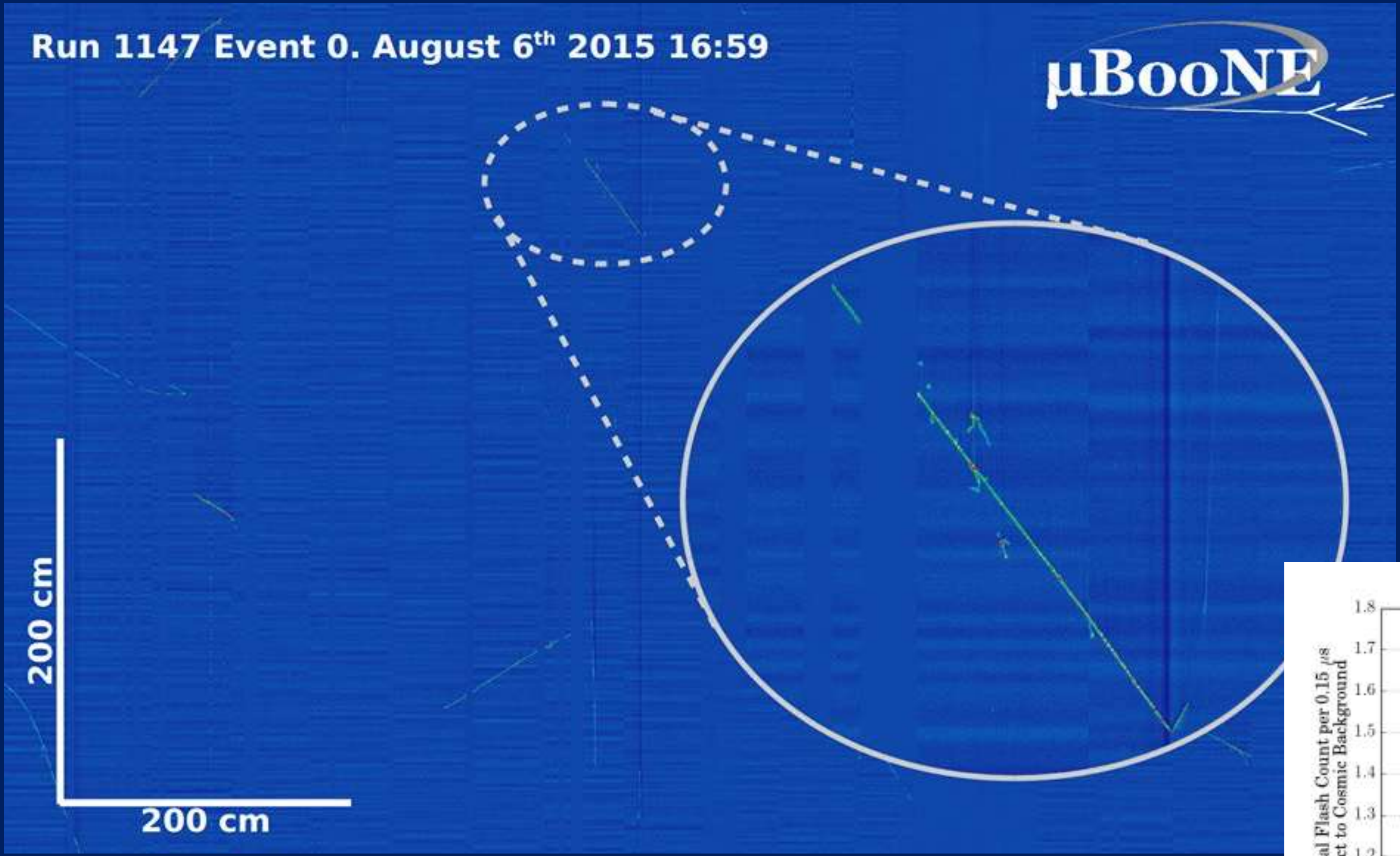


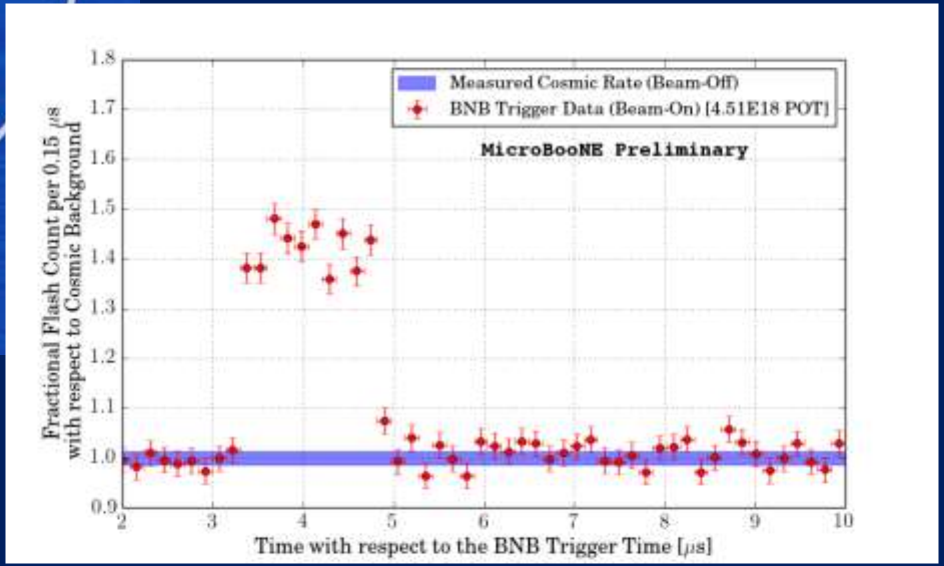
ArgoNeut ν_e CC search
Phys. Rev. D 95, 072005 (2017)



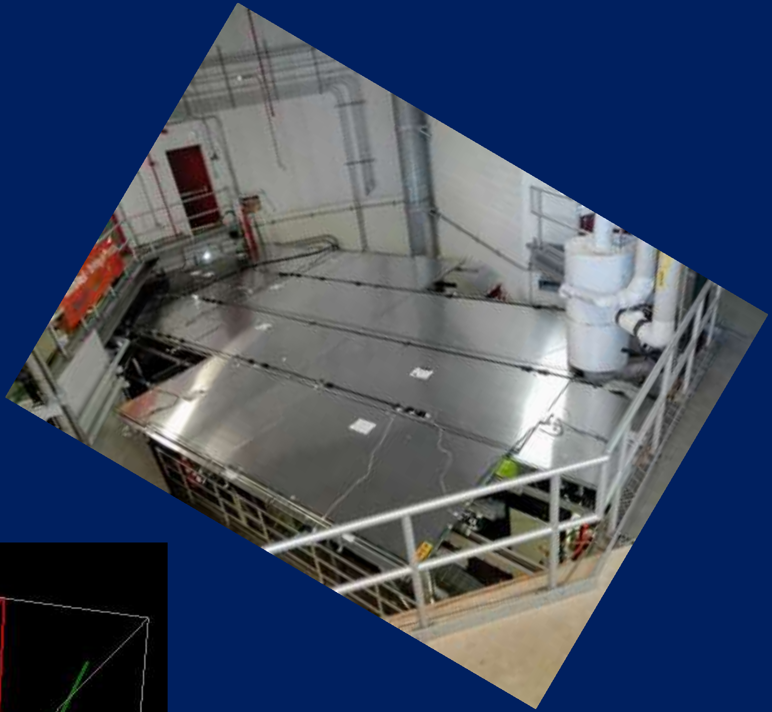
MiniBooNE
MicroBooNE
WILSON HALL
BOOSTER RING
LEDERMAN SCIENCE CENTER
SBN FAR DETECTOR
MiniBooNE DETECTOR
MicroBooNE/ LArTF
NOvA
MINOS
SBN NEAR DETECTOR
MiniBooNE TARGET HALL
SciBooNE DETECTOR
100m
600m

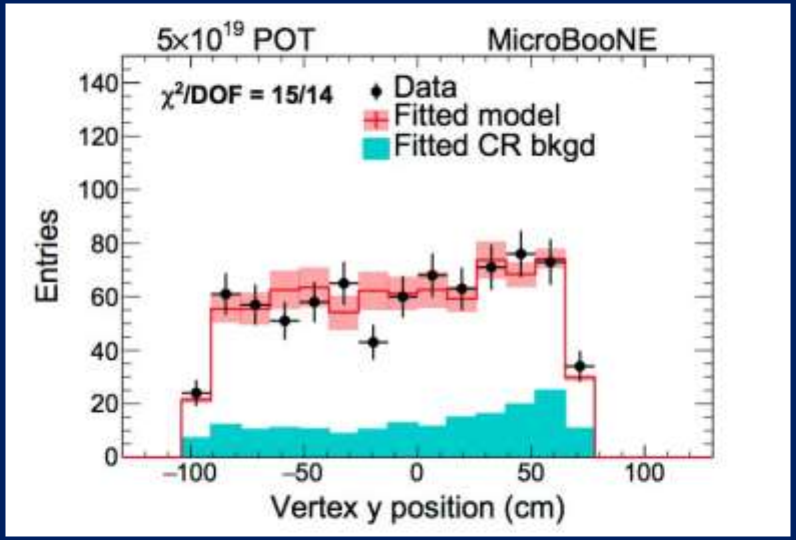

μBooNE
70 cm
70 cm
“Bern UV laser”
UV Laser Run 1306 Event 134. August 10th 2015 11:03


Run 1147 Event 0. August 6th 2015 16:59
μBooNE
200 cm
200 cm

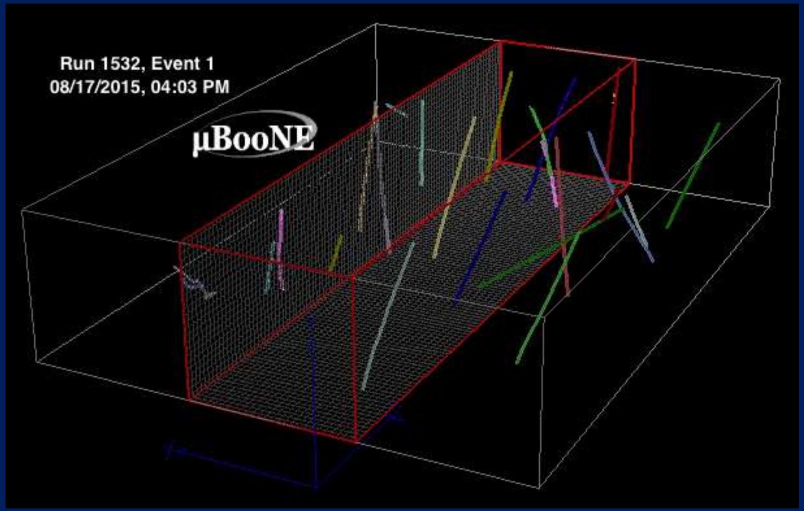

Measured Cosmic Rate (Beam-Off)
BNB Trigger Data (Beam-On) [4.51E18 POT]
MicroBooNE Preliminary
Fractional Flash Count per 0.15 μs with respect to Cosmic Background
Time with respect to the BNB Trigger Time [μs]

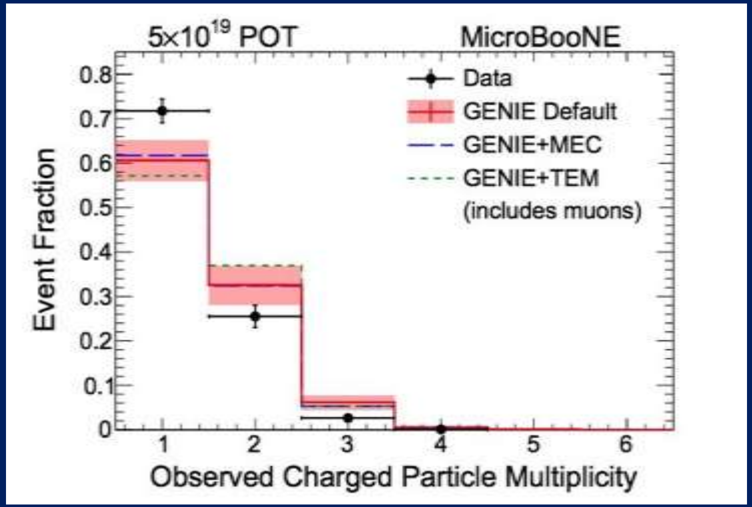
Towards the low energy oscillation result





Eur. Phys. J. C79, 248 (2019))



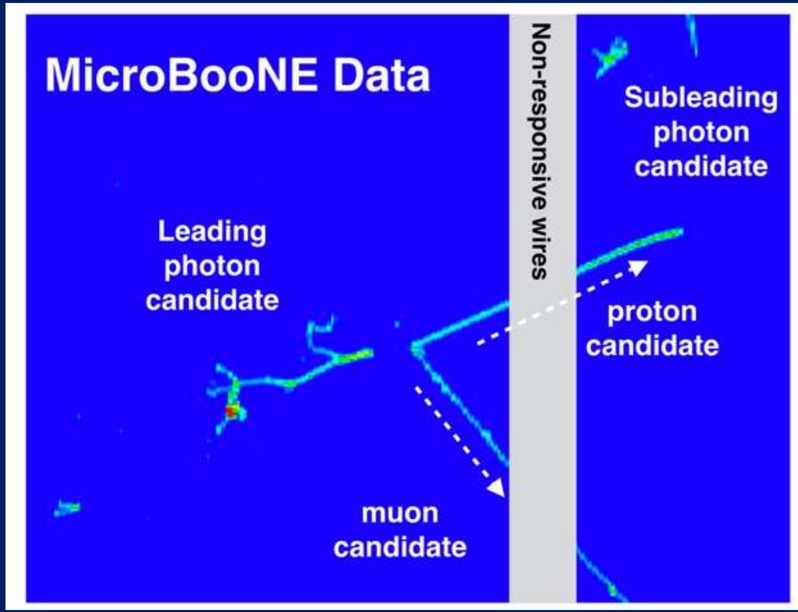


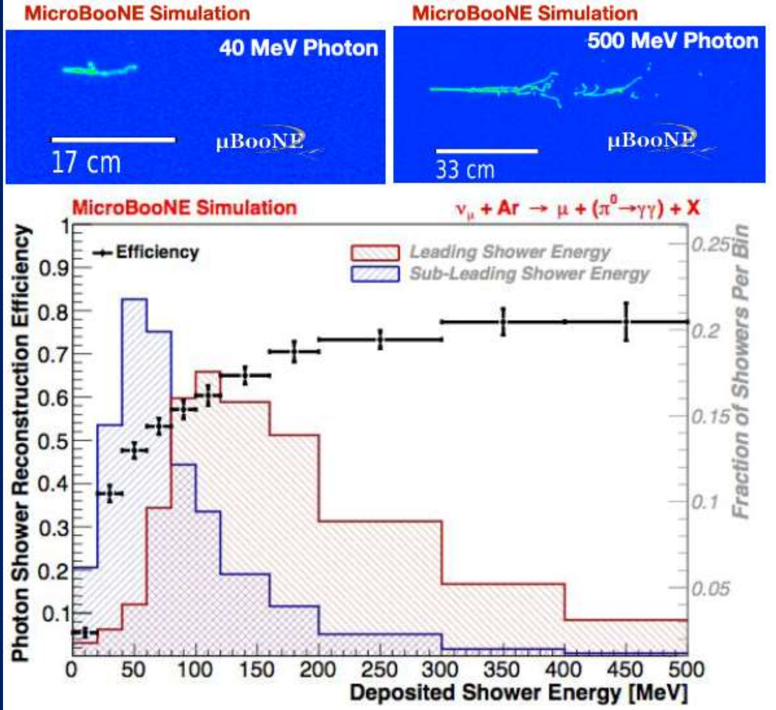
Charged current ν_μ interactions

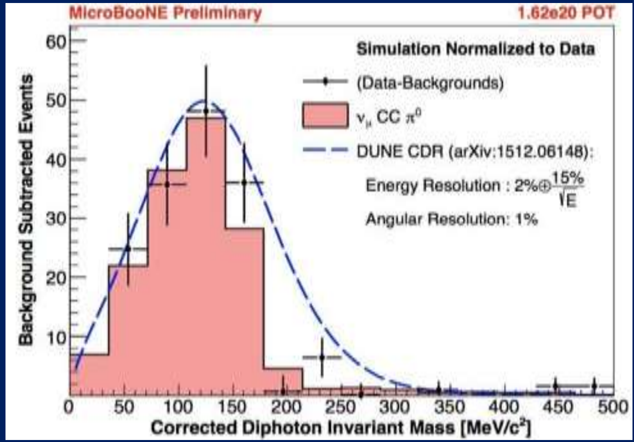
Count tracks attached to vertex

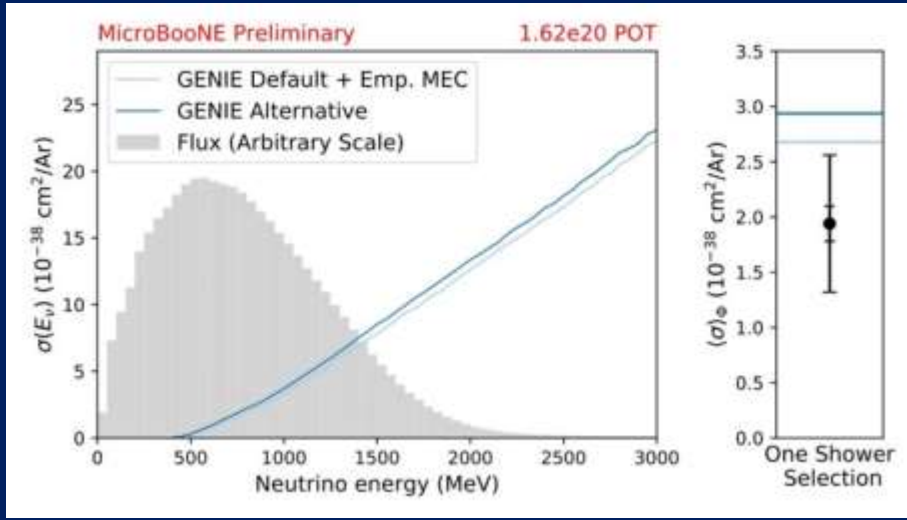
e.m. showers

CC $\nu_\mu \rightarrow \mu + p + \pi^0$





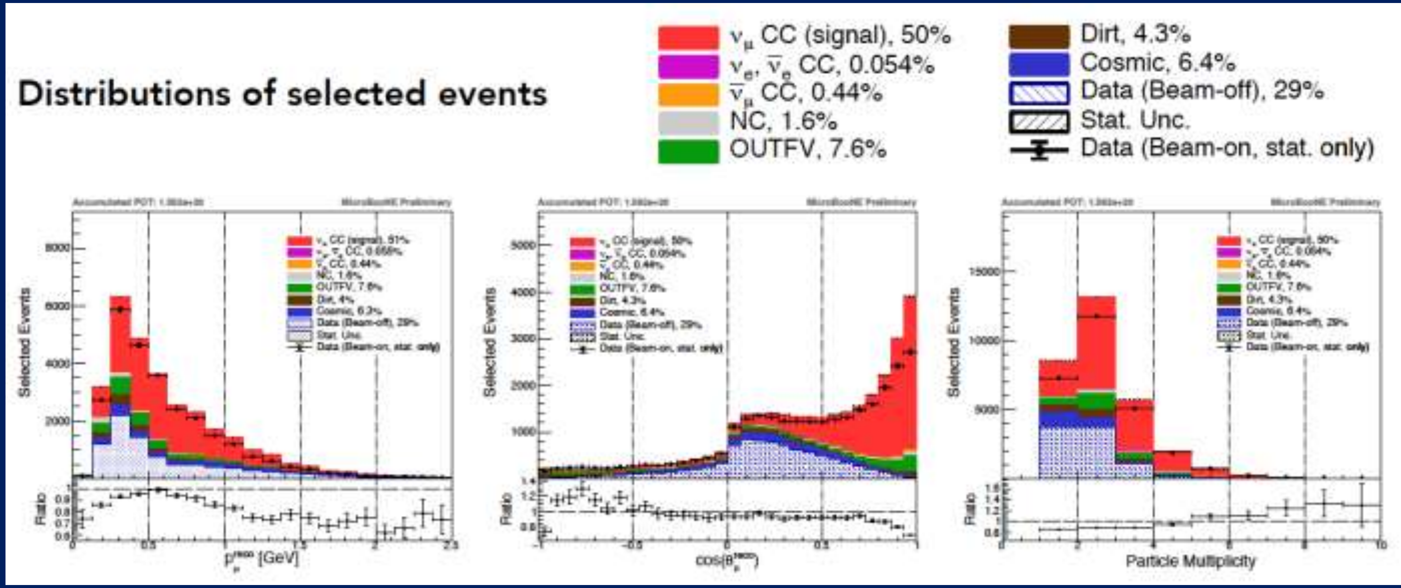


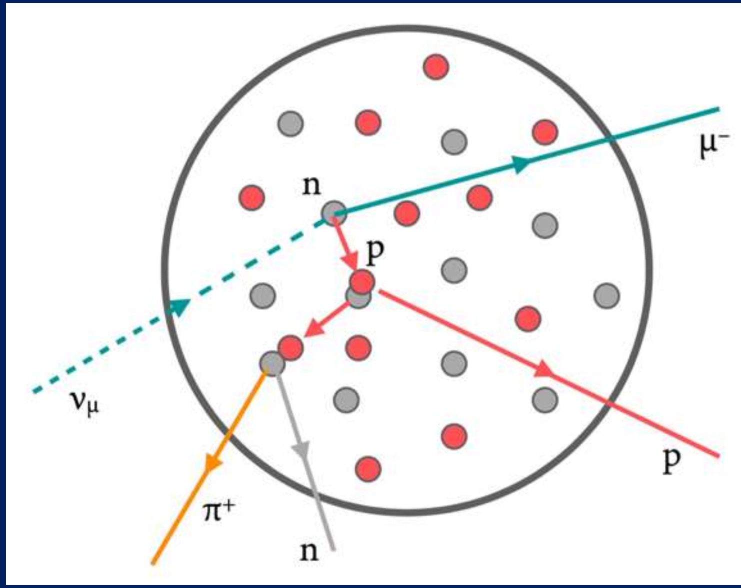


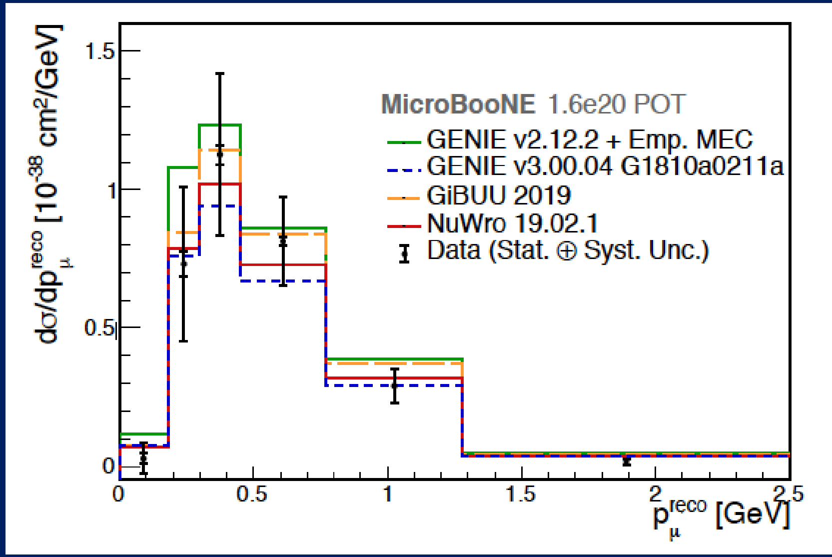
Phys. Rev. D99, 091102(R) (2019)

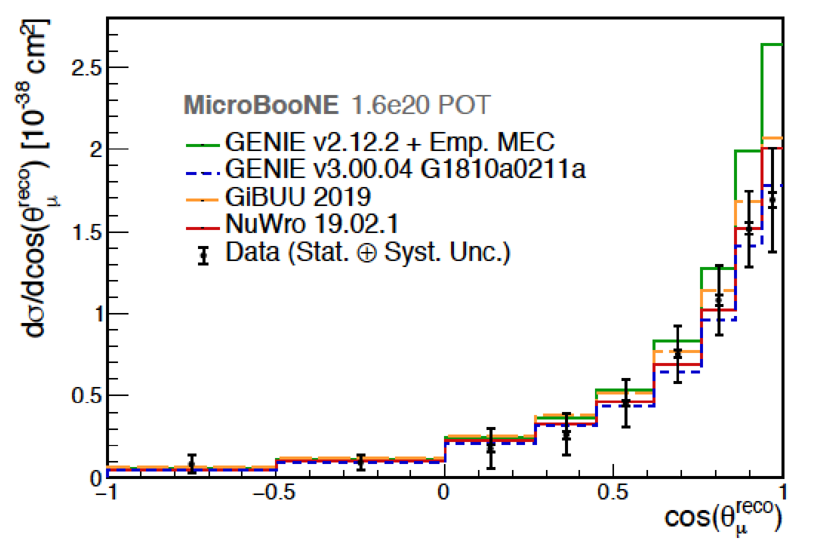
CC ν_μ double differential cross section

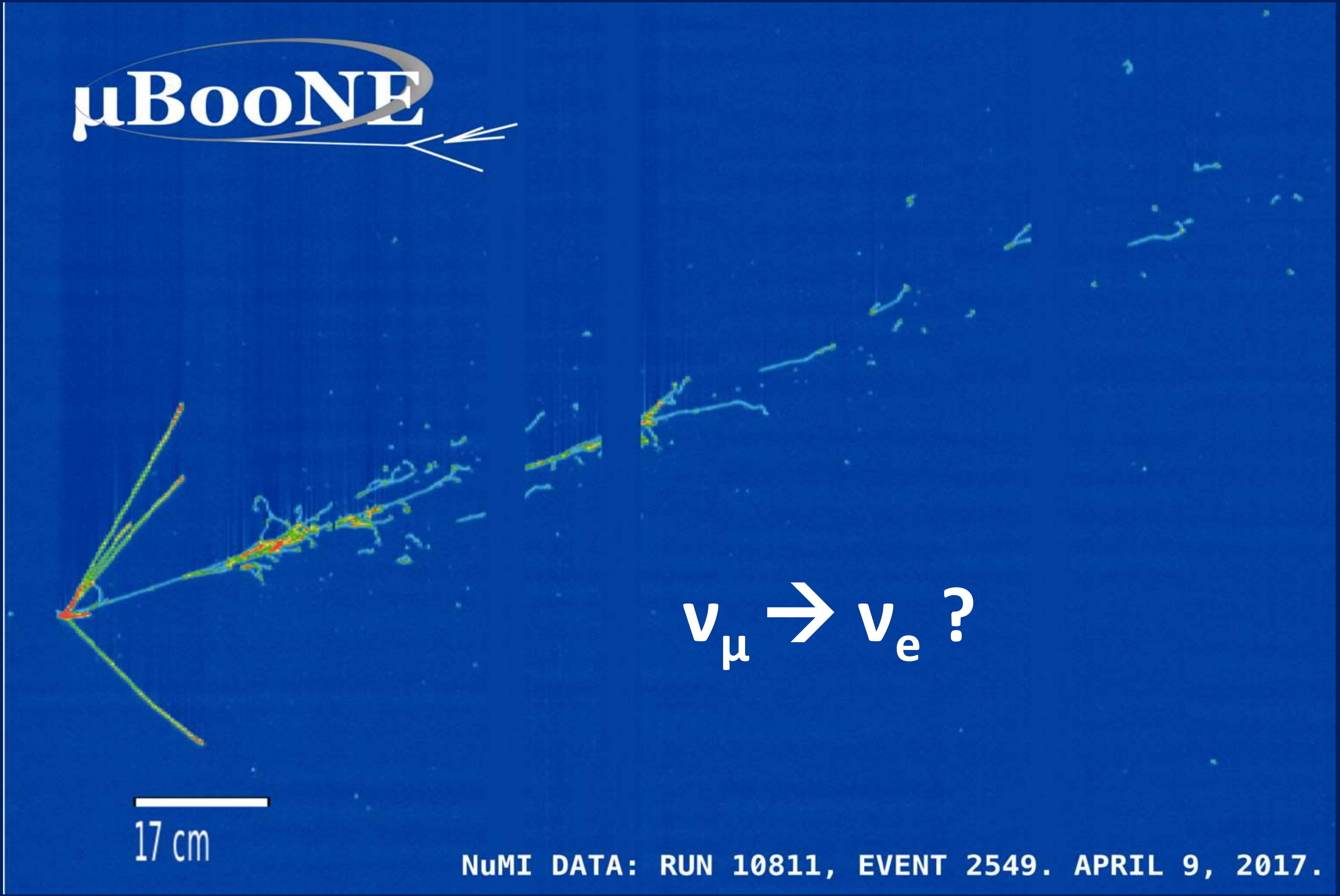
arXiv:1905.09694





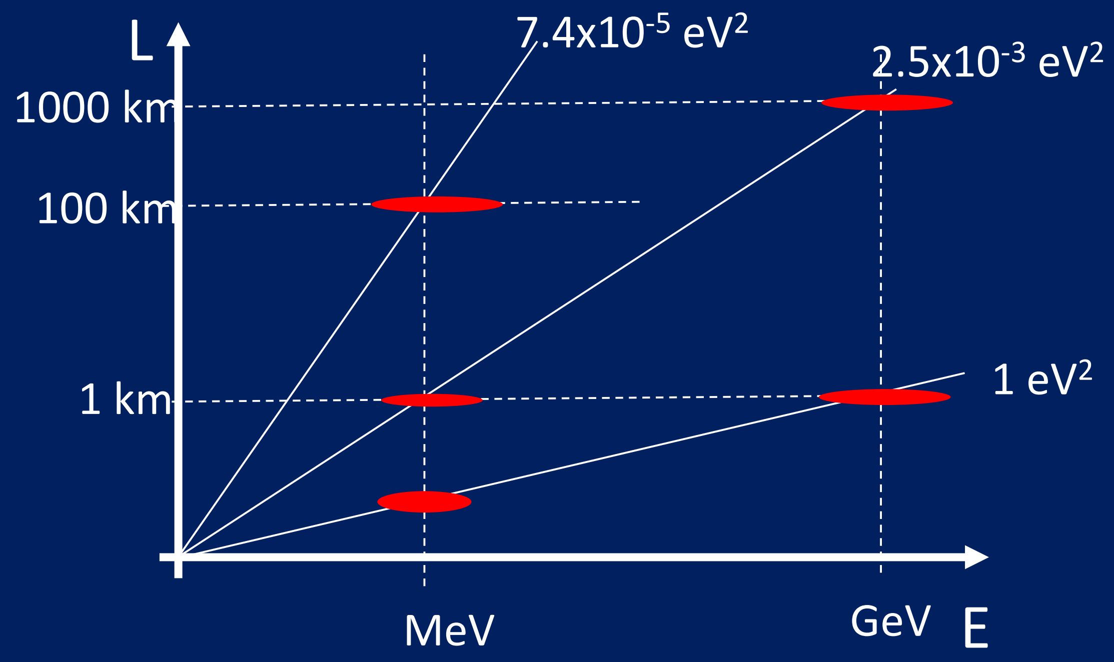




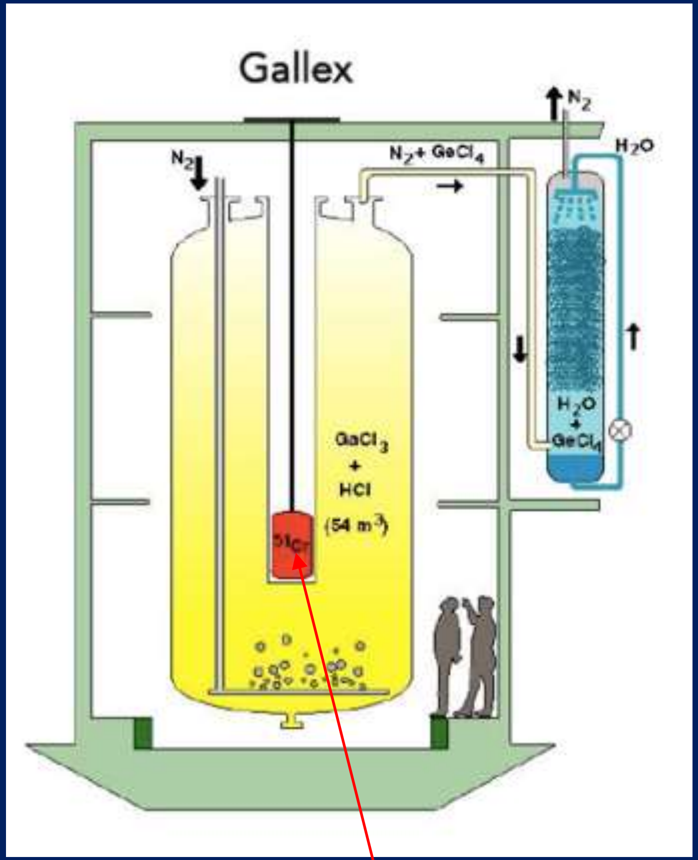

μBooNE
$\nu_\mu \rightarrow \nu_e$?
17 cm
NuMI DATA: RUN 10811, EVENT 2549. APRIL 9, 2017.

Sterile neutrinos: more hints, experiments, searches

- Source experiments
- "Reactor anomaly"
- Dedicated reactors neutrino experiments
- Disappearance analyses at long baseline experiments

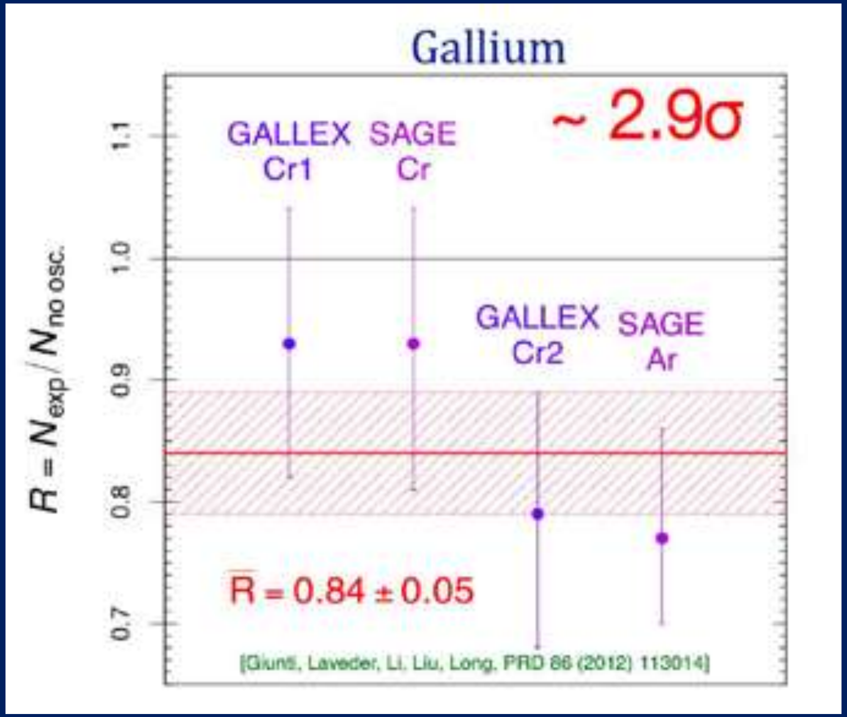


Radioactive source experiments



^{51}Cr

Electron neutrinos disappearing

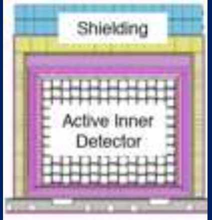


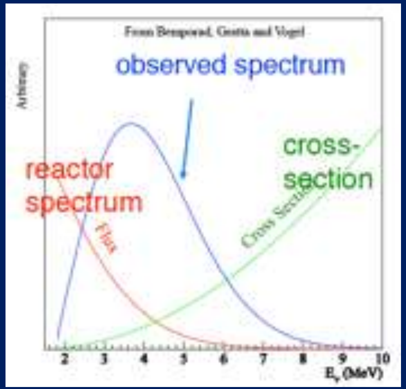
Reactor experiments:

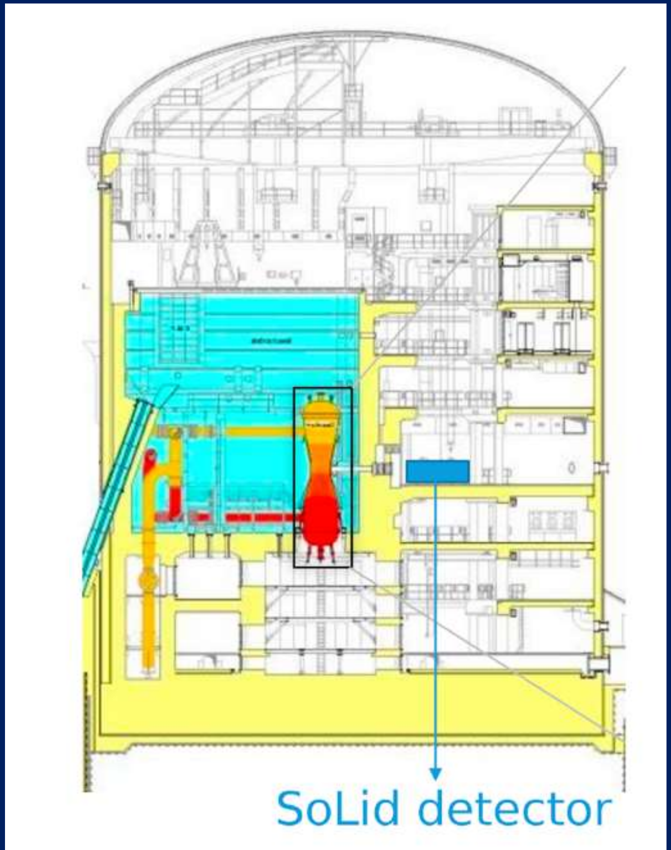
Pure $\overline{\nu}_e$ source produced by fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

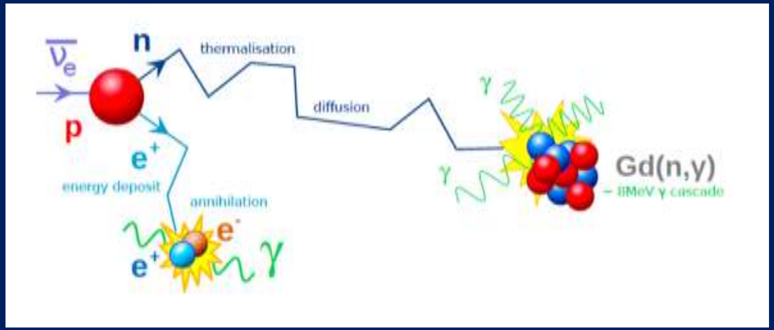
$\overline{\nu}_e$ disappearance

baseline ~m

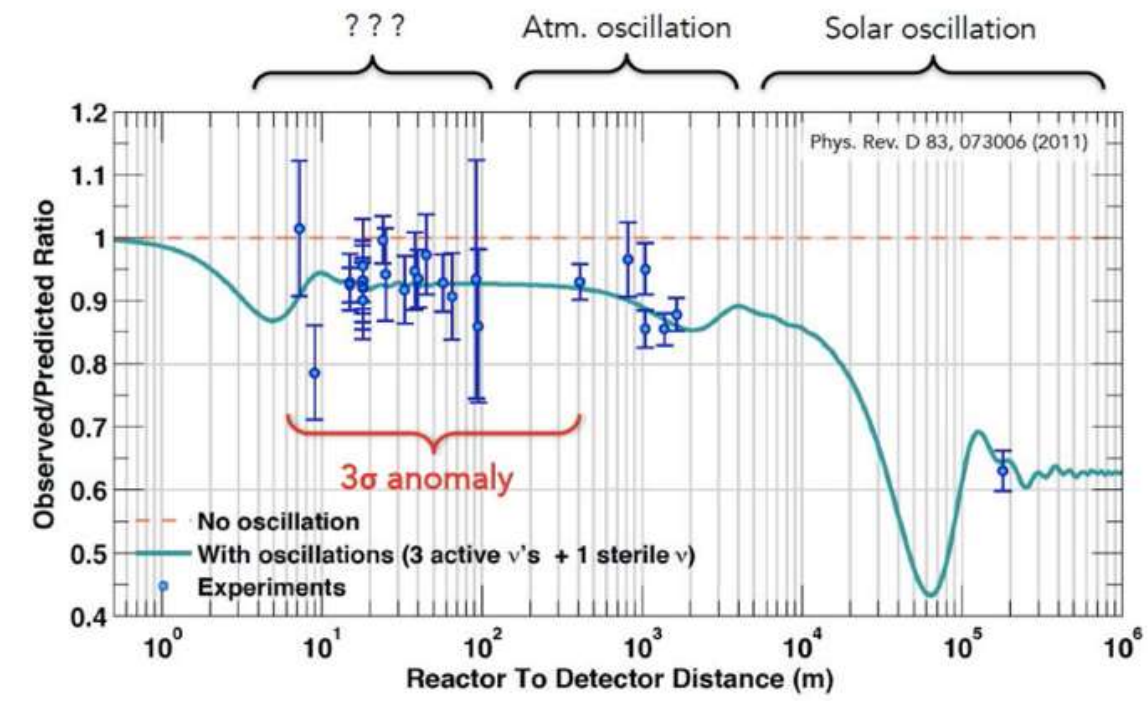




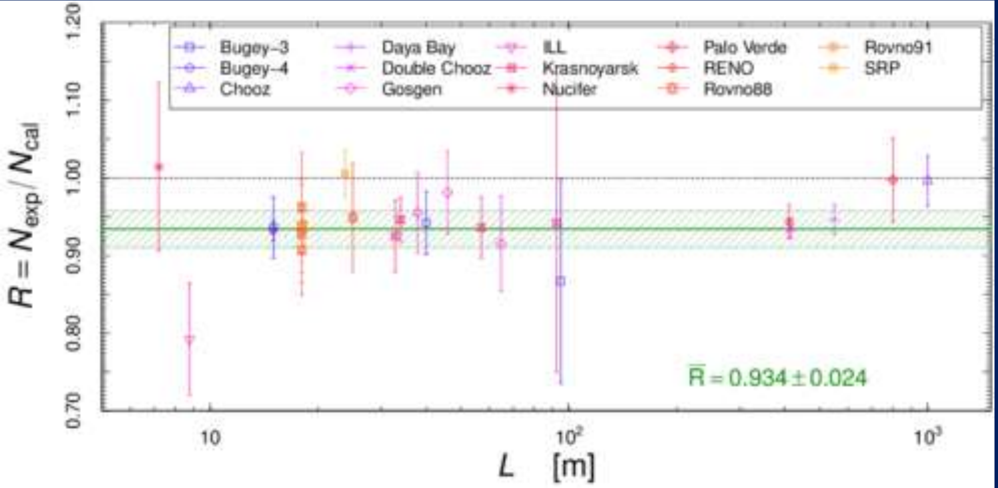




At short baselines experiments see fewer neutrinos than expected (red line)



G. Mention, M. Fechner, Th. Lasserre, Th. A. Mueller, D.Lhuillier, M. Cribier, and A. Letourneau, Phys. Rev. D 83, 073006 (2011)



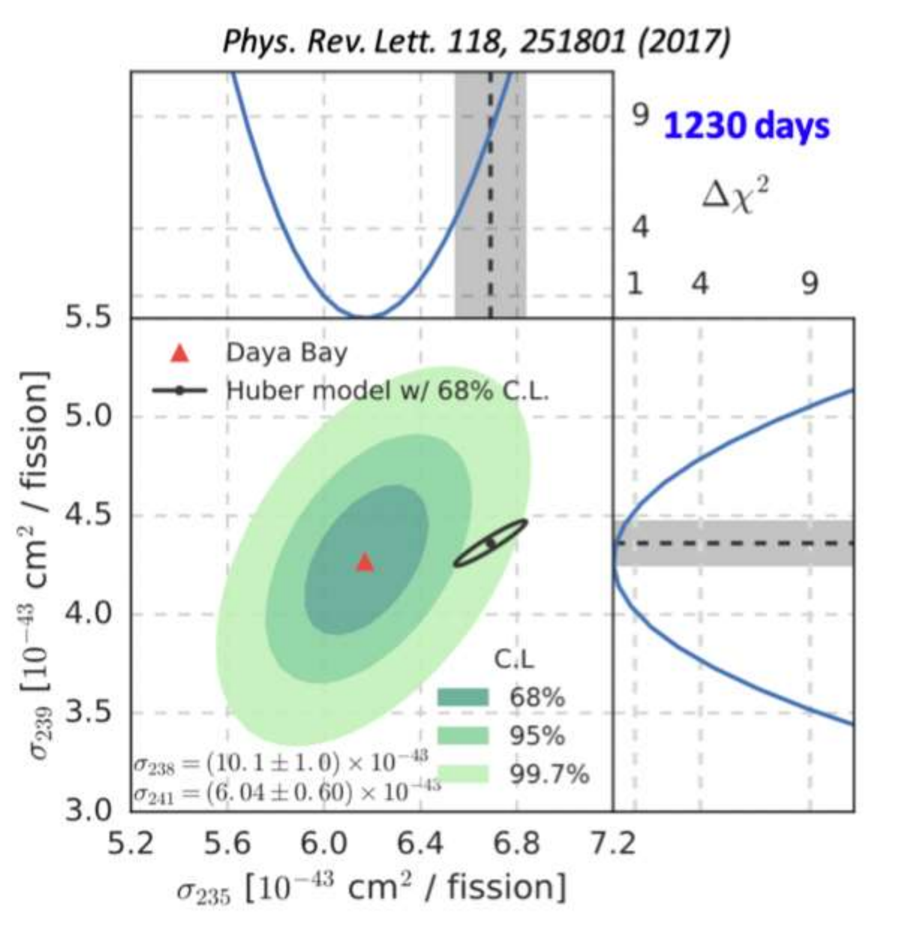
Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$ CC	4.5σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	2.8σ
GALLEX/SAGE	Source - e capture	ν_e disappearance	2.8σ
Reactors	Beta-decay	$\bar{\nu}_e$ disappearance	3.0σ

K. N. Abazajian et al. "Light Sterile Neutrinos: A Whitepaper", arXiv:1204.5379 [hep-ph], (2012)

Taken individually, each anomaly is not significant enough to be convincing….

most commonly interpreted as hint for one or more new **"sterile"** neutrino.

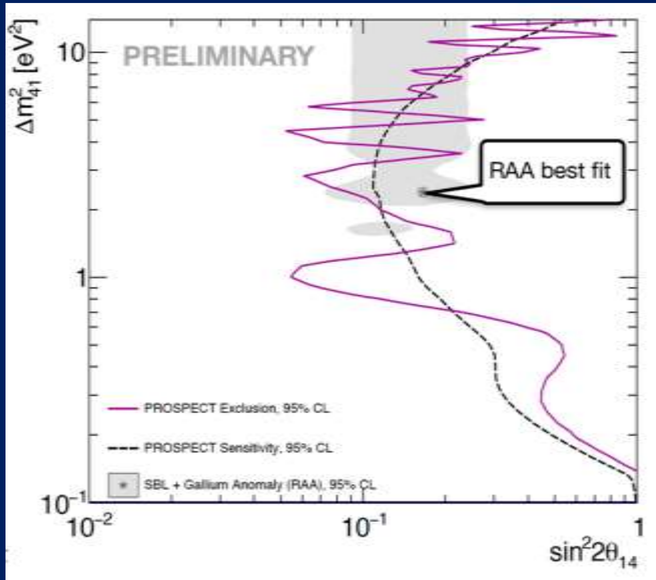
The reactor anomaly can be explained



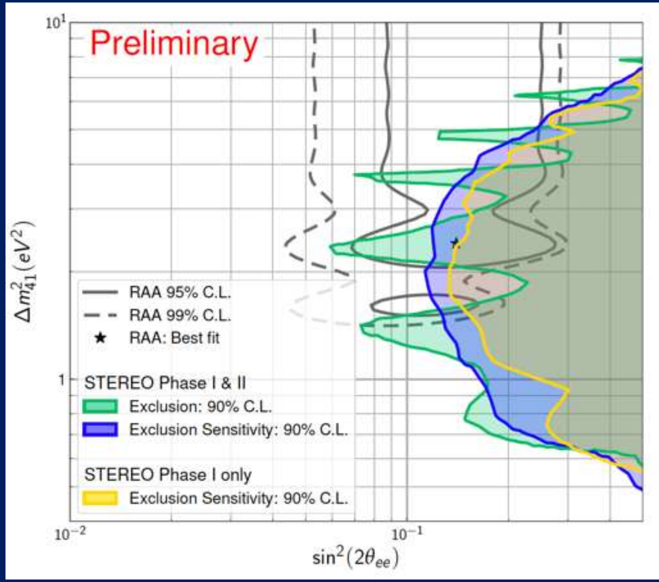
Daya Bay (and RENO) results suggest that the neutrino flux from ^{235}U ~3 sigma below what expected from fission models so far

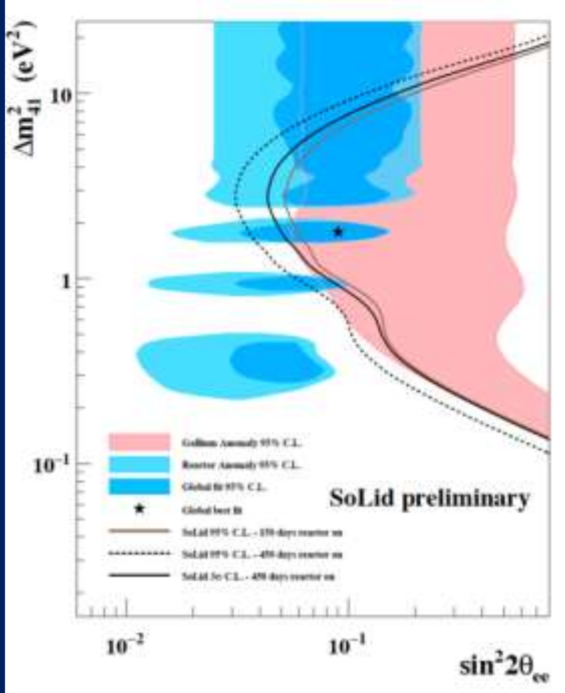
→ Need experiments at Highly Enriched Uranium reactors (20-90% ^{235}U), i.e. research reactors to thoroughly test this

Compact reactors
Highly enriched ^{235}U

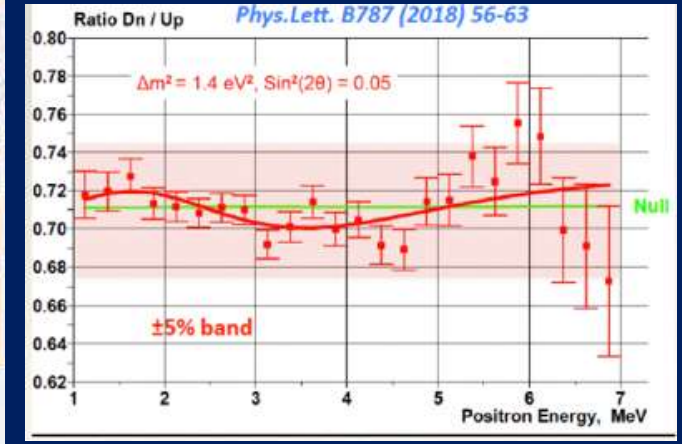


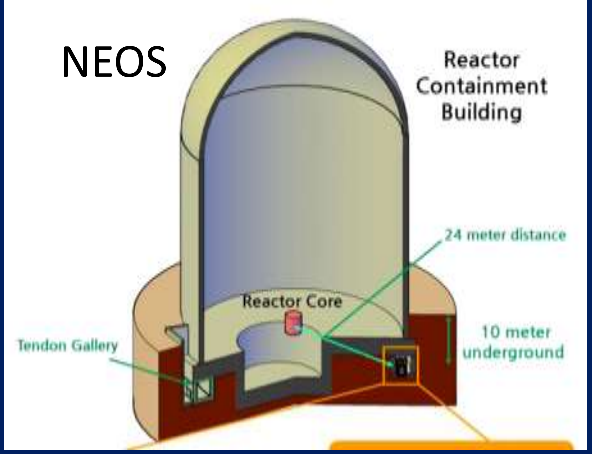
Exclusion and sensitivity of PROSPECT with current data *PROSPECT, arXiv:1806.02784*

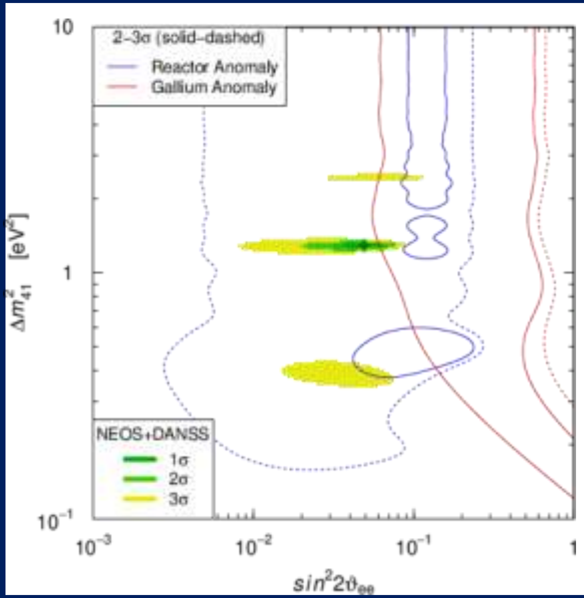




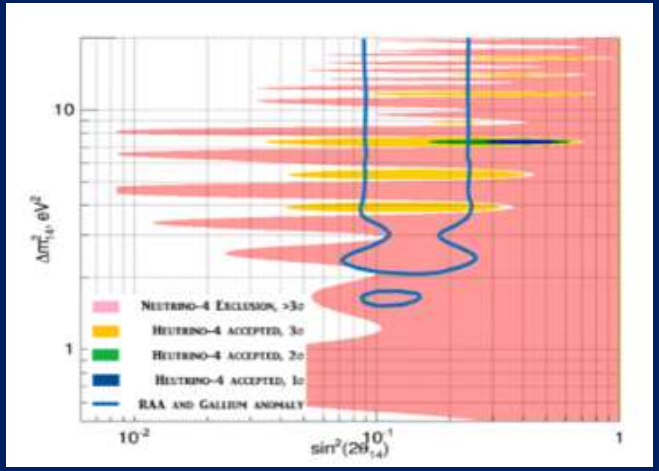
More reactor sterile neutrino searches



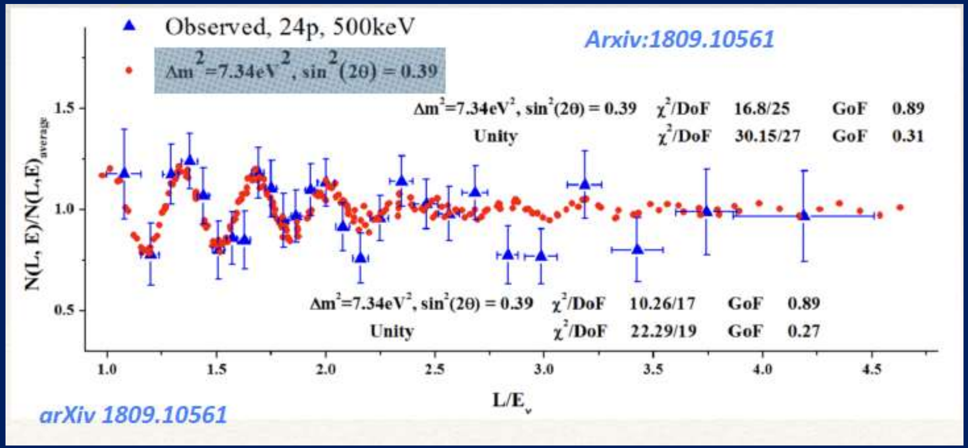




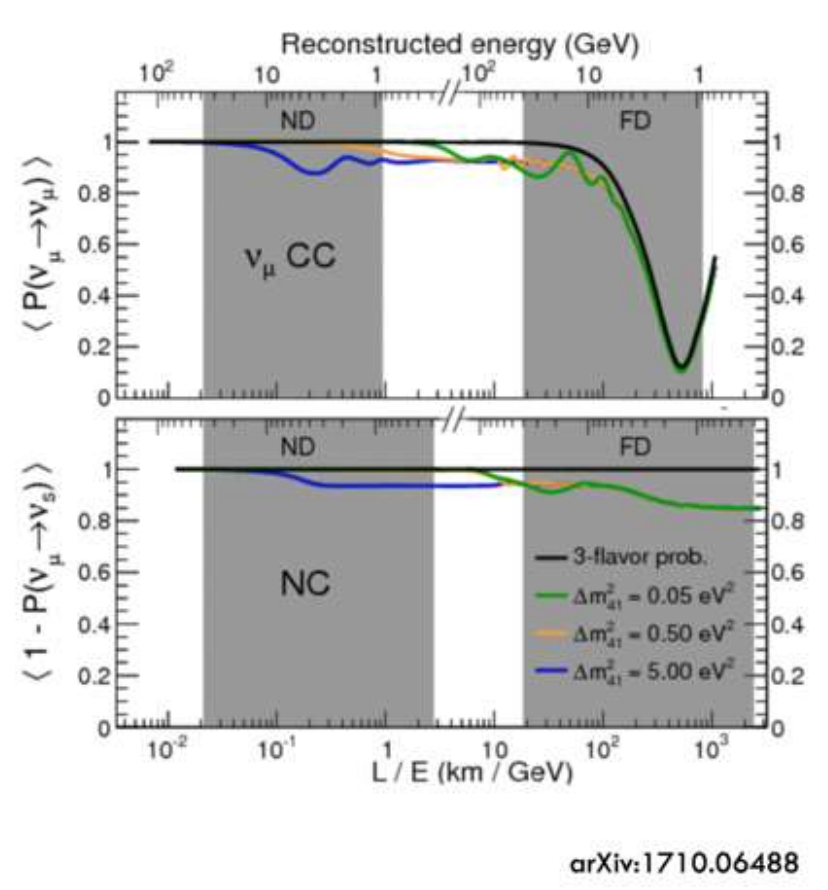
Phys.Lett. B782 (2018) 13-21

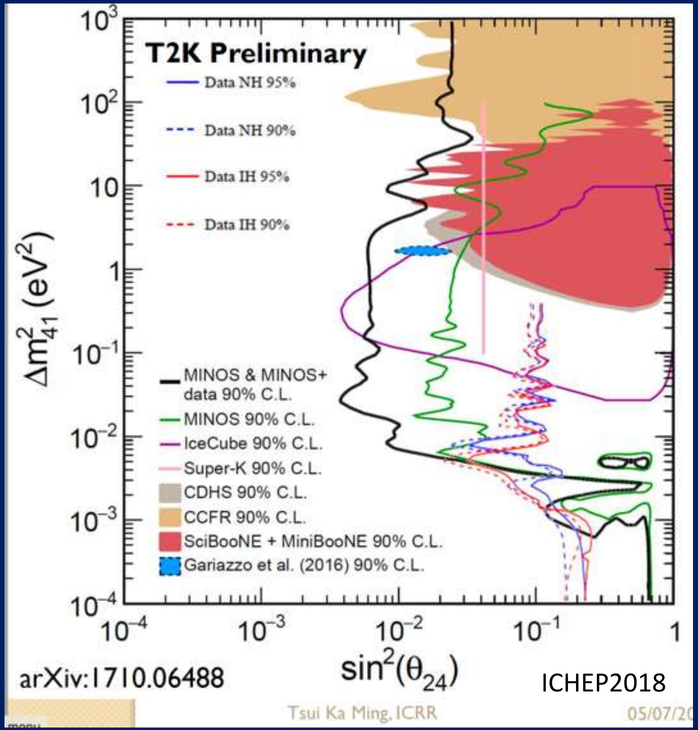


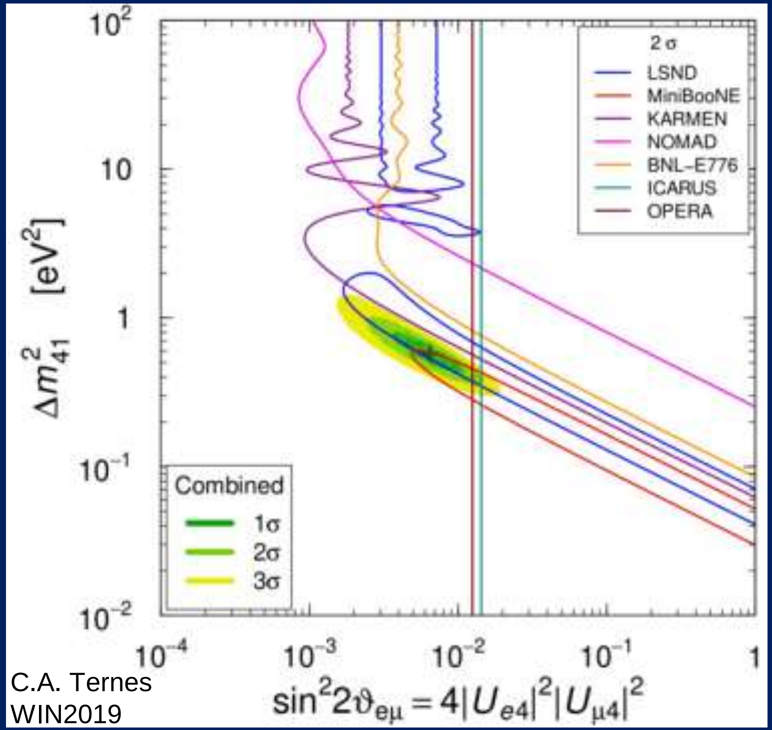
Neutrino-4



Sterile Neutrinos and long baseline experiments





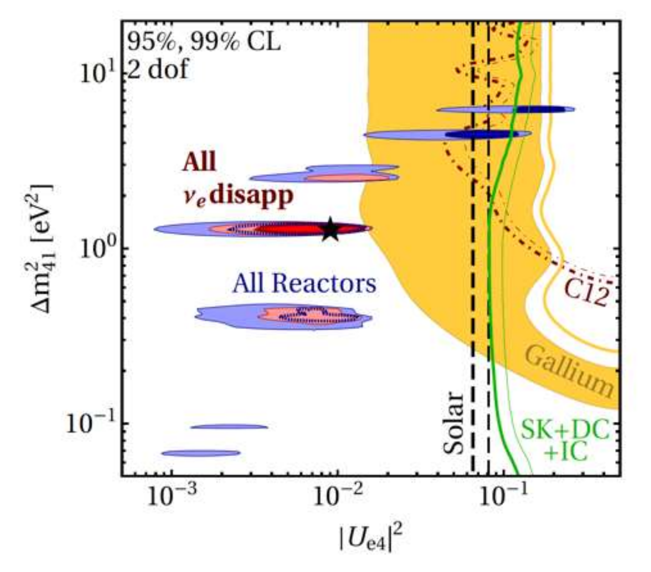


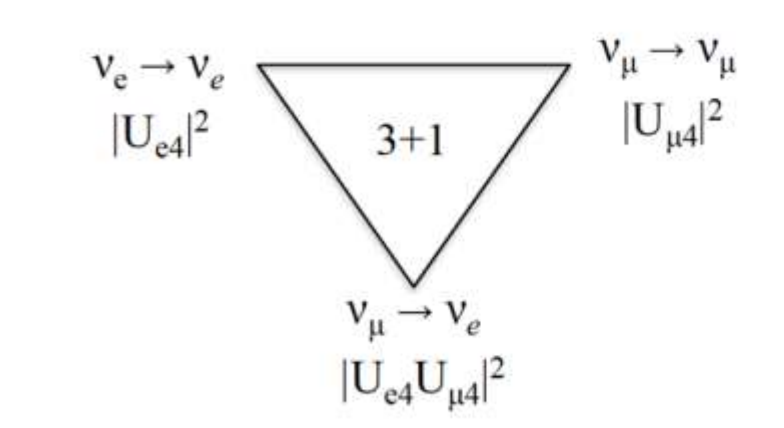
$$\nu_\mu \to \nu_\mu : |U_{\mu 4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14}$$

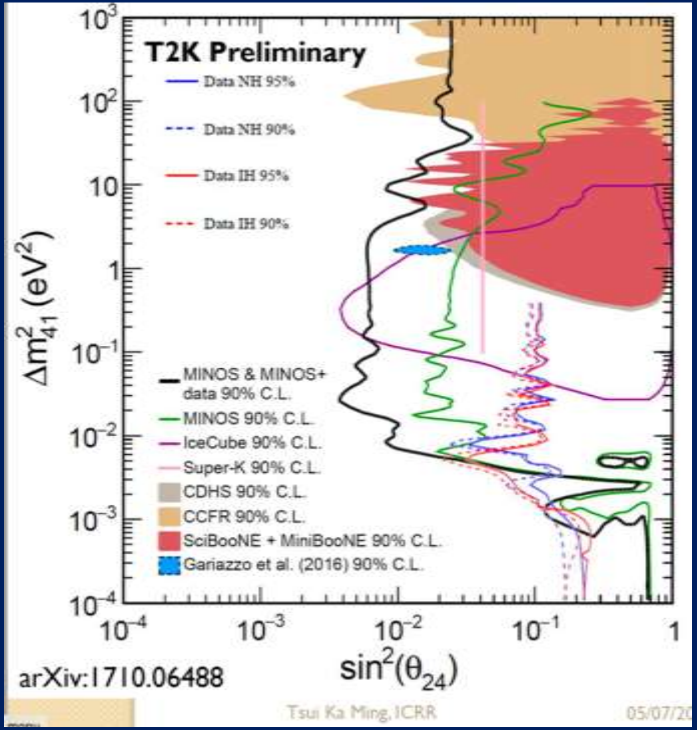
Different oscillation signatures in near and far detectors

Combination and tensions

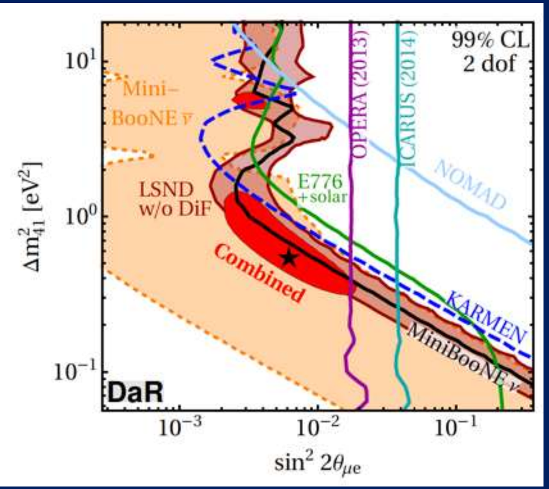
All nu-e disappearance arxiv:1803.10661

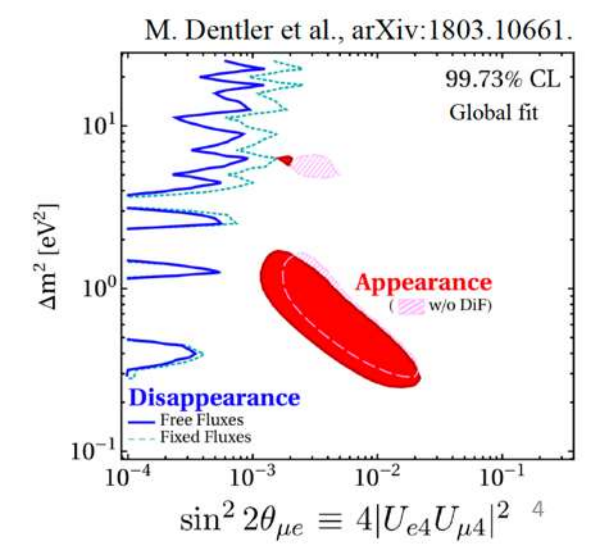




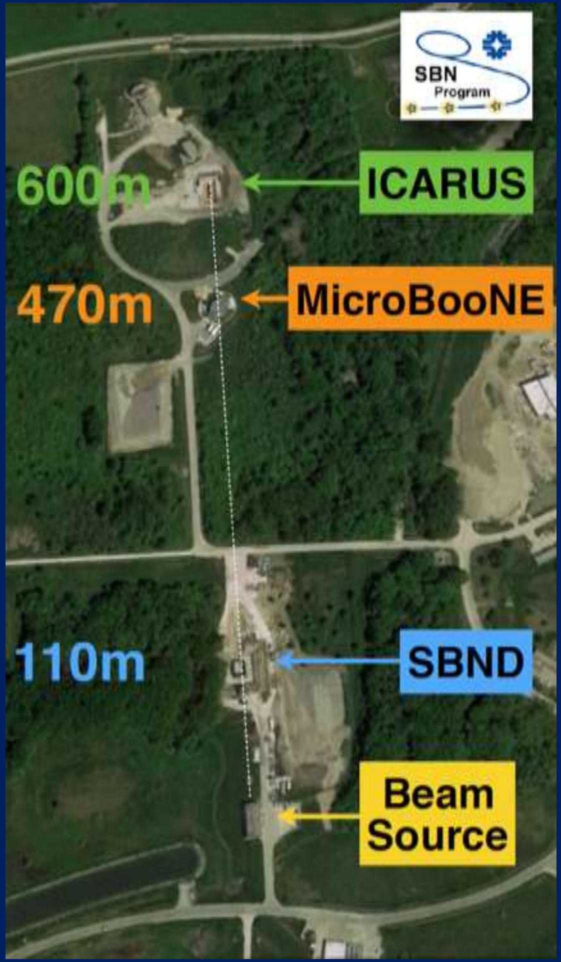


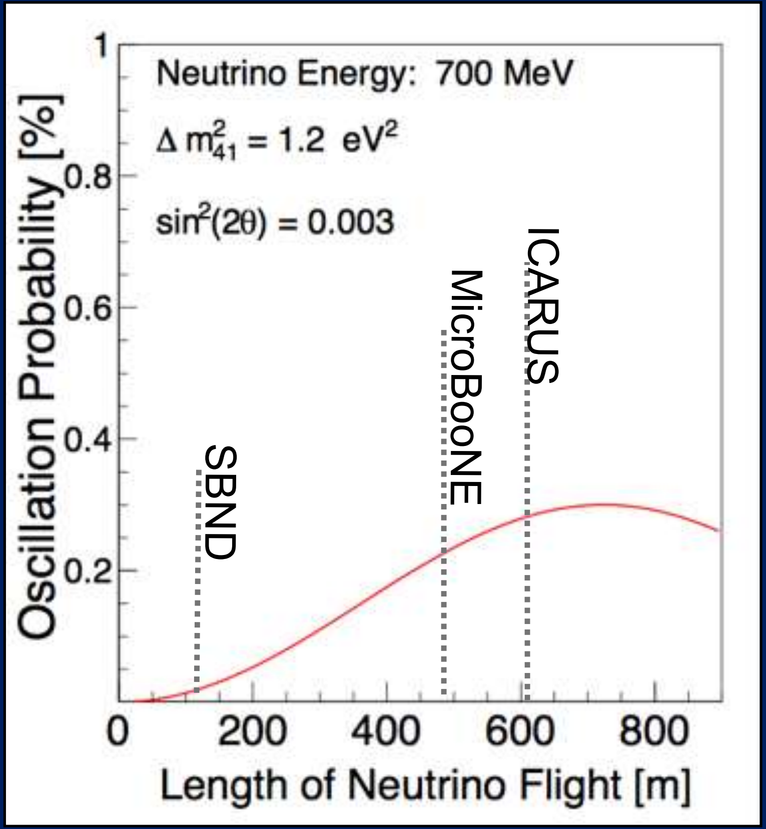
nu-e appearance arxiv:1803.10661

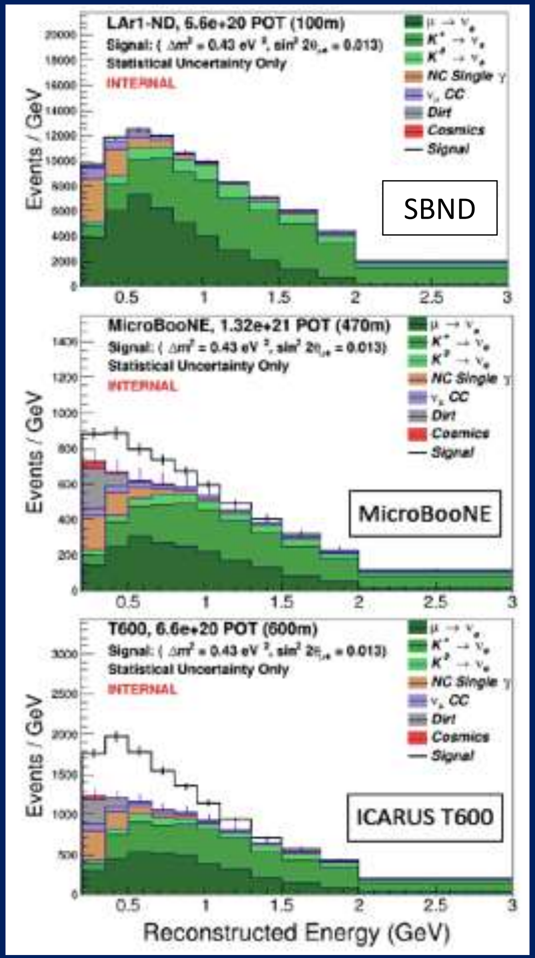


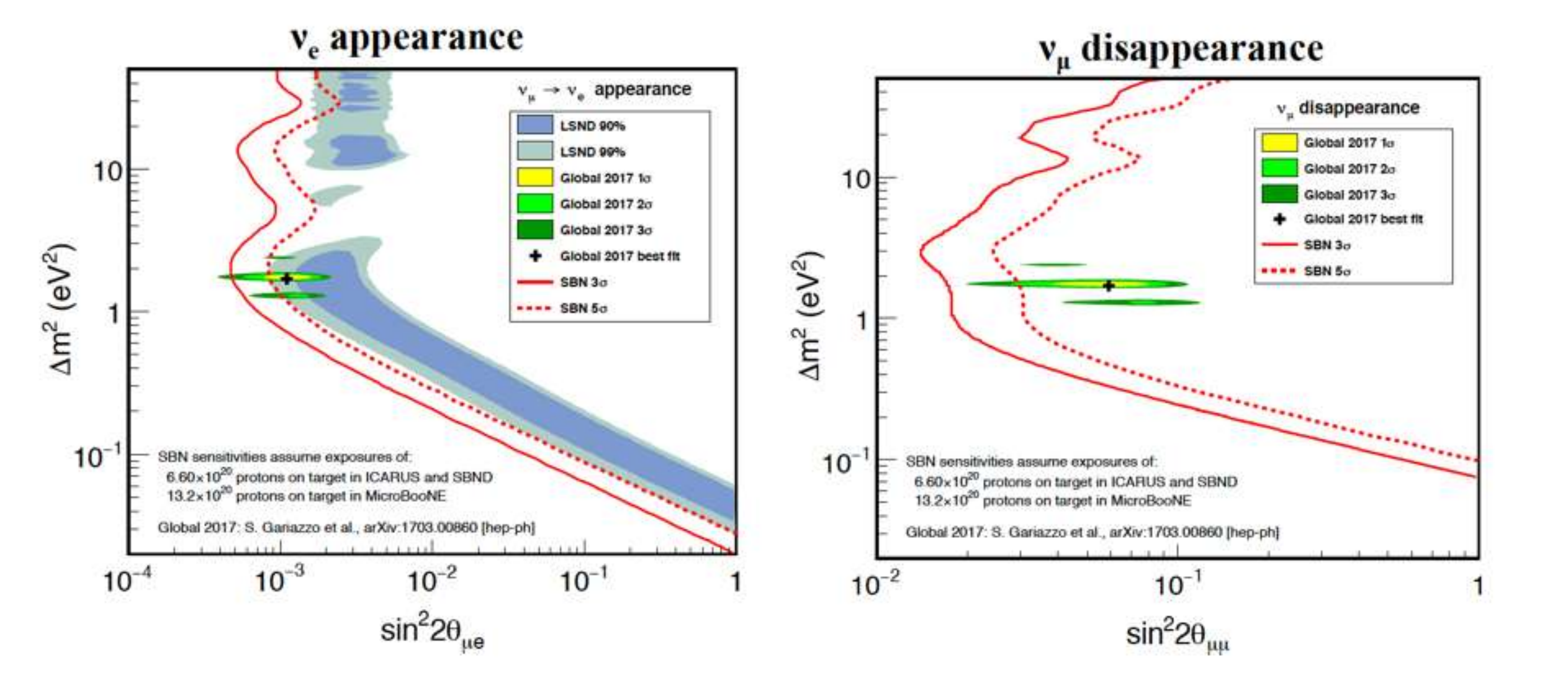


Three-detector setup with LArTPCs









νe appearance
νμ → νe appearance
LSND 90%
LSND 99%
Global 2017 1σ
Global 2017 2σ
Global 2017 3σ
Global 2017 best fit
SBN 3σ
SBN 5σ
SBN sensitivities assume exposures of:
6.60×10^20 protons on target in ICARUS and SBND
13.2×10^20 protons on target in MicroBooNE
Global 2017: S. Gariazzo et al., arXiv:1703.00860 [hep-ph]
Δm² (eV²)
sin²2θμe
νμ disappearance
νμ disappearance
Global 2017 1σ
Global 2017 2σ
Global 2017 3σ
Global 2017 best fit
SBN 3σ
SBN 5σ
SBN sensitivities assume exposures of:
6.60×10^20 protons on target in ICARUS and SBND
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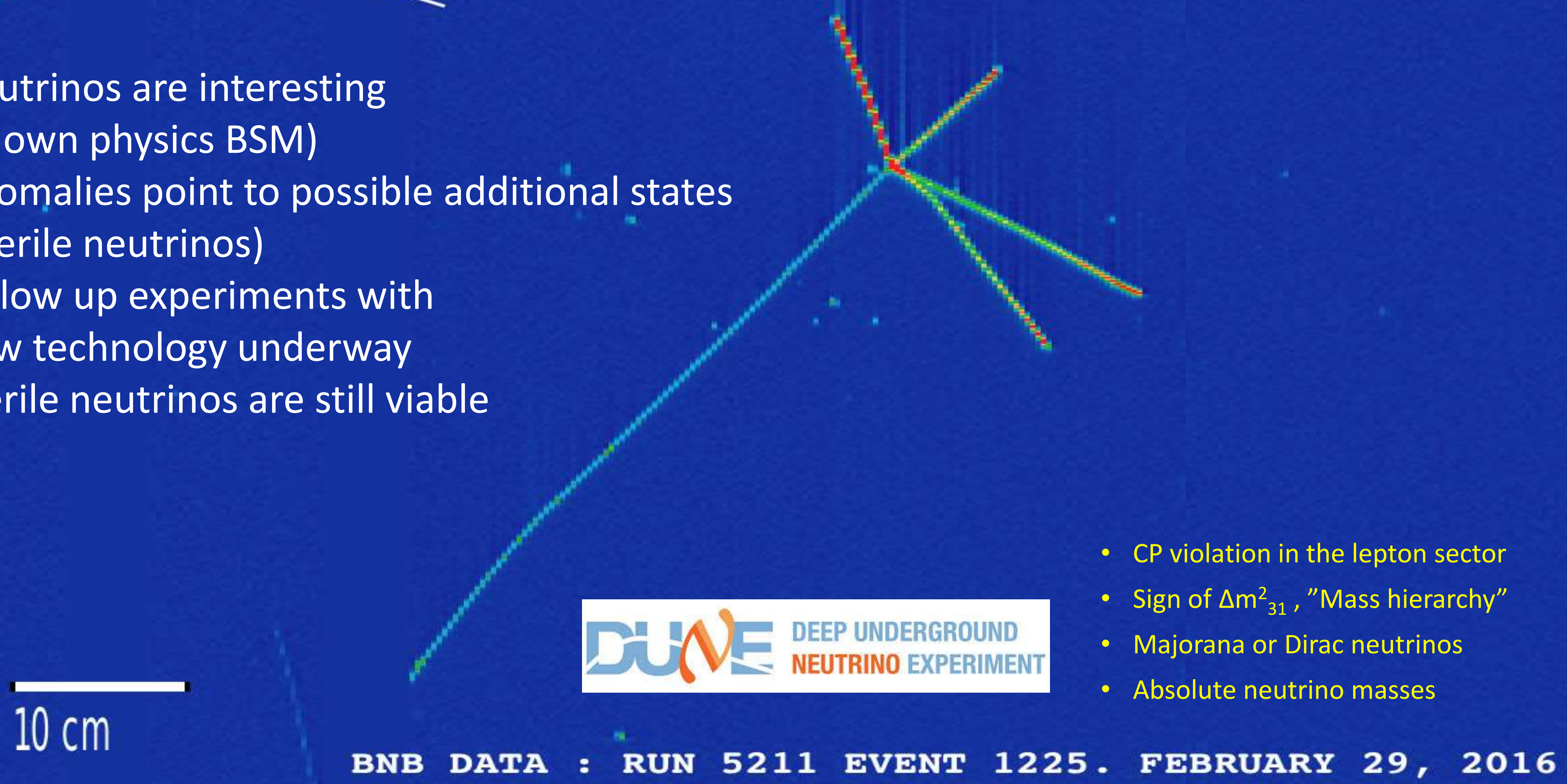
Global 2017: S. Gariazzo et al., arXiv:1703.00860 [hep-ph]
Δm² (eV²)
sin²2θμμ

µBooNE

- Neutrinos are interesting (known physics BSM)
- Anomalies point to possible additional states (Sterile neutrinos)
- Follow up experiments with new technology underway
- Sterile neutrinos are still viable



DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

- CP violation in the lepton sector
- Sign of Δm^2_{31} , ”Mass hierarchy”
- Majorana or Dirac neutrinos
- Absolute neutrino masses

+++++++

BACKUP

+++++++

MicroBooNE
15 papers
33 public notes

CC nu-mu double differential
arXiv:1905.09694

Cosmic Ray Rejection for CCQE
arXiv:1812.05679

Cosmic Ray Tagger
JINST 14, P04004 (2019)

CC Pi0 xsec
Phys. Rev. D99, 091102(R) (2019)

Deep NN e.m. reco
Phys. Rev. D99, 09200

Charged particle multiplicity
Eur. Phys. J. C79, 248 (2019)

Signal processing I and II
JINST 13, P07006 (2018) JINST 13, P07007 (2018)

Noise and filtering
JINST 12, P08003 (2017)

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

Multiple Coulomb Scattering
JINST 12 P10010 (2017)

Cosmic ray studies
JINST 12, P12030 (2017)

Michel electron reconstruction
JINST 12, P09014 (2017)

CNN use for LArTPC
JINST 12, P03011 (2017)

Detector paper
JINST 12, P02017 (2017)

Electron neutrino selection
Electron neutrino selection
1mu1p selection and reconstruction
Search for single photon events
Unfolding the MB signal
CC-Np cross section
CCpi0 cross section
Inclusive CC cross section
Reconstruction performance
Booster neutrino Flux
Ar-39 use for calibration
Wire Cell reconstruction
dE/dx calibration
Drift electron lifetime
Side piercing tracks with t0
Space charge
Signal formation
Proton ID
MCC7 Data/MC
Detector stability
3D shower reconstruction
CC event from 5E19 POT
NC event selection in MC
Cosmic shielding
MC study of expected events
Purity of the LAr
Neutrino identification
Noise dependence on temperature

Public notes

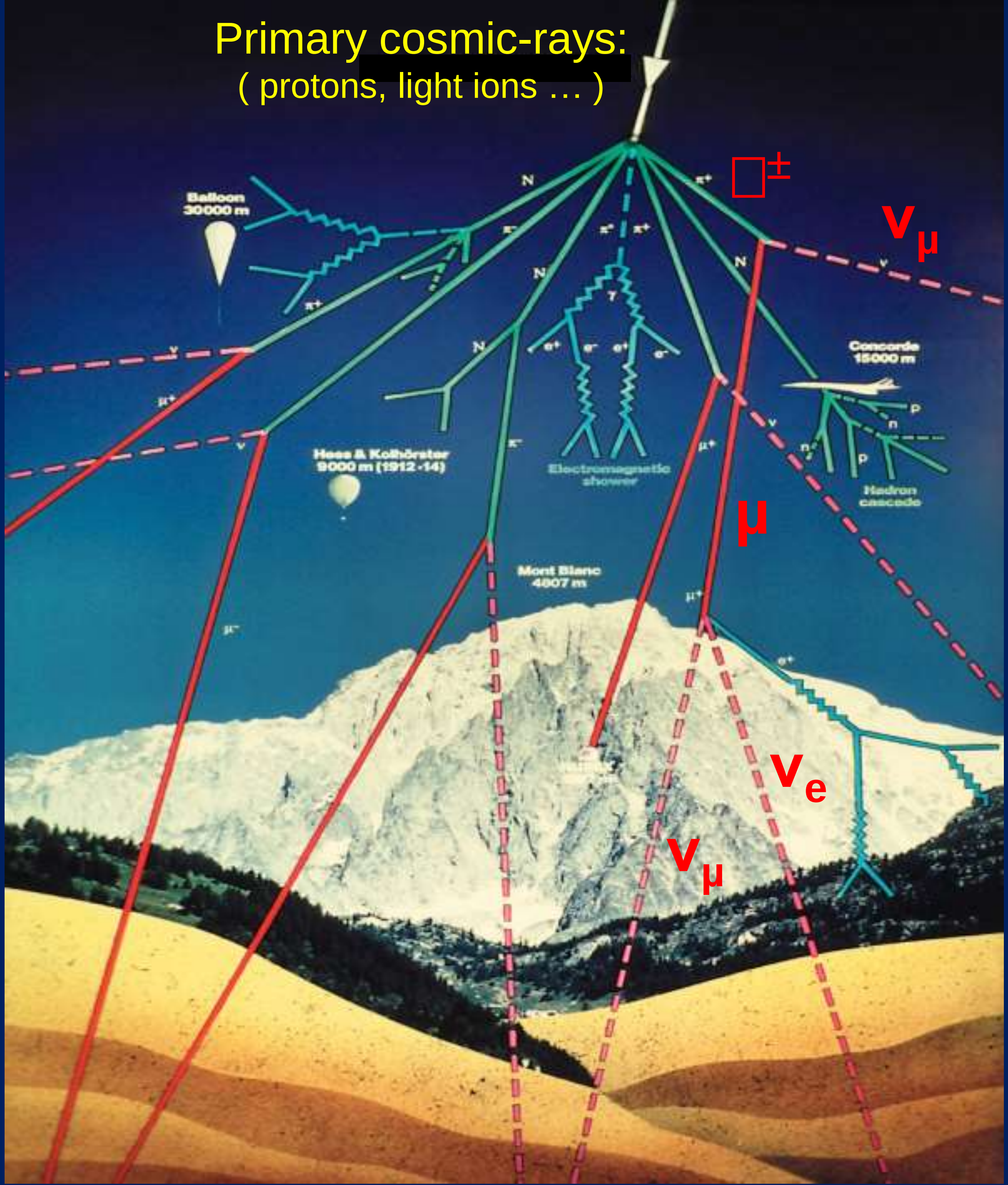
2019-2020
- Flagship results with flagship MC that makes extensive use of uB data as a constraint

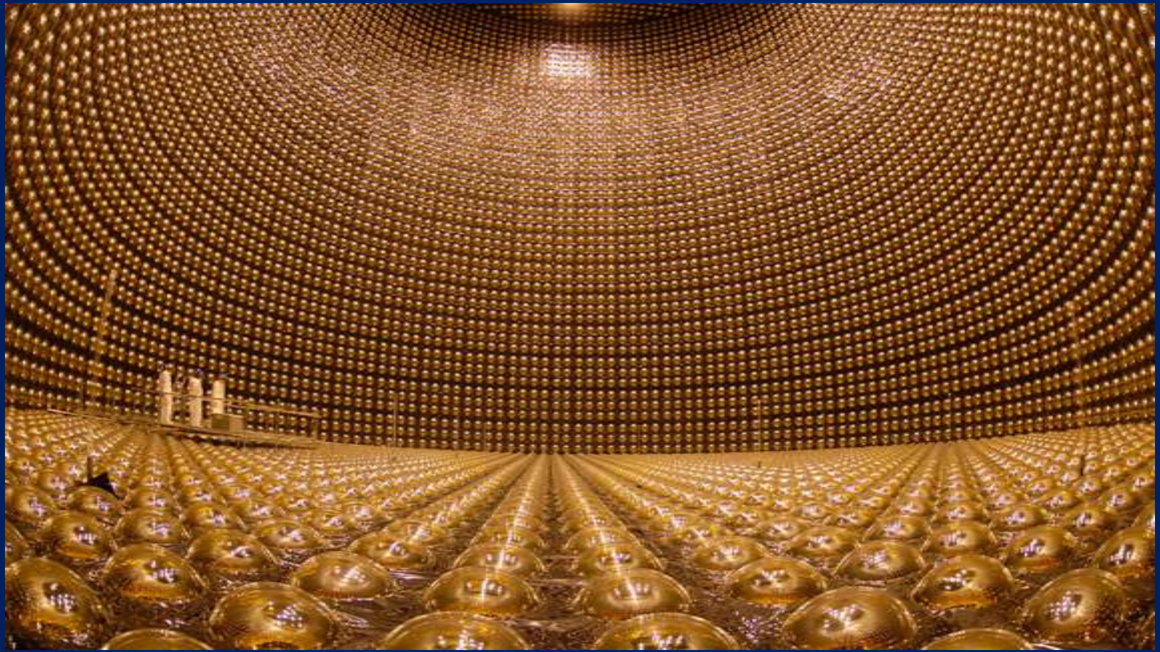
2018
- Exploiting MCC8 for 1st physics results
- Identified limitations in signal processing and efficiencies
- 1st iteration on calibrations, systematics
  → targeted development of a new MC (MCC9)

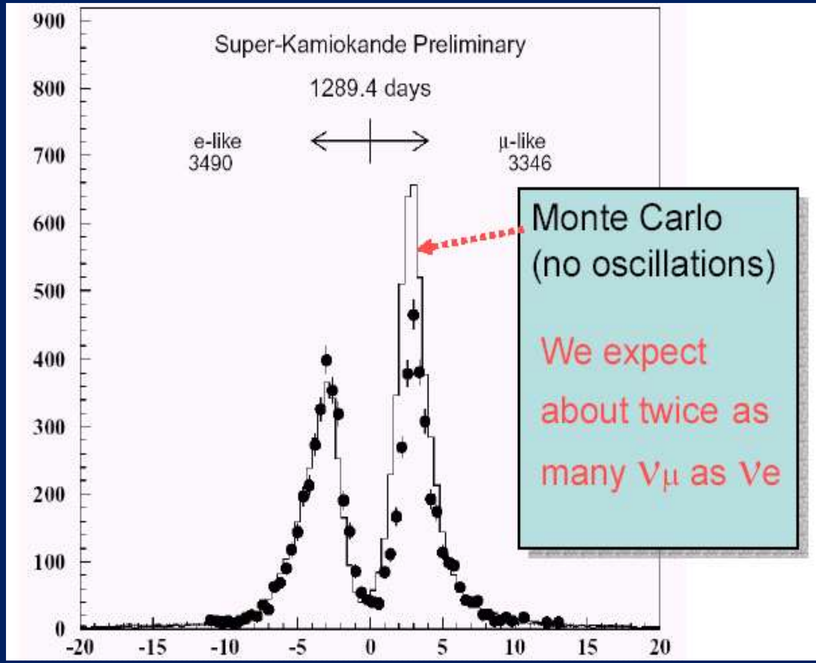
2017
- CRT installation
- Converging on a new robust MC (MCC8), first MC using data as input
- Efforts on modelling, first calibrations, particle ID, 1st systematics, computing speed up

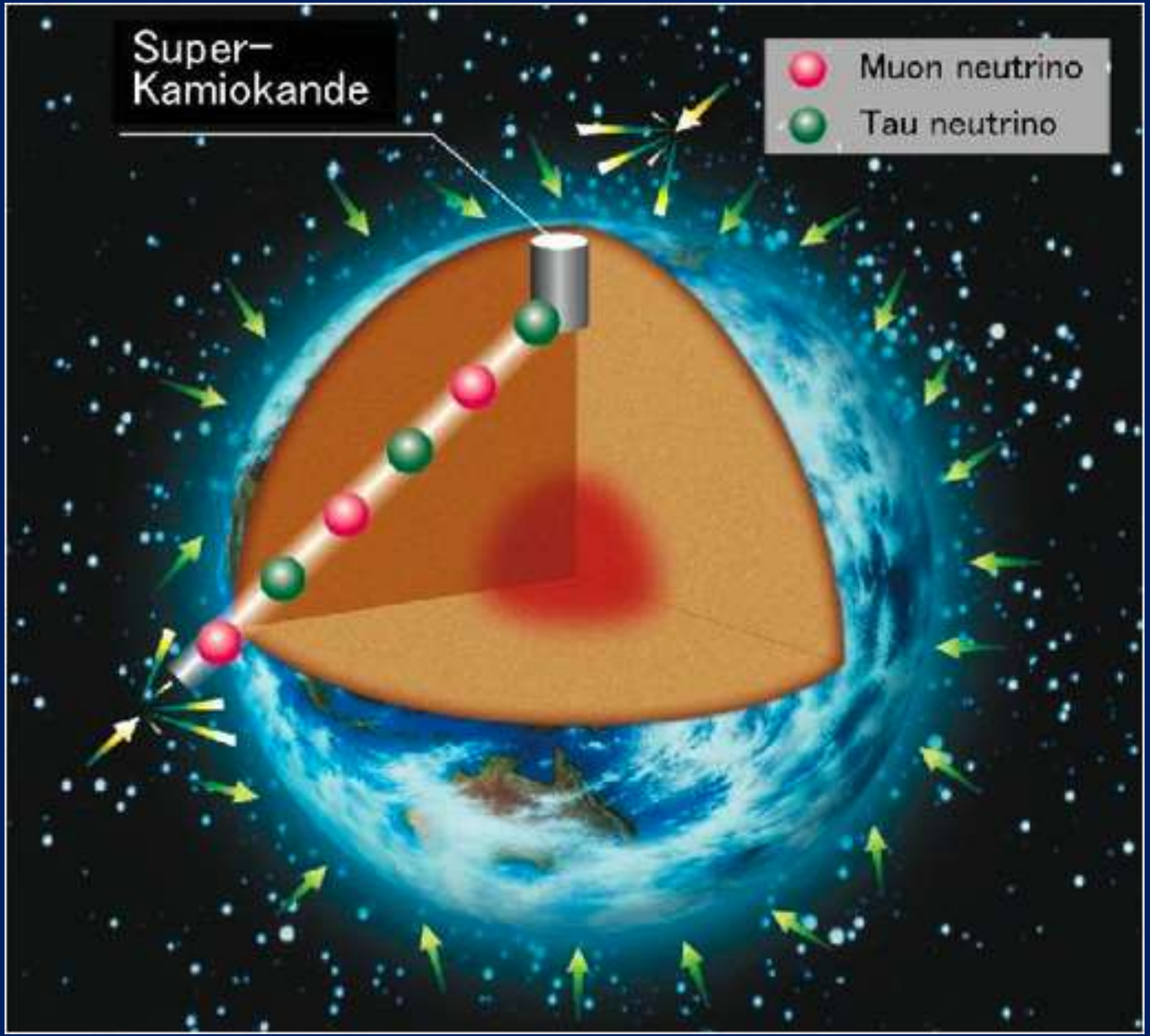
2016
- First MC release of automated LArTPC reconstruction (MCC7)
- Performance results and Data/MC discrepancies
- "Open development" phase, investigate novel ideas, major effort on low level and high level reconstruction

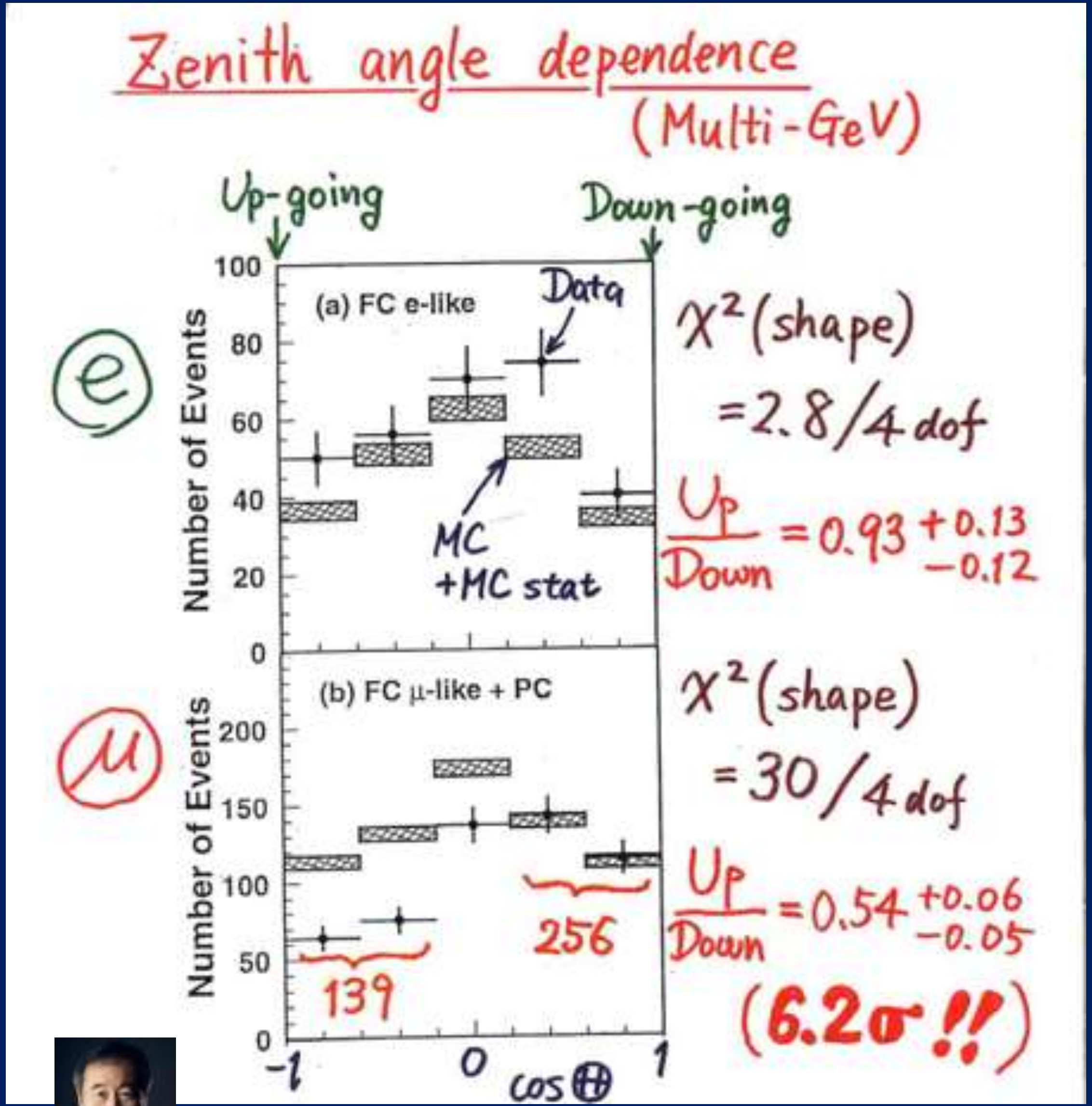
2015
- Detector turn on (October)
- Cosmic and beam data
- Immediate identification of neutrinos


Primary cosmic-rays:
(protons, light ions …)
ν_μ
μ
ν_e
ν_μ
Balloon 30000 m
Concorde 15000 m
Hess & Kolhörster 9000 m (1912-14)
Electromagnetic shower
Hadron cascade
Mont Blanc 4807 m




Super-Kamiokande Preliminary
1289.4 days
e-like 3490
μ-like 3346
Monte Carlo (no oscillations)
We expect about twice as many ν_μ as ν_e
0
100
200
300
400
500
600
700
800
900
-20
-15
-10
-5
0
5
10
15
20

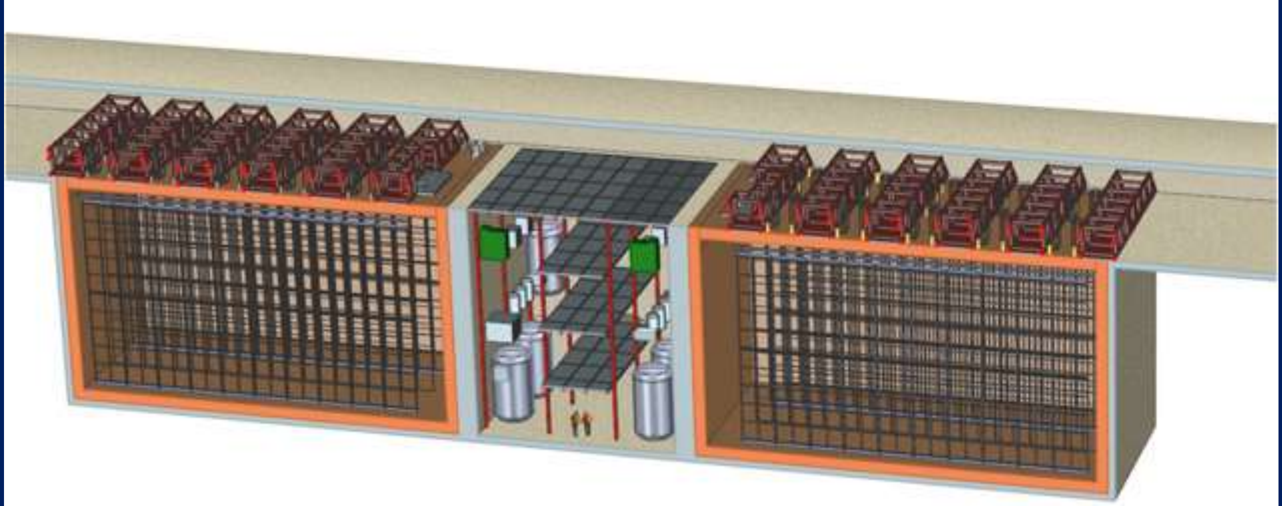




Takaaki Kajita, Neutrino '98

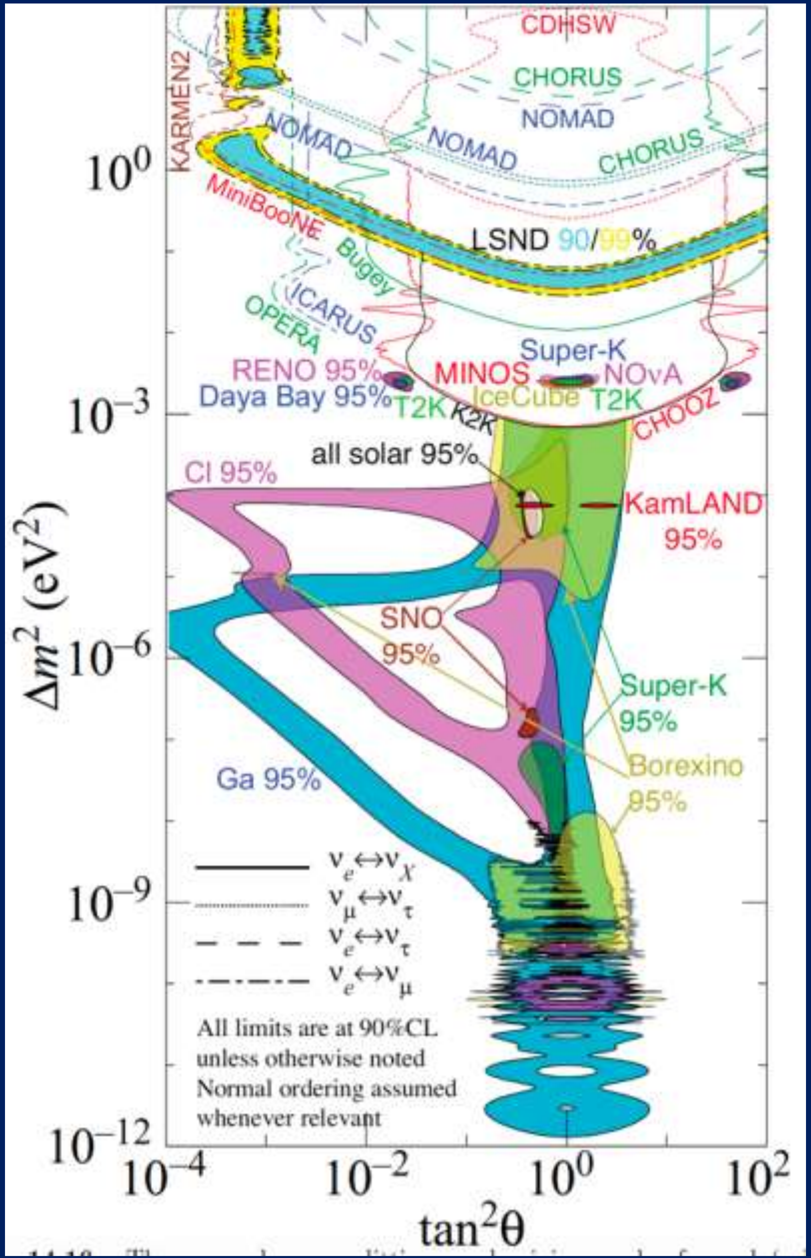
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

In den 2020er…

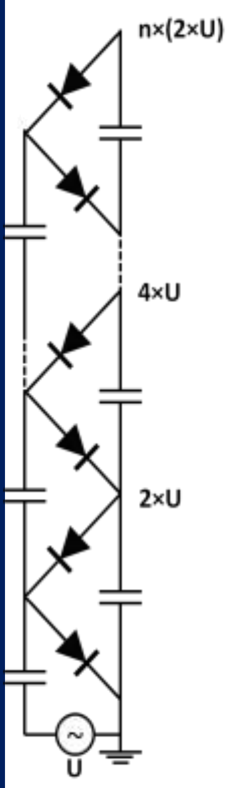


LArTPC development in Bern

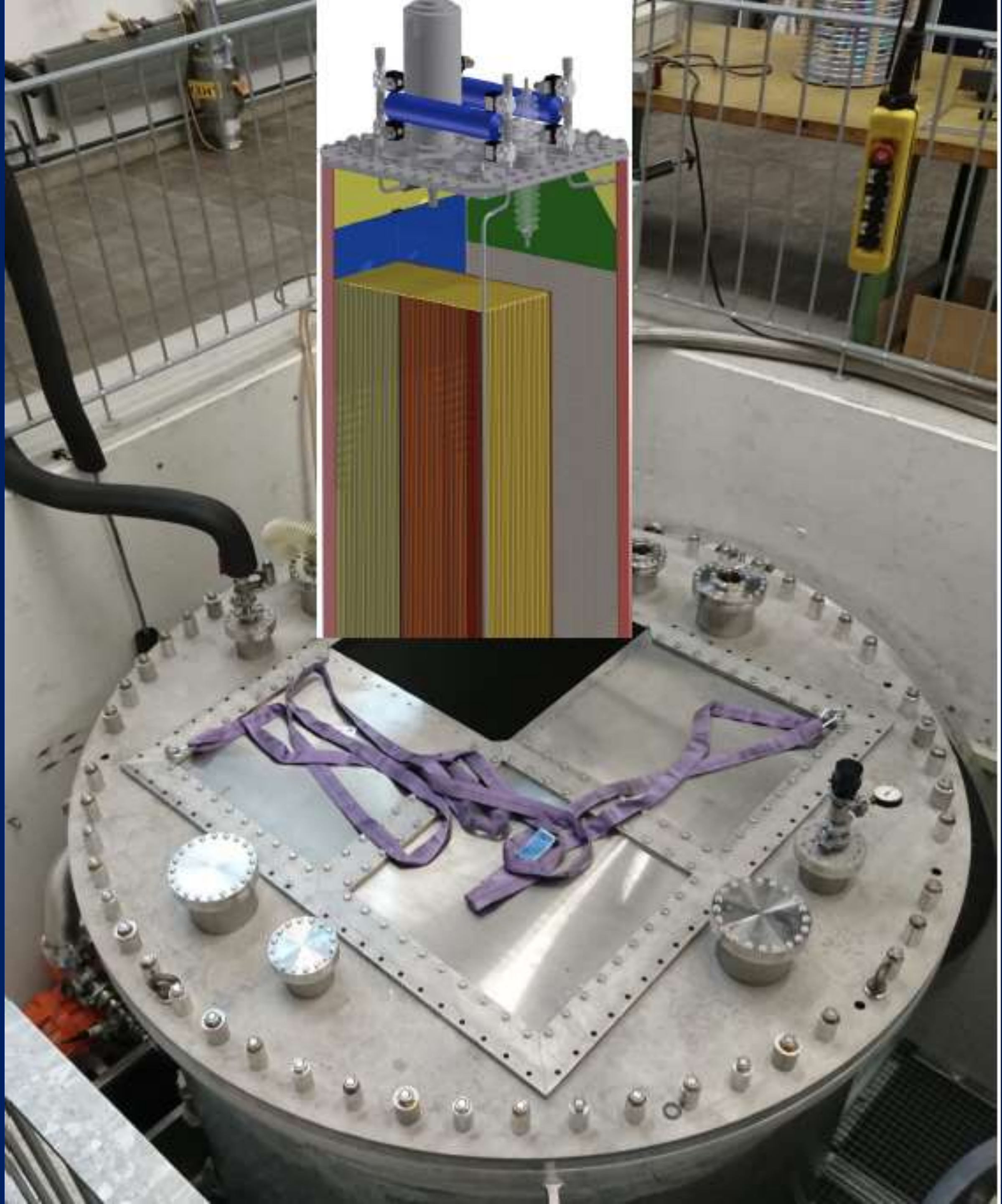
ArgonTUBE
2009-2015

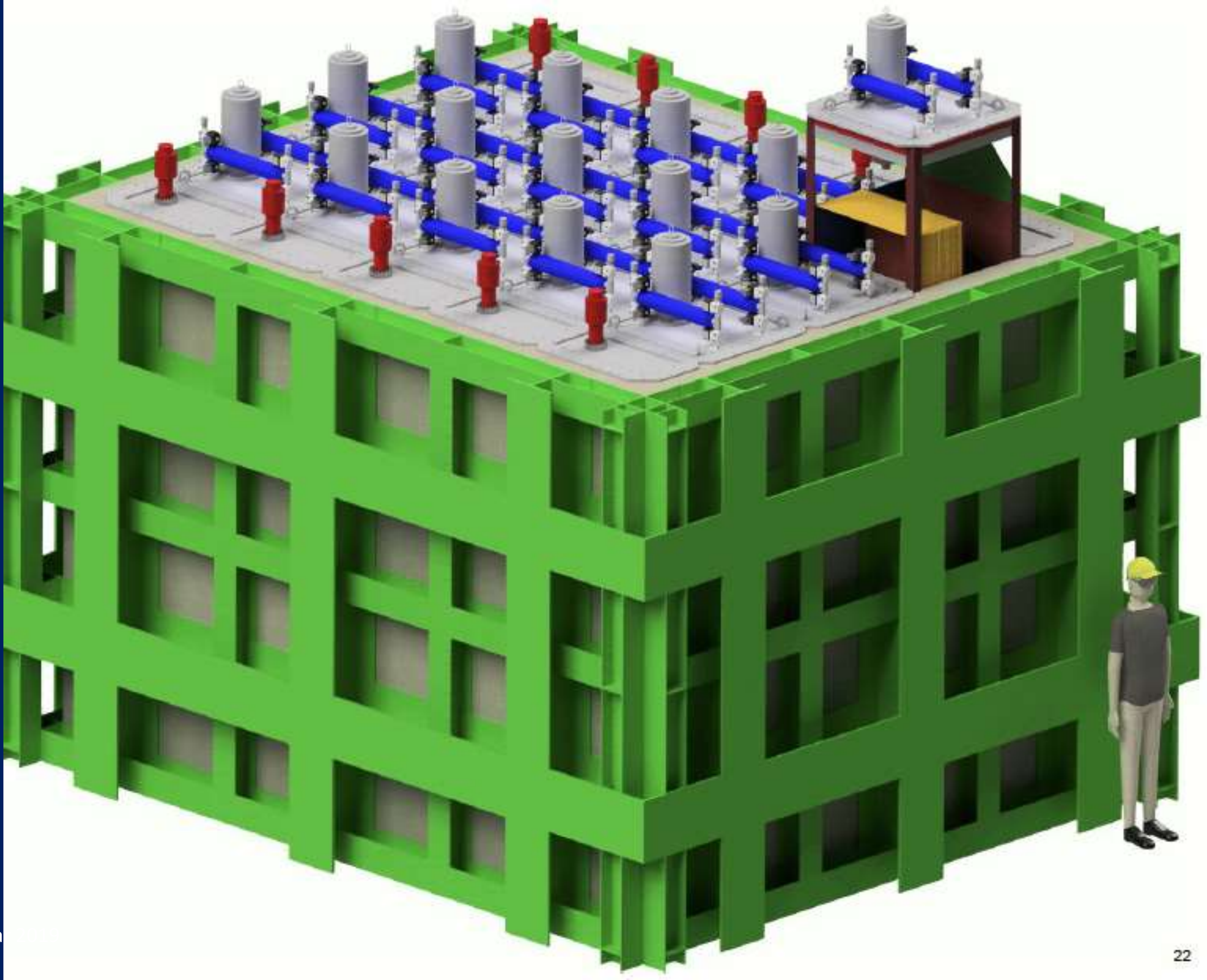

CDHSW
CHORUS
NOMAD
NOMAD
NOMAD
CHORUS
KARMEN2
MiniBooNE
Bugey
LSND 90/99%
ICARUS
OPERA
RENO 95%
Daya Bay 95%
T2K
K2K
MINOS
Super-K
NOvA
IceCube
T2K
CHOOZ
all solar 95%
Cl 95%
KamLAND 95%
SNO 95%
Super-K 95%
Borexino 95%
Ga 95%
$\nu_e \leftrightarrow \nu_X$
$\nu_\mu \leftrightarrow \nu_\tau$
$\nu_e \leftrightarrow \nu_\tau$
$\nu_e \leftrightarrow \nu_\mu$
All limits are at 90%CL
unless otherwise noted
Normal ordering assumed
whenever relevant
Δm^2 (eV^2)
10^0
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-4}
10^{-2}
10^0
10^2
$\tan^2\theta$

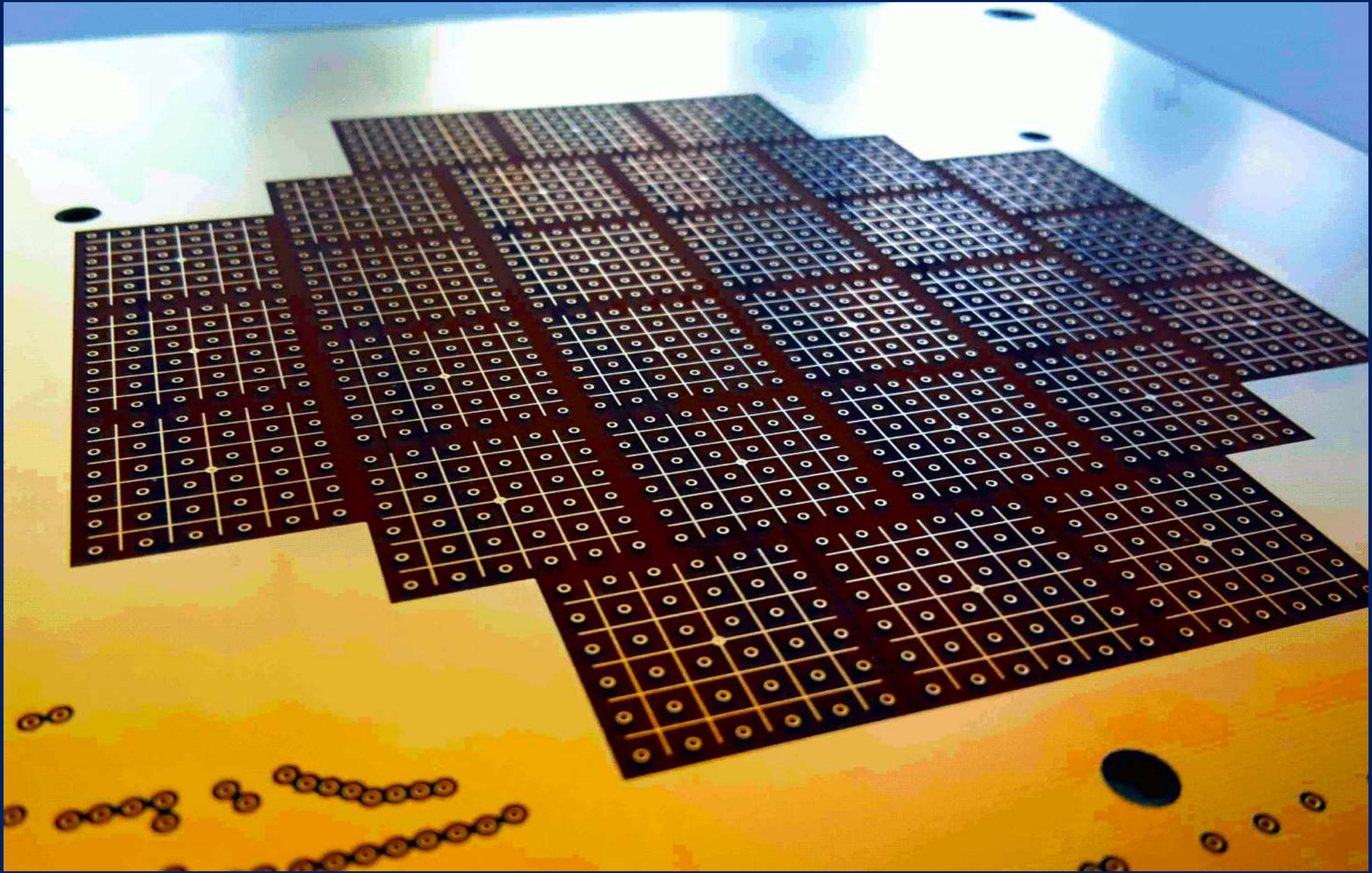
- Greinacher circuit: 125 stages, input 4 kV AC
- COMSOL finite element analysis software to optimize the geometry of the field-shaping rings
- Goal: drift field of 1 kV/cm
- Reached 170 kV (0.34 kV/cm)



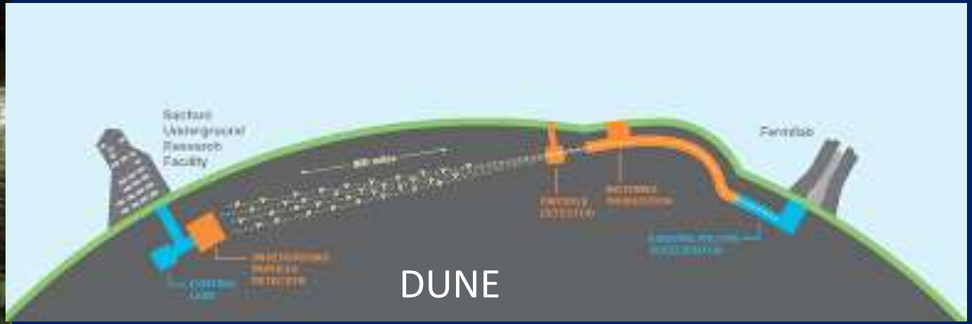
MicroBooNE in USA (2015 —)



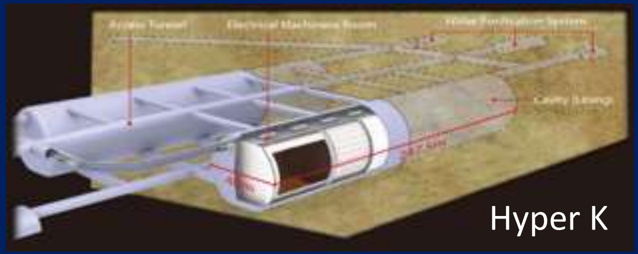

22

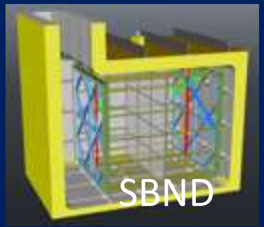


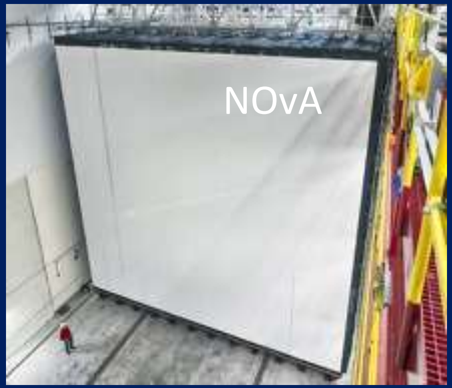

Opera


DUNE

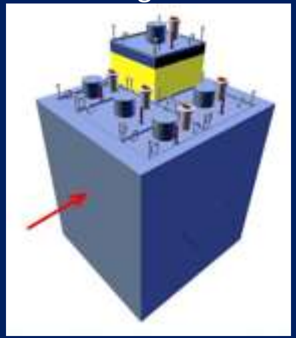

Super-Kamiokande

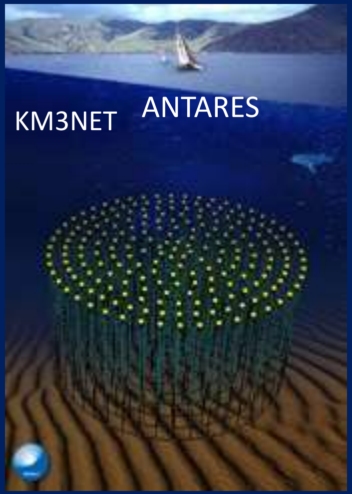

Hyper K


SBND


NOvA

ArgonCUBE




KM3NET
ANTARES

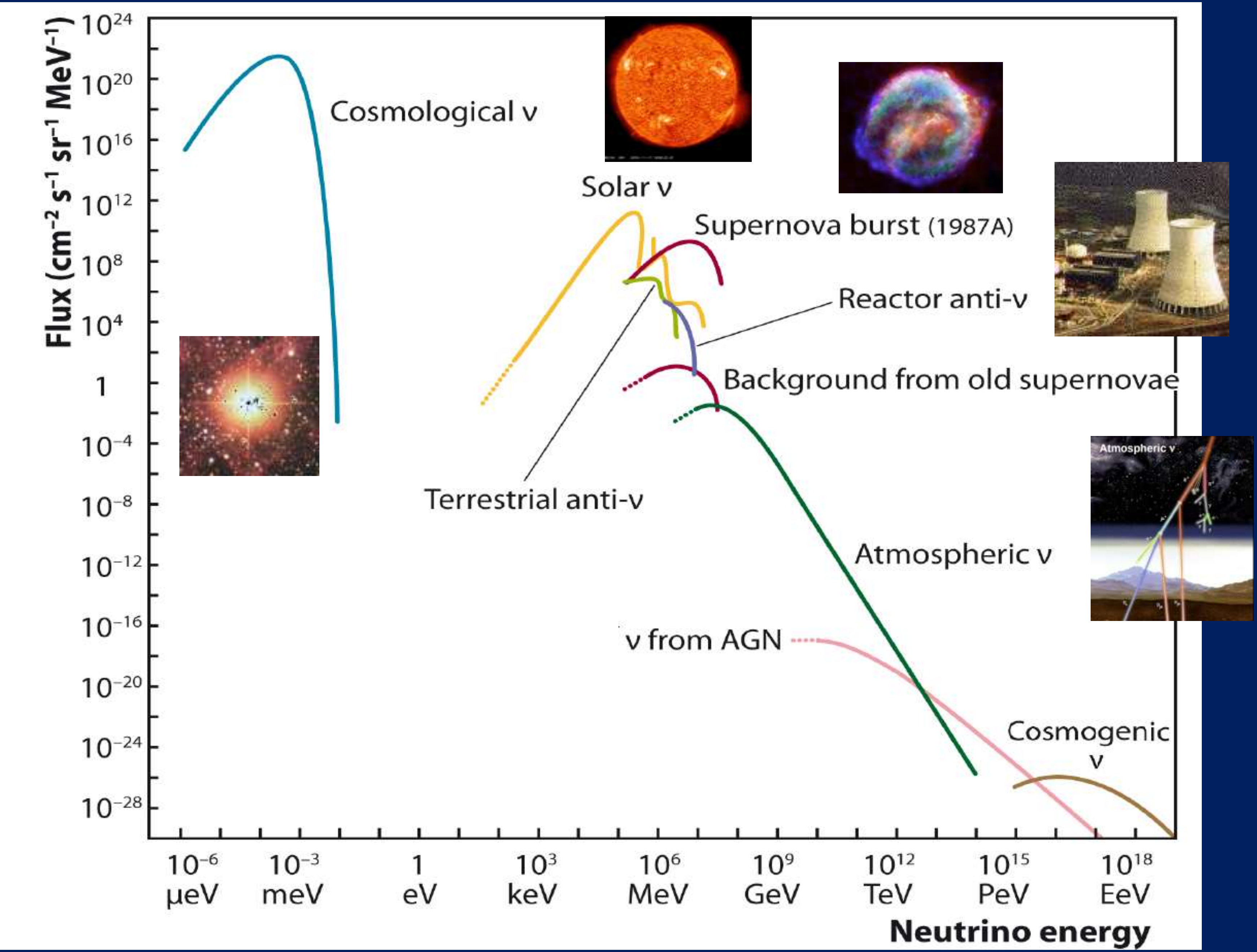

Katrin


DayaBay

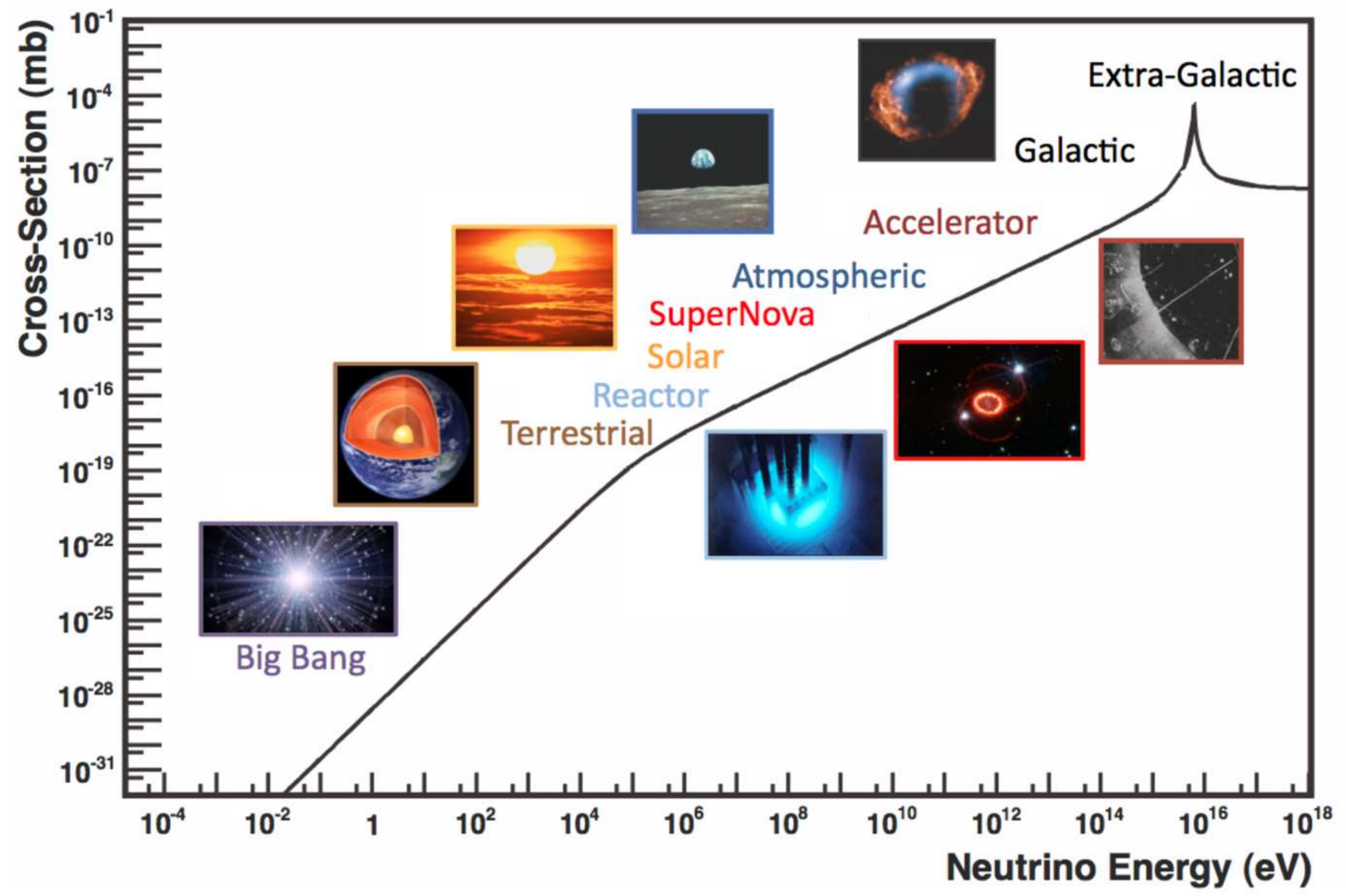

IceCube

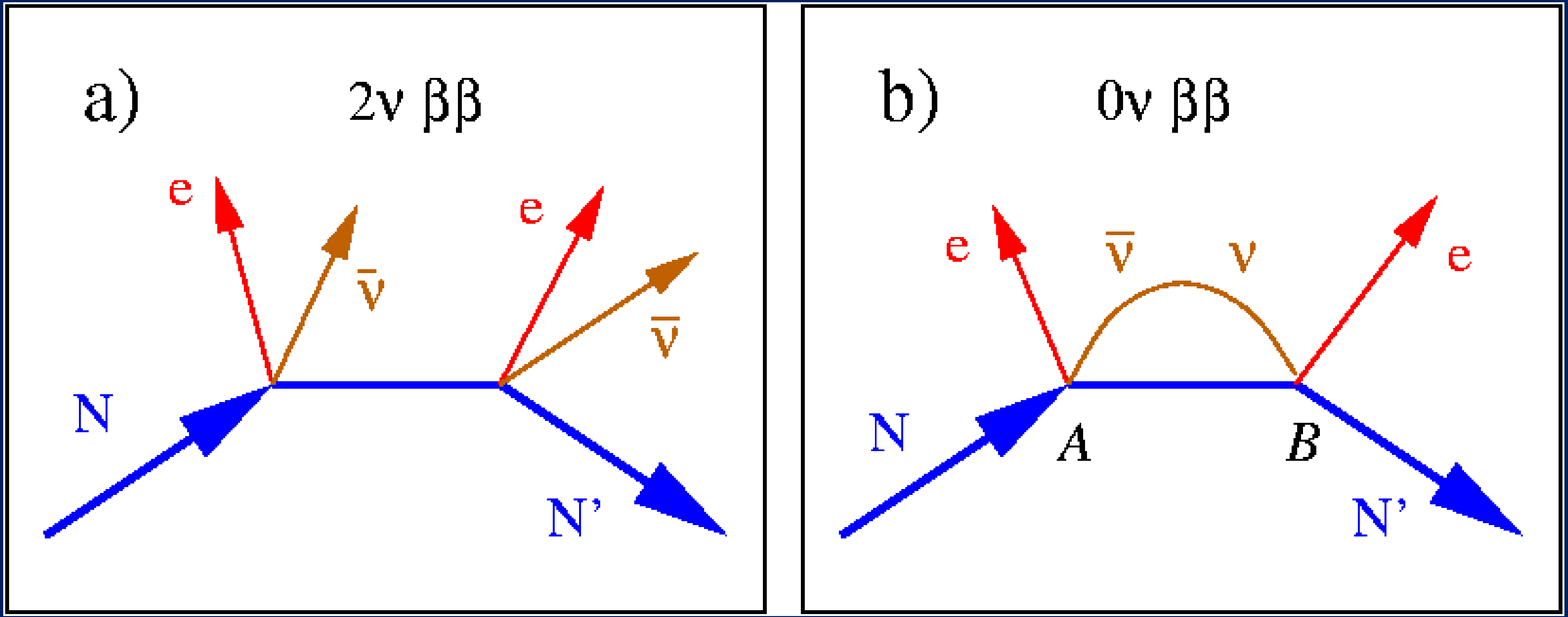

MINOS


uBooNE



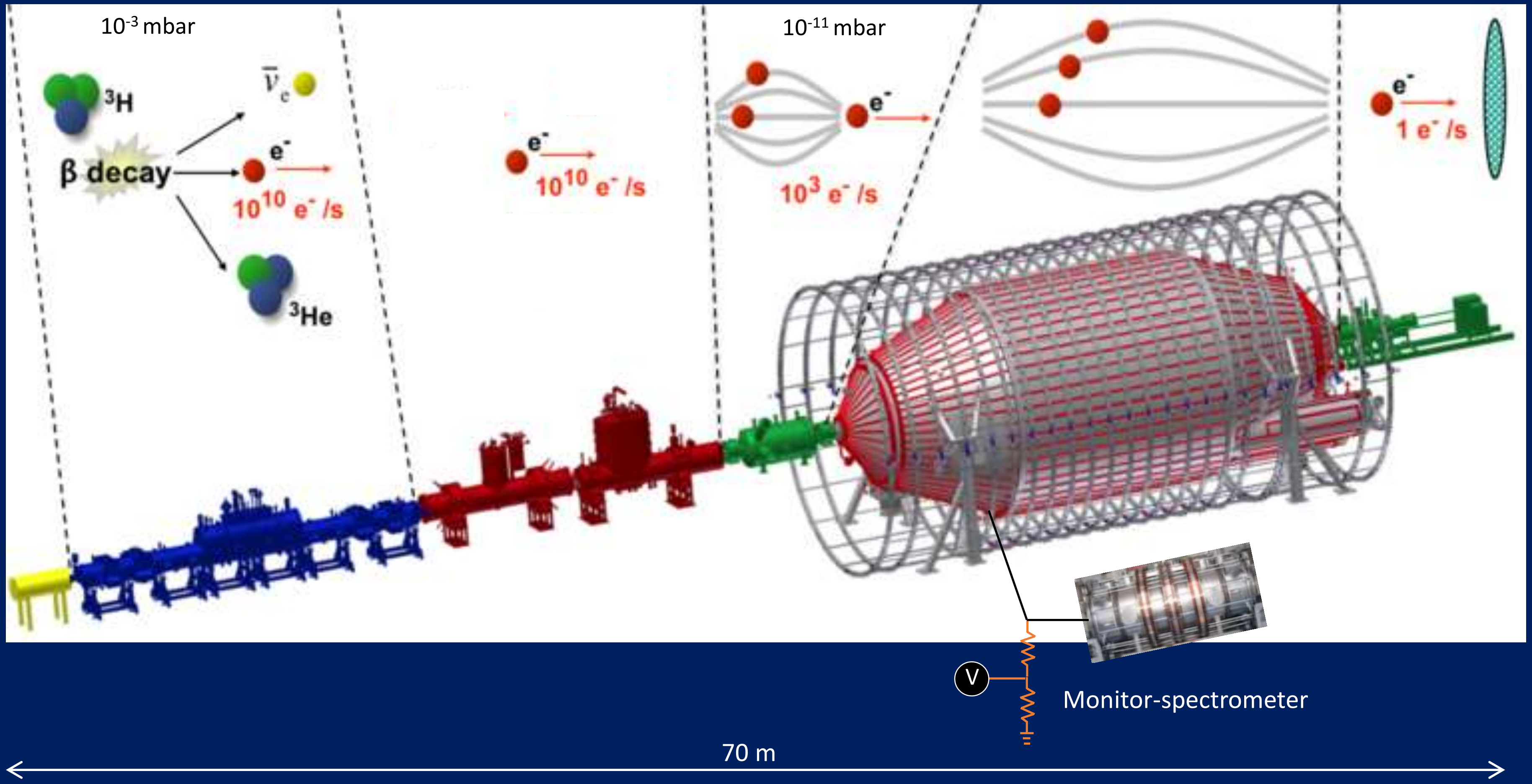
Flux (cm^{-2} s^{-1} sr^{-1} MeV^{-1})
10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
Atmospheric ν
ν from AGN
Cosmogenic ν
10^{-6} μeV
10^{-3} meV
1 eV
10^{3} keV
10^{6} MeV
10^{9} GeV
10^{12} TeV
10^{15} PeV
10^{18} EeV
Neutrino energy


Cross-Section (mb)
10^-1
10^-4
10^-7
10^-10
10^-13
10^-16
10^-19
10^-22
10^-25
10^-28
10^-31
10^-4
10^-2
1
10^2
10^4
10^6
10^8
10^10
10^12
10^14
10^16
10^18
Neutrino Energy (eV)
Extra-Galactic
Galactic
Accelerator
Atmospheric
SuperNova
Solar
Reactor
Terrestrial
Big Bang


a)
2ν ββ
e
ν̄
e
ν̄
N
N'
b)
0ν ββ
e
ν̄
ν
e
N
A
B
N'

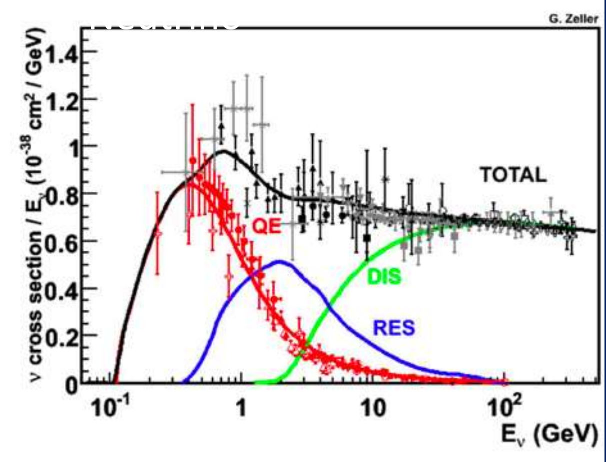
Overview of KArlsruhe TRItium Neutrino Experiment

Windowless gaseous source
Transport section
Pre-spectrometer
Main-spectrometer
Detector



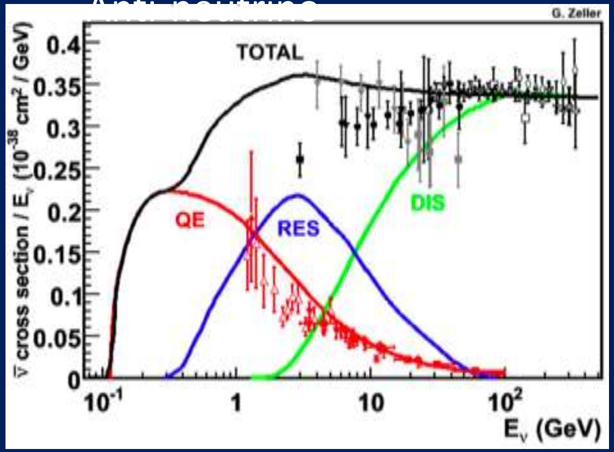
$$P(\nu_\mu \rightarrow \nu_\mu) \sim 1 - \cos^4(\theta_{13}) \sin^2(2\theta_{23}) \sin^2(\Delta m^2_{31} L/4E)$$
$$- \sin^2(2\theta_{13}) \sin^2(\theta_{23}) \sin^2(\Delta m^2_{31} L/4E)$$

Interaction regime

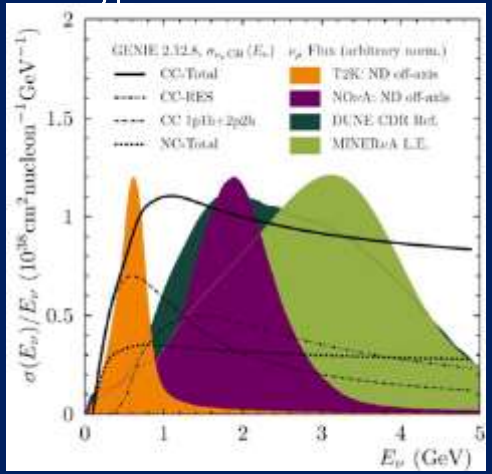


Rev. Mod. Phys. 84, 1307–1341 (2012)

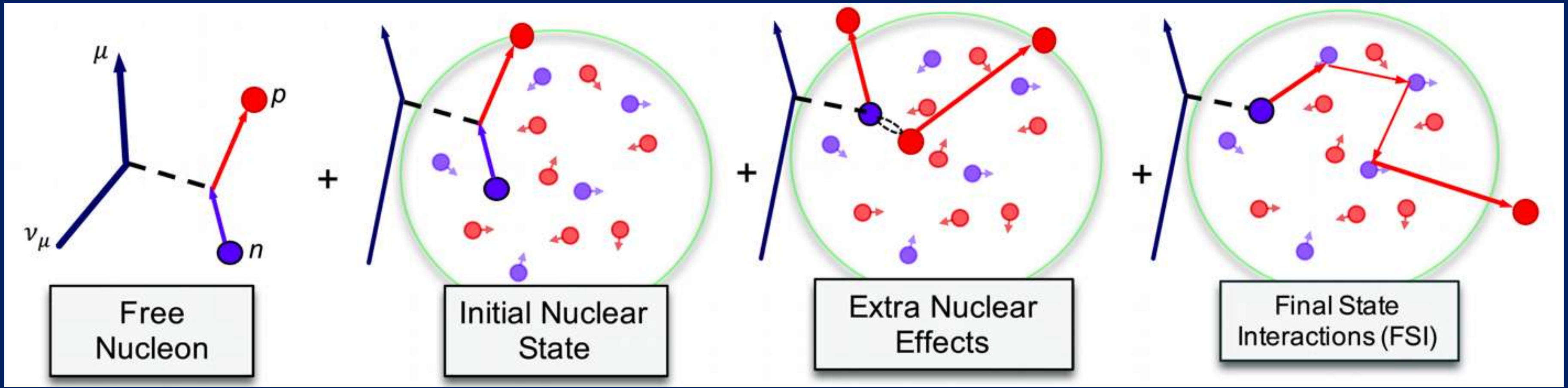
Anti-neutrino



Typical neutrino beams



Nucleus



3+1 neutrino oscillations

We extend the mixing matrix

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \Rightarrow \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

APPearance

$$P_{\alpha\beta}^{\mathrm{SBL}} \approx \sin^2(2\theta_{\alpha\beta}) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$\sin^2(2\theta_{\alpha\beta}) = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

$$\nu_\mu \to \nu_e : \sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2 |U_{\mu 4}|^2$$

@LSND, **Karmen**, **MiniBooNE**, **Opera**

DISappearance

$$P_{\alpha\alpha}^{\mathrm{SBL}} \approx 1 - \sin^2(2\theta_{\alpha\alpha}) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$\sin^2(2\theta_{\alpha\alpha}) = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2)$$

$$\nu_e \to \nu_e : |U_{e4}|^2 = \sin^2\theta_{14}$$

@Reactors and **Gallium**

$$\nu_\mu \to \nu_\mu : |U_{\mu 4}|^2 = \sin^2\theta_{24} \cos^2\theta_{14}$$

@atmospherics and **accelerators**

Mixing (rotation) matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} cos\theta_{12} & sin\theta_{12} \\ -sin\theta_{12} & cos\theta_{12} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$|\nu_e(0) > = cos\theta_{12} \cdot |\nu_1 > \; + \; sin\theta_{12} \cdot |\nu_2 >$$

Next, introduce time evolution **(propagation in space)**

$$|\nu_e(t) > = cos\theta_{12} \cdot e^{-iE_1 t} |\nu_1 > \; + \; sin\theta_{12} \cdot e^{-iE_2 t} |\nu_2 >$$

$$P(n_a \rightarrow n_b) = \sin^2 2q_{ij} \cdot \sin^2\left(1.27\, Dm_{ij}^2 \frac{L}{E}\right)$$