1. LArTPC’s:
   Motivation & challenges
   Worldwide effort
   Physics goals

2. Current experiments:
   ICARUS
   MicroBooNE

3. Future experiments:
   LAr1
   2-LAr@CERN-SPS
   LBNE
   100kton@Okinoshima

Current and Future Liquid Argon Experiments

Georgia Karagiorgi
Columbia University
NuInt’12 -- Rio de Janeiro, Brazil
1. **LArTPC’s: Detector Concept**

Charged particle tracks ionize argon atoms; Ionization charge drifts to **finely segmented charge collection planes** over \( \sim 1\)-few ms.

Scintillation light (~few ns) is typically detected by photo-sensitive detectors for event \( t_0 \) and triggering.
1. LArTPC’s: Motivation

- Liquid argon is ideal for low rate TPCs
  - High-density and relatively cheap medium
  - Factor of ~2 increase in signal detection efficiency and higher background rejection relative to water Cherenkov
    $\rightarrow$ 1:6 detector mass ratio for comparable oscillation sensitivity
  - Possibility for continuous data taking
  - Homogeneous, fully active neutrino interaction volume
  - High ionization charge yield (MIP, ~1fC/mm), small diffusion (~mm for several meters of drift)
  - High scintillation yield, can be used for $T_0$, triggering

- Detector performance
  - High-resolution 3D tracking (~mm-scale spatial resolution) with local dE/dx information
  - Excellent PID (range vs dE/dx) and $e/\gamma$ separation (~80%)
  - Ideal technology for $\nu_e$ measurements!
1. LArTPC’s: Technical challenges

[...being addressed by ongoing and planned R&D projects]

- Large cryogenic system
- Long drift distances
  - Requires ultra high purity and evacuation is impractical
  - Implies high voltage on cathode
- Large number of readout channels with high data volume/channel (data storage, data processing, …)
- Cold electronics
- Reconstruction tools: LArSoft development

LARiAT @ Fermilab
Calibration in controlled test beam

LAPD @ Fermilab
Establishing high purity without evacuation

ArgonTube
5m drift demonstration
1. LArTPC’s: Test Facilities & Experiments

**United States**
- Materials Test Stand
- ArgoNeuT
- LAPD
- MicroBooNE
- LAr1
- LARiAT
- Los Alamos LDRD LArTPC
- GLADE
- LBNE

**Europe**
- 50-liter @ CERN
  - 10m³
- **ICARUS**
  - LArTPC in B-field
  - ArgonTube @ Bern
  - UV Laser
- **2-LAr @ CERN-SPS**
- MODULAr
- LAGUNA/LBNO

**Japan**
- Test-Beam (T32) at J-PARC
- **100 kton @ Okinoshima island**

☆ Covered in this talk

Updated from M. Soderberg
1. LArTPC’s: Test Facilities & Experiments

**United States**
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- Test-Beam (T32) at J-PARC
- 100 kton @ Okinoshima island

- Covered in this talk
- See talks by A. Szelc, K. Partyka, O. Palamara
- See talk by A. Szelc
- See talk by A. Weber
- Backup slides

Updated from M. Soderberg
1. LArTPC’s:

Neutrino Physics Goals [unanswered questions] addressed by LArTPC neutrino experiments

- **CP violation** (long-baseline oscillations: $\nu_e$ appearance)
  - LBNE
  - LAGUNA/LBNO
  - 100kton@Okinoshima
  - MODULAr
  - GLADE

- **Mass hierarchy & Dirac vs. Majorana**
  - (combinations of the above + other expts, in various permutations)

- **Sterile neutrinos** (short-baseline oscillations)
  - MicroBooNE
  - LAr1
  - 2-LAr@CERN-SPS

- **Exclusive and inclusive cross section measurements, Nuclear effects & FSI**
  - MicroBooNE
  - LAr1
  - 2-LAr@CERN-PS
  - ICARUS
  - ArgoNeuT
...And more!

- Proton decay & baryon number violating processes
- Supernova core collapse neutrinos
- Atmospheric neutrinos
- Diffuse SN background

Signature of low energy $\nu_e$ CC absorption on Ar

SN neutrino event rate predictions for MicroBooNE (60 tons)

See talk by F. Cavanna
1. LArTPC’s: $\nu$ Interactions

Goal of next-generation cross-section experiments:
unambiguously measure neutrino cross sections around 1 GeV

- Past cross section measurements (from K2K, MiniBooNE, SciBooNE, MINOS, NOMAD) have revealed limitations in our understanding neutrino interactions from lepton kinematics alone.

Hadronic effects play a critical role and hadronic kinematics should be considered.

- A precise measurement of the hadronic system (vertex activity, hadronic final state multiplicity and momentum, etc.) will provide critical information for testing existing models and developing more robust neutrino interaction event generators for oscillation physics.
1. LArTPC’s: $\nu$ Interactions

LArTPC’s study events after final state interactions in exquisite detail

- Channel of particular interest: Charged Current Quasi-Elastic (CCQE) scattering

  Resolve discrepancy in measured cross section: nucleon-nucleon correlations? which model?

  Measure channels by "final states multiplicity"

  $E_\nu$ from lepton kinematics vs. momentum balance vs. summed total energy

Example: ArgoNeut events

- $\mu + p$
- $\mu + p + p$
- $\mu + p + p + p$
1. LArTPC’s: $\nu$ Interactions

LArTPC’s study events after final state interactions in exquisite detail

- Channel of particular interest: Charged Current Quasi-Elastic (CCQE) scattering

Resolve discrepancy in measured cross section: nucleon-nucleon correlations? which model?

Measure channels by "final states multiplicity"

$E_\nu$ from lepton kinematics vs. momentum balance vs. summed total energy

Example: ArgoNeut events

Generator-level implementation?

See talk by T. Golan
Other channels of interest:

- $\nu$-N NC elastic scattering
  - Measure $\Delta s$ and improve sensitivity of dark matter searches
  - $T_{p,\text{min}} \sim 40$ MeV ($Q^2 \sim 0.08\text{MeV}^2$)

- Kaon production
  - $p$-decay background constraints

- Single-$\pi$ production
  - Resolve theoretical tension?

- Hyperon production

- Single-photon production
  - in low energy scattering

- First conclusive $\nu_e$ cross-section measurements ($\sim1\text{GeV}$)

---

LArTPC’s study events after final state interactions in exquisite detail

1. LArTPC’s: $\nu$ Interactions

LArTPC’s study events after final state interactions in exquisite detail

- $\nu$-N NC elastic scattering
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---

BNB: MicroBooNE, LAr1
CNGS: ICARUS, MODULAR
NuMI: ArgoNeuT, GLADE
New SPS: 2-LAr@CERN-SPS
LBNE
Upgraded T2K:
200kton@Okinoshima
1. LArTPC’s: $\nu$ Interactions

Limitations

- Only one type of target nucleus ($\text{Ar}$)
- No free protons
- No charge ID on event by event basis
  - Magnetized LArTPC’s are challenging
  - Options:
    - High-purity sign-selected beams
    - LArTPC + spectrometer ($\text{ArgoNeuT-style}$) for $\mu$ charge ID
    - LArTPC in a magnetic field ($\text{LBNE-ND}$)
2. Current experiments: ICARUS

[running]
International collaboration:
14 institutions
5 countries
ICARUS

Pioneer LArTPC experiment

- Largest existing LArTPC neutrino experiment
- Detector located underground at Gran Sasso National Lab, Italy
- Detector parameters:
  - Two identical modules: 3.6x3.9x19.6 ~ 275m³ each (2 TPC’s per module)
    - 600 (476) tons total (active) LAr mass
    - 1.5 m drift length (1ms)
    - 3 mm wire pitch
    - 54k wires
  - PMT’s with wavelength shifter for triggering
ICARUS

CNGS beam from CERN

- $\nu_\mu$-pure, $L=732\text{km}$, $E_\nu \sim 17\text{ GeV}$
- Collecting data since 2010
  (~$5\times10^{19}\text{ POT}$ in 2010-11; $3.3\times10^{19}\text{ POT}$ analyzed so far)

$$p + C \rightarrow (\text{interactions}) \rightarrow \pi^+, \ K^+ \rightarrow (\text{decay in flight}) \rightarrow \mu^+ + \nu_\mu$$
ICARUS

Detector performance

- Fully operational since Oct. 2010
- Tracking device:
  - precise event topology ($\sigma_{x,y} \sim 1\text{mm}$, $\sigma_z \sim 0.4\text{mm}$)
  - $\mu$ momentum measurement via multiple scattering: $\Delta p/p \sim 10-15\%$ depending on track length and $p$
- Measurement of local energy deposition $dE/dx$:
  - $e/\gamma$ separation (2\% $X_0$ sampling);
  - particle ID by means of $dE/dx$ vs range
  - $e/\pi^0$ discrimination at $10^{-3}$ by $\gamma$ conversion from vertex, $\pi^0$ mass and $dE/dx$ measurements with 90 \% electron identification efficiency
  - NC/CC rejection at $10^{-3}$ level retaining 90 \% $\nu_e$ CC

- Energy resolution
  
  Low energy electrons: $\sigma(E)/E = 11\% / \sqrt{E(\text{MeV})} + 2\%$
  Electromagnetic showers: $\sigma(E)/E = 3\% / \sqrt{E(\text{GeV})}$
  Hadron shower (pure LAr): $\sigma(E)/E \approx 30\% / \sqrt{E(\text{GeV})}$

Courtesy: A. Guglielmi
ICARUS

Physics scope

- Multipurpose detector:
  - CNGS neutrinos (5-25 GeV), ~2k evts/yr
  - Solar neutrinos (>8 MeV)
  - SN, expected ~200 evts (10kpc)
  - Atmospheric neutrinos, ~100 evts/yr
  - Nucleon decay searches, $3 \times 10^{32}$ nucleons

Results with CNGS beam

- CNGS events analysis is ongoing
- Search for sterile neutrinos in LSND parameter space using CNGS: $\nu_{\mu} \rightarrow \nu_e$ (arXiv:1209.0122)
- Search for the analogue to Cherenkov radiation by high energy CNGS neutrinos at superluminal speeds (Phys. Let. B 711 (3-4): 270-275)
2. Current experiments: MicroBooNE

[under construction]
International collaboration:
91 physicists & engineers
16 institutions
3 countries
MicroBooNE

Located in the **Fermilab Booster Neutrino Beamline**:

- 8 GeV protons (FNAL booster)
- **π⁻** magnetic focusing
- **L = 470m**

**Flux estimate: νµ running in BNB**

Current run plan (approved):
Neutrino mode running, 6.6e20 POT

Possibility of future antineutrino running (sign-selected beam)
MicroBooNE

Located in the Fermilab Booster Neutrino Beamline:

8 GeV protons (FNAL booster)

Intrinsic $\nu_e$ s: 0.5%
Wrong-Sign $\nu$: 6%

Also “sees” NuMI beam: Off-axis

Flux estimate: $\nu_\mu$ running in BNB

![Graph showing flux estimates](image)
MicroBooNE

- Detector parameters:
  - 2.5 m x 2.3 m x 10.2 m TPC
  - 170 (60) tons total (fiducial) mass
  - 2.5 m drift length
  - 3 wire planes, 0,±60° from vertical
  - 3 mm wire pitch
  - 8256 wires
  - 30 PMT’s for $T_0$ and triggering for empty beam spill rejection

Cross section of detector:
MicroBooNE

Primary physics goal I

- Investigate the nature of the $\nu_e$-like excess previously observed by MiniBooNE (cherenkov detector)

What MicroBooNE expects to see if excess is due to:

- **single e**
  
  $5.7\sigma$

- **single $\gamma$**
  
  $4.1\sigma$

Estimated spectra: scaling from MiniBooNE ($^{12}$C !) for fiducial mass, POT, and efficiency
Possible explanation: $\nu_\mu \rightarrow \nu_e$ nonstandard oscillations (sterile neutrinos, extra dimensions, NSI, …)

What MicroBooNE expects to see if excess is due to:

- Single $e$
  - $\nu_e$ from $\mu^+$
  - $\nu_e$ from $K^+$
  - $\nu_e$ from $K^0$
  - Other
  - Electron-like hypothesis signal

- Single $\gamma$
  - $\pi^0$ misid
  - $\Delta \rightarrow N\gamma$
  - Dirt
  - Other
  - Photon-like hypothesis signal

Estimated spectra: scaling from MiniBooNE ($^{12}$C) for fiducial mass, POT, and efficiency

Possible explanation: background $\gamma$ or $\pi^0$ or “new” single photon production e.g.

- R. Hill arXiv: 0905.0291
- Jenkins et al arXiv: 0906.0984
- Serot et al arXiv: 1011.5913
MicroBooNE

Primary physics goal II

- First large-statistics neutrino exclusive final states in 1 GeV range and cross section measurements

Expected rates from upgraded NuMI beam (700kW, 6E20POT/yr)
1 yr, 60 ton fiducial volume

Higher energy beam + increased $\nu_e$ content

<table>
<thead>
<tr>
<th>Production mode</th>
<th># events</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC QE ($\nu_\mu, n \rightarrow \mu^- p$)</td>
<td>60,161</td>
</tr>
<tr>
<td>NC elastic ($\nu_\mu N \rightarrow \nu_\mu N$)</td>
<td>19,409</td>
</tr>
<tr>
<td>CC resonant $\pi^+$ ($\nu_\mu N \rightarrow \mu^- N \pi^+$)</td>
<td>25,149</td>
</tr>
<tr>
<td>CC resonant $\pi^0$ ($\nu_\mu n \rightarrow \mu^- p \pi^0$)</td>
<td>6,994</td>
</tr>
<tr>
<td>NC resonant $\pi^0$ ($\nu_\mu N \rightarrow \nu_\mu N \pi^0$)</td>
<td>7,388</td>
</tr>
<tr>
<td>NC resonant $\pi^+$ ($\nu_\mu N \rightarrow \nu_\mu N' \pi^+$)</td>
<td>4,796</td>
</tr>
<tr>
<td>CC DIS ($\nu_\mu N \rightarrow \mu^- X$, $W &gt; 2$ GeV)</td>
<td>1,229</td>
</tr>
<tr>
<td>NC DIS ($\nu_\mu N \rightarrow \nu_\mu X$, $W &gt; 2$ GeV)</td>
<td>456</td>
</tr>
<tr>
<td>NC coherent $\pi^0$ ($\nu_\mu A \rightarrow \nu_\mu A \pi^0$)</td>
<td>1,694</td>
</tr>
<tr>
<td>CC coherent $\pi^+$ ($\nu_\mu A \rightarrow \mu^- A \pi^+$)</td>
<td>2,626</td>
</tr>
<tr>
<td>NC kaon ($\nu_\mu N \rightarrow \nu_\mu K X$)</td>
<td>39</td>
</tr>
<tr>
<td>CC kaon ($\nu_\mu N \rightarrow \mu^- K X$)</td>
<td>117</td>
</tr>
<tr>
<td>Other $\nu_\mu$</td>
<td>3,678</td>
</tr>
<tr>
<td>Total $\nu_\mu$ CC</td>
<td>98,849</td>
</tr>
<tr>
<td>Total $\nu_\mu$ NC+CC</td>
<td>133,580</td>
</tr>
<tr>
<td>$\nu_e$ QE</td>
<td>326</td>
</tr>
<tr>
<td>$\nu_e$ CC</td>
<td>657</td>
</tr>
</tbody>
</table>
MicroBooNE

Secondary goals

- Physics goals:
  - Backgrounds to $\bar{p}$ decay for larger (underground) detectors
  - Supernova neutrinos

- R&D goals:
  - Purity without evacuation
  - Foam insulation
  - Cold (in liquid) electronics
  - LArTPC operation on surface
  - Continuous readout for supernova searches
  - Event reconstruction software
MicroBooNE

Current status

- Experiment is well under construction
  - TPC field cage constructed
  - Wire planes constructed
  - Electronics (front end and readout) in production
  - Cryostat to be delivered to Fermilab by March 2013
  - LArTF building nearing completion

- Expected start of data taking: early(?) 2014

- Current MicroBooNE run plan:
  neutrino mode running, 6.6e20 POT (2-3 years to complete)
3. Future experiments: LArI

[proposal]

US collaboration:
13 institutions
~50 physicists & engineers
**LAr1**

- LAr1 concept: developed from 1kton-scale LAr engineering prototype for LBNE
- A second LArTPC placed in the Booster Neutrino Beam at Fermilab, in line with MicroBooNE
- Near/far comparison for short-baseline oscillation search
- **Definitive test (5σ) of MiniBooNE/LSND anomalies**

Far detector: LAr1

Near detector: MicroBooNE
LAr1

Far detector parameters

- Conceptual design: same as engineering prototype for LBNE: Membrane cryostat
- Larger mass (1kton fiducial volume) and fully instrumented
- TPC constructed as an array of modular units
  - Anode plane assemblies (2.7m x 7m x 0.10m)
  - Cathode plane assemblies (2.5m x 7m)
**LAr1**

**Neutrino flux predictions**

![Graph showing neutrino flux predictions](image)

- **LAr1 @ 700m**
  - $\nu_\mu$
  - Anti-$\nu_\mu$
  - $\nu_e$
  - Anti-$\nu_e$

  $\nu_\mu$: Preliminary

  $\nu_\mu$ flux is approximately $1/2 \times \mu B @ 470m$

- **MicroBooNE @ 200m**
  - $\nu_\mu$
  - Anti-$\nu_\mu$
  - $\nu_e$
  - Anti-$\nu_e$

  $\nu_\mu$ flux is approximately $5 \times \mu B @ 470m$

**Second LArTPC @ 700m**

**MicroBooNE I @ 470m**

**MicroBooNE II @ 200m**
Physics reach: Definitive test of LSND and MiniBooNE in both neutrino and antineutrino modes

Assumptions:
- Neutrino events were generated with GENIE from BNB fluxes at 200m, 700m
- Two-neutrino oscillations
- 80% reconstruction efficiency flat in E
- Fiducial volume: 61.4t for MicroBooNE and 1kt for LAr1

Also $\bar{\nu}_e$ and $\bar{\nu}_\mu$ disappearance!
A Letter of Intent for a Neutrino Oscillation Experiment on the Booster Neutrino Beamline: LAr1

June 13, 2012

Brookhaven National Laboratory, Upton, NY

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Bertoszek Engineering

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LAr1

Status

- Letter of Intent submitted to Fermilab Directorate

- Strong ongoing effort to develop this into a proposal by summer 2013

- Projected start of construction: 2016(?)

3. Future experiments:

2-LAr @ CERN-SPS

[proposal]

ICARUS+NESSiE collaborations
2-LAr @ CERN-SPS

- New neutrino facility in the CERN North Area
- New short-baseline neutrino beam: $E_\nu \sim 2$ GeV
- Two (or three) LArTPC’s & Iron Spectrometers
  - ICARUS-T600 transported to CERN and exposed to new neutrino beam from SPS at 1600 m from neutrino production
  - Second 150ton LArTPC to serve as a near detector at 330 m

$\langle E_\nu \rangle \approx 2$ GeV
2-LAr @ CERN-SPS

- Expected sensitivity for the proposed experiment: $\nu_\mu$ beam (left) and anti-$\nu_\mu$ (right) for $4.5 \times 10^{19}$ pot (1 year) and $9.0 \times 10^{19}$ pot (2 years) respectively. LSND allowed region is fully explored in both cases.

- Also $\nu_e$ and $\nu_\mu$ disappearance!
3. Future experiments: LBNE

[planned]
US collaboration
500+ physicists and engineers
Proposed plan:
- Near detector at FNAL: 18 tons active mass + B field
- Far detector at Homestake (1300 km): 40 ktons active mass, 1.5km underground
- New high-intensity neutrino beam: $6.5 \times 10^{20} \text{POT/yr}$, $E_{\nu} = 0.5-5 \text{ GeV}$

Physics goals
- Long baseline oscillation physics through $\nu_{\mu} \rightarrow \nu_{e}$ and anti-$\nu_{\mu} \rightarrow \text{anti-} \nu_{e}$
- Non-accelerator neutrino measurements (atmospheric, SN) and proton decay
LBNE

- LBNE technology decision: January 2012 (LaArTPC over water Cherenkov)

- March 2012: **staged approach** to LBNE in order to maximize scientific output given projected US funding situation
  - “**Reconfiguration**” study
  - Stage I: on-surface operation of 10 kton far detector + new low energy beam from Fermilab
  - Workshop to establish viability of on-surface operation

- Current stage: CD1 review

- Construction expected to begin in 2020(?)
LBNE

LBNE Stage I

- Far Detector Stage I conceptual design (as of Sep. 2012)
  - 10 kton LArTPC in an excavated pit near surface at Sanford Underground Research Facility (SURF)
  - 3m overburden for cosmic ray shielding

- Low intensity beam

- Realizable in 2015-2020(?)

![Diagram of LBNE Stage I](image)
LBNE

- Beam plan:
  - Begin operations with new, low-energy, lower-intensity-than-final beam (LBNE Stage 1); 700kW, 6e20 POT/yr
  - Upgradable in the future to 2 MW (Project X)
3. Future experiments: 100kton @ Okinoshima

[proposal]
International collaboration: ETH & KEK
20+ collaborators
100kton @ Okinoshima

- 100kton detector + new (higher intensity) neutrino beam from JPARC (E ~ 1GeV)
- L=660km, 0.76 deg off-axis
- Upgrade of the J-PARC 30 GeV Main Ring operation from 750 kW to 1.66 MW
- 5 year neutrino running, possibly extended with additional 5 year antineutrino running
- Physics goals:
  - Long-baseline oscillation parameters through (anti-)ν_e appearance and (anti-)ν_μ disappearance
  - Non-accelerator neutrino measurements (supernova, atmospheric) & proton decay
100kton @ Okinoshima

- GLACIER design concept
  (1x100k, 3x40k, or 4x30k)
  - Much improved S/N (>100)
    compared to single-phase LArTPC
    operation (S/N~15-30)

- LEM-TPC
  Double phase: liquid to gas for charge
  amplification and extraction in gas phase
100kton @ Okinoshima

Status

- R&D proposal at J-PARC: EK_J-PARC-PAC2009-1
- ETHZ/KEK MoU for collaboration on LAr R&D

SUBMITTED TO J-PARC PAC

Towards a Long Baseline Neutrino and Nucleon Decay Experiment with a next-generation 100 kton Liquid Argon TPC detector at Okinoshima and an intensity upgraded J-PARC Neutrino beam

A.Badersteker¹, A.Curioni¹, S.DiLuisi¹, U.Degunda¹, L.Epprecht¹, L.Esposito¹, A.Gendotti¹, T.Hasegawa², S.Horikawa¹, L.Knecht³, T.Kobayashi³, C.Lazzaro¹, D.Luzi¹, A.Marchioni¹, A.Meregaglia¹,², T.Maruyama³, G.Matterer³, K.Nishikawa³, F.Resnati¹, A.Rubbia¹, C.Strabel¹, M.Tanaka², and T.Viomi¹
(1) ETH Zurich, (2) KEK IPNS

December 18, 2009
Conclusions

- **LAr technology is maturing and it is becoming a credible alternative to water cherenkov detectors**
  - The LArTPC can offer **truly unique and superior imaging performance**, in physics measurements where excellent energy resolution and good background rejection power are required
  - Ideal instrument for studying and constraining FSI and nuclear effects in neutrino-nucleus interactions
  - Low-energy neutrino measurements: opportunity for high-statistics SN neutrino data set

- Prepare for a “fun ride”:
  - ArgoNeuT and ICARUS results should continue over next 2-3 years
  - MicroBooNE begins data taking in ~1.5 yrs
  - Experiments which may begin construction over the next 5-10 years (if approved): LAr1, 2-LAr@CERN-SPS, GLADE, MODULAr
  - Experiments on a 10+ year timescale: LBNE, LAGUNA/LbNO, 100kton@Okinoshima
Thank you!
<table>
<thead>
<tr>
<th>Experiment</th>
<th>LAr mass (tons)</th>
<th>Physics goal</th>
<th>Baseline (km)</th>
<th>$E_v$ (GeV)</th>
<th>Where</th>
<th>Status</th>
<th>Online</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICARUS</td>
<td>600</td>
<td>R&amp;D, Long baseline (single detector)</td>
<td>732</td>
<td>~5-25</td>
<td>Gran Sasso (CNGS beam)</td>
<td>Running</td>
<td>Fully operational in 2010</td>
</tr>
<tr>
<td>ArgoNeuT</td>
<td>175L</td>
<td>R&amp;D, Cross sections</td>
<td>1</td>
<td>~0.1-10</td>
<td>NuMI near</td>
<td>Completed</td>
<td>N/A</td>
</tr>
<tr>
<td>MicroBooNE</td>
<td>170 (60 fiducial)</td>
<td>R&amp;D, Short baseline (single detector)</td>
<td>0.47</td>
<td>~0.1-3</td>
<td>FNAL (BNB)</td>
<td>Under construction</td>
<td>2014</td>
</tr>
<tr>
<td>LAr1</td>
<td>60 + 1000 (fiducial)</td>
<td>Short baseline (2 detectors)</td>
<td>0.2 + 0.7</td>
<td>~0.1-3</td>
<td>FNAL (BNB)</td>
<td>LOI</td>
<td>~5 yrs</td>
</tr>
<tr>
<td>2-LAr @ CERN-SPS</td>
<td>150 + 478 (fiducial)</td>
<td>Short baseline (2 detectors)</td>
<td>0.3 + 1.6</td>
<td>~2</td>
<td>CERN (new beam from SPS)</td>
<td>Proposal</td>
<td>~5 yrs</td>
</tr>
<tr>
<td>MODULAr</td>
<td>5,000</td>
<td>Long baseline (shallow depth)</td>
<td>730</td>
<td>~5-25</td>
<td>Gran Sasso</td>
<td>Planned</td>
<td>~5-10 yrs</td>
</tr>
<tr>
<td>GLADE</td>
<td>5,000</td>
<td>Long baseline (surface)</td>
<td>810</td>
<td>~0.5-2</td>
<td>NuMI off-axis</td>
<td>LOI</td>
<td>~5-10 yrs</td>
</tr>
<tr>
<td>LBNE</td>
<td>Start with 10,000</td>
<td>Long baseline (surface FD initially)</td>
<td>1300</td>
<td>~0.5-5</td>
<td>Homestake (new FNAL beam)</td>
<td>Planned (CD-1)</td>
<td>10+ yrs</td>
</tr>
<tr>
<td>LAGUNA/LbNO</td>
<td>Start with 20,000</td>
<td>Long baseline (underground FD)</td>
<td>2300</td>
<td>~few</td>
<td>Finland (new CERN beam)</td>
<td>EOI in preparation</td>
<td>10+ yrs</td>
</tr>
<tr>
<td>100kton @ Okinoshima</td>
<td>Up to 100,000</td>
<td>Long baseline (underground FD)</td>
<td>665</td>
<td>~0.5-2</td>
<td>Okinoshima island (new J-PARC beam)</td>
<td>R&amp;D Proposal at J-PARC</td>
<td>10+ yrs</td>
</tr>
</tbody>
</table>

+ various R&D and test experiments:

US: Materials Test Stand, LAPD, LARiAT, Los Alamos LDRD LArTPC
Europe: 50-liter @ CERN, 10m$^3$, LArTPC in B-field, ArgonTube, UV Laser
Japan: Test-beam T32 @ J-PARC
Future experiments: GLADE

Global Liquid Argon Detector Experiment
[US & European Collaboration]

- 5kton LArTPC
- GEM (Gas Electron Multipliers) rather than wire planes, developed at ETH
- Existing (soon-to-be-updated) NuMI beam at Fermilab
- Off-axis, on-surface, at Ash River (Nova far detector site): 810km from neutrino source
- 5-7 years of data taking
Future experiments: GLADE

Primary physics goals:

- CP violation and mass hierarchy
  (in combination with Nova and T2K near-future results)

The incorrect mass hierarchy hypothesis can be ruled out ~90%
Future experiments: GLADE

Current status:

- Support for further studies is being considered by CERN management (rolling CERN R&D program)

- LOI has been submitted to the Fermilab Directorate (May 2012):
  - www.fnal.gov/directorate/program_planning/June2012Public/P-1029,GLADE,LOI.pdf
Future experiments: MODULAr

MODULAr 5kton near LNGS

- Single phase LAr TPC about 10 kt fiducial mass, realised with a modular set of two identical, but independent units, each of about 5 kt, “cloning” the basic design of T600
- Parameters of unit
  - 5370 ton active LAr mass
  - 4 meter drift length
  - 6 mm wire pitch, three wire planes, \( \approx 50k \) channels
  - Warm electronics
- Physics goals:
  - off-axis of existing CNGS
  - long baseline neutrino oscillations, cf. Preliminary physics studies by A. Longhin, NUTURN12 workshop, LNGS May 2012
  - proton decay and neutrino astrophysics if underground
- Technology challenges:
  - Linear extrapolation of ICARUS T600 design by factor x2.66 in each dimension for a total unit volume of 8x8m\(^2\) and 60m long
  - New passive thermal insulation (perlite)
  - Ultra-pure liquid argon without evacuation (R&D needed and proposed with SLICE 8x8x4m\(^3\))
  - Cavern stability

Courtesy: A. Rubbia
Future test experiments: LARiAT

LArTPC + controlled testbeam for calibration studies

- Primary goal: study particle interactions in LAr
  - Energy reconstruction, particle identification, detector response, hadronic cross section studies

- (Decommissioned) ArgoNeuT detector placed in a controlled testbeam @ Fermilab: p, π, e, μ
  Upgrade to larger LArTPC in the future (hadronic shower containment).

- Planned start of data taking: 2013