ICARUS

A Second-Generation Proton Decay Experiment and
Neutrino Observatory at the Gran Sasso Laboratory
and
The CNGS beam from CERN to Gran Sasso

Antonio Ereditato
INFN Napoli
The ICARUS program: introduction

- **ICARUS was proposed to INFN in 1993**
  

- **The experiment is based on**
  - the novel detection technique of the liquid Argon TPC
  - its extrapolation to large (kton) masses
  - a rich physics program
    - proton decay
    - atmospheric neutrinos
    - solar neutrinos
    - supernovae neutrinos
    - LBL neutrino oscillations (CNGS, future LE beams,...)
General features and past experience
**Principle and signals**

Ionization electrons drift (msec) over large distances (meters) in a volume of highly purified liquid Argon (0.1 ppb of $O_2$) under the action of an $E$ field. With a set of wire grids (traversed by the electrons in $\sim 2-3 \, \mu s$) one can realize a massive, continuously sensitive electronic “bubble chamber”.
Liquid Argon TPC properties

- High density, heavy ionization medium
  \( \rho = 1.4 \text{ g/cm}^3, \ X_0=14 \text{ cm}, \ \lambda_{\text{int}} = 80 \text{ cm} \)

- Very high resolution detector
  3D image 3 x 3 x 0.6 mm\(^3\) (400 ns sampling)

- Continuously sensitive

- Self-triggering or through prompt scintillation light

- Stable and safe
  Inert gas/liquid
  High thermal inertia (230 MJ/m\(^3\))

- Relatively cheap detector
  Liquid argon is cheap, it is “stored” not “used” in the experiment
  TPC: number of channels proportional to surface

- Cryogenic temperature
  \( T = 88 \text{ K at 1 bar} \)

- High purity required for long-drift time
  0.1 ppb of \( \text{O}_2\) equivalent for 3 ms drift

- No signal amplification in liquid
  1 m.i.p. over 3 mm yields 20000 electrons
  equivalent noise charge 1200 electrons

Cryogenic plant

Argon purification

Low noise electronics
Drift velocity, HV and signal attenuation

- Working drift field
  \[ E = 500 \text{ V/cm} \Rightarrow \text{drift velocity } v_d = 1.6 \text{ mm/\mu s} \]
  For a 3 m drift: \( H_{\text{drift}} = 150 \text{ kV} \), maximum drift time \( \tau_{\text{max}} = 1.875 \text{ ms} \)
- Require high level of purity in order to avoid charge attenuation
- Measured electron lifetime: 50 liter prototype: \( \tau > 10 \text{ ms} \)
Milestones: LAr Imaging


50 litres prototype 1.4 m drift chamber

1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

10 m³ industrial prototype

1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.
Milestones: LAr purity

First purity monitor chamber

Measured Lifetime > 10 ms

3 ton prototype

1991-1995: First demonstration on large masses
Argon recirculation in gas phase
Long duration test.

Liquid Phase purification

1994

10 m³ industrial prototype

1998-1999: Ultra-pure LAr technique
industrialization.
Forced LAr recirculation.
Milestones: LAr Scintillation

1997: Measurements in pure and Xenon doped LAR


PMs and WLS

1999-2000: Wavelength shifters test and choice. Design and test of the final system for the T600

2000: Chosen Large size (8") PMs especially designed to work at cryogenic temperature. Performance and reliability tests.
**Past experience and results - 50 liter prototype**

- Active volume: 50 liters
- Readout planes: 2
  \[ (0^\circ, 90^\circ) \]
- Max. drift distance: 45 cm

- Fermi-motion
- Track direction by \( \delta \)-rays
- \( dE/dx \) versus range for K, \( \pi \), p discrimination
- Max. electron lifetime > 10 ms

- LAr purification by vapor filtering and recondensation
- LAr purity monitors
- Optimization of FEE for induction and collection
- Warm and cold electronics
- Readout chain calibration studies
- Signal treatment
- Collection of scintillation light
- 1.4 m drift length (special test)
- Test in the CERN neutrino beam (see figures)
Past experience and results - 15 ton prototype

Total volume: 10 m³
Readout planes: 2 (-60°, 60°)
Max. drift distance: 35 cm

- Final electronics
- DAQ
- External trigger
- 100 days run at LNGS surface
- Max. electron lifetime ≈ 2 ms

- Purification in liquid phase
- HV feed-through
- Cryogenic technology
- Signal feed-through
- Variable geometry wire chamber

T15 @ LNGS
The T600 module
Experience and results: 600 ton detector

Industrial module made of two independent LAr containers
½ module equipped and filled with LAr (300 ton)
Total volume: 350 m³
Readout planes: 2 x 3 (–60°, 60°, 0°), about 54000 wires
Maximum drift distance: 150 cm

- Full scale technical run of the T300 detector in Pavia (2001)
  - Cryogenics ✓
  - Wire chamber mechanics ✓ ✓
  - Argon purification ✓
  - Electronic noise ✓
  - High voltage for the drift ✓ ✓
  - PMTs for scintillation light collection ✓
  - Readout & DAQ ✓
  - Slow control ✓

- Event reconstruction SW with real events and data analysis (ongoing effort)
  - Imaging ✓ ✓
  - Event reconstruction ✓
  - 3 plane readout ✓
  - Calibration ✓
  - Resolution ✓
≈300'000 kg LAr
= T300

ICARUS T600 cryostat (1 out of 2)
ICARUS T300 detector

View of the inner detector

- Cryostat (half-module)
- Readout electronics

Dimensions:
- 4 m x 4 m x 20 m

Components:
- Wires of the TPC
- Drift Length (1.5 m)
- Cathode
- Wire Chamber Structure
- Field Shaping Electrodes (during installation)
ICARUS T600 semimodule (front-face), Feb. 7th 2001
Technical run held in Pavia in Summer 2001: ascertain the maturity of large scale liquid Argon imaging TPC. Main phases:
- clean-up (vacuum) 10 days, cool-down 15 days, LAr filling 15 days, debug and data-taking 68 days.

In addition to the 18 m long track requested by the Scientific Committees, a large number of cosmic-ray events was collected:
- about 28000 triggers with different topologies
- 4.5 TB of data, 200 MB/event.

Valuable data: check performance of a such large scale detector. Found that:
- results of the same quantitative quality as those obtained with small prototypes (e.g. 3 ton, 50 liter, …) are achieved with a 300 ton device.

scaling up is successful
Answering the SPSC request: the 18 meter long track…

“The Committee congratulates (...) progress (...) in the construction of the T600 module and awaits recording of long tracks in this module.”, SPSC September 2000
Longitudinal muon track crossing the cathode plane

Track Length = 18.2 m

3-D reconstruction of the long track

dE/dx = 2.1 MeV/cm

dE/dx distribution along the track
Examples of events: “electronic” bubble chamber (I)

**Hadronic interaction (T600)**

![Image of bubble chamber event](image-url)
“Electronic” bubble chamber (II)

Cosmic ray showers (T600)
“Electronic” bubble chamber (III)
“Electronic” bubble chamber (IV)

Left chamber (collection view)

Right chamber (collection view)

Muon bundle event (Run 959, Event 17)
Signal extraction procedure

\[ f(t) = B + A \left( e^{\frac{t - T_0}{\tau_1}} + e^{\frac{t - T_0}{\tau_2}} \right) \]

- \( B = \) baseline, \( A = \) amplitude
- \( \tau_1, \tau_2 = \) rise and fall time, \( T_0 = \) peak position

Collection plane wire: charge = signal area
Compression with de-noising: CR = 21.4
CR = 42.5
3D reconstruction

- 3D reconstruction: drift time coordinate (y-coordinate) shared among all three views.
- Matching between the views is redundantly done at the “hit”-level

\[ x_{1,2} = \frac{p}{2 \cos \theta} (w_1 - w_2 + w_0) \]
\[ x_3 = p w_3 \]
\[ y = \frac{s v}{f} \]
\[ z_{1,2} = \frac{p}{2 \sin \theta} (w_1 + w_2 - w_0) \]
\[ z_{2,3} = \frac{p}{\tan \theta} (w_3 + \frac{w_2 - w_0}{\cos \theta}) \]
\[ z_{1,3} = \frac{p}{\tan \theta} (\frac{w_1}{\cos \theta} - w_3) \]

\[ p = 2.99 \text{ mm} \]
\[ \theta = 60^\circ \]
\[ \omega_0 = 528 \]
\[ f = 2.5 \text{ MHz} \]
Stopping muon reconstruction example

\[ \mu^+ [AB] \rightarrow e^+ [BC] \]

Run 939 Event 95 Right chamber

\[ T_e = 36.2 \text{ MeV} \]
\[ \text{Range} = 15.4 \text{ cm} \]
Stopping muon automatic 3D reconstruction

---

Antonio Ereditato – INFN Napoli – Nov. 2002
$\delta$-rays

Two consecutive wires

1.8 MeV

3.2 MeV

10 MeV

T600
In-flight annihilation of positron

≈20% of positron from μ decays expected to annihilate before stopping

Run 844, Event 24

Collection view

Induction 2 view

Annihilation point

$e^+e^-$ pair

γ

$e^+$

$\mu^+$
Bremsstrahlung + pair-production

Run 975, Event 163

Fitted signal shapes on single wire

Induction 2 view

Collection view

e\(^+\) e\(^-\) pair (24 MeV)

e\(_1\) (9 MeV)

(2.5 MeV)
Bremsstrahlung track selection

Rejection of noise and out of time tracks:

$\theta < 40^\circ$

$d < 60 \text{ cm}$
Reconstruction Bremsstrahlung photons (T600)

Good agreement between data and MC
Calorimetric reconstruction Michel electrons (T600)

Energy resolution:

\[
\frac{\sigma}{E} = \frac{(13 \pm 2)\%}{\sqrt{E(\text{MeV})}} - (1.8 \pm 0.3)\%
\]
$\pi_0$ candidate (preliminary)

Reconstruction of $\gamma$-showers

- $\theta = 141^\circ$
  - $M_{\text{inv}} = 650$ MeV

- $\theta = 25^\circ$
  - $M_{\text{inv}} = 140$ MeV

Run 975, Event 151
**ICARUS T600: absolute time reconstruction**

PM#1 | PM#2 | PM#3 | PM#4 | PM#5 | PM#6 | PM#7 | PM#8 | PM#9

---

**ADC counts**

- Time (µs): 0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50
- 1 PE = 12 Ch.

**VUV light:** 128 nm, 10000 γ/MeV

**PMT:** 8” FLA - Elect. Tubes Ltd, coated with Tetra-Phenil-Butadiene
The full detector: T3000
LNGS Hall B
First step: T600 installation at LNGS
Next: the basic layout of the T1200 unit

Shock absorbers
ICARUS detector configuration at LNGS Hall B (T3000)

- First Unit: T600 + Auxiliary Equipment
- T1200 Unit (two T600 superimposed)
- T1200 Unit (two T600 superimposed)

Approximately 35 m

Approximately 60 m
PMTs installation for the T1200
T3000 physics program
Proton decay in ICARUS (I)

\[ p \rightarrow K^+ \bar{\nu}_e \]

Simulated event

K$^+$

\[ p = 425 \text{ MeV} \]

65 cm

53 cm

T600: Run 939 Event 46

Antonio Ereditato – INFN Napoli – Nov. 2002
Proton decay in ICARUS (II)

\[ p \rightarrow e^+ \pi^0 \rightarrow e^+ \gamma \gamma \]

Missing momentum 150 MeV/c, Invariant mass 901 MeV

\[ p_e = 474 \text{ MeV} \]
\[ \pi_0 = 417 \text{ MeV} \]
Particle identification (I)

dE/dx in the 3 ton prototype

energy loss profile along K and π tracks

distribution of the distance from the K fit function along π and K tracks
Particle identification (II)

- dE/dx in 50 liter
- dE/dx in T600

Run 939 Event 46

K+  
µ+
Proton decay: ICARUS expected sensitivities

- Very low backgrounds
- Inclusive analyses accessible
- Relevant results for few kton × year exposure already
- Expected range in few $10^{32}$ years after 5 kton × year exposures.
SuperK $e^+\pi^0$ final state candidate

1997-09-24 12:02:48 : rejected because compatible with background

Particle momentum thresholds in water:
- Electron 0.6 MeV/c
- Muon 120 MeV/c
- Pion 159 MeV/c
- Kaon 568 MeV/c
- Proton 1070 MeV/c
- Water Cerenkov are good at back-to-back three-rings events, hence in $e\pi^0$ and $\mu\pi^0$ channels. SuperK gains on the mass.

- In the favoured $p \rightarrow \nu K$ channel the efficiency in LAr is $\approx 10$ times better than the channels investigated.

- ICARUS T3000 fiducial is equivalent to 23.5 kton $H_2O$ to be compared to SuperK 22.5 kton.

- Rather complementary approaches/abilities.

---

**Proton decay: comparison with SuperK**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Eff. (%)</th>
<th>Observed (evts.)</th>
<th>Bkg. (evts.)</th>
<th>Exposure (kTon×yr)</th>
<th>$\tau/B$ limit ($10^{32}$ yr)</th>
<th>Needed Exp. to reach SK (kTon×yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p \rightarrow e^+ \pi^0$</td>
<td>SuperK: 43</td>
<td>0</td>
<td>0.2</td>
<td>79</td>
<td>$50 \rightarrow 30$ [1 evt]</td>
<td>94</td>
</tr>
<tr>
<td></td>
<td>ICARUS: 45</td>
<td>–</td>
<td>0.005</td>
<td>5</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>$p \rightarrow K^+ \bar{\nu}$</td>
<td>SuperK: 8.7</td>
<td>0</td>
<td>0.3</td>
<td>79</td>
<td>$19 \rightarrow 13$ [1 evt]</td>
<td>94</td>
</tr>
<tr>
<td>prompt $\gamma \mu^+$</td>
<td>SuperK: 6.5</td>
<td>0</td>
<td>0.8</td>
<td>5</td>
<td>10 \rightarrow 7</td>
<td></td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \pi^0$</td>
<td>SuperK: 97</td>
<td>–</td>
<td>0.005</td>
<td>5</td>
<td>7.5 \rightarrow 5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ICARUS: 45</td>
<td>–</td>
<td>0.04</td>
<td>5</td>
<td>5.7</td>
<td></td>
</tr>
<tr>
<td>$p \rightarrow \mu^+ \pi^0$</td>
<td>SuperK: 32</td>
<td>0</td>
<td>0.4</td>
<td>79</td>
<td>$37 \rightarrow 24$ [1 evt]</td>
<td>102</td>
</tr>
<tr>
<td></td>
<td>ICARUS: 45</td>
<td>–</td>
<td>0.04</td>
<td>5</td>
<td>2.6</td>
<td></td>
</tr>
</tbody>
</table>
Atmospheric neutrinos

Present situation:
- SuperK: resuming with 50% coverage
- ICARUS: look with a new technique at such astrophysical source

Atmospheric neutrino analysis in ICARUS characterized by
- Unbiased, systematic-free observation whereas:
  SuperK focuses to single-ring CC events
  Other analyses rely on MC
  (e.g. “NC enriched sample”, $\tau$-appearance neural networks, …)
- Excellent energy and angular reconstruction
- Advances in MC of the atmospheric $\nu$ rates: match improved measurements possible with ICARUS

Expertise within the Collaboration. Improvements expected in:
- Low energy events
- Clean electron sample
- All final states, and with $\nu$ and $\bar{\nu}$ statistical separation
- Neutral currents
### Atmospheric neutrino rates

Mass is not the only issue!

<table>
<thead>
<tr>
<th></th>
<th>Solar minimum</th>
<th>Solar maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No osc.</td>
<td>No osc.</td>
</tr>
<tr>
<td>Muon-like</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu + p$</td>
<td>$266 \pm 16$</td>
<td>$249 \pm 16$</td>
</tr>
<tr>
<td></td>
<td>$59 \pm 8$</td>
<td>$71 \pm 8$</td>
</tr>
<tr>
<td></td>
<td>$39 \pm 6$</td>
<td>$35 \pm 6$</td>
</tr>
<tr>
<td>$P_{\text{lepton}} &lt; 400$ MeV</td>
<td>$114 \pm 11$</td>
<td>$98 \pm 10$</td>
</tr>
<tr>
<td>$\mu + p$</td>
<td>$32 \pm 2$</td>
<td>$28 \pm 5$</td>
</tr>
<tr>
<td></td>
<td>$20 \pm 4$</td>
<td>$18 \pm 4$</td>
</tr>
<tr>
<td>Electron-like</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e + p$</td>
<td>$150 \pm 12$</td>
<td>$138 \pm 12$</td>
</tr>
<tr>
<td></td>
<td>$35 \pm 6$</td>
<td>$40 \pm 6$</td>
</tr>
<tr>
<td></td>
<td>$35 \pm 6$</td>
<td>$40 \pm 6$</td>
</tr>
<tr>
<td>$P_{\text{lepton}} &lt; 400$ MeV</td>
<td>$74 \pm 9$</td>
<td>$66 \pm 8$</td>
</tr>
<tr>
<td>$e + p$</td>
<td>$20 \pm 4$</td>
<td>$18 \pm 4$</td>
</tr>
<tr>
<td></td>
<td>$20 \pm 4$</td>
<td>$18 \pm 4$</td>
</tr>
<tr>
<td>NC-like</td>
<td>$192 \pm 14$</td>
<td>$175 \pm 13$</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$608 \pm 25$</td>
<td>$562 \pm 24$</td>
</tr>
</tbody>
</table>
Simulated atmospheric neutrino events in ICARUS

Atmospheric $\nu_\mu$ interaction, $E_\nu = 1.73$ GeV

Atmospheric $\nu_e$ interaction, $E_\nu = 0.730$ GeV

In 1 year of T600 running ICARUS will collect about 100 events of this quality (in presence of oscillations).
Reconstruction of atmospheric neutrinos

Containment

- ≈ 60% of νµ CC events fully contained
- Contained tracks measured by range and calorimetrically (dE/dx)
  - 7%/√E(MeV) for stopping tracks
  - 12%/√E(MeV) for soft e- from Bremsstrahlung
  - 3%/√E(GeV) for EM showers
- Range vs dE/dx provides particle ID

Measurement of escaping muons performed in different ways

- By multiple scattering
  Exploit the momentum dependence of scattering
  \( \sigma_p/p \approx 0.10 + 0.048 \ln(p[GeV]) \) for 5 m long track

- By precise measurement of the energy loss rate
  Use relativistic rise of dE/dx measured by combining successive samples
  \( \sigma_p/p \approx 20-30 \% \)
Muon momentum reconstruction by multiple scattering

Resolution Dependence from Energy

\[ \delta \frac{RMS}{RMS} = p_0 + p_1 \ln(E \text{ (GeV)}) \]

\[
\begin{align*}
p_0 &= 0.1815 \pm 0.8028 \\
p_1 &= 0.06575 \pm 0.8451
\end{align*}
\]

T600 data

2m track length
Reconstructed L/E distribution

\[ P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \left( 1.27 \Delta m^2 \frac{L}{E} \right) \]

\[ \Delta (L/E)_{RMS} \approx 30\% \]

- Oscillation parameters:
  \[ \Delta m^2_{32} = 3.5 \times 10^{-3} \text{ eV}^2 \]
  \[ \sin^2 2\theta_{23} = 0.9 \]
  \[ \sin^2 2\theta_{13} = 0.1 \]

- Electron sample can be used as a reference for no oscillation case

After 10 years...

Electrons

Muons
Astrophysical low energy neutrinos: from Sun and Supernovae

[Graph showing neutrino flux and energy spectra]
Low energy reactions in Argon

- Elastic scattering from neutrinos (ES)
  \[ \phi(\nu_e) + 0.15 \phi(\nu_\mu + \nu_\tau) \]

- Electron-neutrino absorption (CC)
  \[ \phi(\nu_e) \]
  \[ Q = 5.885 \text{ MeV} \]

- Elastic scattering from antineutrinos (ES)
  \[ \phi(\bar{\nu}_e) + 0.34 \phi(\bar{\nu}_\mu + \bar{\nu}_\tau) \]

- Electron-antineutrino absorption (CC)
  \[ \phi(\nu_e) \]
  \[ Q \approx 8 \text{ MeV} \]
Expected solar neutrino rates in T600

<table>
<thead>
<tr>
<th>Electron kinetic energy threshold (MeV)</th>
<th>BP2000 SSM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Elastic</td>
</tr>
<tr>
<td>0.0</td>
<td>367919</td>
</tr>
<tr>
<td>1.0</td>
<td>2143</td>
</tr>
<tr>
<td>2.0</td>
<td>872</td>
</tr>
<tr>
<td>3.0</td>
<td>689</td>
</tr>
<tr>
<td>4.0</td>
<td>524</td>
</tr>
<tr>
<td>5.0</td>
<td>380</td>
</tr>
<tr>
<td>5.5</td>
<td>318</td>
</tr>
<tr>
<td>6.0</td>
<td>262</td>
</tr>
<tr>
<td>6.5</td>
<td>212</td>
</tr>
<tr>
<td>7.0</td>
<td>168</td>
</tr>
<tr>
<td>7.5</td>
<td>131</td>
</tr>
<tr>
<td>8.0</td>
<td>99</td>
</tr>
<tr>
<td>8.5</td>
<td>74</td>
</tr>
<tr>
<td>9.0</td>
<td>53</td>
</tr>
<tr>
<td>9.5</td>
<td>36</td>
</tr>
<tr>
<td>10.0</td>
<td>24</td>
</tr>
<tr>
<td>10.5</td>
<td>15</td>
</tr>
<tr>
<td>11.0</td>
<td>9</td>
</tr>
</tbody>
</table>

Full FLUKA simulation with T600 geometry

BP2000 SSM used

(no oscillation hypothesis)

1521 evt/year
Solar neutrino absorption event

(Simulation using observed correlated noise in T600)
Hit reconstruction (200 keV threshold)
Elastic event analysis (I)

Events per year in T600

<table>
<thead>
<tr>
<th>CUT</th>
<th>Signal</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{detec}} &gt; 150 \text{ keV}$ and $E_{\text{clus}} &gt; 5 \text{ MeV}$</td>
<td>296</td>
<td>13100</td>
</tr>
<tr>
<td>Angular cut at $\cos (\theta_{\text{sun}}) = 0.9$</td>
<td>213</td>
<td>655</td>
</tr>
<tr>
<td>$E_{\gamma}$’s $&lt; 1 \text{ MeV}$</td>
<td>202</td>
<td>432</td>
</tr>
</tbody>
</table>

Statistical significance:

$S / \sqrt{B} \approx 10$
**Elastic event analysis (II)**

<table>
<thead>
<tr>
<th>CUT</th>
<th>Signal</th>
<th>Backg</th>
<th>S/√B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{detec}} &gt; 150$ keV</td>
<td>2142</td>
<td>1080000</td>
<td>2.1</td>
</tr>
<tr>
<td>$E_{\gamma}$s $&lt; 1$ MeV</td>
<td>2102</td>
<td>260200</td>
<td>4.1</td>
</tr>
<tr>
<td>$\cos (\theta_{\text{sun}}) &gt; 0.9$ + $E_{\text{clus}} &gt; 5$ MeV</td>
<td>202</td>
<td>432</td>
<td>9.7</td>
</tr>
<tr>
<td>$E_{\text{clus}} &gt; 6$ MeV</td>
<td>137</td>
<td>74</td>
<td>15.9</td>
</tr>
<tr>
<td>$E_{\text{clus}} &gt; 7$ MeV</td>
<td>82</td>
<td>63</td>
<td>10.3</td>
</tr>
<tr>
<td>$E_{\text{clus}} &gt; 8$ MeV</td>
<td>45</td>
<td>6</td>
<td>18.4</td>
</tr>
<tr>
<td>$E_{\text{clus}} &gt; 9$ MeV</td>
<td>21</td>
<td>0</td>
<td>-</td>
</tr>
</tbody>
</table>

Angular cut with Sun efficiency:

- 72%
- 77%
- 81%
- 84%
- 86%
Correlation electron-photon energy

A better separation is achieved if one considers electron and $\gamma$ correlations

(Best separation probably achievable with likelihood analysis)
Statistical significance

Normalized 1 year T600

For $E_{\text{vis}} > 8.8$ MeV

Background-free events

$S/\sqrt{B} > 4$
BG free solar events (E > 8 MeV)

Solar $\nu$ events per year in T600

<table>
<thead>
<tr>
<th></th>
<th>Elastic</th>
<th>Fermi</th>
<th>Gamow-Teller</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>38</td>
<td>165</td>
<td>295</td>
</tr>
</tbody>
</table>
The CNGS neutrino beam
Proton beam features

Protons are accelerated through the existing CERN chain of Linac, Booster, Proton Synchrotron and Super-Synchrotron (SPS). The proton energy at extraction from the SPS to CNGS is 400 GeV. Examples of SPS supercycles during CNGS operation with other users.

Protons are extracted from the SPS with a fast kicker in two batches (FE = fast extraction) of 10.5 ms each, with 50 ms between the two extractions. The microstructure of the beam reflects the 200 MHz radiofrequency of the SPS. Each batch consists of a train of bunches interspaced by 5 ns, the length of a single bunch is 2-3 ns.

The intensity in the SPS per cycle can reach $4.8 \times 10^{13}$ protons, thus about $2.4 \times 10^{13}$ protons per fast extraction. Assuming an overall efficiency of 55% and a running time of 200 days per year in a shared mode (filling LHC, etc.), **$4.5 \times 10^{19}$ protons can be delivered to the CNGS target per year.**
In the hypothesis of no oscillation:

**2600 \( \nu_\mu \)** charged current events **per kton**

detector mass **per year**

Assuming \( \nu_\mu - \nu_\tau \) oscillation, with the parameters \( \sin^2 2\theta = 1 \) and \( \Delta m^2 = 3 \times 10^{-3} \text{ eV}^2 \):

**22 \( \nu_\tau \)** charged current **events per kton** of

detector mass **per year**

---

Radial distribution at LNGS
...News from the CNGS

Schedule: start-up in May 2006 (depending on details of the SPS schedule 2006, not yet made).
Possible delays: none (one year more time to build CNGS than what was originally planned).
Civil engineering: all but the last 160 m of galleries are excavated (connection muon detectors to TI8 is missing);
excavation should be complete mid-January 2003. Concreting of the target chamber: completed last week
(concreting of the proton beam tunnel attacked now).
Decay tunnel: adjudication made in September 2002; price well within the cost estimate.
Activities in 2003:
- finish civil engineering works (June 2003)
- installation of hadron stop (iron from WANF, graphite and cooling plates in production)
- start installation of decay tube (Oct 2003). In parallel: equip muon detector regions and their access galleries
  with light, ventilation, GSM, emergency services, etc.
Horn and Reflector: first final horn inner conductor arriving now. First complete horn: May 2003.
Target: design advancing well; 5 target units in one target magazine (i.e. 4 spare targets available at start-up).
Protons per cycle: progress at the PS, good chance to have $7 \times 10^{13}$ per 6 s cycle already in 2006 (up from 4.8).
Problems under study: vacuum windows SEM monitors around target: standard titanium windows will melt at the
high intensities now expected; other options under study, e.g. beryllium window for vacuum system, etc.
Overall budget: contingency still small; a review to be held (likely) end of April 2003 should provide the full picture.
No huge cost overrun for the moment.
CNGS beam layout at CERN site.

Progress in the civil engineering work (excavation)
CNGS schedule: commissioning by Q2 2006
**ICARUS and the CNGS beam**

- ICARUS as a LBL experiment between CERN and LNGS already discussed in 1993: simultaneous study of accelerator and non-accelerator $\nu$ is possible due to the nature of the detection technique
  - continuously sensitive and isotropic
  - CNGS events: separated from other events by timing (SPS spill)
- ICARUS physics program enriched by CNGS oscillation searches.
- ICARUS contributed to design and optimization of the CNGS beam for $\tau$ appearance.
- Real-time detection, excellent granularity and energy resolution of LAr TPC will allow to collect and identify interactions from CNGS neutrinos:
  - $\nu_\mu$ CC: online study of beam profile, steering and normalization
  - $\nu_e$ CC: search for $\nu_\mu \rightarrow \nu_e$ oscillations: best sensitivity until the JHF-SK
  - $\nu_\tau$ CC: search for $\nu_\mu \rightarrow \nu_\tau$ oscillations with sensitivity similar to OPERA
  - NC events: search for $\nu_\mu \rightarrow \nu_s$ oscillations or exotic models.
ICARUS-CNGS experiment

- Detector configuration
  T3000 (Active LAr: 2.35 ktons)

- 5 years of CNGS running
  Shared mode (4.5 x 10^{19} pot/year)

- 280 $\nu_\tau$ CC expected for
  $\Delta m^2_{23}=3 \times 10^{-3}$ eV$^2$ and max. mixing

<table>
<thead>
<tr>
<th>Process</th>
<th>Expected Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ CC</td>
<td>32600</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$ CC</td>
<td>652</td>
</tr>
<tr>
<td>$\nu_e$ CC</td>
<td>262</td>
</tr>
<tr>
<td>$\bar{\nu}_e$ CC</td>
<td>17</td>
</tr>
<tr>
<td>$\nu$ NC</td>
<td>10600</td>
</tr>
<tr>
<td>$\nu$ NC</td>
<td>243</td>
</tr>
</tbody>
</table>

$\nu_\tau$ CC, $\Delta m^2$ (eV$^2$)

- 1 x 10^{-3} | 31 |
- 2 x 10^{-3} | 125 |
- 3 x 10^{-3} | 280 |
- 5 x 10^{-3} | 750 |

Average resolution on total visible energy: $\approx 10\%$
A. External muon spectrometer

In 1999 the Collaboration put forward the possibility to complement LAr imaging by an external device for magnetic analysis of escaping muons

Physics motivation:
- measure muon charge via magnetic analysis
- online monitoring of beam energy spectrum
- kinematical properties of closed $\nu_\mu$ CC events
- direct measurement of background for $\tau$ searches
- improve $\mu$ momentum resolution by combining MS and magnetic analysis

Magnet design:
- simple geometry, compatible with transverse dimensions of the T1200 module
- detection technique: drift tubes + fast trigger devices

B. Front muon “veto”

Muon detection walls: beam monitoring & tagging of rock interactions
Spectrometer artist view

Muon spectrometer
CNGS $\nu_\mu$ interaction, $E_\nu=26$ GeV

Vertex : 3 $\pi^0$, 1p, 3$\gamma$, 1$\mu$

CNGS $\nu_\tau$ interaction, $E_\nu=18.7$ GeV

e$^- 9.5$ GeV, $p_T=0.47$ GeV/c

$\tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\tau$
Direct detection of flavor oscillation

Expected $\nu_e$ and $\nu_\tau$ contamination (in absence of oscillations) is of the order of $10^{-2}$ and $10^{-7}$ relative to the main $\nu_\mu$ component.

\[\nu_\mu \rightarrow \nu_\tau\]

$\nu_\tau + \text{Ar} \rightarrow \tau + \text{jet}$

Charged current (CC)

\[
\begin{aligned}
\{ e\nu \nu \} & \quad \text{18\%} \\
\{ \mu\nu\nu \} & \quad \text{18\%} \\
\{ h^- h^- h^- n_0 \nu \} & \quad \text{50\%} \\
\{ h^- h^+ h^- n_0 \nu \} & \quad \text{14\%}
\end{aligned}
\]

\[\nu_\mu \rightarrow \nu_e\]

$\nu_e + \text{Ar} \rightarrow e + \text{jet}$
τ → e search: 3D likelihood

A simple analysis approach: a likelihood method based on 3 variables

3 variables
\[ E_{\text{visible}}, P_T^{\text{miss}}, \rho_l = \frac{P_T^{\text{lep}}}{P_T^{\text{lep}} + P_T^{\text{had}} + P_T^{\text{miss}}} \]

Exploit correlation between them
\[ L_S ([E_{\text{vis}}, P_T^{\text{miss}}, \rho_l]) \text{ (signal)} \]
\[ L_B ([E_{\text{vis}}, P_T^{\text{miss}}, \rho_l]) \text{ (ν}_e \text{ CC BG)} \]

Discrimination given by
\[ \ln \lambda \equiv L ([E_{\text{vis}}, P_T^{\text{miss}}, \rho_l]) = \frac{L_S}{L_B} \]

More sophisticated approaches (e.g. neural net,…) under study.
**τ → e search: 3D likelihood summary**

5 year “shared” CNGS running
T3000 configuration

<table>
<thead>
<tr>
<th>Cuts</th>
<th>( \nu_\tau ) Eff. (%)</th>
<th>( \nu_e ) CC</th>
<th>( \nu_\tau ) CC ( \Delta m^2 = 3 \times 10^{-3} \text{ eV}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>100</td>
<td>262</td>
<td>49</td>
</tr>
<tr>
<td>Fiducial volume</td>
<td>63</td>
<td>169</td>
<td>31</td>
</tr>
<tr>
<td>One candidate with momentum &gt; 0.5 GeV</td>
<td>57</td>
<td>165</td>
<td>28</td>
</tr>
<tr>
<td>ln ( \lambda ) &gt; 0</td>
<td>45</td>
<td>5.4</td>
<td>22</td>
</tr>
<tr>
<td>ln ( \lambda ) &gt; 0.5</td>
<td>39</td>
<td>2.8</td>
<td>19</td>
</tr>
<tr>
<td>ln ( \lambda ) &gt; 1.0</td>
<td>33</td>
<td>1.6</td>
<td>16</td>
</tr>
<tr>
<td>ln ( \lambda ) &gt; 1.5</td>
<td>31</td>
<td>1.2</td>
<td>15</td>
</tr>
<tr>
<td>ln ( \lambda ) &gt; 2.0</td>
<td>26</td>
<td>0.7</td>
<td>13</td>
</tr>
<tr>
<td>ln ( \lambda ) &gt; 2.5</td>
<td>18</td>
<td>0.6</td>
<td>9</td>
</tr>
<tr>
<td>ln ( \lambda ) &gt; 3.0</td>
<td>14</td>
<td>0.4</td>
<td>7</td>
</tr>
<tr>
<td>ln ( \lambda ) &gt; 3.5</td>
<td>10</td>
<td>0.3</td>
<td>5</td>
</tr>
<tr>
<td>ln ( \lambda ) &gt; 4.0</td>
<td>8</td>
<td>0.2</td>
<td>4</td>
</tr>
</tbody>
</table>

Maximum sensitivity
**\( \nu_\mu \rightarrow \nu_\tau \) appearance search summary**

- T3000 detector (2.35 kton active, **1.5 kton fiducial**)
- Integrated pots = \( 2.25 \times 10^{20} \)
- Several decay channels are exploited (electron = golden channel)
- (Low) backgrounds measured in situ (control samples)
- High sensitivity to signal, and oscillation parameters determination

**Super-Kamiokande:** \( 1.6 < \Delta m^2 < 4.0 \) at 90% C.L.

<table>
<thead>
<tr>
<th>( \tau ) decay mode</th>
<th>Signal ( \Delta m^2 = 1.6 \times 10^{-3} \text{ eV}^2 )</th>
<th>Signal ( \Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2 )</th>
<th>Signal ( \Delta m^2 = 3.0 \times 10^{-3} \text{ eV}^2 )</th>
<th>Signal ( \Delta m^2 = 4.0 \times 10^{-3} \text{ eV}^2 )</th>
<th>BG</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau \rightarrow e )</td>
<td>3.7</td>
<td>9</td>
<td>13</td>
<td>23</td>
<td>0.7</td>
</tr>
<tr>
<td>( \tau \rightarrow \rho \text{ DIS} )</td>
<td>0.6</td>
<td>1.5</td>
<td>2.2</td>
<td>3.9</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>( \tau \rightarrow \rho \text{ QE} )</td>
<td>0.6</td>
<td>1.4</td>
<td>2.0</td>
<td>3.6</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4.9</strong></td>
<td><strong>11.9</strong></td>
<td><strong>17.2</strong></td>
<td><strong>30.5</strong></td>
<td><strong>0.7</strong></td>
</tr>
</tbody>
</table>
Oscillation parameters determination

5 years exposure combining beam and atmospheric neutrino events (within the same detector)
Search for subleading $\nu_\mu \rightarrow \nu_e$ (I)

The emerging scenario:

\[ |\Delta m^2_{21}| = (4 \div 12) \times 10^{-5} \text{ eV}^2 \]
\[ \tan^2 \theta_{12} = 0.32 \div 0.51 \Rightarrow 30^\circ < \theta_{12} < 36^\circ \]
\[ |\Delta m^2_{32}| = (1.6 \div 3.9) \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2 2\theta_{23} > 0.92 \Rightarrow 37^\circ < \theta_{23} < 45^\circ \]

- The confirmation that $\nu_\mu \rightarrow \nu_\tau$ oscillations will be an important milestone
- The measurement of a non-vanishing $\theta_{13}$ would be an important discovery, proving that the mixing matrix is 3x3 and opening the door to CP-violation searches in the leptonic sector (CP-violation effects will only be visible for relatively large $\theta_{13}$)
Search for subleading $\nu_\mu \rightarrow \nu_e$ (II)

- Search for excess of electrons, on top of $\tau$ electronic decays
- Takes advantage of unique $e/\pi^0$ separation in ICARUS
- Assume 5 years @ $4.5 \times 10^{19}$ pots, 2.35 kton fiducial
- Limited by statistics: needs more intensity (low E) to exploit ICARUS features

$$\Delta m^2_{32} = 3 \times 10^{-3} \text{ eV}^2; \sin^2 2\theta_{23} = 1$$
Example: low energy CNGS optimization

The current CNGS optimization for $\tau$ appearance is not optimal for the search for subleading $\nu_\mu \rightarrow \nu_e$ oscillation. Try to optimize

<table>
<thead>
<tr>
<th>$\Delta m^2$ (eV$^2$)</th>
<th>$1 \times 10^{-3}$</th>
<th>$2 \times 10^{-3}$</th>
<th>$3 \times 10^{-3}$</th>
<th>$4 \times 10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>E$_{\text{max}}$ (MeV)</td>
<td>590</td>
<td>1180</td>
<td>1771</td>
<td>2361</td>
</tr>
<tr>
<td>E$_{\text{min}}$ (MeV)</td>
<td>295</td>
<td>590</td>
<td>885</td>
<td>1180</td>
</tr>
</tbody>
</table>

Maximize flux between 0 and 2.5 GeV
Comparison between $\tau$ and LE optimizations

<table>
<thead>
<tr>
<th>$E_p$ GeV</th>
<th>focus</th>
<th>decay tunnel length (m)</th>
<th>$\nu_\mu$ flux $\nu$/cm$^2$</th>
<th>$\nu_e$ flux</th>
<th>$10^{19}$ p.o.t. $\nu_\mu$ CC $\nu_e$ CC ev/kton</th>
<th>$&lt;E_\nu&gt;$, CC $\nu_\mu$</th>
<th>$\nu_e$ GeV</th>
<th>$\nu_\mu/\nu_e$ CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>p.f</td>
<td>350</td>
<td>$1.3 \cdot 10^{-13}$</td>
<td>$2.6 \cdot 10^{-15}$</td>
<td>9.0</td>
<td>0.12</td>
<td>1.8</td>
<td>1.3%</td>
</tr>
<tr>
<td>400</td>
<td>horn</td>
<td>350</td>
<td>$1.0 \cdot 10^{-15}$</td>
<td>$9.0 \cdot 10^{-16}$</td>
<td>4.5</td>
<td>4.2 $\cdot 10^{-2}$</td>
<td>1.8</td>
<td>0.9%</td>
</tr>
<tr>
<td>400</td>
<td>p.f †</td>
<td>CNGS</td>
<td>$1.6 \cdot 10^{-14}$</td>
<td>$3.2 \cdot 10^{-16}$</td>
<td>1.8</td>
<td>2.2 $\cdot 10^{-2}$</td>
<td>2.1</td>
<td>1.2%</td>
</tr>
<tr>
<td>400</td>
<td>$\tau$ †</td>
<td>CNGS</td>
<td>$1 \cdot 10^{-14}$</td>
<td>$9.4 \cdot 10^{-17}$</td>
<td>0.9</td>
<td>8.7 $\cdot 10^{-3}$</td>
<td>1.8</td>
<td>0.9%</td>
</tr>
</tbody>
</table>

Table 3: Neutrino beam parameters for the CNGS baseline, with $E_\nu < 2.5$ GeV. The † cases correspond to the present CNGS design for target, acceptance and focusing system.

Factor of 5 improvement at low energy
### Expected number of events

<table>
<thead>
<tr>
<th>$\theta_{13}$ (degrees)</th>
<th>$\sin^2 2\theta_{13}$</th>
<th>$\nu_e \text{ CC}$</th>
<th>$\nu_{\mu} \rightarrow \nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$E_\nu &lt; 4 \text{ GeV}$</td>
<td>$E_\nu &lt; 50 \text{ GeV}$</td>
</tr>
<tr>
<td>9</td>
<td>0.095</td>
<td>5</td>
<td>44</td>
</tr>
<tr>
<td>8</td>
<td>0.076</td>
<td>5</td>
<td>44</td>
</tr>
<tr>
<td>7</td>
<td>0.059</td>
<td>5</td>
<td>44</td>
</tr>
<tr>
<td>5</td>
<td>0.030</td>
<td>5</td>
<td>44</td>
</tr>
<tr>
<td>3</td>
<td>0.011</td>
<td>5</td>
<td>44</td>
</tr>
<tr>
<td>2</td>
<td>0.005</td>
<td>5</td>
<td>44</td>
</tr>
<tr>
<td>1</td>
<td>0.001</td>
<td>5</td>
<td>44</td>
</tr>
</tbody>
</table>

Table 4: Events from the CNGS L.E. beam, assuming $\Delta m_{23}^2 = 3 \times 10^{-3} \text{eV}^2$, $\theta_{23} = 45^\circ$, 5 years of operation and 2.35 kton fiducial mass.

<table>
<thead>
<tr>
<th>$\theta_{13}$ (degrees)</th>
<th>$\sin^2 2\theta_{13}$</th>
<th>$\nu_e \text{ CC}$</th>
<th>$\nu_{\mu} \rightarrow \nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$E_\nu &lt; 4 \text{ GeV}$</td>
<td>$E_\nu &lt; 50 \text{ GeV}$</td>
</tr>
<tr>
<td>9</td>
<td>0.095</td>
<td>1.5</td>
<td>150</td>
</tr>
<tr>
<td>8</td>
<td>0.076</td>
<td>1.5</td>
<td>150</td>
</tr>
<tr>
<td>7</td>
<td>0.059</td>
<td>1.5</td>
<td>150</td>
</tr>
<tr>
<td>5</td>
<td>0.030</td>
<td>1.5</td>
<td>150</td>
</tr>
<tr>
<td>3</td>
<td>0.011</td>
<td>1.5</td>
<td>150</td>
</tr>
<tr>
<td>2</td>
<td>0.005</td>
<td>1.5</td>
<td>150</td>
</tr>
<tr>
<td>1</td>
<td>0.001</td>
<td>1.5</td>
<td>150</td>
</tr>
</tbody>
</table>

Table 5: Events from the CNGS $\tau$ beam, assuming $\Delta m_{23}^2 = 3 \times 10^{-3} \text{eV}^2$, $\theta_{23} = 45^\circ$, 5 years of operation and 2.35 kton fiducial mass.
For $\Delta m^2 = 2.5 \times 10^{-3}$

$(\sin^2 2\theta_{13})_{\text{CNGS}} < 0.04$ or $\theta_{13} < 6^\circ$

$(\sin^2 2\theta_{13})_{\text{CHOOZ}} < 0.14$ or $\theta_{13} < 11^\circ$

$(\sin^2 2\theta_{13})_{\text{MINOS}} < 0.06$ or $\theta_{13} < 7^\circ$
Status, organization, outlook
The ICARUS program and plans

The ICARUS detector approved in 1997 by the Italian INFN; currently financed as part of the LNGS program. Innovative nature of the LAr technology → graded approach:

1. Full scale 600 ton module constructed in Pavia in collaboration with industry.
2. Successful operation of the T300 half-module (Summer 2001) showed that the technique has matured.
3. Second T300 half-module being completed.
4. Physics program of its own: installation of T600 recommended by Gran Sasso Scientific Committee (LNGSSC), placed in Hall B of LNGS (2003) and commissioned for physics right after.
5. Reach the design mass: cloning the T600 for further modules recommended by LNGSSC and CERN-SPSC.
6. INFN approved the T3000 scientific program and the design of successive T1200 modules. The first T1200 module is funded and its design ongoing.
7. Extend the T600 with two new T1200 modules by early 2006 (for CNGS start up).
The ICARUS Collaboration


SWITZERLAND: ETHZ Zürich.
CHINA: Academia Sinica Beijing.
USA: UCLA Los Angeles.
SPAIN: Univ. of Granada.
Present institute responsibilities

- **Pavia**
  - cryostat, inner chamber, PMT, pad electrodes, software
- **Aquila/LNGS**
  - installation at LNGS, purity monitors, software
- **Padova**
  - electronics + DAQ, online software
- **Pisa/UCLA**
  - H.V.
- **Frascati**
  - R&D, tracking detectors
- **Milano**
  - software and simulations
- **Napoli**
  - laser calibration, trigger electronics, installation at LNGS, beam monitoring
- **ETH/Zurich**
  - slow control, pad electrodes, magnet (spectrometer), software
- **Polish Groups**
  - wiring
- **Granada**
  - drift tubes (spectrometer), software

All groups involved in data analysis
**COSTS & TIMETABLE**

- **Costs and time schedule estimates**: based on experience gained with R&D and with the realization of the T600.

- **Contingency** is therefore reduced (5% for costs).

- **The T600 experience**: evaluate the time needed for different construction phases except for the cryostats build-up inside the underground Hall. However, also this last phase should not take a large amount of time.

- **Present cost estimate**: based on offers for the first T600. New bidding to other suppliers may bring to reductions.

- **Large savings** for the T1200 layout:
  - reduction of electronics chann. and mech. components (from drift length doubling);
  - re-utilization of tooling and services used for assembly, installation and run of T600.
Cost for a single T1200 Super Module

- Cryogenic liquids (LAr and LN2)
- Slow controls & monitoring
- Read out Pads
- Scintillation light collection
- Read out cabling
- Read out Wires
- Read out electronics
- Cryogenics & purification
- Inner mechanical structure

23.415 M€
Conclusions

After many fruitful years of R&D the ICARUS Collaboration has operated at surface a large mass (300 ton) liquid Argon TPC proving that the scaling from prototypes to full scale detectors is successful. The ICARUS agenda now foresees:

- the completion of the 2nd 300 ton half-module to form the T600 detector
- operation with the T600 at LNGS with data taking of astrophysical events in 2003
- the progressive realisation of two additional T1200 modules, with the T600 as basic cloning unit, to be operational by 2006

In this configuration, due to the unique potential offered by the LAr technology, ICARUS will be able to perform a vast physics program in the domain of

- nucleon decay
- atmospheric neutrinos
- solar and supernovae neutrinos
- CNGS neutrinos

ICARUS will run with the CNGS beam from 2006 to

- provide real-time study of the beam properties
- search for $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\tau$ flavor appearance
- further future: exploit ICARUS with a LE beam for an improved measurement of the subleading $\nu_\mu \to \nu_e$ oscillation
A new astroparticle observatory...soon on duty!