Underground Physics with DUNE

Vitaly A. Kudryavtsev
University of Sheffield

on behalf of the DUNE Collaboration

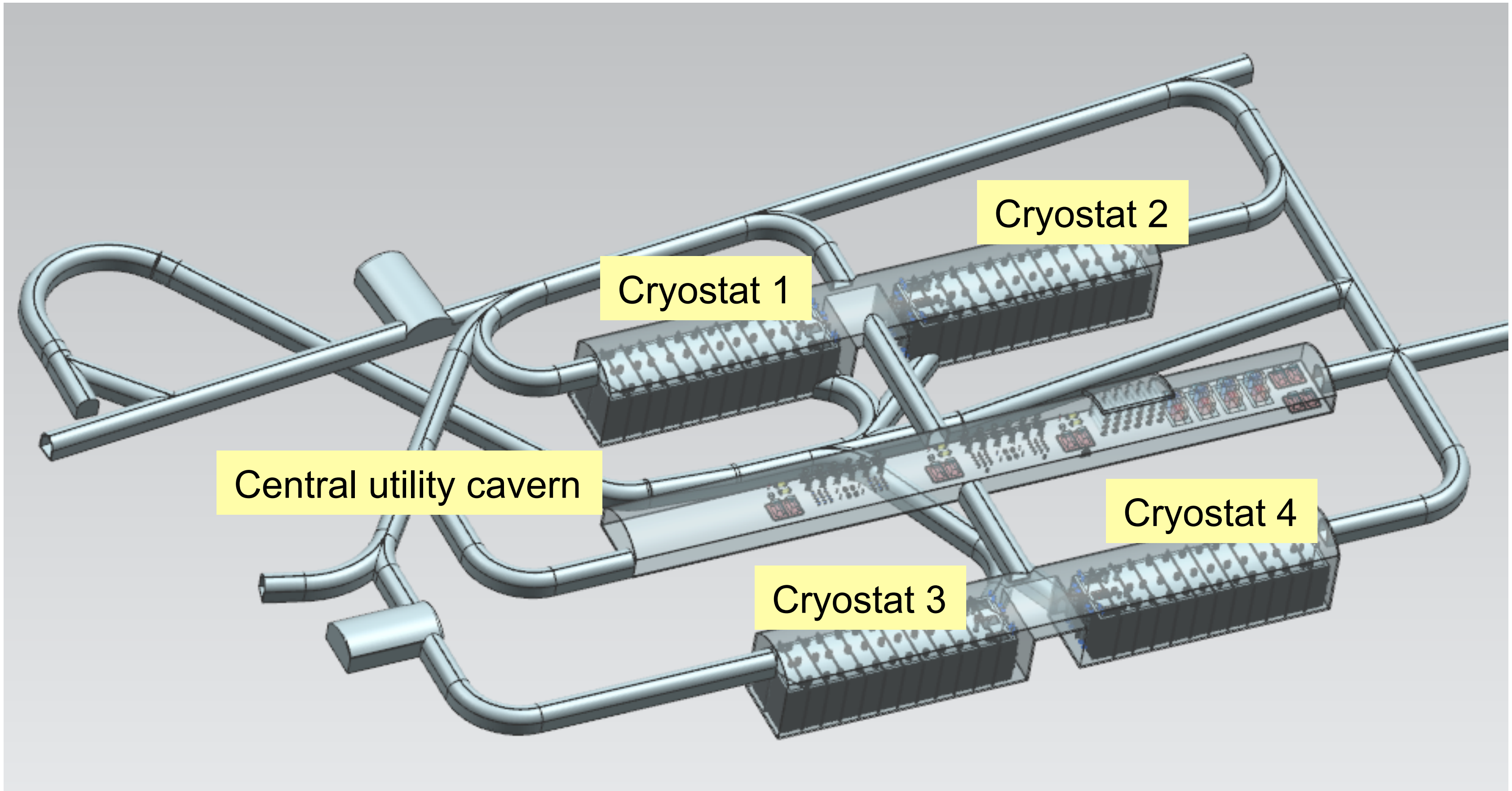
Outline

- The Deep Underground Neutrino Experiment – DUNE.
- Underground physics with DUNE.
- Proton decay.
- Supernova neutrinos.
- Atmospheric neutrinos.
- Conclusions.

The DUNE experiment

- Recently formed collaboration in response to P5 recommendations.
- Bringing together broad expertise from LBNE, LBNO and other interested institutes.
- Currently about 800 scientists from 144 institutes, 26 countries on 5 continents.
- Far Detector site: SURF in the South Dakota, 4850 ft underground.
- Scientific goals:
  - Studying CP violation and mass hierarchy in the lepton sector using multi-kilotonne liquid argon (LAr) underground detector and high-intensity neutrino beam from Fermilab.
  - Searching for proton decay.
  - Searching for neutrinos from supernovae.
  - Ancillary science programme including precise atmospheric neutrino measurements to complement beam neutrino physics.
- More details in the talk by **Mary Bishai at TAUP2015 (Tuesday)**.

The Far Detector

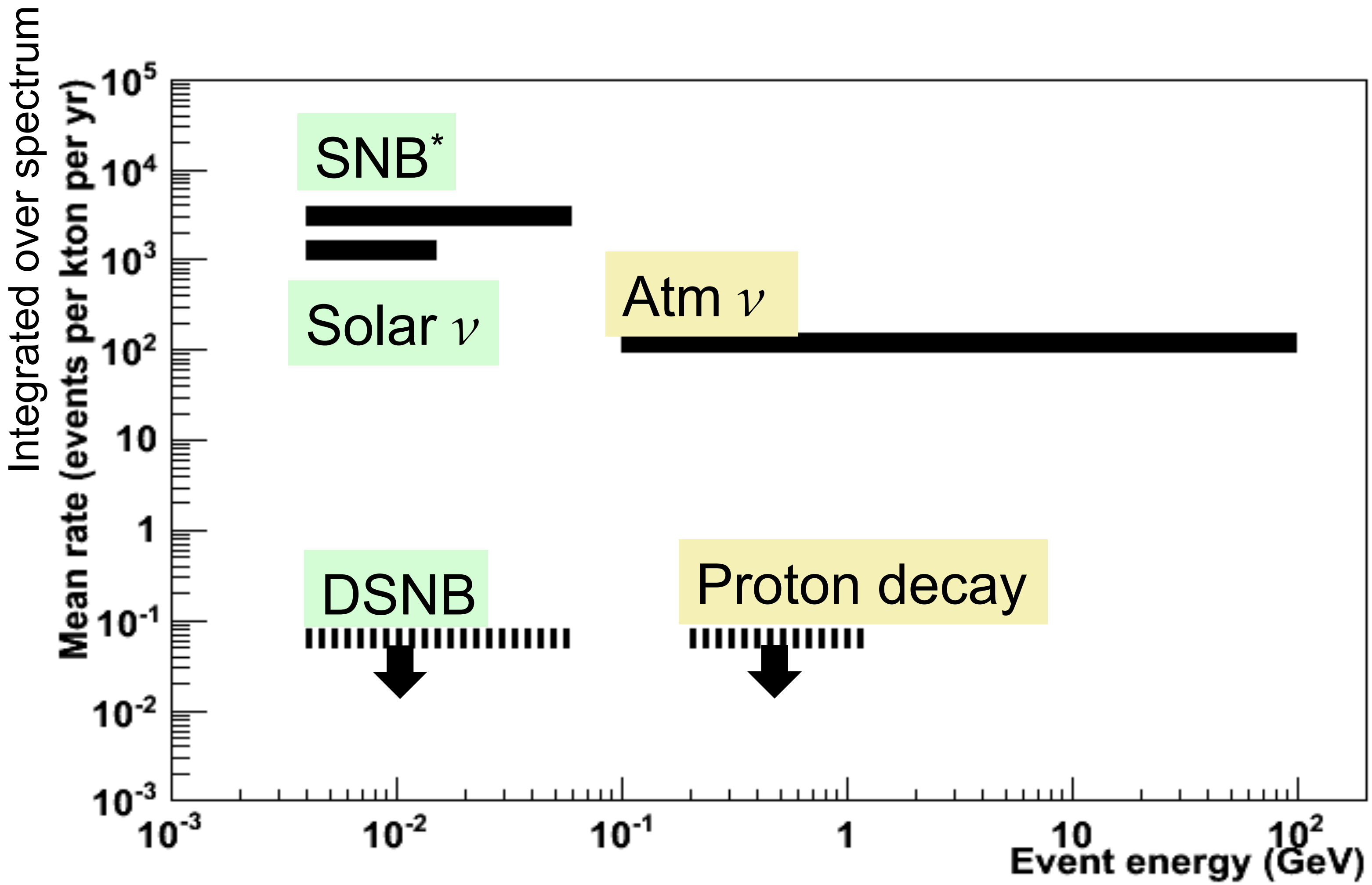


- 4 similar modules: 17.1/13.8/11.6 kt total/active/fiducial mass each.
- Staged construction, allows flexibility in the technology choice: single-phase as baseline design vs two-phase as an alternative design.
- Photon detection for initial time reconstruction for underground physics.

Underground physics

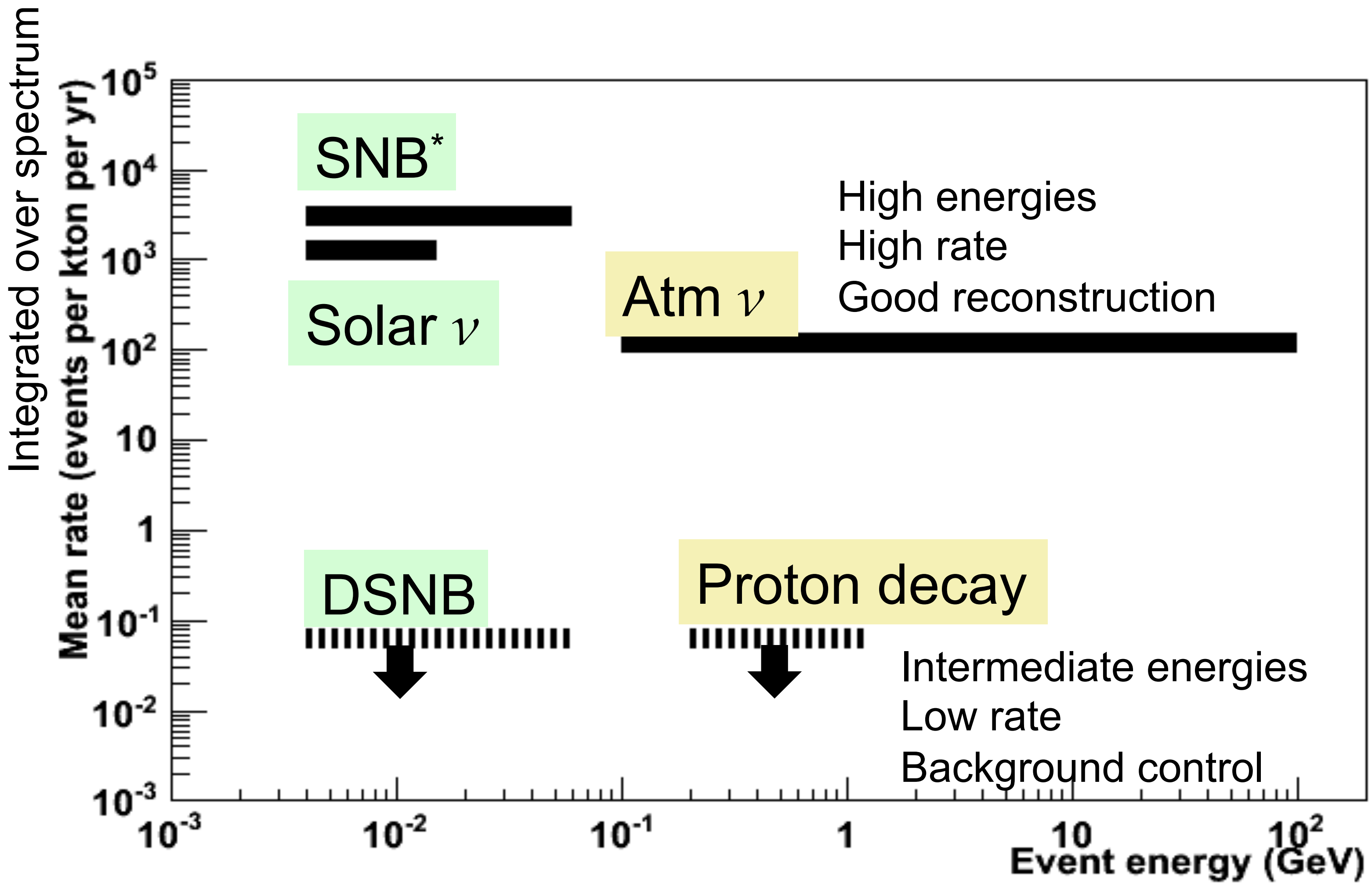
Physics	Energy range	Rate, kt^{-1} $year^{-1}$
Proton decay	hundreds MeV	unknown
Atmospheric neutrinos	0.1 – 100 GeV	~ 120
Supernova neutrino burst (SNB)	~ 5 – 50 MeV	~ 100 within ~10 s (at 10 kpc)
Solar neutrinos	~ 5 – 15 MeV	~1300
Diffuse supernova neutrinos (DSNB)	20 – 50 MeV	< 0.06

Expected event rate versus energy

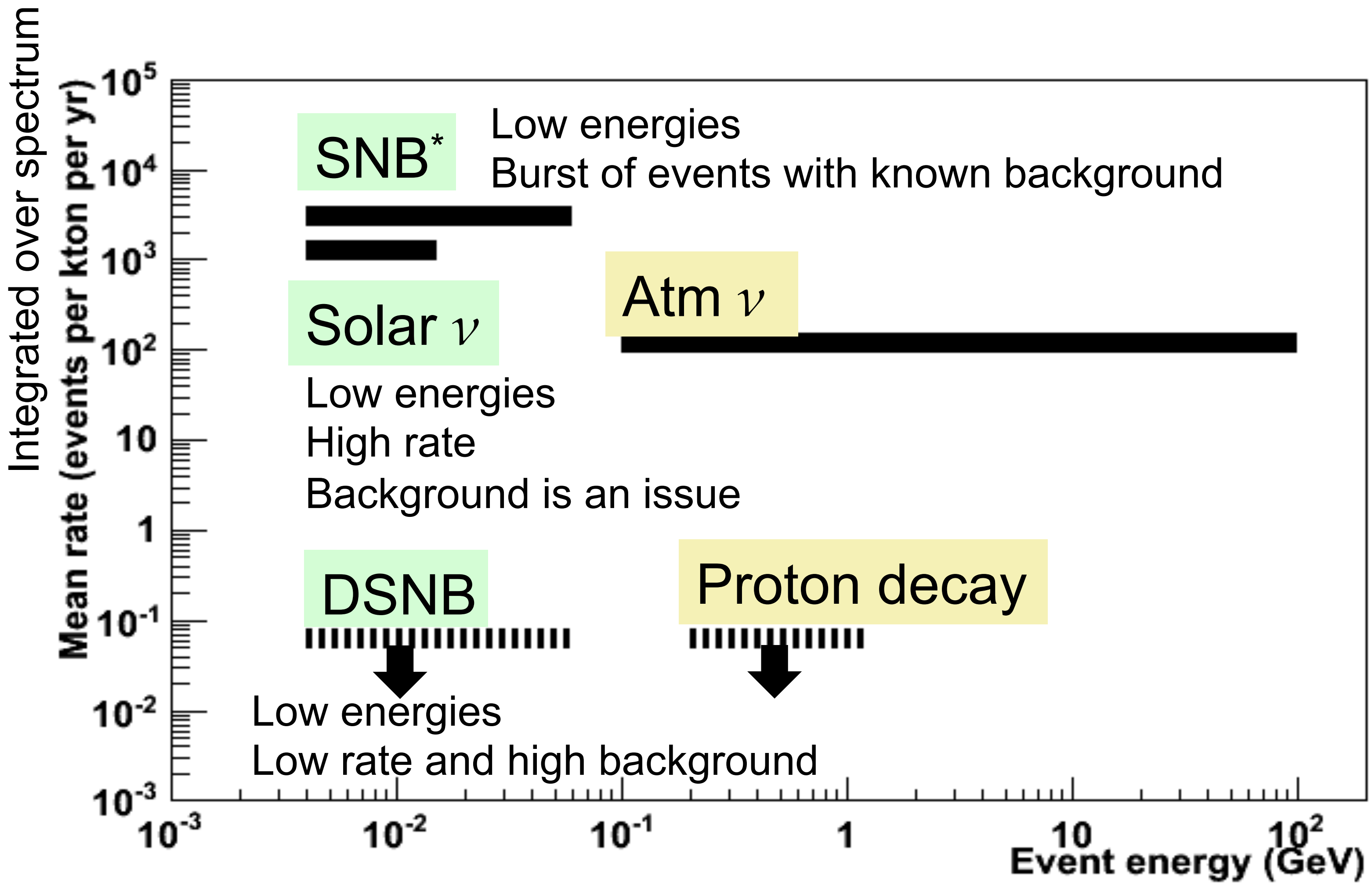


* SNB at 1 kpc, rate integrated over the time window of ~30 s.

Expected event rate versus energy

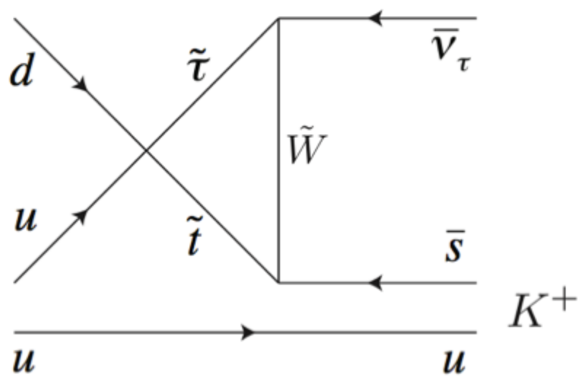


Expected event rate versus energy



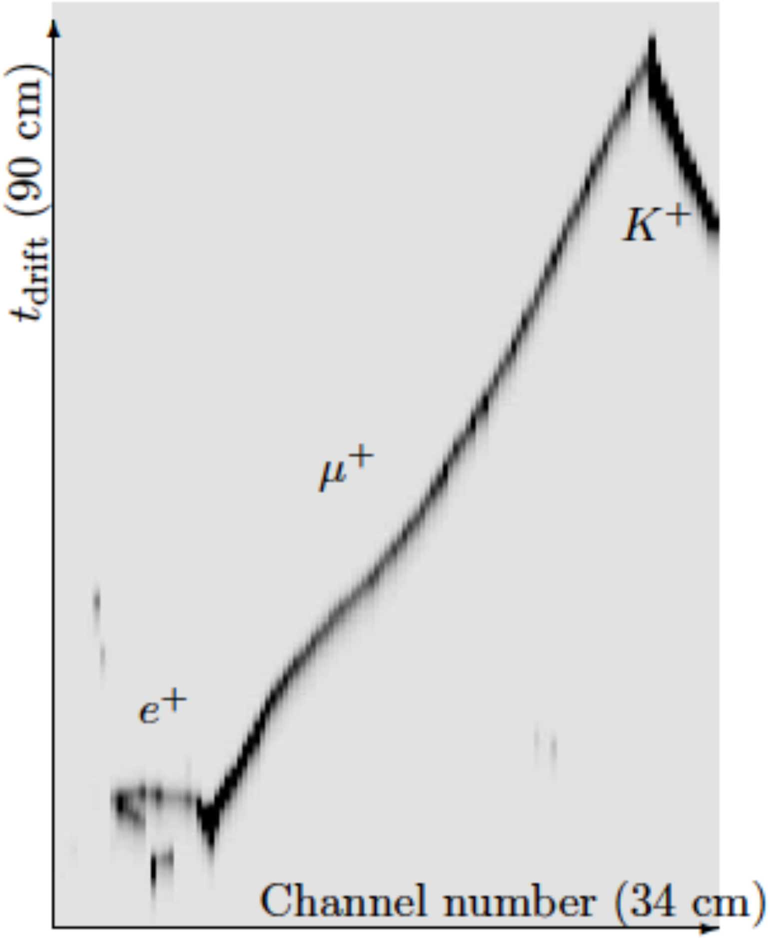
Proton decay

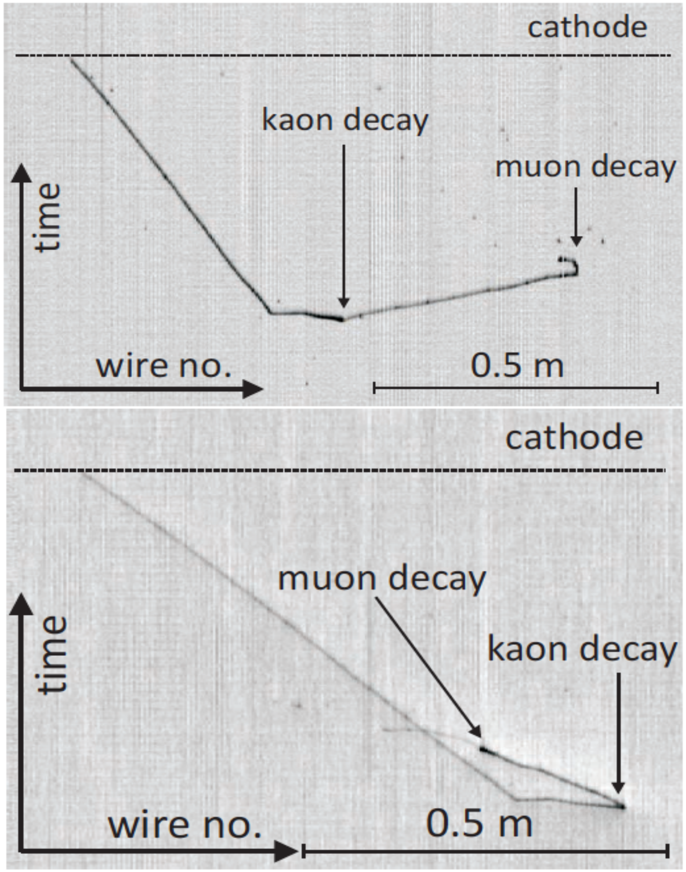
- Baryon number violation ➔ physics beyond the standard model ➔ testing GUT models.
- Best current limits on most decay modes (for instance $p \to e^{+}\pi^{0}$) are from Super-K. Current LAr detectors can see most modes and have a better event reconstruction capability but the sensitivity is not as good as for Super-K/Hyper-K because of smaller exposure.
- The strength of LAr: $p \to K^{+}\overline{\nu}$



- SUSY motivated.
- Low threshold in LAr (no Cherenkov threshold).
- Good event reconstruction.
- Background is under control.

Events with kaons

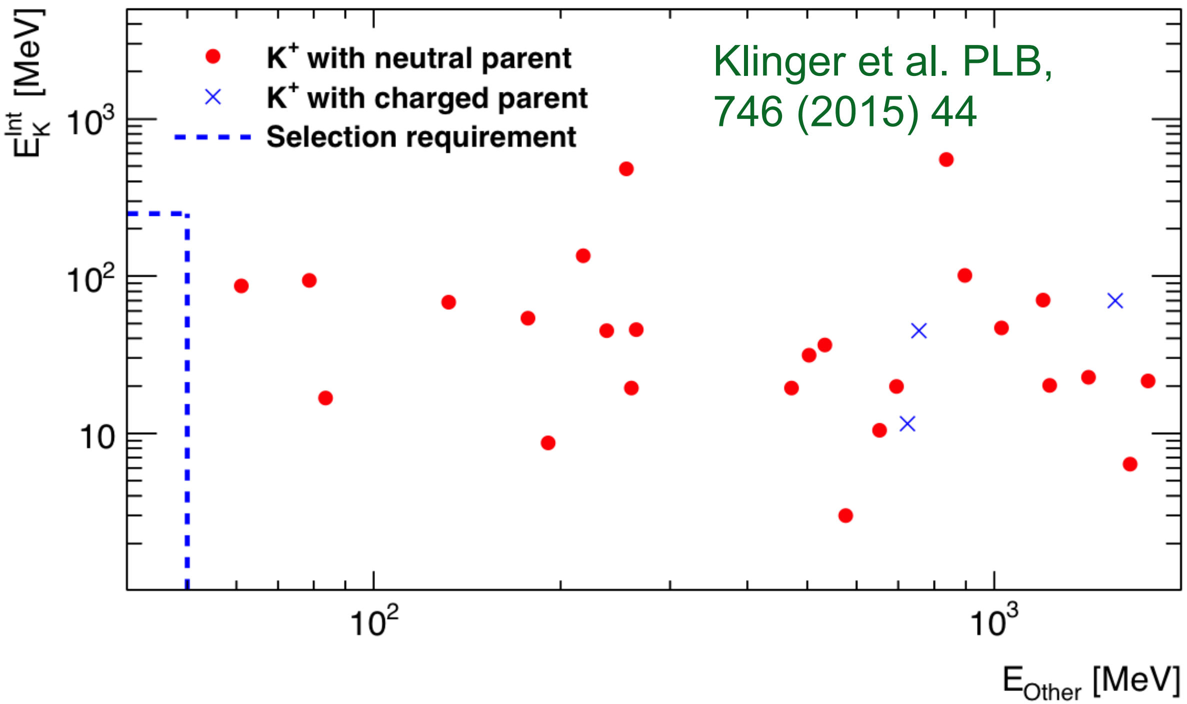




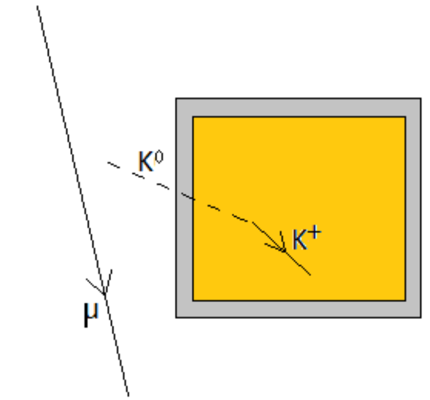
- Event simulation from Bueno et al. JHEP04 (2007) 041.

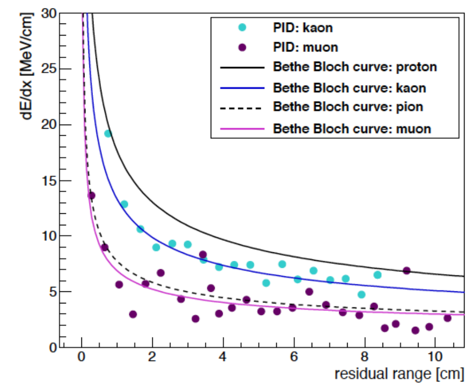
- ICARUS T600 event from Antonello et al. Adv. High Energy Phys. (2013) 260820.

Cosmogenic background



Klinger et al. PLB, 746 (2015) 44





- Kaon momentum 340 MeV (E_{kin}=106 MeV) smeared by Fermi motion and intranuclear scattering.
- Kaon ID and energy from dE/dx and range (see Antonello et al. Adv. High Energy Phys. (2013) 260820).
- Efficient background rejection: no other energy deposition.

Background and its suppression

- Cosmogenic background:
  - Depth ~4300 m w. e.
  - Fiducialisation.
  - Cuts on other secondaries.
- Atmospheric neutrino background:
  - The main background may come from NC interactions resulting in a K^+ and no other charged particles, such as: $\nu p \rightarrow \nu K^+ \Lambda^0 (\Sigma^0)$. Cut on associated strange baryon.
  - There are also CC processes with a K^0 production followed by the charge exchange reaction and a K^+ as a result. Cuts on a lepton.
  - Misidentification of a pion. Cuts on dE/dx and range.

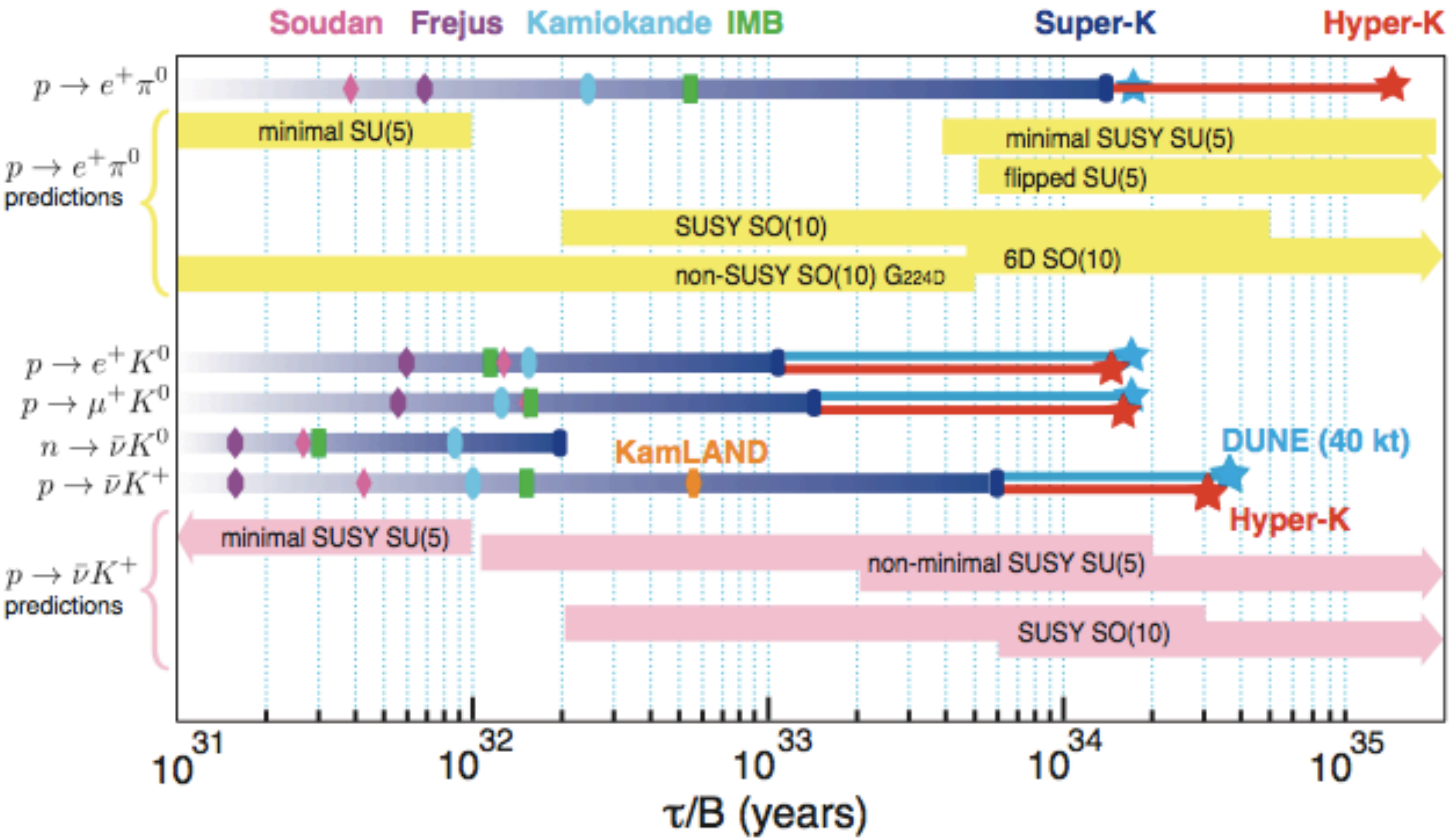
Background and efficiency

- Efficiency and background rate per Mton per year:

Decay mode	Water Cherenkov		Liquid argon	
	Efficiency	Background	Efficiency	Background
$p \to K^+\overline{\nu}$	19%	4	97%	1
$p \to K^0\mu^+$	10%	8	47%	<2
$p \to K^+\mu^-\pi^+$			97%	1
$n \to K^+e^-$	10%	3	96%	<2
$n \to e^+\pi^-$	19%	2	44%	0.8

Estimate for water Cherenkov: Kearns (Snowmass, 2013).
For LAr: LBNE Collaboration, arXiv:1307.7335v3 based on Bueno et al. JHEP04 (2007) 041.
Several decay modes with high efficiency and low background in LAr.

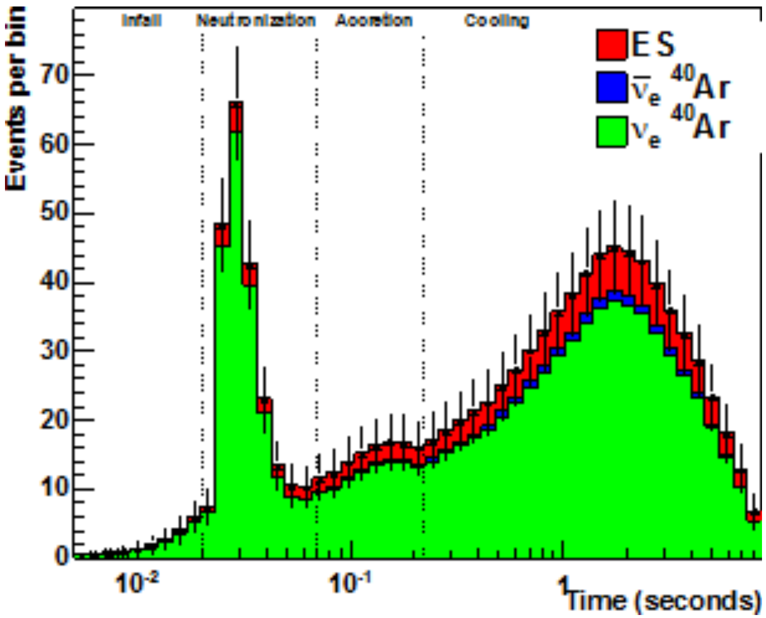
Sensitivity

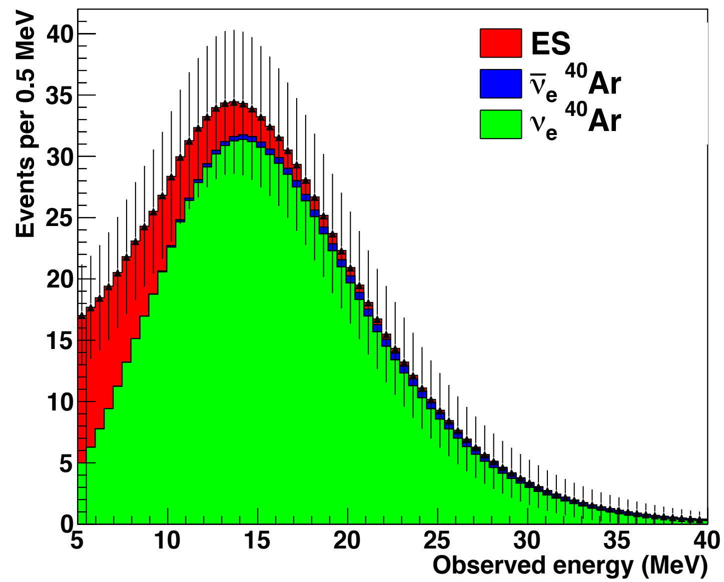


Neutrinos from supernovae

- At the late stages of star evolution, massive stars may explode as supernovae.
- Prior to visible explosion, the core of the star collapses and cools down emitting a few $\times 10^{53}$ ergs in neutrinos (99% of the total energy emitted).
- All neutrino flavors: the energy is assumed to be equally split between all 6 neutrino types.
- Total duration of the burst ~10 s.
- Only ν_e in the first 10 ms – neutronisation.
- Energies up to 50 MeV.

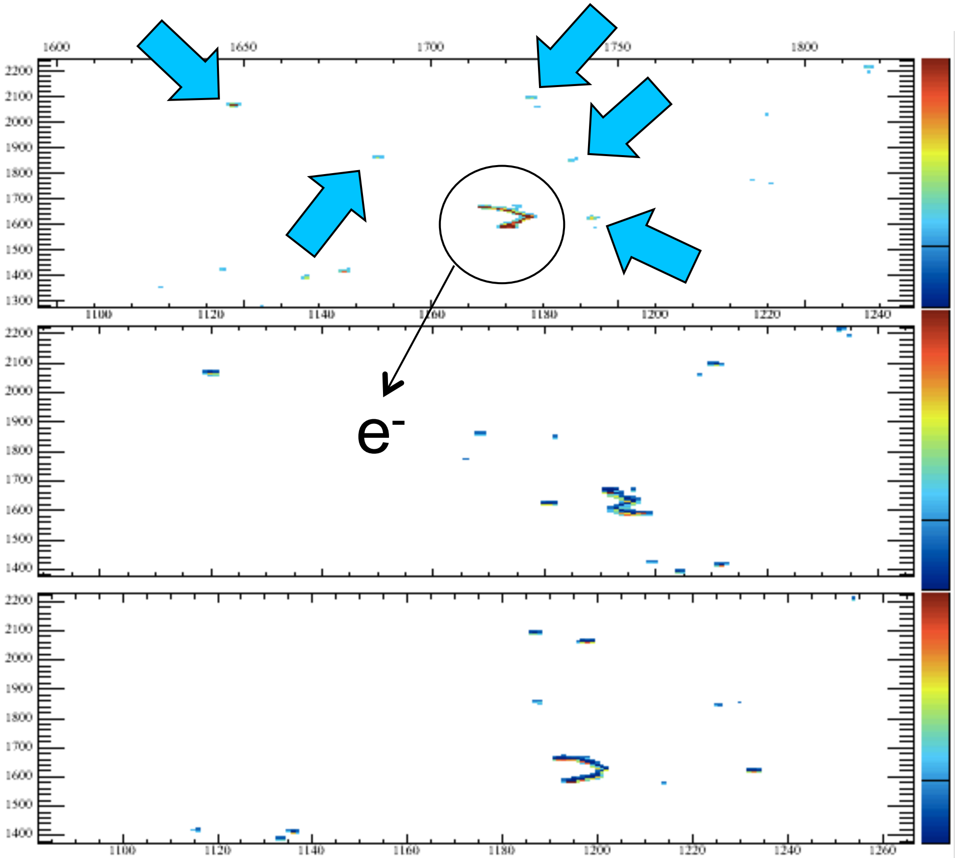
Supernova neutrino burst

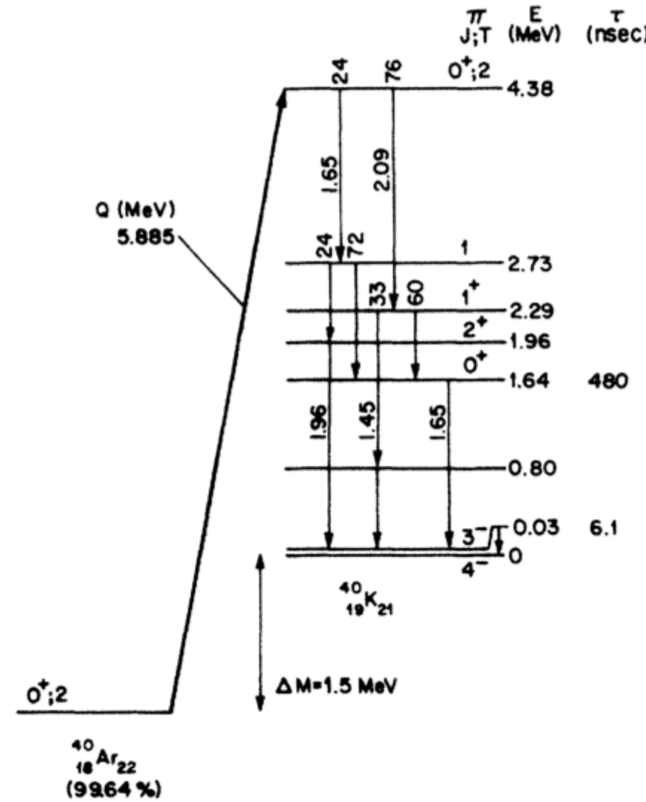




- LAr detectors are sensitive predominantly to ν_e: $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$
- Complementary to other experiments (water Cherenkov and scintillators), sensitive primarily to $\bar{\nu}_e$
- Significant variations in event rates between different collapse models ➔ testing models, in particular neutronisation stage.
- Burst of neutrinos, background is measurable (radioactivity, activation).

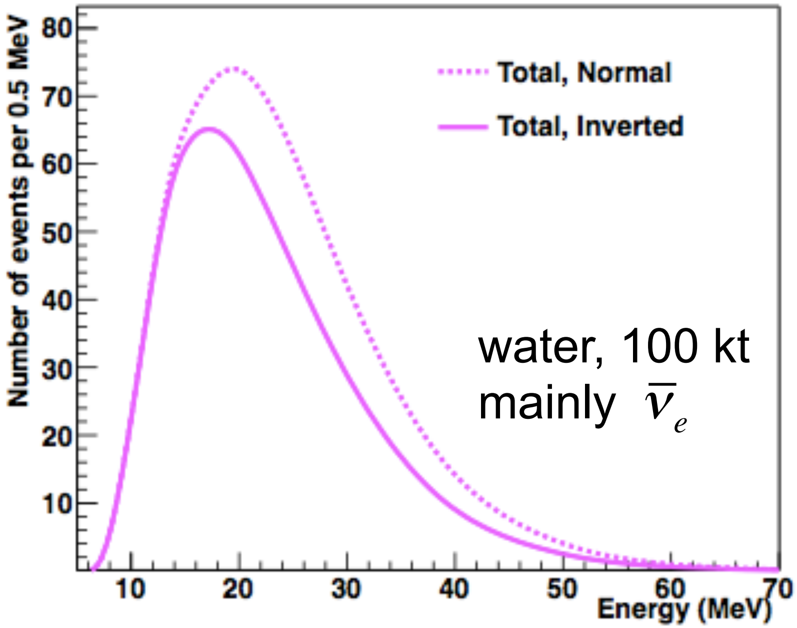
Event simulation

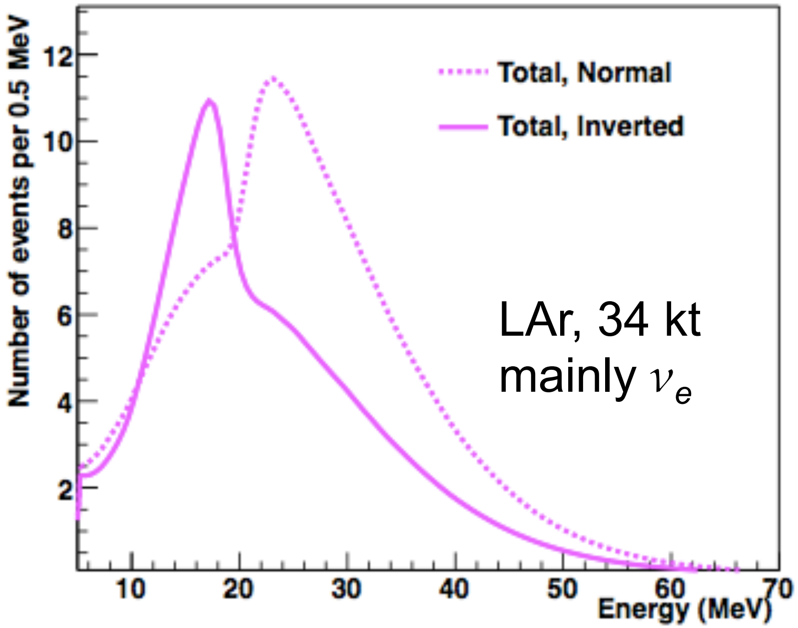




- Simulation (MicroBooNE geometry): 20 MeV ν_e, 14.1 MeV e^-.
- Background: cosmogenic activation and local radioactivity.
- Tagging de-excitation gammas may be possible, studies are underway.

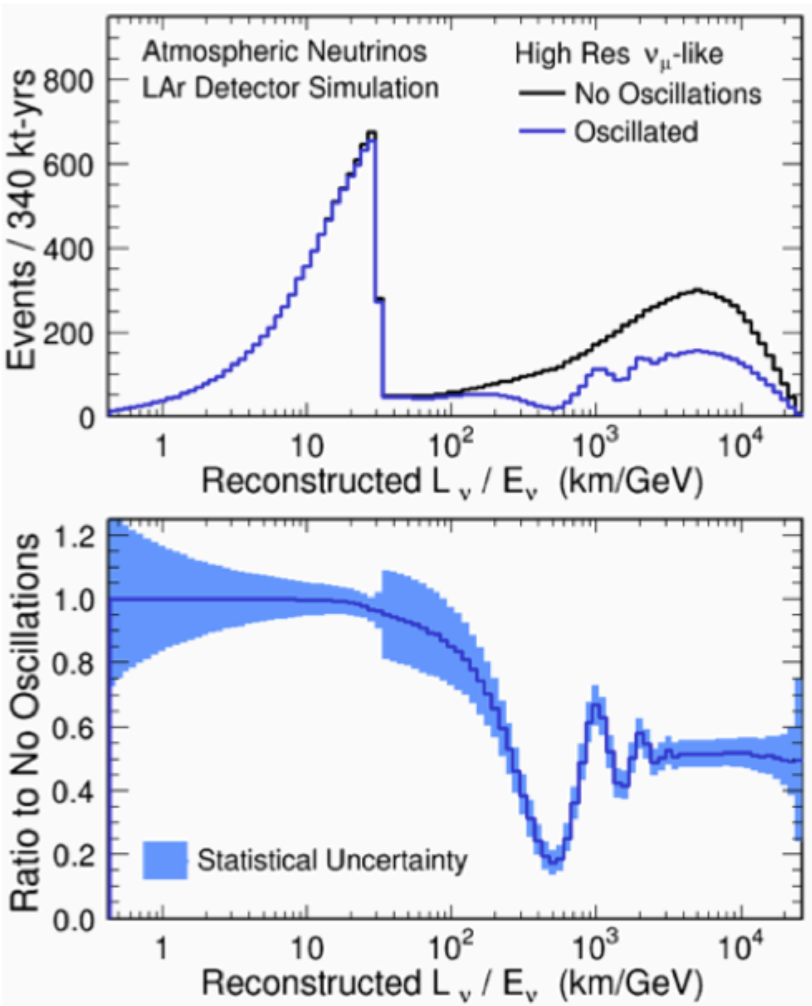
Water / LAr complementarity





Example spectra at the late stage (1 s time slice) of the NS 'cooling'.
Model from Duan and Friedland, PRL, 106 (2011) 091101.
Mass hierarchy (MH) can be resolved.
MH information is contained also in the time profile.

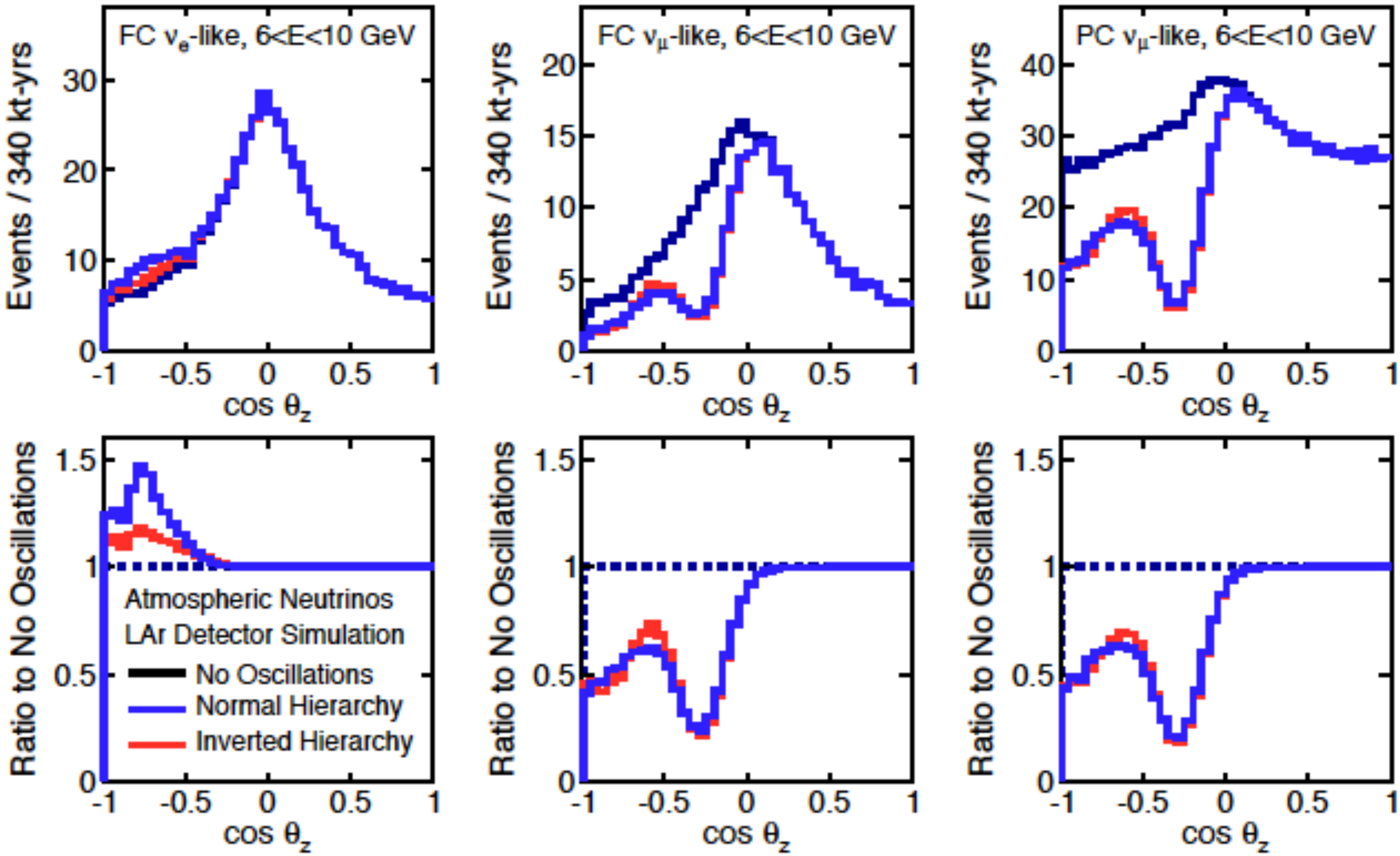
Atmospheric neutrinos



- Wide range of angles and energies, sampling matter (MSW effect) with both neutrinos and antineutrinos.
- Good energy and angular resolution.

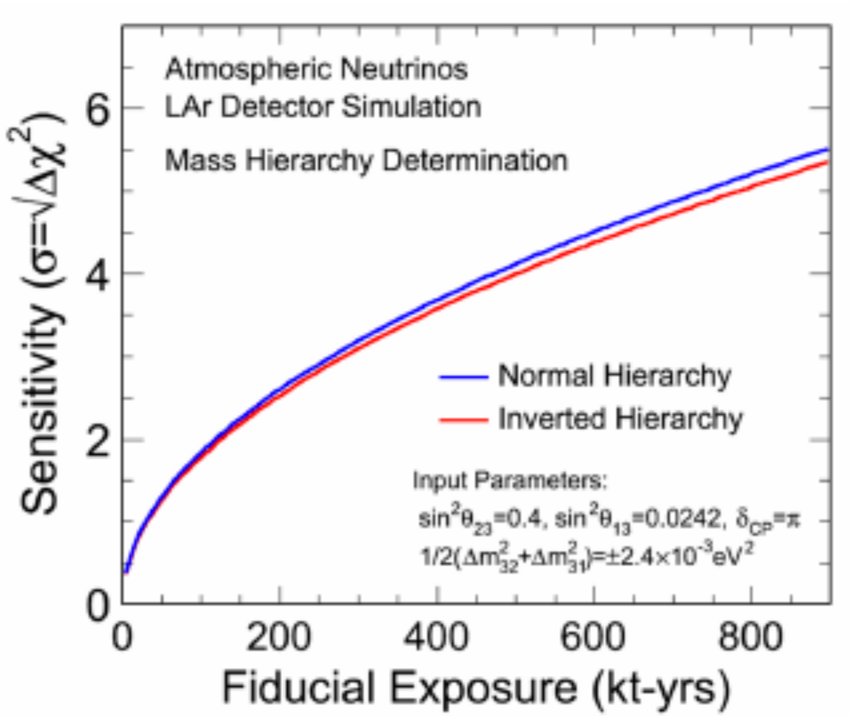
Event type	Event rate in 350 kt×years
e-like, contained	14053
μ-like, contained	20853
μ-like, partly contained	6871

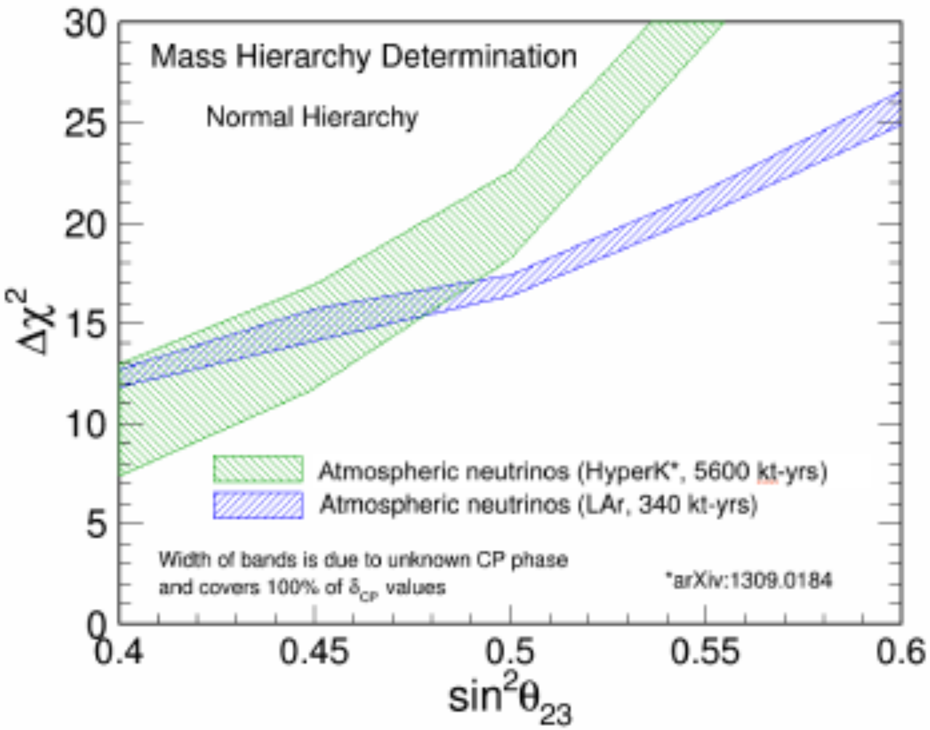
Sensitivity to mass hierarchy



Enhancement for neutrinos in NH and for antineutrinos in IH.

Sensitivity to mass hierarchy





- Improved sensitivity with beam and atmospheric neutrinos.
- Sensitivity to mass hierarchy with atmospheric neutrinos does not depend on the value of δ_{CP} – complementarity to beam oscillations.
- Sensitivity improves if proton and muon-decay tagging are employed to separate neutrino and antineutrino events.

Conclusions

- A wide programme covering various topics in ‘underground’ physics.
- Proton decay search ➔ testing GUT models.
- Supernova neutrinos: unique opportunity to detect with high statistics electron neutrino events ➔ testing collapse models, complementary to other detectors.
- Atmospheric neutrinos ➔ sensitivity to mass hierarchy, complementary to beam neutrino oscillation studies.
- Also cosmic rays: precise testing of the cascade models, stopping and multiple muons, annual modulation etc.
- Something that is difficult to do: solar neutrinos, diffuse supernova neutrinos and other astrophysical neutrinos but who knows?