Physics at Planned Underground Facilities

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Outline

- Neutrinoless Double Beta Decay
- Dark Matter Direct Detection
- Proton Decay
- Dark Matter – Indirect Detection
- Supernova Neutrinos
  - Burst
  - Diffuse SN Background
- Neutrino Oscillations
  - Accelerator
  - Atmospheric
- Geoneutrinos
- Gravity Waves

What I will not talk about

- Geophysics
- Seismology
- Geomicrobiology
- Hydrology
- Geology
- However, one comment: perhaps another non-physics topic should go here

Depravity

- Perhaps we should add research on psychology of the underground scientist?

Reaction of ``normal'' people to going underground

- What sort of depravity leads us to these depths?

Depravity

Reaction of ``normal'' people to going underground

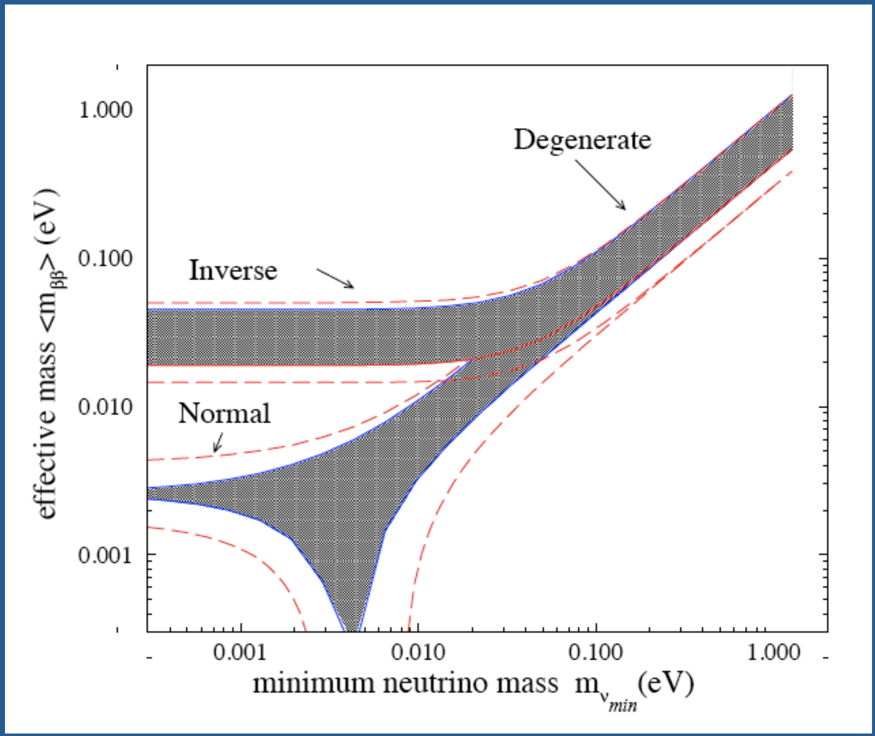
- Then again, perhaps some questions are best left unanswered!

Why go deep?

- Nigel Smith alluded to this on Tuesday:
  - The Deeper the Better: low background for double beta-decay, direct dark matter searches – cosmic-ray muons, neutrons from cosmic-ray muon-induced spallation
  - Deep Enough: proton decay, accelerator neutrinos, atmospheric neutrinos, supernova physics

Neutrino-less Double Beta-decay

- Determine if the neutrino is Majorana
- Measurement of effective mass
- Through several nuclei – further physics beyond the standard model
- Comparisons with direct mass measurements (e.g. KATRIN, cosmology) determine the mass hierarchy
- Low energy requires pristine environment and pristine detector
- See talks from Wednesday: Rodenjohann, Pavan, Dolinski, Nakamura; Today: Simkovic



$0\nu2\beta$ decay effective mass.

From: **hep-ph/0412300**

Direct Searches for Dark Matter

- SUSY LSP a good candidate
- Complementary with LHC searches
- Could discover at LHC, require direct detection or vice-versa
- Low energy requires pristine environment and pristine detector
- Go Deep (or DEAP)
- Many approaches including liquid noble gas detectors
- See talk tomorrow: Bertone

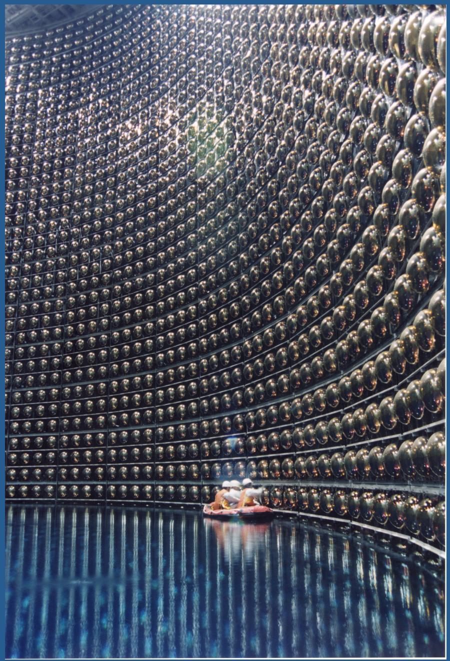
Andrew Hime

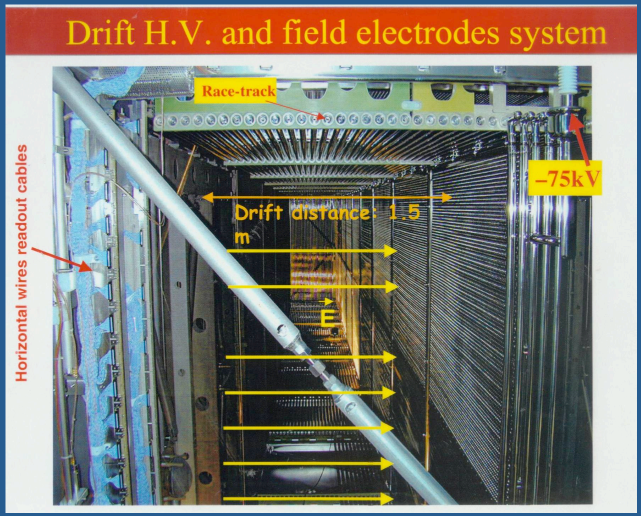
Very Large Detectors

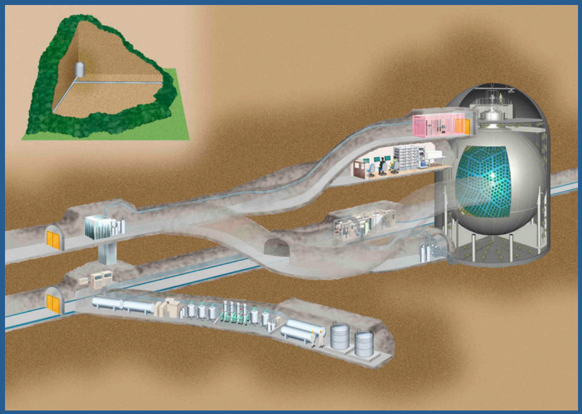
Water Cherenkov:
Hyper-Kamiokande*
Memphys
LBNE-Homestake

Liquid Argon:
Homestake
GLACIER
GLAO

Liquid Scintillator:
Lena*







* See later talks this session

Proton Decay

- In the Standard Model, protons are stable – baryon number is conserved
- Accidental symmetry – fortunate for us!
- Theories beyond the Standard Model in general predict proton decay:

Grand Unified Theories

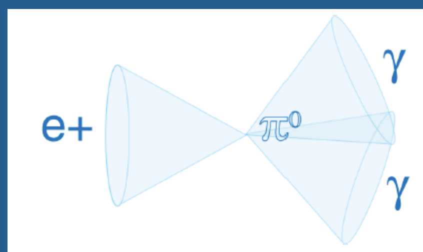
$$p \longrightarrow e^+ \pi^0$$

SUSY

$$p \longrightarrow K^+ \overline{\nu}$$

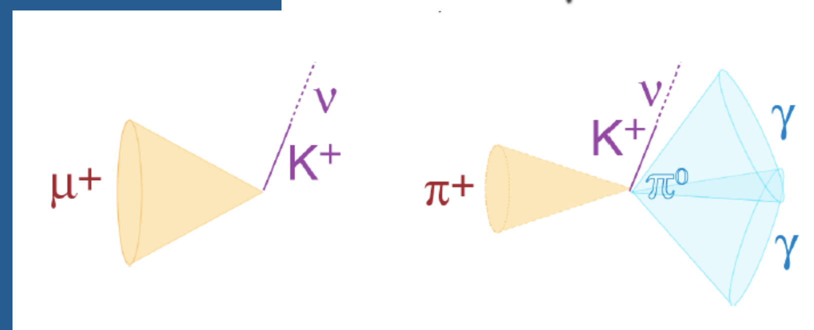
Detecting Proton Decay

- Water Cherenkov: made for $e^{+} \pi^{0}$



$K^{+} \to \pi^{+} \pi^{0}$	21%
$K^{+} \to \mu^{+} \nu_{\mu}$	65%

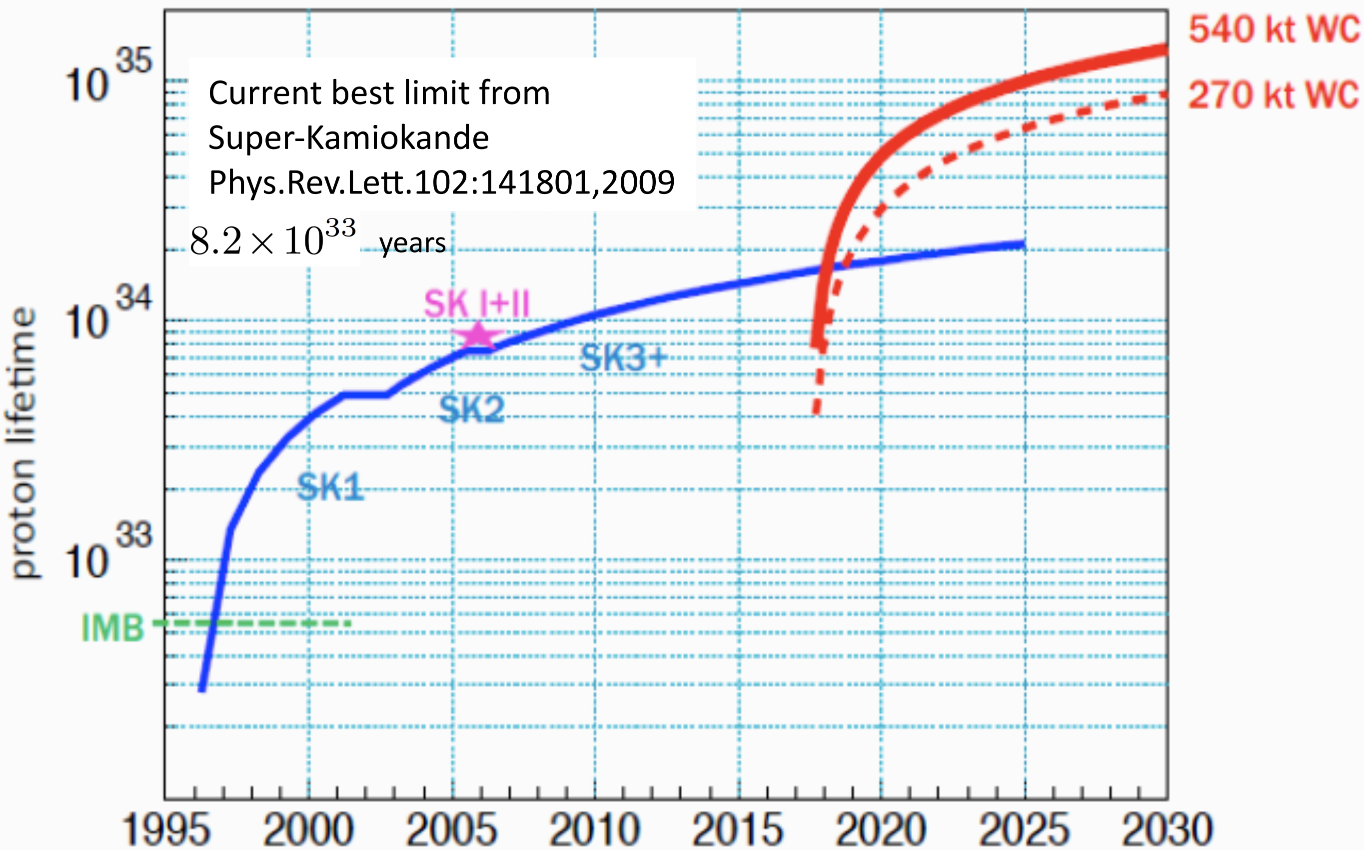
  – Kν is more tricky:



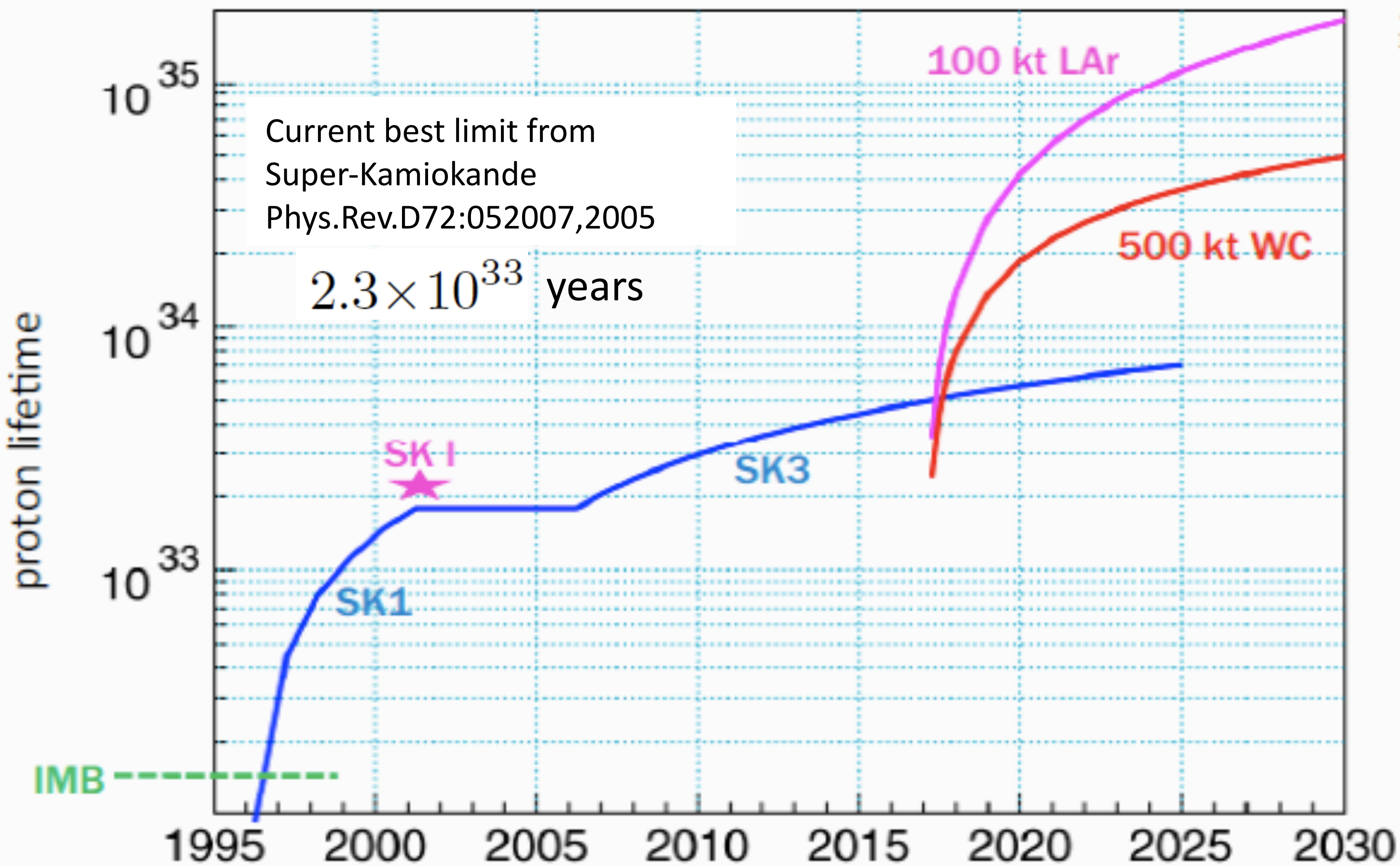
Ed Kearns

- Liquid Argon detection with little background
- Liquid Scintillator can detect the kaon

$$p \rightarrow e^+ \pi^0$$



$$p \rightarrow K^+ \nu$$



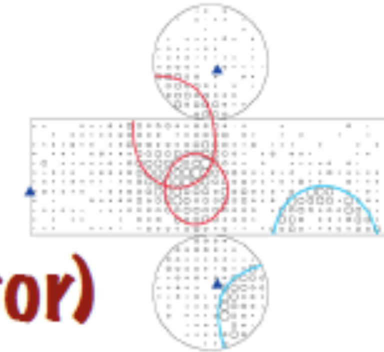
Current best limit from
Super-Kamiokande
Phys.Rev.D72:052007,2005

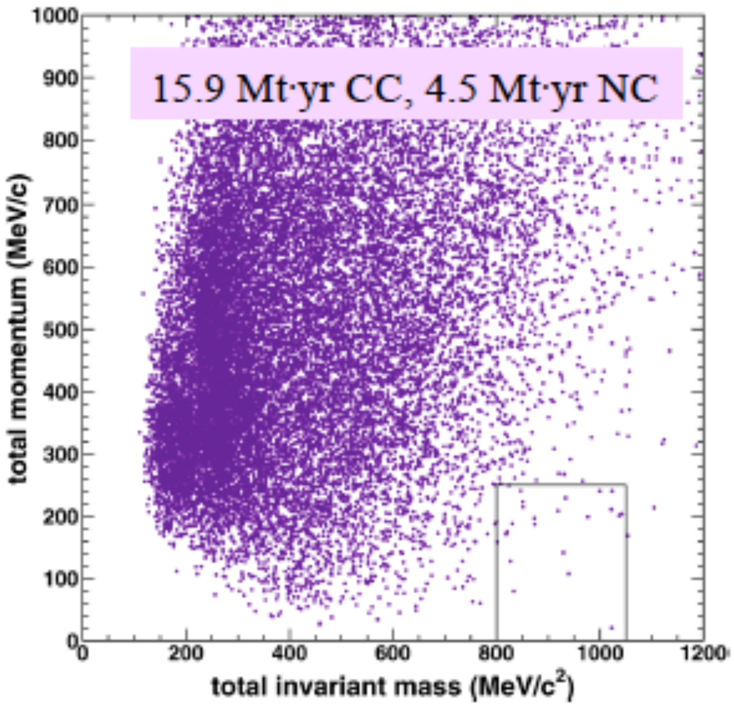
2.3×10^{33} years

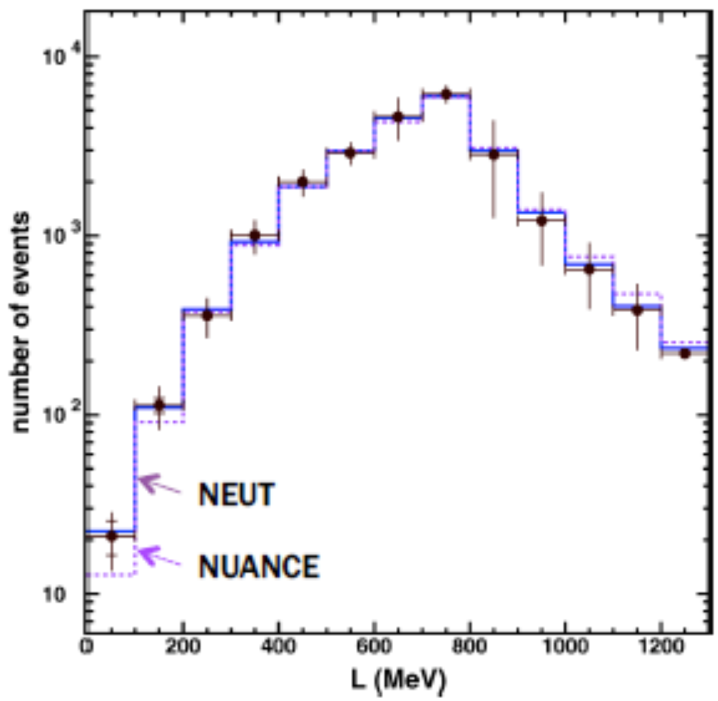
Going Beyond Super-Kamiokande

- IMB, Kamiokande initially built to do proton decay – atmospheric neutrinos are the background
- Path to Super-Kamiokande to focus on neutrinos
- Current justification for large detectors is coming from neutrinos
- Large-scale detectors need bread-and-butter physics
- Also, need good background predictions

Direct measurement of proton decay background using K2K neutrino beam (1KT near detector)





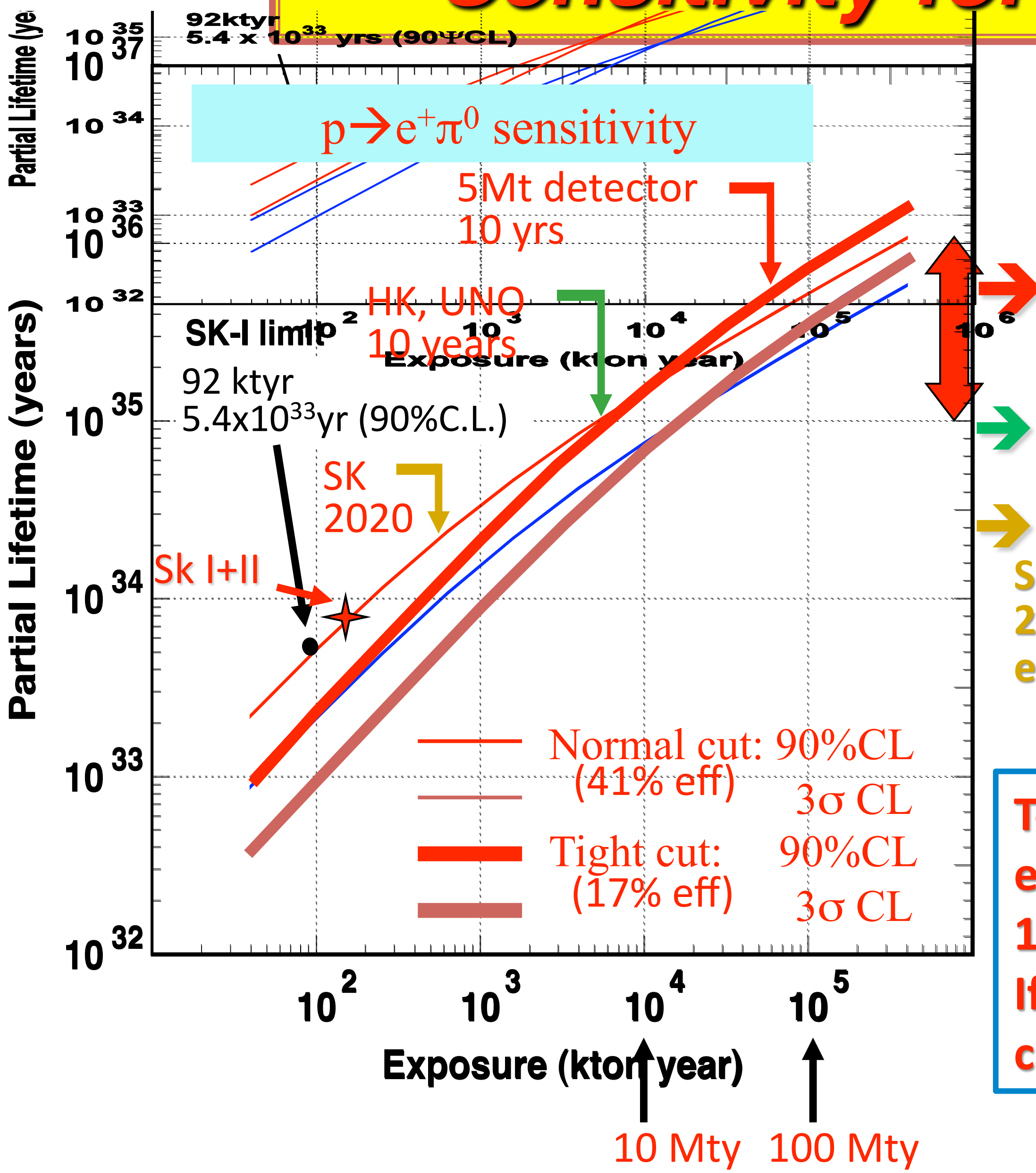


$$e^{+}\pi^{0}\ \text{BG} = 1.63^{+0.42}_{-0.33}\,(\text{stat})^{+0.45}_{-0.51}\,(\text{sys.})\ \text{evts/Mt}\cdot\text{yr}$$

Phys.Rev.D77:032003,2008

Ed Kearns

Sensitivity for $p \rightarrow e^+\pi^0$



5 Mt detector
10 yrs operation

~7×10^{35} yrs

~1×10^{35} yrs

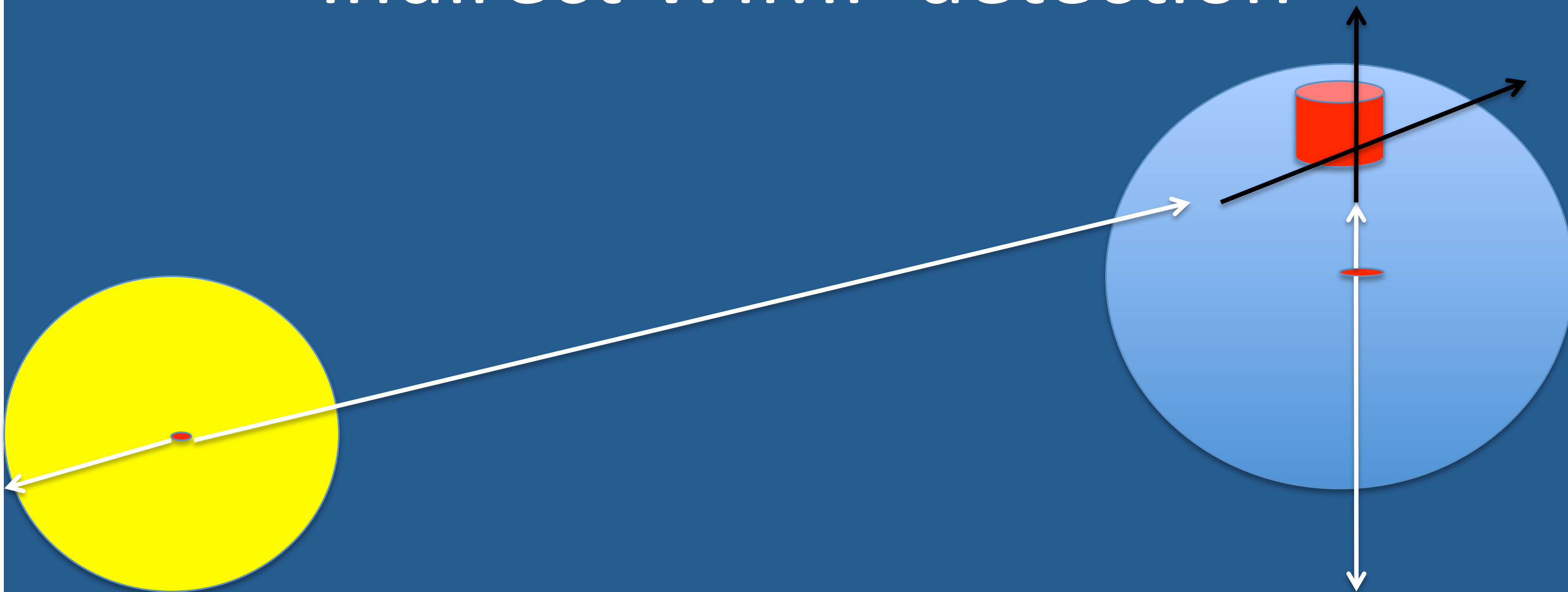
0.5Mt detector
10 yrs operation

~3×10^{34} yrs

SK ~~(22.5 kt)~~
25 yrs operation (2020)
effective: close to 0.5Mty exposure

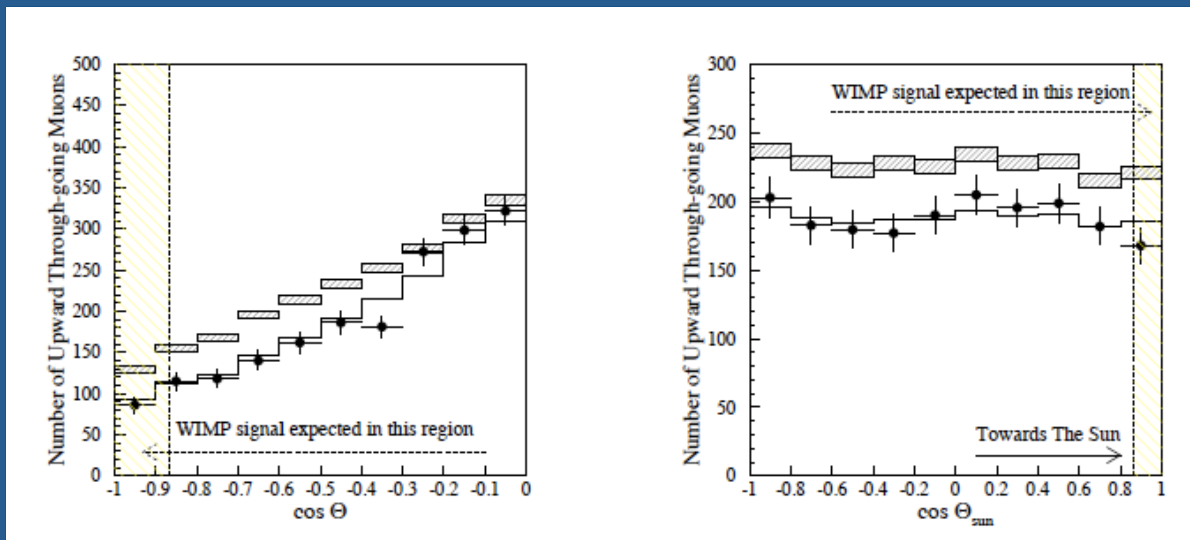
To reach 10^{36} years, need 200Mty exposure--10Mt 20years, but 5Mt 10years reaches to ~7×10^{35}yr.
If detector is expandable, then we can start with 5Mt or less

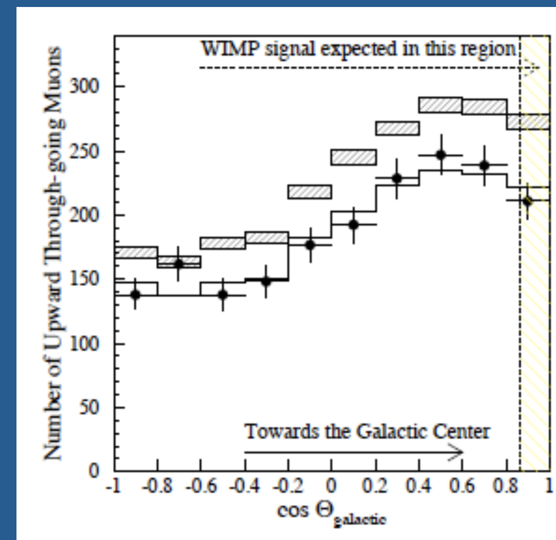
Indirect WIMP detection



- WIMPs accumulate in the cores of the earth and sun (and galactic center), occasionally annihilate, possibly producing a neutrino pair
- Large underground detectors can detect these neutrinos that should point back to the sun or core of the earth

WIMP searches from Super-Kamiokande

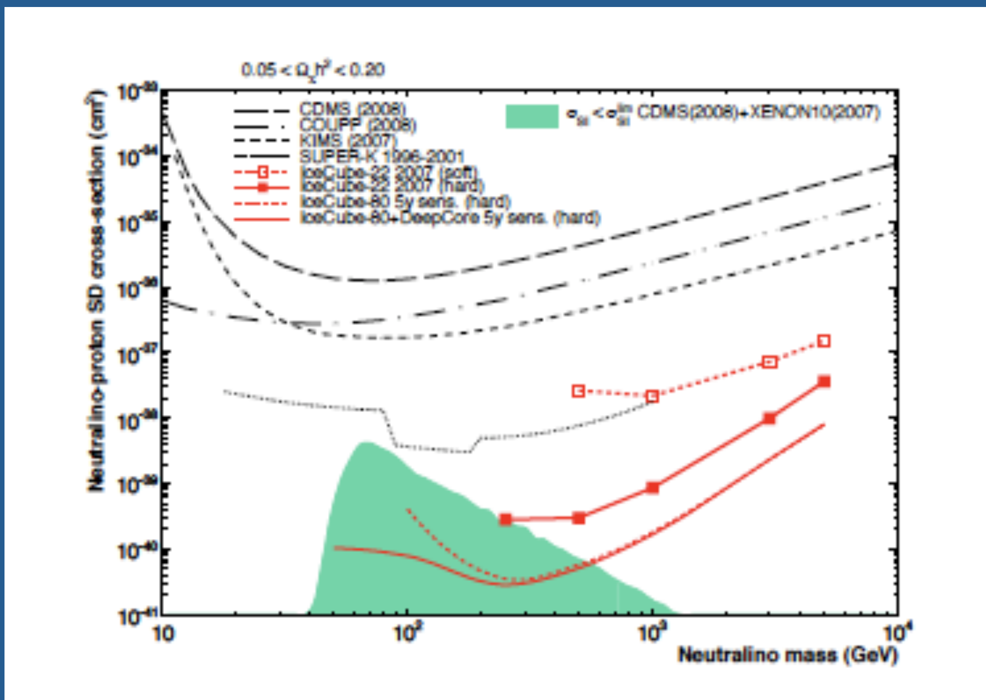


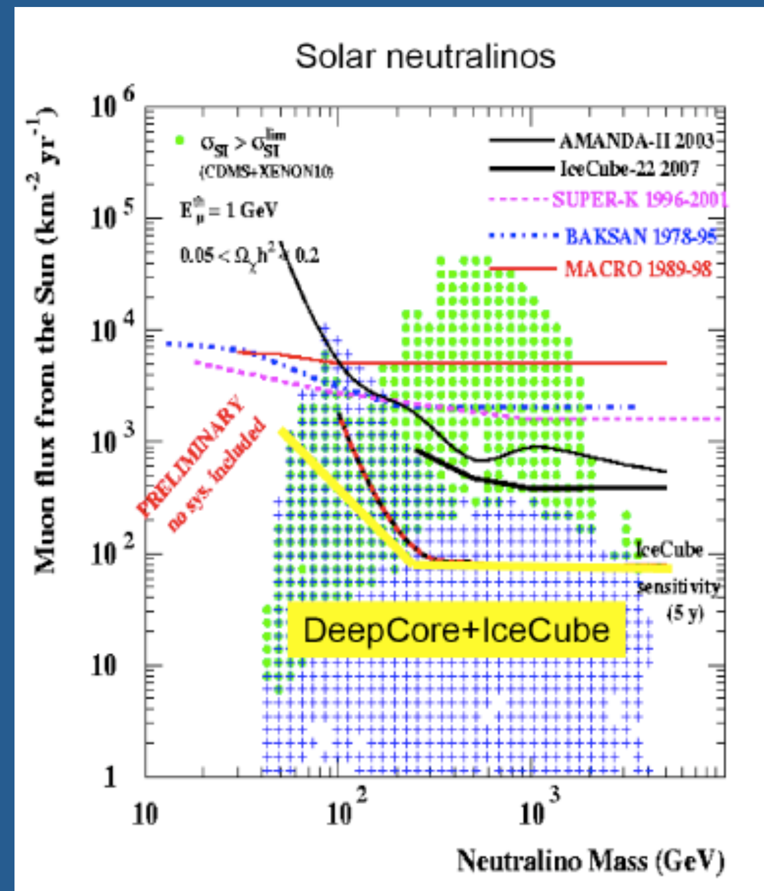


Phys.Rev.D70:083523,2004

- Complementary information to direct searches and other indirect searches
- At high WIMP mass, not competitive with IceCube
- Niche at lower WIMP mass: future, large, underground detectors could use contained events

Searches for upward-going muons from the sun





Spin dependent

New J.Phys.11:105019,2009

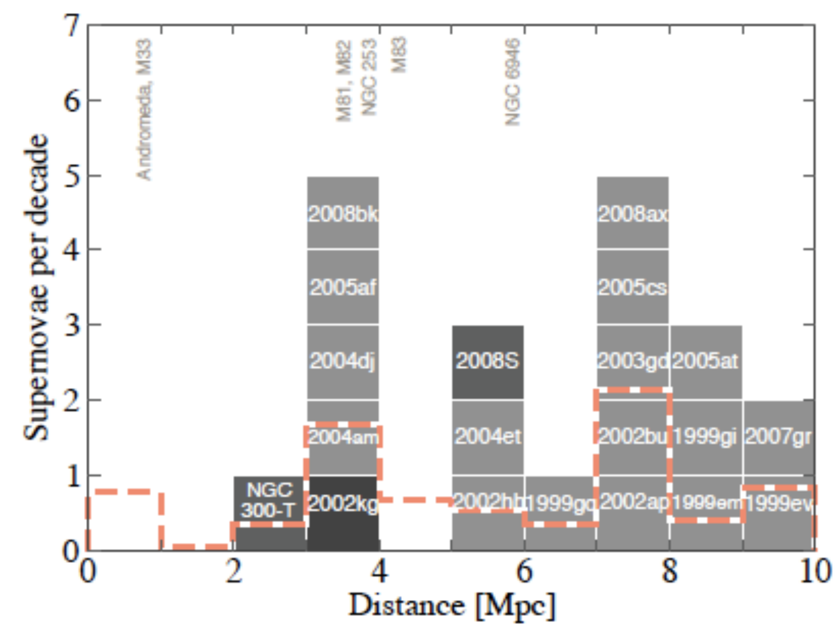
Spin Independent

Supernova Bursts

		32 kton (SK)	0.5 Mton (HK)	5 Mton (Deep-TITAND)
10 kpc	(Milky Way)	10^4	10^5	10^6
1 Mpc	(M31, M33)	1	10	10^2
3 Mpc	(M81, M82)	10^{-1}	1	10

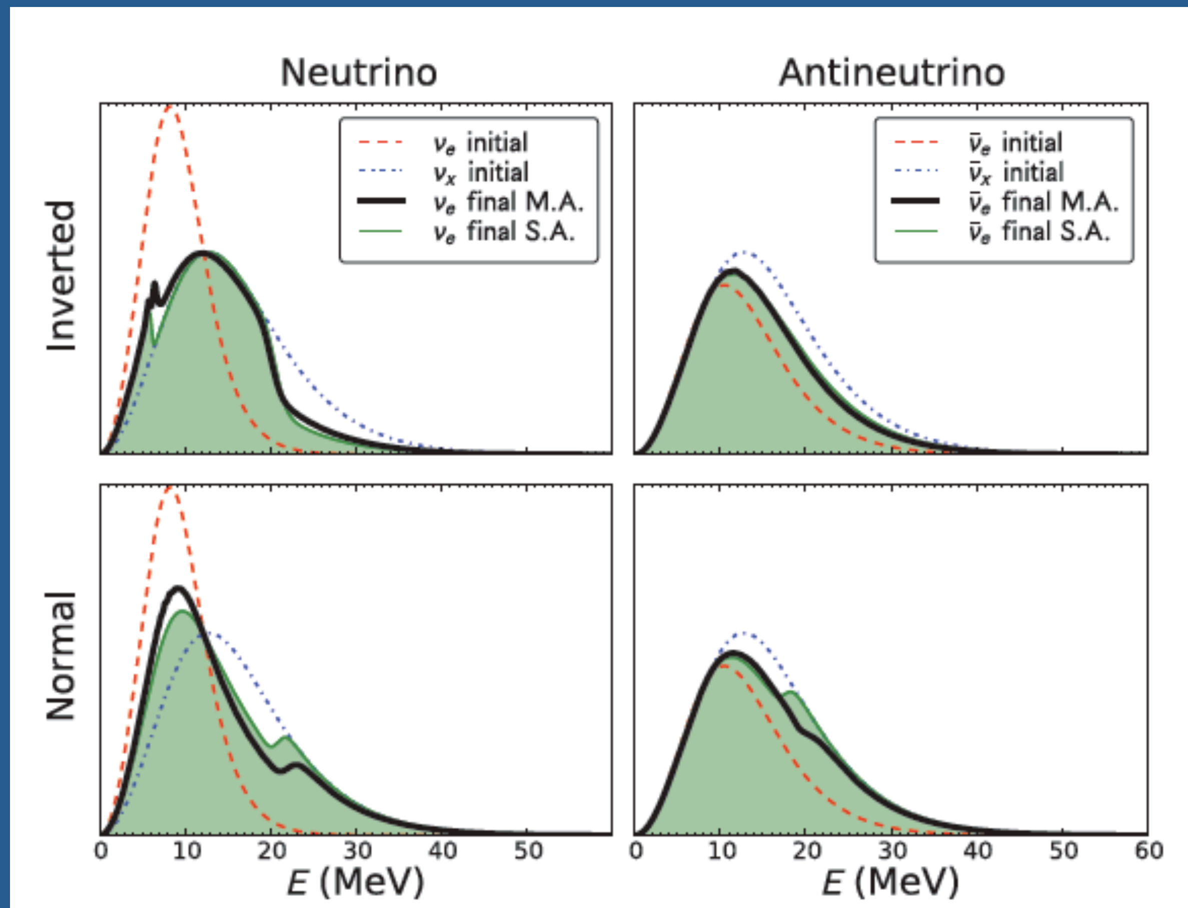
arXiv:0810.1959

- Core-collapse supernova produce copious fluxes of neutrinos
- >99% of their energy is emitted as neutrinos
- Studying the time, energy and flavor composition gives us insights into astrophysics and particle physics
- Rate in our galaxy ~ 3 per century



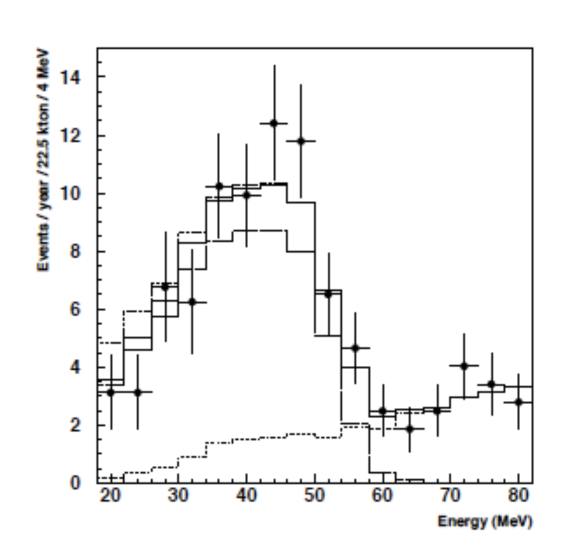
Particle Physics from Supernova Observation

- Can discern oscillation parameters from the energy spectra of neutrinos and anti-neutrinos
- Can also determine some of the dynamics of the explosion from energy spectra and time-profiles
- See talks tomorrow morning: Cardall, Mirizzi, Vagins



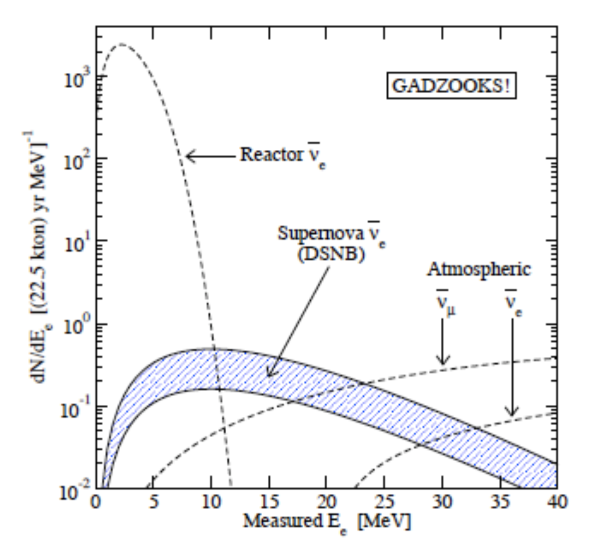
arXiv:1006.2359

Diffuse Supernova Background



Phys.Rev.Lett.
90:061101,2003

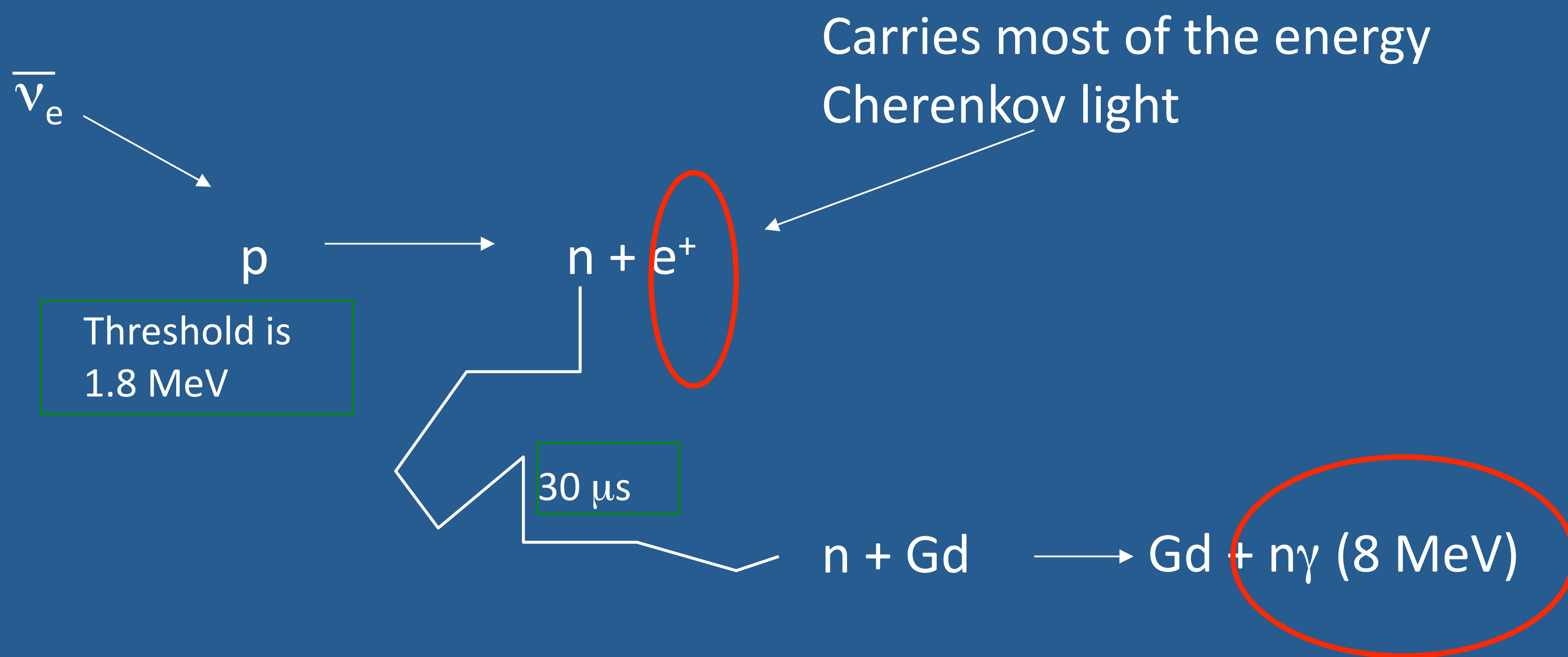
Phys.Rev.Lett.
93 (2004) 171101



- Super-Kamiokande searches for electron anti-neutrinos that are part of the gas of neutrinos from all previous SN explosions
- Probes the star-formation rate
- Most promising signal, inverse beta-decay
- Currently background limited due to atmospheric neutrino interactions

Gd-loaded $\overline{\nu}_e$ detection method

Inverse β^-decay - Delayed Coincidence



Load the water with Gadolinium, search for Cherenkov light from the gamma cascade:

GADZOOKS! See talk by Mark Vagins tomorrow.

Primary Goals: Neutrino Oscillation Studies

See talks by: Parke, Valle, Sakashita, Wildner, Long as well as the rest of the talks in this session

Physics with Accelerators

- Many experiments constitute searches/ measurements of θ_{13} with some sensitivity to the mass hierarchy and δ_{CP}
- The future program is focussed on high precision studies of the oscillation parameters and a determination of the mass hierarchy
- These experiments require high fiducial mass far detectors
- See the talks in this session

Example: Super Beam from Fermilab to DUSEL

Plots to come are from the 2007 U.S. Long-Baseline Neutrino Study:

arXiv:0705.4396

Current Far Detector Mass and Beam Parameters a bit different (See Svoboda talk tomorrow, posters: Bradford, Mauger, Ouedraogo, Soderberg)

Data in 300 kT of Water Cherenkov

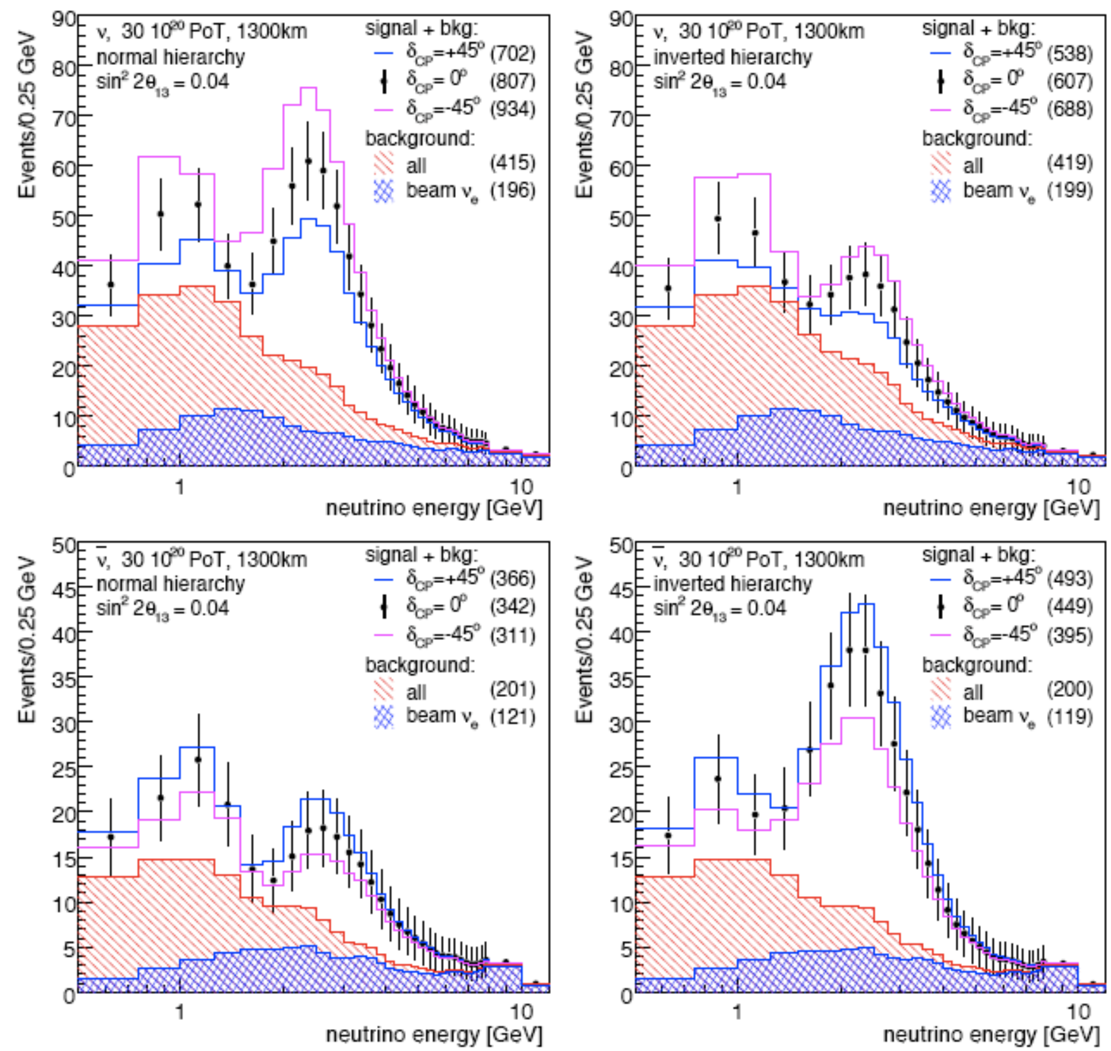
- Intrinsic ν_e – measure in a near detector
- NC background – mostly neutral pion
- Uncertainties on NC backgrounds large – measure in a near detector
- Better resolution of the first maximum
- 90k CC interactions total after oscillations, three years running, 1.2 Mwatts
- 10% uncertainty on background assumed
- Quasi-elastic events only – many charged π's are below Cherenkov threshold

arXiv:0705.4396

Normal hierarchy　　Inverted hierarchy

Neutrino

Antineutrino

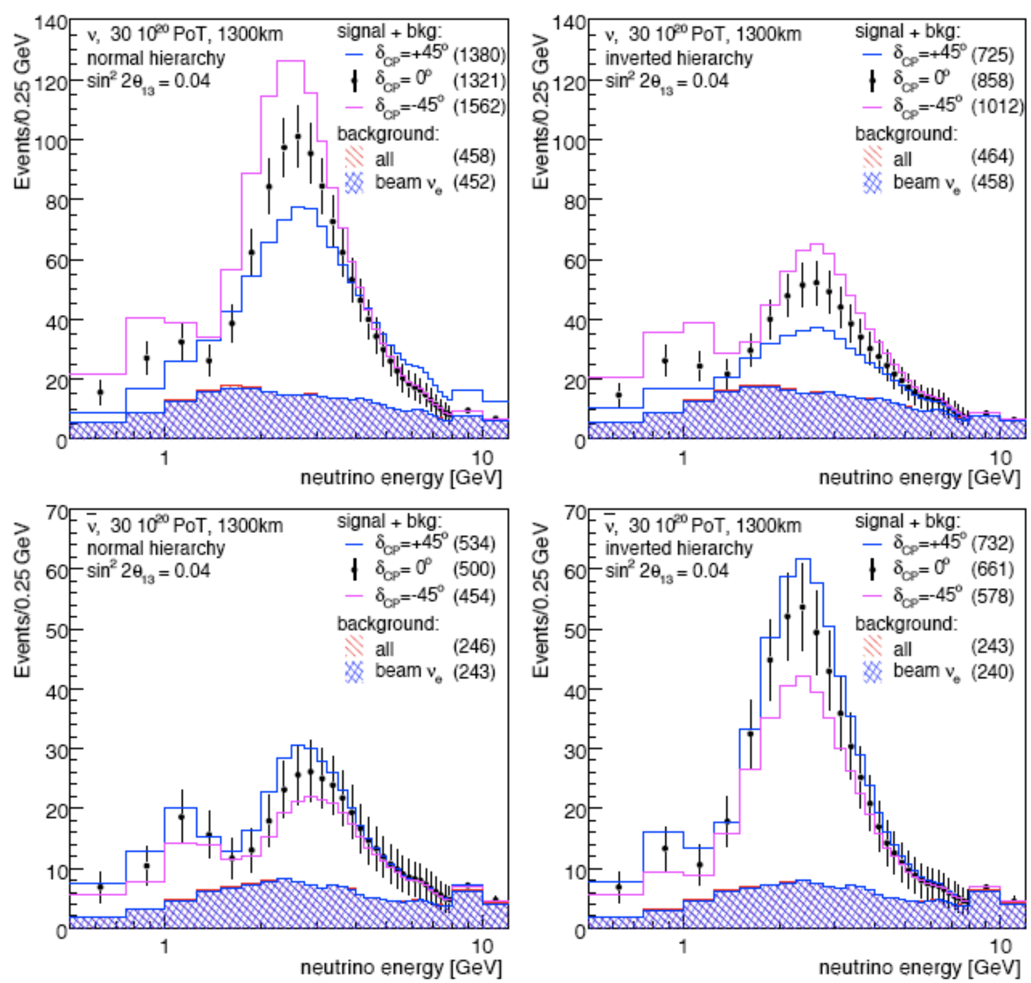


Data in a large LAr TPC

- 100 kT of liquid argon
- 3e21 POT
- background almost entirely intrinsic ν_e
- 30k CC interactions total after oscillations, 3 years running, 1.2 Mwatt
- 10% uncertainty on background assumed
- All CC events used

Normal hierarchy | Inverted hierarchy

Neutrino | Antineutrino

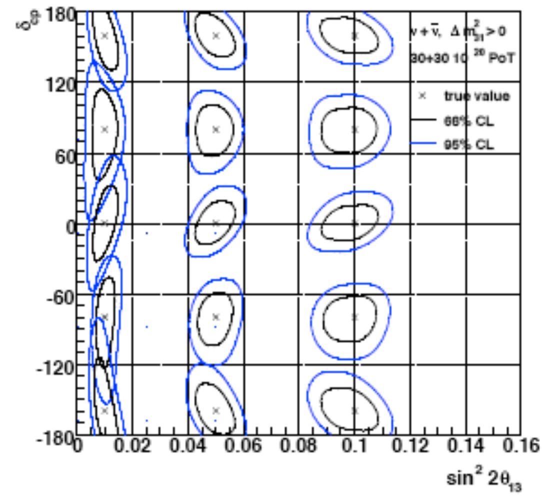


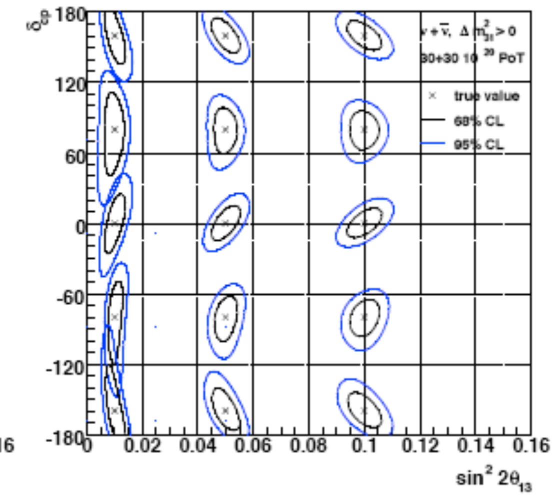
arXiv:0705.4396

Sensitivities (60 x 10^{20} POT)

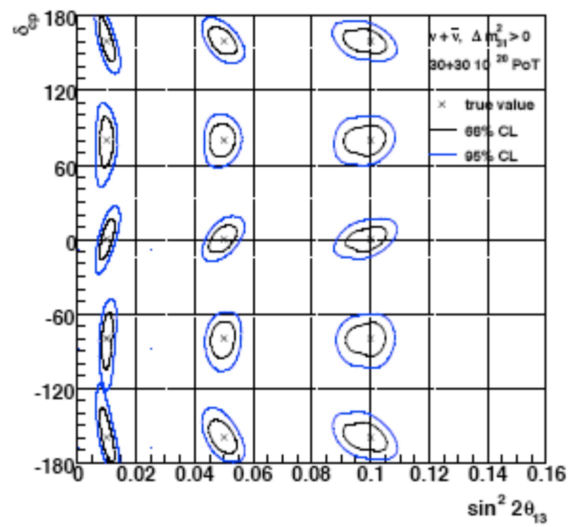
Stat and Systematic (10%)   Statistical Only

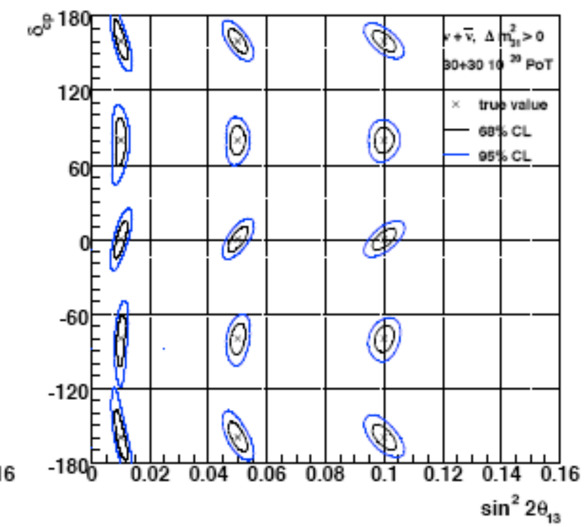
Water
Cherenkov
(300 kT)





Liquid Argon
TPC
(100 kT)



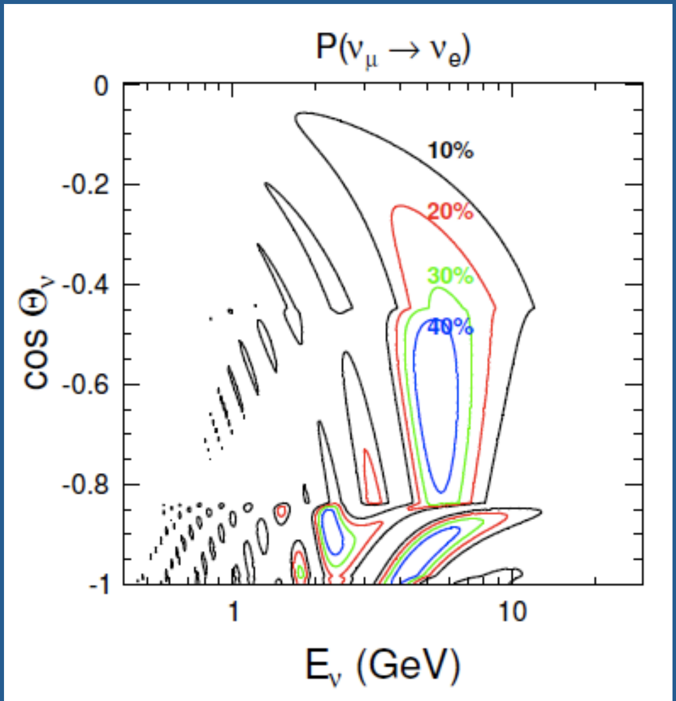


arXiv:0705.4396

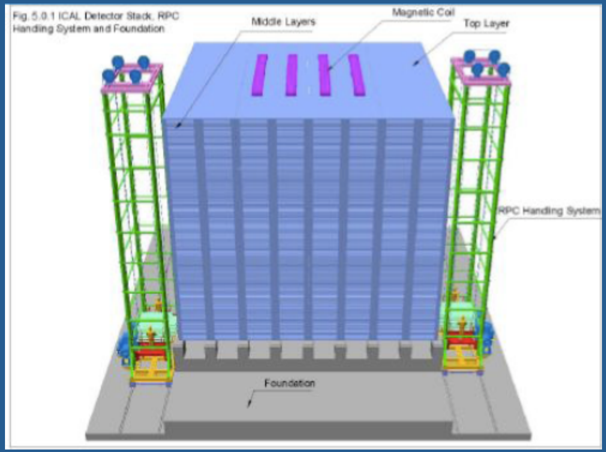
Atmospheric Neutrinos: Largest L/E of any sizable neutrino flux above muon production threshold

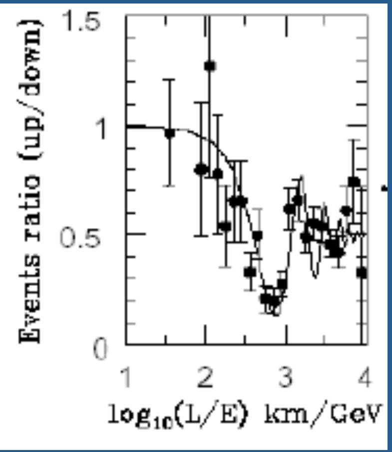
- Larger detectors means higher event rates and higher energy contained events

- Below: INO (India-based Neutrino Observatory)
- Magnetized Steel Plates interspersed with RPCs
- μ^+/μ^- separation
- Mass hierarchy and high precision oscillation parameter measurements (e.g. θ_{23} octant)
- Also a potential far detector for the neutrino factory



- Above: Super-Kamiokande sub-leading effects (arXiv:1002.3471)
- Can explore ν_e appearance – matter effect





N. Mondal

Solar Neutrinos

Vacuum vs. MSW energy regime

Precision measurements of sub-dominant effects/ sterile neutrinos

See talk by Raghavan tomorrow

See Tuesday talks: Klein, Calaprice, Takeuchi

Geoneutrinos

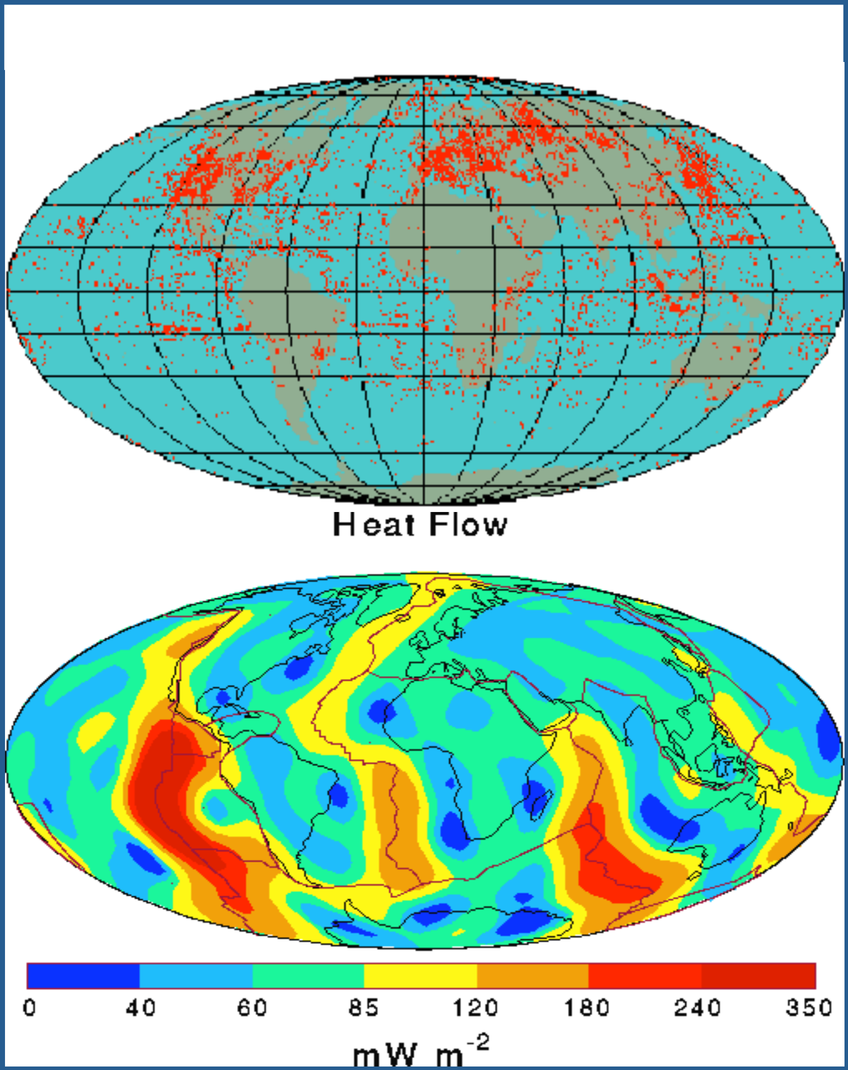
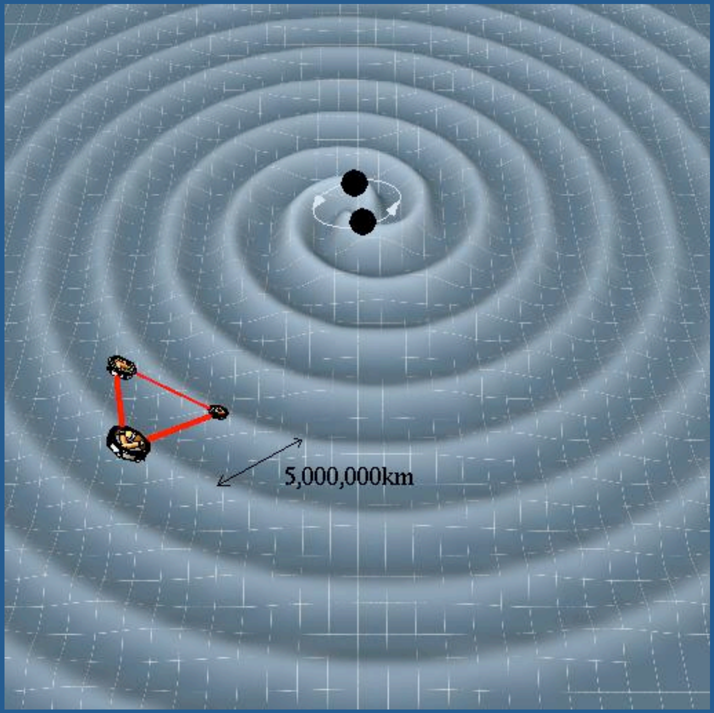


Image: Pollack *et. al*

- Conductive heat flow measured from bore-hole temperature gradient and conductivity
- Total heat flow 44.2±1.0TW or 31±1TW
- Radiogenic heat from U/Th/K decay ~ 19 TW
- Search for geoneutrinos by inverse beta-decay
- Need low energy threshold, low background detector with lots of protons (liquid scintillator)
- See review by Tolich tomorrow

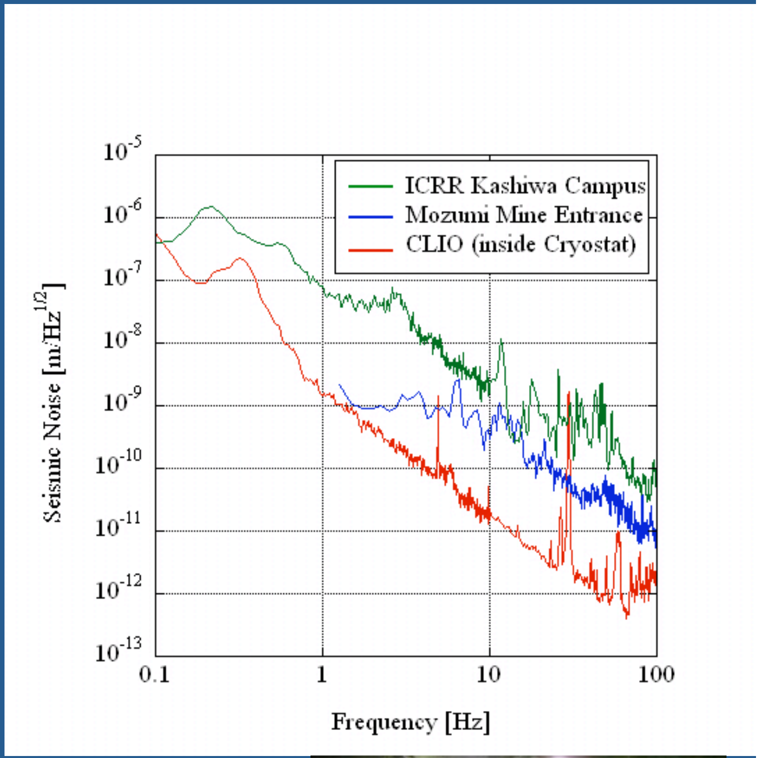
Gravity Waves

- Detecting coalescing binary neutron starts
- Need large reach to see events ``often'' – this means low noise



Gravity Wave: Fabry-Perot Interferometer

- **LCGT**
  - **3km Fabry-Perot Interferometer**
  - **Mirrors: sapphire at 20K**
  - **Sensitivity to 180Mpc for binary coalescence – expect more than one per year!**
  - **Low seismic noise at underground**
  - **➔ Budget request**
- **CLIO (100m proto-type)**
  - **➔ commissioning /running**



- 100m Laser straninmeter (Interferometer): low BG and stable, 10^{-13} in strain resolution

Slide courtesy of Yoichiro Suzuki

Conclusions

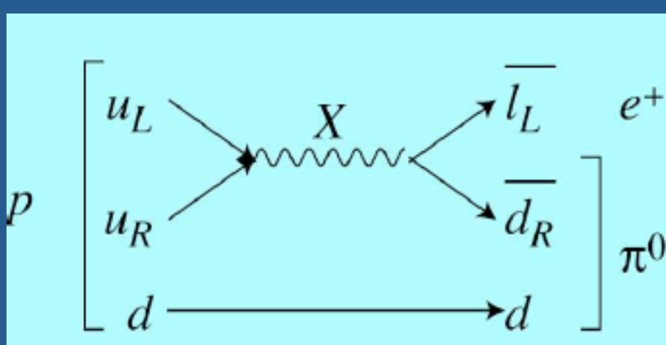
- There is a very rich program of underground physics to be done at the expanding number of facilities worldwide
- Some experiments require (or would like) extreme depth, while others just need to be deep enough
- The future of neutrino physics, nucleon decay and many other exciting topics looks bright
- Thank you very much to the organizers

Backups

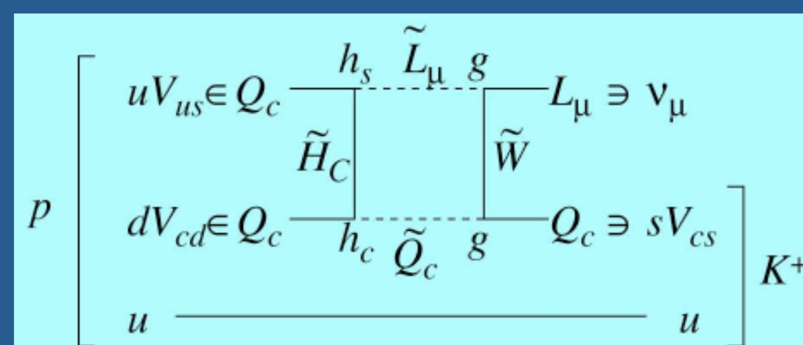
Proton Decay

- In the Standard Model, protons are stable – baryon number is conserved
- Accidental symmetry
- Theories beyond the Standard Model in general predict proton decay:

Grand Unified Theories



SUSY



From H. Murayama, SUSY 05