

# **DUSEL: Particle Physics and Astrophysics Underground**

National Research Council

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Bob Svoboda



# Particle Physics Underground:

## Scientific Context

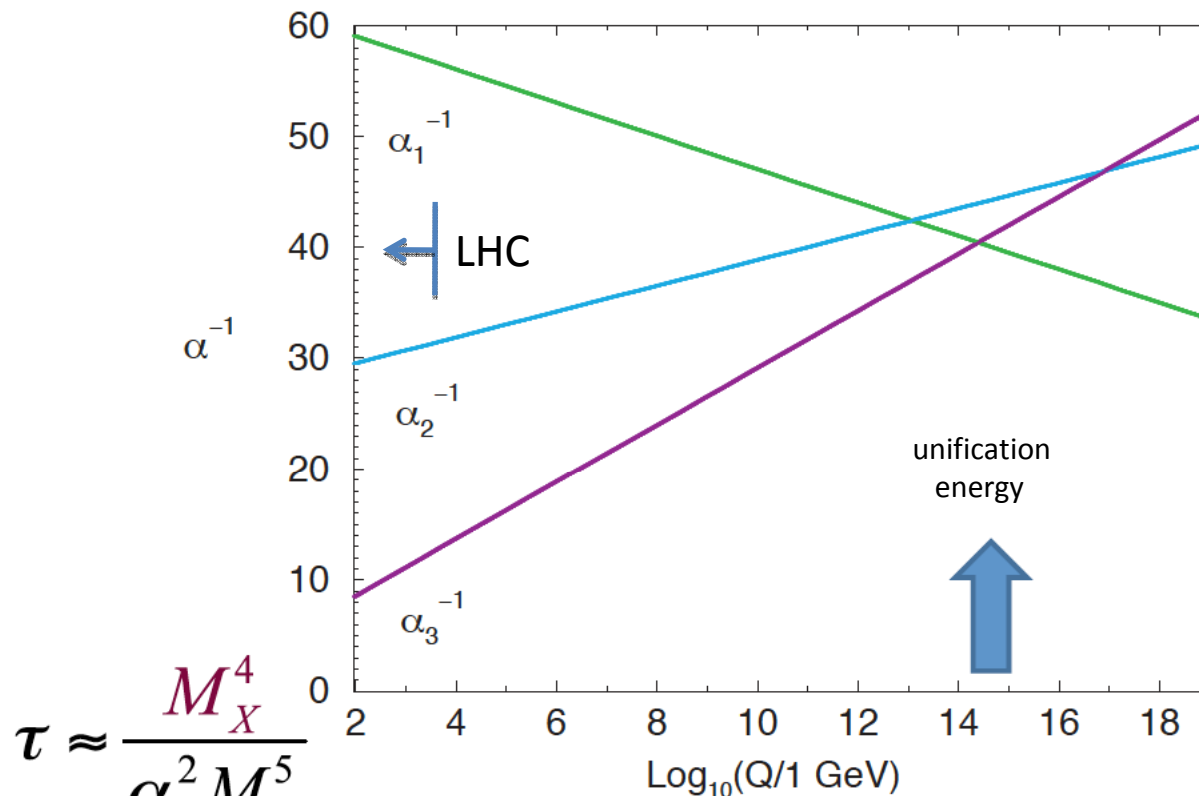
- Neutrinos have been found to be quite **different** than other known forms of matter
- Neutrinos can be used make measurements in astrophysics **not possible with optical or radio observations**
- Unique measurements in **geology** and **cosmology** are now known to be feasible
- There are three active underground labs in Europe, one in Japan, one in Canada, one being built in China – **but none in the United States.**

# The Questions

- Does seeming convergence of coupling constants at high energy imply unification of forces of nature? **Is normal matter stable?**
- **What is the mechanism for stellar collapse?** Can we directly observe the birth of a black hole?
- The flux of diffuse SN neutrinos can be predicted if the stellar formation rate as a function of  $z$  and the collapse mechanism is understood. **Are such neutrinos really there?**
- What is the exact mechanism of neutrino oscillations? What is the ordering of the masses? **What can Cosmic Ray neutrinos tell us?**
- **What fraction of the Earth's heat comes from radioactivity?**
- Are there any more surprises in the flux of neutrinos from the sun's core? **Is the Standard Solar Model correct in detail?**

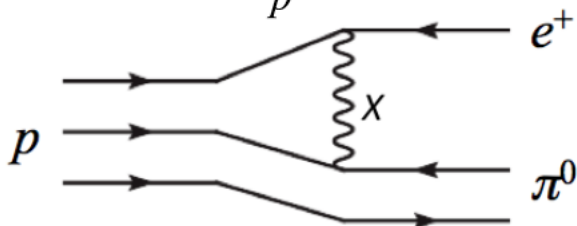
# Proton Decay: Is Normal Matter Stable?

## Gauge Coupling Unification



Three of the four forces of nature are thought to become similar in strength at very high energies – far above any conceivable accelerator

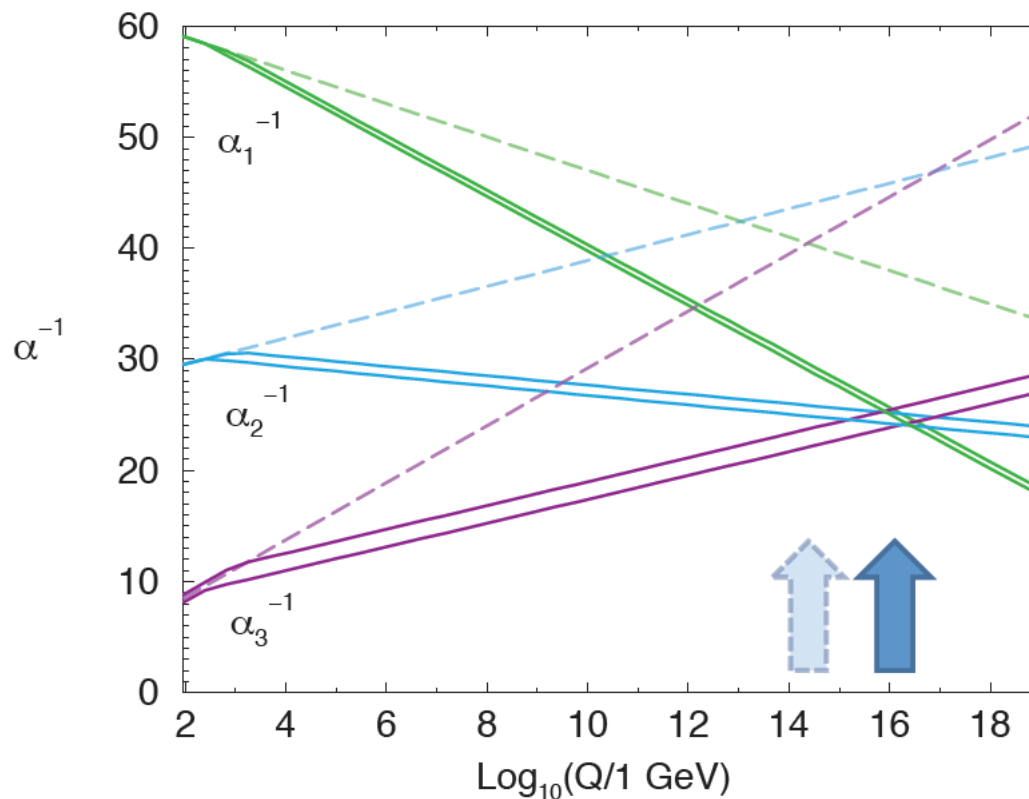
Simple unification theory ruled out by data – proton decay is an effective way to test such theories



$$\tau(e^+\pi^0) = 4.5 \times 10^{29 \pm 1.7} \text{ years (predicted)}$$

$$> 6.6 \times 10^{33} \text{ years (PRL 102 2009)}$$

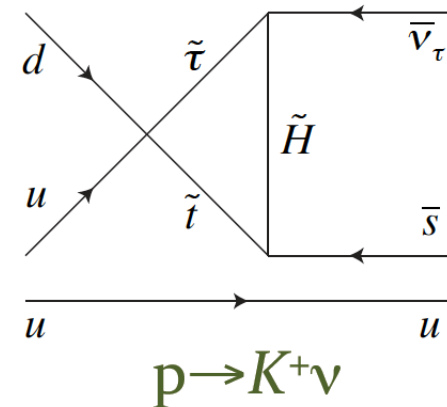
# New theories (e.g. SUSY) can push up unification scale



Unification scale pushed up...

$$\tau(e^+\pi^0) \approx 10^{35-38} \text{ years}$$

...But new decay modes now predicted



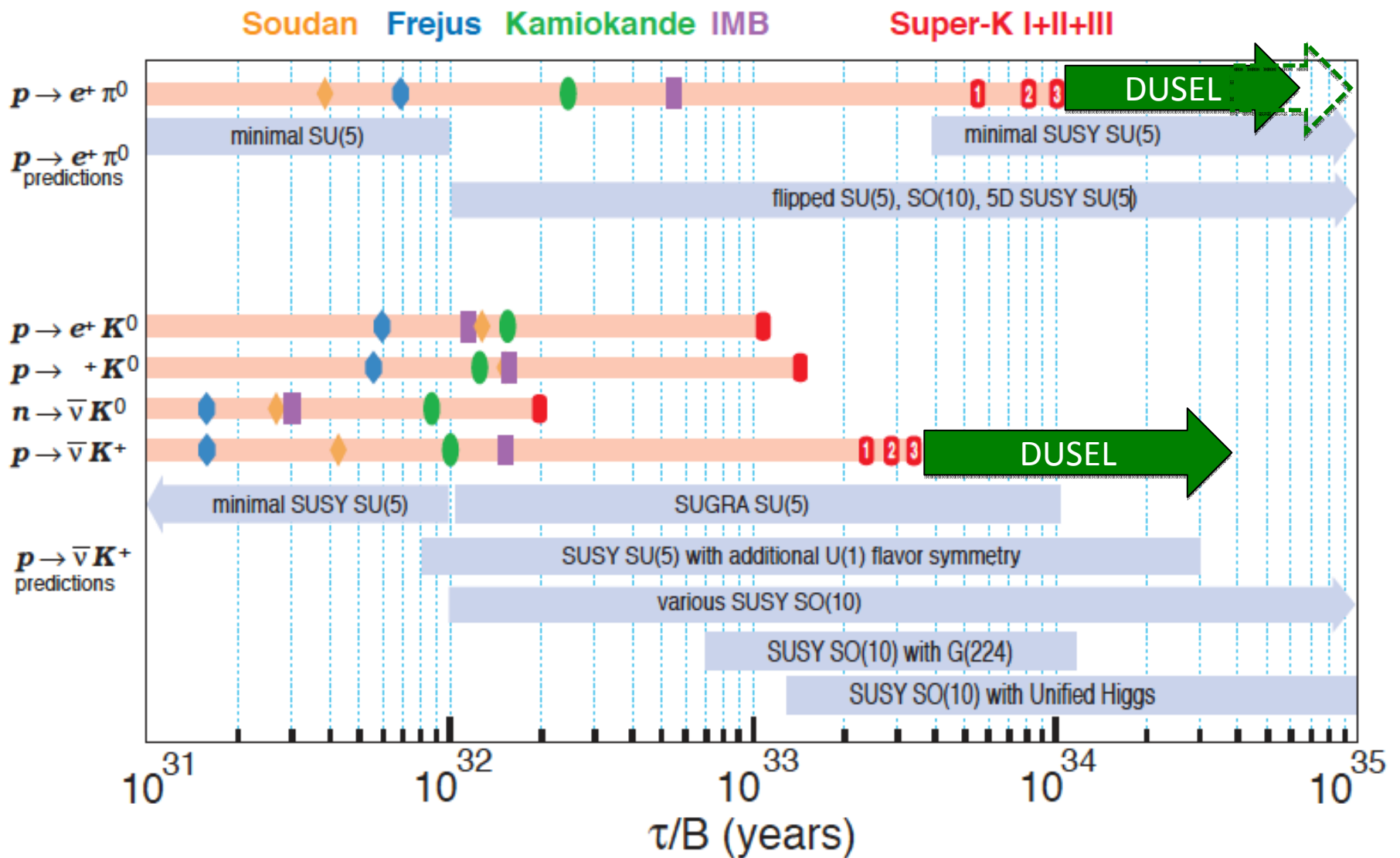
Example of a possible proton decay through supersymmetric particles.

Observation of virtual processes like proton decay is our **only known way** to access physics at these energies

# Existing and Planned Proton Decay Detectors

Detector	Mass (kTons)	Type	Status
Super-Kamiokande	22	Cherenkov	Operational
ICARUS	0.5	Liquid Argon	Operational
LBNE (WC option)	200	Cherenkov	Under Design
LBNE (LAr option)	34	Liquid Argon	Under Design
LENA	50	Liquid Scintillator	Concept
MEMPHYS	400	Cherenkov	Concept
Hyper-Kamiokande	500	Cherenkov	Concept
Glacier	100	Liquid Argon	Concept

\*LBNE is considering both Cherenkov and Liquid Argon detectors.



New experiments are feasible that would extend current reach by an order of magnitude or more. This is a severe test of some Grand Unification models.

# Expected Backgrounds for $p \rightarrow e^+\pi^0$

Calculated:  $2.1 \pm 0.9$  ev/Mton/yr

Measured\*

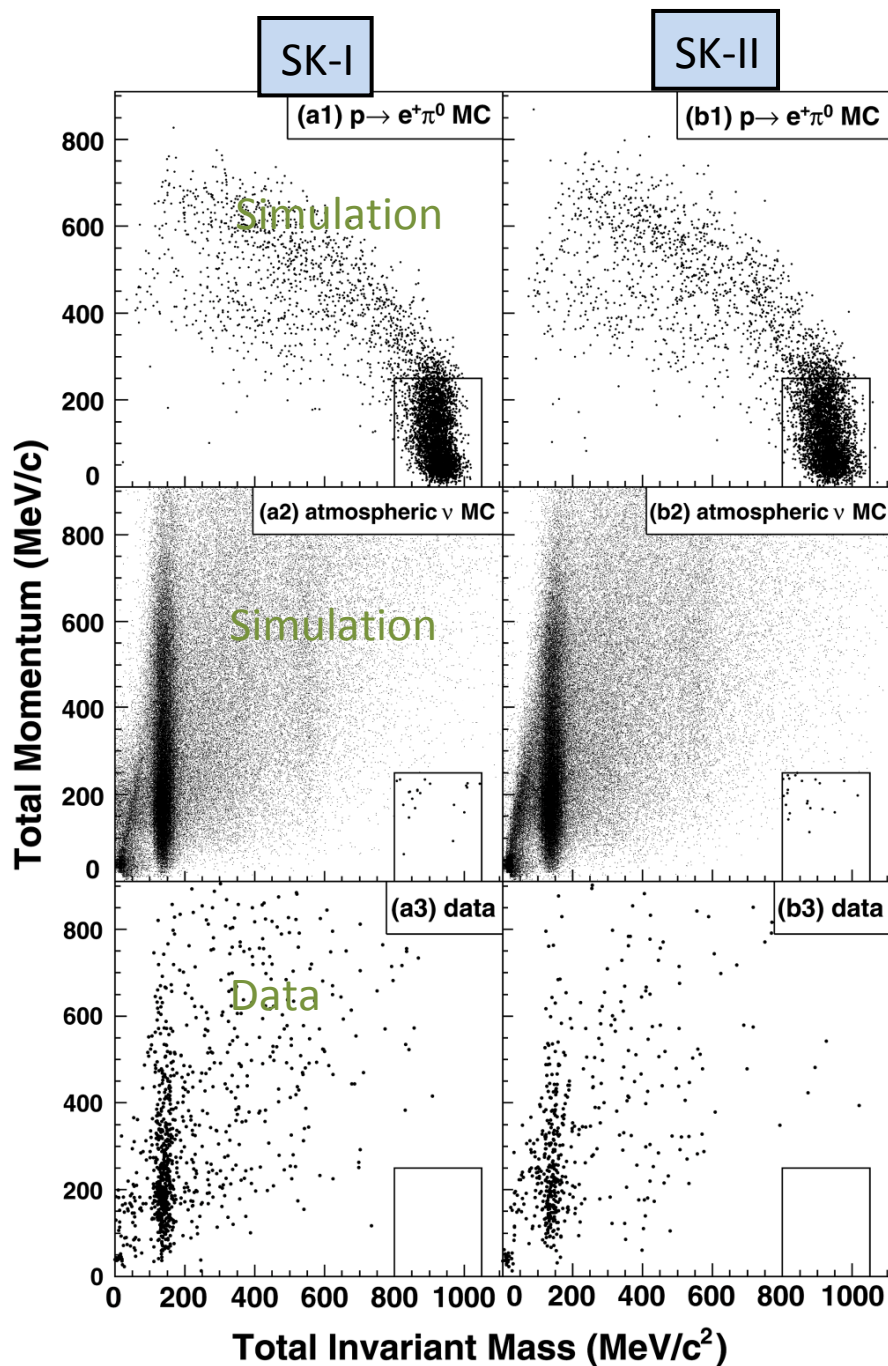
in LE beam:  $1.63 (+0.42/-0.33 \text{ stat}) (+0.45/-0.51 \text{ syst.})$  ev/Mton/yr

- Super-Kamiokande currently has **NO** candidates at 0.141 Mton-yr
- A 0.2 Mton detector would have  $\sim 8$  background events after 20 years.
- **Can this be improved?**

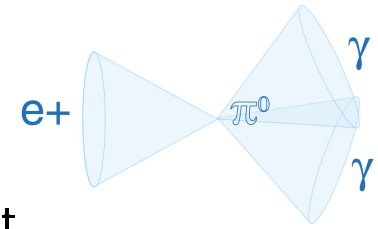
History shows that backgrounds have been systematically reduced without sacrificing efficiency

\*PRL 102:141801 (2009)

	$\varepsilon \times B_{\text{meson}}$	<i>BKG</i> (/Mtonyr)	<i>BG</i> (/yr)
<i>IMB3</i>	0.48	26	0.087
<i>KAM-I</i>	0.53	<15	<0.015
<i>KAM-II</i>	0.45	<8	<0.008
<i>Super-K</i>	0.44	2.1	0.047



The search for proton decay hinges on looking for events with an invariant mass of  $m_p$  and momentum  $< P_{\text{Fermi}}$



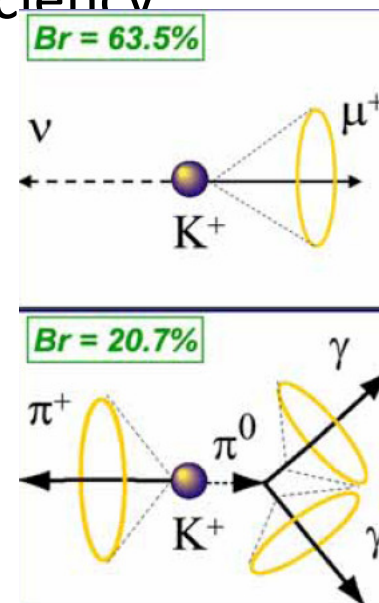
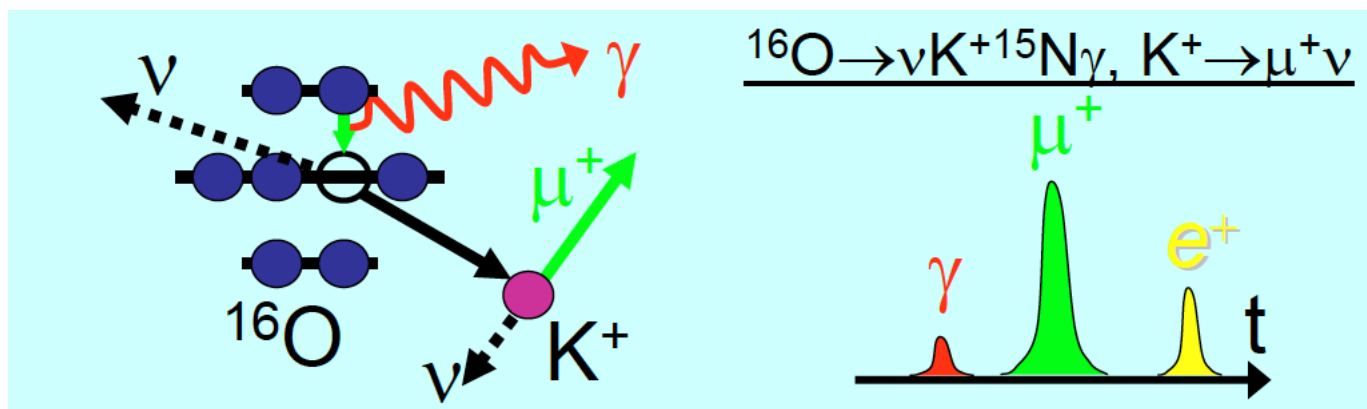
Backgrounds come from atmospheric neutrino interactions—dominated by pion scattering in nucleus and water. Preliminary estimates from Hyper-Kamiokande guess that as much as **80-90%** of this events could be rejected by neutron tagging\*. **This needs to be tested.**

Many BG are accompanied by neutrons		
Background events for $p \rightarrow e^+ \pi^0$ (4.5 Megaton years)		
	$\nu$ interactions	secondary interactions in water
1	$\nu n \rightarrow e p \pi^0$	Neutron production by the proton
2	$\nu p \rightarrow e p \pi^+$	Neutron by $\pi^+$
3	$\nu p \rightarrow e p (\pi^+) \pi^0$	
4	$\nu n \rightarrow \nu p \pi \pi^0$	
5	$\nu n \rightarrow e p$	Neutron by the proton
6	$\nu n \rightarrow e n \pi^+ \pi^-$	
7	$\nu p \rightarrow e p (\pi^+) \pi^0$	
8	$\nu p \rightarrow \nu p p$	
9	$\nu O \rightarrow e O \pi^+$	Neutron by $\pi^+$
10	$\nu n \rightarrow n p$	neutron and $\pi^-$ by the neutron

\* Shiozawa (2009)

$$p \rightarrow \bar{\nu} K^+$$

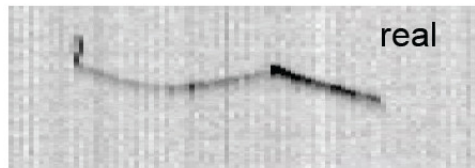
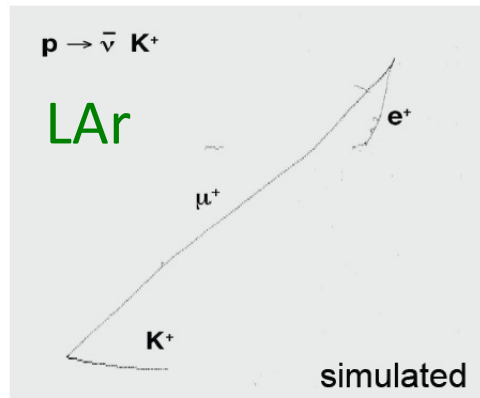
- $K^+$  below Cherenkov threshold is 560 MeV/c. Super-Kamiokande detects  $K^+$  daughters plus nuclear de-excitation tag. A triple coincidence, but low efficiency



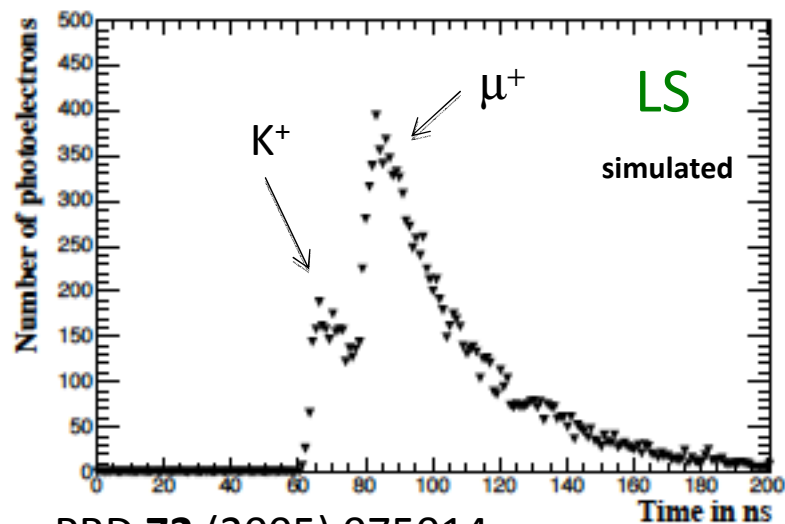
Mode	effxB.R.	Background(/Mton/yr)
$K^+ \rightarrow \mu \nu$	36.0%	2000
$K^+ \rightarrow \mu \nu + \gamma$	7.2%	1.7
$K^+ \rightarrow \pi^+ \pi^0$	6.2%	4.7

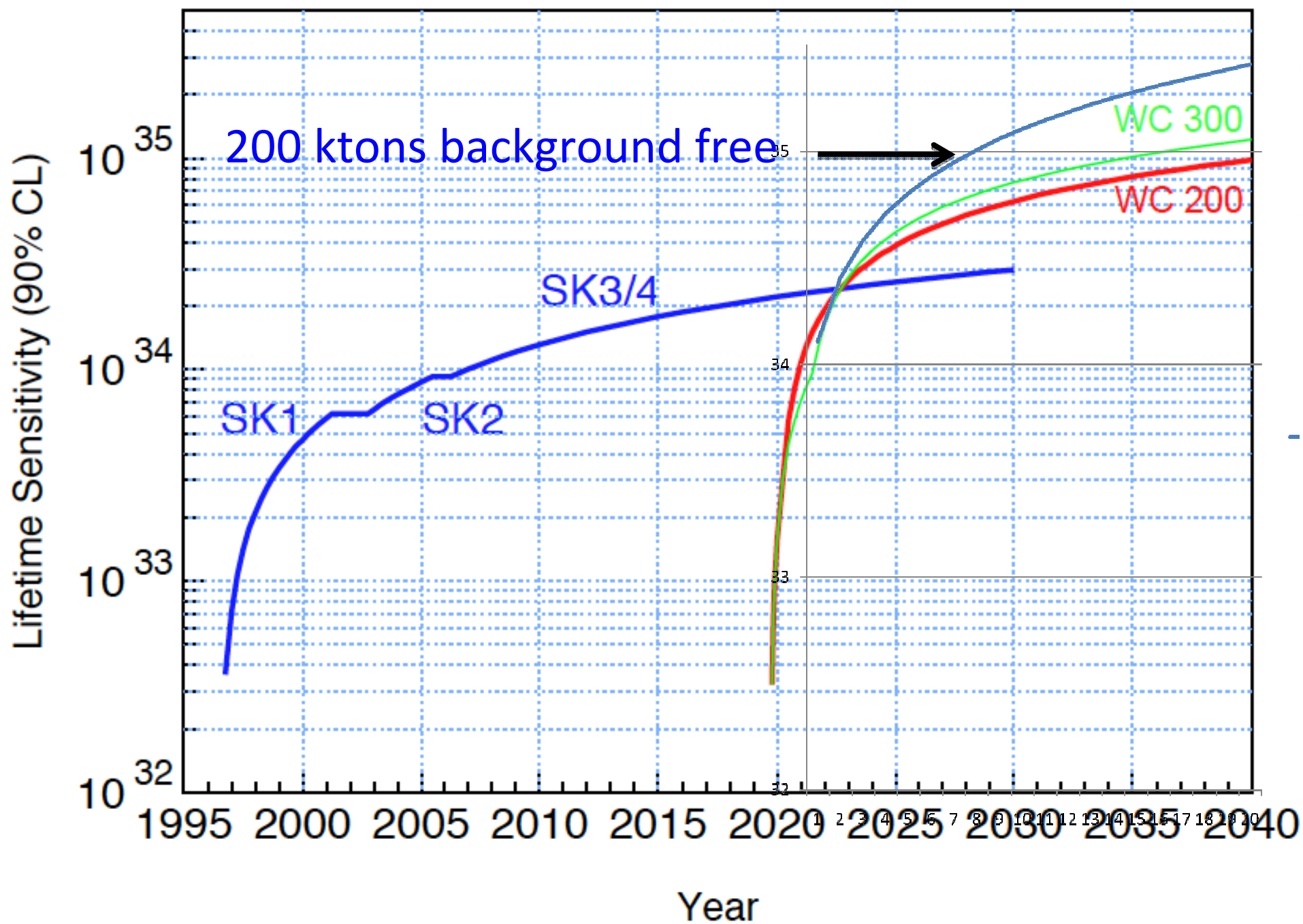
$K^+$  sensitive detectors could improve the situation

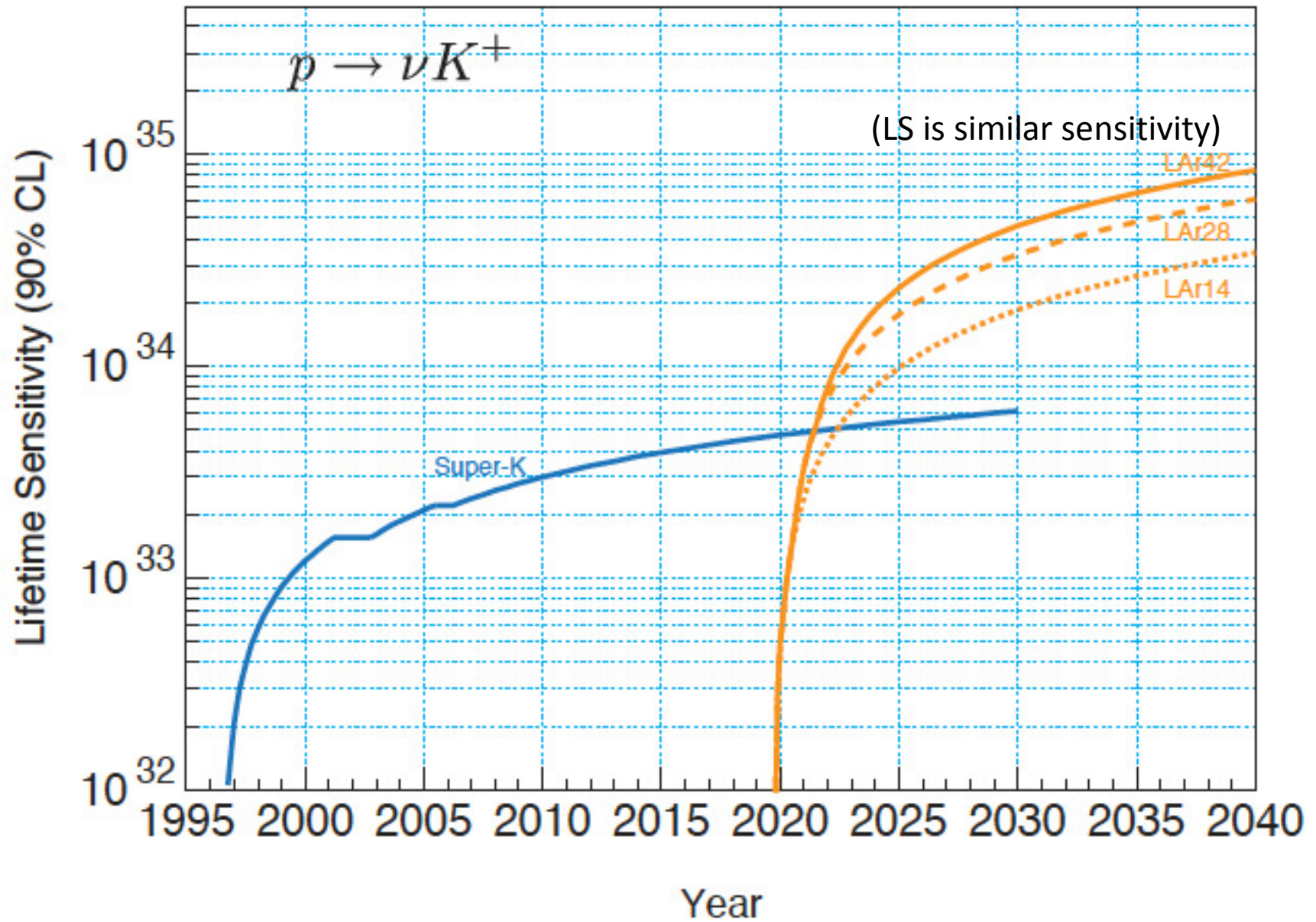
# LAr/LS Development: K<sup>+</sup> Sensitive Detectors



- Potential to identify K<sup>+</sup> with little ambiguity.
- Liquid Argon (LAr) development to scale up mass. (Current largest is ICARUS at 480 tons)
- Need a reliable measurement of backgrounds at depth.
- Liquid Scintillator (LS) technique is being developed in Europe, since it does very well in looking for geo-neutrinos and neutrinos from nuclear reactors.

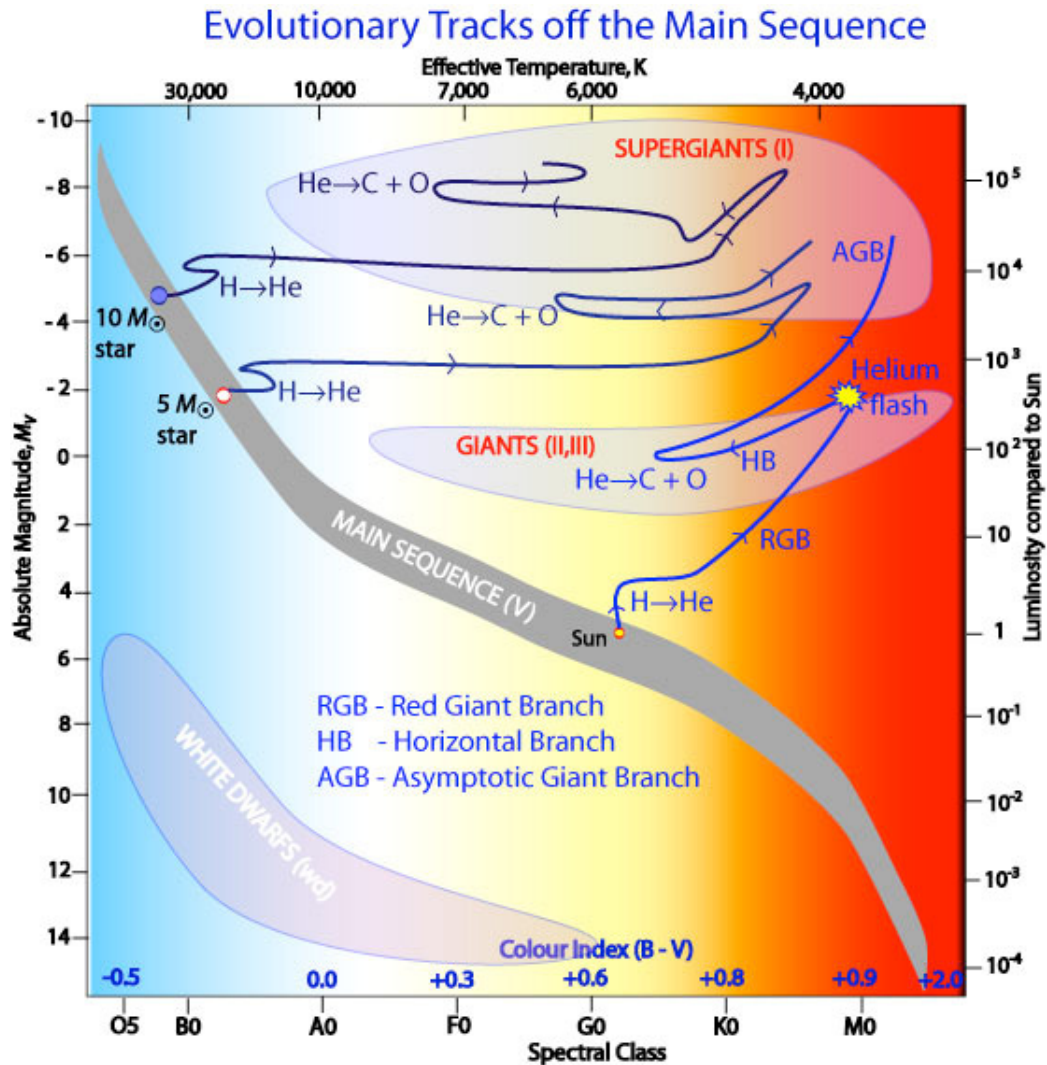






NOTE: LENA would reach  $4 \times 10^{34}$  years after 10 years with 50 ktons

# Supernova Neutrinos: Viewing Stellar Evolution in Real Time

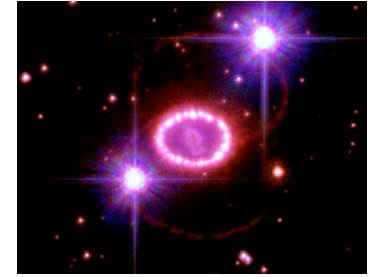


The evolution of massive stars is thought to culminate in a Type II SN explosion, caused by the collapse of an **iron core** when gravity finally overcomes electron degeneracy pressure

Type Ia, on the other hand, should be “neutrinoless”. But are they?



# Type II Supernovae: The Theory

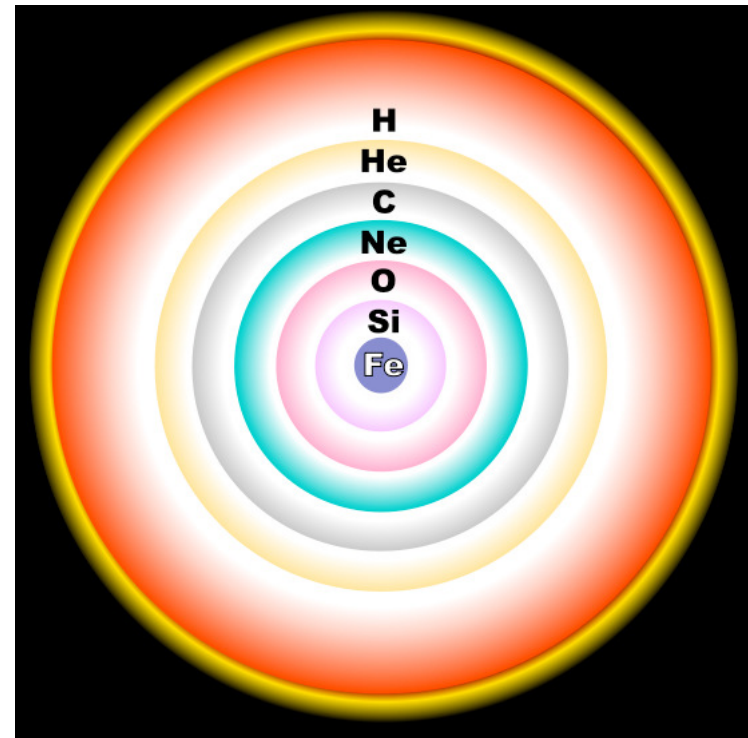
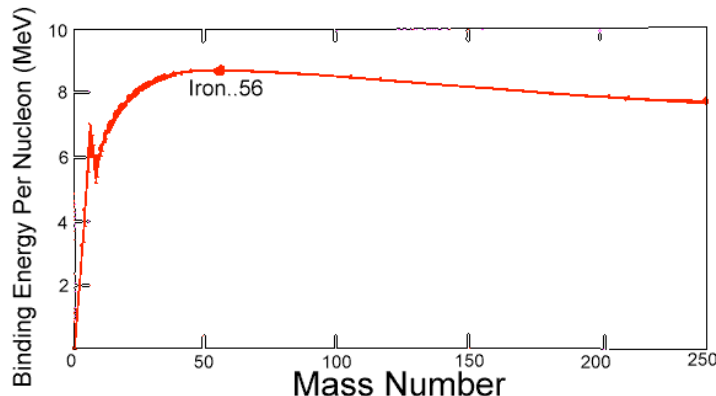


When the core begins to collapse the iron nuclei undergo photo-disintegration, an endothermic process.

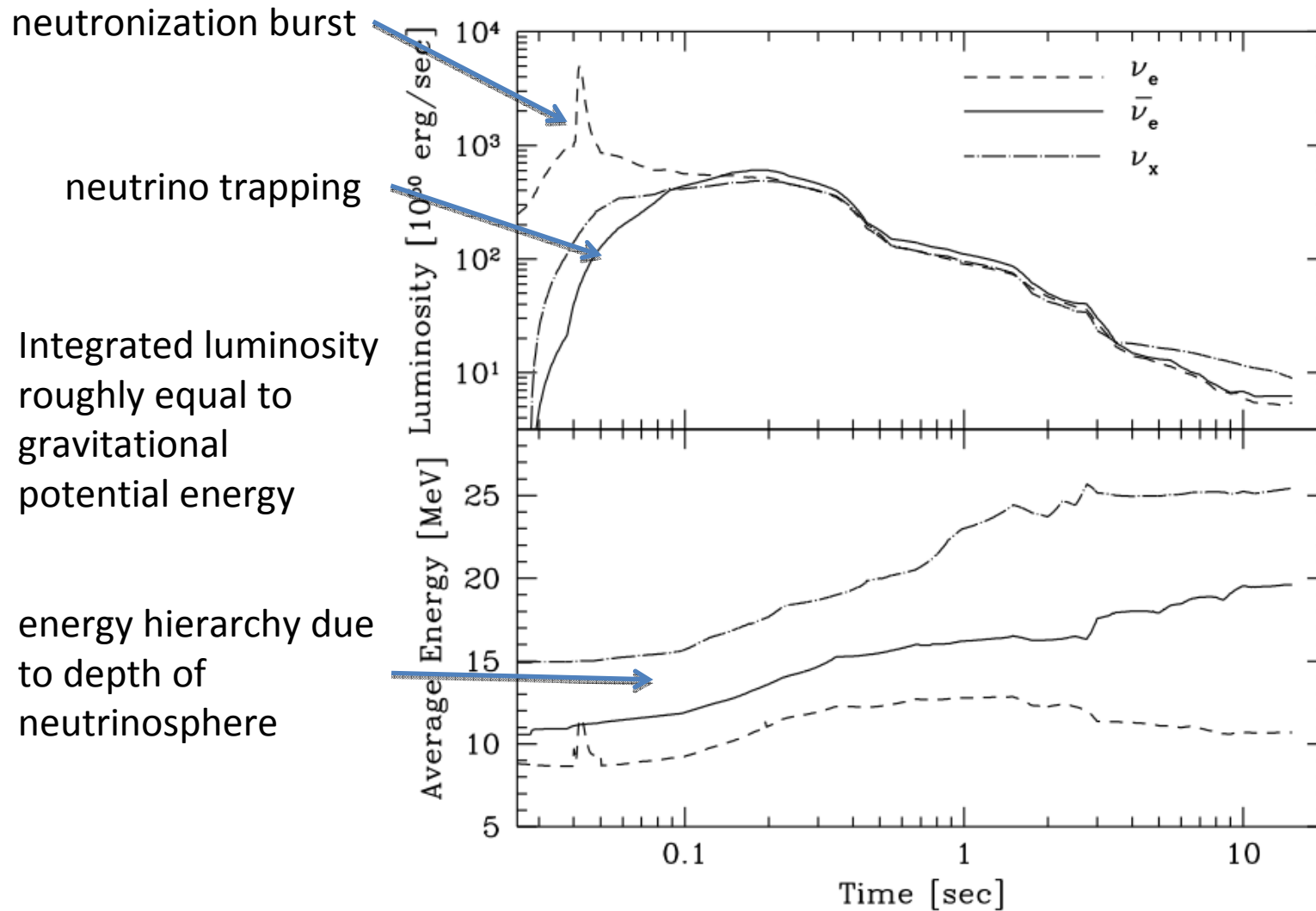
This takes energy from the core accelerating the collapse and eventually leading to  $e^- + p \rightarrow n + \bar{\nu}_e$

Core density reaches nuclear density and beyond, then rebounds to blow off the stellar mantle. Or density could become high enough to form a black hole

Type Ib,c are thought to be “stripped” core collapse events – but no definitive evidence



# Neutrino Emission from a typical SN Model



Livermore Model

# SN Model Differences

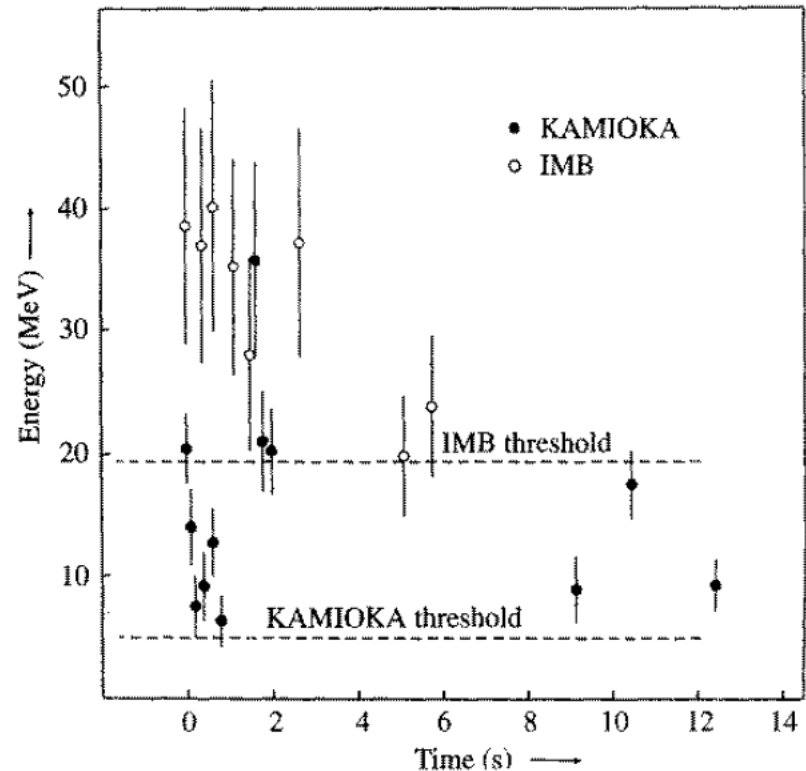
TABLE 7  
FLAVOR-DEPENDENT FLUX CHARACTERISTICS FROM THE LITERATURE

Literature	Time Postbounce (s)	$\langle\epsilon_{\nu_e}\rangle$ (MeV)	$\langle\epsilon_{\bar{\nu}_e}\rangle$ (MeV)	$\langle\epsilon_{\nu_\mu}\rangle$ (MeV)	$\langle\epsilon_\nu\rangle/\langle\epsilon_{\bar{\nu}_e}\rangle$	$L_{\nu_e}$ ( $\times 10^{51}$ ergs s $^{-1}$ )	$L_{\bar{\nu}_e}$ ( $\times 10^{51}$ ergs s $^{-1}$ )	$L_{\nu_\mu}$ ( $\times 10^{51}$ ergs s $^{-1}$ )
Mayle et al. (1987).....	1.0	12	24	22	0.50 : 1 : 0.92	20	20	20
Totani et al. (1998).....	0.3	12	15	19	0.80 : 1 : 1.26	20	20	20
	10	11	20	25	0.55 : 1 : 1.25	0.5	0.5	1
Bruenn (1987) .....	0.5	10	12	25	0.83 : 1 : 2.08	3	5	16
Myra & Burrows (1990) .....	0.13	11	13	24	0.85 : 1 : 1.85	30	30	16
Janka & Hillebrandt (1989b).....	0.3	8	14	16	0.57 : 1 : 1.14	30	220	65
Suzuki (1990) .....	1	9.5	13	15	0.73 : 1 : 1.15	4	4	3
	20	8	10	9	0.80 : 1 : 0.90	0.3	0.3	0.07
Suzuki (1991) .....	1	9.5	13	15	0.73 : 1 : 1.15	3	3	3
	15	8	9	9.5	0.89 : 1 : 1.06	0.4	0.4	0.3
Suzuki (1993) .....	1	9	12	13	0.75 : 1 : 1.08	3	3	3
	15	7	8	8	0.88 : 1 : 1.00	0.3	0.3	0.3
Accretion phase model I (original) .....	0.32	13	15	18	0.86 : 1 : 1.20	31	29	14
Accretion phase model I (our run).....	0.32	12	14	14	0.84 : 1 : 1.02	32	32	18
Accretion phase model II (original).....	0.15	13	16	17	0.82 : 1 : 1.09	66	68	32
Accretion phase model II (our run) .....	0.15	13	15	16	0.84 : 1 : 1.02	74	74	28
R. Buras et al. (2003, private communication) .....	0.25	14.1	16.5	16.8	0.85 : 1 : 1.02	43	44	32
Mezzacappa et al. (2001) <sup>a</sup> .....	0.5	16	19	24	0.84 : 1 : 1.26	25	25	8
Liebendörfer et al. (2001) <sup>a</sup> .....	0.5	19	21	24	0.90 : 1 : 1.14	30	30	10

<sup>a</sup> These lines show  $\langle\epsilon\rangle_{\text{rms}}$  instead of  $\langle\epsilon\rangle$ .

# Observables from SN Neutrinos

- Temperature
  - $\nu_e, \bar{\nu}_e, \nu_x$  neutrino spheres
- Spectral shape
  - Modified by  $\nu N$  interactions
- Luminosity
- Time information
  - Delayed blast
  - Collapse to black hole



IMB and Kamioka observations are insufficient to distinguish between models.

# Large detectors (100 ktons) can discriminate between core collapse models

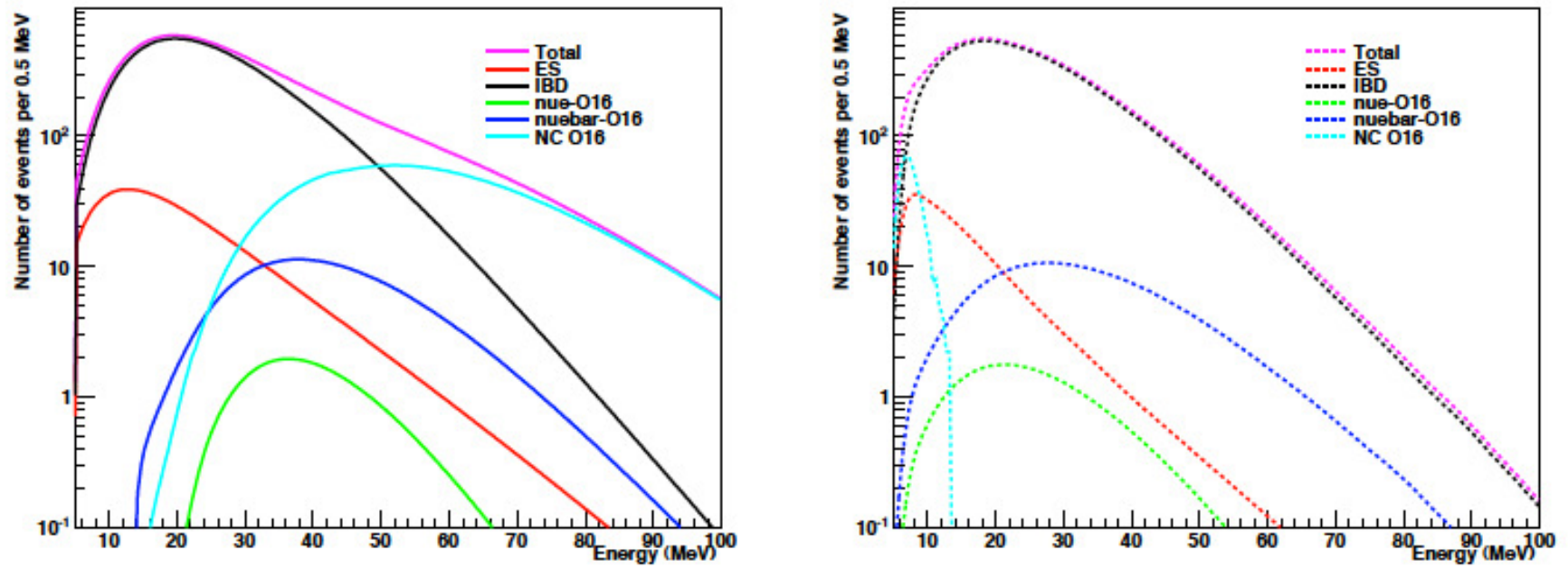







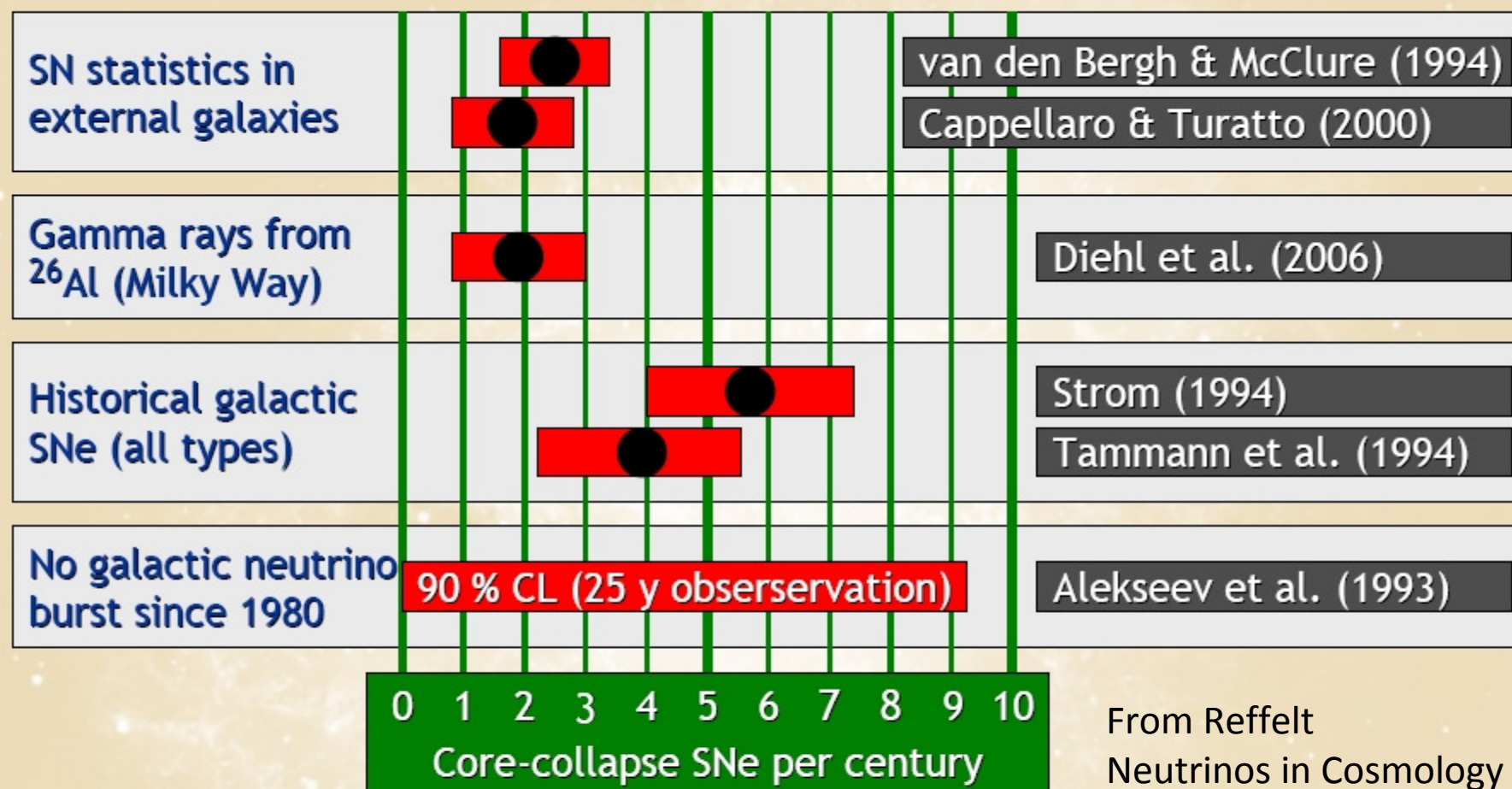
FIG. 41. Event rates in water, for the Livermore model and 30% coverage (events per 0.5 MeV).

	Channel	Events, "Livermore" model	Events, "Kneller" model
	$\bar{\nu}_e + p \rightarrow e^+ + n$	27116	16210
	$\nu_x + e^- \rightarrow \nu_x + e^-$	868	534
	$\nu_e + {}^{16}\text{O} \rightarrow e^- + {}^{16}\text{F}$	88	378
	$\bar{\nu}_e + {}^{16}\text{O} \rightarrow e^+ + {}^{16}\text{N}$	700	490
	$\nu_x + {}^{16}\text{O} \rightarrow \nu_x + {}^{16}\text{O}^*$	513	124
	Total	29284	17738

# SN Detector Characteristics

Water Chernkov	Liquid Scintillator	Liquid Argon
<p><math>\nu_e p \rightarrow n e^+</math></p> <ul style="list-style-type: none"> <li>– Direct information on <math>E_\nu</math></li> <li>– 1.8 MeV threshold</li> </ul> <ul style="list-style-type: none"> <li>• Directional information from <math>\nu_e e^- \rightarrow \nu_e e^-</math></li> <li>• Well-developed technology</li> <li>• Potential for neutron tagging</li> <li>• Fewer non- <math>\nu_e</math> events</li> </ul>	<ul style="list-style-type: none"> <li>• <math>\bar{\nu}_e p \rightarrow n e^+</math> <ul style="list-style-type: none"> <li>– Direct information on <math>E_\nu</math></li> <li>– 1.8 MeV threshold</li> </ul> </li> <li>• Well-developed technology</li> <li>• Neutron tagging</li> <li>• Good NC sensitivity</li> <li>• Fewer non- <math>\nu_e</math> events</li> </ul>	<ul style="list-style-type: none"> <li>• Potential <math>\nu_e</math> sensitivity via <math>^{40}\text{Ar}(\nu_e, p)^{40}\text{K}</math> <ul style="list-style-type: none"> <li>– 1.5 MeV threshold</li> </ul> </li> <li>• Less well-developed technology</li> <li>• No neutron tagging</li> <li>• Potential for NC sensitivity if nuclear-</li> <li>• Many non- <math>\nu_e</math> events</li> </ul>

# Core-Collapse SN Rate in the Milky Way



From Reffelt  
Neutrinos in Cosmology  
2009, Erice, Sicily

References: van den Bergh & McClure, ApJ 425 (1994) 205. Cappellaro & Turatto, astro-ph/0012455. Diehl et al., Nature 439 (2006) 45. Strom, Astron. Astrophys. 288 (1994) L1. Tammann et al., ApJ 92 (1994) 487. Alekseev et al., JETP 77 (1993) 339 and my update.

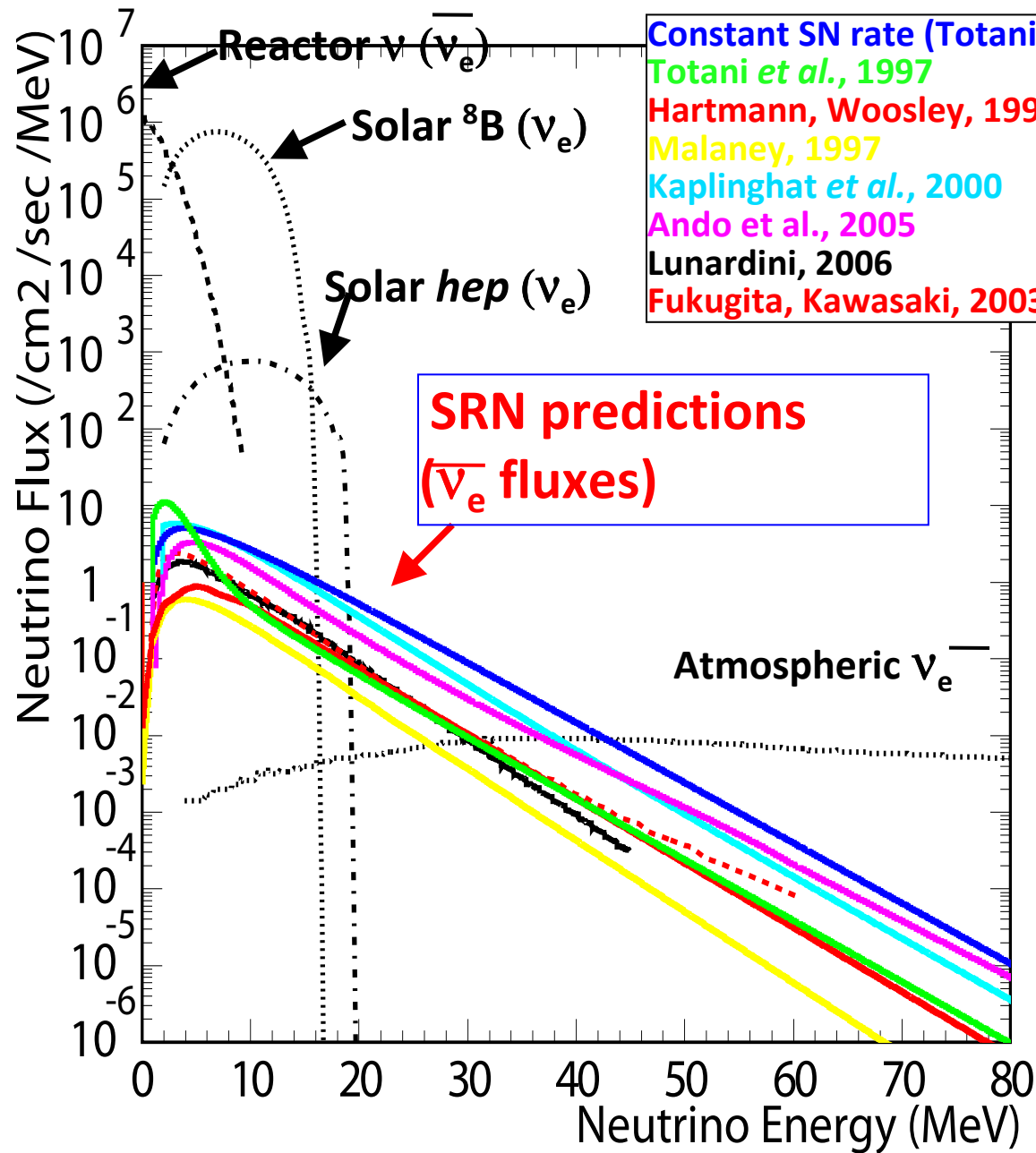
# Supernova Burst Detectors

Detector	Location	Target	Mass (ktons)	Events@8.5 kpc	Status
Baksan	Russia	LS	0.33	50	Operational
LVD	Italy	LS	1	300	Operational
Super-Kamiokande	Japan	WC	32	8000	Operational
ICARUS	Italy	LAr	0.5	200	Operational
KamLAND	Japan	LS	1	300	Operational
HALO	Canada	Pb	0.07	80	Operational
SNO+	Canada	LS	0.8	300	Under Construction
LBNE WC	USA	WC	200	78000	Under Design
LBNE LAr	USA	LAr	34	10000	Under Design
MEMPHYS	Europe	WC	400	160000	Concept
Hyper-K	Japan	WC	500	130000	Concept
GLACIER	Europe	LAr	100	29000	Concept
LENA	Europe	LS	50	15000	Concept

\*The U.S. has only some near-surface HEP detectors and ICE CUBE (which sees only an increase in PMT noise rate) - less capable now than in 1987.

# Detecting SN at Cosmological Distances

- Understanding supernovae is central to understanding many aspects of the present physical universe.
- The shape of the SRN spectrum will provide a test of the uniformity of neutrino emissions in core-collapse supernovae, determining both the total and average neutrino energy emitted.
- Was SN1987A a “normal” explosion or not?
- How common are optically dark SN?



Constant SN rate (Totani *et al.*, 1996)

Totani *et al.*, 1997

Hartmann, Woosley, 1997

Malaney, 1997

Kaplinghat *et al.*, 2000

Ando *et al.*, 2005

Lunardini, 2006

Fukugita, Kawasaki, 2003(dashed)

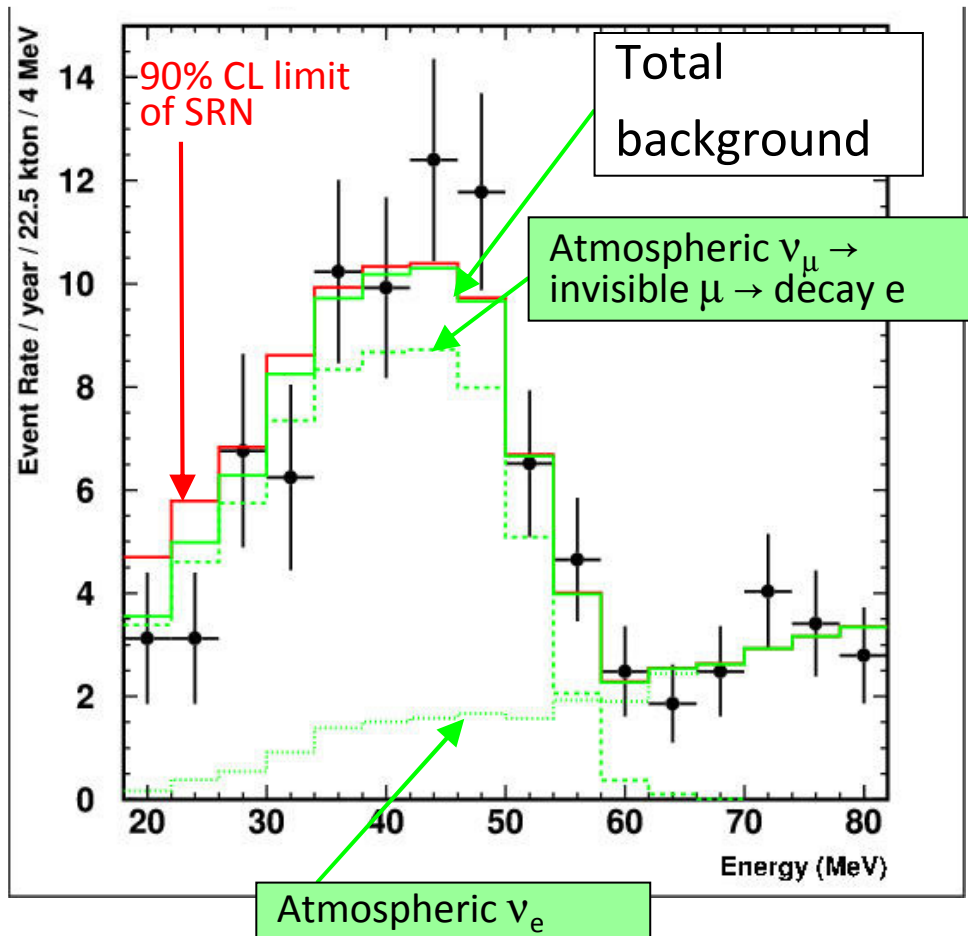
Differences due to core collapse models and assumed SN rate and luminosity

Large WC detector or LS detectors are best.

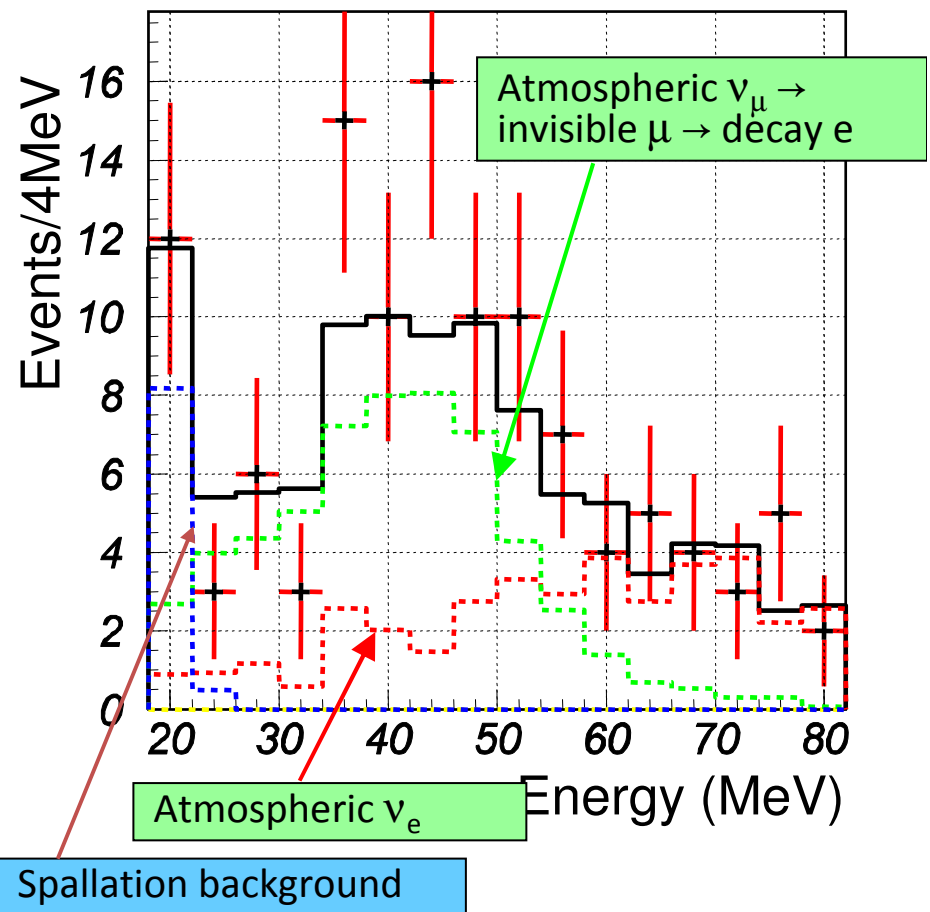
HEP solar neutrinos limits LAr sensitivity ( $\nu_e$ ) – plus need for large size.

# SRN results of SK-I and SK-II

SK-I (1496days)

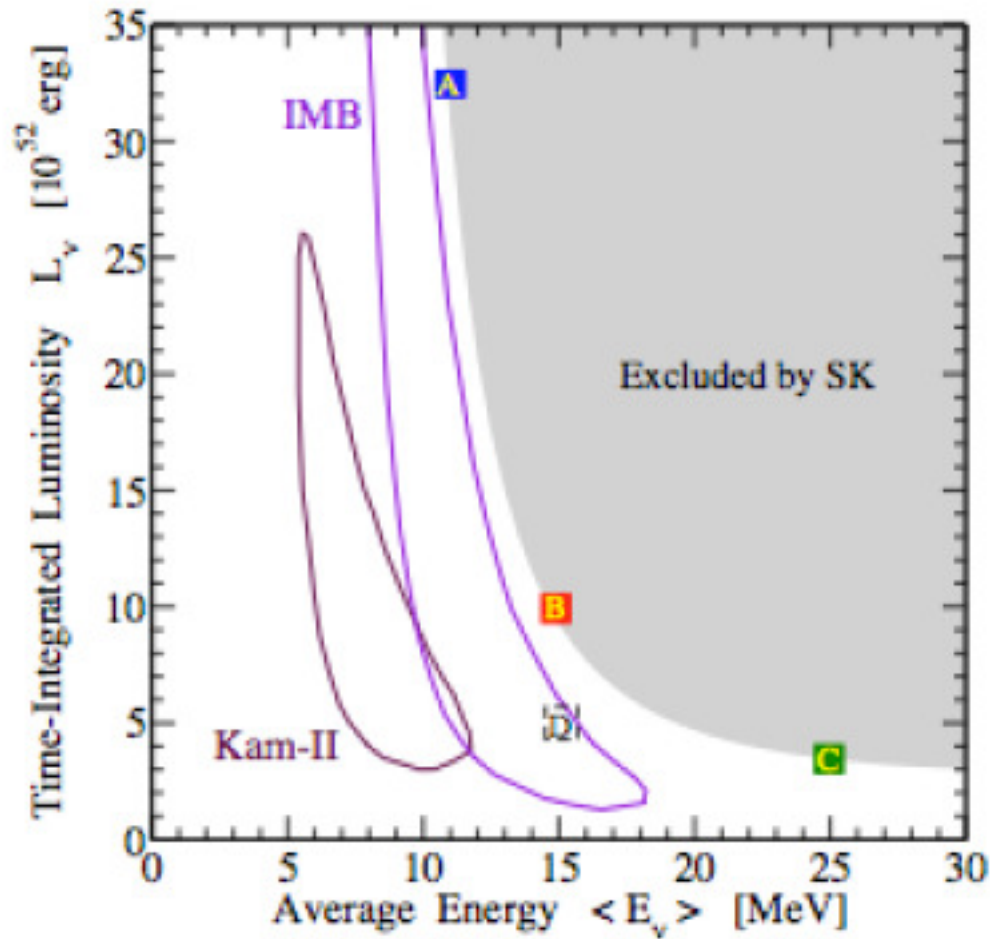


SK-II (791 days)



Observed spectra are consistent with estimated backgrounds.  
Searches are limited by the invisible muon background (SK-I)  
and the spallation background (SK-II)..

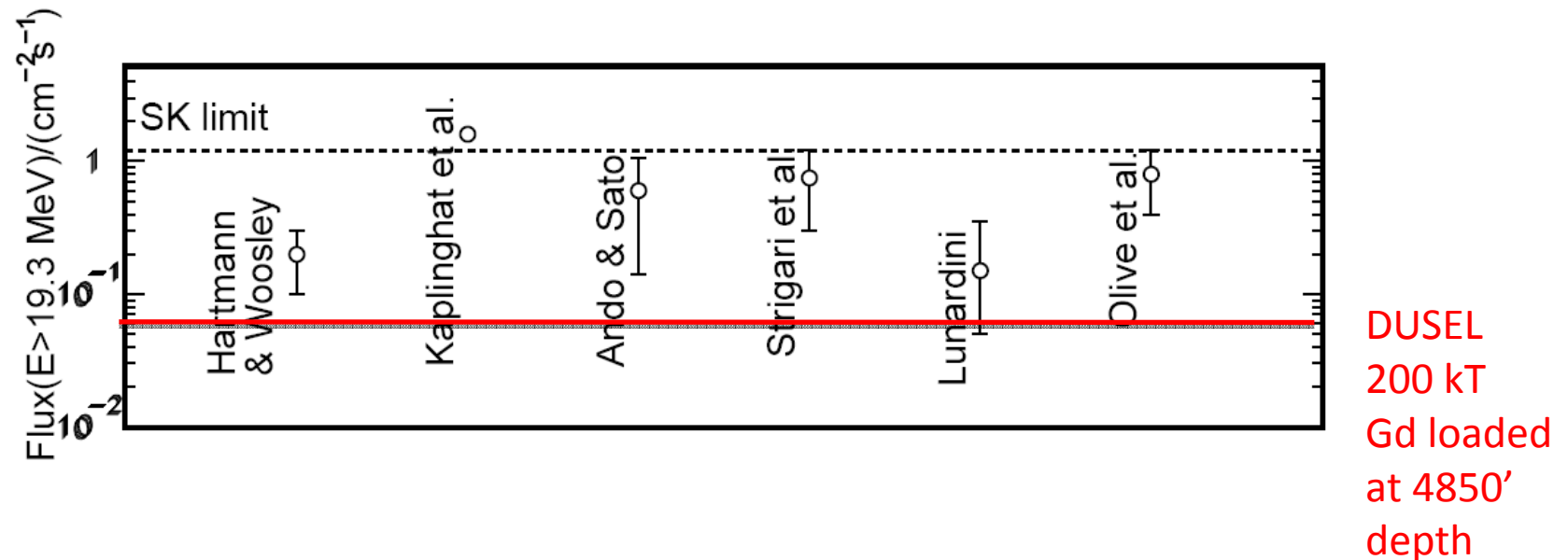
# Total luminosity and average energy results



Improving on SK sensitivity  
will allow testing “average”  
SN versus SN1987A

A factor of ten improvement  
in sensitivity would allow  
a better comparison

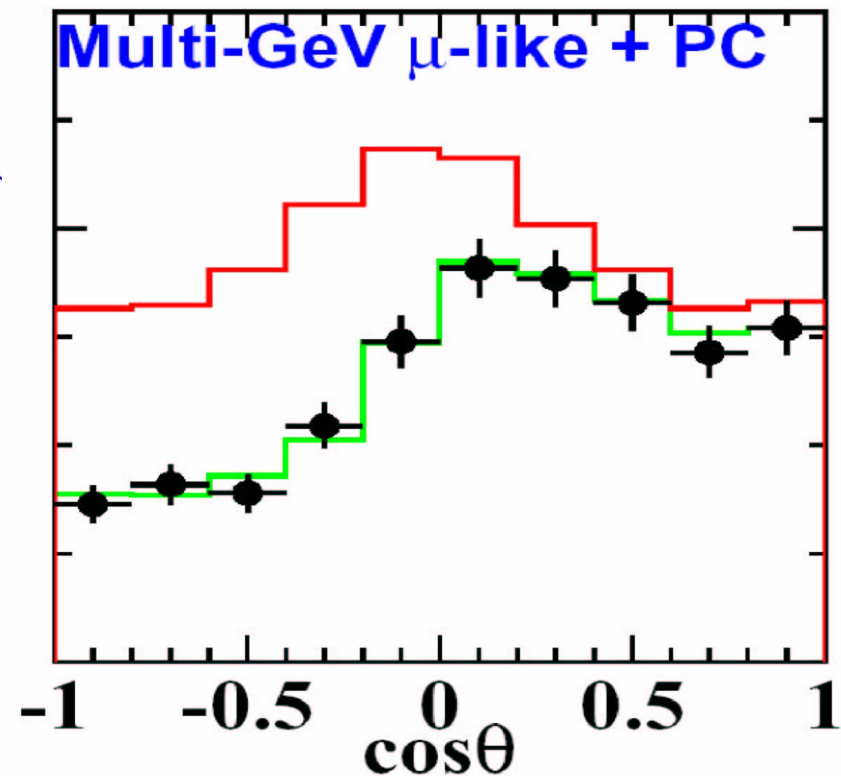
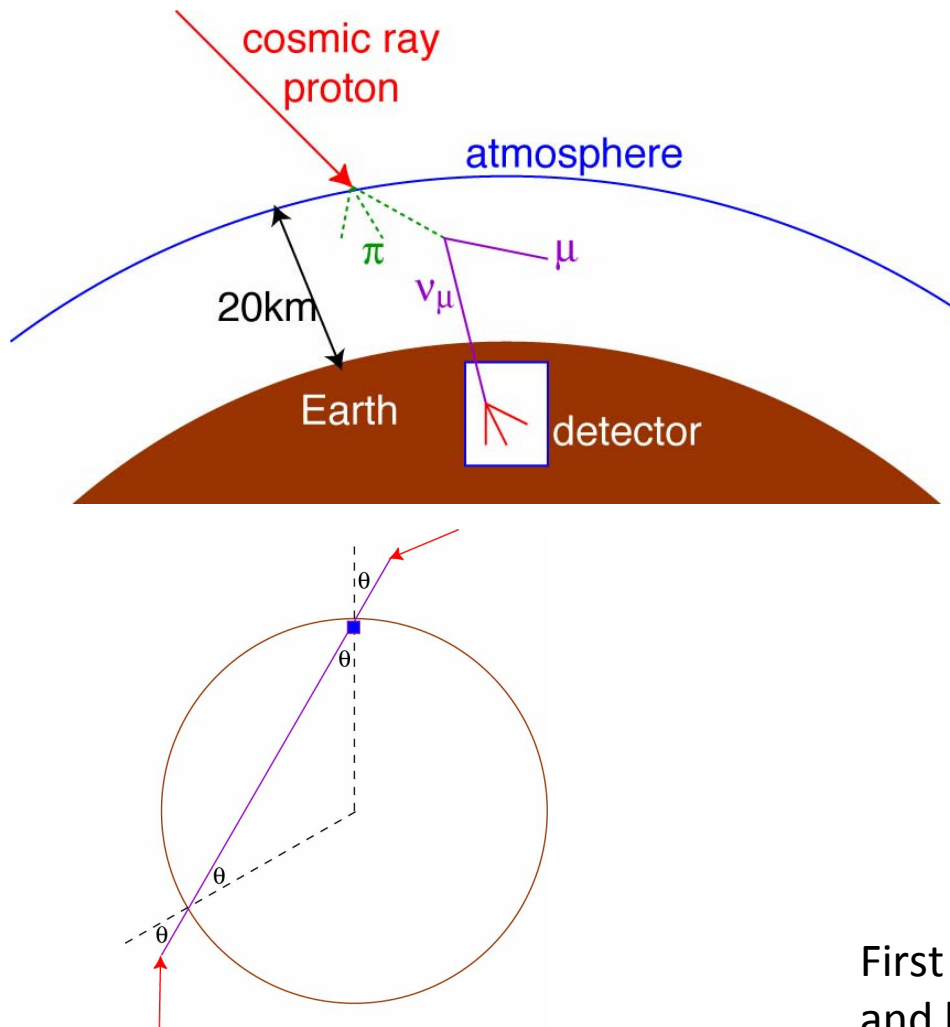
Added depth at DUSEL and large detector mass  
would makes detection possible



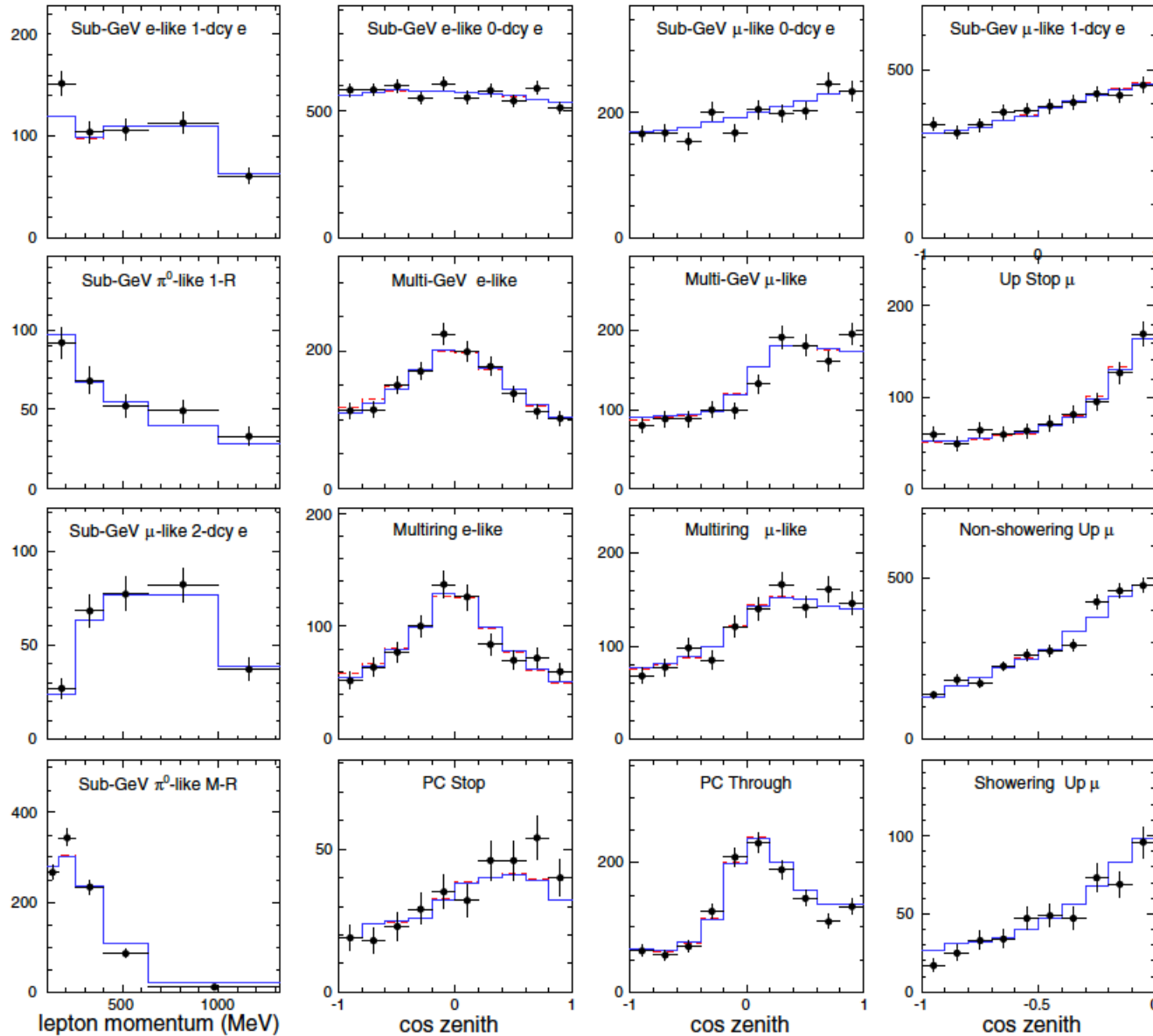
The DUSEL muon rate an order of magnitude smaller than Kamioka,  
so expect 15.5 MeV threshold instead of 19.3 MeV. **This enhances signal by 40%  
in addition to just detector mass scaling.**

Gadolinium loading *plus* extra depth would increase sensitivity by ~factor of two.  
Thus improvement of factor of roughly twenty is possible.

# Cosmic Ray Neutrinos: Exploiting an Intense Natural Source for Science



First unambiguous evidence for neutrino mass and lepton family number violation (1998)



Super-Kamiokande atmospheric neutrino data (2010). The flux model plus basic neutrino oscillations now agrees very well with the data.

DUSEL can exploit this to look for 2<sup>nd</sup> order effects from matter Effects.

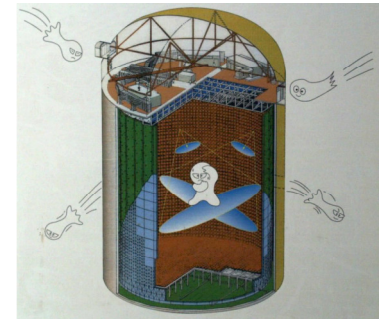
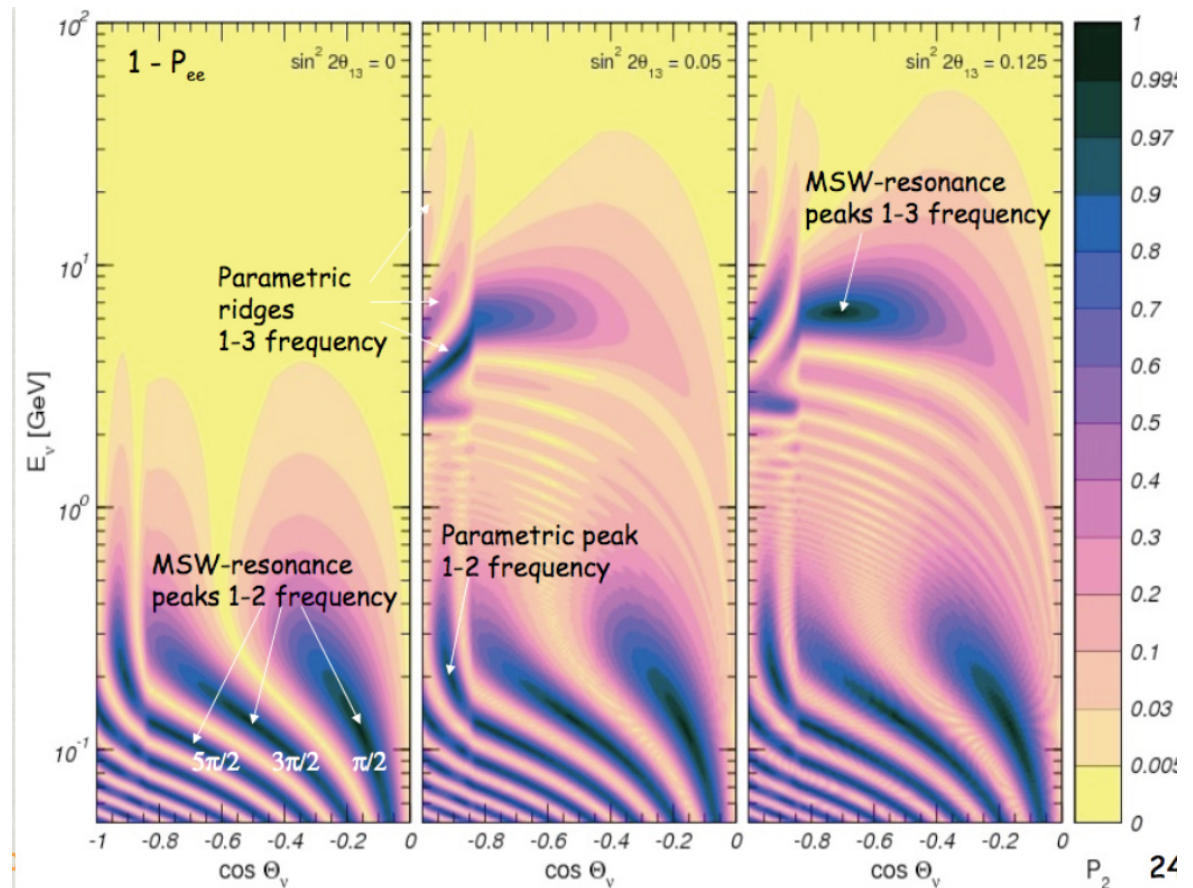


FIG. 10 (color online). SK-I + II + III zenith angle and lepton momentum distributions of the event samples used in the analyses. Black dots represent the data with statistical errors, the solid lines are the MC expectation at the best fit from the  $\theta_{13}$  analysis, and dashed lines show the expectation at the best-fit atmospheric variables but with  $\theta_{13}$  at the Chooz limit.

# Example of Precision Atmospheric Neutrino Measurement

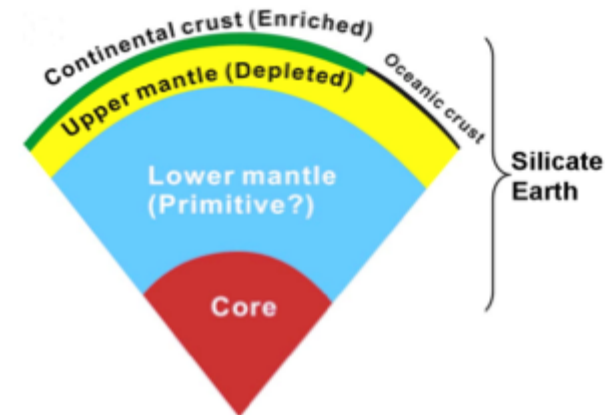
- Angle-Energy resonance in atmospheric neutrinos depends on  $\theta_{13}$  and mass hierarchy
- Requires high precision angular measurements and excellent energy resolution
- Evaluation for LBNE in progress



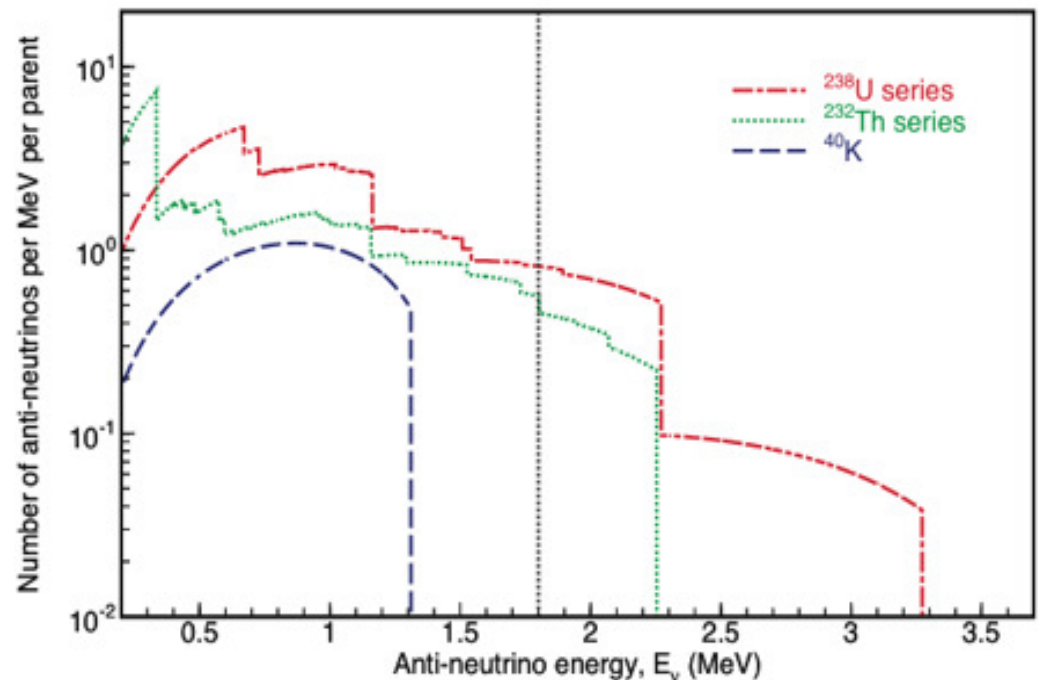
A. Yu. Smirnov

# Geo-neutrinos

- Uncertainty in Earth's energy budget
- Recent low significance measurements from KamLAND and Borexino prove feasibility
- Potential for high statistics measurements in future detectors in Europe and at DUSEL



**Bulk Silicate Earth model:**  
~1/2 of U, Th, K in crust  
~1/2 of U, Th, K in mantle  
~no U, Th, K in core



# Geo-neutrino Sensitivity

Detector	$\times 10^{32} \text{ p}^+$
KamLAND	0.62
Borexino	0.18
SNO+	0.57
DUSEL	36.7
Baksan	4.0
LENA	36.7
Hanohano	7.34

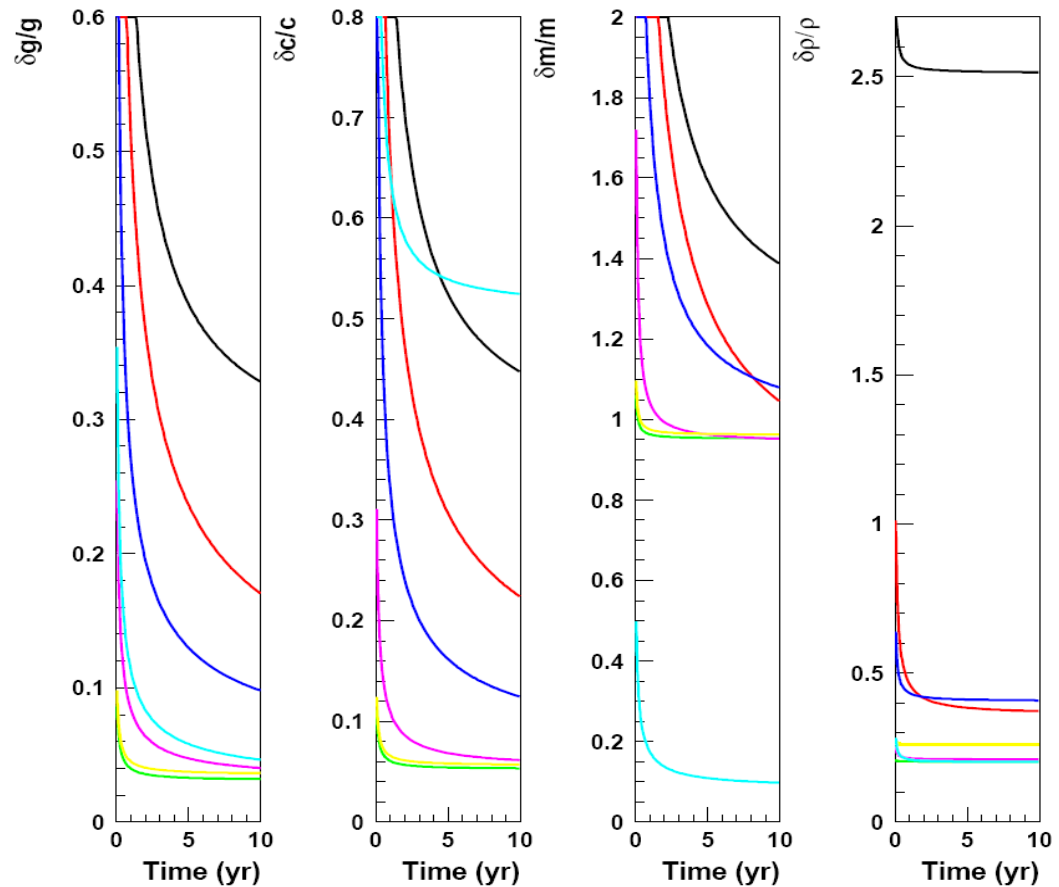
Event rates

$$n = g + r$$

$$g = c + m$$

$$\rho = Th/U$$

Reference flux from Mantovani et al.  
2004 hep-ph/0309013



arXiv:0912.2775

w/ 50 kT-yr measure:  
Geo-nus to ~5%  
Crustal nus to ~6%  
Th/U to ~20%

# Other Topics

- Long-Term measurements of 8-B neutrinos from the sun (need a low threshold)
- Potential for CNO neutrinos (need LS)
- Potential for high-precision solar 7-Be and matter effects (need LS)
- Search for dark matter annihilation in the sun
- Development of long range reactor detection techniques
- The science will evolve as questions arise

# The U.S. Neutrino Community – Where Do They Work?

- UNDERGROUND: ICE CUBE (US,**15**), Super-Kamiokande(Japan,**7**), SNO(Canada,**5**), KamLAND(Japan,**11**), Borexino(Italy,**3**)
- BEAM: MINOS(US,**17**), miniBooNE(US,**12**), Minerva(US,**14**), T2K(Japan,**10**), OPERA(Italy,**0**), ICARUS(Italy,**1**)
- REACTOR: Double Chooz(France,**12**), Daya Bay(China,**12**), RENO(Korea,**0**)

In bold is the number of U.S. University Research Groups working on the experiment. NSF currently operates the only U.S. underground neutrino laboratory at their large South Pole facility.

# DUSEL Large Neutrino Detector Collaboration (LBNE)

Argonne  
Alabama  
Boston University  
Brookhaven  
Caltech  
Cambridge  
Catania  
Columbia  
Chicago  
Colorado  
Colorado State  
Columbia  
Crookston  
Davis  
Drexel  
Duke  
Duluth  
Fermilab  
Hawaii  
Indian Universities:  
[BHU, Delhi U., IIT(G), Panjab U.]  
Indiana  
Iowa State  
IPMU-Tokyo  
Irvine  
Kansas State  
Lawrence Berkeley National Lab  
Livermore

London UCL  
Los Alamos  
Louisiana State  
Maryland  
Michigan State  
Minnesota  
MIT  
NGA  
New Mexico  
Notre Dame  
Oxford  
Pennsylvania  
Pittsburgh  
Princeton  
Rensselaer  
Rochester  
South Carolina  
South Dakota State  
SDSMT  
Southern Methodist  
Texas  
Tufts  
UCLA  
Virginia Tech  
Washington  
Wisconsin  
Yale

**At the universities there  
are **141** professors,  
postdocs, and graduate  
students.**

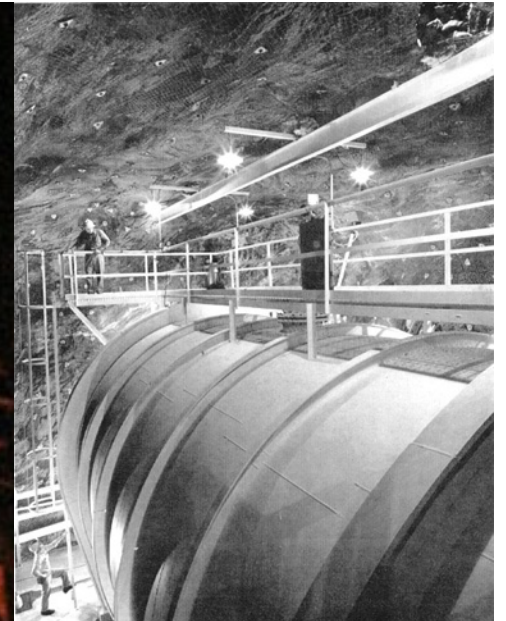
**At the national labs there  
are **113** physicists,  
Engineers, and postdocs.**

**There are **26** untenured  
Or recently tenured  
young researchers – the  
toughest review committee  
of all.**



# Thanks!

**Disassembly of the Davis solar neutrino experiment to make room for new experiments.**



backup

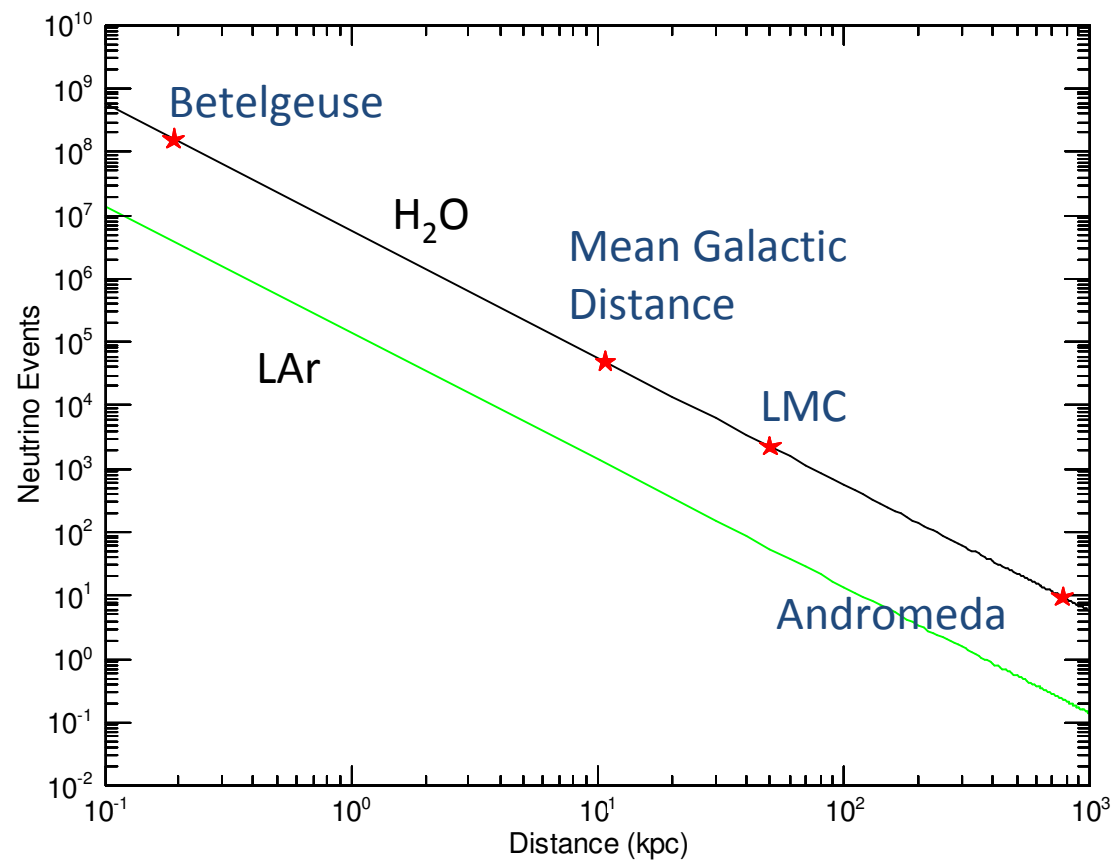
# Supernova Model Physics

- Nuclear equations of state
  - Energy exchange
    - Neutrino bremsstrahlung
    - Inelastic scattering
    - $e^+e^-$  annihilation
- Rotation
- Convection
- Magnetic Fields
- Acoustic waves driven by proto-neutron star oscillations
- Symmetry

# SN Rate Estimates

- Historical
  - 6 over 1 millennium
- Nucleosynthesis estimates
  - $^{26}\text{Al}$  product of SN
- Galaxy survey
  - Subdivide events by galaxy morphology types
    - Parent population estimates
  - 60-80 SN/yr in galaxies of known parameters
  - SN Distribution since 1989
    - 49.5% SN II, 1b, 1c
    - Excludes very distant SN (mostly 1a)

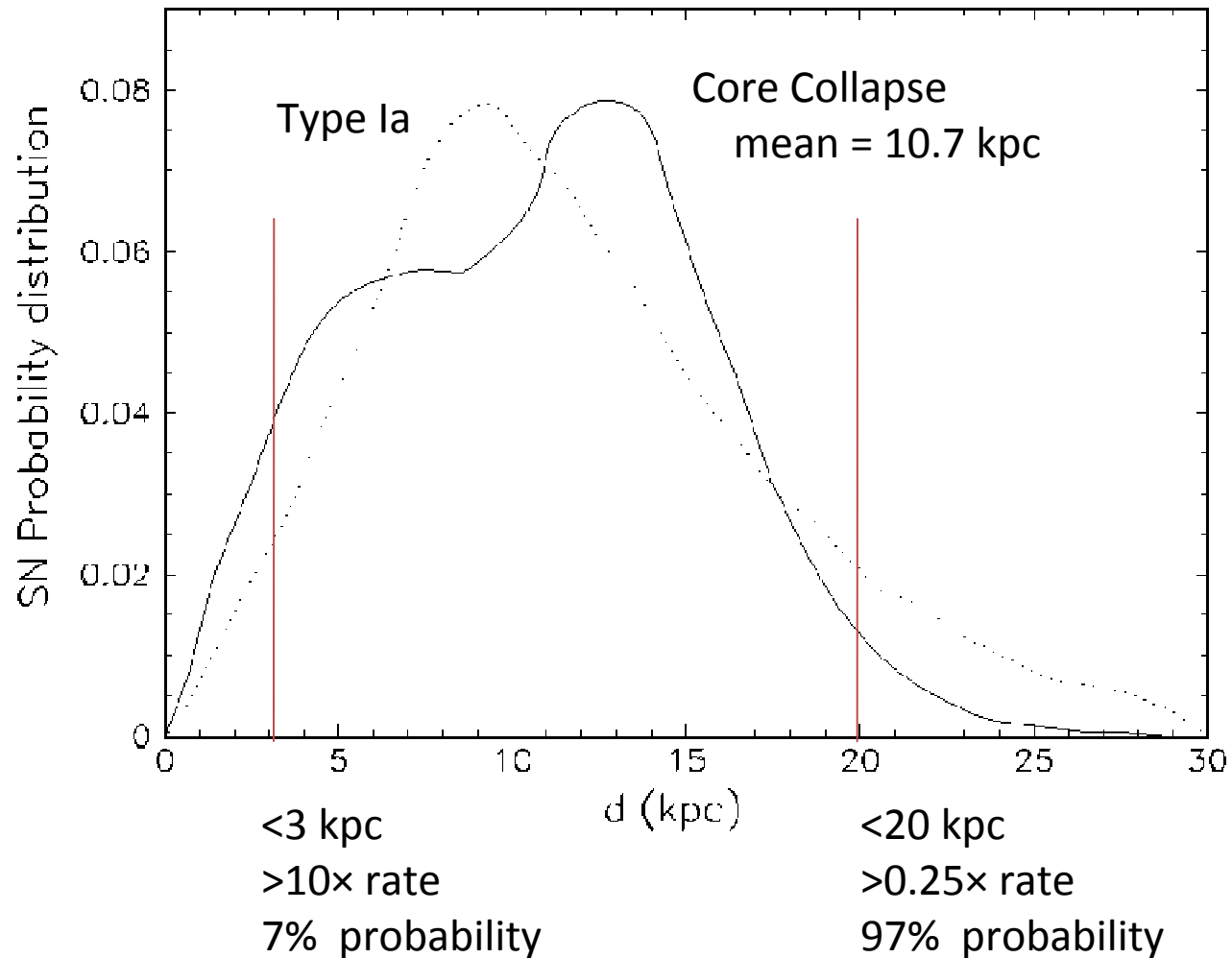
# SN Neutrino Events as a Function of Distance



# SN Distance in Galaxy

Mirizzi, Raffelt and Serpico

JCAP 0605, 012(2006)



# $C_nH_{2n}$ Targets

- Low threshold
- Neutron tagging

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- Sensitive to NC events

$$\nu + p \rightarrow \nu + p$$

Fraction of  
KamLAND events

~40%

$$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$$

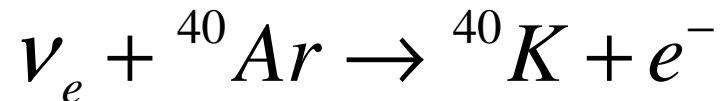
~8 %

$$\nu + {}^{12}C \rightarrow {}^{12}B^* + p$$

~6%

# Liquid Argon Targets

- Good sensitivity to  $\nu_e$ 
  - 1.5 MeV threshold



- NC sensitivity
  - 1.46 MeV threshold



- Event identification with de-excitation  $\gamma$ 's

# H<sub>2</sub>O Targets

- Strong sensitivity to  $\bar{\nu}_e$ 
  - Decent energy resolution
  - 1.8 MeV threshold

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- Directional information

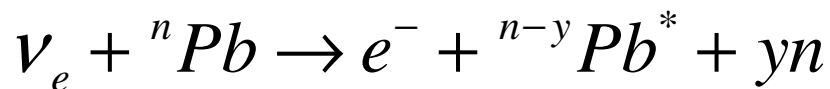
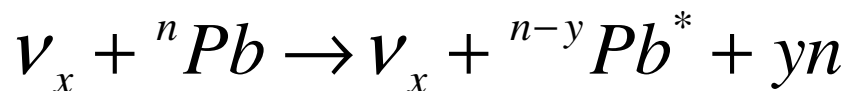
$$\nu + e^- \rightarrow \nu + e^-$$

- Few non- $\bar{\nu}_e$  events
  - CC, NC on  $^{16,18}\text{O}$

# Lead Targets

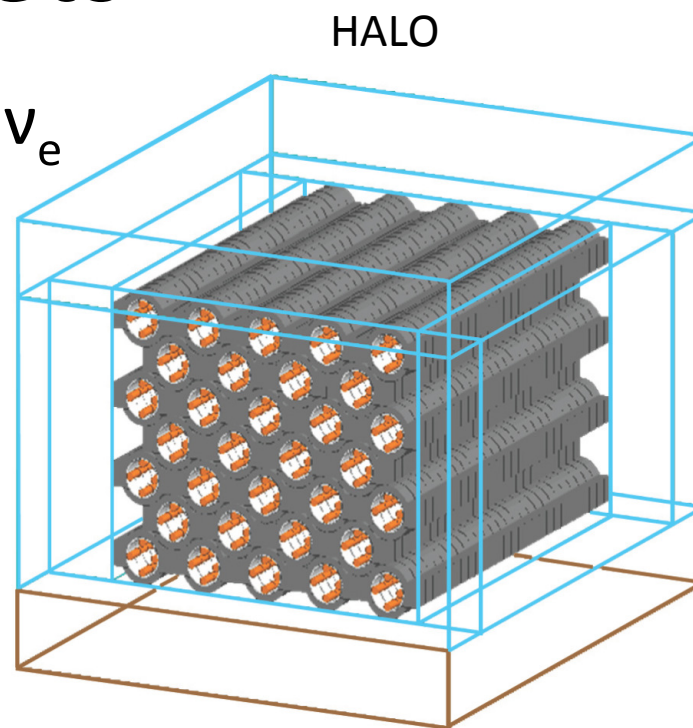
- Strong sensitivity to high energy  $\nu_e$
- Good for time structure
- Tricky to obtain  $\nu_e$  energy, spectrum shape, NC-CC separation

Detector	Mass	Events 8.5 kpc
HALO	0.07	80



Per 1 kT @ 8.5 kpc  
180

777



# LAr Rates

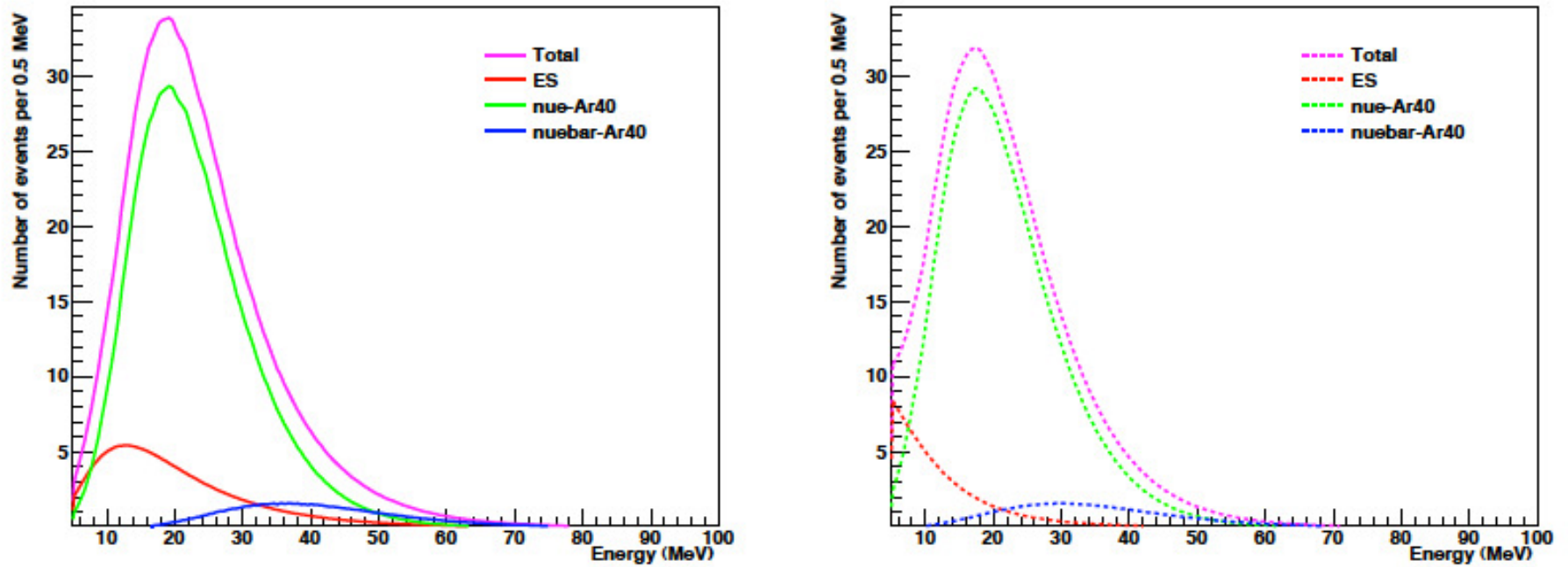


FIG. 44. Event rates in 17 kt of argon (events per 0.5 MeV).

Channel	Events, "Livermore" model	Events, "Kneller" model
$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$	1154	1424
$\bar{\nu}_e + {}^{40}\text{Ar} \rightarrow e^+ + {}^{40}\text{Cl}^*$	97	67
$\nu_x + e^- \rightarrow \nu_x + e^-$	148	89
Total	1397	1580

TABLE XVII. Event rates for different models in 17 kt of LAr.