DESY2004@Hamburg
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Cosmic star formation history and supernova relic neutrinos

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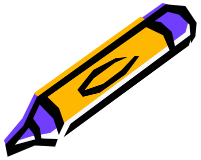
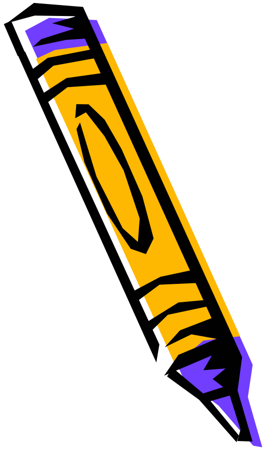


S. Ando, Astrophys. J. **607** (2004) 20

1. Introduction

Supernova relic neutrinos

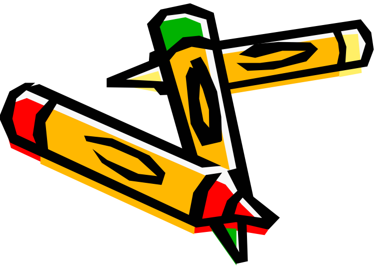


Supernova Explosion

99% of its gravitational binding energy is released as neutrinos.

It is considered to trace the cosmic star formation rate (SFR).

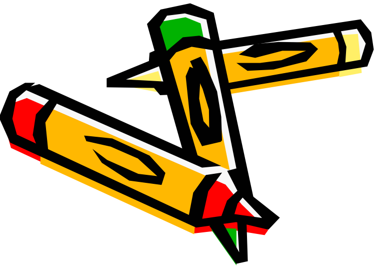
There should be a diffuse background of neutrinos which were emitted from past supernova explosions.



"Supernova Relic Neutrinos (SRN)"

Motivations

- Is it really detectable?
  - Precise rate and background estimates are essential.
    - Kaplinghat, Steigman & Walker (2000); Ando, Sato & Totani (2003)
- Galaxy evolution and cosmic star formation rate
    - Totani, Sato & Yoshii (1996); Malaney (1997); Hartmann & Woosley (1997); Fukugita & Kawasaki (2003); Strigari et al. (2004); Ando (2004)
- Physics of supernova neutrinos
- Neutrino properties as an elementary particle
  - Neutrino oscillation
    - Ando & Sato (2003)
  - Neutrino decay (coupling with e.g. Majoron)
    - Ando (2003); Fogli et al. (2004)



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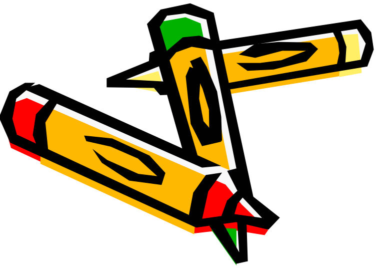
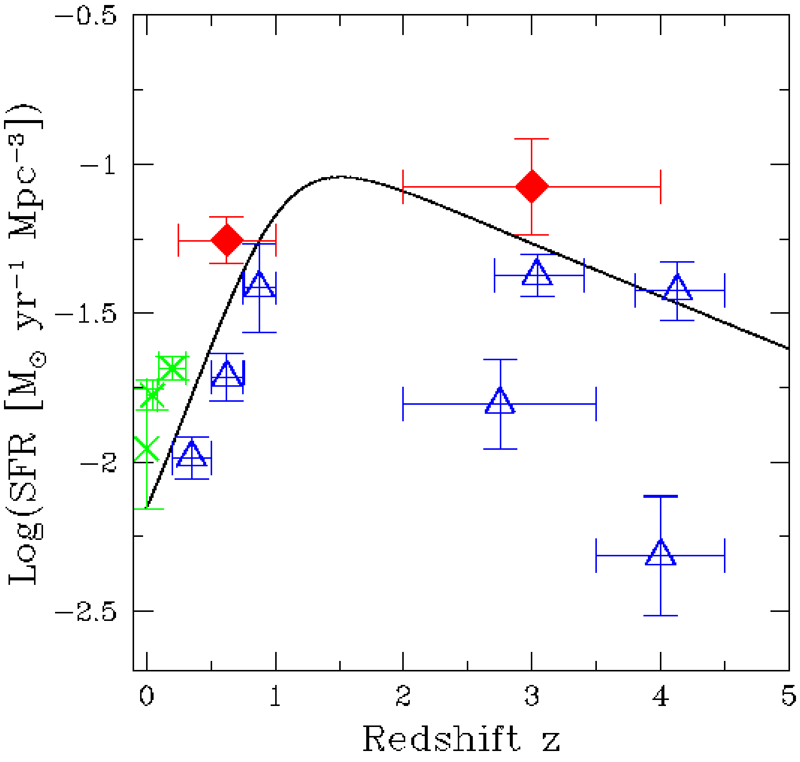
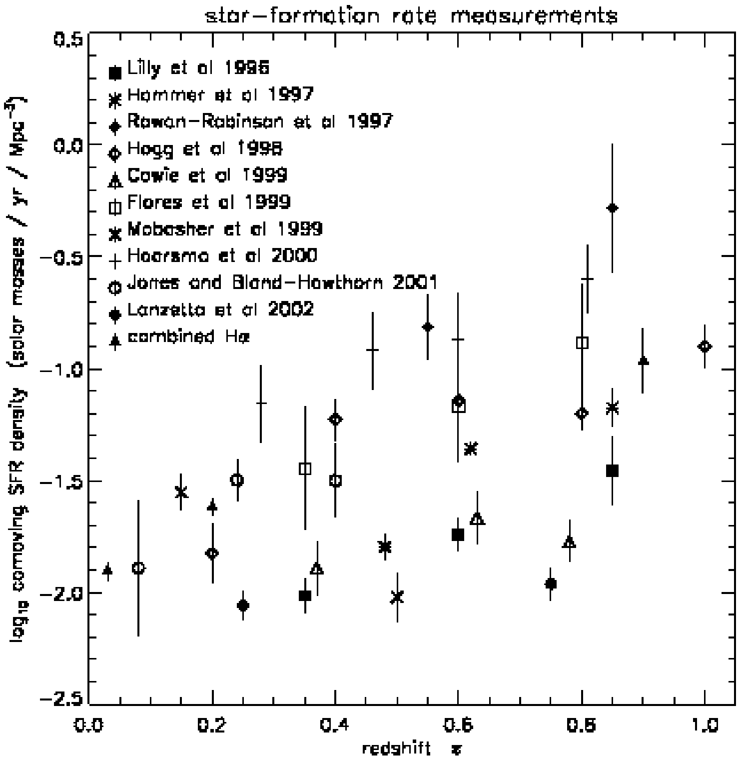


Cosmic star formation rate



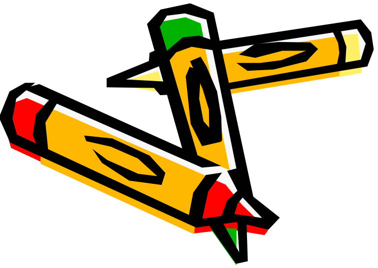
- Cosmic SFR is inferred from UV, Hα, submm/FIR luminosity density.

Cosmic star formation rate

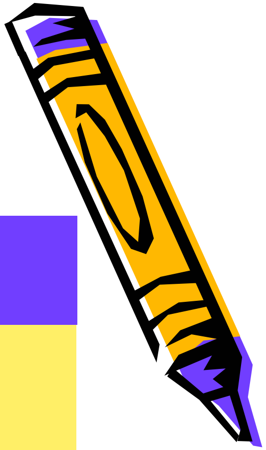


Hogg, astro-ph/0105280

- Cosmic SFR is inferred from UV, Hα, submm/FIR luminosity density.
- Although there seems to be a general trend at low-z, these estimates are quite uncertain!
- We deserve other independent methods.



SRN as an SFR indicator

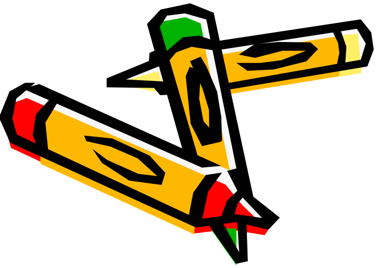


UV luminosity density

- Advantages
  - Easier observation
  - Spectral features such as line/edge → enables redshift measurement
- Disadvantages
  - *Dust extinction*

SN relic neutrinos

- Advantages
  - *Completely free from dust*
  - Directly connected with the death of massive stars → good SFR tracer
- Disadvantages
  - Difficult!!
  - No spectral feature



But, the detection is within reach in the near future!!

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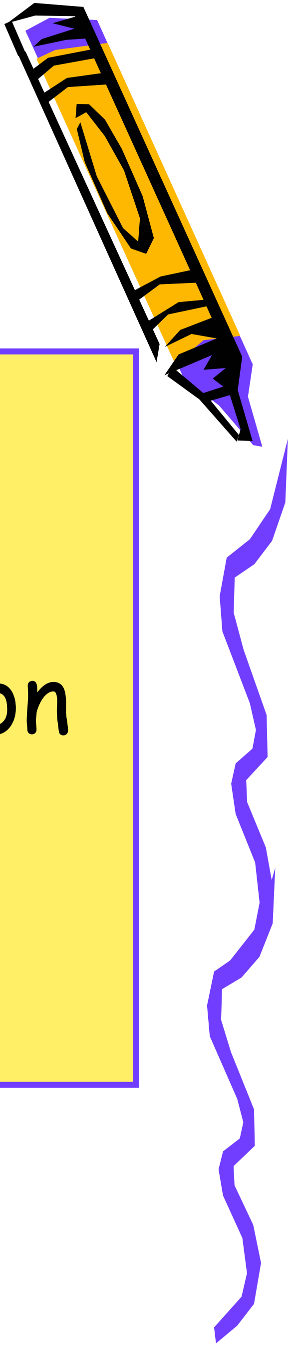

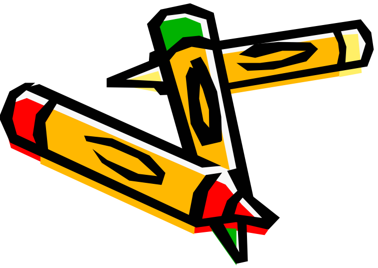

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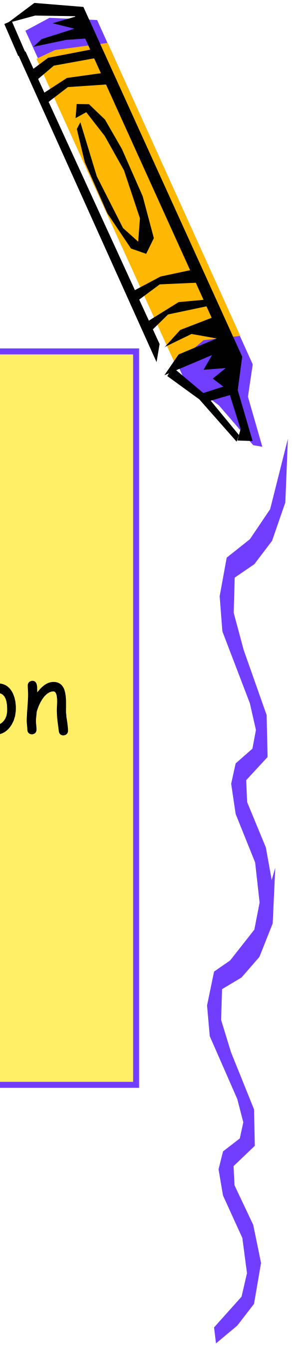

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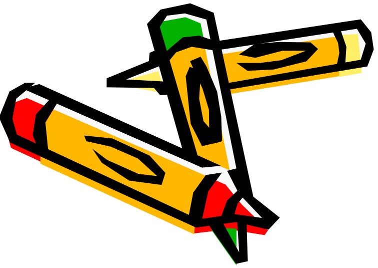
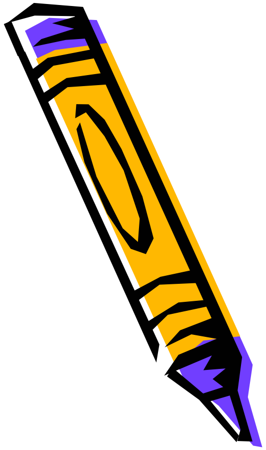
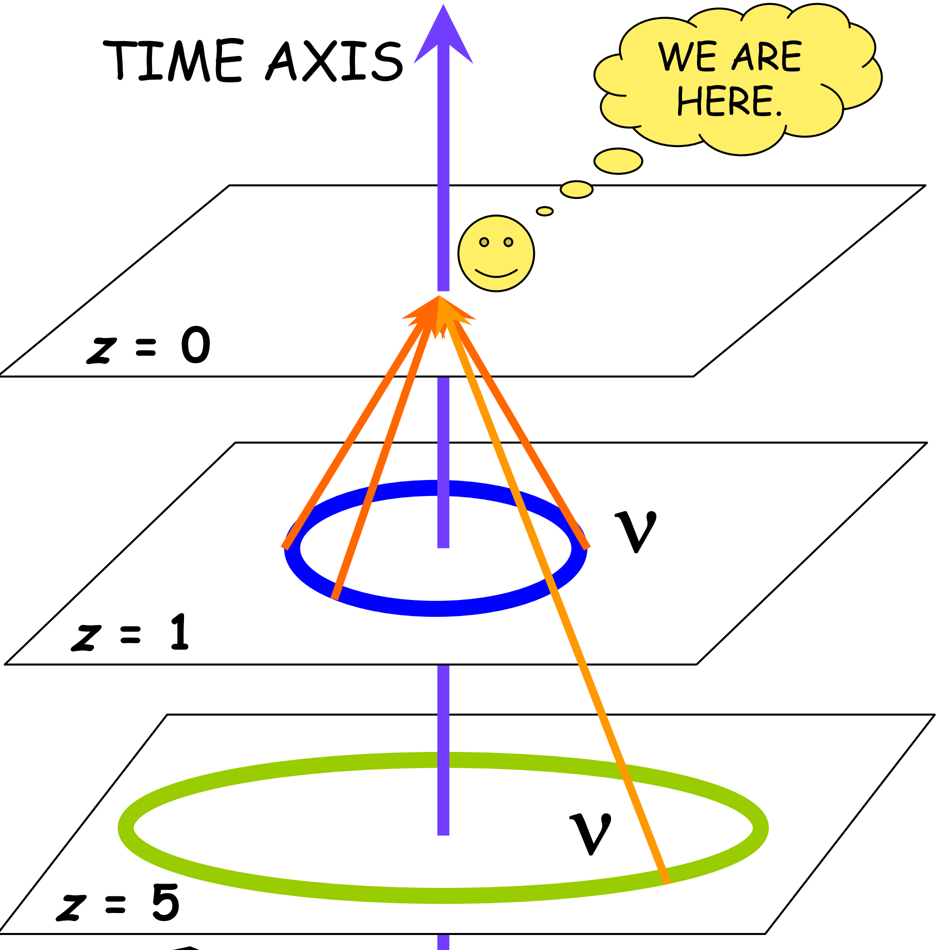
3. Results of Numerical Calculation
4. Future Detector Performance
5. Conclusions



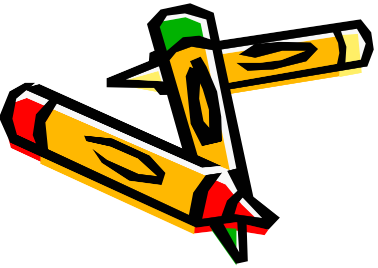
Forumulation





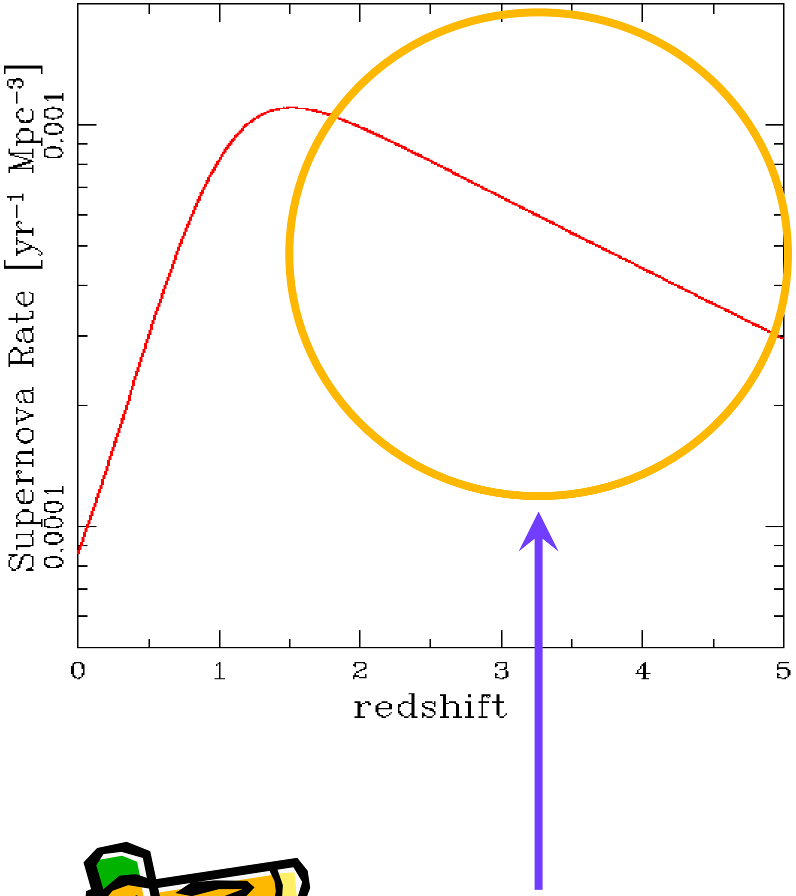
Physics involved:

1. Neutrino spectrum from each supernova
    - Simulation by Lawrence Livermore (LL) group
2. Neutrino oscillation during propagation in SN envelope
    - Quite well understood by experiments
3. Supernova rate evolution



$$\frac{dF_\nu}{dE_\nu} = c\int_0^{z_{\max}} R_{\rm SN}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)\frac{dt}{dz}dz$$

Supernova rate history

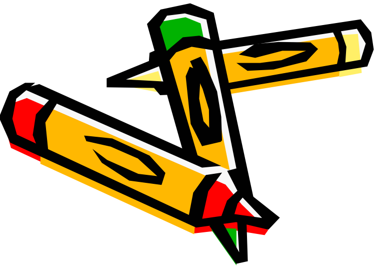


- Supernova rate is inferred from SFR via

$$R_{\rm SN}(z) = \psi_*(z)\,\frac{\int_{8M_\odot}^{125M_\odot} dm\,\phi(m)}{\int_{0}^{125M_\odot} dm\,m\phi(m)}$$

- Behavior at high redshift contains substantial uncertainties.
- But, high redshift behavior is found irrelevant.

The uncertainty around here is not important so much.



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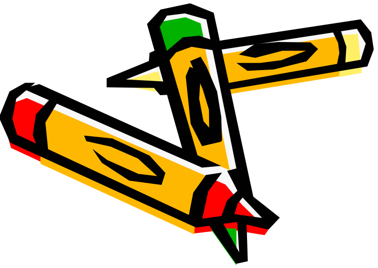
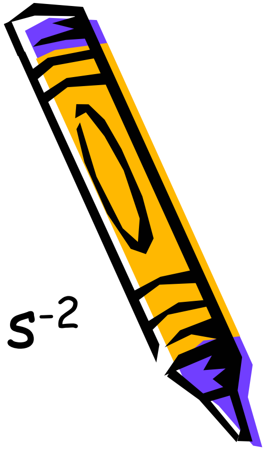
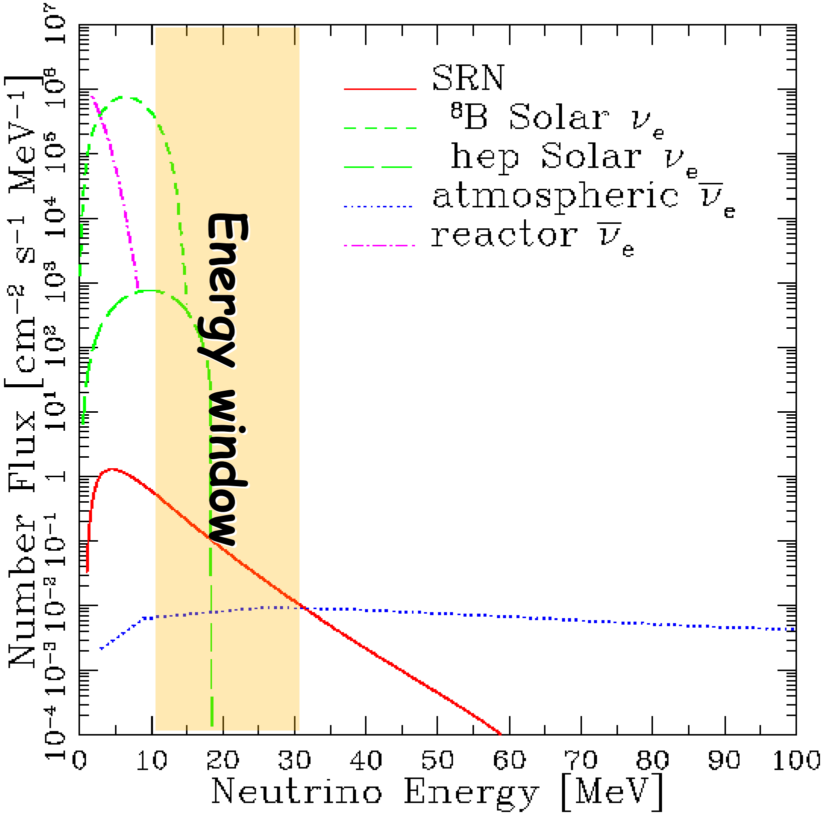


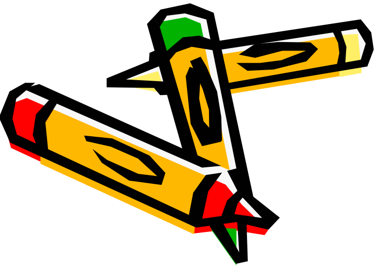
SRN flux and backgrounds

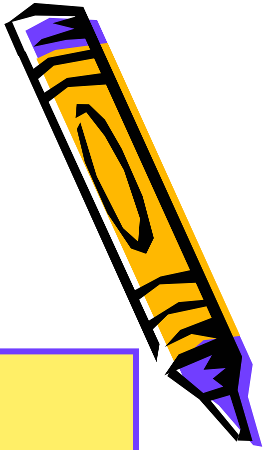




Ando, Sato & Totani (2003)

- Flux will be ~ 2 cm^{-2} s^{-2} above 10 MeV.
- Event rate is estimated to be ~ 2 yr^{-1} at Super-K (E_e > 10 MeV).
- Backgrounds are solar, atmospheric, reactor neutrinos etc.
- In the near future, the energy range 10—30 MeV will be background free (Beacom & Vagins 2004).





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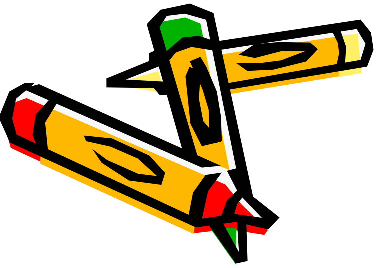
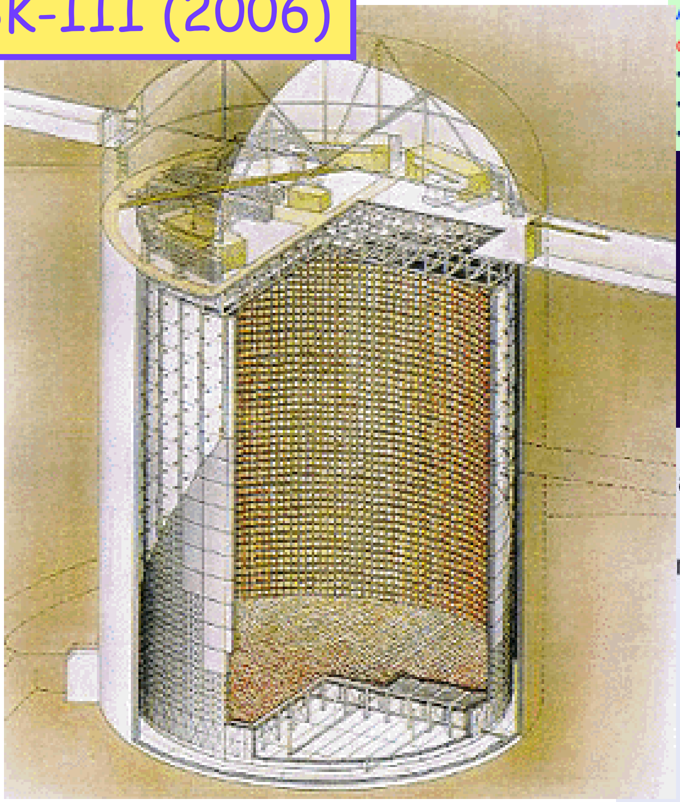
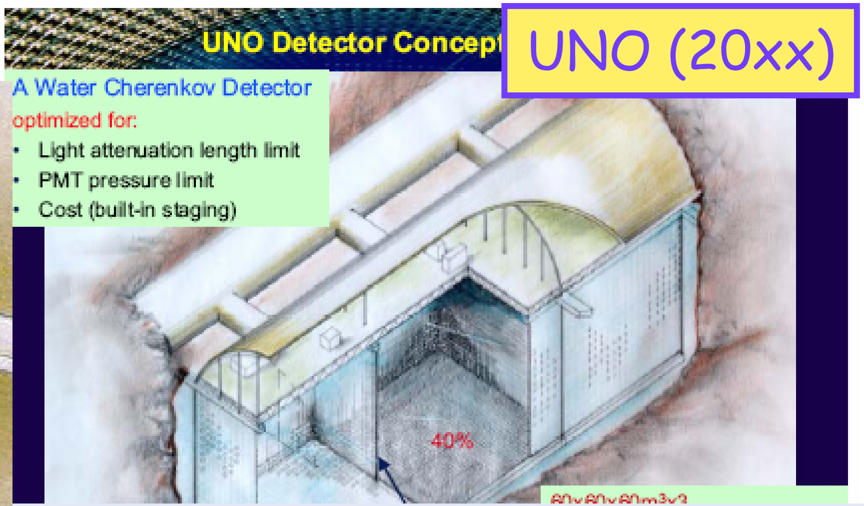


Upcoming detectors

SK-III (2006)



UNO (20xx)

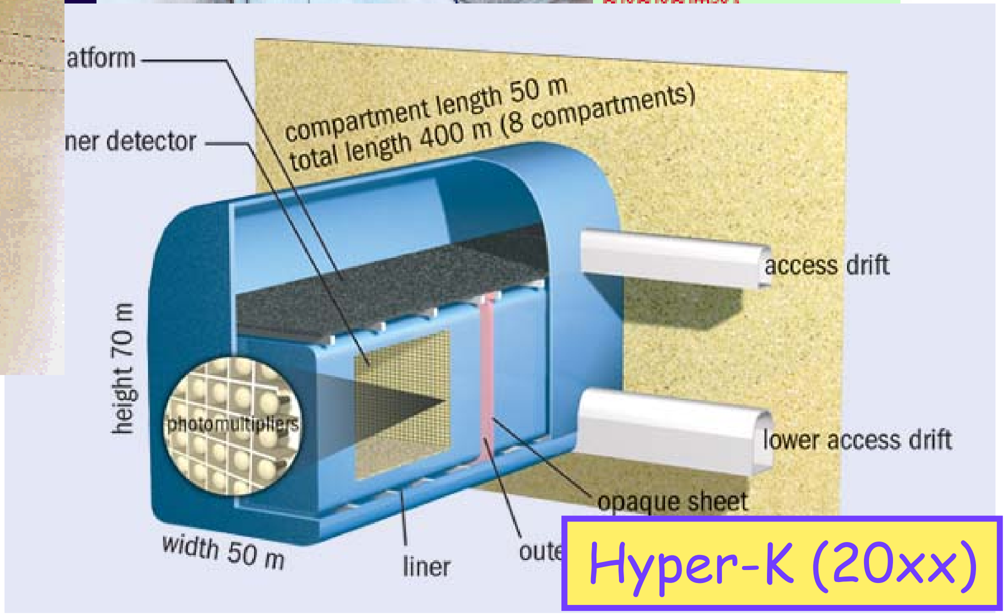


UNO Detector Concept

A Water Cherenkov Detector

optimized for:

- Light attenuation length limit
- PMT pressure limit
- Cost (built-in staging)

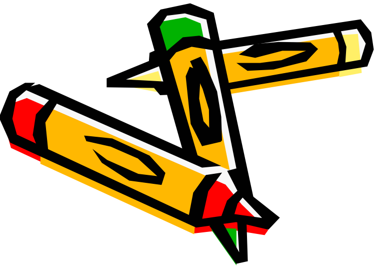


Hyper-K (20xx)

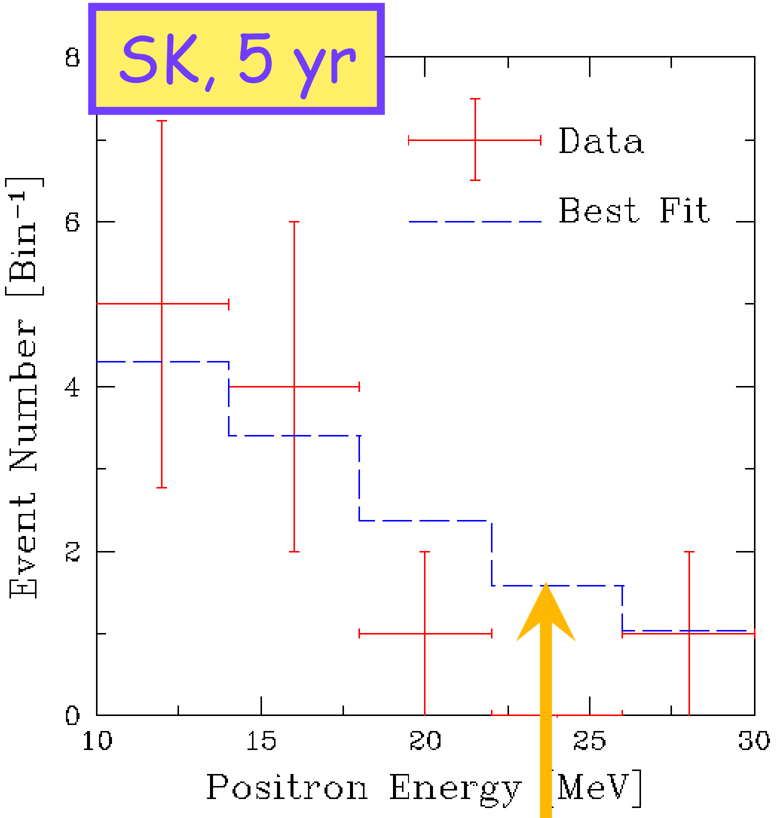
Monte Carlo simulation

Procedure

1. Simulate the SRN signal at 10—30 MeV
2. Analyze the simulated data with simple parameterization ▶
3. Repeat the procedures 1. & 2., 1000 times
4. Obtain distribution of best fit values for adopted parameters ▶



Simulated SRN data

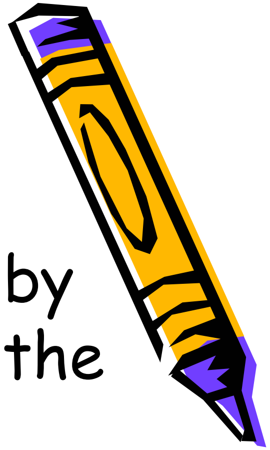


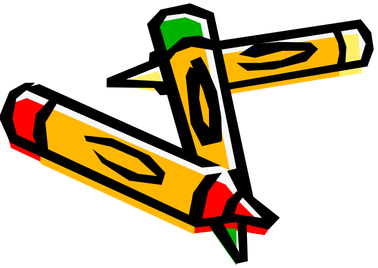
R_{SN}^0 : fixed
Best fit value: $\alpha = 3.0$

- Data are generated by MC simulation using the LL model.
- We analyze the data with two free parameters related to SN rate as,

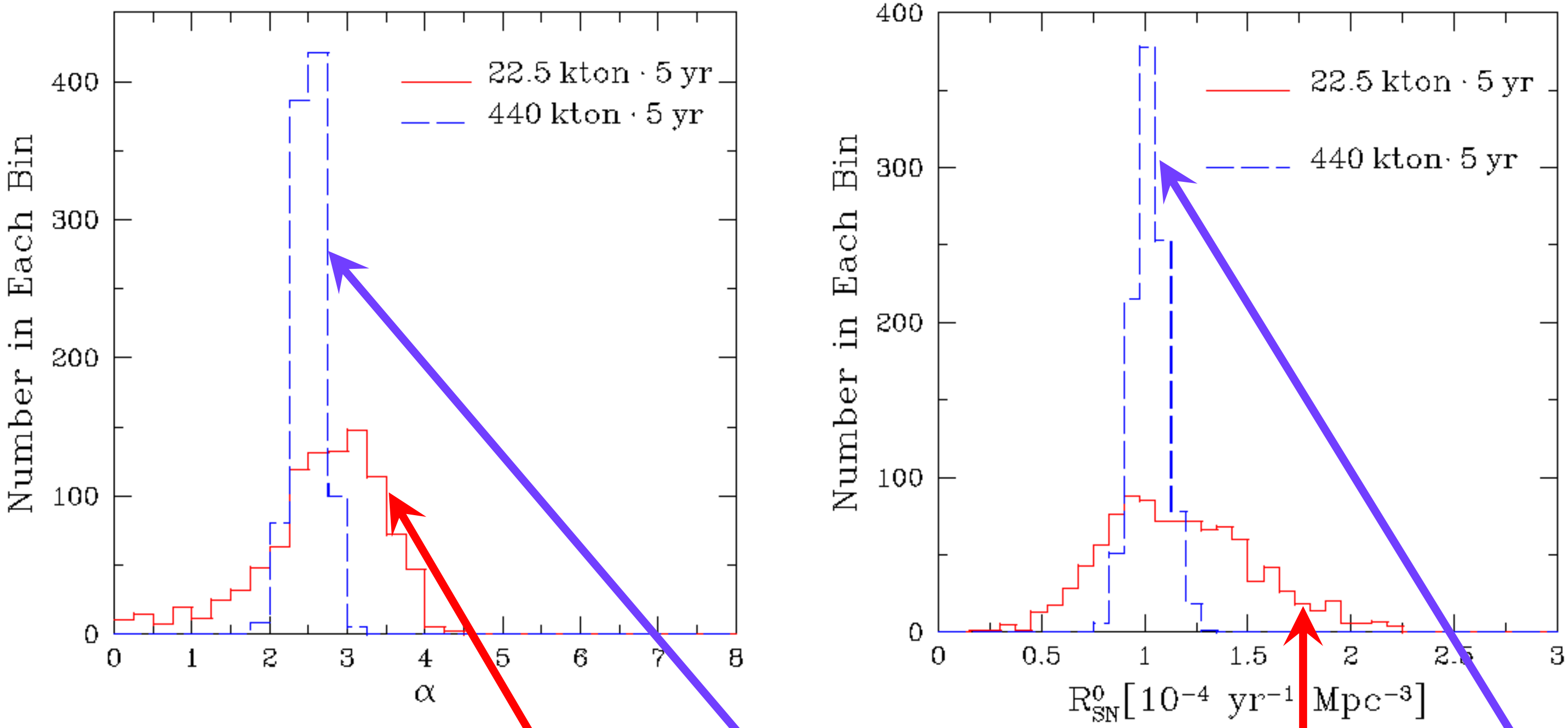
$$R_{\rm SN}(z) = R_{\rm SN}^0(1+z)^{\alpha}$$

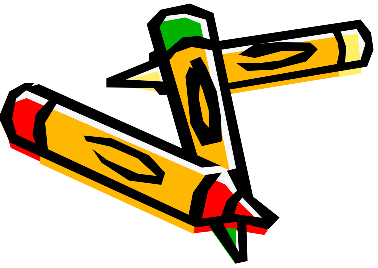
- We assume that the supernova neutrino spectrum is quite well known.
  - Galactic SN will give us rich information.





Distribution of best fit parameters

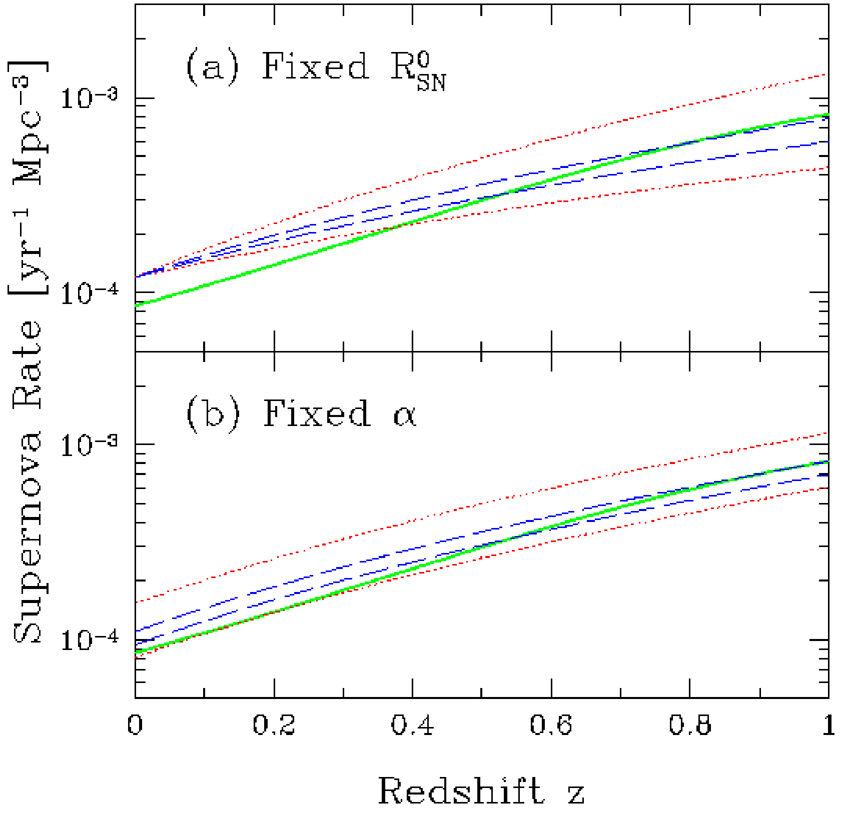




α = 2.7+/-0.8 (2.5+/-0.2);
Fixed $R_{SN}{}^0$ (1.2)

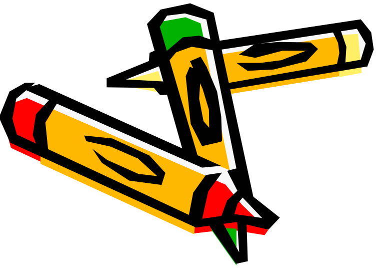
$R_{SN}{}^0$ = 1.2+/-0.4 (1.0+/-0.1);
Fixed α (2.9)

Comparison of model/obtained SN rate

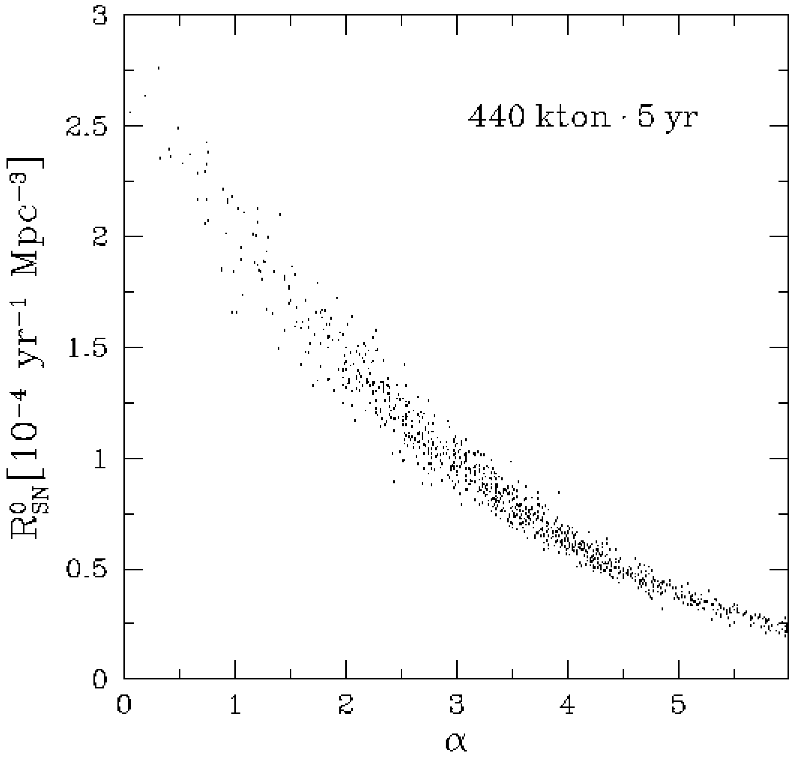


- SRN observation well reproduces assumed SN rate history.

Model SN rate
22.5 kton 5 yr
440 kton 5 yr



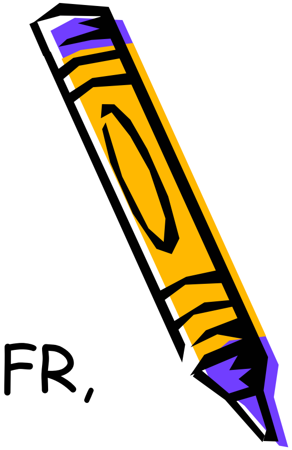
Distribution of best fit parameters (2)

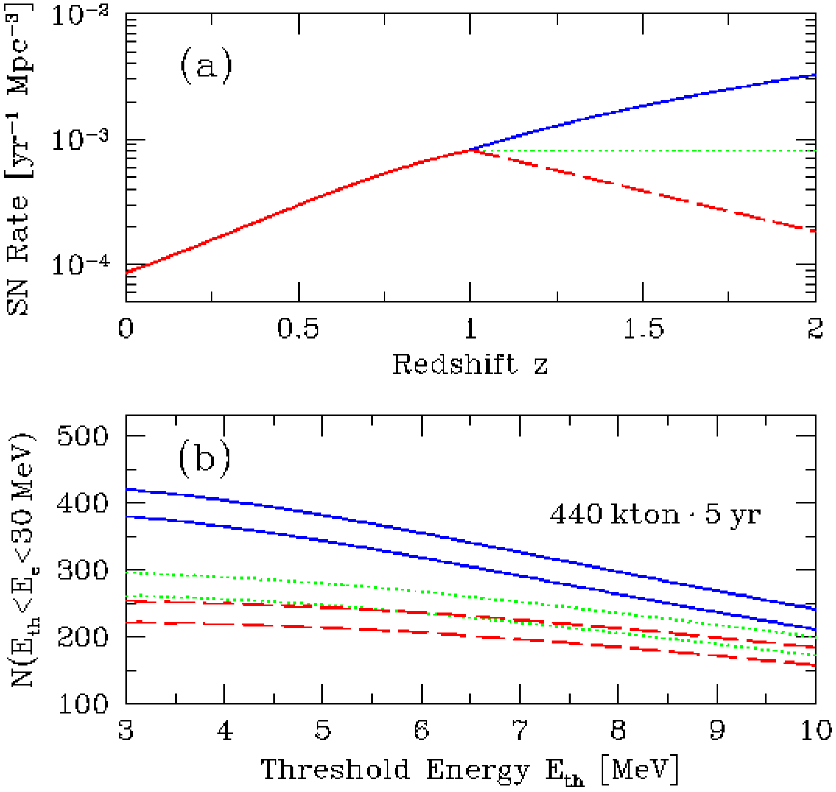


- Distribution of (α, $R_{SN}{}^0$) without parameter fixing.
- Even with Hyper-K or UNO, it is difficult to obtain the both values without prior knowledge.

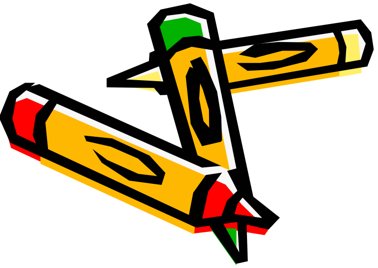
$\alpha = 3.5$+/-1.3
$R_{SN}{}^0 = 0.88$+/-0.48

High-z SFR by SRN





- To probe high-z SFR, lower threshold is needed.
- If E_{th} can go down from 10 MeV, high-z (z > 1) SFR will be probed by the SRN observation.
- Three toy models are statistically well separated from one another.



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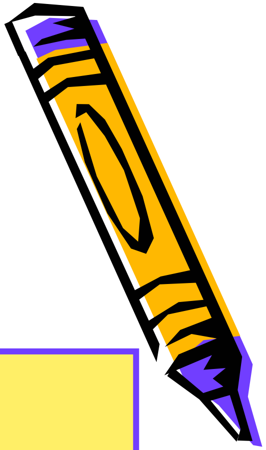

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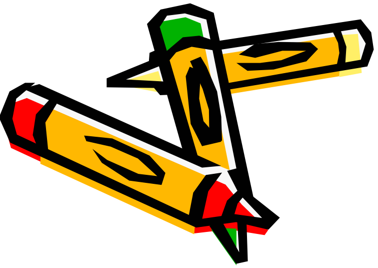
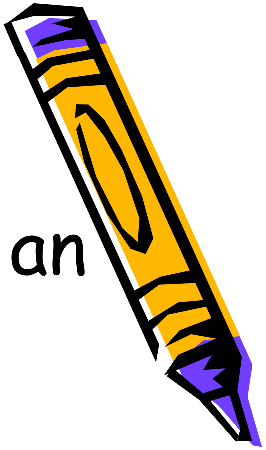
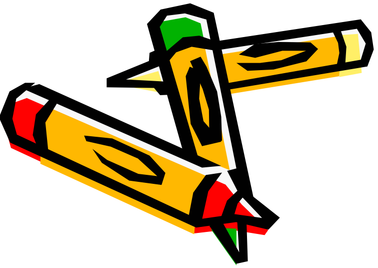


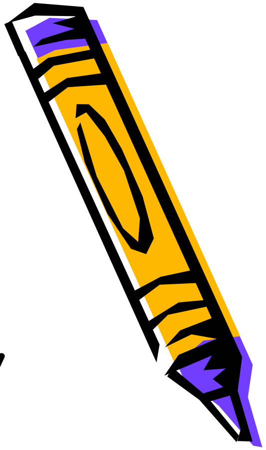
Conclusions

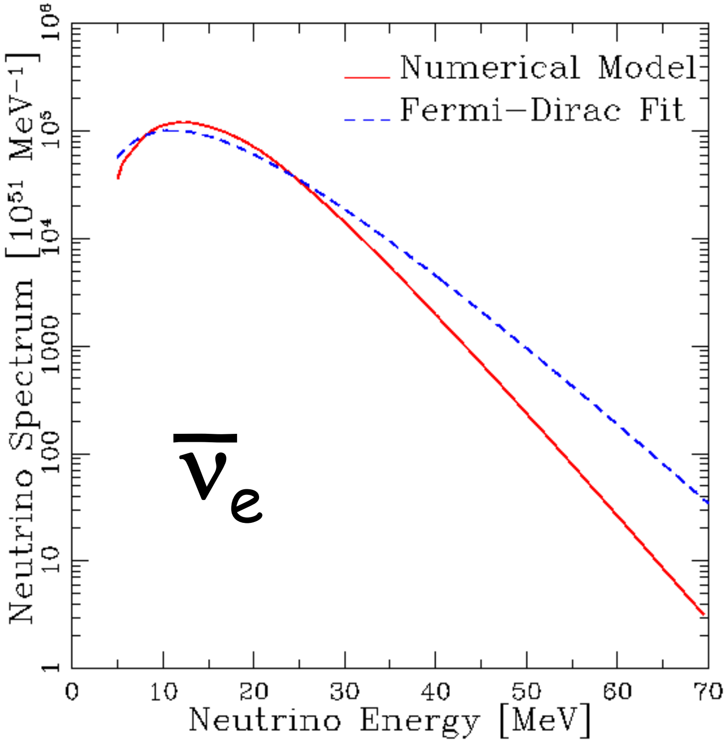


- SRN flux and event rate is investigated as an SFR indicator.
- The advantages of this method are:
  1. Neutrinos are completely free of dust extinction.
  2. It is expected to trace SFR quite well.
- In the near future, 10—30 MeV will be available as an energy window.
- SFR evolution at low-z could be inferred with accuracy of ~30% (8%) by using the detector of 22.5 kton 5 yr (440 kton 5 yr).



Original neutrino spectrum

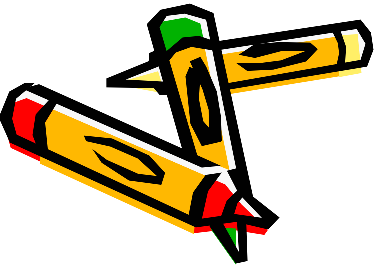




LL model of $20M_\odot$

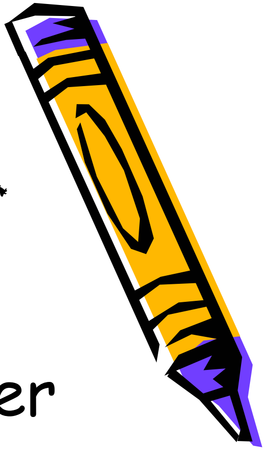
- Neutrino spectra calculated numerically by three independent groups are adopted.
- Average energies (MeV)

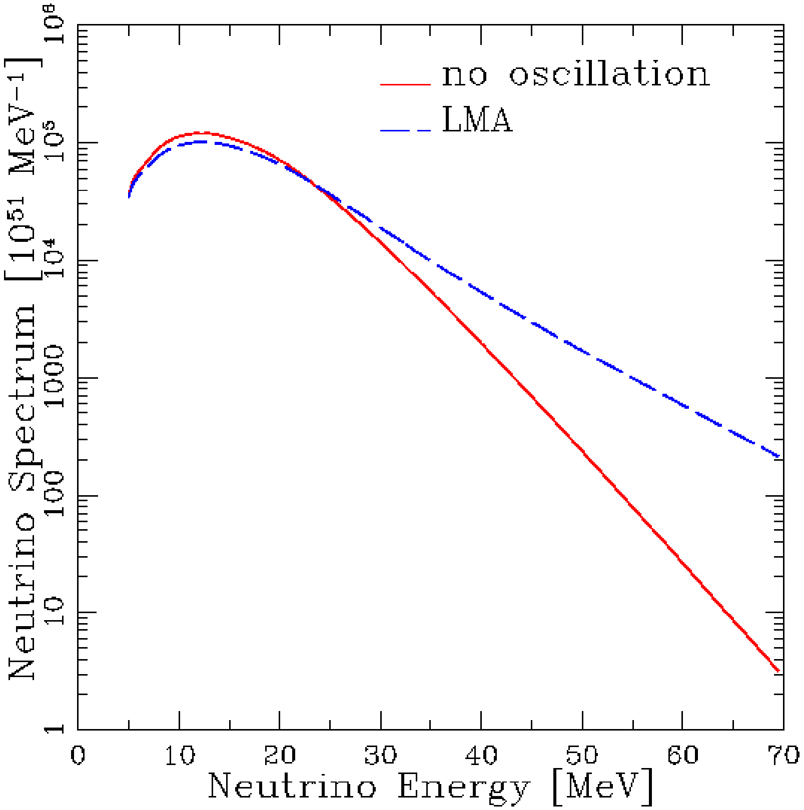
Model	$\bar{\nu}_e$	ν_x	Ratio
LL	15.4	21.6	1.4
TBP	11.4	14.1	1.2
KRJ	15.4	15.7	1.0



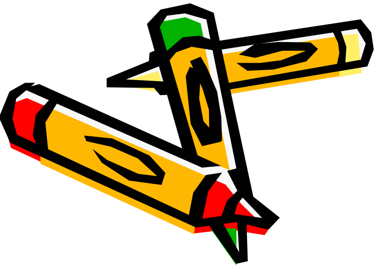
LL: Totani, Sato, Dalhed & Wilson (1998)
TBP: Thompson, Burrows & Pinto (2003)
KRJ: Keil, Janka & Raffelt (2003)

Spectrum after oscillation

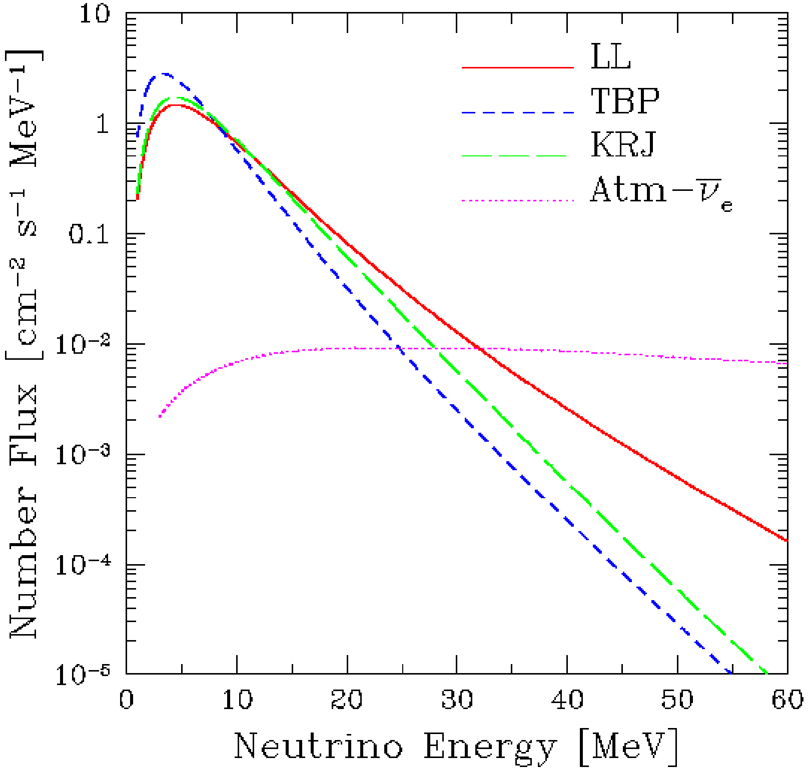




- Here, we only consider the case of normal mass hierarchy without magnetic moment.
- In the case of large mixing, flavor conversion occurs efficiently (~30% mixing).
- The difference in average energies is essential.

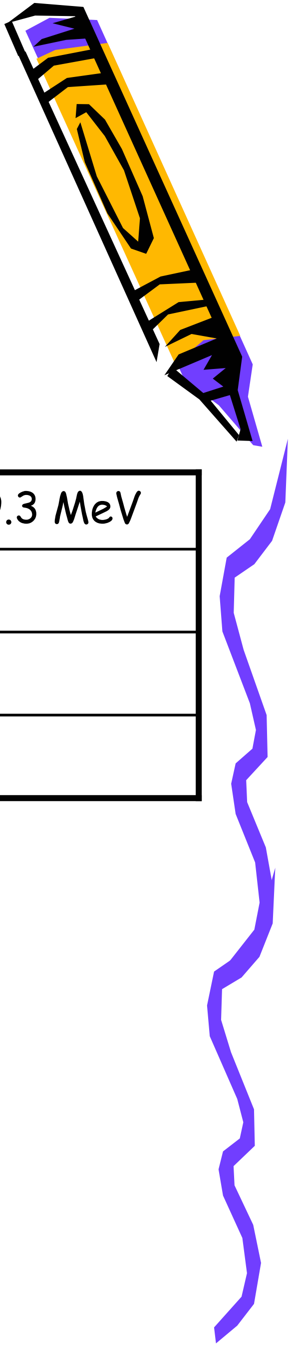


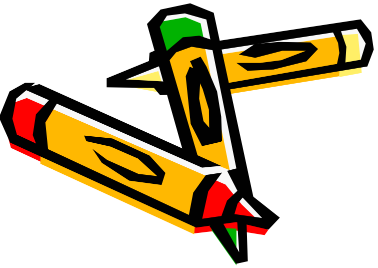
Flux & event rate



- Integrated flux ($\mathrm{cm^{-2}\ s^{-1}}$)

Model	E_ν > 11.3 MeV	E_ν > 19.3 MeV
LL	2.3	0.46
TBP	1.3	0.14
KRJ	2.0	0.28





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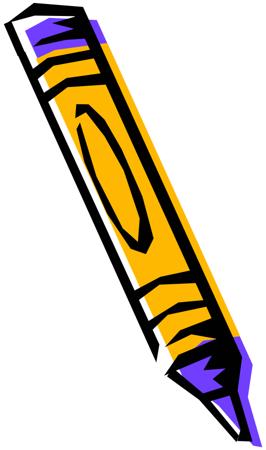
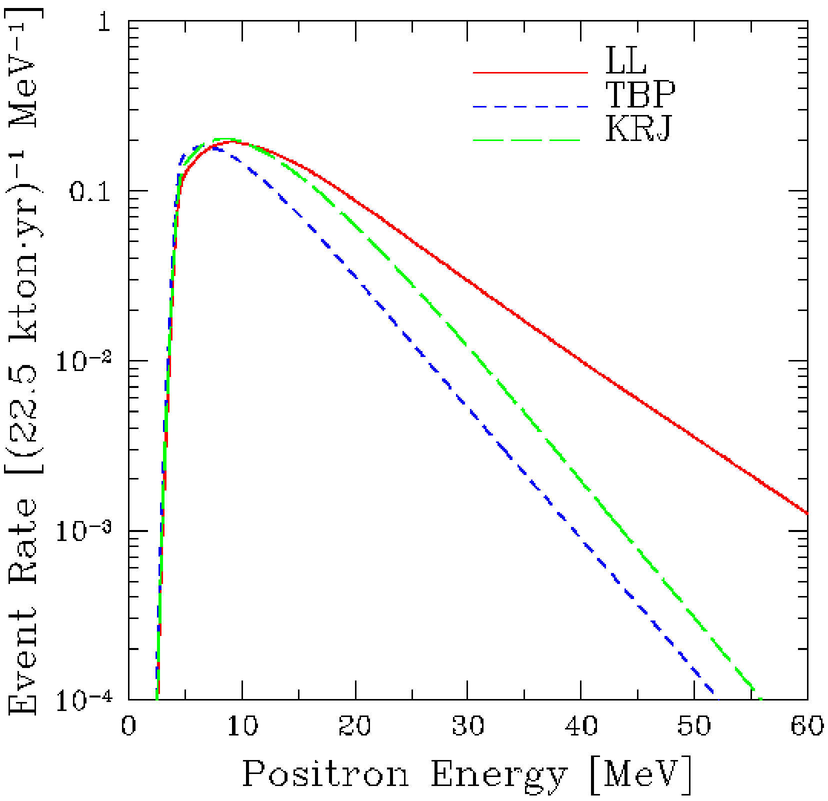


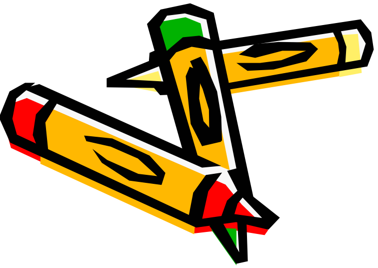


- Integrated flux (cm^{-2} s^{-1})

Model	$E_\nu > 11.3$ MeV	$E_\nu > 19.3$ MeV
LL	2.3	0.46
TBP	1.3	0.14
KRJ	2.0	0.28

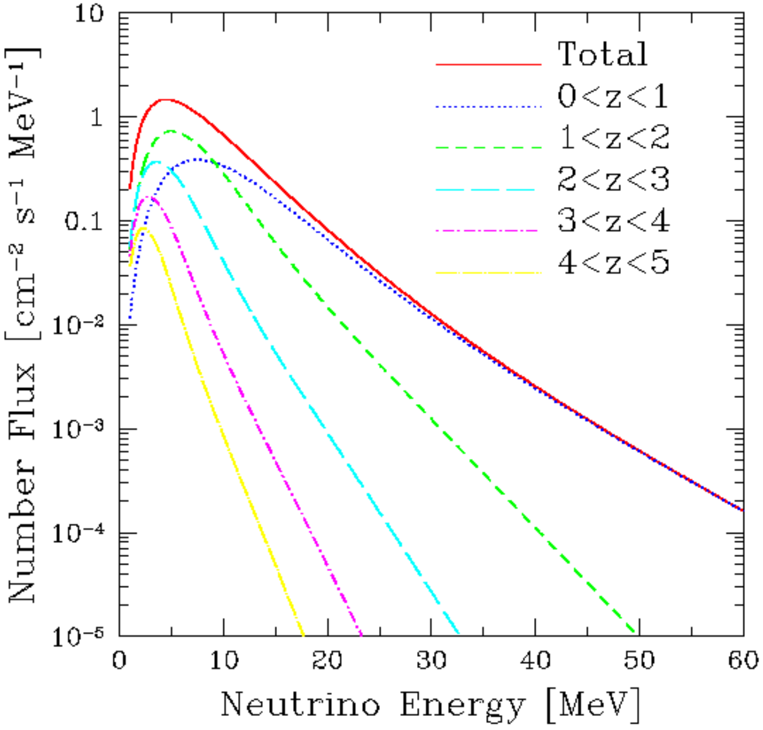
- Event rate at SK (yr^{-1})

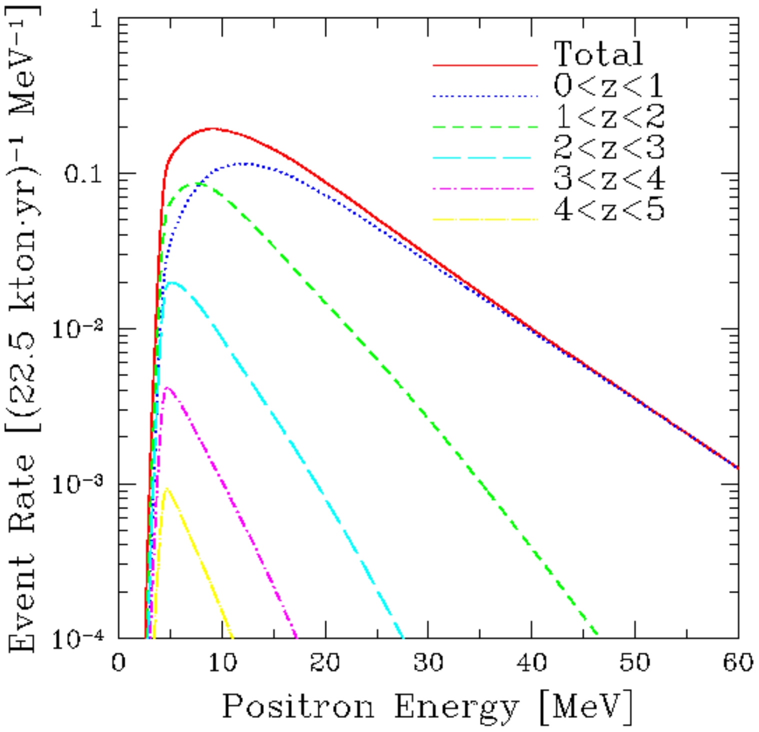
Model	$E_e > 10$ MeV	$E_e > 18$ MeV
LL	2.3	1.0
TBP	0.97	0.25
KRJ	1.7	0.53

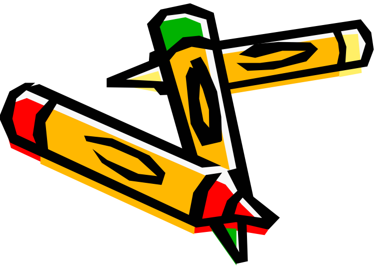


Flux & event rate (2)

LL model

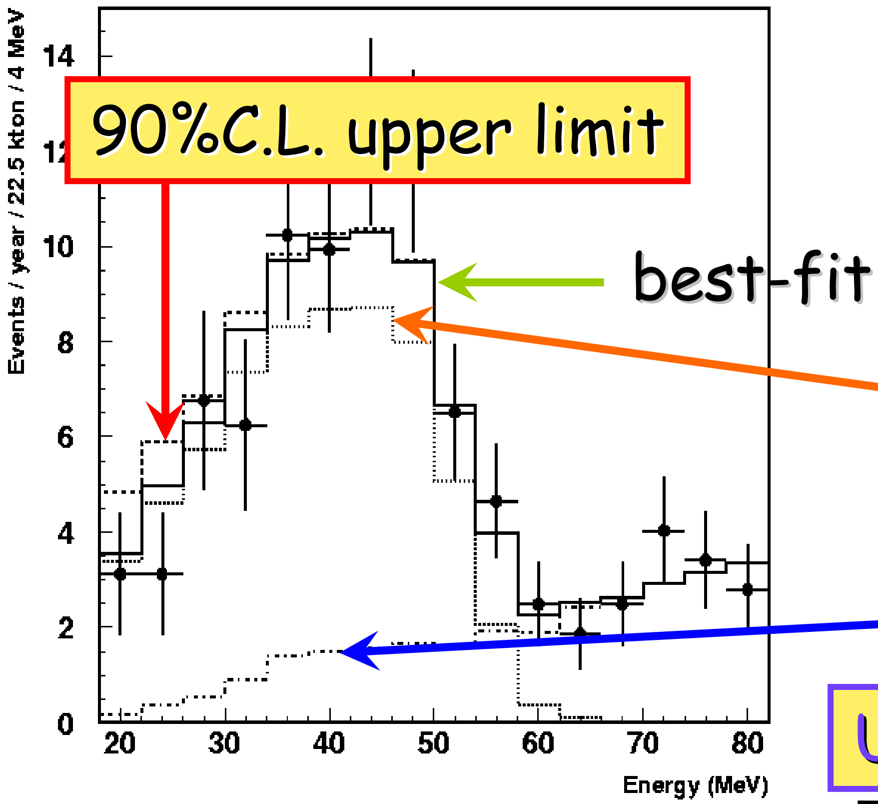






- At high energy region, high-z contribution is much less significant compared with local ($z < 1$) one.

Recent observational result from SK



Malek et al. (2003)

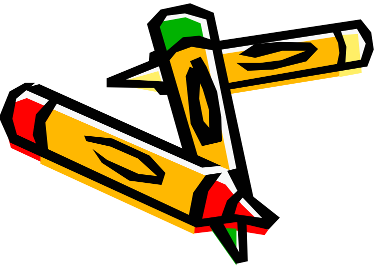
- Recently, SK Collaboration gave a very strong constraint on the SRN flux.

Atmospheric ν_μ → invisible μ → decay e

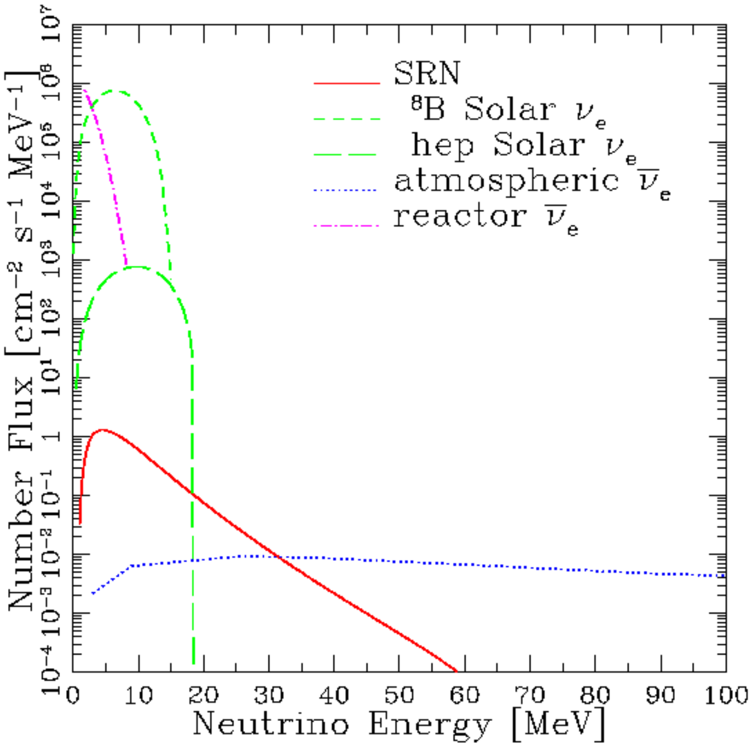
Atmospheric $\overline{\nu}_e$

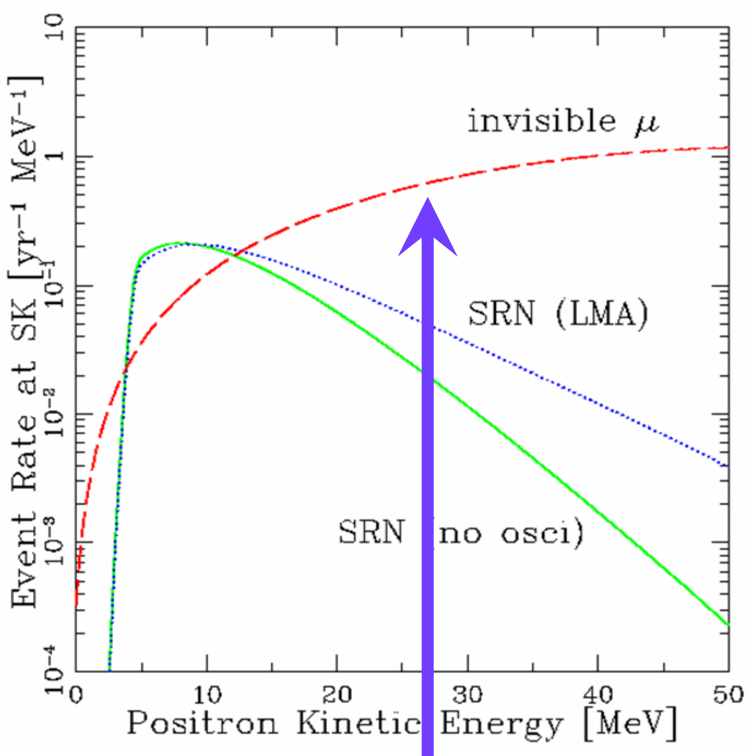
Upper limit for the LL model

Predicted flux	90% C.L. upper limit
12 $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	31 $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$



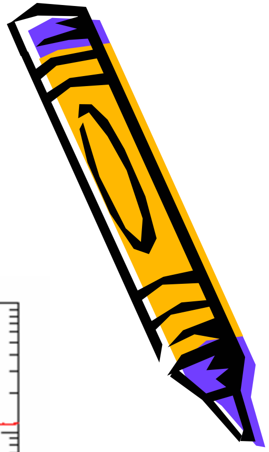
Background events

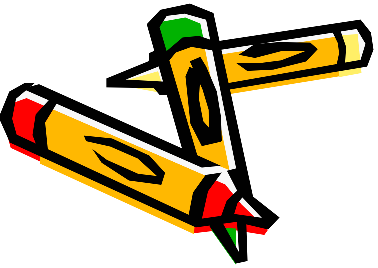




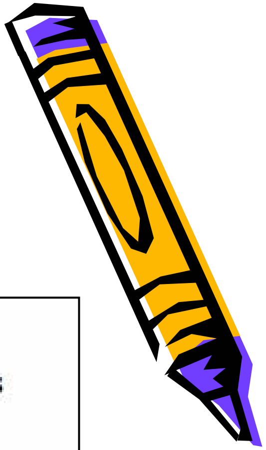
Atmospheric ν_μ → invisible μ → decay e

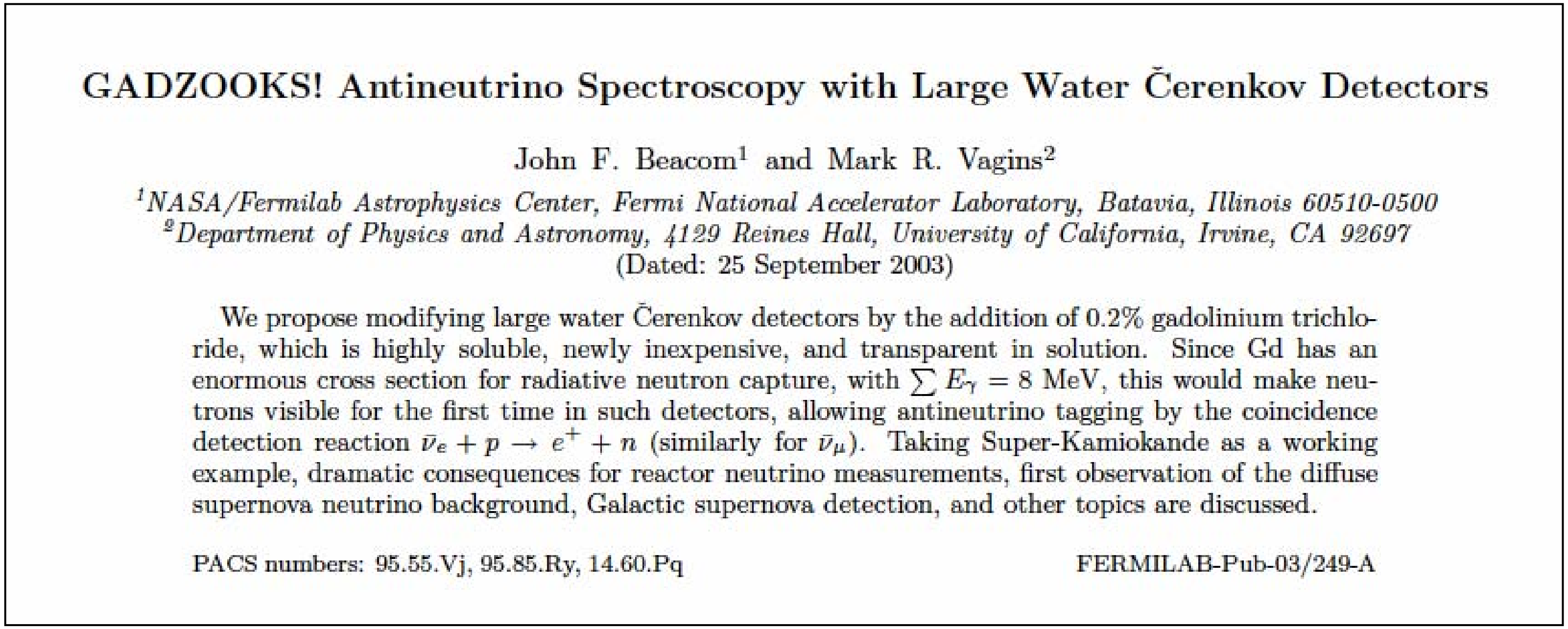
There is no "energy window."





GADZOOKS!





GADZOOKS! Antineutrino Spectroscopy with Large Water Čerenkov Detectors

John F. Beacom[1] and Mark R. Vagins[2]

[1]*NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500*
[2]*Department of Physics and Astronomy, 4129 Reines Hall, University of California, Irvine, CA 92697*

(Dated: 25 September 2003)

We propose modifying large water Čerenkov detectors by the addition of 0.2% gadolinium trichloride, which is highly soluble, newly inexpensive, and transparent in solution. Since Gd has an enormous cross section for radiative neutron capture, with $\sum E_\gamma = 8$ MeV, this would make neutrons visible for the first time in such detectors, allowing antineutrino tagging by the coincidence detection reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ (similarly for $\bar{\nu}_\mu$). Taking Super-Kamiokande as a working example, dramatic consequences for reactor neutrino measurements, first observation of the diffuse supernova neutrino background, Galactic supernova detection, and other topics are discussed.

PACS numbers: 95.55.Vj, 95.85.Ry, 14.60.Pq

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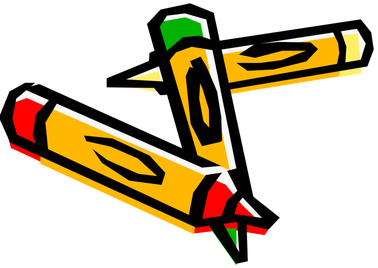
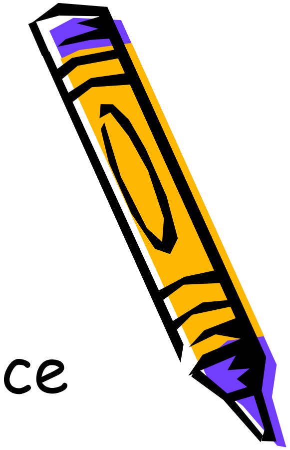
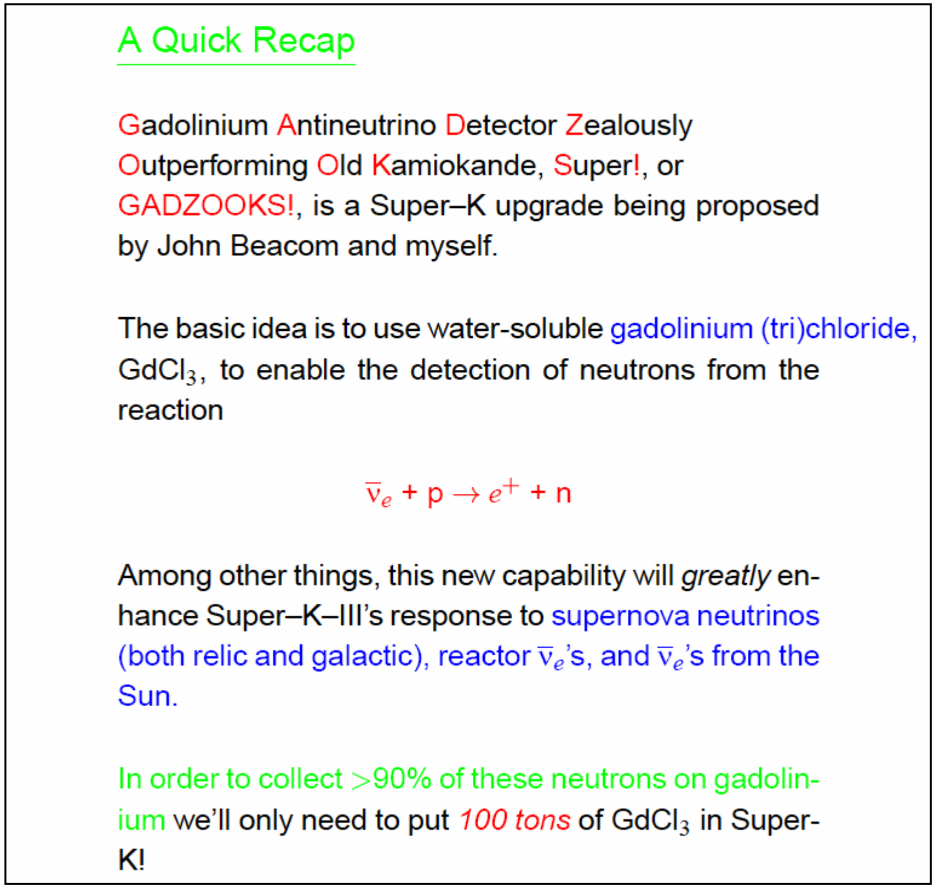


- A proposal for water Cerenkov detectors (SK; Hyper-K; UNO, etc.) by Beacom & Vagins (hep-ph/0309300).

GADZOOKS!





A Quick Recap

Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!, or GADZOOKS!, is a Super–K upgrade being proposed by John Beacom and myself.

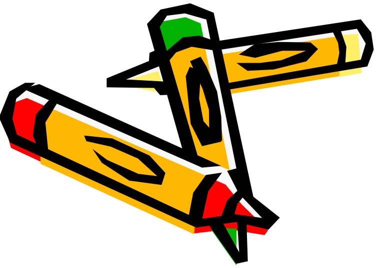
The basic idea is to use water-soluble gadolinium (tri)chloride, $GdCl_3$, to enable the detection of neutrons from the reaction

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

Among other things, this new capability will *greatly* enhance Super–K–III's response to supernova neutrinos (both relic and galactic), reactor $\bar{\nu}_e$'s, and $\bar{\nu}_e$'s from the Sun.

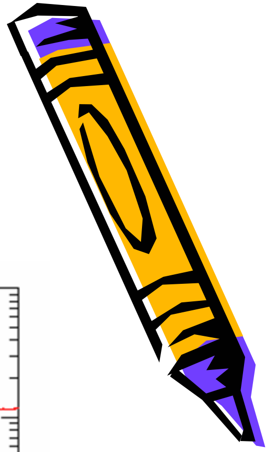
In order to collect >90% of these neutrons on gadolinium we'll only need to put *100 tons* of $GdCl_3$ in Super-K!

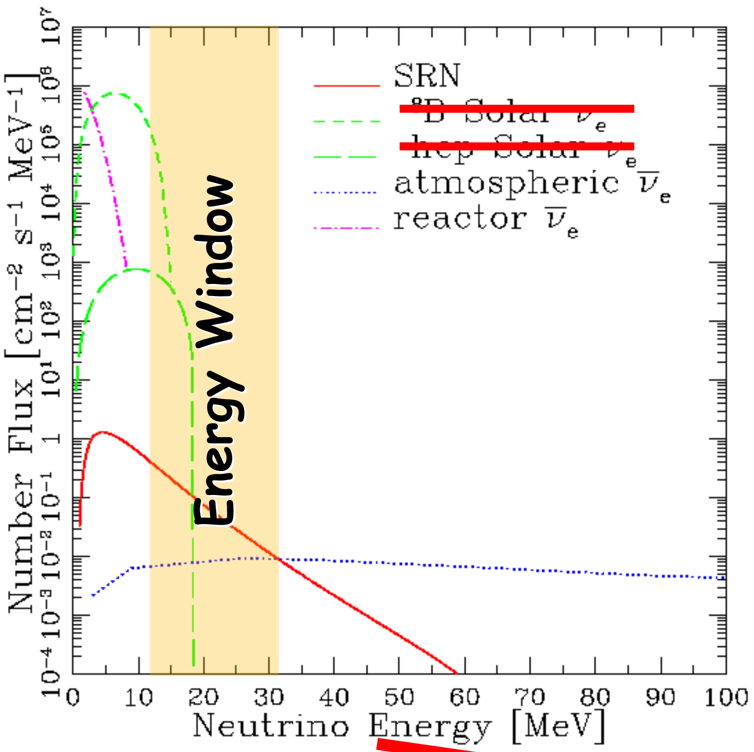
- Delayed coincidence signal of neutrons tagged by Gd.
- It enables to distinguish $\bar{\nu}_e$ from other flavors or μ-induced events.
- It opens up energy window at 10—30 MeV for the SRN detection.

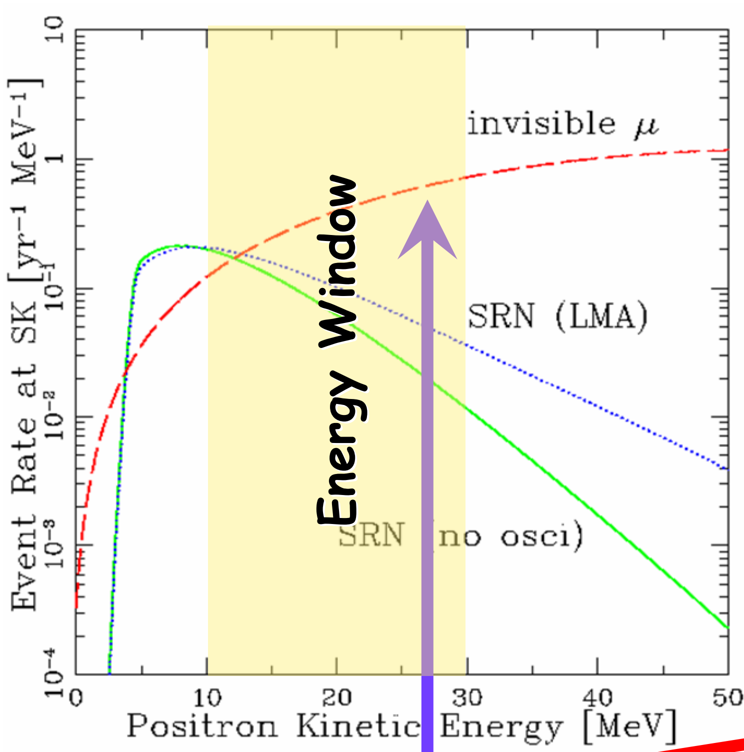


M. Vagins@NOON2004

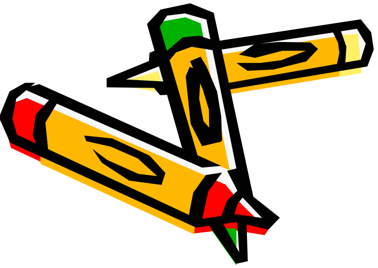
Energy window



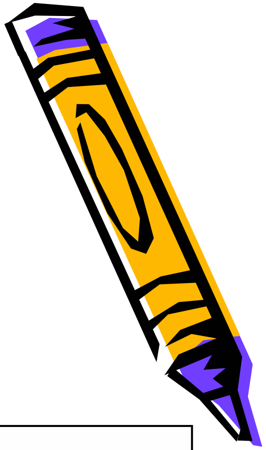




~~Atmospheric ν_μ → invisible μ → decay e~~



- Solar ν_e or invisible μ events become reducible!!



Summary of MC simulation

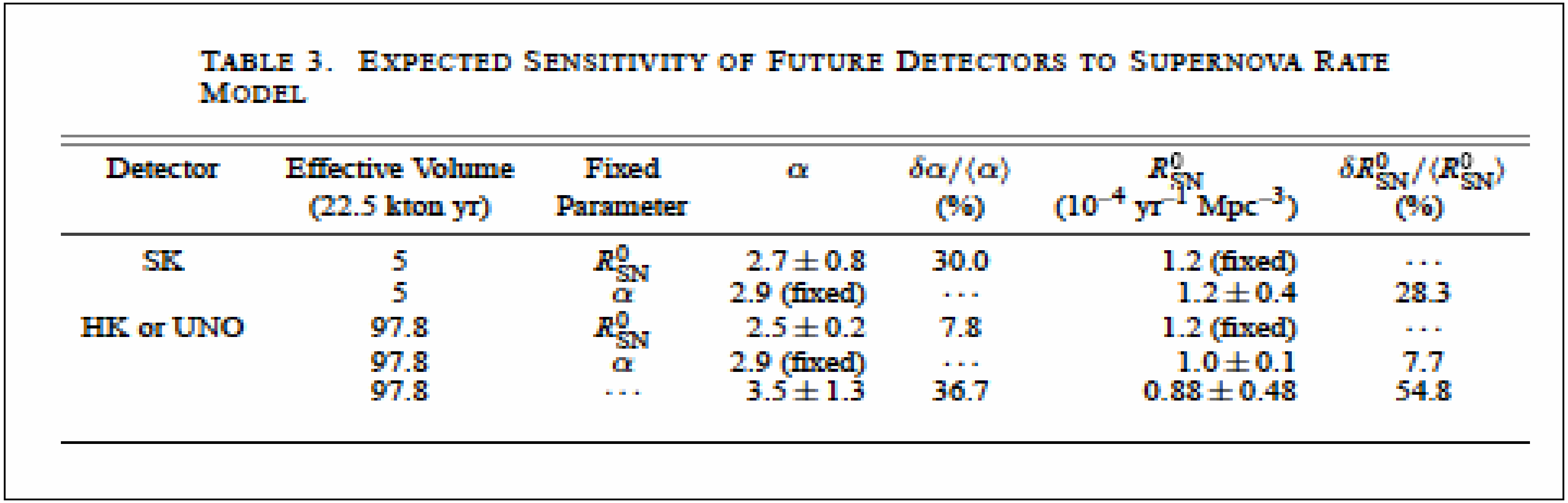


TABLE 3. EXPECTED SENSITIVITY OF FUTURE DETECTORS TO SUPERNOVA RATE MODEL

Detector	Effective Volume (22.5 kton yr)	Fixed Parameter	α	$\delta\alpha/\langle\alpha\rangle$ (%)	$R^0_{\rm SN}$ (10^{-4} yr^{-1} Mpc^{-3})	$\delta R^0_{\rm SN}/\langle R^0_{\rm SN}\rangle$ (%)
SK	5	$R^0_{\rm SN}$	2.7 ± 0.8	30.0	1.2 (fixed)	...
	5	α	2.9 (fixed)	...	1.2 ± 0.4	28.3
HK or UNO	97.8	$R^0_{\rm SN}$	2.5 ± 0.2	7.8	1.2 (fixed)	...
	97.8	α	2.9 (fixed)	...	1.0 ± 0.1	7.7
	97.8	...	3.5 ± 1.3	36.7	0.88 ± 0.48	54.8