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THE SUPERNOVA BURST OBSERVATORY: A PROTOTYPE EXTRA GALACTIC SN DETECTOR AND SUPERNOVA WATCH*

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ABSTRACT

We describe the conceptual study of a new type of supernova neutrino detector that may be scaled to a size adequate to observe extra galactic supernova neutrino bursts. A prototype detector could also be used to measure the mass of the μ or τ neutrino in the $5-50\,\mathrm{eV}$ range. We describe the development of the prototype at the WIPP site in New Mexico. Finally, we discuss a real time supernova watch network using the DOE Energy Sciences Network.

1. Introduction

For several years a small group has been studying the possibility of designing and constructing a supernova neutrino detector to observe extra galactic supernova explosions. The members of this group are M. Balbas and R. Boyd of Ohio State University, D. Cline, D. Chrisman, W. Hong, J. Park, S. Ramachandran and T. Smart of University of California Los Angeles, S. Colgate of Los Alamos National Laboratory, E. Fenyves and T. McCarthy of University of Texas at Dallas, G. Fuller of University of California San Diego, P. Glassley and S. Labov of Lawrence Livermore National Laboratory, B. Meyer and J. Wilson of Lawrence Berkeley Laboratory for Experimental Astrophysics, and H. Wollenberg of the Lawrence Berkeley Laboratory Earth Sciences Division. We call this detector a SuperNova Burst Observatory. This group is also studying the possibility of detecting a finite neutrino mass in the range of $5-50\,\mathrm{eV}$ from the detection of a galactic supernova.

There are two basic methods for neutrino mass determination from stellar collapse neutrinos. The first method is to analyze the total neutrino signal using parameterized models which span the expected possible signals.

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The neutrino mass would be one of the parameters. The neutrino mass is estimated then from the model signal which produces the greatest likelihood when compared to the observed signal. Thus, in the first method, the measurements include both time and neutrino energy. The second method is based on using other detectors sensitive to $\bar{\nu}_e$, for example Super Kamiokande, to give the time of a stellar collapse and then use the time shift in the onset of the ν_τ signal using the proposed neutral-current-based SuperNova Burst Observatory (SNBO) detector.

In this paper, contrary to other pessimistic conclusions for the detection of cosmologically significant neutrino mass from the burst of a galactic neutrino burst, we will show that the large volume SNBO detector (10^4 tons as Stage I.) at an extremely low radioactive background underground site, such as the WIPP site in New Mexico, is adequate to measure the τ neutrino mass in $10-50$ eV. The plan of this paper is as follows: (1) general discussion of concept, (2) calculations of the neutral current neutrino inelastic cross sections on nuclei, discuss radioactive background at the WIPP site, (3) calculate the detector efficiency by a Monte Carlo technique (4) show how we can can extract the neutrino mass from the supernova neutrino signal and effects of neutrino oscillation on the detector signal.

The basic detection concept of the SNBO detector is to use neutrino inelastic scattering on nuclei together with subsequent neutron emission from the excited nucleus as the basis of an astrophysical neutrino detector. The process would be

$$\nu_x + A(Z,N) \rightarrow A(Z,N-1) + n + \nu_x' \qquad (1)$$

where ν_x is either a ν_e, ν_μ or a ν_τ (see Fig. 1). Since we use the neutral current channel, $A(N,Z)$ is a nucleus of mass number A with Z protons and N neutrons. n is the final state free neutrons, and ν_x' is the scattered final state neutrino.

The initial SNBO detector would have the active mass of about 10^4 tons of NaCℓ and would be instrumented with a large number of neutron detectors. The detailed detector concept has been described in reference 1. This detector is mainly sensitive to ν_μ and ν_τ neutrinos and anti-neutrinos due to the dynamics of the neutral current process which strongly discriminates against lower energy ν_e and $\bar{\nu}_e$ events. Thus, it is a ν_μ, ν_τ detector.

The advantage of such a detector rests on three points:

(1) The enhancement of neutrino scattering cross sections due to nuclear collective effects[10]
(2) Ease of maintaining the detector over a long period of time
(3) Inexpensively up-scalable due to the economical BF_3 neutron detectors as compared to Ĉerenkov counters.

A conceptual outline of the detection of a supernova by SNBO and data analysis is given in Fig. 1[1].

We believe that there should be a set of complimentary detectors operating in the world to record the next supernova and that they should be interconnected by a realtime link, i.e. the SuperNova Watch Network, as illustrated in Fig. 2[2].

2. Methods

The ultimate goal of SNBO is to detect extra galactic supernovae. Fig. 3 shows the expected rate for SN explosions as a function of distance from earth (from E. Becklin, reference 3). In order to detect one SN per year, a detector of mass 10^7 tons is required. In order to be put forward a feasible project in the current funding climate, we estimate that the detector should cost no more than $\sim$ 5\$ per ton. The goal of SNBO is to be considered a prototype for such inexpensive detectors.

I estimate that the cost of all other techniques – H_2O Ĉherenkov detectors, Liquid Argon detectors, Scintillation detectors – will be at least $\sim$ 1K to 10K per ton. This would make them far to expensive to ever be constructed in the forseeable future.

3. Results

(This work is carried out with G. Fuller, W. Hong, B. Meyer and J. Wilson; see reference 1.)

A schematic of the measurement of a neutrino mass by time of flight from a supernova explosion is shown in Fig. 4. It is extremely important to obtain reliable source functions and detector models in evaluating the prospects for a unique mass determination.

Extracting the neutrino mass from a supernova signal with the SNBO detector is somewhat dependent on the computer model for stellar collapse. The computer model for stellar collapse developed by Wilson and Mayle[6] has given good agreement with the observation of SN 1987a. The calculations give the correct neutrino spectrum and time distribution. The observed total explosion energy and Ni^{56} production is given as well. The property we need from the calculation is the rise time of the $\bar{\nu}_e$ emission, relative to the $\nu_{\mu,\tau}$.

The ν_e production and emission is suppressed until the core becomes hot enough that degeneracy is decreased. Similarly, the $\nu_{\mu,\tau}$ emission is initially limited by the temperature since the $\nu_{\mu,\tau}$ production rate is proportional to T^9. A temperature of about 9 MeV is needed to produce enough $\nu_{\mu,\tau}$ so that the luminosity, $L_{\nu_{\mu,\tau}}$ is diffusion limited. This temperature is also about the same value needed to relieve the degeneracy suppression of the $\bar{\nu}_e$.

The coincidence of the rise time of the $\bar{\nu}_e$ and the $\nu_{\mu,\tau}$ is not strongly model dependent. Fig. 5 shows that the signal rises very rapidly after the stellar core bounce, about 0.1 sec. In Fig. 8 we can see the average energies of $\nu_{\mu,\tau}$ are higher than ν_e average energies.

We propose in order to analyze data from a Supernova to perform computer calculations, starting from likely initial stellar models, the expected ν_e signal and pick the best-fit model from this set. The comparison can be made between the computed $\nu_{\mu,\tau}$ signal for different neutrino masses and the observed $\nu_{\mu,\tau}$ to infer estimates of the neutrino masses. As an example, we carry out an analysis based on the calculated neutrino luminosity energy distributions from our model for SN 1987a.

The SNBO detector is characterized by an inelastic cross section, given in Ref. 5, $\sigma_1 (\epsilon - \epsilon_1)^2$, where the detector threshold is $\epsilon_1 \simeq 11\,\mathrm{MeV}$. Thus, we estimate the count rate by

$$C(t) = \sigma_1 \frac{\int_{\epsilon_1}^{\infty} \epsilon^2 (\epsilon - \epsilon_1)\, e^{-\epsilon/\mathrm{T}_1(t_e)}\, \mathrm{L}_1(t_e)\, d\epsilon}{\int_{\epsilon_1}^{\infty} \epsilon^2\, e^{-\epsilon/\mathrm{T}_1(t_e)}\, d\epsilon} \tag{2}$$

where $t_e = t - 0.514\,(\mathrm{MeV}/\epsilon)^2$ corresponding to the time shift for a neutrino of mass m_{eV} and energy ϵ_{MeV} expected at a distance of 10 kpc. $\mathrm{T}_1(t_e)$ and $\mathrm{L}_1(t_e)$ are taken from the computer model with $\mathrm{T}_0 = 1/3\times$ average $\nu_{\mu,\tau}$ energy and L_1 is normalized so that $\int C(t)\,dt = 12\mathrm{K}$.

In Fig. 6, the count rates are given for a variety of μ or τ neutrino masses[5]. Note that the mean time separation and shape of the time distribution are altered in a characteristic manner by the different neutrino masses. it is this characteristic that must be used to extract a cosmologically significant mass from a galactic supernova.

The strategy for detecting a lower neutrino mass will have to be different than for the higher mass case, i.e. $15-50\,\mathrm{eV}$. Since the time delay is proportional to δm^2, the time separation is very difficult to measure. However, the rise time of the neutrino pulse is expected to be very sharp and will reflect the dispersion due to the neutrino mass. In a detector such as the SNBO, where high energy neutrinos (ν_μ, ν_τ) are directly recorded, it will be possible to measure the rise time precisely.

The so called break-out pulse is shown in Fig. 7 from the most recent J. Wilson calculations[6,7]. Using this pulse, it is possible to see the lower mass effect if the initial neutrino signal is sharp enough, as we see in Fig. 8.

The key to SNBO is the detection of neutrinos produced in the inelastic neutral current reaction

$$\begin{array}{l} \nu_x + \text{Nucleus} \longrightarrow \nu_x + \text{Excited Nucleus} \\ \hspace{14em} \hookrightarrow \text{Neutron} \end{array} \tag{3}$$

This process has a high energy threshold and helps discriminate between $\nu_{\mu,\tau}$ and the other neutrinos due to the higher mean energy of the ν_μ and ν_τ from the supernova. The neutron detector method provides an inexpensive detector concept.

Careful modeling of this reaction has been carried out by G. Fuller, B. Meyer and W. Hong. However, once a site for SNBO has been chosen these calculations must be carried out in greater detail to adapt to the target material at the site and the detector configuration.

4. Conclusions

For sometime the SNBO group has been searching for an appropriate site for the tests of the detector concept[1]. We have found a potentially very low radioactive background site at the WIPP project in New Mexico. For our own purposes, the proposed tests are crucial to design, and evaluate the feasibility of this detection scheme.

The number of neutrino induced events produced by a supernova in our galaxy can be estimated with good accuracy. Therefore, an accurate estimate can be made of the signal to noise obtainable with our detection scheme if the background detection levels are known. Some trade-off between the number, i.e. the size, of the detectors and the detection rates in each, can be made to optimize the signal to noise ratio. However, this requires good knowledge of the background rates. Thus, for a variety of reason, we must know the information which the proposed tests would provide in order to design our detection scheme. We anticipate that such tests might be useful from the the perspective of the WIPP as well.

Development of a detector which could monitor radiation on-line could be extremely useful from the perspective of the mission of the WIPP facility. In this context the long absorption path length of neutrons in solids, i.e. the order of a meter, compared to that of beta or γ rays, i.e. generally centimeters or less, plays a significant role. Obviously, rapid detection of radiation leaks is essential for such a facility, requiring the monitoring of a variety of possible decay mode products. Both neutrons and alpha-particles produced in decays of transuranic nuclei could be detectable with the type of detector we are proposing to test: neutrons (which will be produced by fission) by direct detection and αs through their production of secondary neutrons via interactions with the constituents of nearby rock. Certainly, neutron detectors could provide a monitoring mechanism for leaks occurring in containment vessels in directions which would not produce detectable γ or β radiation at the site, again through detection of secondary neutrons.

Neutron detectors could also provide a scheme for rapid detection of geological disruptions near the site. This could be done in two ways:

(1) A dislocation could cause migration of surrounding material into the salt surrounding the WIPP

(2) A dislocation could cause release of trapped radionucleides

Even if the disruption occurred some meters away, the large difference in activity between the salt of the disposal site and surrounding clay or rock could thus produce a significant change in neutron flux within the disposal site. Therefore, the neutron detectors could have interesting geological applications as well.

The Department of Energy's Waste Isolation Pilot Plant (WIPP) is located approximately 25 miles east of Carlsbad, New Mexico (see Fig. 9). The site has been excavated at a depth of ~ 2200 feet in the Salado Formation, a salt unit of the Permian Age, i.e. ~ 225M years old. The Salado is approximately 2000 feet thick and is composed primarily of halite ($NaC\ell$) but also contains inter-bedded zones of anhydrite ($CaSO_4$). Although within ten feet above and below the depth of the WIPP facility clay beds and some anhydrite occur (inter-bedded with salt), the Salado is nearly pure halite at the depth of the WIPP site. Also occurring with the halite is polyhalite, a KMg, Ca sulfate mineral. Uranium concentrations in halite at WIPP range from 0.03 to 0.11 ppm. Thorium concentrations in halite at WIPP range from less than 0.08 (detectability limit) to 0.15 ppm[8]. The potassium concentration, based on data from other sites in salt, is estimated to range from 0.01 to 0.5%.

WIPP is under construction and experimentation in preparation to receive transuranic defense related waste. Access drifts and experimental drifts comprise several thousand lineal feel. These drifts could possibly accommodate a large array of neutron detectors for a long time. Although, when considering long-term occupancy of a research facility one must take into consideration the deformation of openings in salt in response to its plastic behavior, there are many reasons why this site is particularly attractive for an observatory: modern hoisting, ventilation and communication systems, spacious $\sim 10 \times 20$ foot drift cross sections, a technically capable work force and several decades of DOE presence.

We have done some preliminary test with a BF_3 detector 6 feet in length and 6 inches in diameter that was borrowed from Chalk River (Fig. 10). Excellent energy resolution of the neutron generated signals was obtained. One actually has resolved energy peaks so that backgrounds initiated by particles other than neutrons can be minimized. Cylinders of boron loaded paraffin are presently being constructed which will surround the detector to absorb thermal neutrons. Surrounding these cylinders will be cylinders of paraffin to thermalize any neutrons produced outside the detector. This scheme will allow us to measure the inherent neutron background generated by the materials in the detector which, as mentioned above, is an important number for the design of SNBO. We have measured a background rate of 1.6 events per minute but the conditions under which that measurement took place lead us to believe that the inherent rate may be significantly lower than this.

Results from the tests of the neutron detectors conducted at Ohio State University are shown in Fig. 11 The neutron detector performs as expected.

Shipment of the neutron detector to the WIPP site will occur as soon as the shielding has been fabricated. The boron loaded paraffin cylinders are nearly all fabricated and the materials required for the fabrication of the paraffin outer cylinders in hand. Tests at the WIPP site are expected to start in early 1993.

Discovery of x-ray bursts and γ bursts were completely unexpected. Could there be other sources of neutrino bursts than SN II, etc. explosions? A very large SNBO could search for such bursts.

One possible source for such a burst is decay of a primordial black hole (PBH). Other sources can be imagined (Table 1a). Table 1b lists some of the properties of PBH explosions.[9] Discovery of this phenomenon would be a very profound accomplishment in modern science.

5. References

1. Cline, D.B., et al., 1990, UCLA Report (unpublished); Cline, D.B., et al., 1992, UCLA Report (unpublished).
2. Cline, D.B., et al., 1992, UCLA-APH0054-4/92.
3. Becklin, E., 1991, World Scientific.
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6. Mayle, R., et al., 1989, World Scientific, eds Blair and Buckingham.
7. Burrows, A., et al., 1989, Phys.Rev., **D39**, 1020; Burrows, A., et al., 1992, Phys.Rev., **D45**, 3361.
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9. Cline, D.B., et al., 1992, Ap.J.Lett. (to be published).

TABLE 1a.

Possible Sources of Neutrino Transients
1) <u>PRIMORDIAL BLACK HOLE EVAPORATION</u>:
$M \sim 5 \times 10^{14}$gm decaying today
2) <u>QUIET SUPERNOVA EXPLOSIONS</u>:
Possibly Higher Rate than Visible SN II's
3) <u>COSMIC STRINGS</u>:
4) <u>SN II $\longrightarrow$ BLACK HOLES</u>:

TABLE 1b.

Primordial Black Hole Penomenology

1) Formed IN EARLY UNIVERSE - Zel'dovich Spectrum

2) Follow Beckenstein's and Hawking's 1^{st} law of BH Thermodynamics

3) $T = 10^{16}/M(\text{grams})\,\text{MeV}$

4) All PBH with $M < 5 \times 10^{14}$ GRAMS HAVE DECAYED

$$\dot{M} = -\alpha \left[\frac{M}{M^2}\right] \quad \sim (20/\text{year}\,??)$$

5) We STUDY DECAY of

$$M_{PBH} = 5 \times 10^{14}\,\text{g}$$

$$T = 20\,\text{MeV}$$

FINAL EXPLOSION PICTURE

- QCD-Like - Hard Spectrum
- Hagedorn-like $\sim$ Soft Spectrum (∞ # grams)
- Hybrid - Mixture of Hard and Soft
- In this model we get energy release of $\sim 10^{33}$ergs in $\sim \mathcal{O}(\text{ms})$

6) COMPARE WITH γ BURSTERS

A small fraction are compatible with this picture

7) What are CONSEQUENCES OF ASSUMING A FEW % ARE PBH

i) They are local [r < few parsecs]

ii) Neutrino Burst - SNBO

iii) Perhaps a small flux of higher energy γ's

- that can be detected in future γ telescopes
- $\sim (1 - 10)\,\text{m}^2$

6. Figure Captions

Fig.1: The super neutrino burst observatory concept.

Fig.2: Concept of a supernova or transient watch neutrino.

Fig.3: Estimated SN II rate as a functionof distance from Earth from the recent UCLA workshop.

Fig.4: Model SN neutrino burst characteristics and detector response to obtain range of neutrino masses that can be detected.

Fig.5: The neutrino luminosity function and average energies of the various neutrinos vs. time.

Fig.6: Dispersion of ν_τ signal due to neutrino mass for masses in the range of $20-40\,\mathrm{eV}$.

Fig.7: Example of the break-out pulse from calculations fo Burrows and Wilson.

Fig.8: Dispersion of ν_τ signal using the berak-out pulse for masses in the range $5-12\,\mathrm{eV}$.

Fig.9: The WIPP Site

Fig.10: Schematic of neutron detector tests at Ohio State University.

Fig.11: Neutron signal from the Ohio State tests

The Super Neutrino Burst Observatory Concept

1) GOAL: To measure τ neutrino mass

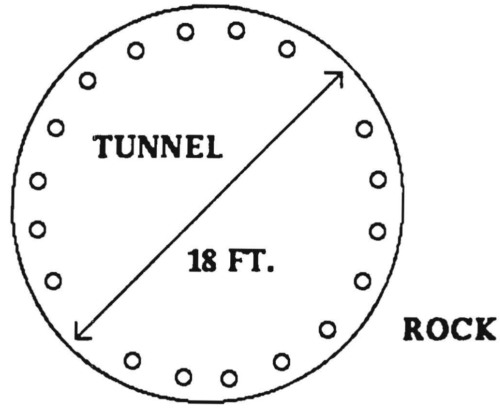
- direct unambiguous measurement -

2) METHOD: Use time of flight from Galactic SN

3) DETECTOR: Rock ($\nu + A \rightarrow \nu' + A' + n$)

(threshold exists since n is initially bound)

4) ENERGY: Average ν_τ energy is about 3/2 average $(\nu_e, \bar{\nu}_e)$ energy



5) COUNTS: More than 10^4 counts expected from Galactic SN

Use "inexpensive" neutron detectors - and

detectors requiring little direct maintenance

6) FROM CALCULATIONS:

$\langle E_{\nu_e} \rangle = 12\text{MeV} \quad \langle E_{\bar{\nu}_e} \rangle = 15\text{MeV} \quad \langle E_{\nu_{\mu,\tau}} \rangle = 25\text{MeV}$

7) RISE TIME: $L_{\bar{\nu}_e}$ and $L_{\nu_{\mu,\tau}}$ rise rapidly at

almost the same time (about 0.1sec)

8) FIRST PREDICTION: Take model output for spectra and $L_{\bar{\nu}_e}$

and $L_{\nu_{\mu,\tau}}$ and feed into detector response

to predict first 0.35 seconds of detection

9) MEASUREMENT DATA: Use Kamiokande II data for supernova

in Milky Way to measure $L_{\bar{\nu}_e}$ rise time

10) LIMITS: Compare ν_μ and/or ν_τ signal to find limits on m_{ν_μ} and/or m_{ν_τ}

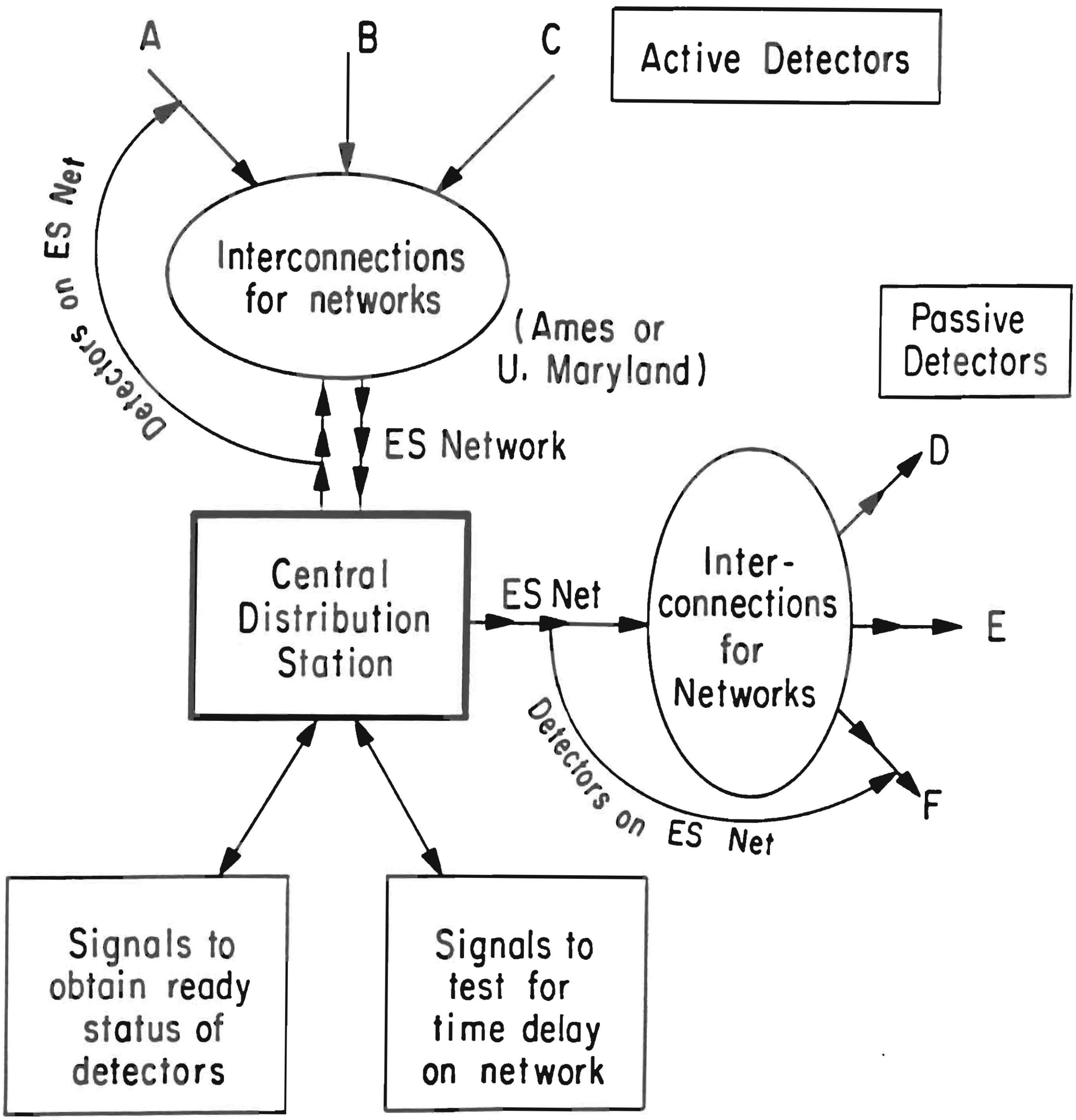
LLNL Cal. for SNBO Detector:

No. of Counts = $2 \times 10^4 \; \frac{V}{R^2}$ with V in meters^3, R in Mpc;

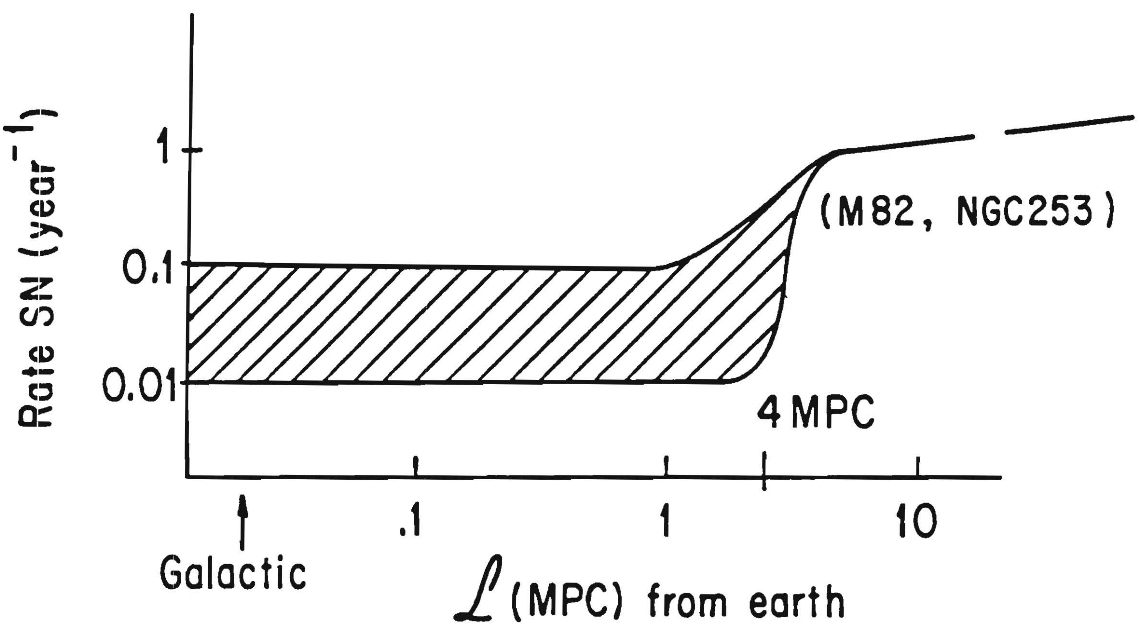
For Milky Way R = 0.01 Mpc; Let V = 10^4 meters^3

Then No. of Counts = 2×10^4

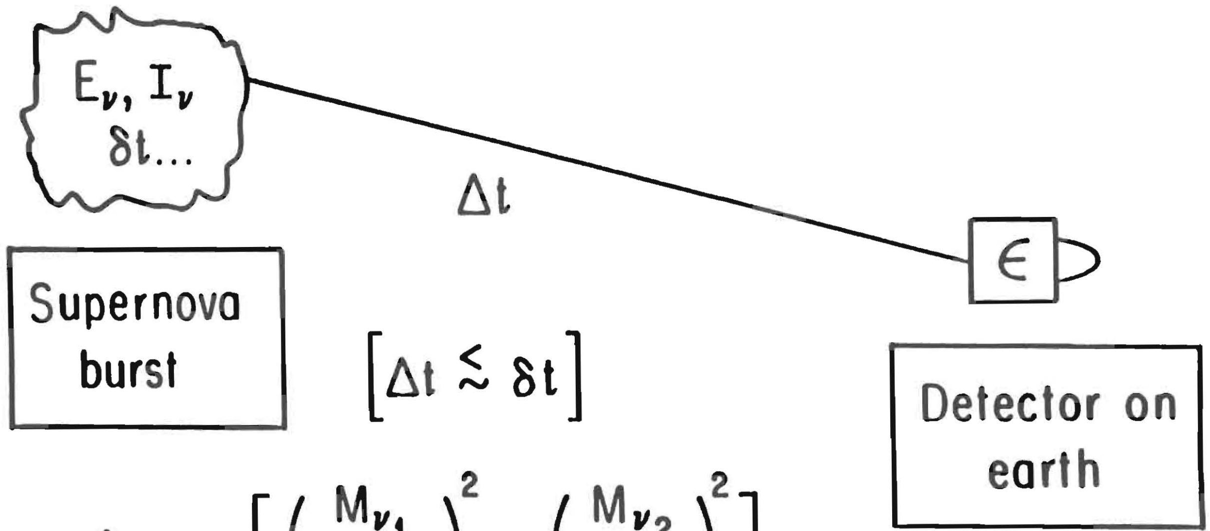
CONCEPT OF A SUPERNOVA OR TRANSIENT WATCH NETWORK



Example of use of network:
- Supernova detection coordination
- Correlation between γ bursts in space and interactions on earth (i.e. air showers)

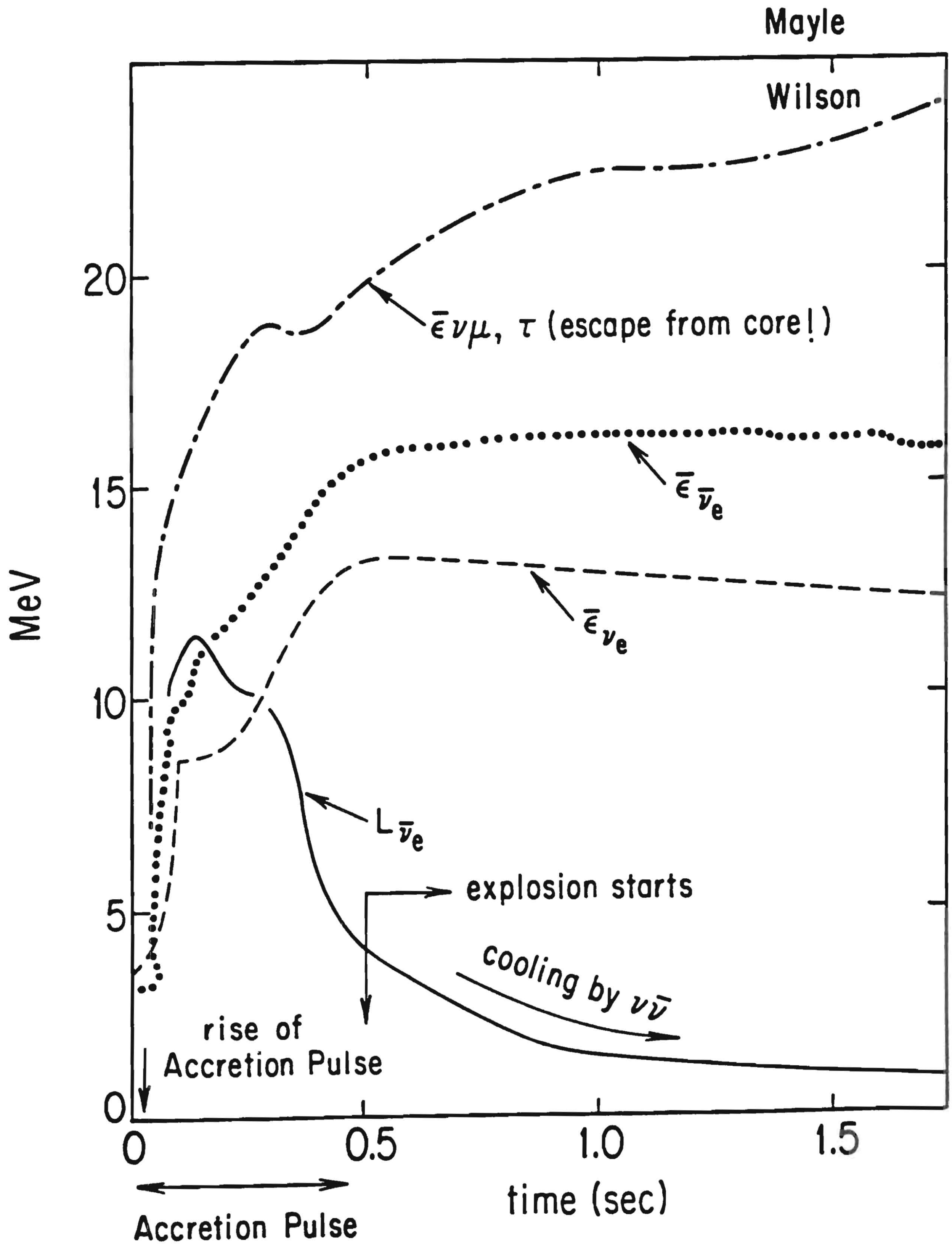


Rate SN (year^{-1})
1
0.1
0.01
(M82, NGC253)
4 MPC
.1
1
10
Galactic
$\mathcal{L}$ (MPC) from earth

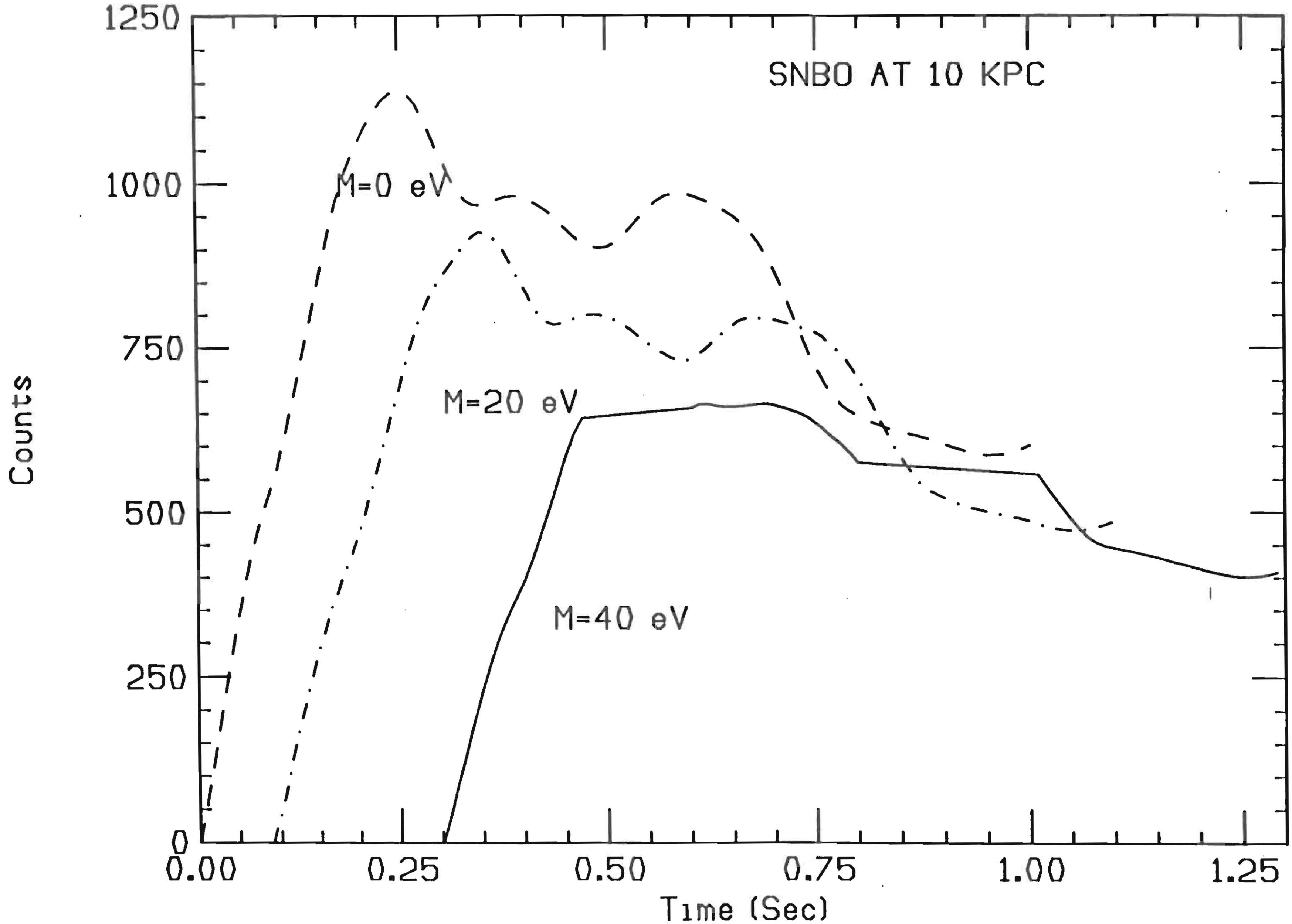


$$\Delta t \propto \left[\left(\frac{M_{\nu_1}}{E_1} \right)^2 - \left(\frac{M_{\nu_2}}{E_2} \right)^2 \right]$$

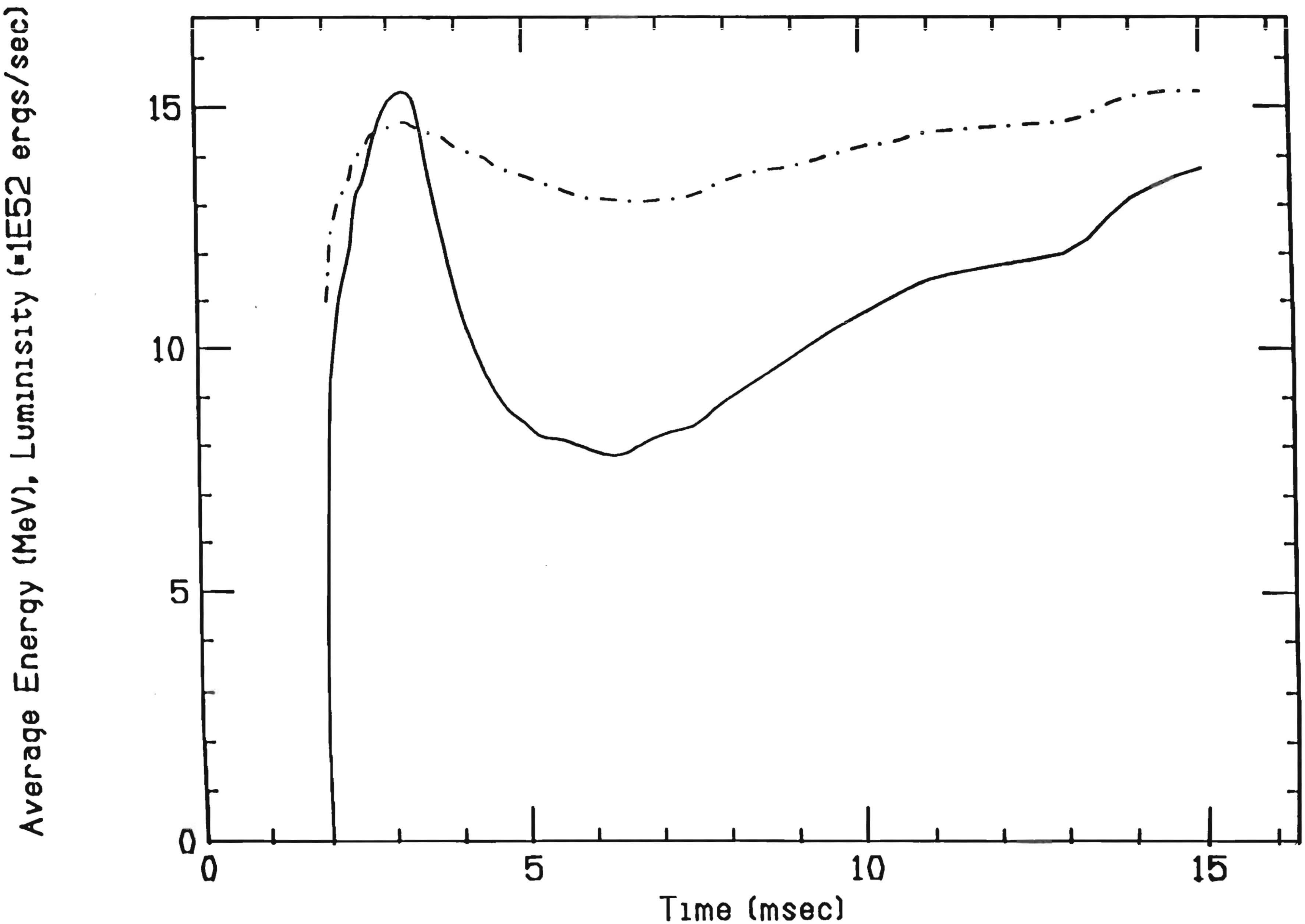
Model SN Neutrino Burst Characteristics and Detector Response to Obtain Range of Neutrino Masses that can be Detected



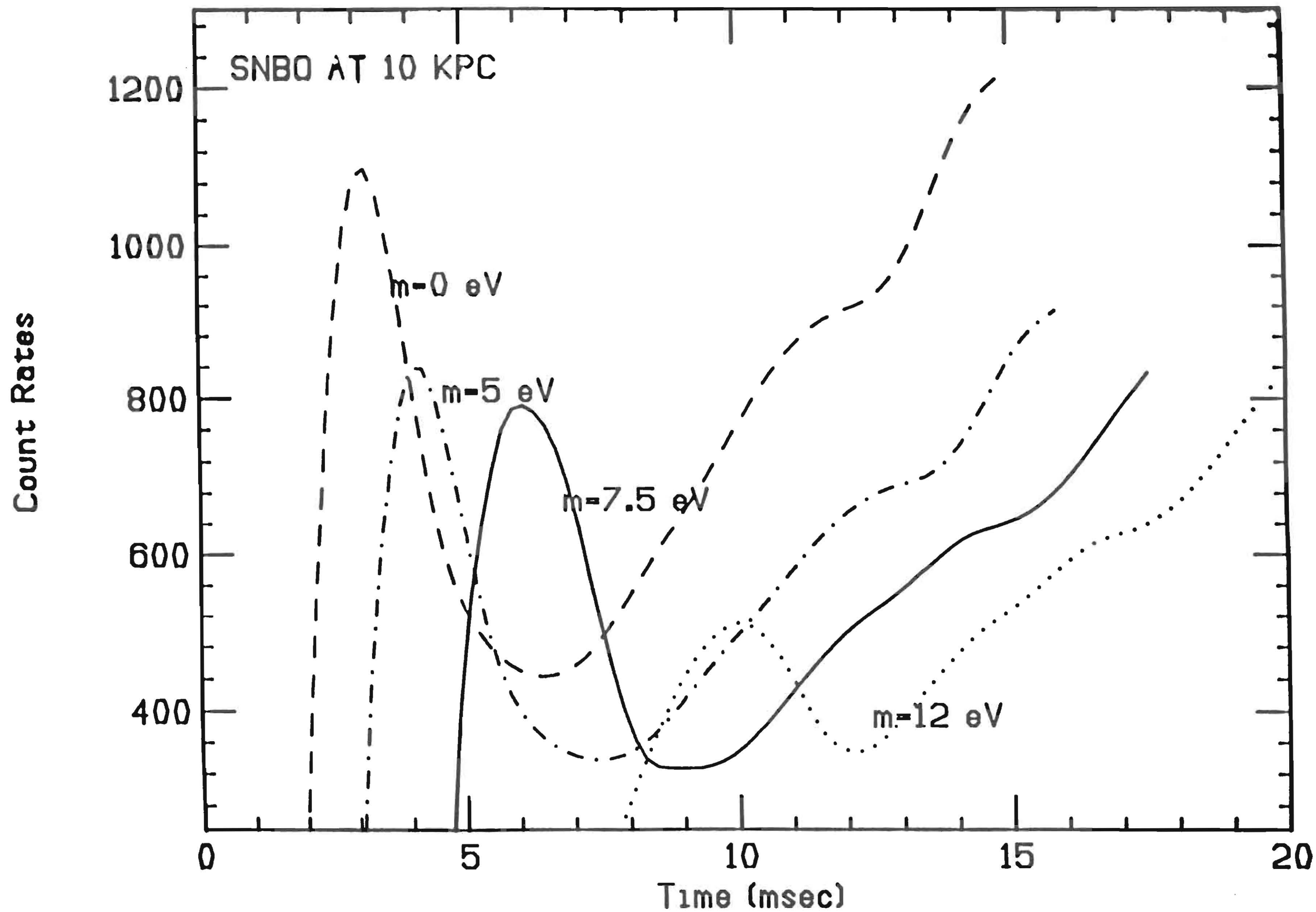
Mayle
Wilson
$\bar{\epsilon}\,\nu\mu,\ \tau$ (escape from core!)
$\bar{\epsilon}_{\bar{\nu}_e}$
$\bar{\epsilon}_{\nu_e}$
$L_{\bar{\nu}_e}$
explosion starts
cooling by $\nu\bar{\nu}$
rise of
Accretion Pulse
MeV
0
5
10
15
20
0
0.5
1.0
1.5
time (sec)
Accretion Pulse

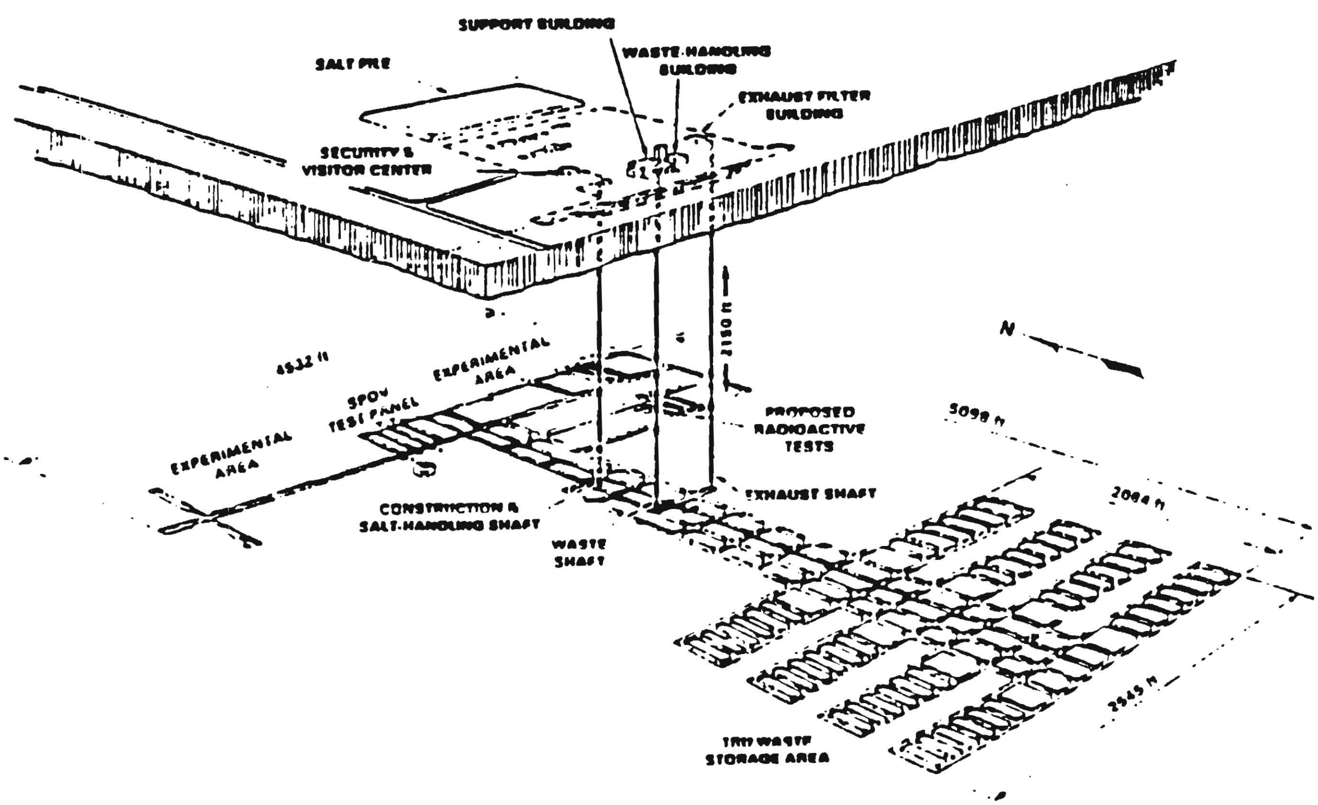


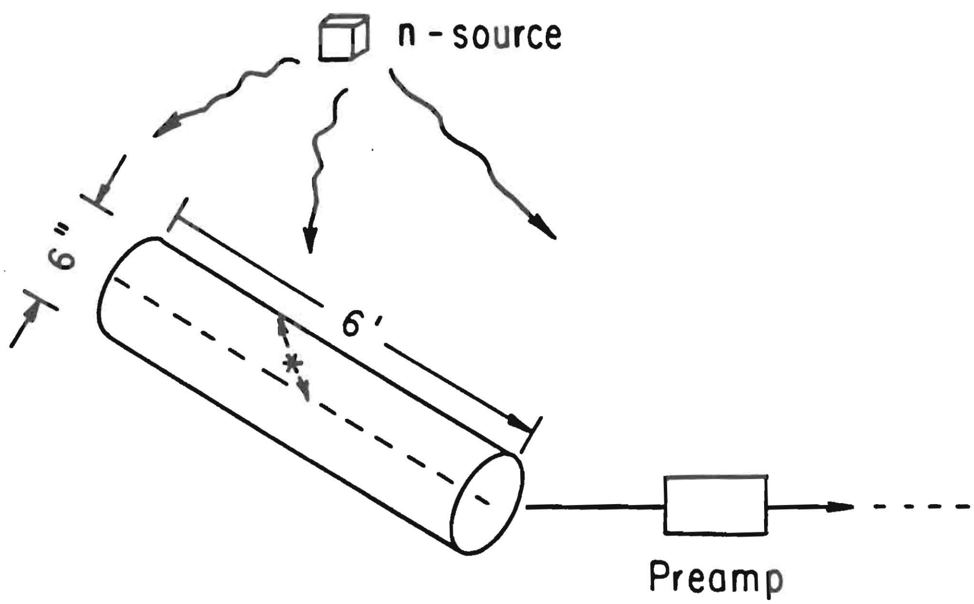
SNBO AT 10 KPC
M=0 eV
M=20 eV
M=40 eV
Counts
Time (Sec)
0
250
500
750
1000
1250
0.00
0.25
0.50
0.75
1.00
1.25



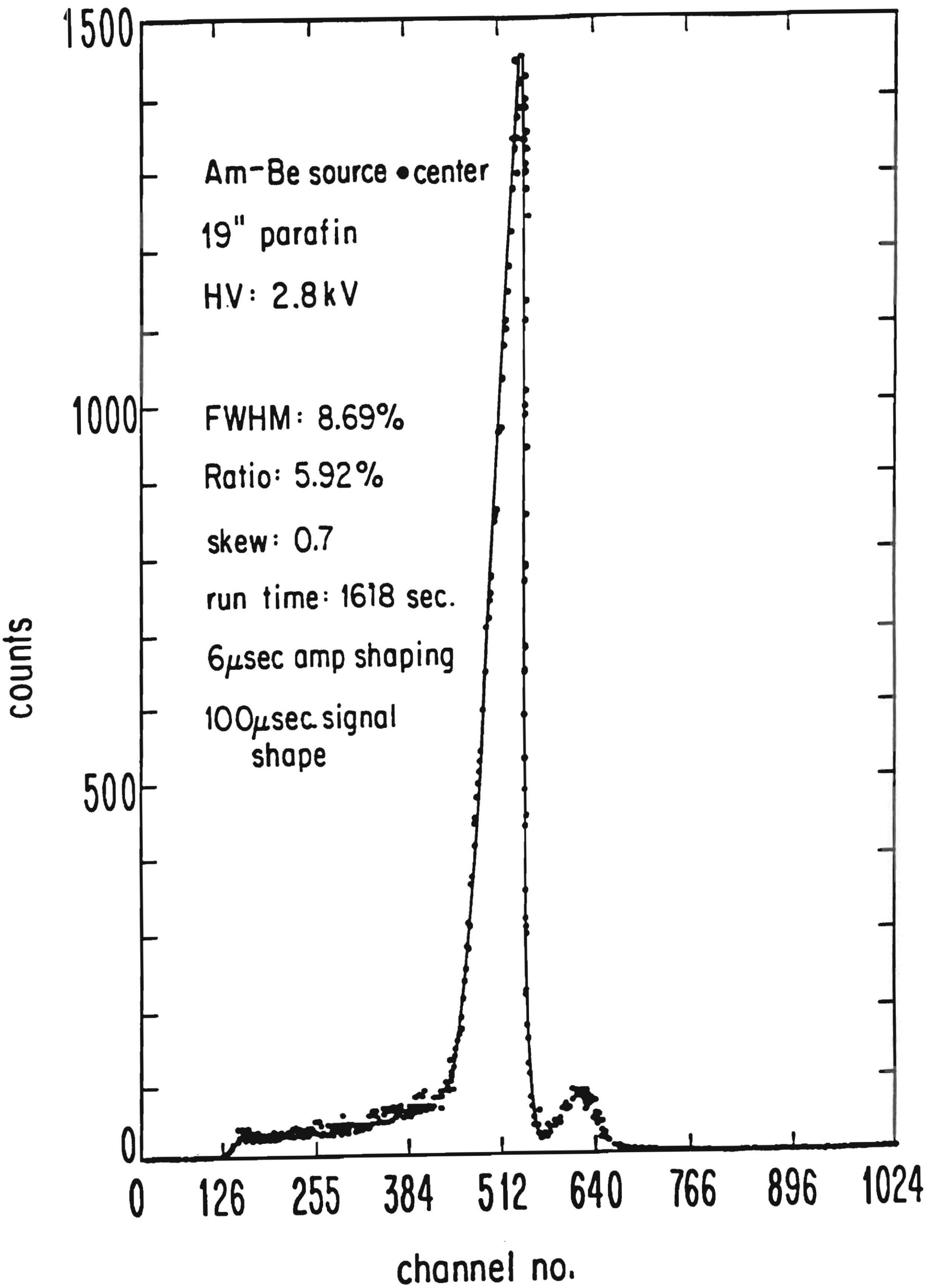
Average Energy (MeV), Luminisity (=1E52 ergs/sec)
Time (msec)
0
5
10
15


SNBO AT 10 KPC
m=0 eV
m=5 eV
m=7.5 eV
m=12 eV
Count Rates
Time (msec)
1200
1000
800
600
400
0
5
10
15
20


SUPPORT BUILDING
WASTE-HANDLING BUILDING
SALT PILE
EXHAUST FILTER BUILDING
SECURITY & VISITOR CENTER
2150 ft
N
EXPERIMENTAL AREA
SPDV TEST PANEL
EXPERIMENTAL AREA
PROPOSED RADIOACTIVE TESTS
5098 ft
EXHAUST SHAFT
CONSTRUCTION & SALT-HANDLING SHAFT
WASTE SHAFT
2084 ft
2545 ft
TRU WASTE STORAGE AREA



$$n + {}^{10}B \longrightarrow \alpha + {}^{7}Li$$



Am-Be source • center
19" parafin
HV: 2.8kV
FWHM: 8.69%
Ratio: 5.92%
skew: 0.7
run time: 1618 sec.
6μsec amp shaping
100μsec signal shape
1500
1000
500
0
counts
0
126
255
384
512
640
766
896
1024
channel no.