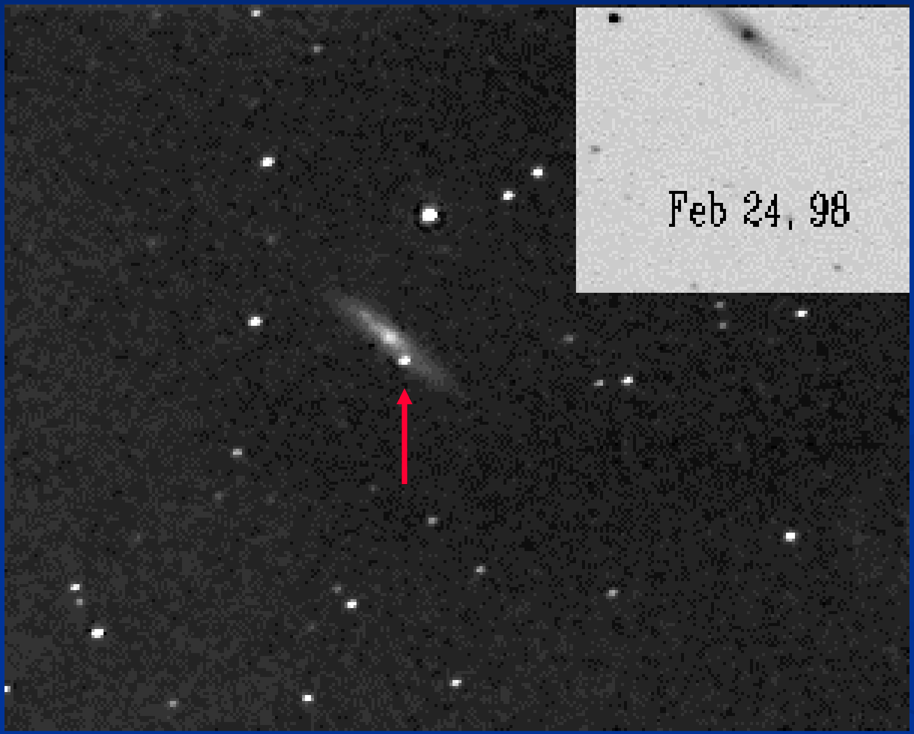
Supernovae and Neutrino Elastic Scattering



SN1998S, April 2, 1998 (8" SCT homemade CCD)

Trento, June, 2003

Keywords (Prof. Fujita)

- Weak magnetism corrections to the β decay of supernovae as observed via ν-A elastic scattering in solar ν, double β decay, and dark matter detectors,
- Implications for neutrino oscillations, nucleosynthesis, and close in massive planets.
- The FINESE accelerator experiment on elastic ν-p scattering to determine the strange quark contribution to the spin of the nucleon.

Supernovae and Weak Interactions

- Core collapse SN dominated by weakly interacting neutrinos. Unique chance for macroscopic manifestations of symmetries and features of standard model weak interactions.
- Example: Large P violation related to large C viol. $\rightarrow$ ν-N interaction fundamentally stronger then anti-ν-N.
- Difference between ν and anti-ν is of recoil order, E_ν/M, but has a large coefficient from weak magnetism,

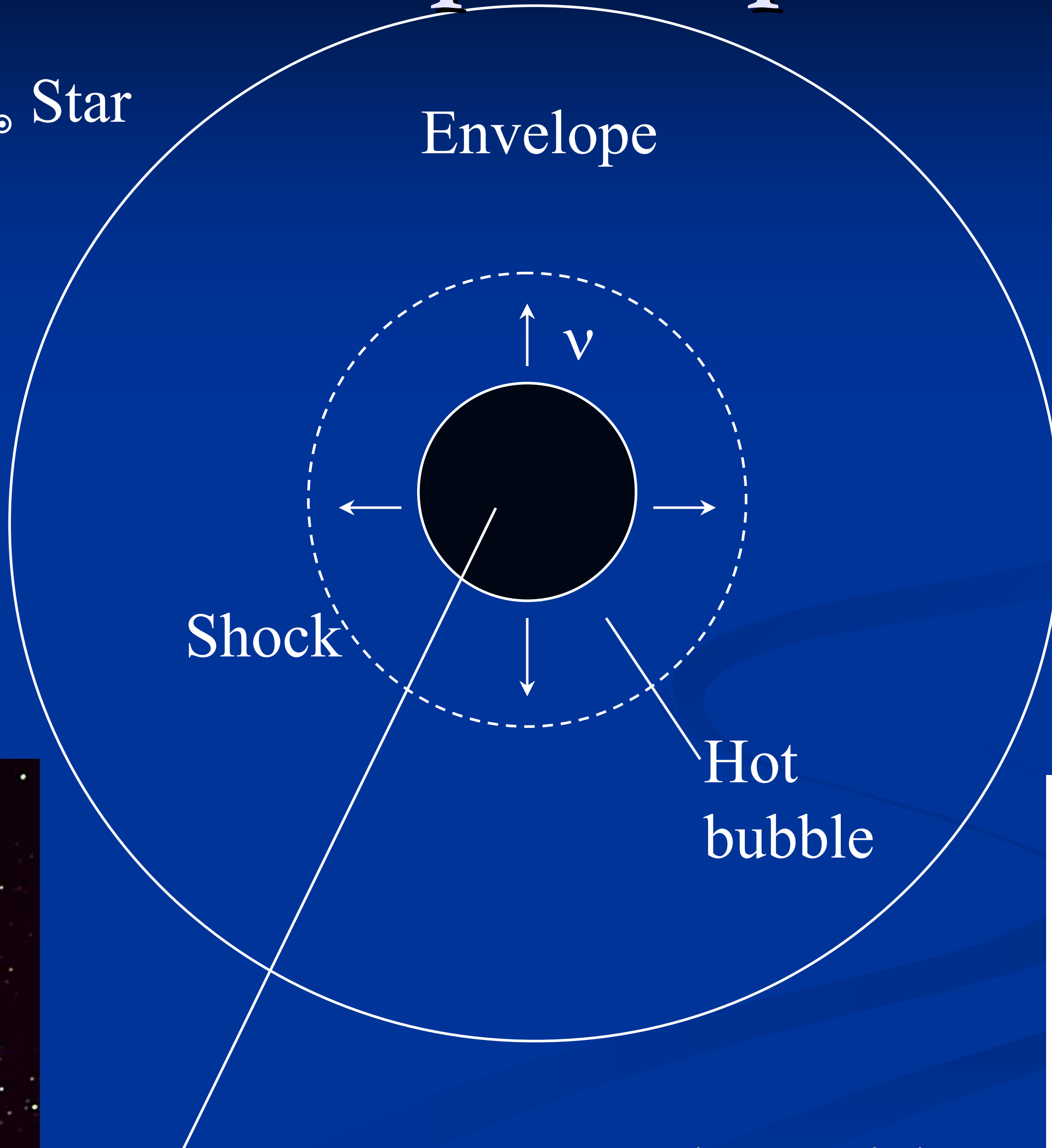
$$J_\mu = F_1\gamma_\mu + F_2 i\sigma_{\mu\nu}q^\nu/2M$$

and is important for both charged and neutral currents.

- Weak magnetism in SN: Gang Li, Angeles Perez-Garcia and CJH: Phys.Rev. D65 (2002) 043001, **astro-ph/0305138.**

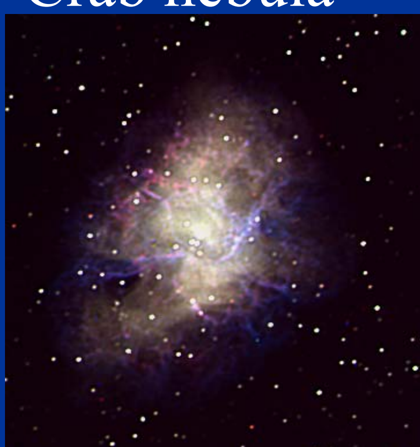
Core Collapse Supernova

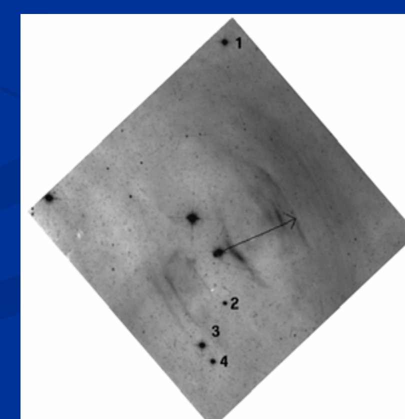
$>8M_{\odot}$ Star



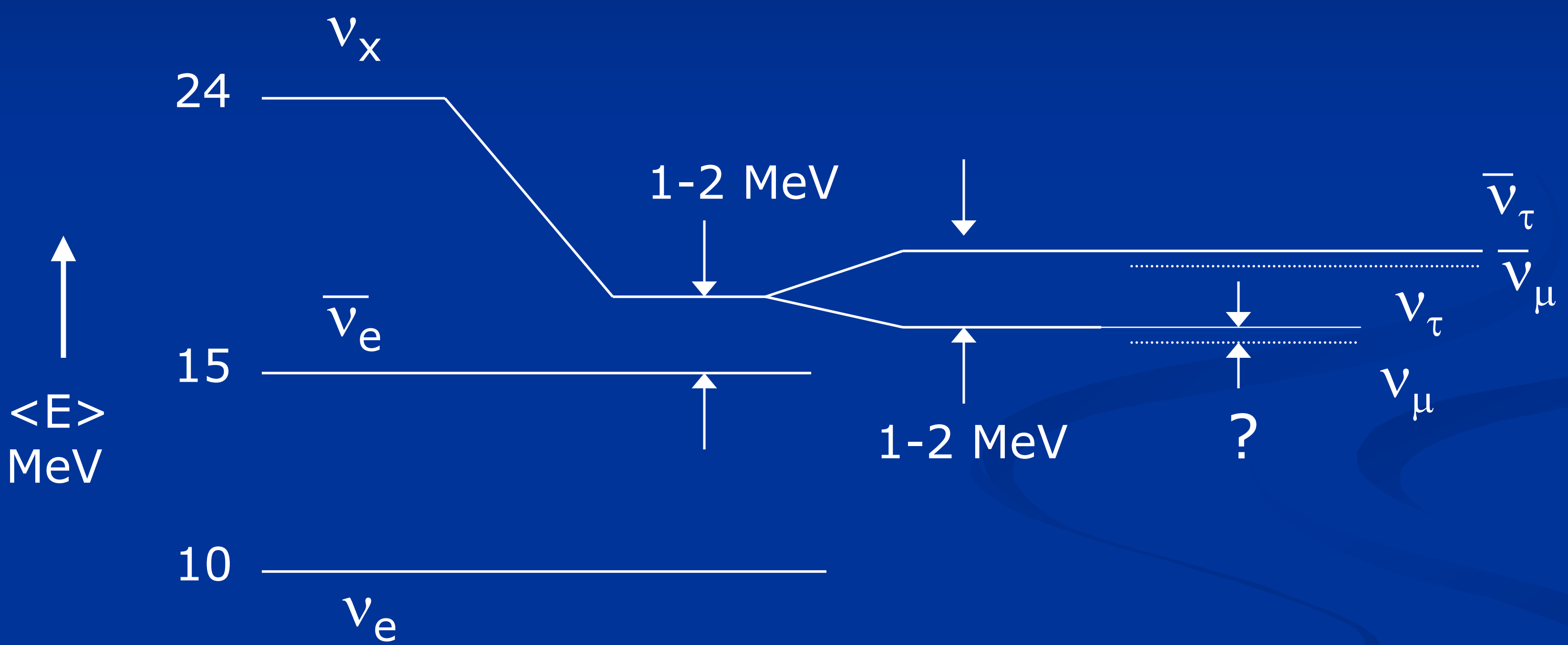
July 5, 1054

Crab nebula





ν Spectra (Before Osc.)



Structure:
Charged Currents
split ν_e from ν_x

Fine Structure:
Weak Magnetism
splits ν_x from $\bar{\nu}_x$

Hyper-fine:
Muons split
ν_μ from ν_τ ?

Measure Energy of ν_x

- $E(\nu_x)-E(\nu_e)$ is "lever arm" for neutrino osc.
- Measure total E of SN. This is binding energy of neutron star.
  - Most of SN energy in ν_x.
  - N Star binding E ~ M^2/R.
  - Mass of NS interesting, could later collapse to black hole.
  - Nucleosynthesis depends on "compactness" M/R. Larger value gives higher entropy for escaped material.

Existing SN ν Detectors

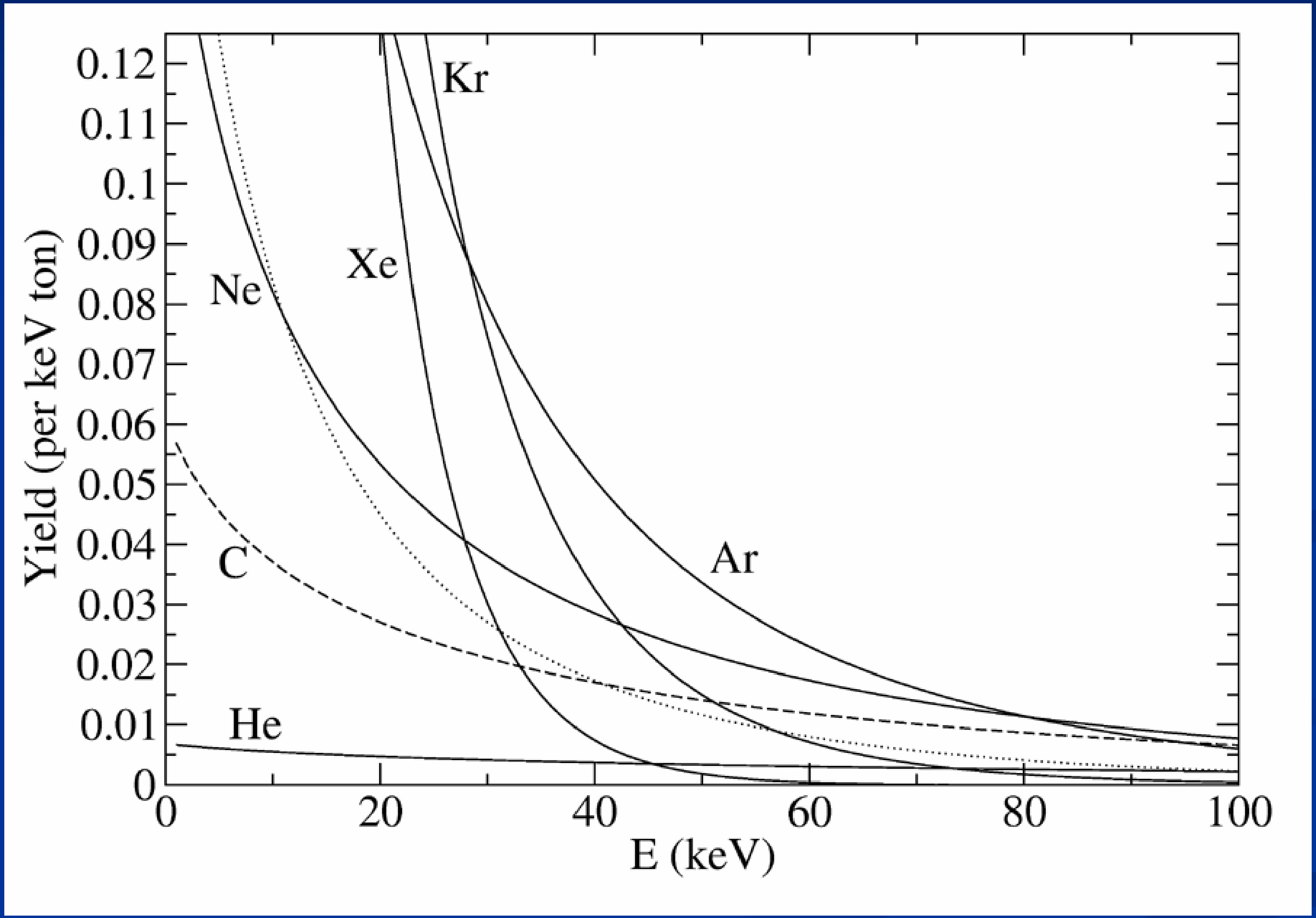
- Measure E of anti-ν_e well: $\bar{\nu}_e + p \rightarrow n + e^+$.
- Detect ν_x without direct E information.
  - $^{16}O(\nu_x,\nu_x')^{16}O^* \rightarrow \gamma + {}^{16}O$ in SK.
  - $d(\nu_x,\nu_x')np \rightarrow$ count n in SNO.
- To directly measure $E(\nu_x)$ need two body final state: ν-e (small cross section), ν-p elastic (perhaps possible in Kamland –J. Beacom), ν-A elastic.
- Coherent ν-A cross section very large and spectrum of recoils gives ν_x spectrum. But E is low ~ 50 keV.

Huge Elastic Signal

- Assume SN at 10 kpc, 3×10^{53} ergs total energy, equal partition of energy among six flavors, and $T(\nu_x)$, $T(\text{anti-}\nu_e)$, $T(\nu_e)$ = 8, 5, 3.5 MeV see **astro-ph/0302071.**
- Yield much larger then existing detectors (100s of anti-ν_e and 10s of ν_x per *kilo*-ton).

Nucleus	Events/ ton	<E>
^{4}He	0.9	240 keV
^{12}C	2.5	83
^{20}Ne	4.0	46
^{76}Ge	18.6	9.5
^{132}Xe	31.1	4.8

Recoil Spectra for Different Targets



Dotted curve for ^{20}Ne assumes T for ν_x = 5 MeV others use 8 MeV.

Detecting Low E Recoils

- Physics of detecting low E solar ν, dark matter via nuclear recoils, and double β decay similar to SN ν-A elastic.
- Lots of work on large mass, low threshold, low background detectors.
- Background for SN ν much less severe then others because of high count rate.
- ββ decay: Proposed Majorana and Genius detectors will involve ½-1 ton of ^{76}Ge. [Existing Ge exps have needed threshold and background rates.] These should be sensitive to a galactic SN!
- Dark Matter: It may take ton quantities of Xe or other materials coupled with extraordinary background rejection to probe most of SUSY parameter space.

CLEAN Detector

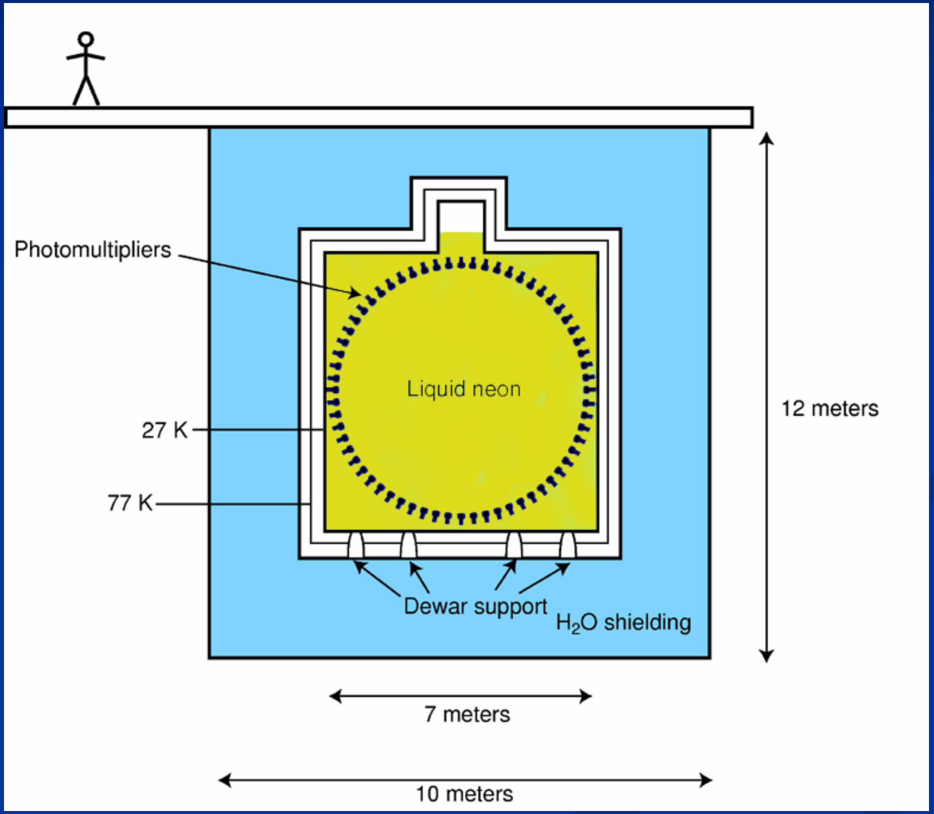
- Cryogenic Low Energy Astrophysics with Noble gases.
- Based on liquid Ne which scintillates in UV and is easy to purify (little intrinsic background).
- "Day job" detect low E pp solar ν via ν-e elastic. Constrains Θ_{12} … important to verify fundamental pp flux.
- Sensitive to dark matter.

CNO ν

- CNO cycle captures 4 protons on CNO nuclei with two beta decays to produce an alpha particle. No net change in C, N, O.
- CNO cycle is energy source for stars slightly hotter then sun. In sun CNO is only about 1-2% of pp burning.
- CNO ν flux very sensitive to both T and metal abundance. Central metal abundance also important for opacity which determines temperature.
- Measure both ^{8}B and CNO ν fluxes. Allows determination of both central T and metal abundance of sun.
- Can test for contamination of outer convection zone with metals from fallen "hot Jupiters".
- Final search for the planet Vulcan???

CLEAN Simulation

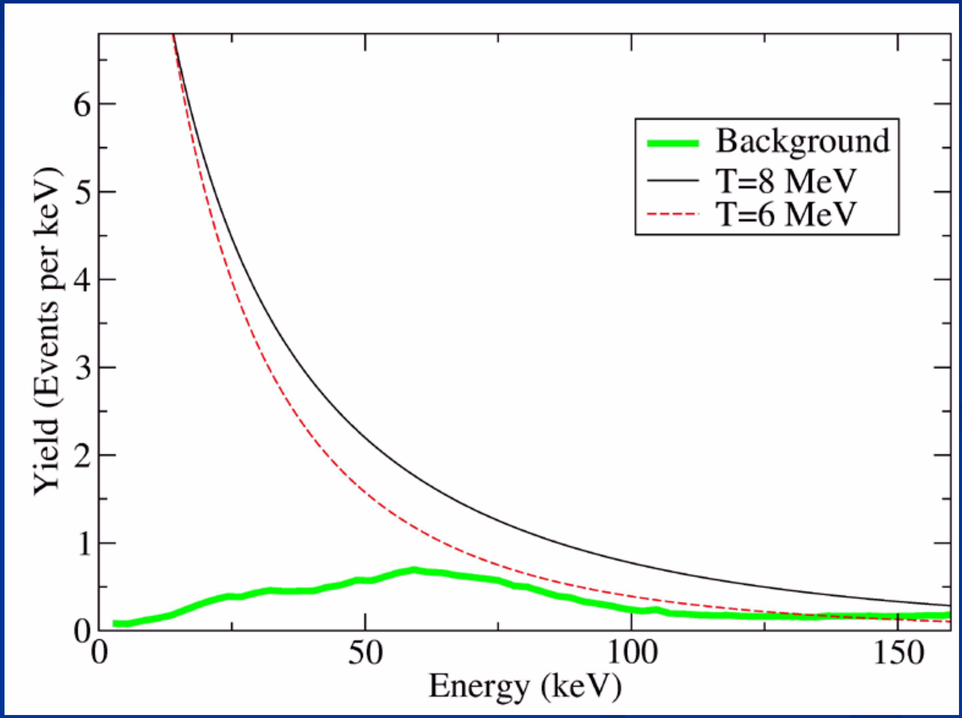
- Kevin Coakly, Dan Mckinsey, CJH, **astro-ph/0302071.**
- Phototubes with wavelength shifters view 100 tons of liquid Ne.
- Assume background dominated by U, Th, K… in phototubes, shifters and support structure.
- Find event position from hit pattern in phototubes.



Assume quenching factor of ¼ for light from Ne ions compared to e.

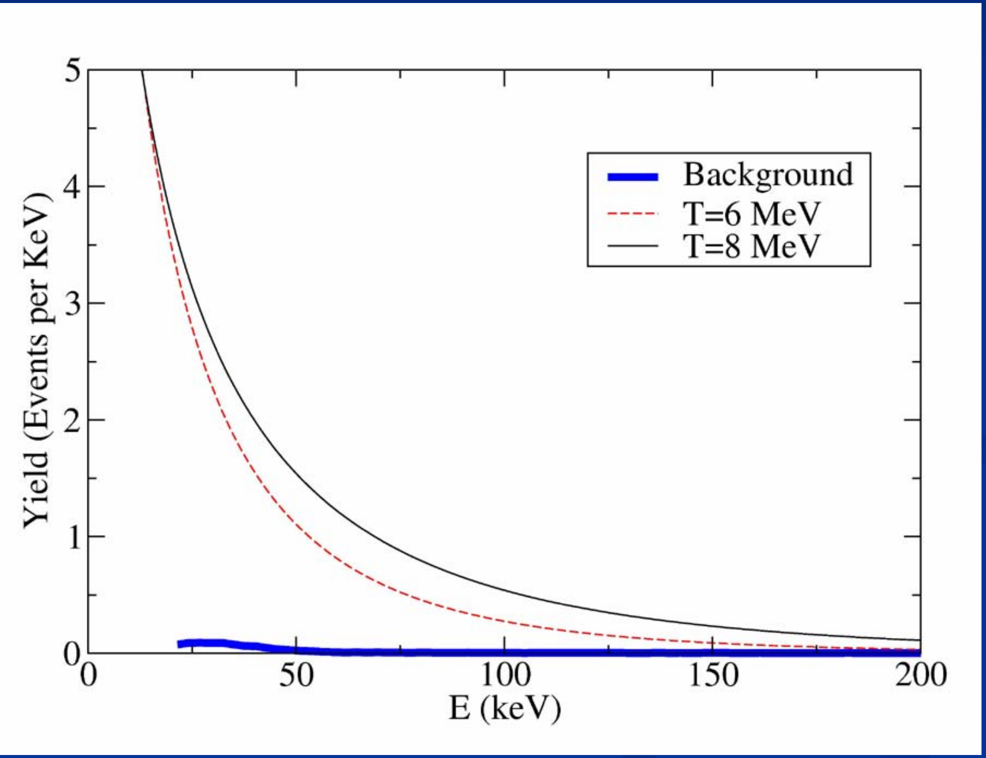
Supernova at 10 kpc in CLEAN

- Simulation of full 100 ton active mass.
- Threshold (no position resolution) about 5 keV.
- Green curve is total low energy background in 10 seconds.
- Black or red curves are SN signal (≈ 400 events) for different ν_x temperatures.



Simulation of Inner 70 Tons

- Can reduce background with position cuts. Most background events on outside edges.
- Threshold, if position resolution, ~ 25 keV.
- If background matches simulations don't need cuts.
- Many ways to reduce background further.
- Supernova detection in CLEAN looks robust.



Very large elastic cross section may allow larger statistics in future

Supernova ν detectors

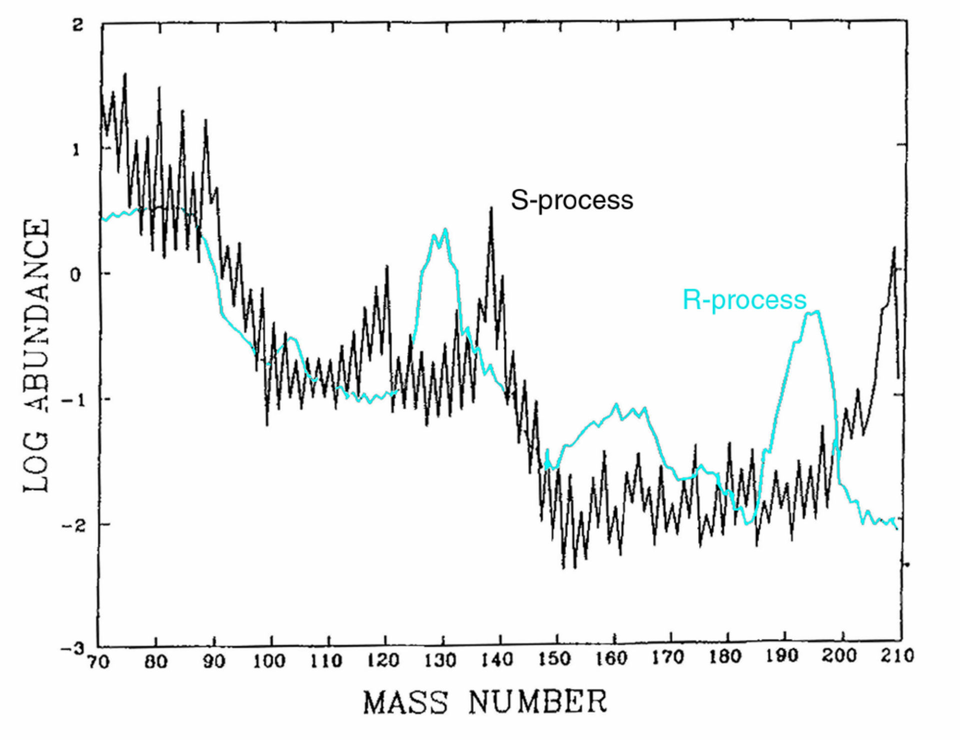
- Important to make model independent measurements!
- Do not assume everything is known but one parameter in your model!
- One wants a simple well known detector response.
- Elastic scattering has almost no theoretical uncertainty in cross section.
- Important to have multiple redundant experiments.
- Important to hope for surprises! This is how we will learn the most.

"Ultimate Flux Normalization"

- The ν-A elastic cross section is both very accurately known and very large.
- If the recoil ions can be detected, they could provide a very accurate absolute calibration of the neutrino flux.
- Micropattern gas detectors may observe reactor antineutrinos via elastic ν-A scattering, see P. Barbeau et al, hep-ex/0212034.

R-Process Nucleosynthesis

- As neutron rich medium cools, nuclei capture n to make heavy nuclei.
- Results depend on initial n/p ratio, entropy and expansion time scale.
- Need large n excess and high entropy
- Is ν-driven wind in supernovae r-process site?



Solar system heavy element abundances divided into s-process (red giant) and r-process

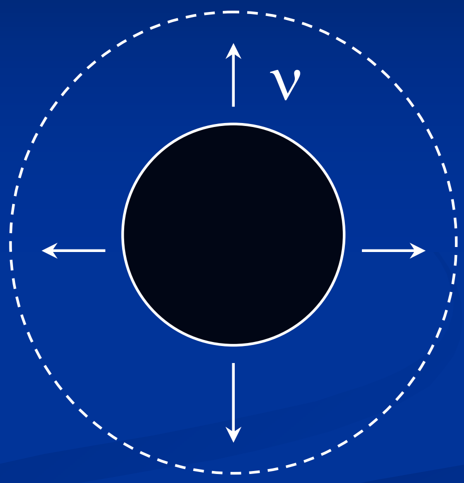
R-process in Neutrino driven wind

- Low density region above proto-neutron star dominated by large ν flux.
- Initial neutron to proton ratio and Y_e in wind set by relative rates:

$$\nu_e + n \rightarrow p + e^- \qquad (1)$$

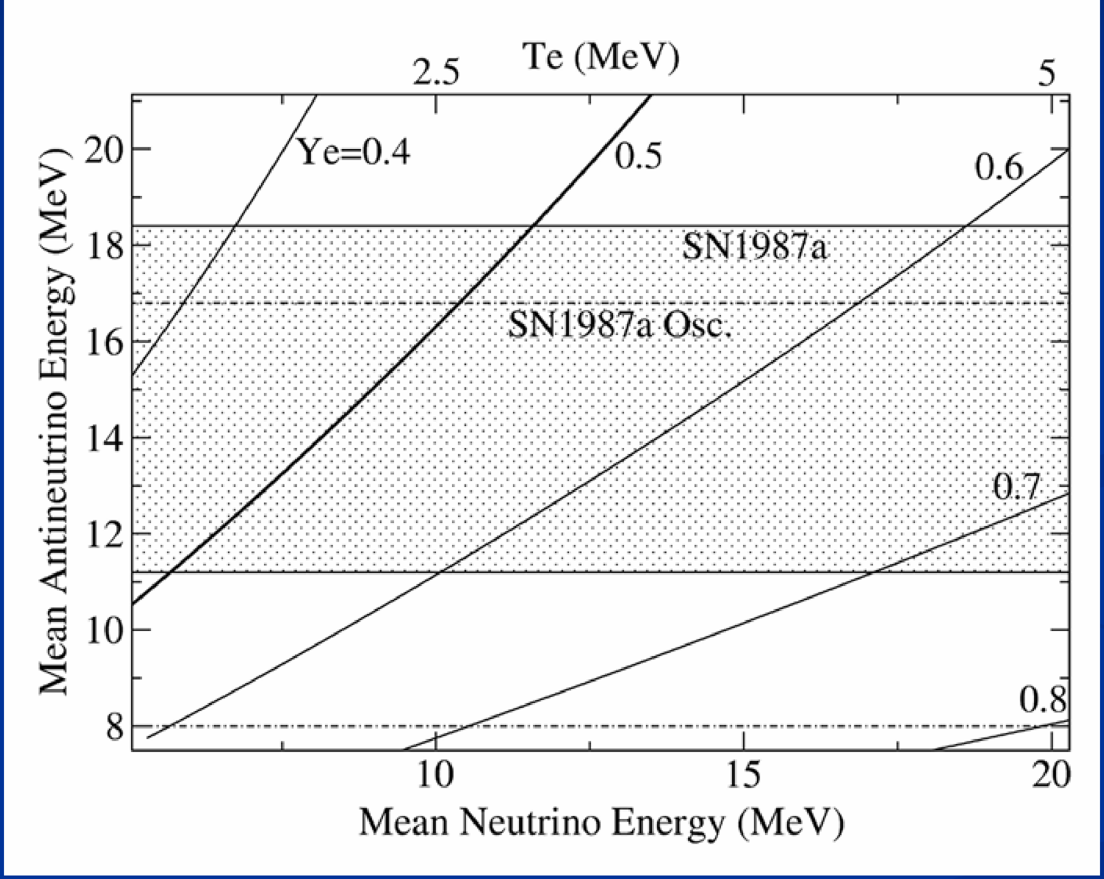
$$\bar{\nu}_e + p \rightarrow n + e^+ \qquad (2)$$

- Cross section for (1) > (2) because of n-p mass difference and because of weak magnetism. For fixed ν flux, weak magnetism increases Y_e by 20%.



In neutrino driven wind, ν eject a few baryons from surface of protoneutron star.

n/p ratio in ν-driven wind



For wind to be neutron rich must be above dark Y_e=0.5 line and below SN1987A limit line. This requires cold ν_e temperatures, top scale.

Neutrino Driven Wind is Not Significantly Neutron Rich

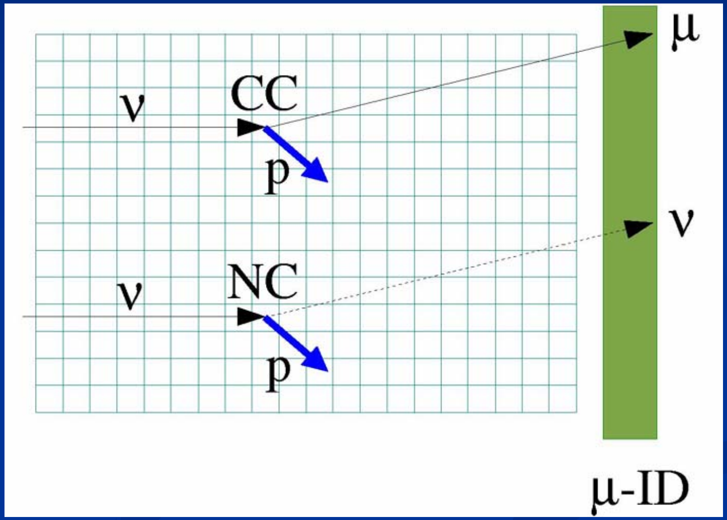
- Not site for r-process?
- New neutrino physics such as oscillations to sterile neutrinos that decreases Y_e.
- R-process occurs at much higher entropies (somehow) with Y_e just below 0.5.
- Example, very strong magnetic fields $\sim 10^{15}$G keep material in ν heating region longer to greatly increase S.

ν-n Elastic Important for Opacity

- Significant energy transport by ν_x ($\equiv \nu_\mu, \nu_\tau$) because twice as many as ν_e and without charged currents, ν_x have longer mean free paths.
- Opacity of ν_x mostly from ν-n elastic.
- Incorrect elastic cross sec caused Oak Ridge simulation to explode when it did not with correct one.
- Uncertainty in ν-n cross sec from strange quarks relevant for SN simulations.

FINESE: Fermi Lab Intense ν Scattering Experiment

- Proposed near detector on MiniBooNE beam line.
- Measure Δs via ratio of neutral to charged current.



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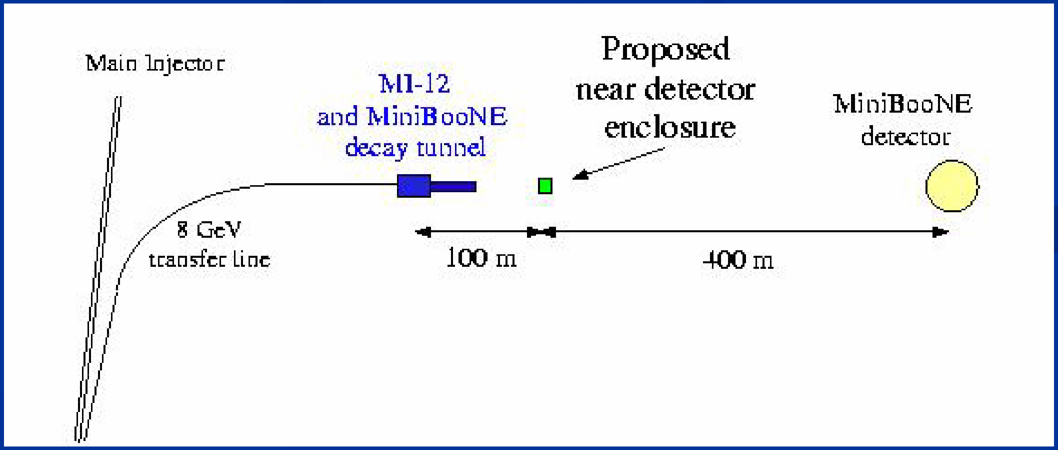


Strange quark content of nucleon

- Three form factors
- F_1^s, F_2^s, G_a^s
- Low Q limits:
  - $F_1^s(0)=0$, $dF_1^s/dQ^2 \rightarrow$ strangeness radius ρ_s,
  - $F_1^s=(\rho_s+\mu_s)\, Q^2/4M^2$ for small Q^2
  - $F_2^s(0)=\mu_s$ strange magnetic moment,
  - $G_a^s(0)=\Delta s$, fraction of nucleon spin carried by s

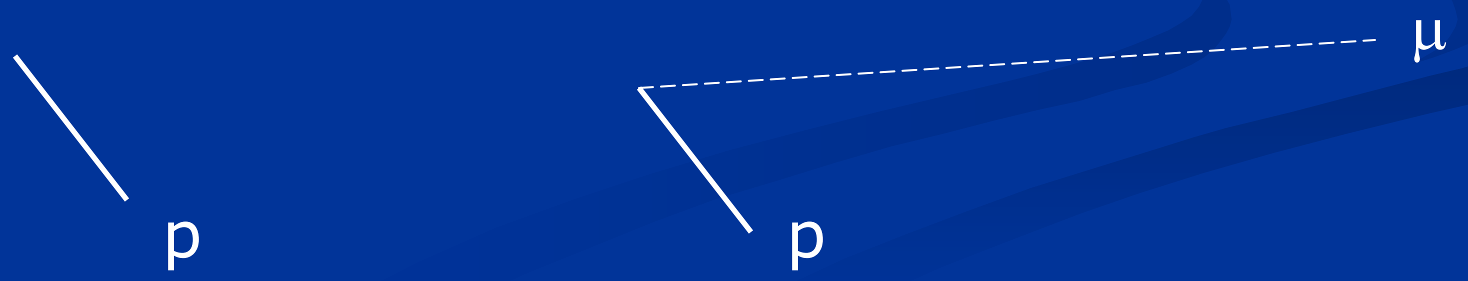
$$\langle f \,|\, J_\mu^H \,|\, i \rangle = \bar{u}_f(p') \left[\gamma_\mu F_1(Q^2) + i \frac{\sigma^{\mu\nu}}{2M_p} q^\nu F_2(Q^2) + \gamma_\mu \gamma_5 G_A(Q^2) \right] u_i(p) \,,$$

A Future ν-p Elastic Experiment

- Physics goals are compelling:
  - $G_a^s(Q^2)$ and Δs.
  - F_2^s independent of PV radiative correc.
- Very attractive ν fluxes at beam lines for long baseline ν-oscillation exp.
- Measuring ratio of neutral to charged currents is simple and controls many systematic errors.

Measure Δs via Ratio of Neutral to Charged Current Scattering

- Ratio of protons from: $\nu + p \rightarrow \nu + p$ to protons from: $\nu + n \rightarrow \mu^- + p$.
- Note, both are quasielastic scattering from an N=Z nucleus such as ^{12}C.
- Very simple observable: ratio of protons of a given E without muons to those with muons.



Example: E_ν=0.8 GeV, Q^2=0.5

- Neutral to CC ratio R ≈ 0.14
- Error in extracted Δs

	Δs
5% measurement of R	0.04
±0.03 GeV uncer. in M_A	0.01
±0.3 uncer. in μ_s	0.07
±2 uncer. in ρ_s	0.002

[Assume $G_a^s = \Delta s/(1+Q^2/M_A^2)^2$]

- 5% ratio sensitive to Δs at ±0.04
- Determine one combination of Δs and μ_s from ν and another from anti-ν.

Experimental Considerations

- Many systematics, such as absolute flux, proton efficiency, cancel in ratio.
- Need to identify pions to separate elastic from inelastic events. [This may require a segmented detector.]
- Possible backgrounds from neutrons and multiple nucleon knockout.
- Many nuclear structure issues also cancel in ratio, however don't go too low in Q^2 . Want proton recoil energy to be large compared to giant resonances T_{lab}>50-100 MeV (can use more calculations).
- Note, more counts and closer to $Q^2=0$ limit for Δs at low Q. Tradeoff in Q^2 choice.

Conclusions

- Important to measure ν_μ, ν_τ since they contain most of E and benchmark for ν oscillation measurements.
- ν-A elastic scattering has large yield, information on ν_μ, ν_τ energy spectrum, and very clean theoretical interpretation.
- Good way to measure total E of SN which is important and interesting.
- Liquid Ne [CLEAN] looks very good, 4 events/ton for galactic SN. This is a factor of 20 or more greater yield than large yield ν_e-bar capture in H_2O.