# The Substandard Supernova Model

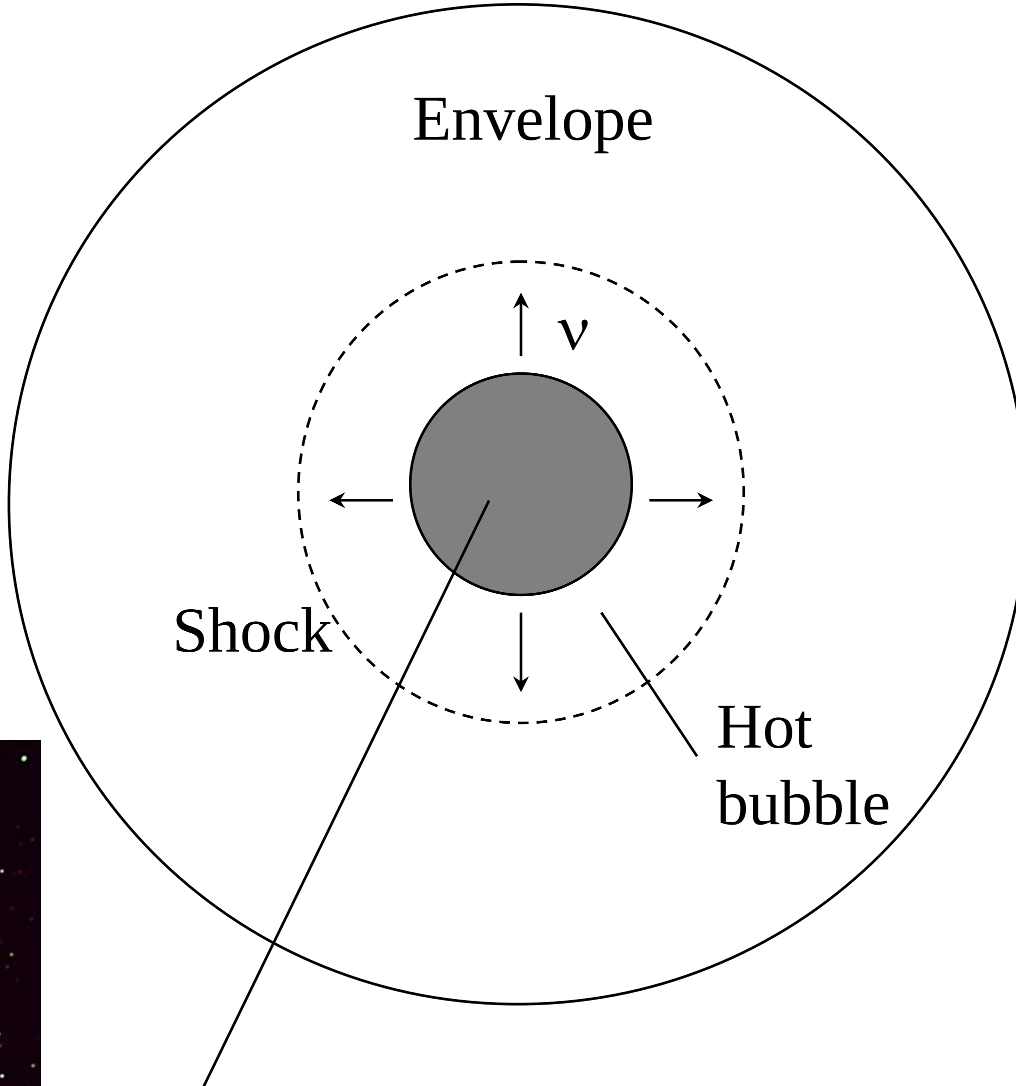
- Substandard: neutrino oscillations are not included.
- Substandard: it is not the Standard Solar Model.
- Substandard: it does not explode??

# SN Neutrinos Before Oscillations

- Introduction: $0^{th}$ order description of SN $\nu$ spectra.
- Supernova quantum numbers and sensitivity to new physics.
- Measuring total SN energy and new $\nu$-nucleus elastic scattering detectors.
- r-process nucleosynthesis in $\nu$-driven winds and sensitivity to $\nu$ physics.
- Model independent Virial expansion for nuclear matter properties near neutrinosphere. [Solving $\nu$-atmosphere problem.]

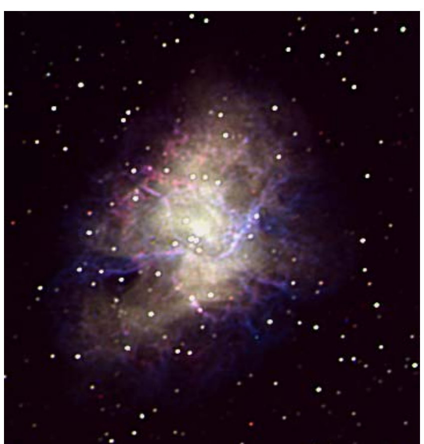
# Core Collapse Supernova

Core of massive star collapses to form proto-neutron star. νs form neutron star energizes shock that ejects outer 90% of star.

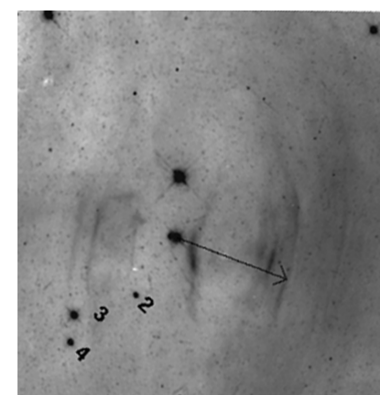



July 5, 1054

Crab nebula



Crab Pulsar




Hubble ST

# Supernova Neutrino Flavors

- The weaker the interaction, the further into the hot supernova core one probes, and the higher the emission temperature.
- $\nu_x$ ($\nu_\mu$, $\nu_\tau$, anti-$\nu_\mu$, anti-$\nu_\tau$) have no charged current interactions. $T \approx$ 6-8 MeV or <E>$\approx$3T=18-24 MeV.
- Anti-$\nu_e$ capture on protons $T \approx$ 5 MeV or <E> $\approx$ 15 MeV.
- $\nu_e$ capture on abundant neut. $T \approx$ 3.5 MeV or <E>$\approx$ 10 MeV
- Equal partition: *very roughly* about equal energy radiated in each of the six flavors.

# Cautions

- Spectra are not thermal.
- Equal partition is only approximate.
- Large energy difference between $\nu_x$ and anti-$\nu_e$ is now disfavored. Old simulations left out ways for $\nu_x$ to exchange energy with nucleons. [nucleon recoil and nn bremstrahlung…]
- Do not assume particular nu spectra before oscillations! Instead look for ways to measure or constrain them.

# Neutrino Interactions in SN

- Some important interactions: $\nu_e$+n$\rightarrow$p+e, $\nu$+N$\rightarrow$ $\nu$+N, $\nu$+A elastic …
- In general lots of negative feedback so changes in one neutrino rate may not have large impact.
- There are some special cases where SN simulations are sensitive to microphysics.
- Example: weak magnetism introduces differences between neutrino-nucleon and antineutrino-nucleon interactions.

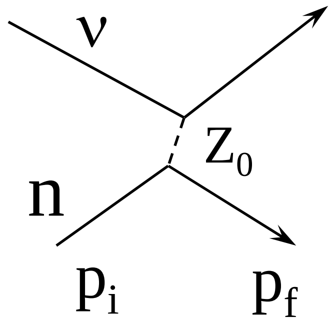
# Weak Magnetism

- Lowest order $\nu$-N cross section $\sigma=\sigma_0 E_\nu^2$ just given by $\nu$ phase space. Same for $\nu$ and anti-$\nu$.
- CP approx. conserved.
- P violation $\rightarrow$ C violation. $\sigma_{\nu\text{-n}} > \sigma_{\text{anti}\nu\text{-n}}$
- $\nu$–N cross sec. systematically larger then anti-$\nu$
- T invariance: if no recoil then $\sigma_\nu=\sigma_{\text{anti-}\nu}$.

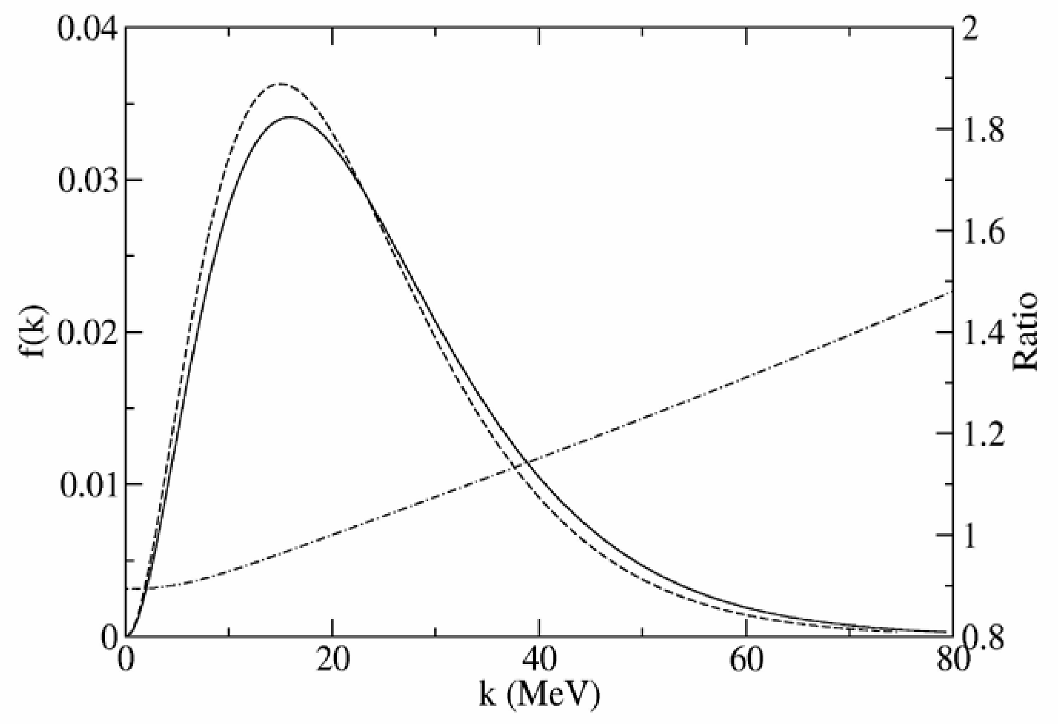
  $\sigma=\sigma_0 E^2 (1\pm \delta E/M)$, + for $\nu$, - anti-$\nu$
- C violating recoil term

  $\delta=8c_a(c_v+F_2)/(c_v^2+5c_a^2)$

  has big contribution from $F_2$ of weak mag.

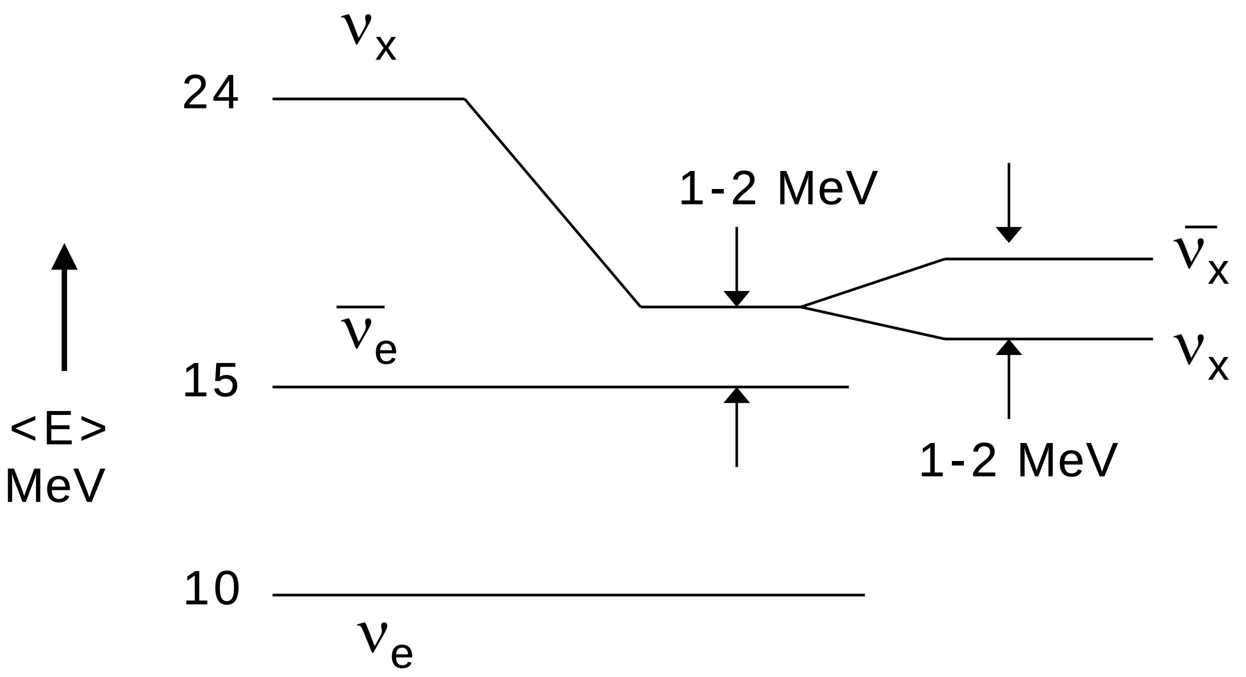


# Difference in $\nu_\mu$ and $\bar{\nu}_\mu$ spectra




$\nu$ (dotted curve) and $\nu$-bar (solid) produced in pairs. Because of C violation of weak interactions, $\nu$-bar have longer mean free path and escape hotter. Highest energy $\nu$ from supernova are antineutrino rich (ratio of $\nu$-bar to $\nu$ dashed curve with right hand scale).

# $\nu$ Spectra (Before Osc.)




Charged Currents split $\nu_e$ from $\nu_x$

Weak Magnetism splits $\nu_x$ from $\bar{\nu}_x$

# Sensitivity of SN to New Physics

# Supernova Quantum Numbers

| | Pre-SN Core | Proto-N Star | Neutron Star |
|---|---|---|---|
| Mass ($M_\odot$) | 1.6 | 1.6$\rightarrow$ 1.4 | 1.4 |
| $\nu$ radiated | small | $10^{58}$ | small |
| Baryon # | $10^{57}$ | $10^{57}$ | $10^{57}$ |
| Electron # | $10^{57}$ | $10^{57} \rightarrow$ $10^{56}$ | $10^{56}$ |
| Muon # | small | $\rightarrow$ $10^{55}$ | $10^{55}$ |
| Tau # | small | $10^{54}$ | small |
| Strangeness | small | ? | ? |

# Sensitivity to New Physics

astronomical

- SN involve ~~macroscopic~~ changes in 1st, 2nd, and 3rd generation quantum numbers.
- Sensitive to new sources of lepton number violation.
  – Violation of individual lepton # (convert $\nu_e$ to $\nu_\mu$ for example)
  – Violation of total lepton #.  Could impact SN dynamics if large e # did not have to diffuse out.
- Set strict limits on new long range “flavor forces” that only couple to 2nd or 3rd generation particles.

# Total Energy of Supernova

- Core of massive star collapses to form NS.
- Most basic #, gravitational binding energy of neutron star, $E_b \approx 3/5\ GM^2/R$.
- This is directly observable as total energy radiated in neutrinos! Most energy in $\nu_\mu$, $\nu_\tau$.
- If $E_b$ is large this implies M is large (perhaps metastable star that will later collapse into a black hole. NS still not seen in SN1987a.) or R is small (conventional NS has $R \geq 10$ km), suggests exotic strange quark matter or other … star that can have small R.
- Very interesting if $E_b$ is small
  - R can't be big (millisecond pulsars would fly apart) and M unlikely to be small. Small M core won't collapse.
  - Some energy not in active neutrinos! Probes for sterile neutrinos, axions, large extra dimensions…

# Existing SN Detectors

- Super-K very good anti- $\nu_e$ detector via capture on p. Few 1000 or more events for Galactic SN.
- SNO may be good $\nu_e$ detector via $\nu_e\, d \rightarrow pp\, e$. How long will SNO last? When will the $D_2O$ be returned?
- Existing detectors do not directly measure $\nu_x$ energy. Example $\nu_x + {}^{16}O \rightarrow {}^{16}O^* \rightarrow {}^{16}O + \gamma$ in SK. All you know is $\nu$ has E above threshold.
- Was proposed Pb detector to give some E info from ratio of single n to double n knockout. ${}^{208}Pb(\nu_x,n)$ or $(\nu_x,nn)$. Cross section uncertainties may be reduced via calibration with stopped $\pi$ $\nu$ beam.
- Need for good $\nu_x$ detectors with energy information.

# Supernova Detection With $\nu$–Nucleus Elastic Scattering

# $\nu$-Nucleus Elastic Scattering

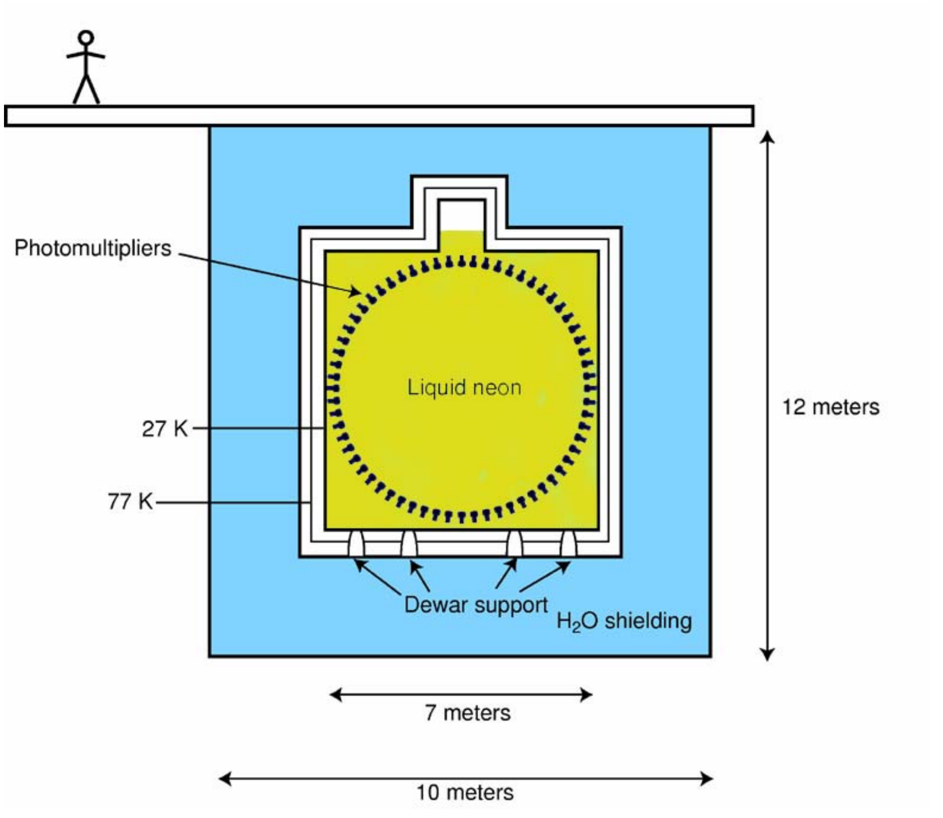
- Large coherent cross section.
- Most sensitive to higher E $\nu_x$.
- Measured recoil energy provides direct information on $\nu$ spectrum.
- Independent of $\nu$ oscillations.
  - Best way to get astrophysical info.
  - Compare to flavor dependent detectors to constrain oscillations.
- Cross sections very well known.
- Unique and uniquely clean information.

# Next Generation Dark Matter and $\beta\beta$ Detectors

- Large mass, low background, low threshold experiments.
- Big $\nu$-A elastic cross section implies large yields of 4 (Ne) to 30 (Xe) events per ton for a ‘standard’ galactic SN at 10 kpc.
- Ton scale experiments will be sensitive to supernovae via $\nu$-A elastic scattering.

# CLEAN Detector for pp Solar $\nu$

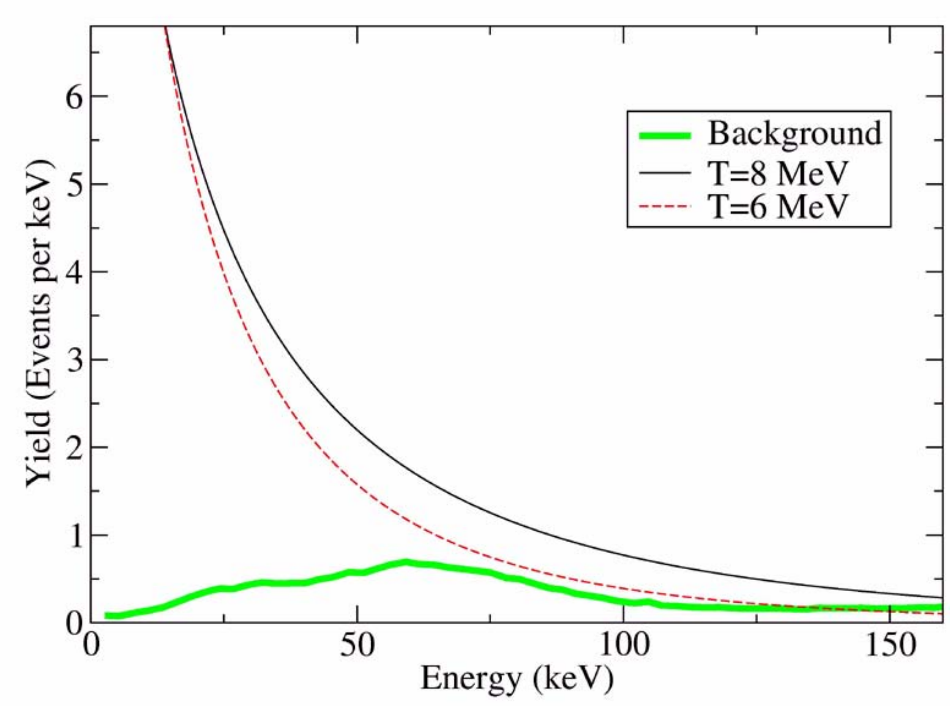
- SN simulation with Kevin Coakly, Dan Mckinsey, CJH, Phys.Rev. **D68** (2003) 023005
- Phototubes with wavelength shifters view 100 tons of liquid Ne.
- Assume background dominated by U, Th, K… in phototubes, shifters and support structure.




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

# Supernova at 10 kpc in CLEAN

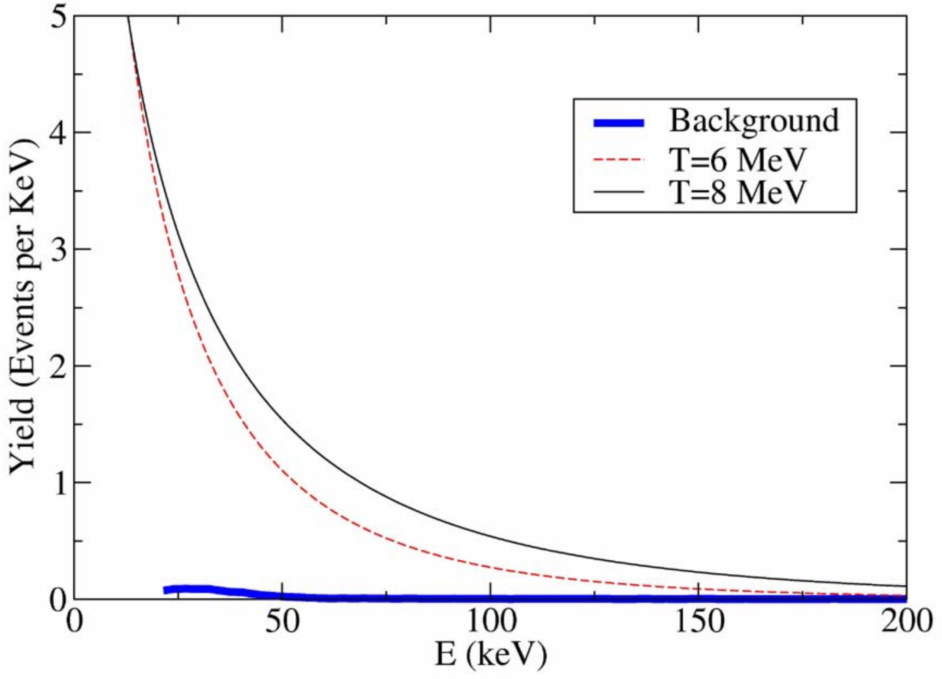
- Simulation of full 100 ton active mass.
- Threshold (no position resolution) about 5 keV.
- Green curve is total low energy back-ground in 10 sec.
- Black or red curves are SN signal (≈ 400 events) for different $\nu_x$ temperatures.




Background much easier for SN compared to solar ν because signal in ~10 sec.

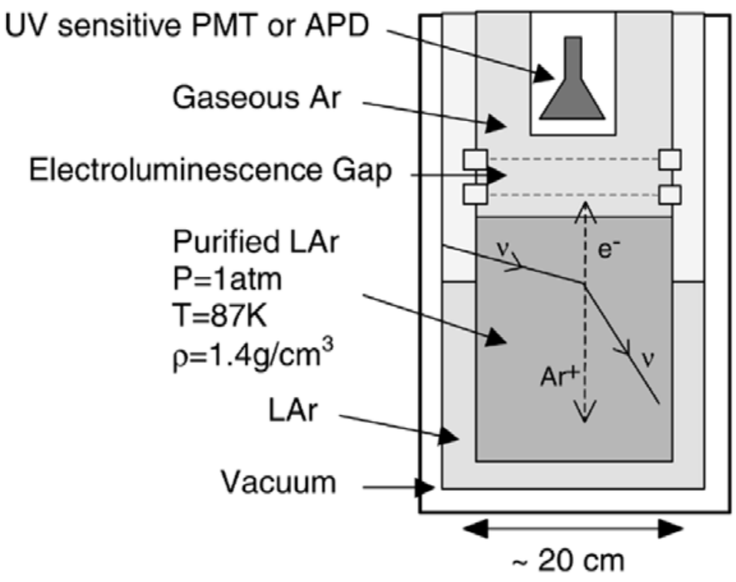
# Simulation of Inner 70 Tons

- 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.



# Reactor $\bar{\nu}_e$ Detection

- Coherent $\nu$-A never observed in lab.
- Some proposals to detect low E –recoils from reactor $\nu$.
- J.I. Collar et al. propose micropatern gas detector.
- Application for reactor $\nu$ osc ?? Compare nu-A signal to conventional $\nu_e$-bar. Compare two nu-A detectors at different distances to probe nu-sterile…




C. Hagmann and Adam Bernstein: Ionization in LAr observed as electro-luminescence in gaseous Ar. 560 events/d-10kg, 25 m from 3GWt reactor <E>=234 eV

# ν–Nucleus Elastic at SNS?

- Test small version of CLEAN or Ar, Xe, or Ge detector in SNS beam from stopped pion decay.
- Detect nuclear recoils from ν-nucleus elastic scattering.  Need to deal with neutron backgrounds…
- Technology used for dark matter searches, could be used in future osc experiments, and has large cross sections.   Example, compare elastic flavor blind signal to charged current rate or compare two elastic detectors at different distances to search for osc to sterile neutrinos.

# r-Process Nucleosynthesis in Supernovae

Sensitive to (new) $\nu$ physics

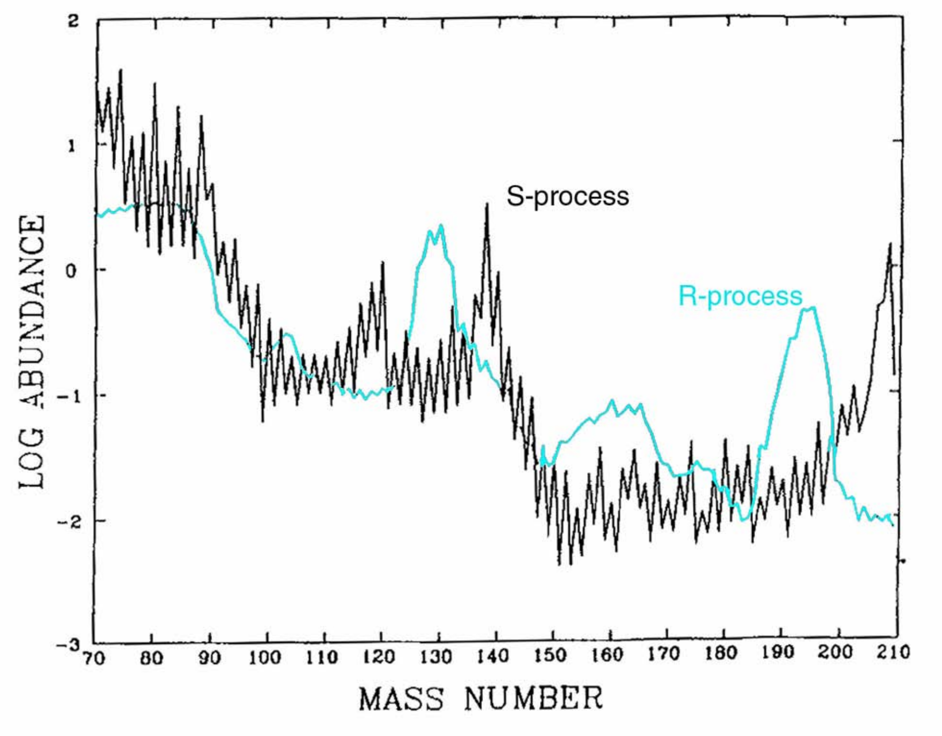
# r-Process Nucleosynthesis

•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

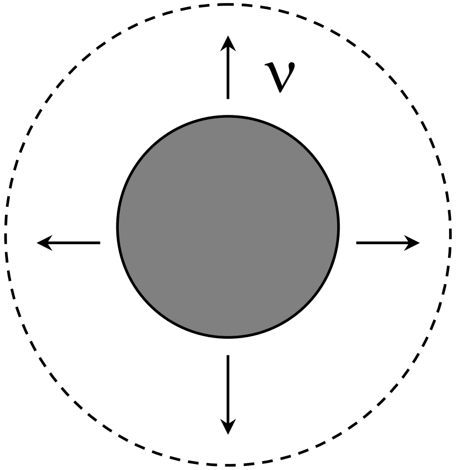
# r-process in Neutrino driven wind

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

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

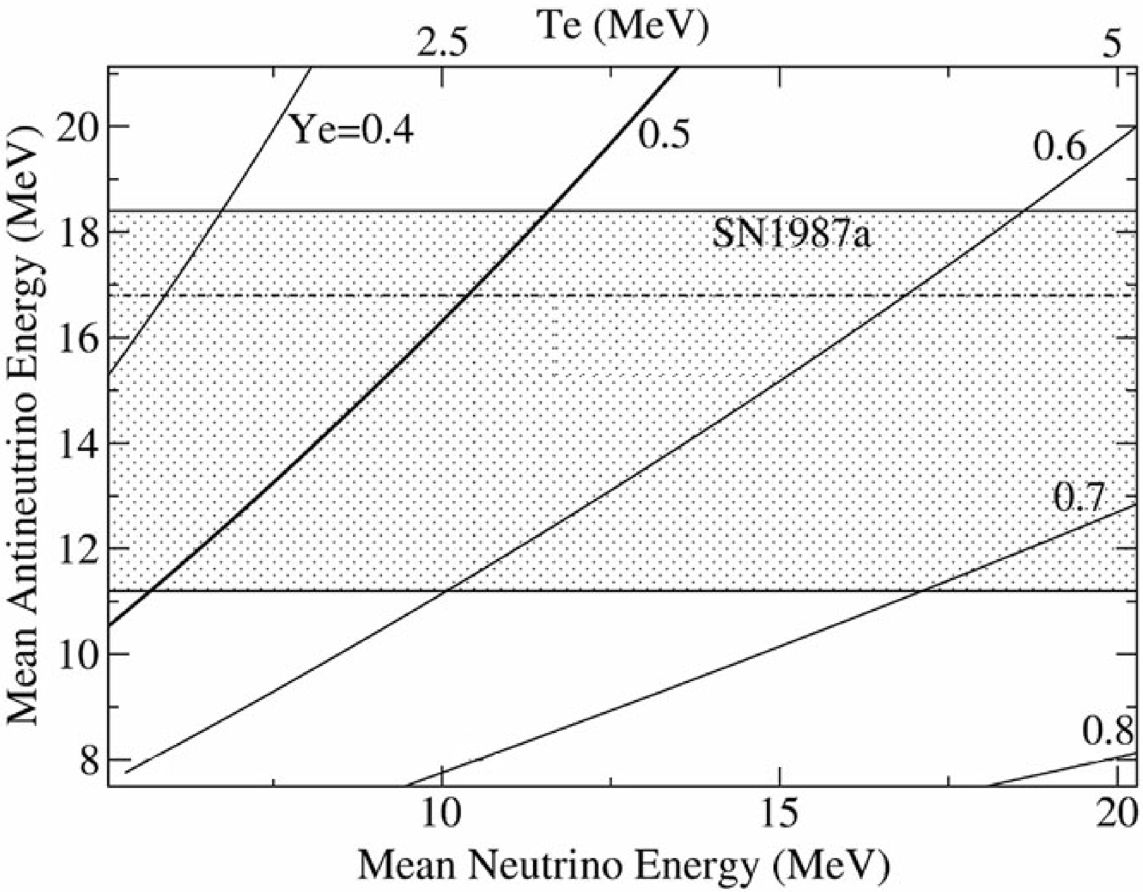
$$\bar{\nu}_e + p \rightarrow n + e^+ \quad (2)$$

- Cross section for (1) > (2) because of weak magnetism. For fixed $\nu$ flux, weak magnetism increases $Y_e$ by 20%.
- Cross sec. depends on $\nu$ E.




Neutrino driven wind: $\nu$ eject a few baryons from surface of protoneutron star.

# n/p ratio in ν-driven wind

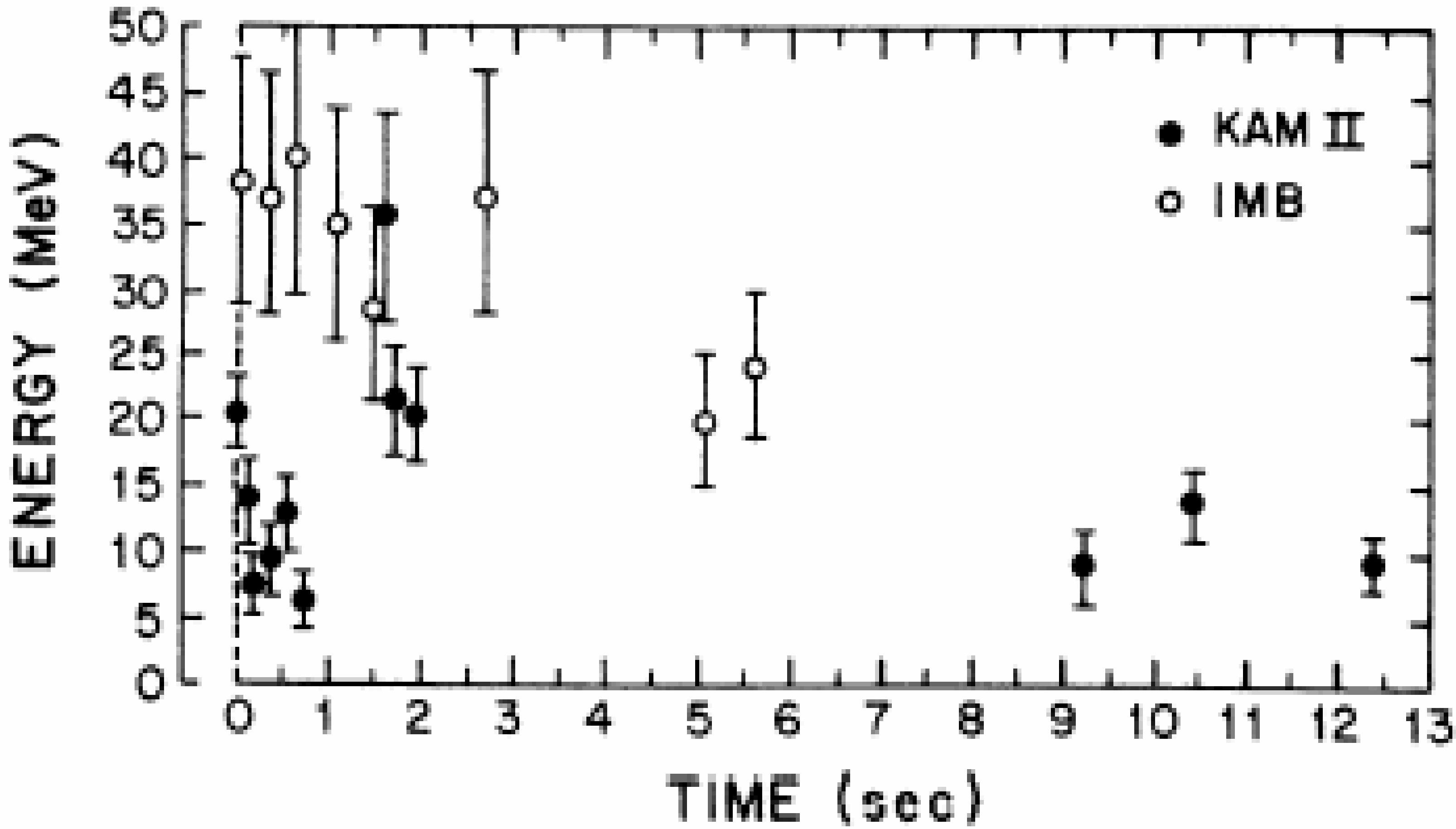



For wind to be neutron rich must be above dark $Y_e$=0.5 line and below SN1987A limit line.  This requires cold $\nu_e$ temperatures, top scale.

# 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 $\nu$ heating region longer to greatly increase S.

# SN1987a Data



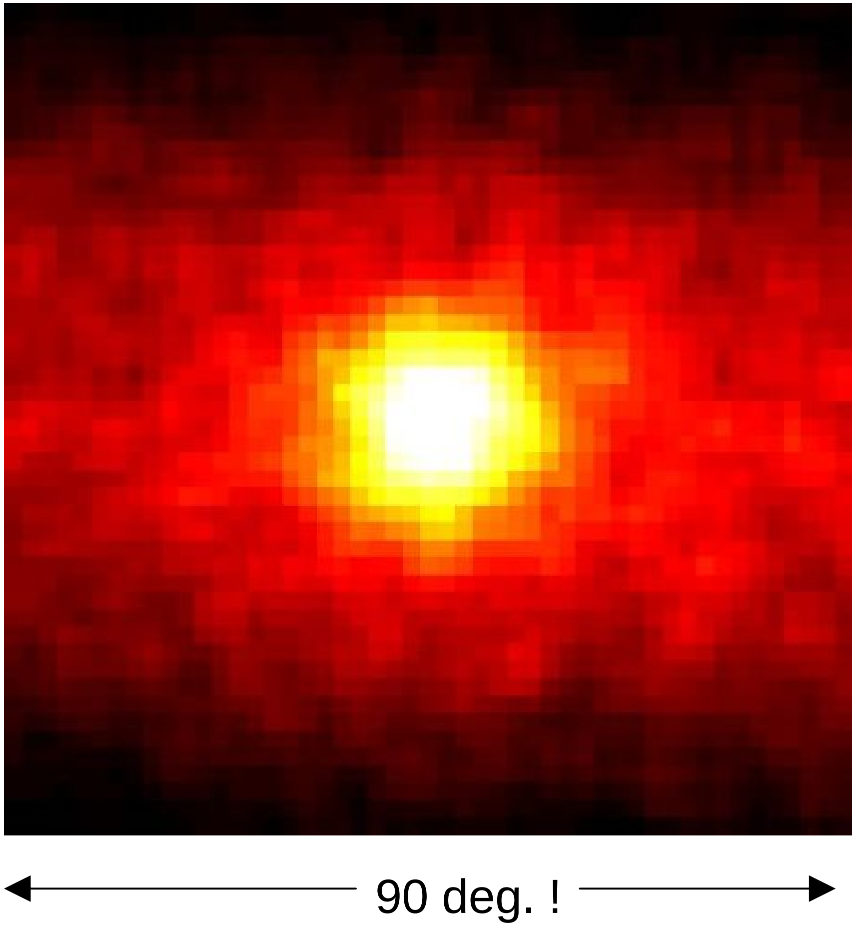

The anti-nu appear to be cooling with time not getting warmer.

# Virial Expansion for Equation of State

Determine composition, neutrino interactions of matter near neutrinosphere

# The Neutrinosphere Problem

- View sun in neutrinos, see angular resolution of $\nu$-e scattering in Super-K.
- View SN in neutrinos, see neutrinosphere. What does it look like? What is it made of? What are its properties?



# Neutrinosphere in a Supernova

- View supernova in neutrinos and see neutrinosphere. Mean free path $\lambda \sim 1/\sigma\rho \sim R \sim 10$ km is size of system.
- Conditions at neutrinosphere:
  - Temperature ~ 4 MeV crudely observed with 20 SN1987a events.
  - $\sigma \sim G_F^2 E_\nu^2$ and $E_\nu \sim 3T$
  - $\rho \sim 10^{11}$ g/cm$^3$ [$\sim 10^{-4}$ fm$^{-3}$]
  - Proton fraction starts near ½ and drops to small values.
- What is the composition, equation of state, and neutrino response of nuclear matter near the neutrinosphere?
- *Virial expansion gives model independent answers!*

# Virial 101

- Assume gas phase at low density $\rightarrow$ where fugacity $z=e^{\mu/T} \ll 1$ with $\mu$ the chemical pot.
- Expand grand canon. partition function Q in powers of z:
  $P=T \ln Q/V$, $n=z\, d/dz \ln Q/V$

  $P=2T/\lambda^3[z+b_2z^2+b_3z^3+\ldots]$, $n=2/\lambda^3[z+2b_2z^2+3b_3z^3+\ldots]$

  Here $\lambda$=thermal wavelength$=(2\pi/mT)^{1/2}$
- $2^{nd}$ virial coef. $b_2(T)$ calculated from 2 particle partition function: $Q_2=\sum_{states} \mathrm{Exp}[-E_2/T]$

  $E_2$ is energy of 2 particle state. Thus $b_2$ depends on density of states.

# Density of states

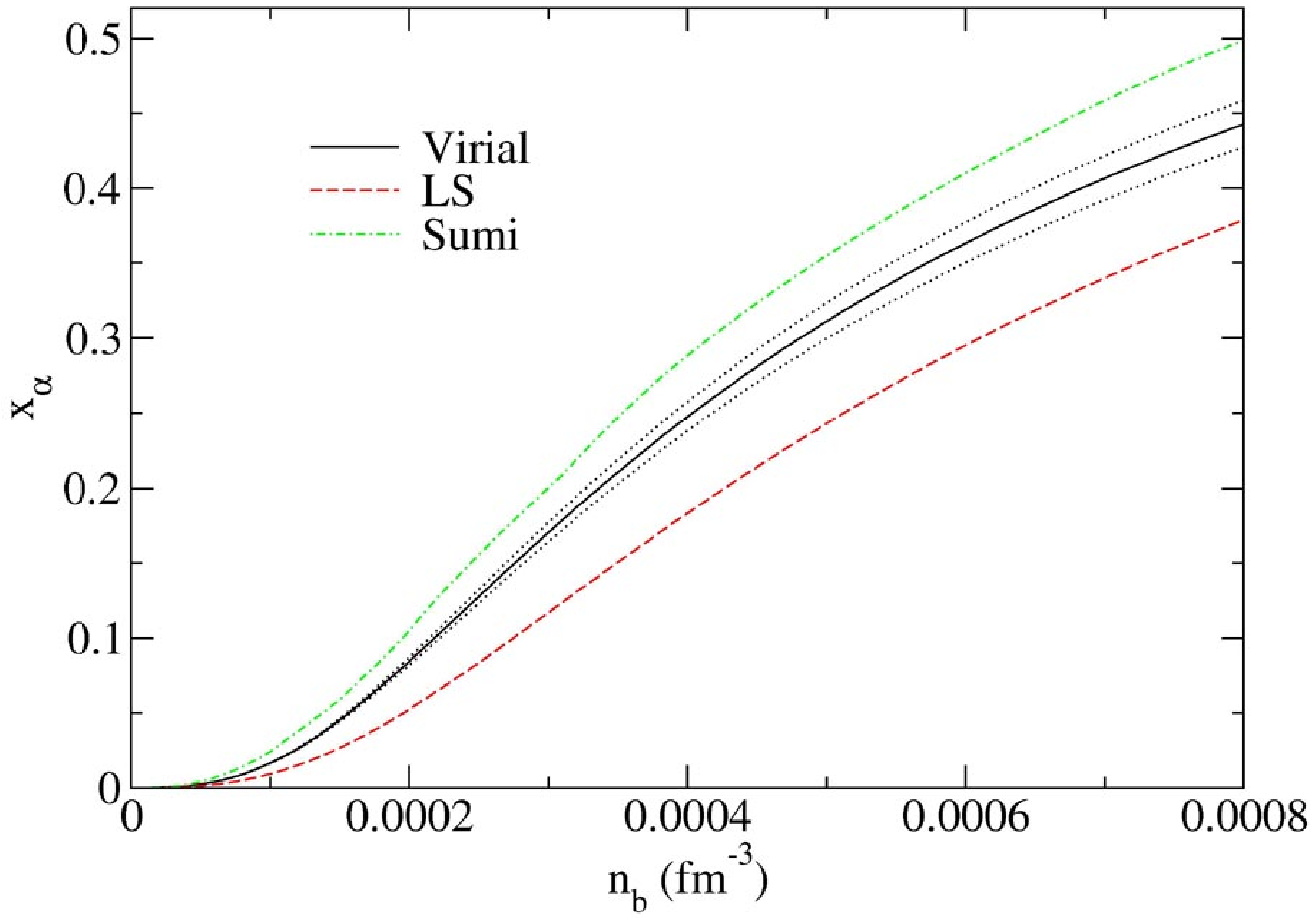
- Put system in big spherical box of radius R
- Relative mom. k from $E_2=k^2/2m_{reduced}$.
- $\psi(r_1-r_2=R\to\infty)=0=\sin[kR+l\pi/2+\delta_l(k)]$ or
  $kR+l\pi/2+\delta_l(k)=n\pi$.
- Distance between states $\Delta k=\pi/(R+d\delta/dk)$ so $dn/dE \propto 1/\Delta k \propto R + d\delta/dk$
- $b_2=2^{1/2}\sum_B e^{E_B/T} + 2^{1/2}/\pi \int_0^\infty dk\, e^{-E_k/2T} \sum_l{}' (2l+1)\, d\delta_l(k)/dk \pm 2^{-5/2}$
  with + for bose and – for fermions.
- $b_2$ Includes both bound states and scattering resonances on equal footing.

# $n$, $p$, $\alpha$ system

- $P/T=2/\lambda^3[z_p+z_n+(z_p^2+z_n^2)b_n + 2z_pz_n(b_{nuc}-b_n)]$
  $+ 1/\lambda_\alpha^3[z_\alpha+z_\alpha^2b_\alpha+z_\alpha(z_p+z_n)\, b_{\alpha\, n}]$
- Need four 2nd virial coef: $b_n$ for neutron matter, $b_{nuc}$ for symmetric nuclear matter, $b_\alpha$ for interaction between two alphas, and $b_{\alpha\, n}$ for interaction between an $\alpha$ and a $n$ or $p$.
- Guess $z_p$, $z_n$, and calculate $z_\alpha$ for chem. equilibrium $z_\alpha=z_p^2z_n^2\, e^{E\alpha/T}$. Next calculate $n_p$, $n_n$, and $n_\alpha$. Adjust $z_p$, $z_n$ to reproduce desired proton fraction and total baryon density.

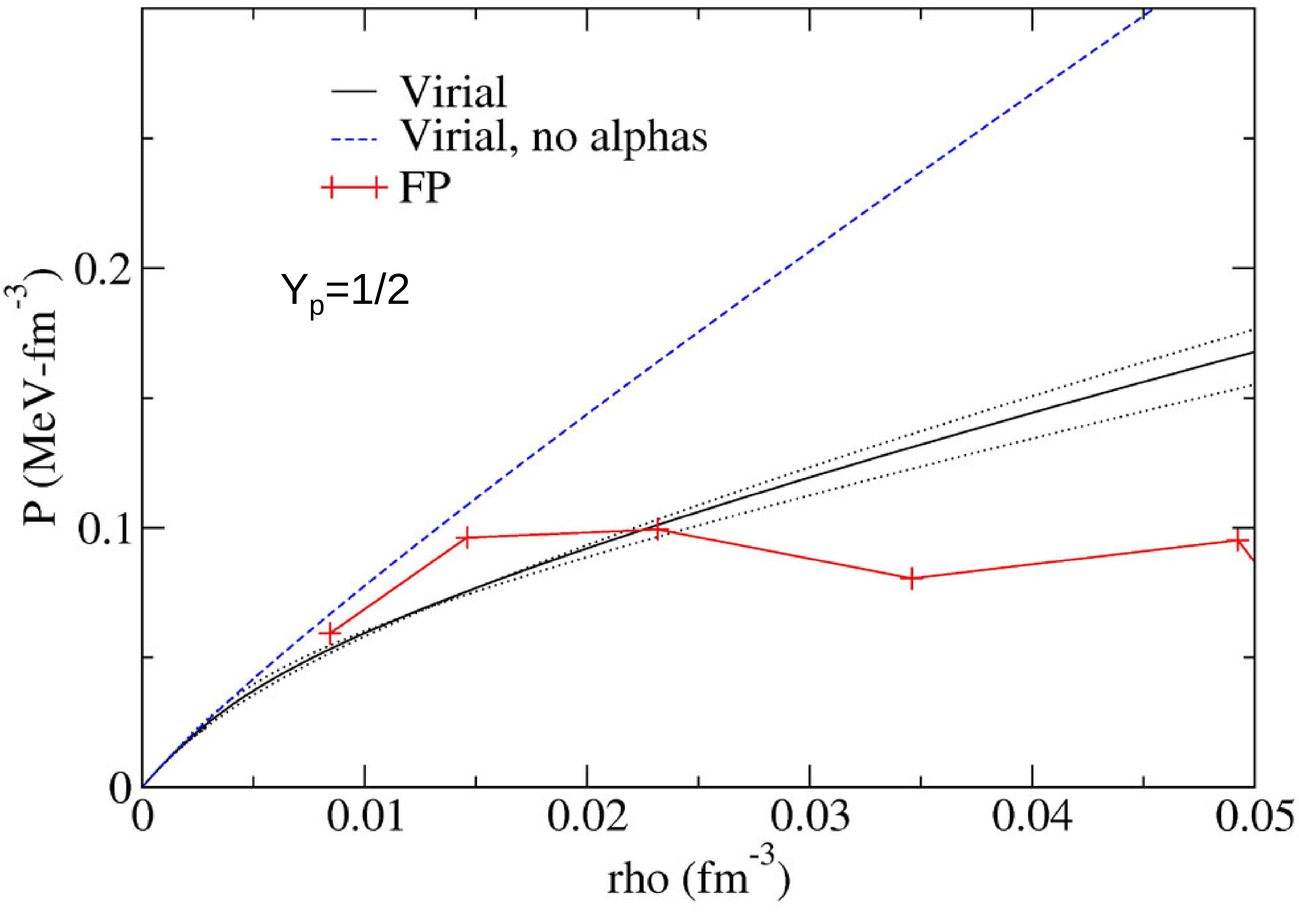
$$n_b=n_p+n_n+4n_\alpha, \qquad Y_p=(n_p+2n_\alpha)/n_b$$

# $\alpha$ Mass Fraction at T=4 MeV




$\alpha$ particle mass fraction in symmetric nuclear matter vs density. The widely used phenomenalogical EOS by Lattimer Swesty is dashed while Sumi is an EOS based on a rel mean field interaction (dot-dashed).

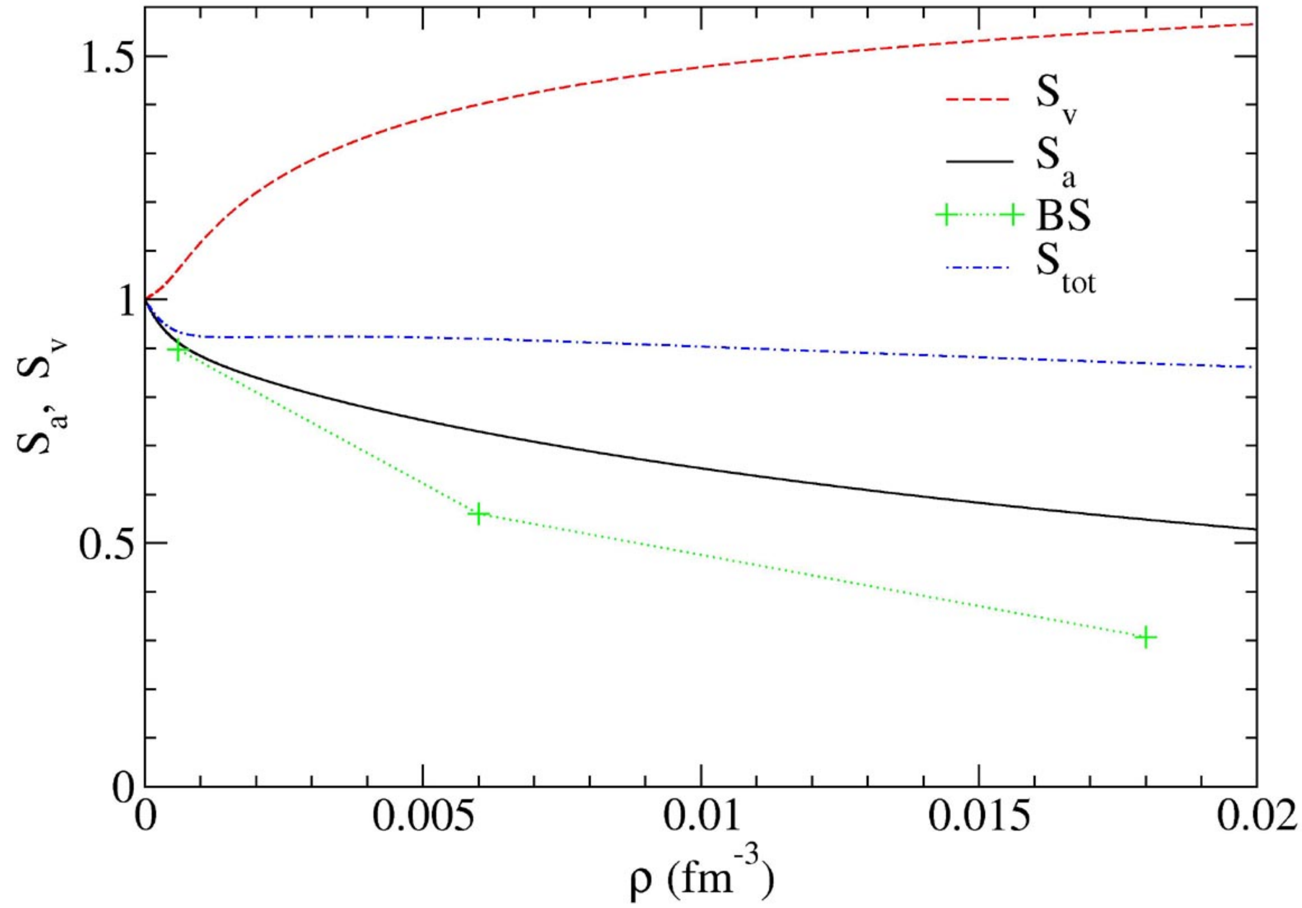
# Nuclear matter EOS at T=10 MeV



# Neutrino Response

- Static structure factor $S_q$ in $q \to 0$ limit
  $S_v = S_{q=0} = T/(dP/dn)$
- Axial or spin response from spin polarized neutron matter. $z_+$ is fugacity of spin up, and $z_-$ spin down, neutrons. $z_a = (z_+/z_-)^{1/2}$
  $S_a = (1/n)\, d/dz_a\, (n_+ - n_-)\, |_{n_+ = n_-}$
- Neutrino-neutron elastic cross section
  $d\sigma/d\Omega = (G^2 E_\nu^2/16\pi^2)\, [(1+\cos\theta) S_v + g_a^2 (3-\cos\theta) S_a]$
- Add contributions from $\nu$-p and $\nu$-$\alpha$ scattering
- Response is only model independent in $q \to 0$ limit.

# $\nu$ response T=4 MeV, $Y_p$=0.3




Total response is given by $S_{tot}$ and this is much larger then traditional RPA calculation of Burrows and Sawyer (BS) because of $\alpha$ contributions.

# Virial Expansion

- Virial expansion for low density gas of n, p, and $\alpha$.
- $2^{nd}$ virial calculated from NN, N$\alpha$, $\alpha\alpha$ elastic scattering phase shifts.
- Expansion gives model independent composition, equation of state, and neutrino interactions for material near neutrinosphere.
- This nuclear physics input will help make better neutrino atmosphere calculations that should allow more reliable neutrino spectra.

# The Substandard Supernova Model

- The $\nu$ spectra depend on $\nu$ interactions. Example, weak magnetism makes $\nu$ interactions stronger then anti-$\nu$.
- Expect <E> of $\nu_x$ > anti-$\nu_e$ > $\nu_e$. But not necessarily by a lot. Spectra are not thermal and equal partition may not hold. Try and constrain spectra to better observe oscillations.
- Supernovae involve macroscopic changes in $1^{st}$, $2^{nd}$, and $3^{rd}$ generation quantum #s and may be sensitive to new physics such as lepton # violating interactions.
- The total E of a SN is very important. It can be measured better with new $\nu_\mu$, $\nu_\tau$ detectors that provide energy information.
- The $\nu$ driven wind in a SN is not significantly neutron rich and this is a problem for r-process nucelosynthesis in the wind.

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