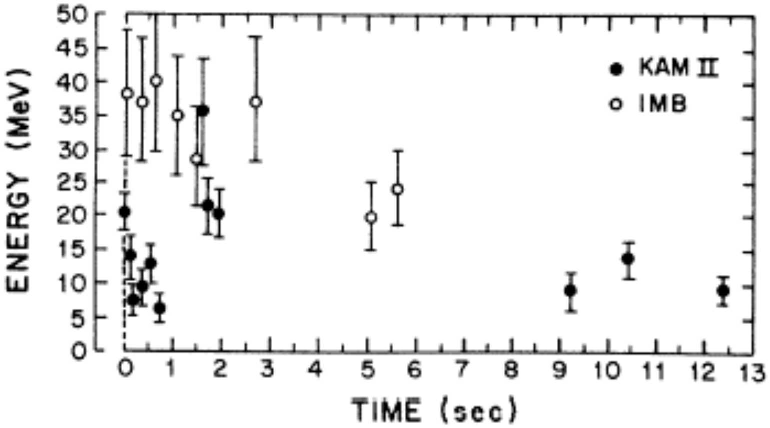
Fundamental Neutron Physics in Supernovae

SN1987A before and after



Historic neutrino events from SN1987A.
Filled circles recognized with Noble Prize.

C. J. Horowitz
Indiana University

INT program: Fundamental n physics, May ‘07

Fundamental Neutron Astrophysics

- Fundamental Symmetries
  - P violation and supernova asymmetries
  - C violation and nucleosynthesis
  - **Experiment**: SN detection via gravitational waves and neutrino-nucleus elastic scattering.
- Fundamental Many-body Physics
  - Neutrino-sphere in SN is low density n gas.
  - Low density n matter and the universal unitary gas.
  - Model independent virial expansion results.

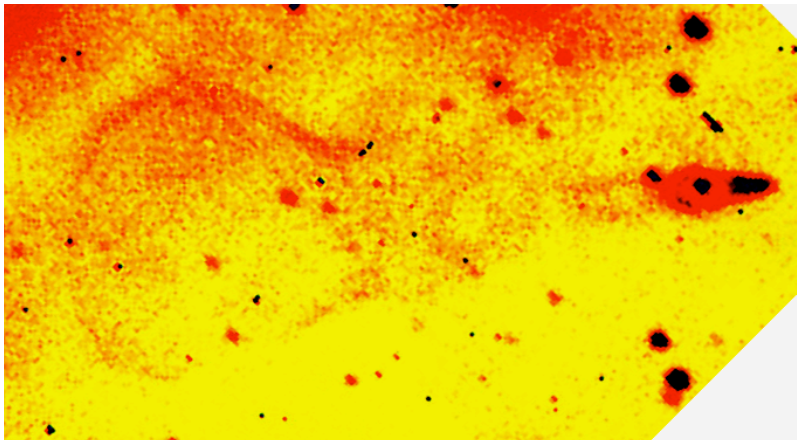
Macroscopic Parity Violation in Astrophysics

Journey to the Far Side of The Sun

- 1960s Science Fiction movie staring Roy Thinnes, Ian Hendry, Patrick Wymark.
- Voyage to parity double of Earth.
- Early vision of European Space Agency.

Fundamental Symmetries

- Core collapse supernovae are dominated by weakly interacting neutrinos which radiate 99% of energy.
- This provides a unique chance to study the symmetries and features of the Standard Model weak interactions.
- Search for macroscopic quantities influenced by microscopic features of weak interactions.
- Example, macroscopic parity violation?

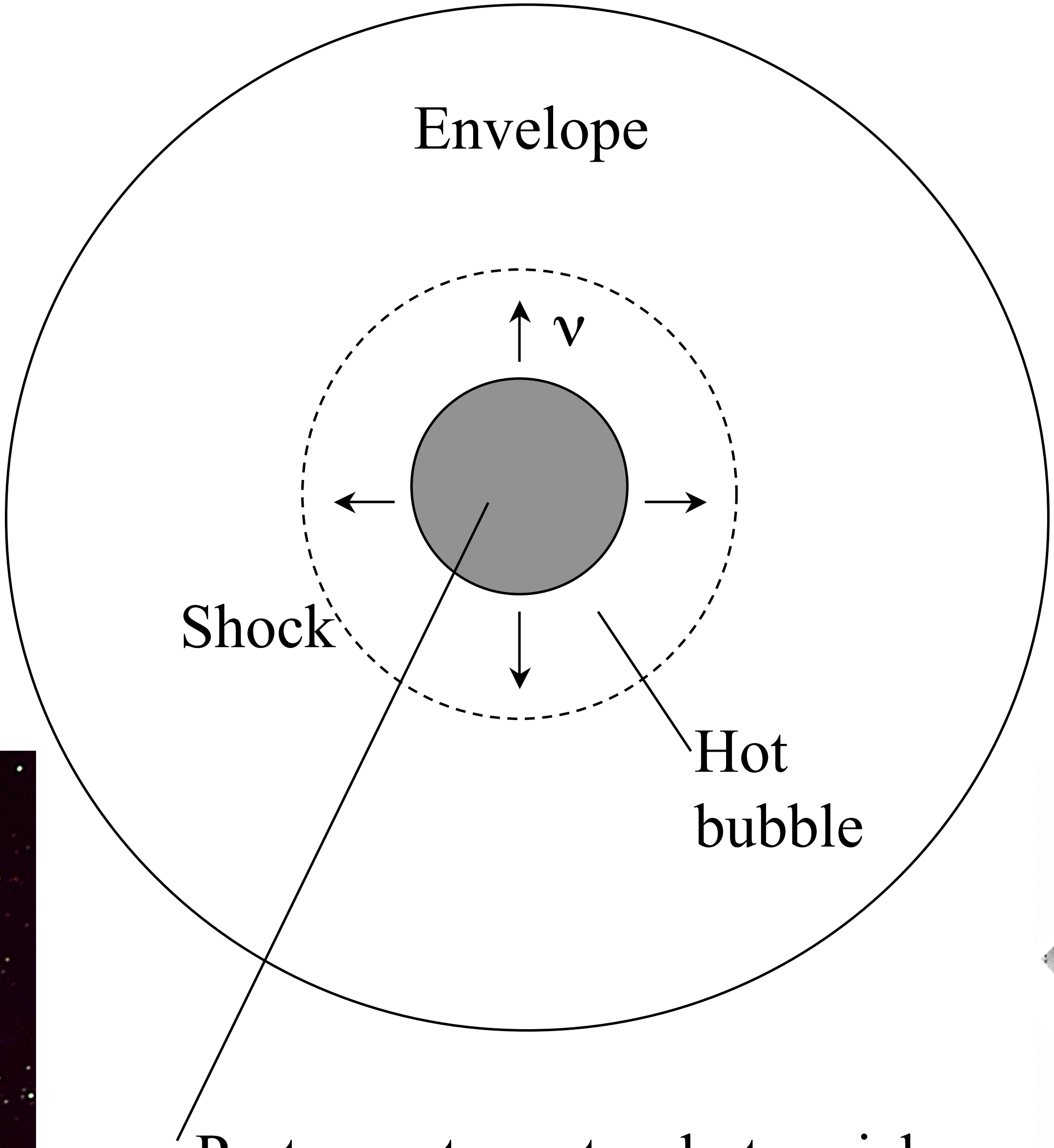


- Guitar Nebula: SN centered at left, neutron star now at far right.
- Neutron stars observed with high velocities, some ~1000 km/s or more.
- Origins of NS velocities are asymmetric SN explosions.
- Why are SN asymmetric at few % level?

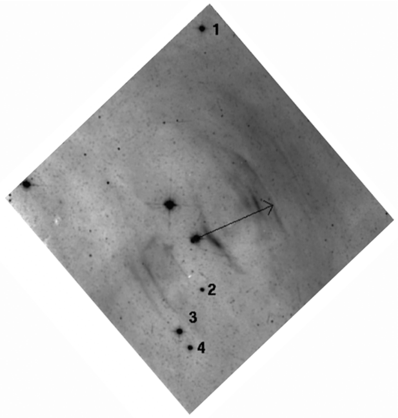
Core Collapse Supernova

- Explosion of massive star dominated by neutrinos.
- Unique opportunity for large scale parity violation.

Crab nebula

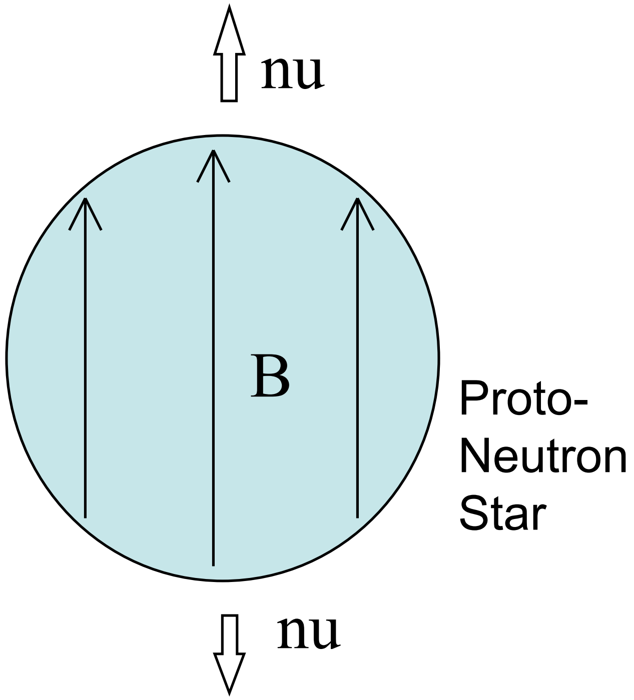


July 5, 1054



Macroscopic Parity Violation in Supernovae?

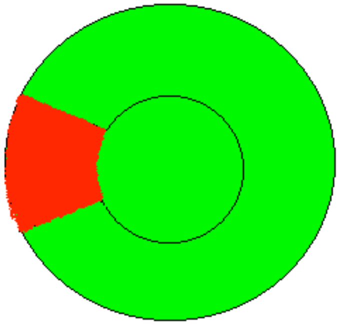
- A few % asymmetry in ν radiation from PV in strong B field produces ~500 km/s recoil of neutron star.
- Example, neutrinos scatter asymmetrically from polarized nucleons.
- Microscopic calculation of asymmetry very complicated, controversial, appears to need very strong ~$10^{15\text{-}16}$ G fields.

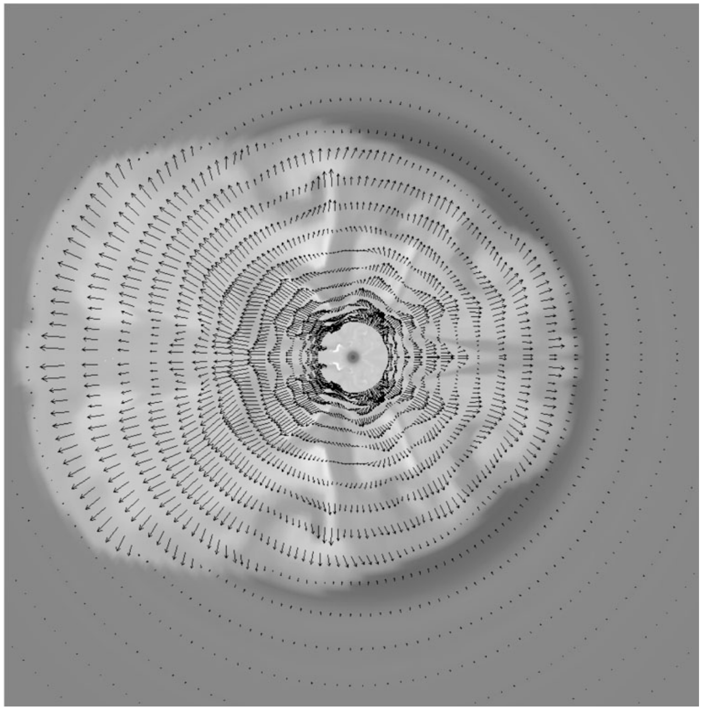


Madam Wu Experiment

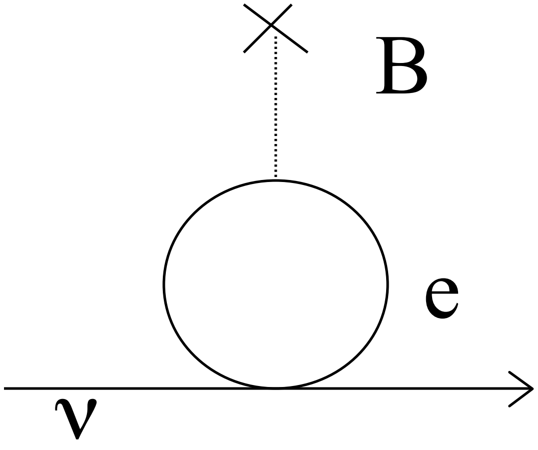
Alternatives

Burrows + Hayes:
preexisting
asymmetry.





Kusenko + Segre: MSW ν oscillations in B field. Need strong fields and ~100 eV masses.



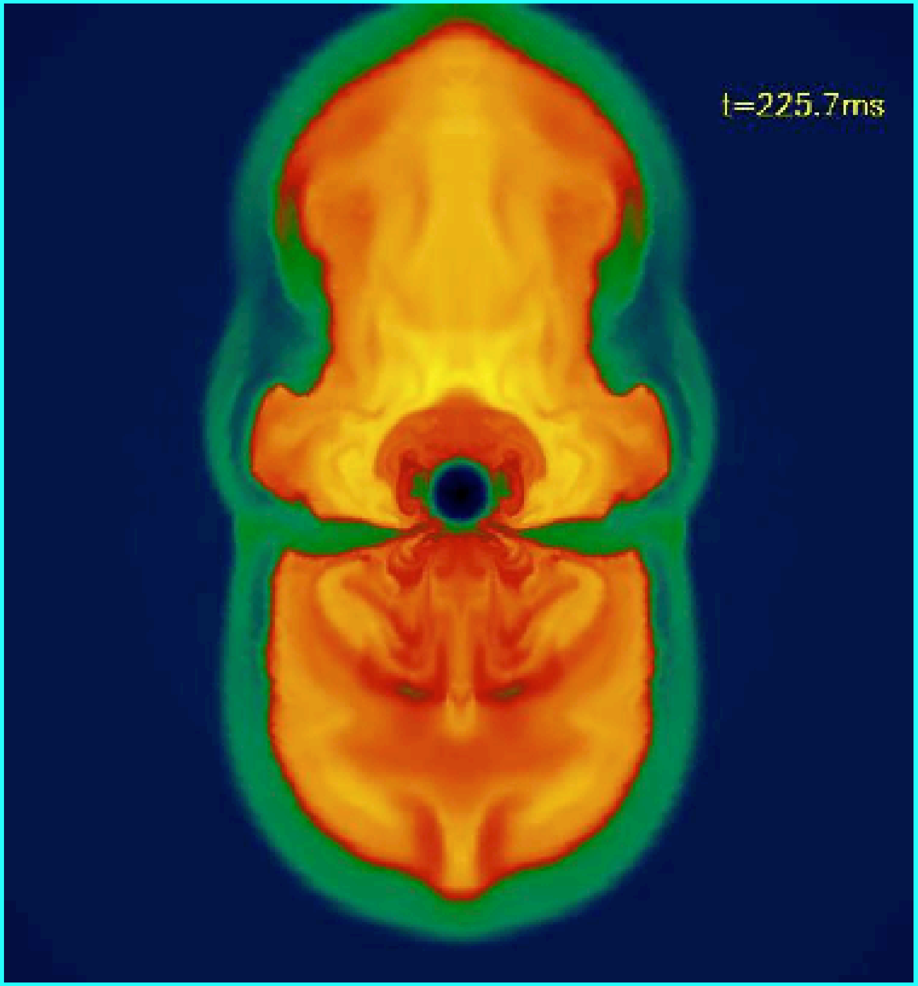
Spherical shock is unstable to asymmetric perturbations which can grow via convection or the standing accr shock instability (SASI).

SN Simulations: $M > 11\ M_{sun}$

- $M = 11.2\ M_{sun}$ (Woosley et al. 2003)
- Full 180° grid
- allows low (dipolar and quadrupolar, l=1,2) (convective) modes to occur
- global anisotropy develops
- weak explosion takes place

Globally aspherical explosion by the neutrino-heating mechanism without rotation!

(l=1 mode shock instability recognized by Blondin, Mezzacappa and DeMarino (ApJ 584 (2003) 971); Foglizzo 2002; Thompson 2001; Chandrasekhar 1980)



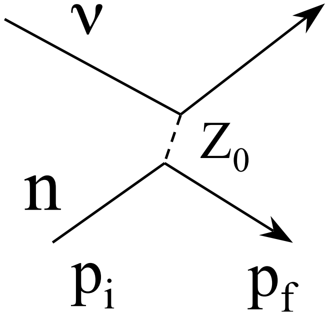
Buras et al., A&A 457 (2006) 281

Large Scale Effects From Charge Conjugation Violation in SN?

- C violation closely related to P violation.
- Because of $\not{C}$ $\bar{\nu}_e$ + p cross section smaller then ν_e + n.
- This difference decreases ratio of n to p in ν wind above proto-neutron star by 20%.
- Composition set by ratio $\bar{\nu} + p \rightarrow n + e^{+}$ to $\nu + n \rightarrow p + e^{-}$
- This has large implications for r-process nucleosynthesis (that makes half of heavy elements including gold, U) in ν wind.
- With $\not{C}$ wind is not significantly neutron rich.
- Origin of “neutron rich” conditions for r-process is a mystery.

Phys. Rev. D**65** (2002) 083005

- In laboratory, ν-N σ > $\overline{\nu}$-N σ
- At low E, σs are equal and ~E^2.



- C invariance of QED: $\sigma_{e-p} = \sigma_{e+p}$
- CP approx. conserved.
- P violation → C violation. $\sigma_{\nu\text{-}n} \neq \sigma_{\nu bar\text{-}n}$
  (ν cross sec. systematically larger.)
- T invariance: if no recoil then $\sigma_{\nu\text{-}n}=\sigma_{\nu bar\text{-}n}$

$$\sigma=\sigma_0 E^2(1 \pm \delta E/M)$$

- C violating weak magnetism
  $\delta=8c_a(c_v+F_2)/(c_v^2+5c_a^2) =3.32$

R-Process Nucleosynthesis

- Half of elements > Fe are made in rapid neutron capture process.
- Here seed nuclei rapidly capture many neutrons to build up heavy, very n rich, nuclei. These later beta decay many times to leave stable nuclei such as Gold or Uranium.
- R-process needs large ratio of free n to seed nuclei.
- Observation of very metal poor stars in galactic halo find abundances of heavy r-process elements equal to scaled solar abundances.
- Fission cycling where nuclei capture so many n that they fission and the fission fragments keep capturing n could produce abundances that depend on nuclear physics but not much on astrophysics site. However this needs even more neutrons!
- Preferred r-process site is neutrino driven wind in supernovae.

ν-Driven Wind

$$\nu_e + n \text{ ---> } p + e^-$$

$$\bar{\nu}_e + p \text{ ---> } n + e^+$$

- In equilibrium: $n/p = \bar{\lambda}/\lambda$

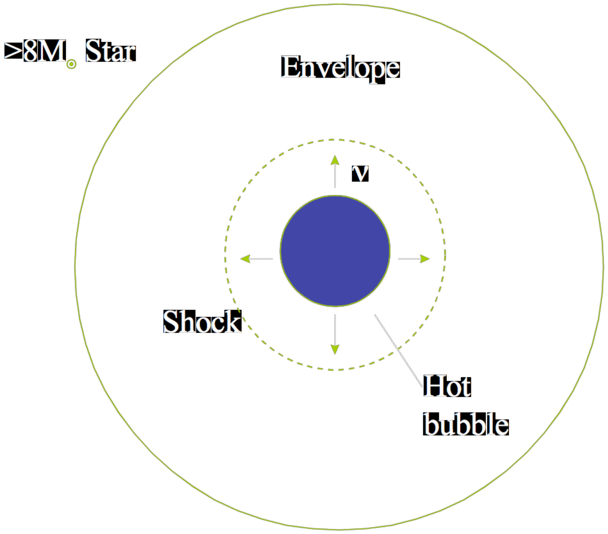
$$\sigma=\sigma_0 E^2 [1 \pm \delta E/M],$$

$$\delta=4g_a(1+2F_2)/(1+3g_a{}^2)=4.12$$

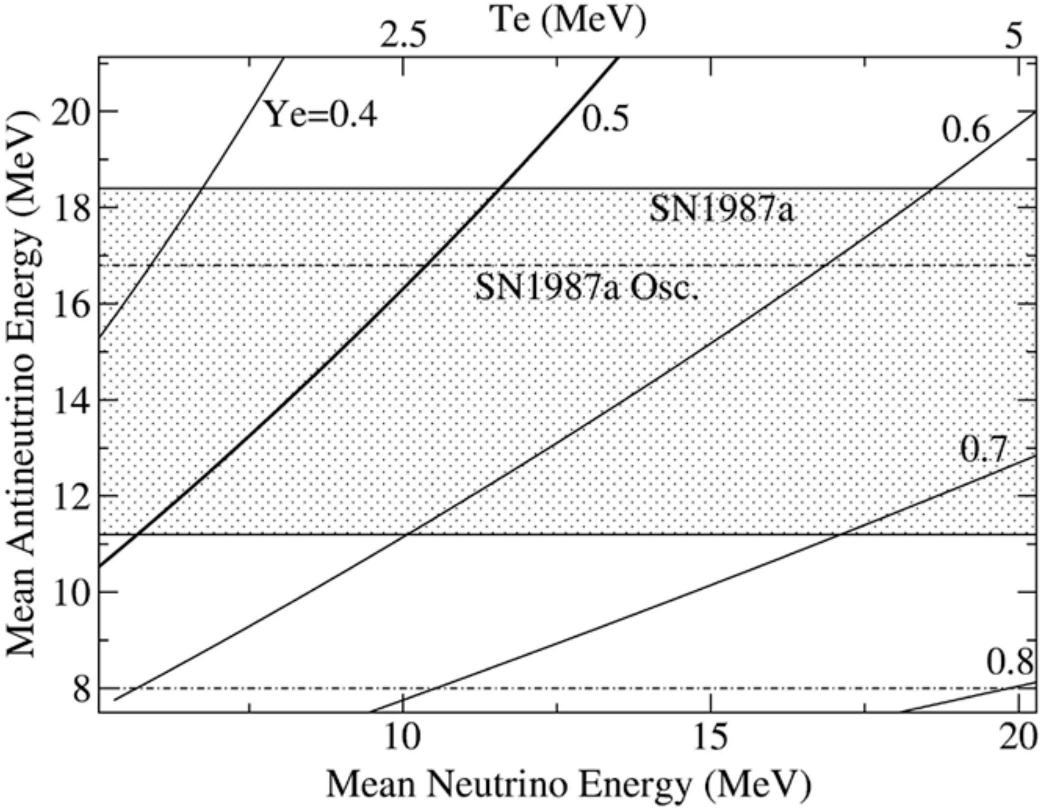
- n/p ratio depends of luminosity, ave. energy for ν_e and anti- ν_e

$$n/p = \bar{L}_\nu \bar{E} / (L_\nu E Q C)$$

$$C=[1+1.2\delta E/M]/[1-1.2\delta\bar{E}/M]$$



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 Osc.

- Active osc. don't help.
  - Osc that increase anti-ν_e E may be in conflict with SN1987A data.
  - Osc. of ν_e-ν_x will increase T and make wind proton rich.
- Only option is osc. to sterile ν. No other calculations, I have seen, produce a robustly neutron rich wind.

Neutron Shortage for r-Process

- With C violation, neutrino-driven wind not significantly neutron rich. Present models have trouble making heavy r-process elements.
- Wind not r-process site?
  - Other sites: neutron star mergers, gamma ray bursts … all have problems.
  - Example, NS mergers take time, but some very old stars in galaxy all ready have r-process elements.
- One astrophysical degree of freedom: entropy. Need large ratio of n to seed nuclei. --> Destroy most seed nuclei with a high entropy. Increase S with shocks, magnetic confinement…???

Sensitivity to New Physics

- SN involve ~~macroscopic~~ astronomical changes in 1st, 2nd, and 3rd generation quantum numbers.
- Sensitive to new sources of lepton number violation.
  - Violation of individual lepton # (convert ν_e to ν_μ 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.
  - Possible new long range field with a very weak coupling to 2nd or 3rd generation matter: weak limits from terrestrial experiments.
  - SN very sensitive because they have large numbers of 2nd and 3rd generation particles.

Supernova Quantum Numbers

	Pre-SN Core	Proto-N Star	Neutron Star
Mass (M_{sun})	1.6	1.6 --> 1.4	1.4
ν radiated	small	10^{58}	small
Baryon #	10^{57}	10^{57}	10^{57}
Electron #	10^{57}	10^{57}-->10^{56}	10^{56}
Muon #	small	10^{55}	10^{55}
Tau #	small	10^{54}	small
Strangeness	small	?	?

Experiment

Gravitational Waves

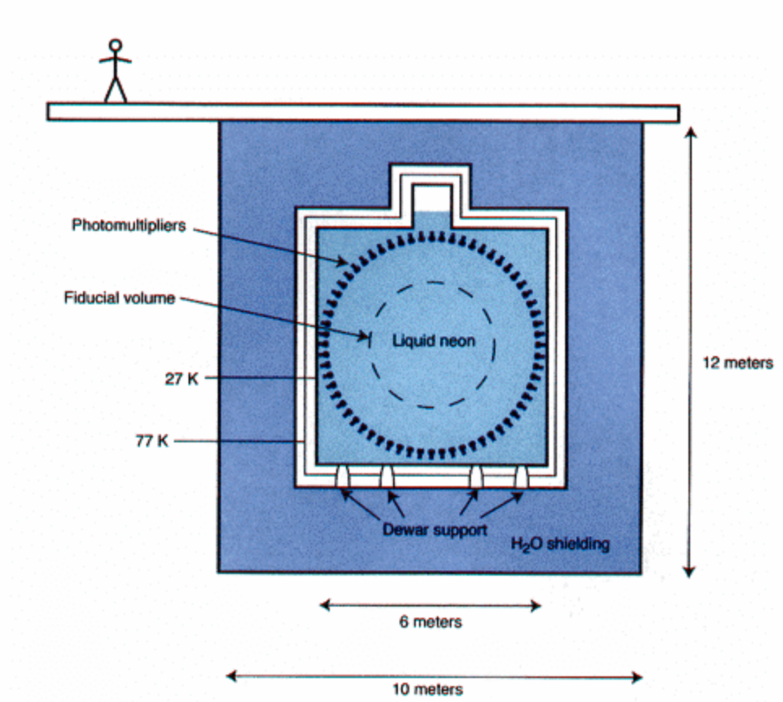
- Spherical collapse does not generate GW because no axis for polarization.
- GW signal directly probes asymmetry of SN explosion.
  - GW probe quadrupole def.
  - NS recoil depends on dipole.
- Galactic SN detectable in GW.
  - Important to keep some detectors running 24/7.
  - Powerful to compare ν, E+M, GW data.
- Parity violation could produce asymmetry. GW signal is fundamental probe of asymmetry at deepest level in star.

LIGO (Hanford)

Supernova Detection via Neutrino-Nucleus Elastic Scattering

- **Super-K** is good anti-ν_e detector via anti-ν+p to n+e^+.
- **SNO** was good ν_e detector via ν+d to ppe.
- Important to measure E of ν_μ and ν_τ.
  - E difference ν_μ to ν_e is lever arm for ν osc.
  - Total E in ν gives binding E of neutron star.
- ν-Nucleus elastic has large cross section but low recoil E.
- **SNOLAB, DUSEL** facilitates low background, low threshold, large mass experiments such as dark matter searches or $\beta\beta$ decay

- **SNO+** (liquid scint. not D_2O) sensitive to nu-p elastic scattering (J. Beacom)
- Example: **CLEAN** is a liquid Ne detector design for low E pp solar ν and dark matter.

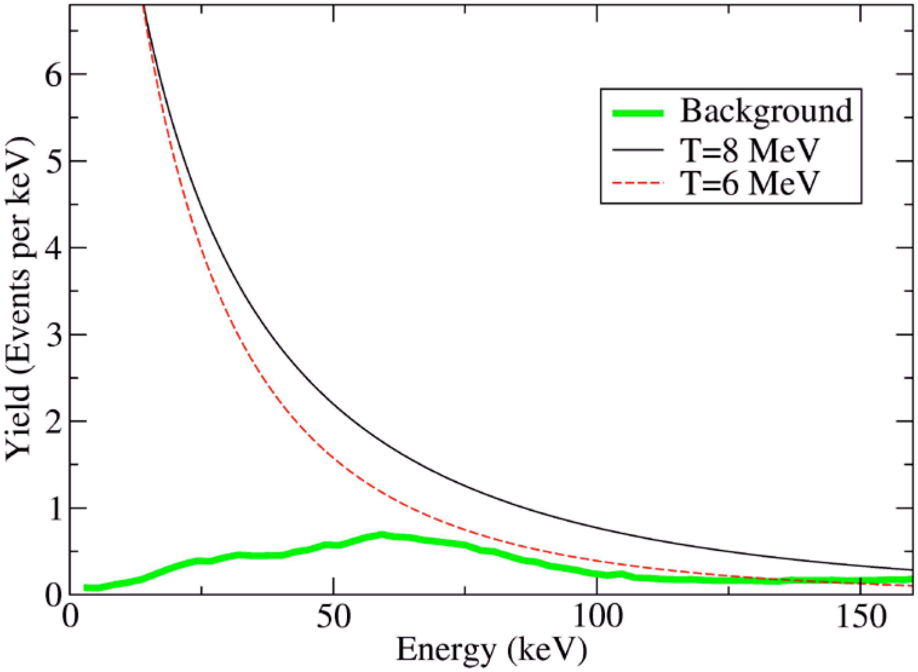


Supernova at 10 kpc in CLEAN

- Simulation of total background in CLEAN. Position cuts (not included) can greatly reduce background.
- Slope of ^{20}Ne recoil spectrum gives ν_μ, ν_τ spectrum.
- Observe ν-A elastic in "miniCLEAN" at SNS using ν from π decay at rest.
- Yield increases with target mass, but recoil E decreases.

Events/ton:	^{20}Ne,	^{76}Ge,	^{132}Xe
	4	18	30

- Next generation ββ decay exp sensitive to SN!



CJH, D. McKinsey, K. Coakly, PRD**68** (2003) 023005.

Lots of info in ν signal!, sensitivity to oscillations and theta13, sterile ν…
Spectrum of ν_e, anti-ν_e imply n/p ratio for nucleosynthesis…

Low Threshold Large Mass Detectors

- Many detectors could soon be sensitive to galactic supernovae via neutrino-nucleus elastic scattering.
- Double beta decay experiments as they approach fraction of a ton masses.
- Dark matter detectors with large masses.
  - Xe detectors very sensitive if low threshold.
  - Even solar neutrinos can produce a significant background for low threshold experiments.

Fundamental Symmetry Violation

- “Asymmetric tail-wagging responses by dogs to different emotive stimuli,” appeared in the March 20, 2007 issue of Current Biology.
- When dogs feel fundamentally positive about something or someone, their tails wag more to the right side of their rumps. When they have negative feelings, their tail wagging is biased to the left.

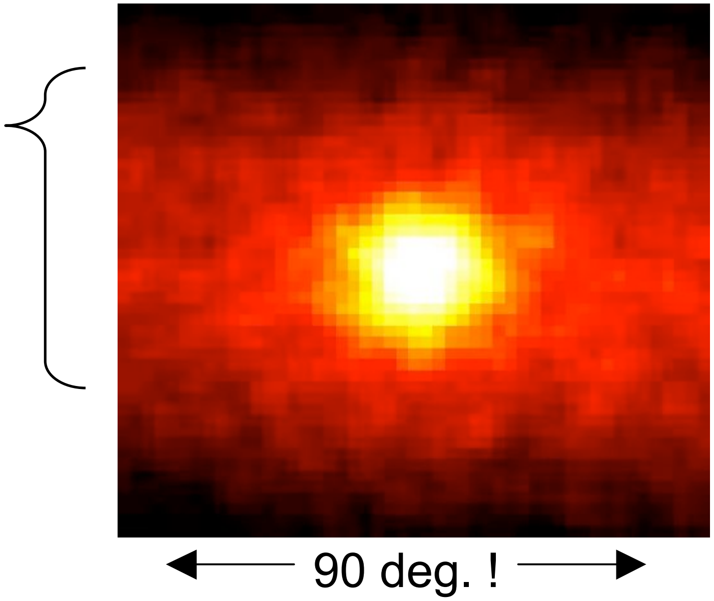
Fundamental Many-Body Physics

Low density neutron matter and unitary gasses:

The nn scattering length is much longer than the effective range or inter-particle spacing.

Neutrinosphere of a Supernova

- View sun in neutrinos, (see angular resolution of ν-e scattering in Super-K).
- View SN in neutrinos, see surface of last scattering called the neutrinosphere. What is neutrinosphere like?
- Conditions at neutrinosphere:
  - Temperature ~ 4 MeV from 20 SN1987a events.
  - Mean free path $\lambda=1/\sigma\rho$ ~R
  - $\sigma \sim G_F^2 E_\nu^2$ and $E_\nu \sim 3T$
  - $\rho \sim 10^{11}$ g/cm^3 [10^{-4} fm^{-3} or 1/1000 nuclear density]



- What is the composition, equation of state, and neutrino response of the neutrinosphere?
- *At low neutrinosphere density, Virial expansion gives model independent answers!*

Virial Expansion

- Assume (1) system in gas phase and has not undergone a phase transition with increasing density or decreasing temp. (2) fugacity $z=e^{\mu/T}$ with μ the chemical pot is small.
- Expand pressure in powers of z :

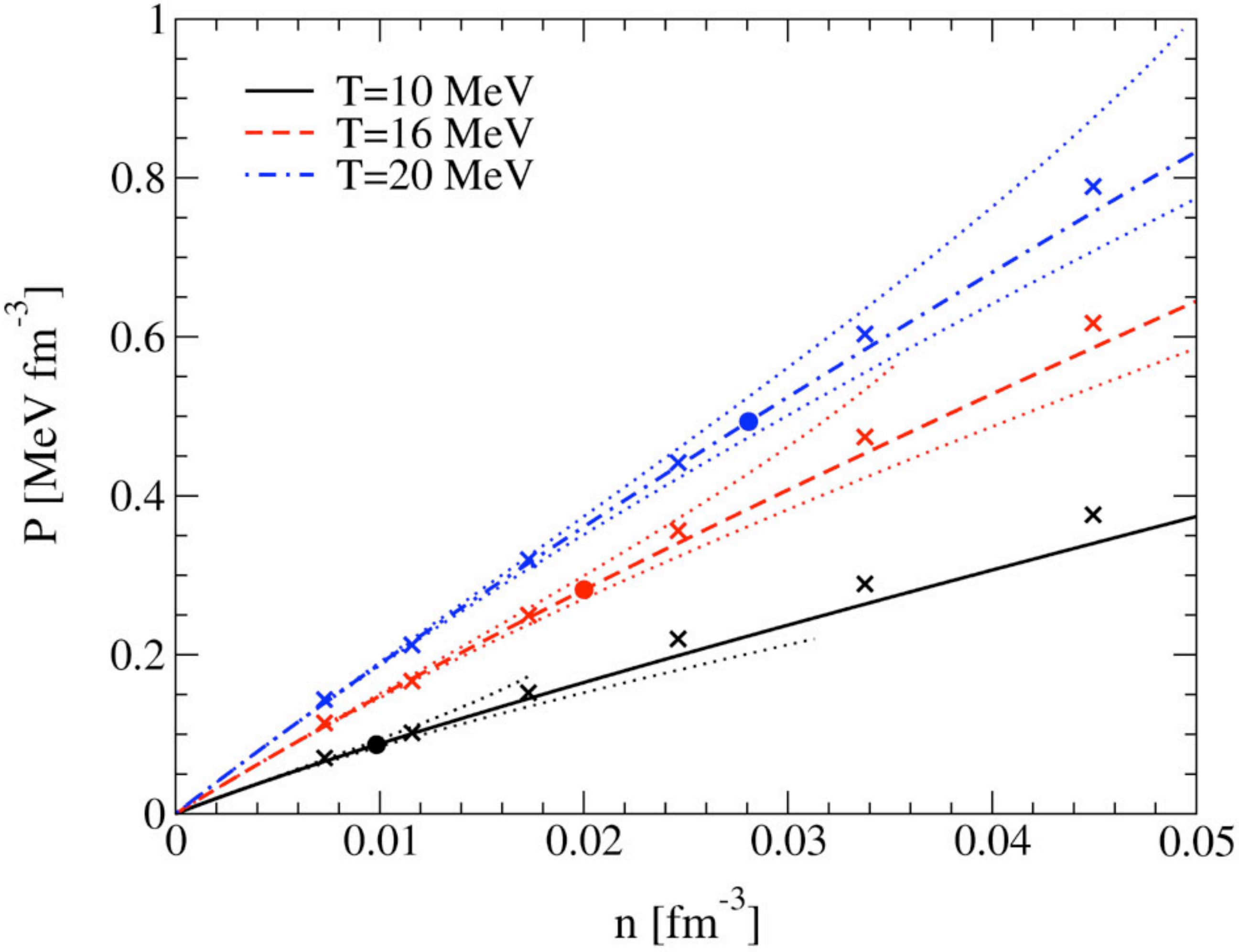
$$P=2T/\lambda^3[z+b_2z^2+b_3z^3+\ldots],$$

Here λ=thermal wavelength=$(2\pi/mT)^{1/2}$

- 2nd virial coef. $b_2(T)$ from 2 particle partition function which depends on density of states determined from phase shifts:

$$b_2 = 2^{1/2}\sum_B e^{E_B/T} + \frac{2^{1/2}}{\pi}\int_0^\infty dk\, e^{-E_k/2T}\sum_l (2l+1)d\delta_l(k)/dk \pm 2^{-5/2}$$

Neutron matter Equation of State



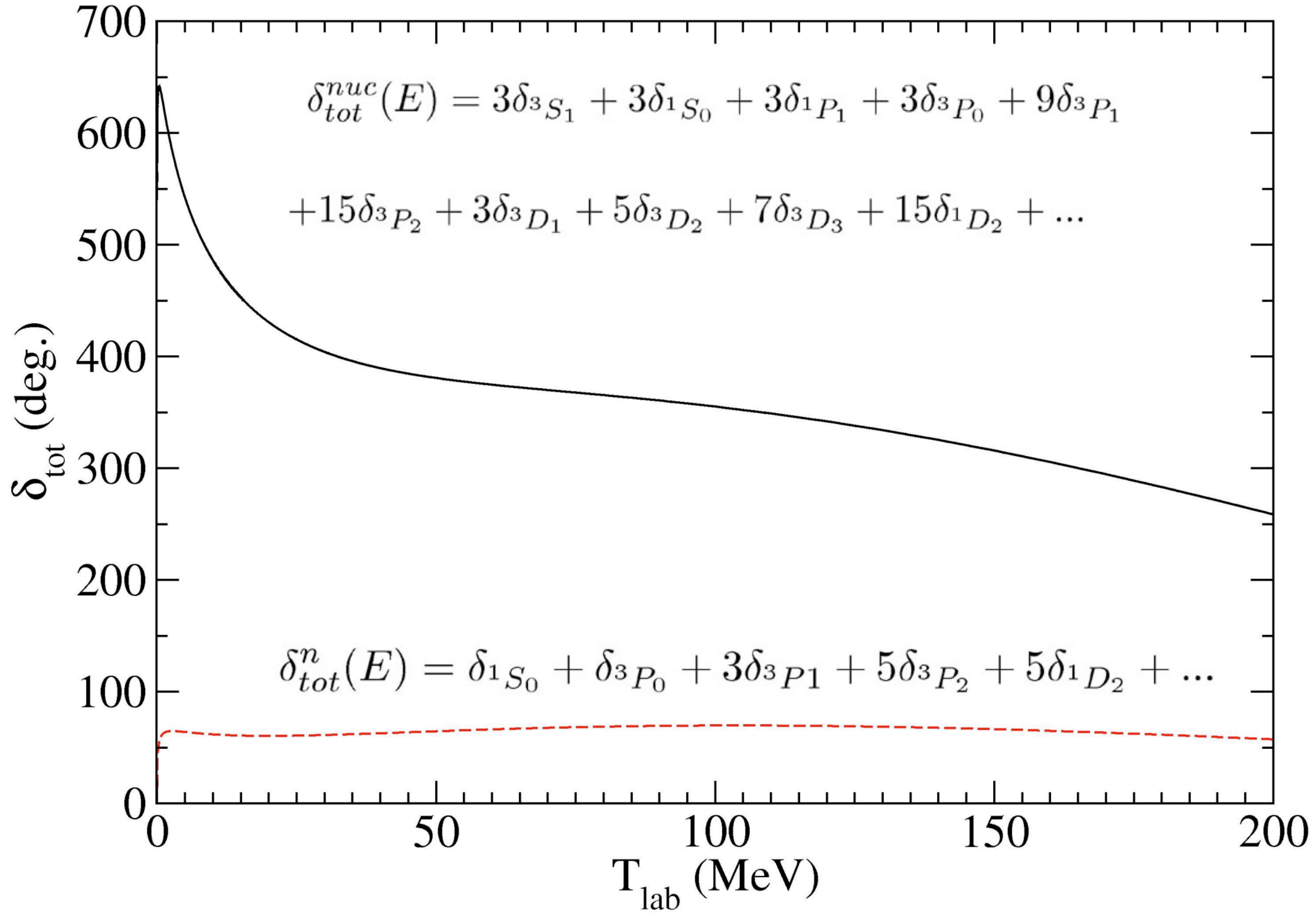
Error bars (dotted) from estimate of b_3

Crosses from microscopic FHNC calc. by Friedman + Pandharipande

Universal Behavior of Neutron Matter

- **Unitary gas:** a low density fermi system with very large scattering length a, and small effective range r.
- There are no length scales associated with interaction.
- Therefore system will exhibit universal behavior independent of details.
- We find the neutron matter EOS scales: P is only a function of density/$T^{3/2}$, instead of depending on density and T separately. The unitary gas EOS also scales.
- A number of cold atom experiments test universal behavior of fermions in this unitary limit.
- Mean free path of neutrinos in supernovae related to spin susceptibility of a warm unitary gas and this can be studied with cold atoms in the laboratory.

Total Phase Shift for Nuclear Matter (top) and Neutron Matter



NN-OnLine

Scaling of Neutron Matter EOS

- If $b_i(T)$ are independent of T the EOS will scale $P/T^{5/2} = f(n/T^{3/2})$. From

  $P/T=2/\lambda^3[z+b_n z^2+\ldots]$ and

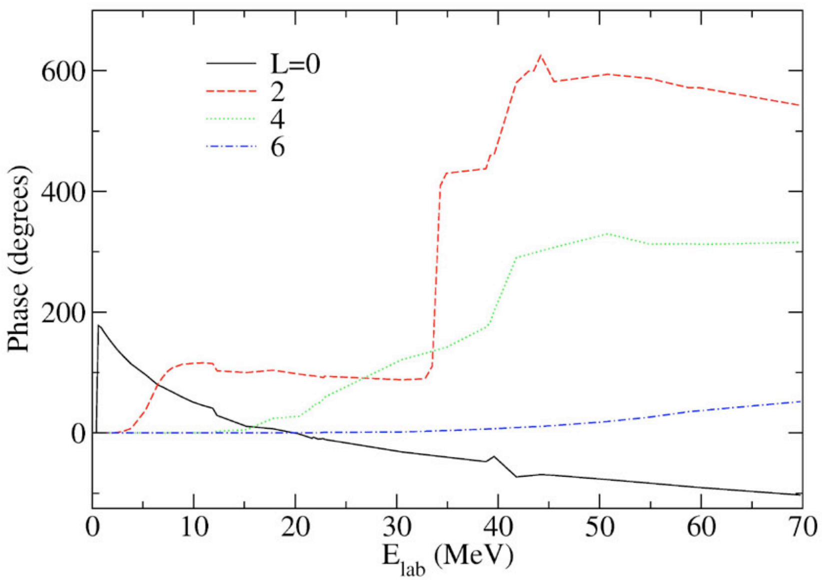
  $n=2/\lambda^3\,[z+2b_n z^2+\ldots]$ with $\lambda\sim T^{-1/2}$.
- Unitary Limit: calculate b_n with only s-wave and a=infinity, r=0. $\delta({}^1S_0)=\pi/2$

  $b_n(T)=3/2^{5/2}=0.5303$ independent of T.
- In unitary limit system clearly scales.
- Real neutron matter scales, to a very good approx., but with a $b_n \sim 0.3$ that is 40% smaller then unitary limit.

Nuclear Matter: *n*, *p*, α system

$$\frac{P}{T} = \frac{2}{\lambda^3}[z_p+z_n+(z_n^2+z_p^2)\enclose{circle}{b_n}+2z_nz_p(\enclose{circle}{b_{nuc}}-b_n)]+\frac{1}{\lambda_\alpha^3}[\underbrace{z_\alpha+z_\alpha^2\enclose{circle}{b_\alpha}+z_\alpha(z_p+z_n)\enclose{circle}{b_{\alpha n}}}_{}]$$

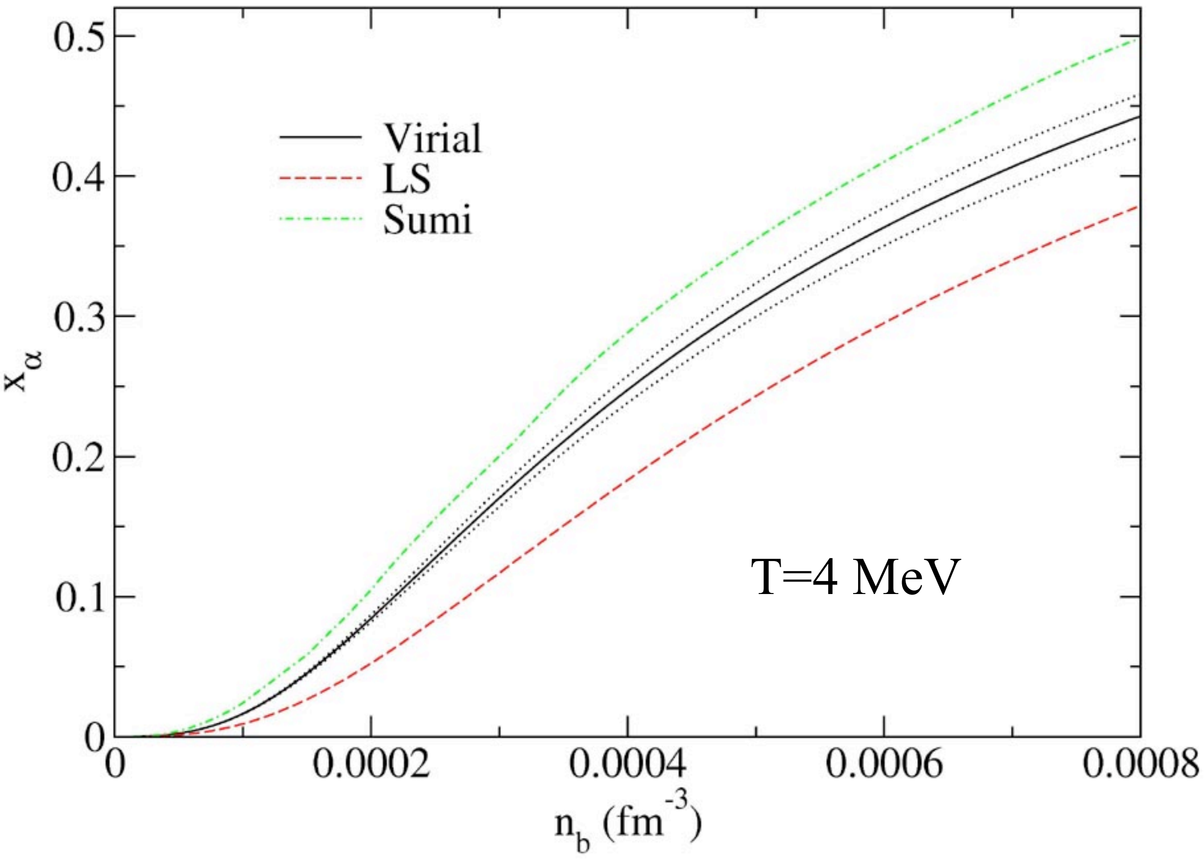
- Need four virial coefficients:
  - b_n for neutron matter,
  - b_{nuc} for symmetric nuclear matter,
  - b_α for alpha system,
  - $b_{\alpha n}$ for interaction between an α and N.
- Virials from NN, Nα and $\alpha\alpha$ elastic scattering phase shifts.



$\alpha-\alpha$ Elastic Phase Shifts

Nuclear Vapor has large α Fraction

- α particle mass fraction in nuclear matter vs density.
- Virial expansion gives model independent compositions.
- Lattimer Swesty EOS is dashed.
- Sumi is an EOS based on a rel. mean field interaction (dot-dashed).



- Most SN simulations used LS EOS -- had error in alpha concentration

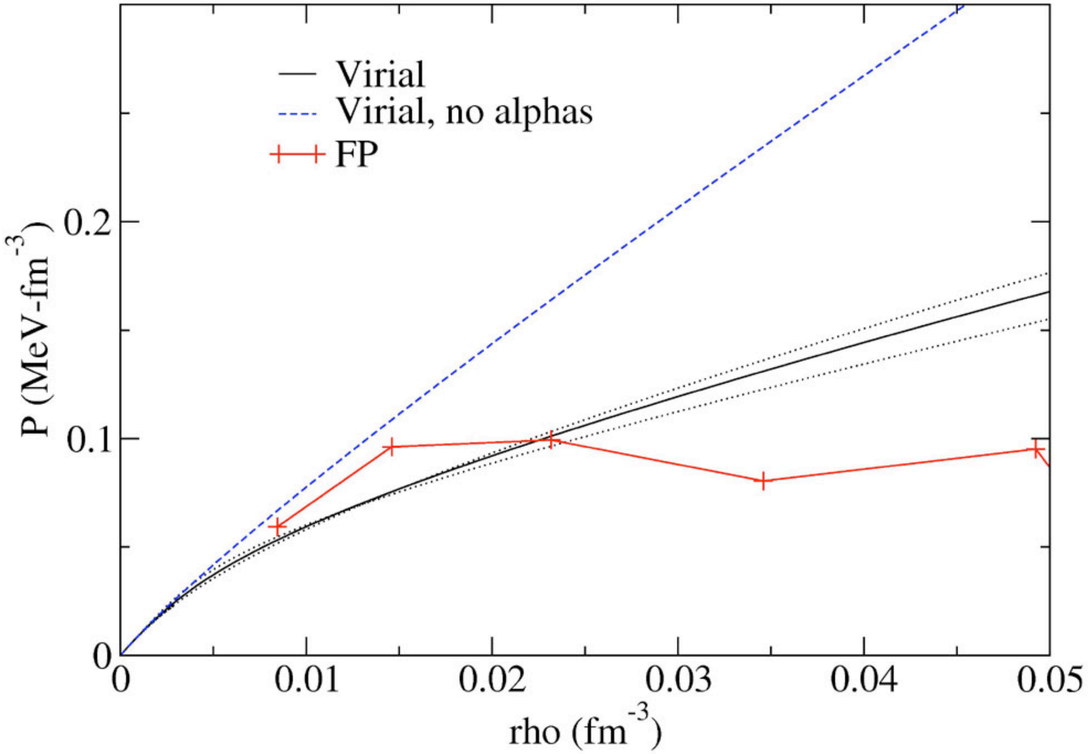
Pressure of Nuclear Matter

- Conventional microscopic approaches fail because of cluster (alpha) formation.
- Variational wave-function

  $\Psi=\Pi_{i<j}\, f(r_{ij})\Phi$

  can only describe a single cluster.

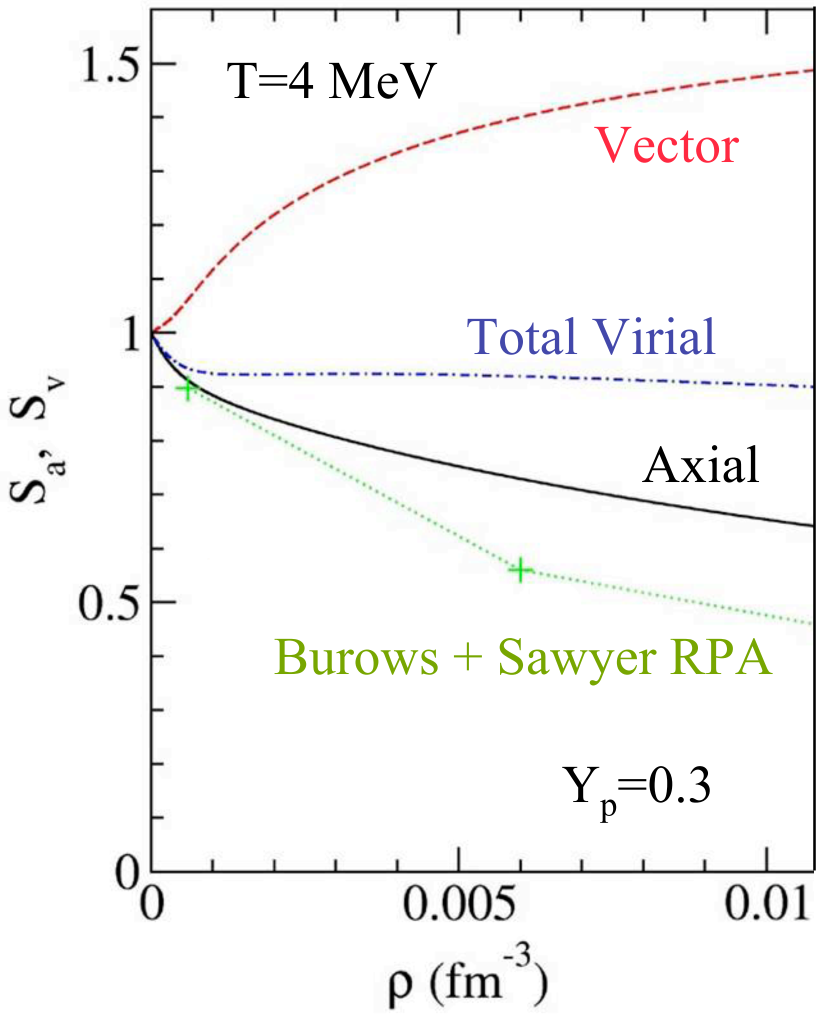
  Friedman+Pandharipande calc. (FP) based on NN+3N pot. and FHNC approximation.



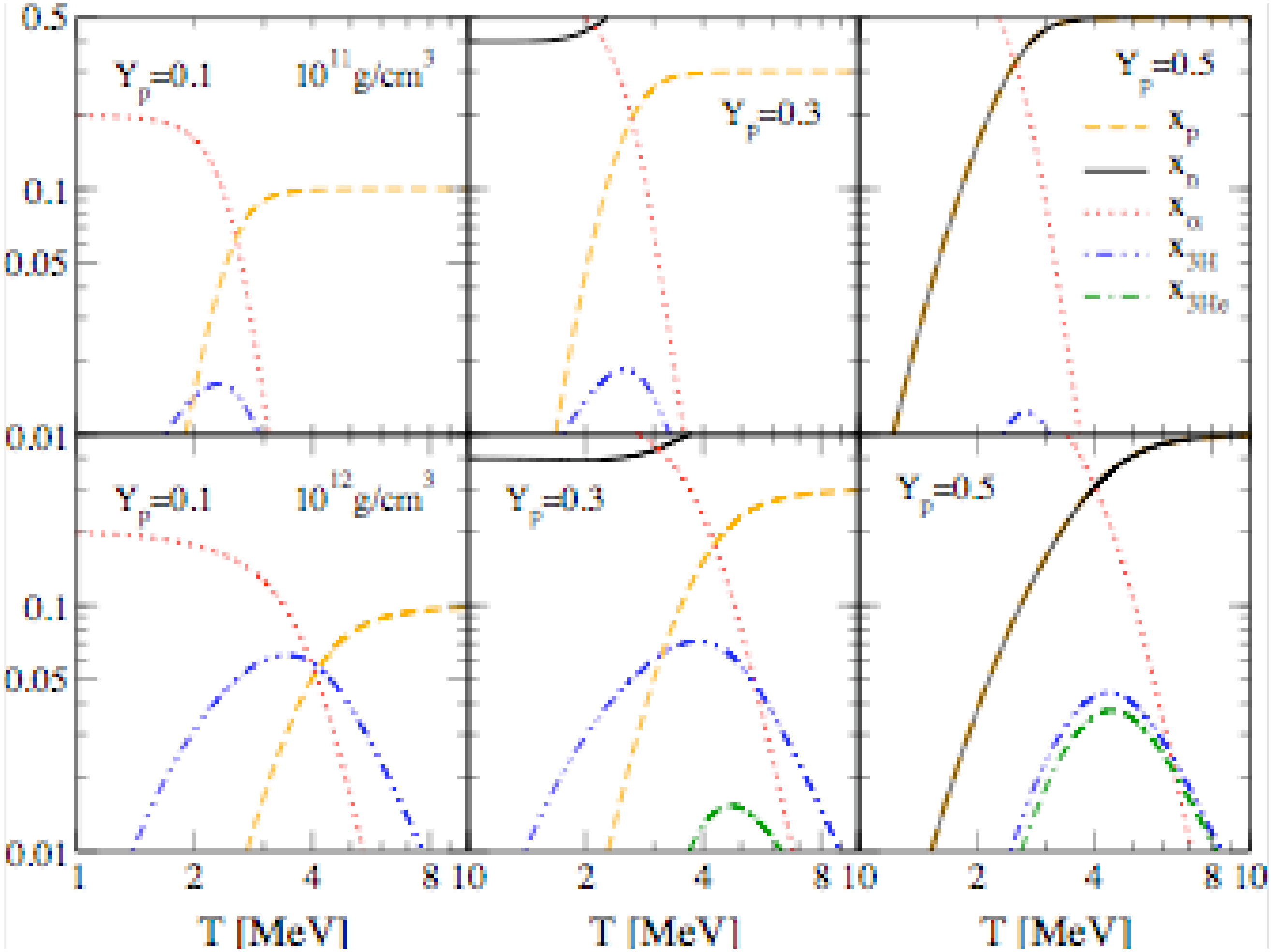
Pressure of symmetric nuclear matter at a temperature of T=10MeV.

Neutrino Response

- ν neutral current cross section $d\sigma/d\Omega = (G^2E_\nu^2/16\pi^2)[(1+\cos\theta)S_v + g_a^2(3-\cos\theta)S_a]$
- Vector response is static structure factor $S_v=S(q)$ as $q \rightarrow 0$
  $S(0)=T/(dP/dn)$
- Axial or spin response from spin polarized matter.
  $S_a=(1/n)\, d/dz_a\, (n_+ - n_-)\,|_{n_+=n_-}$
- Typical RPA calculations neglect alpha particles.
- *Virial expansion provides model independent results for EOS, composition, and ν response of low density neutron rich matter.*

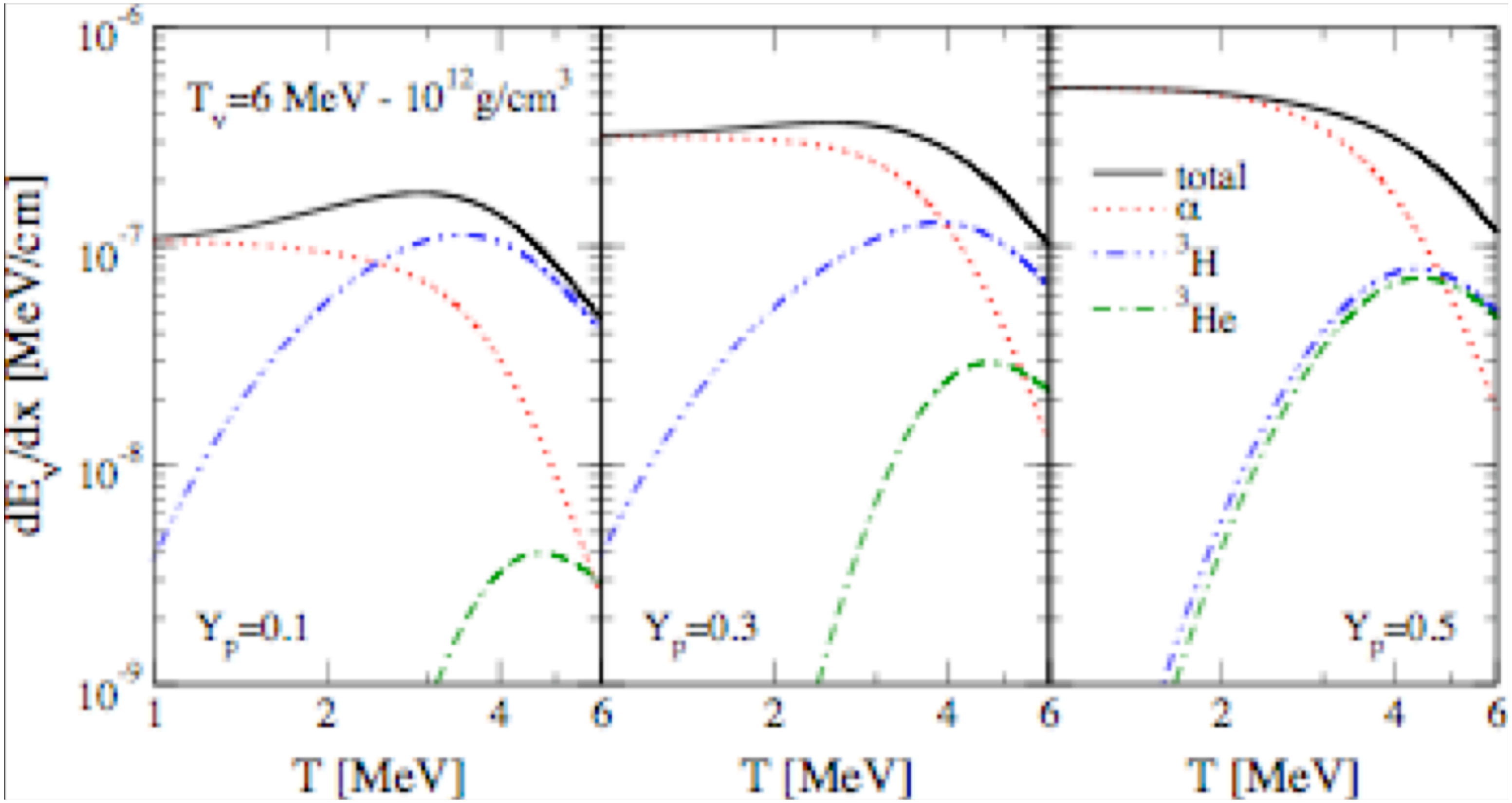


Some Mass 3 nuclei are present



E. O'Connor, D. Gazit, A. Schwenk, N. Barnea, CJH, PRC75 (2007) 055803

Mass 3 can contribute to mu, tau Neutrino Energy Loss



Supernovae are rich laboratories for fundamental physics.

- Dominated by weakly interacting neutrinos: unique opportunity for macroscopic symmetry violation.
  - Parity violation could make explosion asymmetric.
  - C violation reduced n/p ratio in ejecta creating possible “neutron shortage” for r-process.
- Dilute neutron rich matter, near neutrino-sphere, is a fundamental many-body system that is related to the universal unitary gas.
  - Virial expansion provides model independent results for EOS, composition, and long wave-length neutrino response.
  - Neutron matter EOS scales (2nd virial indep of temp) but with a 2nd virial 40% smaller than that for a unitary gas.
  - Nuclear matter is very different from neutron matter because of cluster formation (light nuclei such as 4He)

Fundamental Neutron Physics in Supernovae

- Parity violation with **Jorge Piekarewicz** (FSU), C violation with **Gang Li**.
- Virial Expansion: **Achim Schwenk** (TRIUMF)
  - PRC**75** (2007) 055803 (Mass 3 nuclei),
  - Phys Lett. **B642**(2006) 326 (Neutrino-response),
  - Nucl. Phy **A776**(2006) 55 (Nuclear matter),
  - Phy Lett **B638**(2006) 153 (Neutron matter).
- Students: **Liliana Caballero** (nu interactions), **Helber Dussan** (nonuniform matter at T=0), **Gang Shen** (nonuniform matter at finite T).
- Supported in part by DOE and state of Indiana.