Presupernova Neutrino Spectra

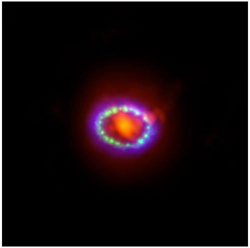
Kelly Patton
Arizona State University

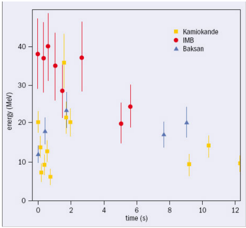
Cecilia Lunardini
Arizona State University

INT 15-2a: Neutrino Astrophysics and Fundamental Properties
03 June 2015

Supernova Neutrinos

- SN neutrino physics has a rich history of study
  - Oscillations in turbulence, collective oscillations and shock effects
  - Contribution to explosion mechanism
  - Effects on nucleosynthesis
  - Actual data!
- Thousands of hits on any database you care to search...





What about before the SN?

- Large amounts of neutrinos are produced in the lead up to the SN
- Some recent work suggests these "presupernova" neutrinos could be detected
    - Advance signal of SN (∼ hours)
    - Insight to interior of the star before the explosion

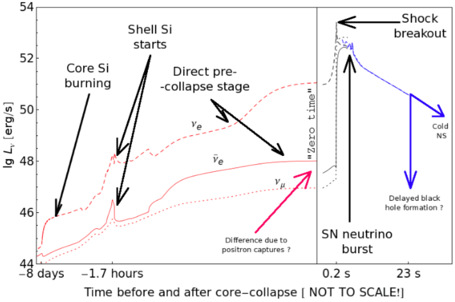


Figure from Odrzywolek and Heger *Acta Physica Polonica B* **41** 2010

What about before the SN?

- Lots of questions to look at
  - What contributes to the ν production?
  - What energies are reached?
  - How many ν are detectable?
- Answering these questions requires information about the spectrum, not just the energy output

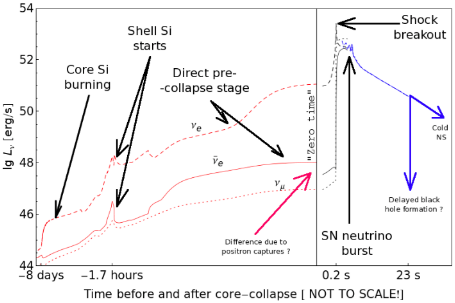


Figure from Odrzywolek and Heger *Acta Physica Polonica B* **41** 2010

What contributes to the spectrum?

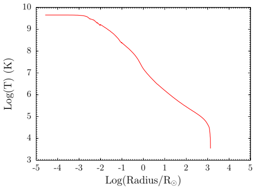
- Two main categories of production

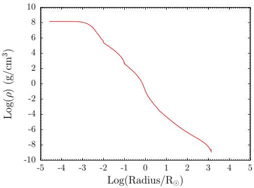
- Nuclear processes
  - $\beta^{\pm}$ decay
  - $e^{\pm}$ capture

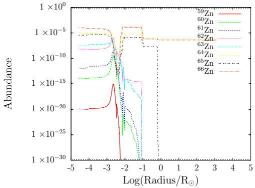
- Thermal processes
  - Plasmon decay
  - Photoneutrino production
  - Pair annihilation

MESA

- All processes depend on temperature (T), density (ρ), and electron fraction (Y_e)
  - Nuclear processes also depend on isotopic abundances
- We use MESA to calculate all of these quantities (Paxton *et al.* arXiv:1301:0319v2)
  - Track variables either as a function of time or radial position in star
- Ex. 25 $M_{\odot}$ during Si burning

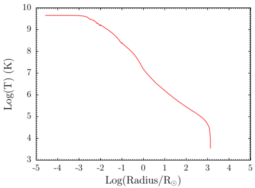


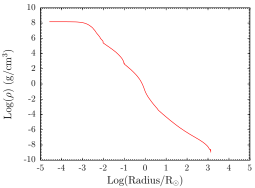


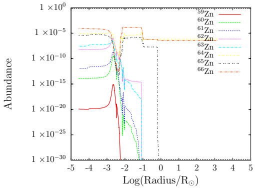


Example Calculation

- Chose a single point in the 25 $M_\odot$ star to focus on
  - T = 4.5 $\times 10^9$ K
  - $\rho\, Y_e = 1.6 \times 10^8$ g/cm^3
  - About 100 km from center of star







Nuclear Processes

$$A(N,Z) \rightarrow A(N-1,Z+1) + e^- + \overline{\nu}_e$$
$$A(N,Z) \rightarrow A(N+1,Z-1) + e^+ + \nu_e$$
$$A(N,Z) + e^- \rightarrow A(N+1,Z-1) + \nu_e$$
$$A(N,Z) + e^+ \rightarrow A(N-1,Z+1) + \overline{\nu}_e$$

- Electron flavor neutrinos and antineutrinos created through $\beta^{\pm}$ decays and e$^{\pm}$ captures
- Rates of these processes are calculated and published in tables
  - G. M. Fuller, W. A. Fowler and M. J. Newman, ApJ **293** 1 (1985)
  - K. Langanke and G. Martinez-Pinedo, Nucl. Phys. A, **673** 481 (2000)
  - T. Oda *et al.*, Atomic Data and Nuclear Data Tables **56** 231 (1994)

Nuclear Processes: Spectrum

$$\phi_{EC,PC}(E_\nu) = N\frac{E_\nu^2(E_\nu - Q)^2}{1+\exp\left((E_\nu - Q - \mu_e)/kT\right)}$$
$$\phi_\beta(E_\nu) = N\frac{E_\nu^2(Q - E_\nu)^2}{1+\exp\left((E_\nu - Q + \mu_e)/kT\right)},$$

- Spectral shape is related to the phase space factors (and a normalization factor)
- To calculate the spectrum, we need the Q-values

$$Q = M_p - M_d + E_p - E_d$$

Nuclear Processes: Effective Q

$$Q = M_p - M_d + E_p - E_d$$

- If excitation states of the parent and daughter are known, Q is easy to find
- We have many transitions to and from different energy levels
- Define an effective Q value to account for different excitation states
  - Treat Q as fit variable (K. Langanke, G. Martinez-Pinedo and J. M. Sampaio, Phys. Rev. C **64** 055801 (2001))
  - Vary until average energy matches that from rate table

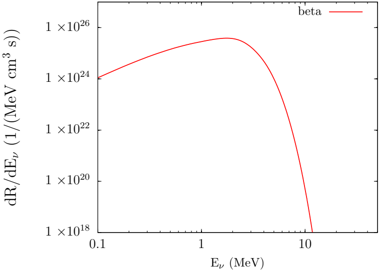
Nuclear Processes: Summing Over Isotopes

- Individual spectra are normalized so that rates match values from tables

T = 4.5×10[9] K

$\rho\, Y_e = 1.6 \times 10^8$ g/cm^3

$$\lambda^i = \int_0^\infty \phi_i dE_\nu \quad i = EC, PC, \beta^\pm$$

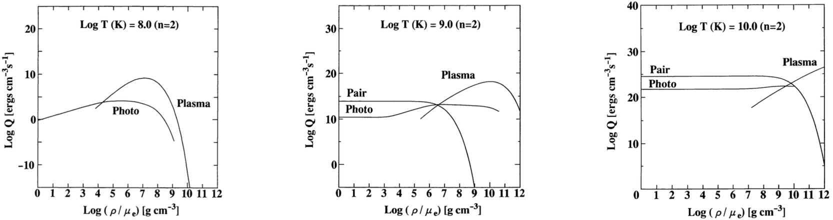


- Weighted sum of isotopes gives total spectrum

$$\Phi = \sum_k X_k \phi_k \frac{\rho}{m_p A_k}$$

Thermal Processes - Itoh *et al.* Formulas

- Itoh *et al.* put out a series of papers with formulas for calculating the neutrino emissivities of thermal processes at different T and ρ values
- But, we want differential rates and emissivities



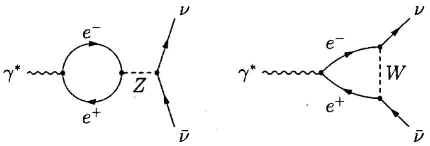
Figures from Itoh *et al.* Astrophys. J. Suppl. Series **102** 411-424 (1996)

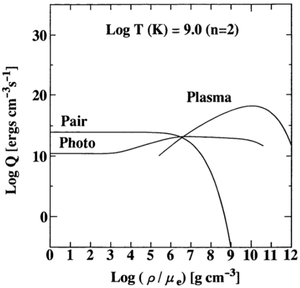
Basic Calculation for Thermal Processes

$$R = \int (\textit{incoming momenta}) * (\textit{incoming distributions})$$
$$\times \int (\textit{outgoing momenta}) * (\textit{outgoing distributions})$$
$$\times |M|^2 \delta^4 (\textit{energy conservation})$$

- Basically the same calculation needs to be done for each process
- Matrix elements will change, as will details of the integration

Plasmon Decay



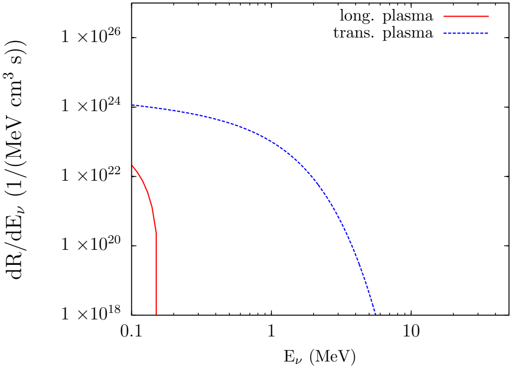


- Excitations in the plasma (plamsons) decay into neutrino/antineutrino pairs
  - Two types of plasmons (transverse and longitudinal) have different spectra

S. Ratković, S. I. Dutta, and M. Prakash, Phys. Rev. D **67** 123002 (2003)
A. Odrzywolek, Eur. Phys. J. C **52** 425-434 (2007)

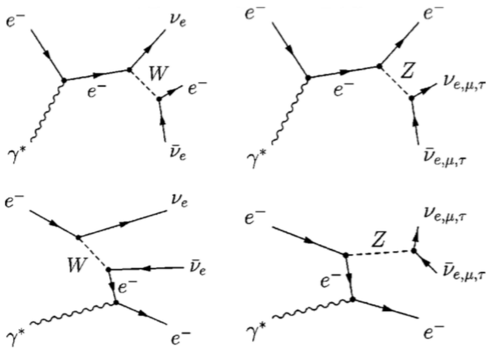
Plasmon Decay

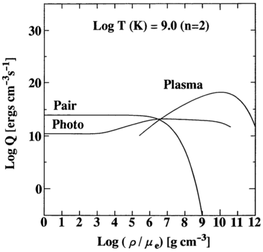
- Braaten-Segel approximations for plasma parameters simplify integral to one that can be done analytically (E. Braaten and D. Segel, Phys. Rev. D **48** 1478 (1993))



T = 4.5×10^9 K
$\rho\, Y_e = 1.6 \times 10^8$ g/cm^3

Photoneutrino Process



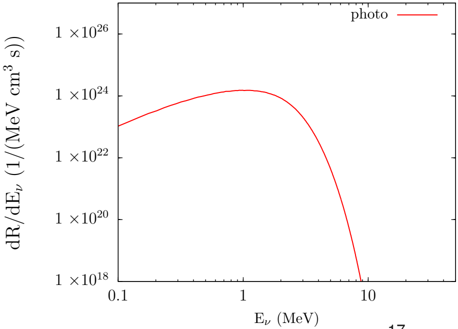


- Modified Compton scattering: Electron scatters from a photon, producing a neutrino/antineutrino pair

S. I. Dutta, S. Ratković, and M. Prakash, Phys. Rev. D **69** 023005 (2004)

Photoneutrino Process

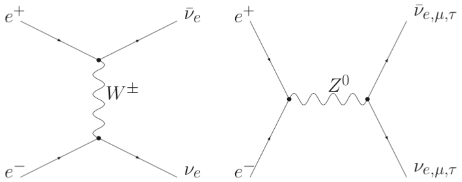
- Matrix elements take a full page to write out in Dutta *et al.* (with simplifying definitions)
- Additional simplification is possible through approximations for dispersion relations and judicious choice of coordinate system



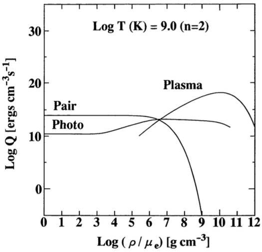
T = 4.5×10^9 K

$\rho\, Y_e = 1.6 \times 10^8$ g/cm^3

Pair Neutrino Process



- Similar to familiar process of $e^+ + e^- \rightarrow \gamma + \gamma$
- Dominant at high T



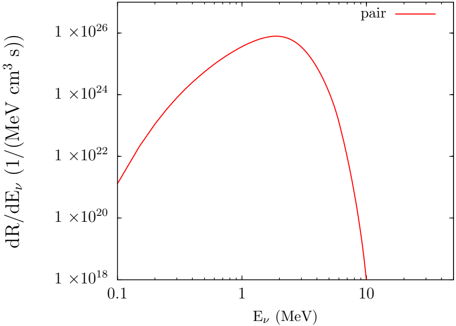
M. Misiaszek, A. Odrzywolek, and M. Kutschera, Phys. Rev. D **74** 043006(2006)

Pair Neutrino Process

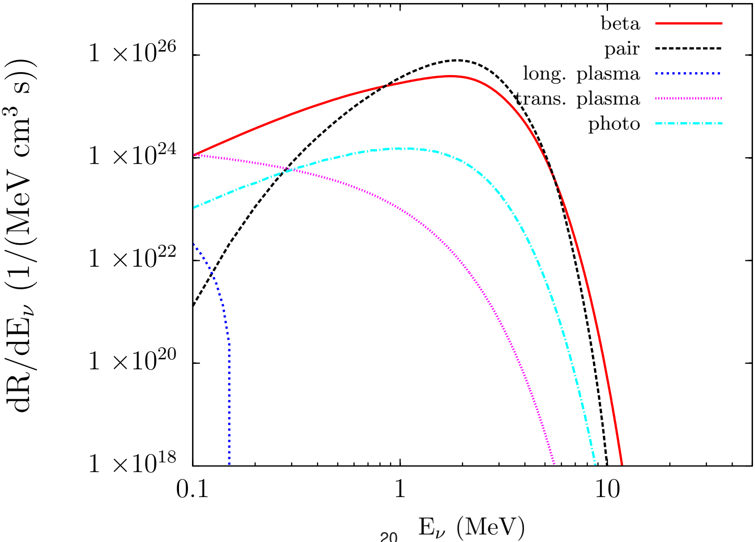
- Getting from generic matrix element to a form that's useful for calculating the spectrum involves a lot of "tedious algebra" (explanation of which can be found in S. Hannestad and J. Madsen, Phys. Rev. D **52** 1764 (1995))

- Final result is another integral done through Monte Carlo integration

$T = 4.5\times10^9$ K
$\rho\, Y_e = 1.6 \times 10^8$ g/cm^3

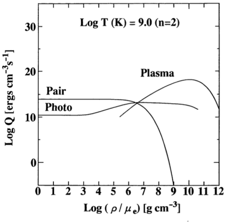


Put it all together...



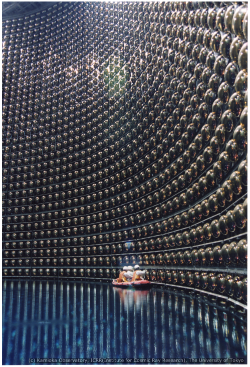
What does the (T,ρ) space look like?

- Itoh et al. produced a great picture of the total energy outputs as neutrinos for various processes in (T,ρ) space



- No real idea of what energies those neutrinos have
- Goal: create Itoh-like plot for neutrinos above a certain energy
  - Which process really dominates in detectable energies?
  - Include the Nuclear processes, which Itoh *et al.* does not take into account

Detectability



- Odrzywolek *et al.* predicted $\mathcal{O}(10)$ events in Super Kamiokande, and $\mathcal{O}(500)$ in next generation detectors for star 1 kpc away
  - That calculation only considered pair neutrinos (A. Odrzywolek, M. Misiaszek, and M. Kutschera arXiv:astro-ph/0311012v2)
- We have more complete picture of the spectrum, need to redo detectability calculation
- Other indirect signals?

Conclusion

- Foundation is down: Spectra calculations for four dominant processes in late stage stellar evolution
- Plenty more to do
  - Evolution of spectrum over star's lifetime?
  - Map of detectable neutrinos in (T,ρ) space
  - Detectability