Why cross sections are important for astrophysics

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Neutrinos in Astropysics

A few environments where neutrinos play an important role

- sun
- Core Collapse Supernovae
- Gamma Ray Bursts
- Big Bang Nucleosynthesis
- Neutron Stars
- Massive Stars
- + many more

About the scattering cross sections

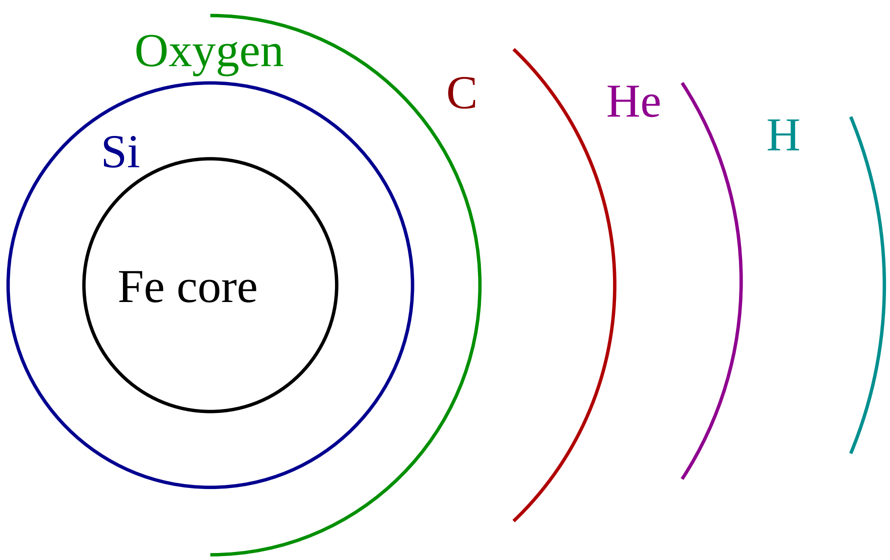
- $\nu + \mathrm{nucleon}$
- $\nu + \mathrm{nucleus}$
- $\nu + e$
- $\nu + \nu$
- production processes
- reverse processes

Complications occur when nuclear physics becomes important, for example when

- scattering on nuclei
- scattering on nucleons in dense matter

Core Collapse Supernovae

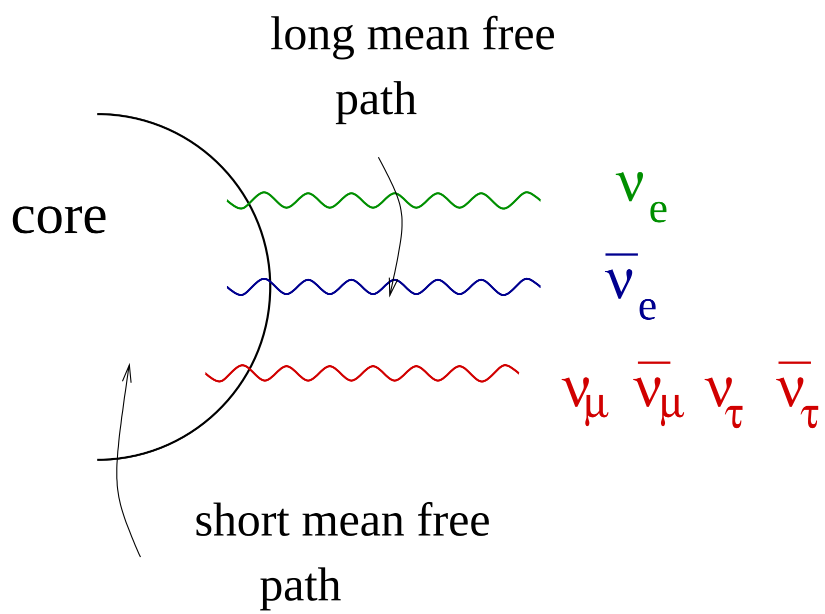
end of the life of a massive star



- core unstable
  $M_{core} \sim 1.5 M_{sun}$
- collapse to nuclear density
- core bounce
- shock produced
- shock stalls
- neutrinos diffuse out of core, may energize shock

Supernova Neutrinos

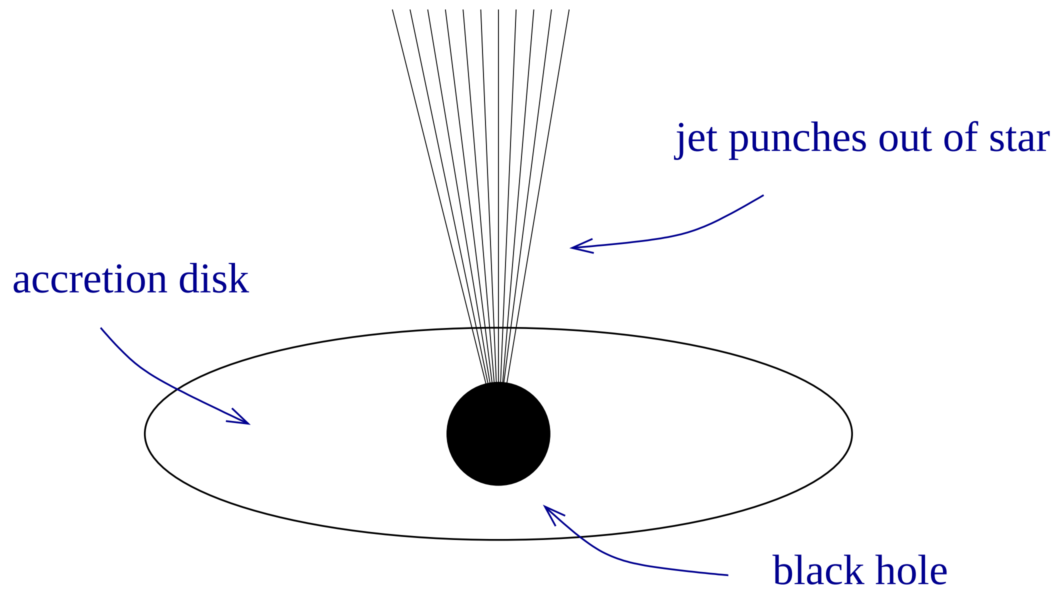
All types of neutrinos emanate from the proto-neutron star core. They travel through the outer layers of the SN, then to earth.



SN neutrinos are important for dynamics, nucleosynthesis, and observation

Model for Long Duration Gamma Ray Bursts: Collapsar/Hypernovae Model

- Failed Supernova
- Too much rotation for real collapse & bounce

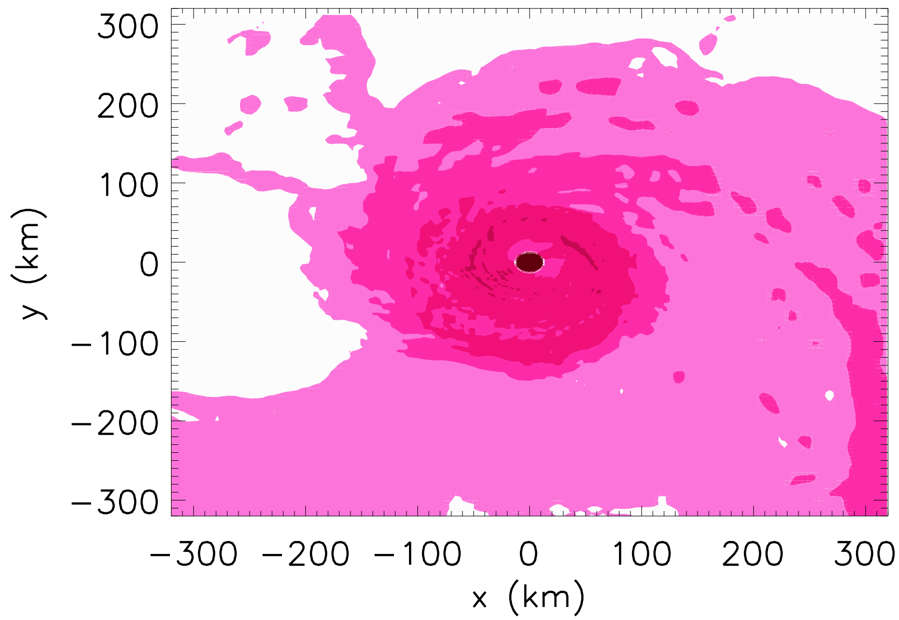


What provides the energy which drives the jet? The neutrinos! (at least in part)

Woosley 1993, MacFadyen and Woosley 1999

Short Gamma Ray Bursts: Compact Object Merger Models

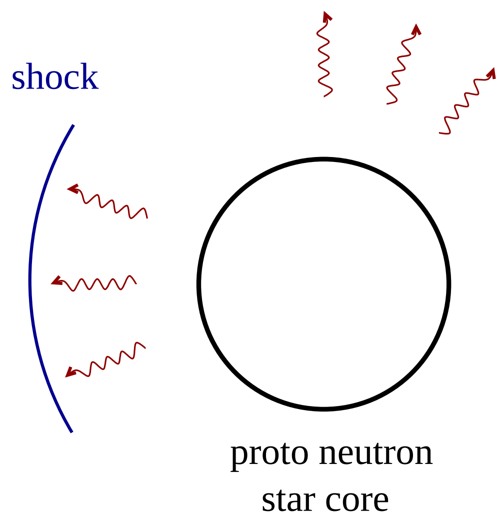
- Neutron star and black hole spiral in
- Create an accretion disk around a black hole

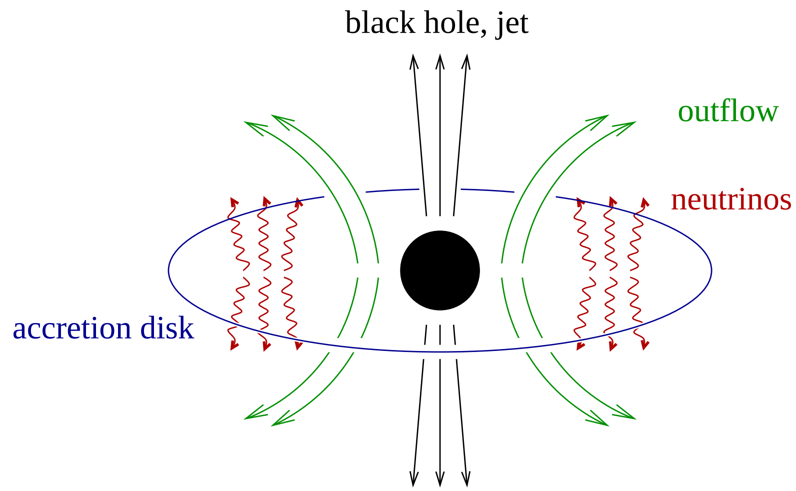


density data from M Ruffert

Explosions of Massive Stars:

What's happening at the center?

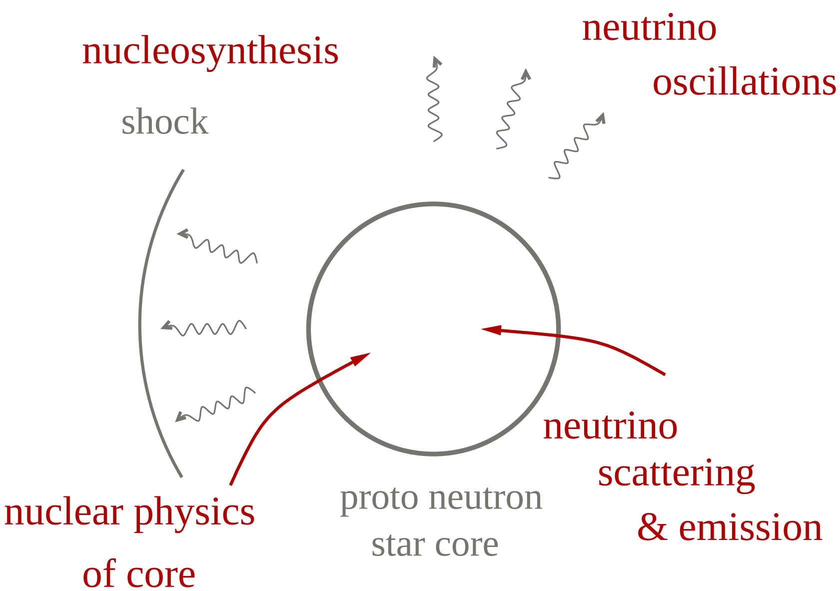


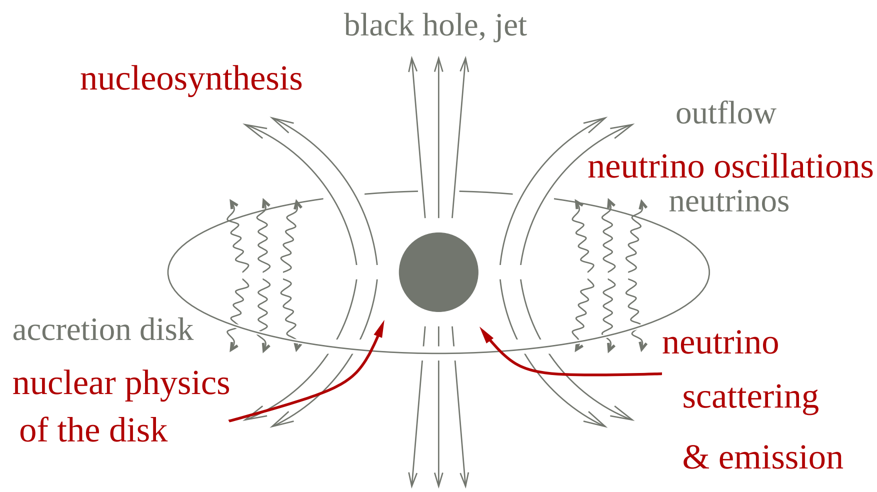


Standard core core collapse SN   gamma ray burst

Explosions of Massive Stars:

Where do the cross sections fit in?





Standard core core collapse SN

gamma ray burst

What do these astrophysical neutrino spectra look like?

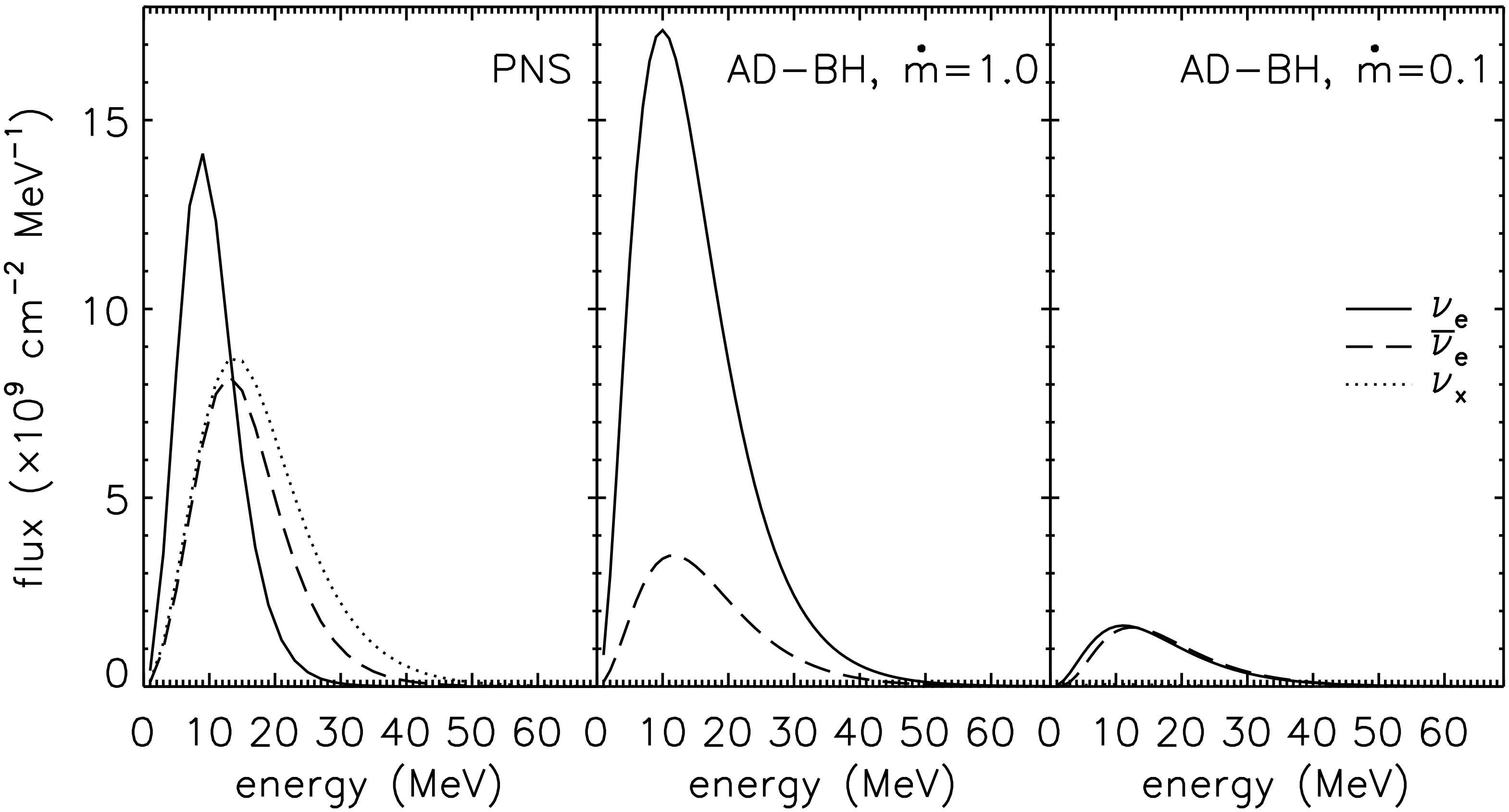
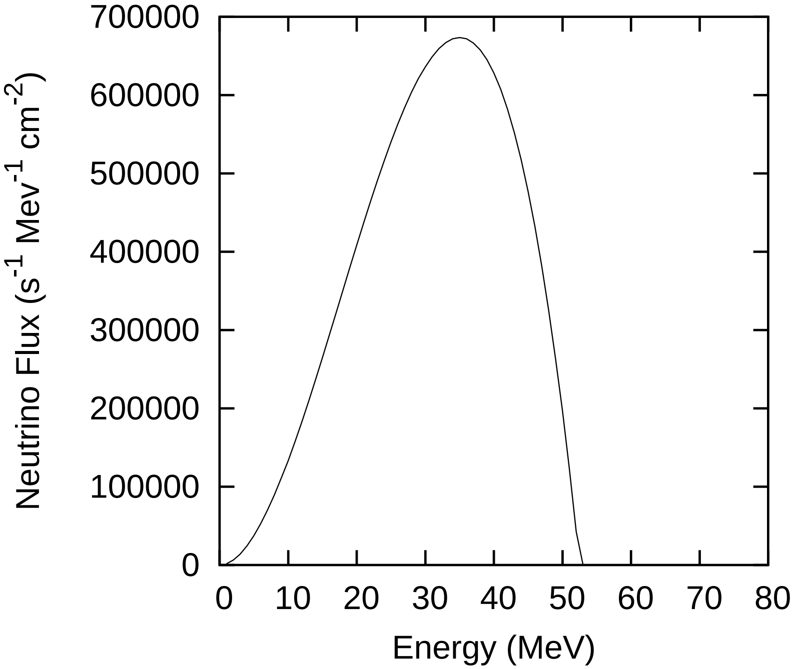
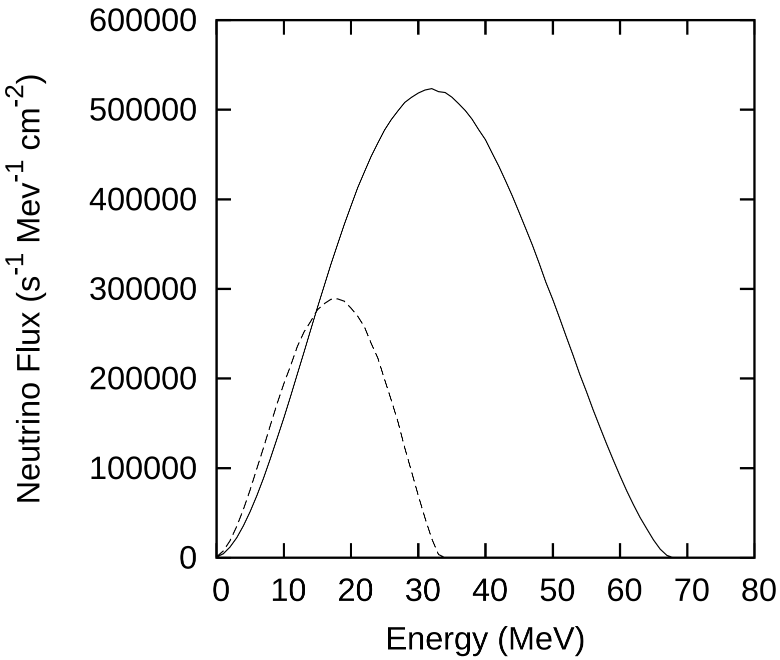


Figure from GM & Surman 2006, neutrino diffusion calculations: Breunn, Cardall, Pons, Prakash, Janka, and more

Spectra from stopped pions and low energy beta beams





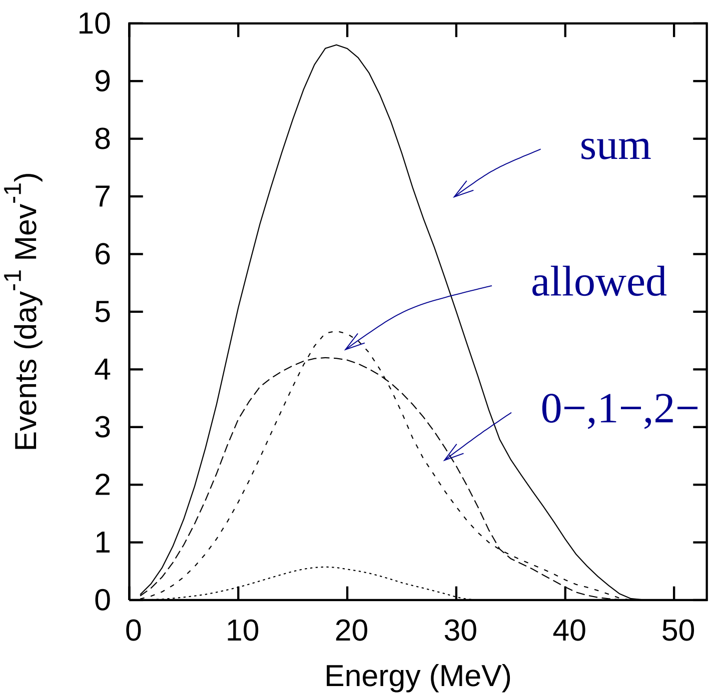
Pion decay at rest ν_e spectrum

proposed applications to astrophysics: nuSNS collaboration

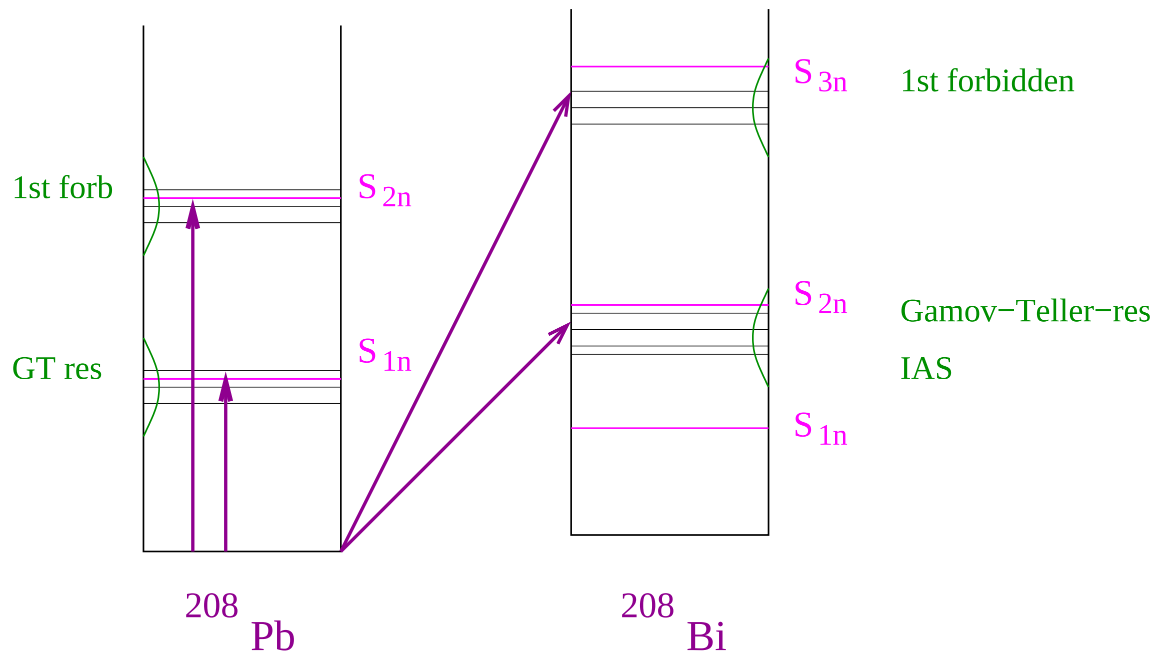
Beta beam spectrum at boost factors of $\gamma = 7$ and $\gamma = 14$.

Low energy beta beam concept and applications: Volpe, Balantekin, Jachowicz, Amanik, de Jesus, GM, etc..

Understanding the neutrino-nucleus cross sections



Multipole contributions to ν_e-lead scattering GM 2004



Schematic of resonances in lead for ~ 40 MeV neutrinos

The neutrino cross section - nucleosynthesis connection

A few types of nucleosynthesis affected by an intense neutrino flux:

- r-process, e.g. Uranium
- p-process, e.g. Molybdenum
- ν-process, e.g. Boron-11

Neutrinos can excite nuclei and spall neutrons and protons creating new nuclei.

Or, they can subtly change the "path" of nuclear flow by converting neutrons to protons (in nuclei or alone).

Supernova Neutrino Nucleosynthesis

Some rare nuclei will be produced from neutrino induced spallation in the outer layers of the star Woosley et al 1990

e.g. Where does the $^{10}\mathrm{B}$ in the universe come from?

The Neutrino Process in Supernovae or Cosmic Ray Spallation?

Neutrinos diffuse out the proto-neutron star core on a timescale of ~10 seconds

$$\nu +^{12}\mathrm{C} \rightarrow^{10}\mathrm{B} + n + p + \nu$$

in the Carbon shell

And many other nuclei too - $^{11}\mathrm{B}$, $^{19}\mathrm{Fl}$, $^{138}\mathrm{La}$, $^{180}\mathrm{Ta}$

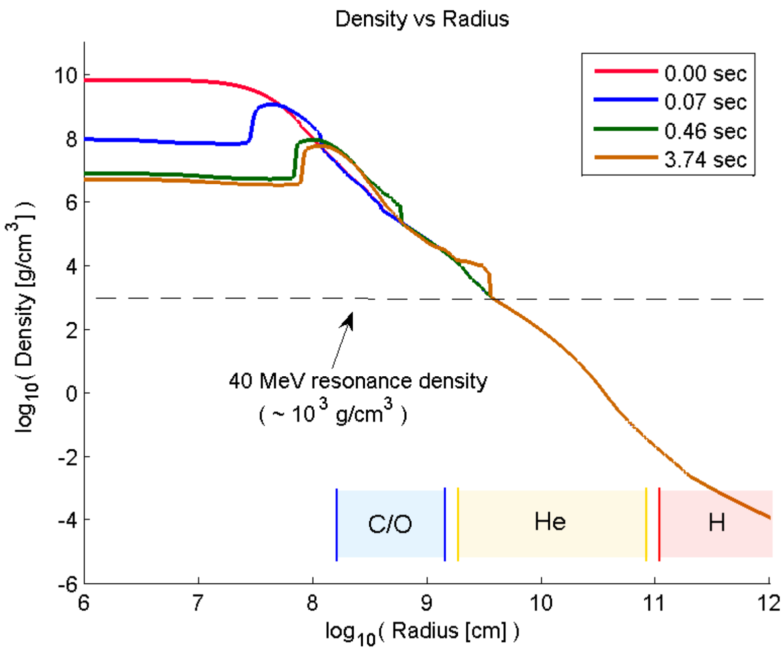


Figure by J. Brockman

The r-process - neutrino cross section connection

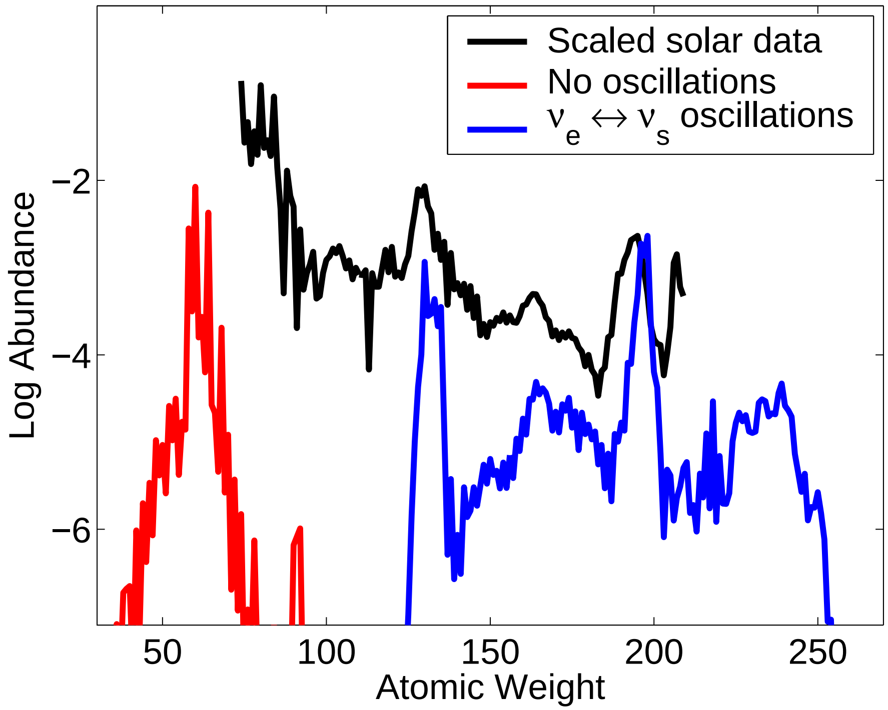


Figure from Beun et al 2006

$$\nu_e + n \rightarrow p + e^-$$

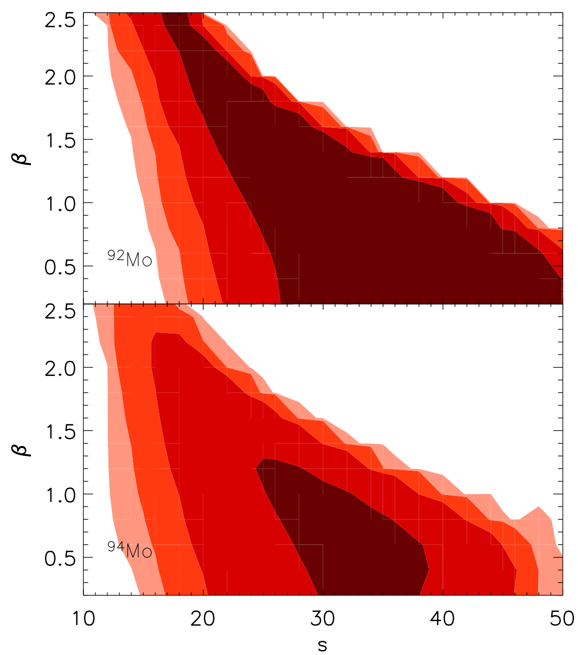
and

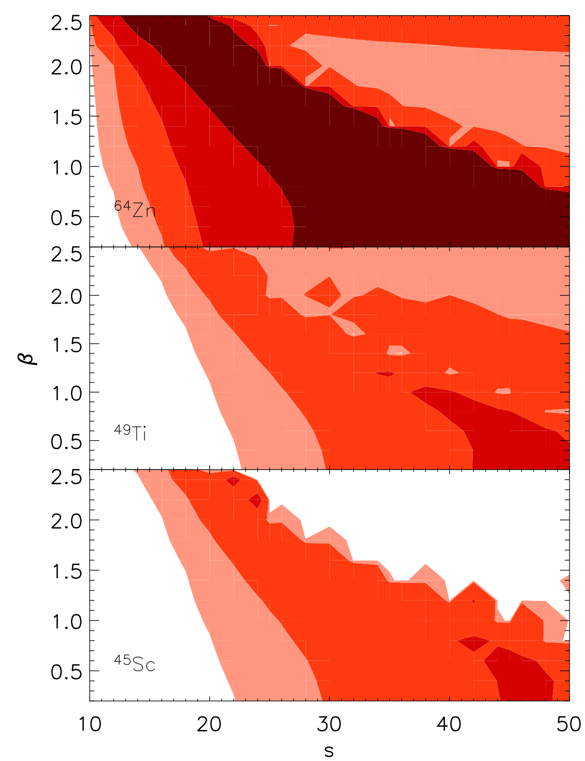
$$\bar{\nu}_e + p \rightarrow n + e^+$$

determine the number of neutrons

neutrino capture (and spallation, fission) on nuclei is important for the details of the pattern see work by Fuller, Haxton, Qian, Langanke, GM

Neutrino captures: the p-process and other rare nuclei:





$^{92}\mathrm{Mo}$,$^{94}\mathrm{Mo}$

p-process from GRBs, Pruet et al 2003, Surman et al 2005

Zinc-64,Titanium-49, Scandium-45

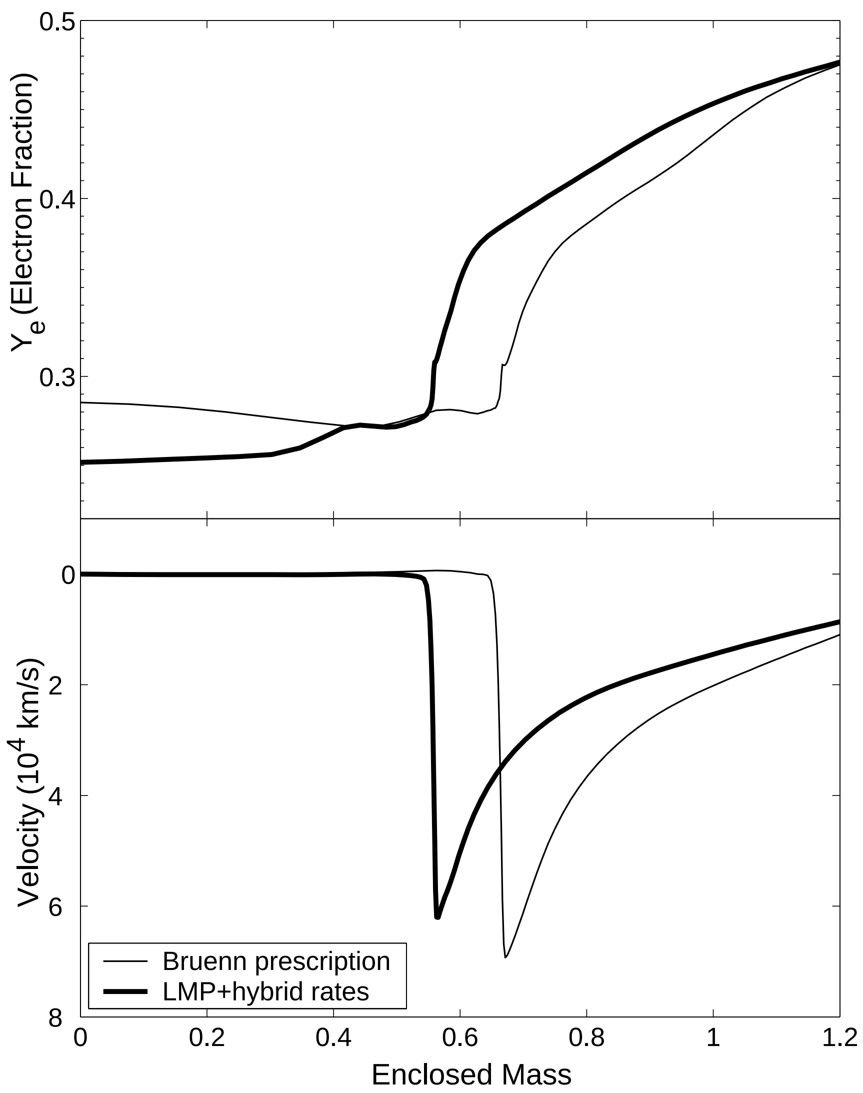
Ways to make the p-process (1) Fine tune n/p (2) ν_e captures on nuclei Fuller and Meyer 1995, (3) late time ν_e captures on nucleons Frohilch et al, Pruet et al

The neutrino cross section - hydrodynamic connection

All phases of massive star collapse and explosion are affected by weak interaction processes

- timescale: how quickly energy is transported out of the core
- cooling: energy loss due to νs
- heating: energy gained below shock due to νs
- deleptonization: loss of lepton number due to νs

Electron capture is important for SN explosions



The influence of

$$e^- + A \rightarrow A + \nu_e$$

on shock dynamics

Hix et al 2003

Neutrino-nucleon scattering is crucial for predicting the supernova neutrino signal

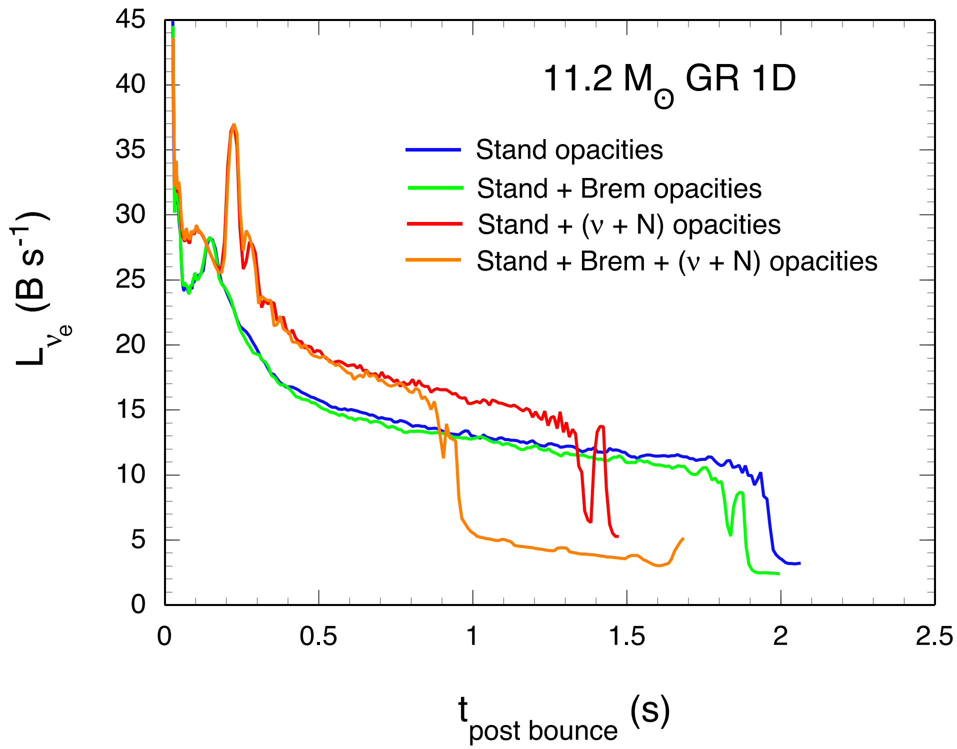
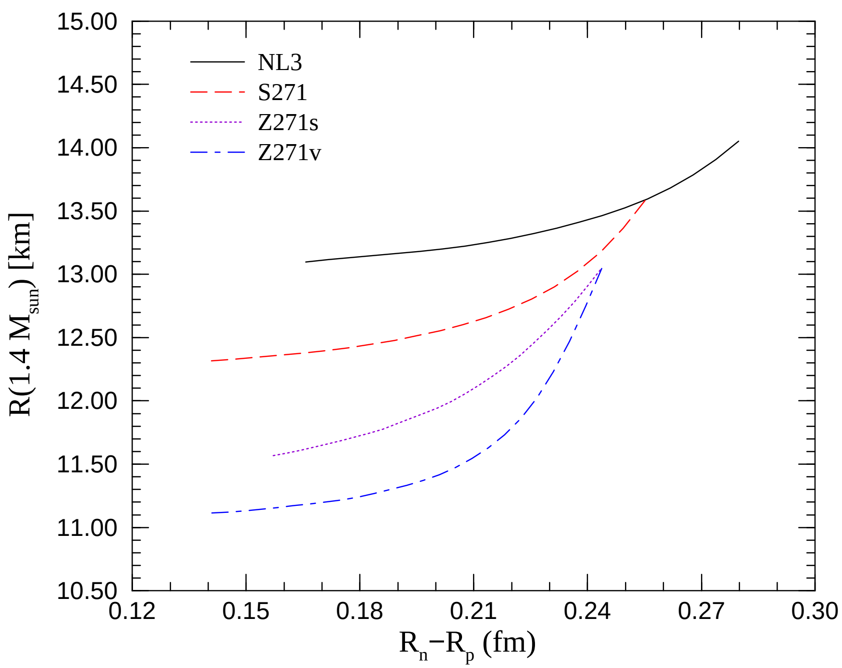
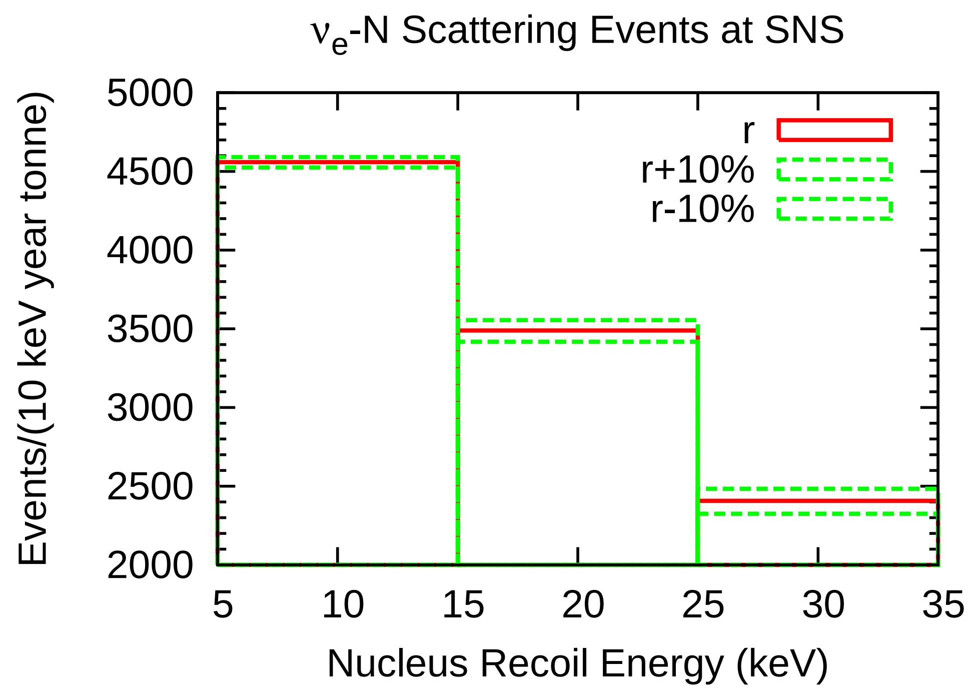


Figure from S. Bruenn

Coherent scattering: learning about neutron star structure





Dependence of neutron star radii on neutron skin of nuclei

Horowitz & Piekarewicz 2001

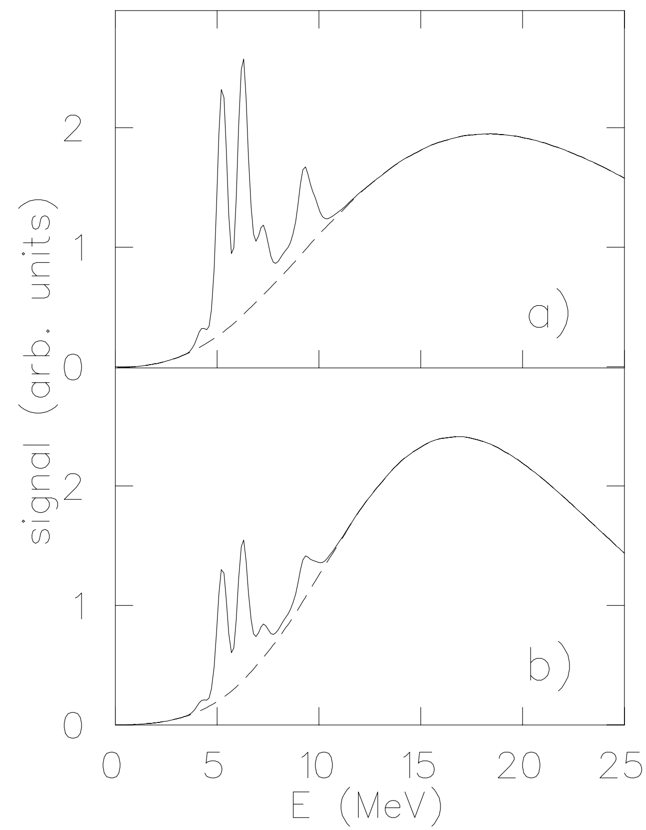
Dependence of coherent neutrino-nuclear scattering on form factor

Amanik & GM 2007

Measuring the Supernova Neutrino Signal

What happens when the neutrinos come?

- water detector: $\bar{\nu}_e + p \to n + e^+$
- heavy water detector (SNO): deuteron break-up in all channels
- $\nu_x +^{16} \mathrm{O} \to^{15} N + p + \nu_x$
  $\nu_x +^{16} \mathrm{O} \to^{15} \mathrm{O} + n + \nu_x$
- lead detector (OMNIS): $A(\nu_e, e)A'$ and neutral current channels



Signal (γs) in a Water Detector, Kolbe et al 2003
bump: from e^+s, peak: decays from $^{15}\mathrm{O}$, $^{15}\mathrm{N}$

We can only interpret the signal as well as we understand the cross section. But there's no cross section data!

Galactic SN ν detectors: SuperKamiokande, KamLAND, MiniBoone and more

Conclusions

- Neutrino cross sections are needed in astrophysics
- Low energy cross sections are relevant for supernovae, gamma ray bursts, neutron stars and other environments
- inelastic processes are important for dynamics
- and for nucleosynthesis
- coherent scattering could reveal hints about neutron star stucture