Supernova Neutrinos and Neutrino Properties

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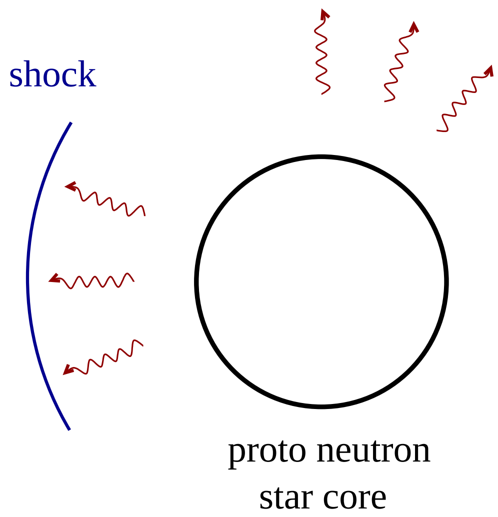
What can SN neutrinos tell us?

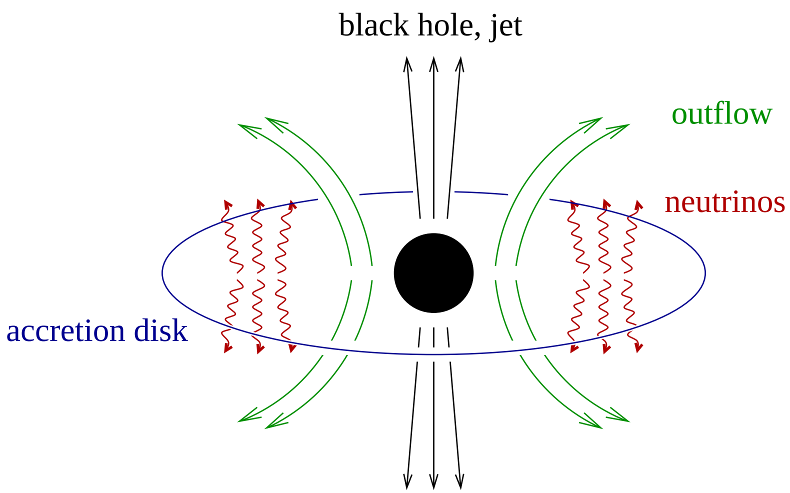
Something about...

- Picture of core of a supernova
- Neutrino fundamental properties
- Supernova hydrodynamics

Explosions of Massive Stars:

What's happening at the center?





Standard core core collapse SN

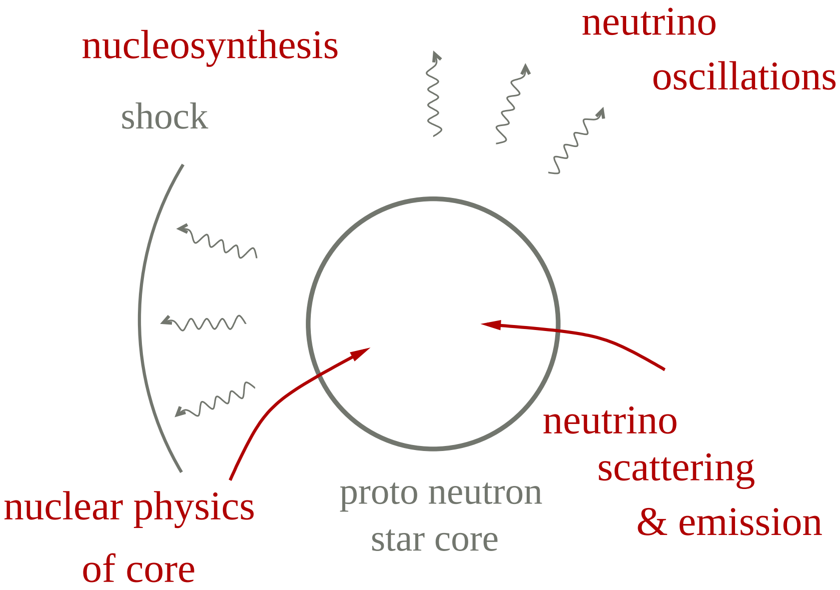
Many, many papers

Accretion Disk SN (GRB?)

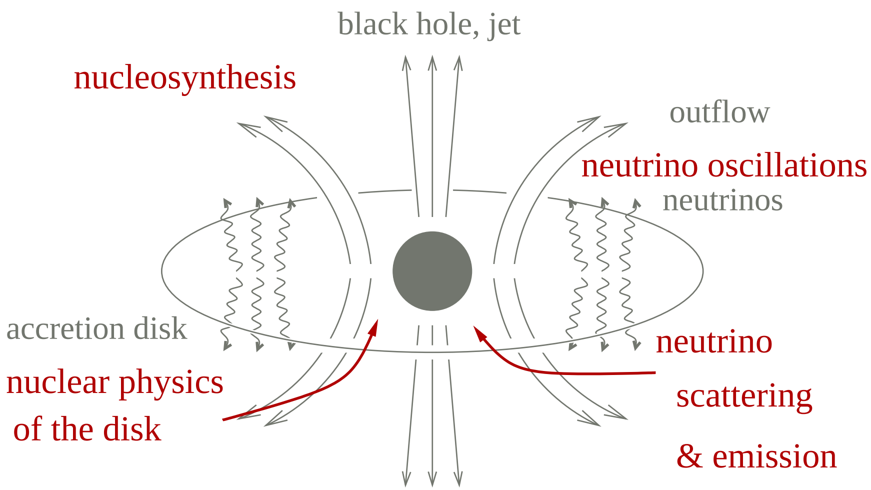
MacFadyen and Woosley 1999, Proga et al 2003, and more

Explosions of Massive Stars:

Where do the neutrinos fit in?



Standard core core collapse SN

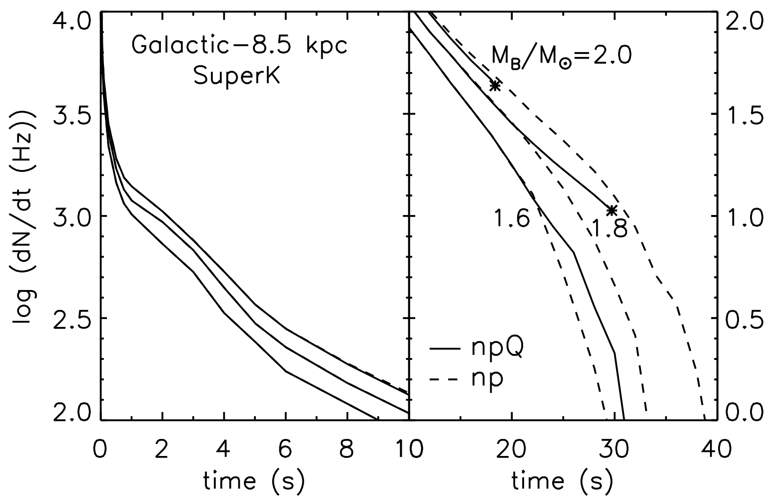


Accretion Disk SN

What can SN neutrinos probe?

Neutrinos spectra, timescales when emitted from the core

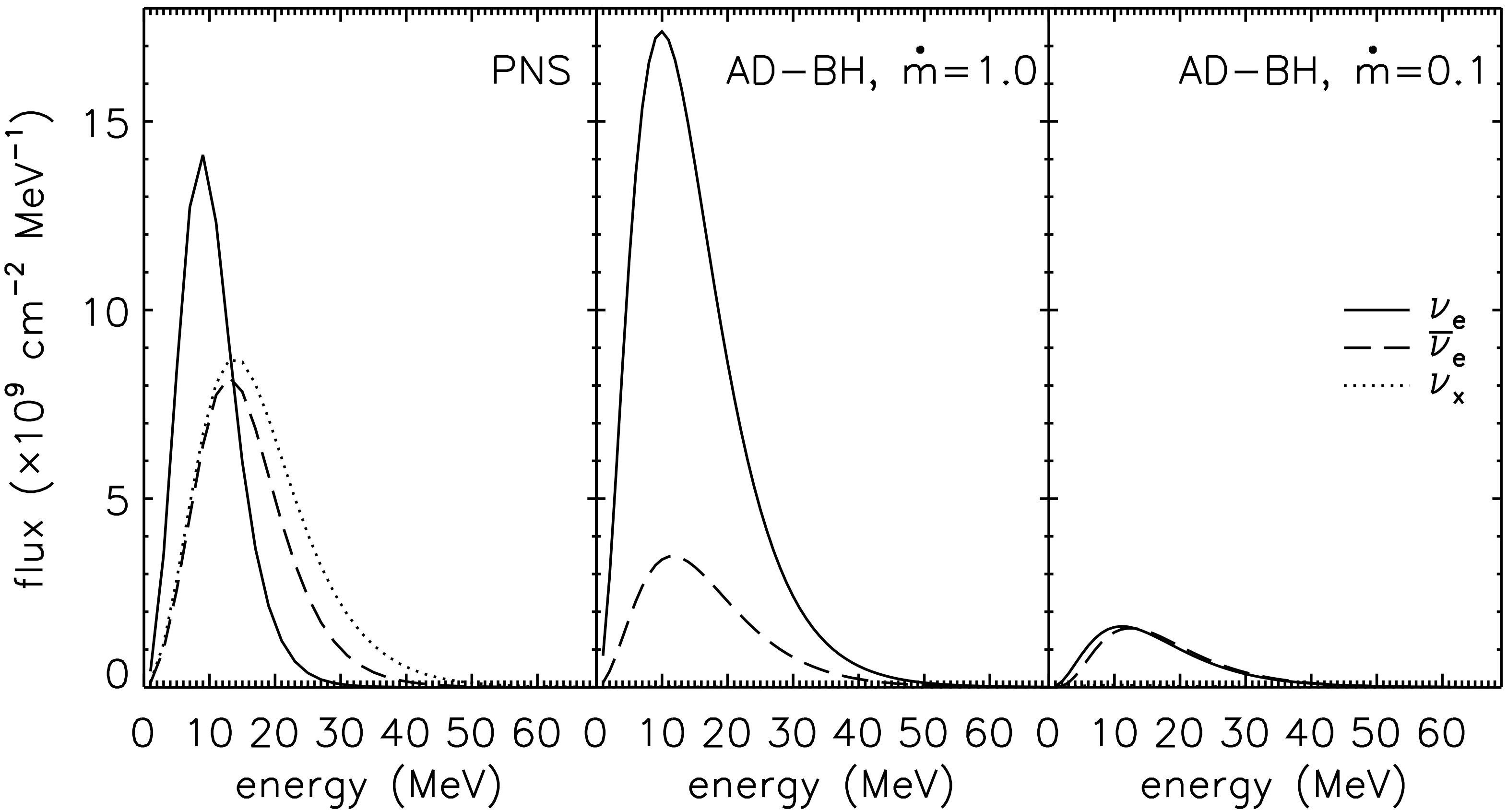
- neutrino opacities
- equation of state
- diffusion calculations



Rates in SuperK for different core masses and equations of state, Pons et al 2002

neutrino diffusion calculations: Breunn, Cardall, Pons, Prakash, Janka, and more

What do these astrophysical neutrino spectra look like?



Proto-neutron star spectral parameters from Keil et al 2003, Figure from GM & Surman 2006

Neutrino Flavor transformation in Supernovae

Spectra measured on earth $\neq$ emitted neutrino spectra

original $\nu_e \longrightarrow$ some combination of ν_e, ν_μ, ν_τ

original $\nu_\mu \longrightarrow$ some combination of $\nu_{\rm e}, \nu_\mu, \nu_\tau$

original $\bar{\nu}_e \longrightarrow$ some combination of $\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$

etc...

Furthermore effect is energy dependent

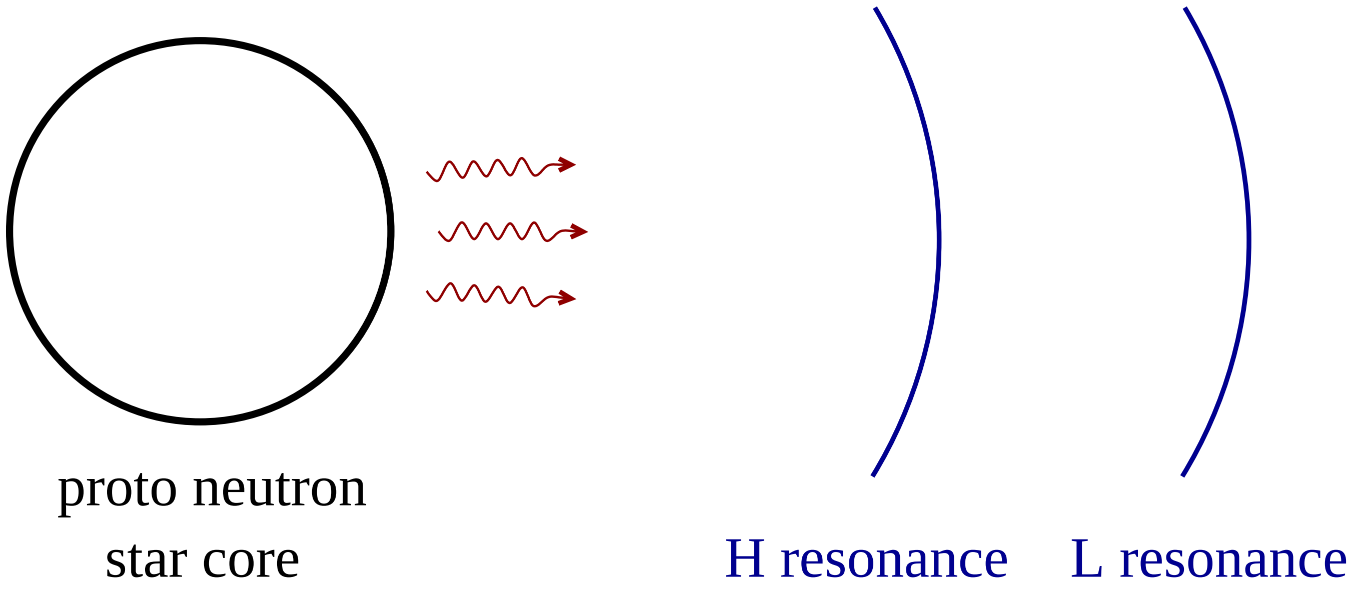
What can SN neutrinos probe?

Fundamental neutrino properties

- δm^2's
- angles
- CP violation (talk later in session)
- magnetic moment, beyond the standard model physics
- sterile neutrinos

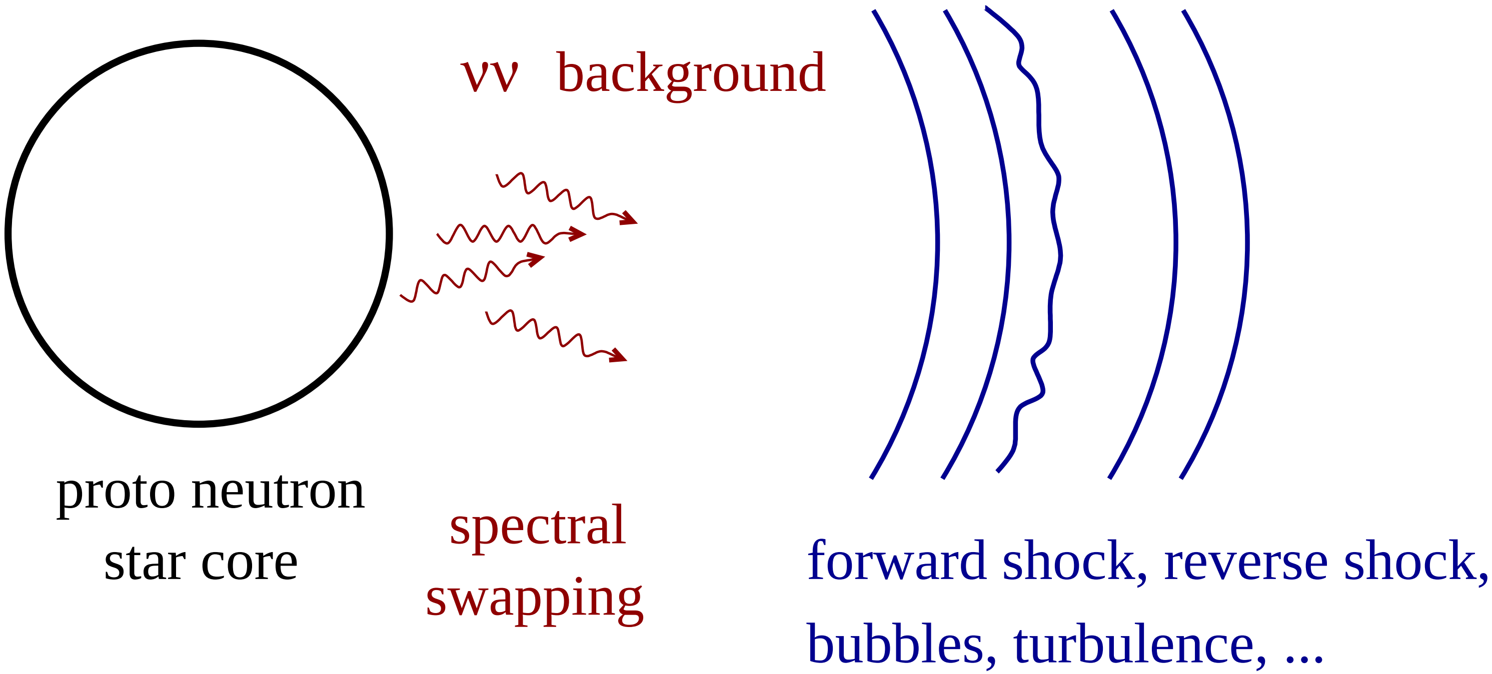
Old Picture of Supernova Neutrino Transformation

Static density profiles, collective effects not included...



Primary uncertainties in evolution: Hierarchy, θ_{13} e.g. Dighe and Smirnov 2000

New Picture of Supernova Neutrino Transformation



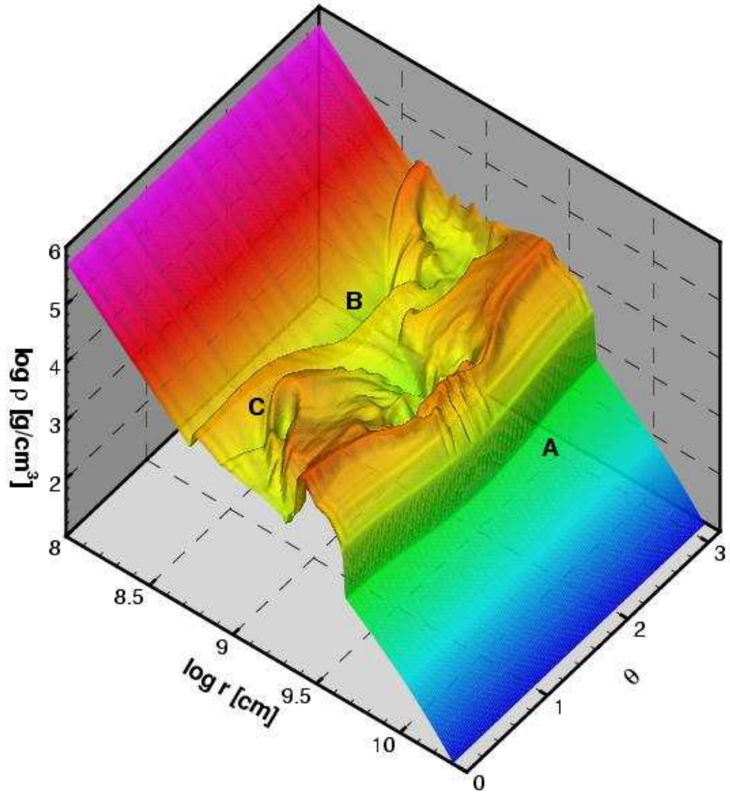
Many more possibilities, depending on: hierarchy, θ_{13}, evolution of density profile

Neutrino evolution calculations much more complex

What can SN neutrinos probe?

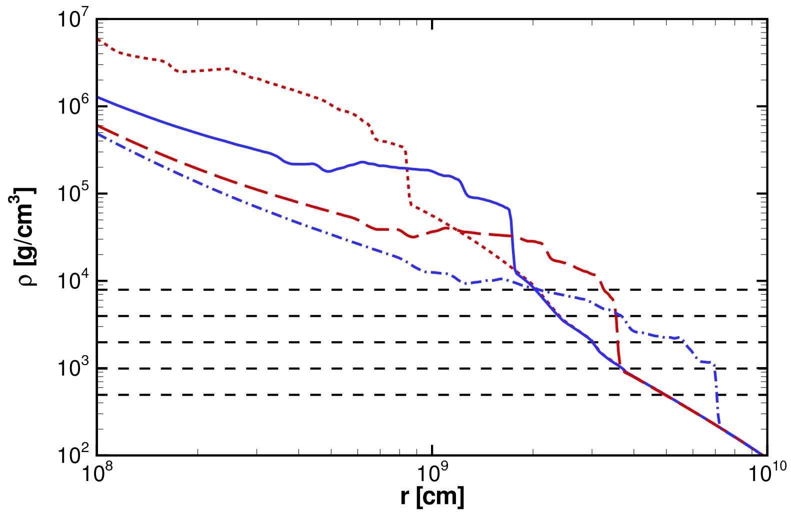
Supernova Hydrodynamics

- initial density profile
- forward/reverse shocks
- “bubbles”, turbulence

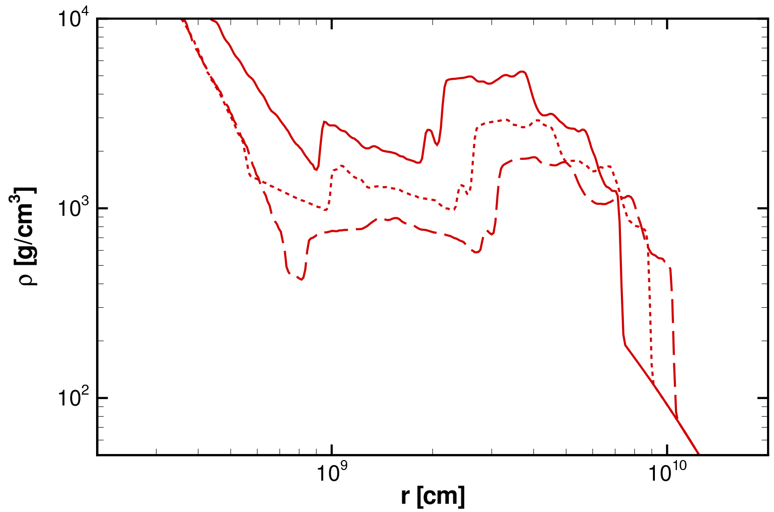


Density profile from a SN toy model at 2.5s, Kneller et al 2008

Supernova Hydrodynamics



Density slices at 0.9s, 1.8s, 3.6s and 7.2s from a 1D toy model. Horizontal dashed lines show resonances densities for 5 MeV, 10 MeV, 20 MeV, 40 MeV and 80 MeV.
Q $= 1.66 \times 10^{51}$ ergs



Density slices at 3.9s, 4.8s and 5.7s from a 2D toy model
Q $= 3 \times 10^{51}$ ergs

Figures from Kneller et al 2008

Matter-enhanced neutrino oscillations depend on the density structure...

Neutrino Flavor Transformation Calculations

Lots of activity in calculating

- resolving features of the density profile

  Fuller & Schirato 2002, Fogli et al 2003, Choubey et al 2007, Tomas et al 2004, Kneller et al 2008

- including those producing finely grained phase effects

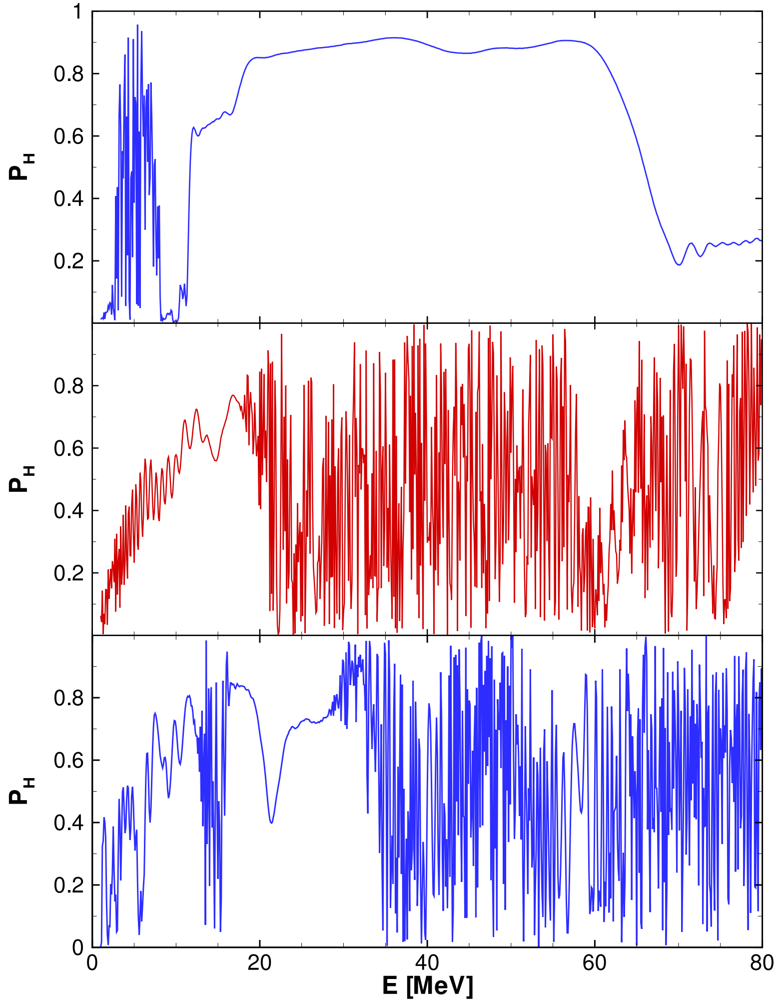
  Friedland & Gruzinov 2006, Kneller et al 2006, 2008, Dasgupta & Dighe 2006

- collective effects/ swapping

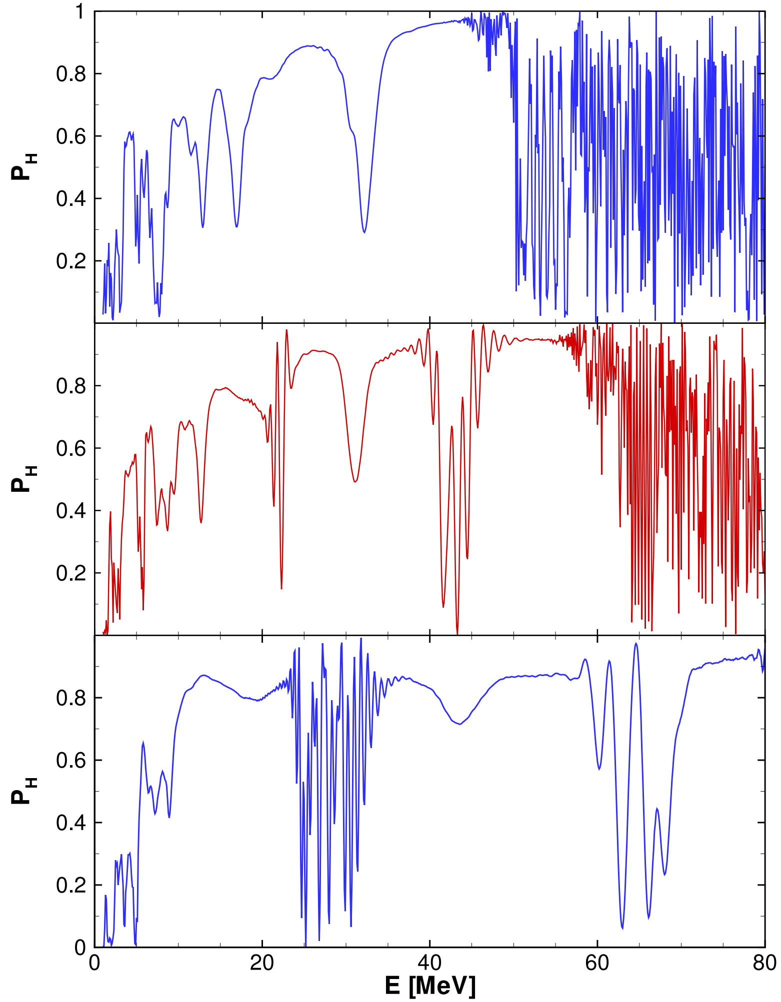
  Dighe, Carlson, Duan, Fuller, Gava, Mirizzi, Raffelt, Sigl, Smirnov, Volpe and more

Calculations become more technical...

Finely grained phase effects due to density perturbation



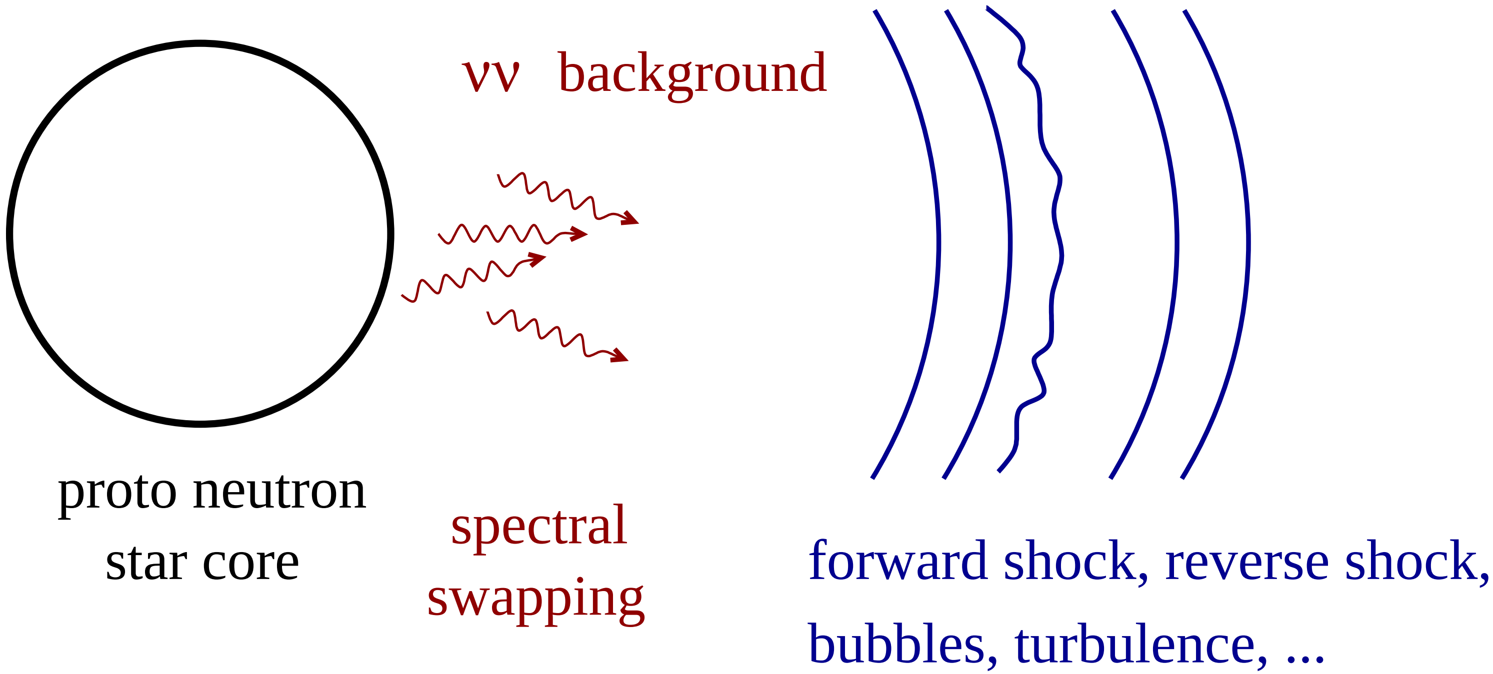
H resonance crossing probability at 2.4s, 5.4s, 6.4s, $\delta m^2 = 10^{-4}$, $\sin^2\theta_{13} = 10^{-1}$



H resonance crossing probability at 7.0s, 8.0s and 9.0s, $\delta m^2 = 10^{-4}$, $\sin^2\theta_{13} = 10^{-1}$

Rapid oscillation as a fct of energy is indicative of multiple resonances

New Picture of Supernova Neutrino Transformation



Many more possibilities, depending on: hierarchy, θ_{13}, evolution of density profile

Neutrino evolution calculations much more complex

Collective effects, single angle

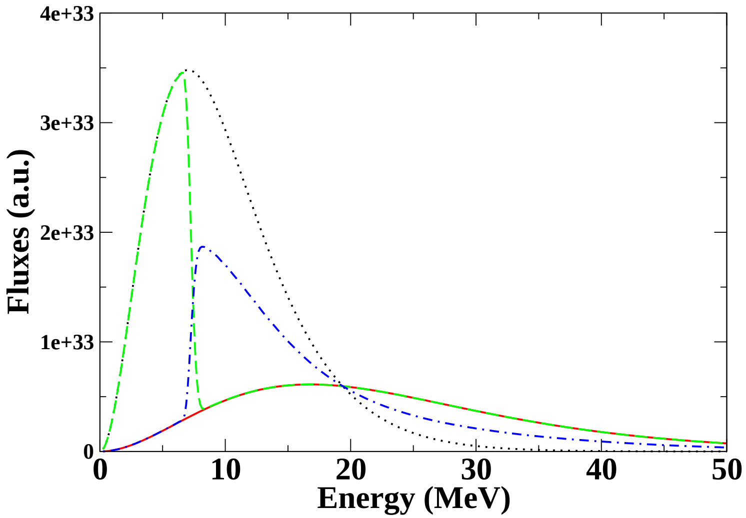
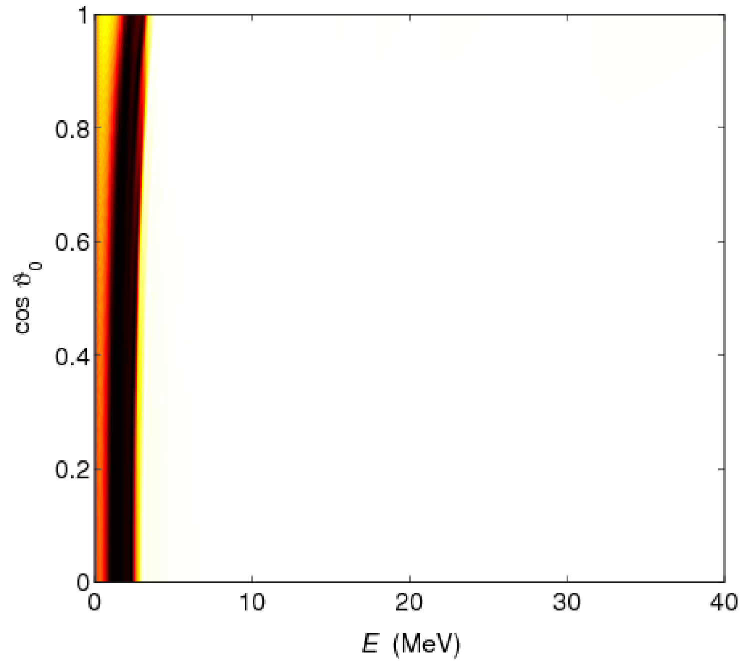


Figure from Gava and Volpe 2008

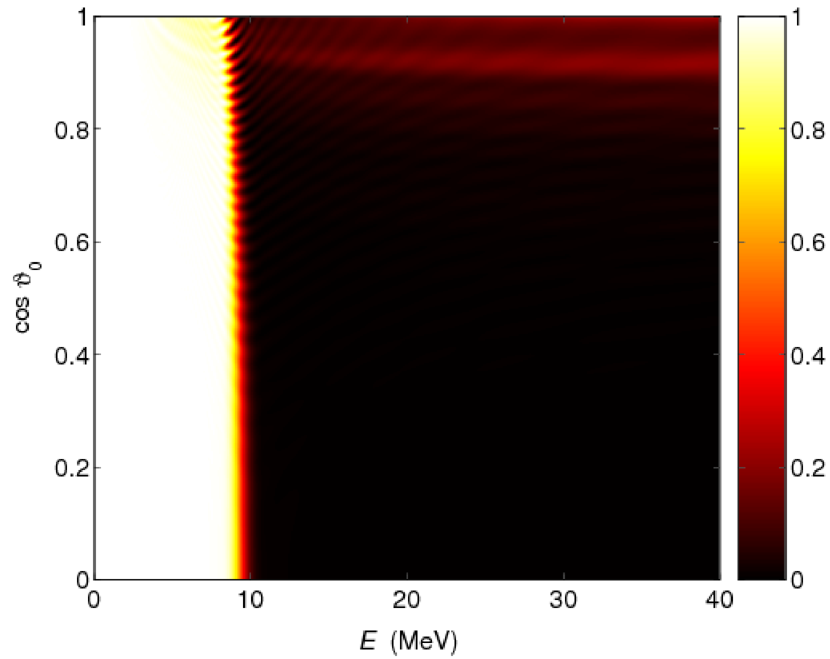
- ν-ν scattering potential included in flavor transformation calculation
- occurs far below traditional resonances

Shows ν_e, ν_μ spectra as emitted and at 200km, "Spectral Split"

Collective effects, multi-angle



Neutrino Survival Probabilities as a function of emission angle (vertical axis). Normal mass hierarchy, with $\theta_\nu = 0.01$.



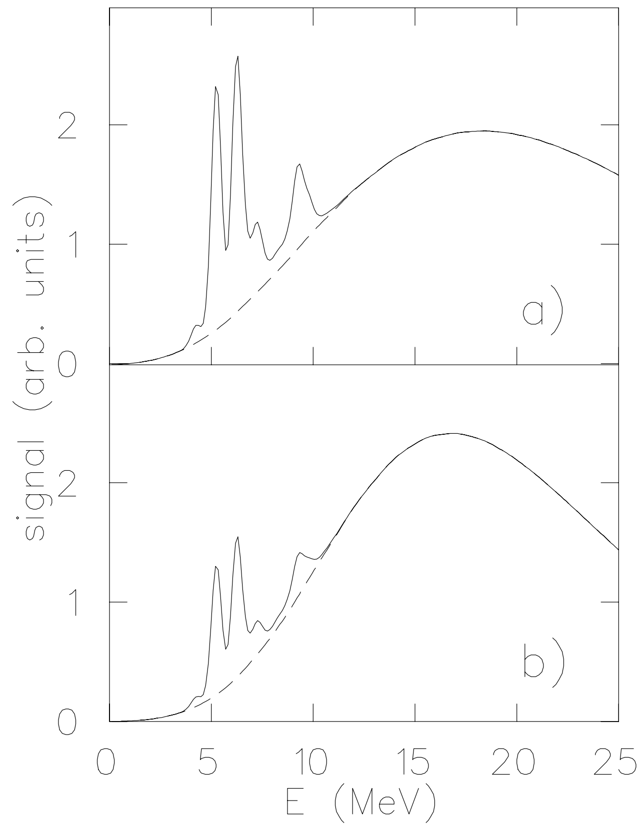
Antineutrino survival probablities.
Inverted mass hierarchy with $\theta_\nu = 10^{-9}$

Figures from Duan, Fuller, Qian 2008

Measuring the Supernova Neutrino Signal

What happens when the neutrinos come?

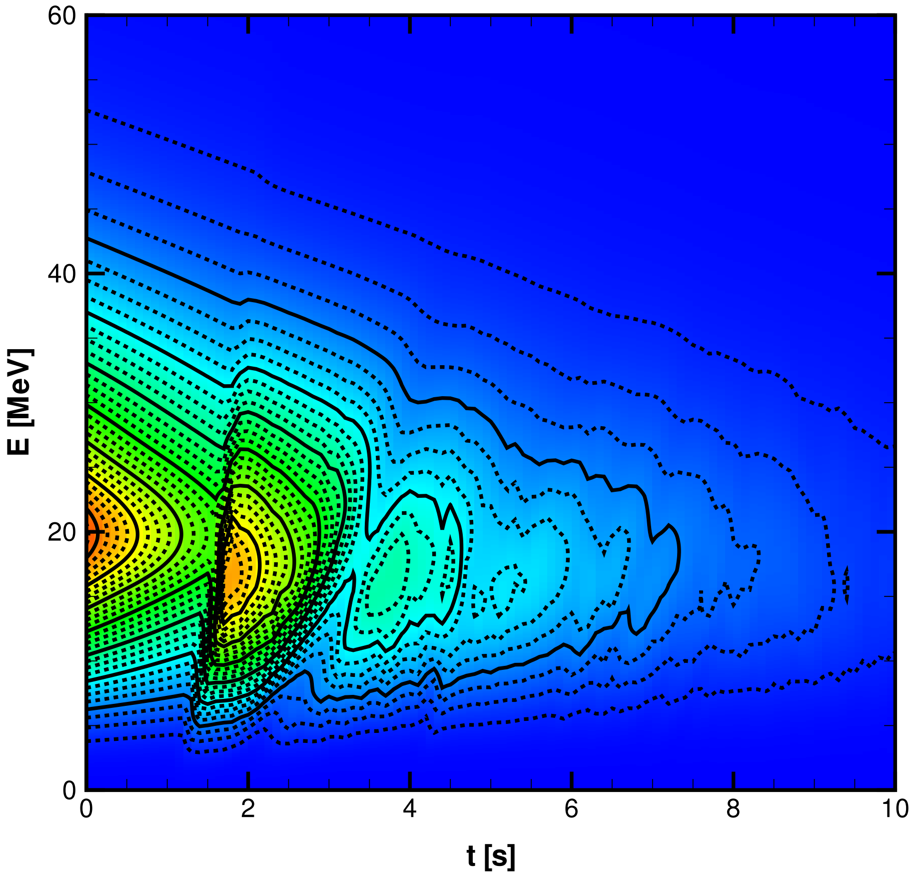
- water detector: $\bar{\nu}_e + p \rightarrow n + e^+$
- $\nu_x +^{16} \mathrm{O} \rightarrow^{15} N + p + \nu_x$
  $\nu_x +^{16} \mathrm{O} \rightarrow^{15} \mathrm{O} + n + \nu_x$
- lead detector (e. g. HALO): $A(\nu_e, e)A'$ & neutral current channels



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

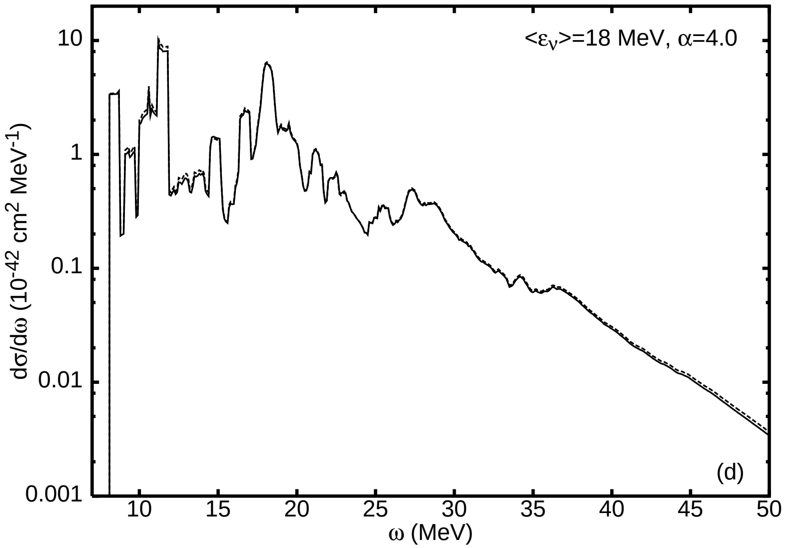
And many more possibilites including, neutrino-nucleus coherent scattering, neutrino-nucleus inelastic scattering

Positron Spectrum in a water detector



Shows the forward shock and "phase effects" due to multiple resonances, collective effects not included,units of 10^{-3}/MeV/s/

Cross section data is needed



Jachowicz et al 2008

- e.g. ν-SNS, proposed for ORNL
- and low energy β beams

Figure: linear combination of neutrino-nuclear responses from beta beam spectra can be used to reproduce that of SN neutrinos.

Conclusions: What we hope to learn from a future SN neutrino signal

- Is it really a core collapse supernova w/ protoneutron star?
- Something about supernova hydrodynamics
- Something about neutrino spectra as emitted from the core
- Something about fundamental neutrino properties

There will be degeneracies... but still new data is eagerly awaited...