MeV Neutrino Astronomy

Solar Neutrinos

Neutrinos from core collapse supernovae

The diffuse flux of neutrinos from core collapse supernovae

References: PDG

Solar Neutrinos

A main sequence star is a star that is in a quasi-stationary state. The radiation pressure due to fusion of hydrogen into helium counteracts the gravitational self attraction of the star. There's no He fusion for main sequence stars.

There are two cycles to do this:

- – pp cycle
- – CNO cycle

For stars with $M \leq 1.5\ M_{sun}$ the pp cycle dominates. For starts with $M > 1.5\ M_{sun}$ the CNO cycle dominates

Solar Neutrinos

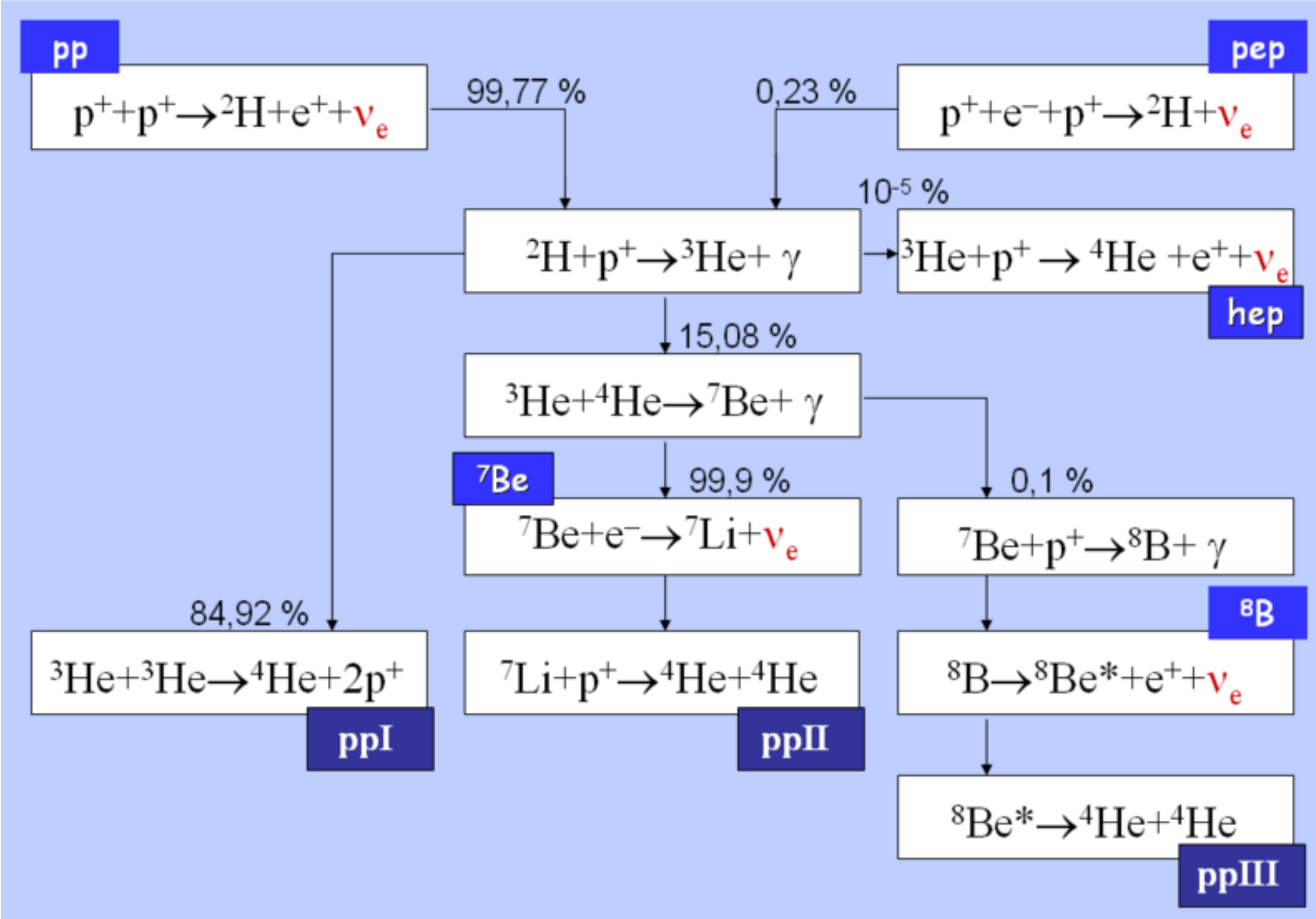
One would expect that the temperature at the center of the Sun is such that the proton-proton electrostatic potential is overcome to allow fusion

$$\frac{3}{2} KT_{fusion} = \frac{Z_1 Z_2 e^2}{r}$$

Using r ~ 1 fm, then $T_{fusion} \sim 10^{10}$ K.

The temperature at the center of the Sun is $T_{core} \sim 1.5\ 10^7$ K. Fusion at the center of the Sun is due to quantum tunneling.

pp Cycle

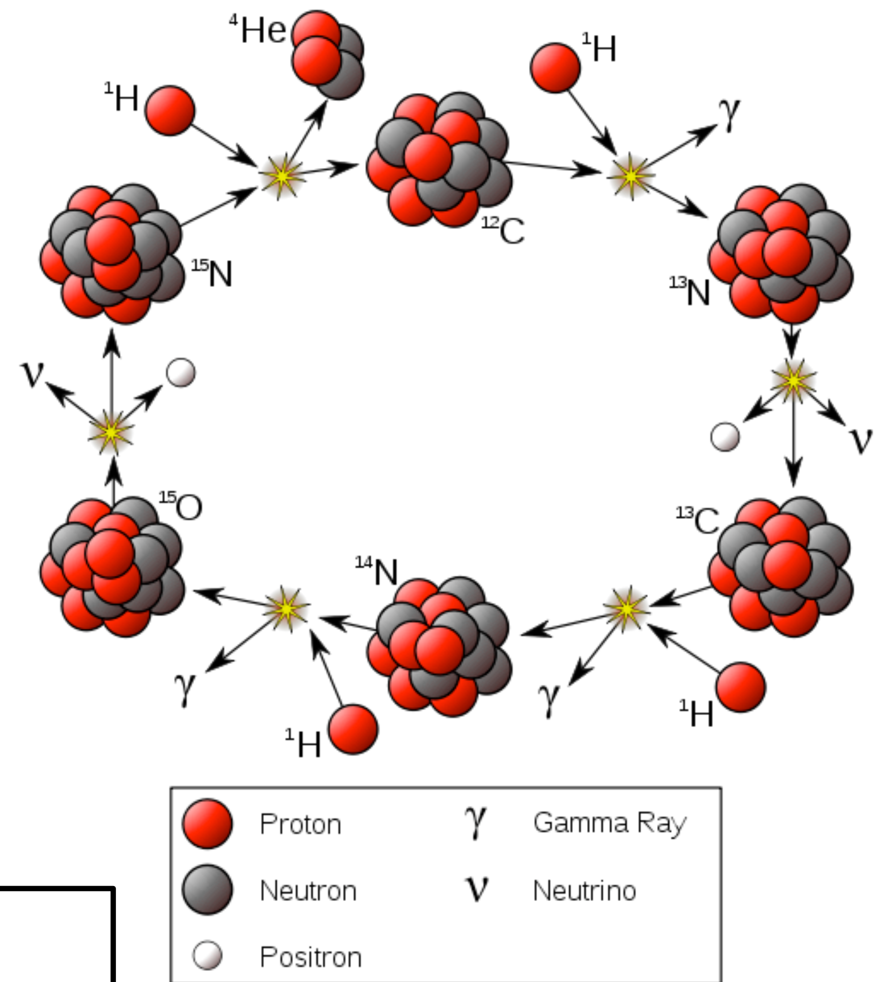


The final result is:

$$4\,p \longrightarrow {}^4He + 2\nu_e + 2e^+ + \gamma\text{'s (pp I)}$$

CNO cycle

$$^{12}C + p \longrightarrow {}^{13}N + \gamma$$
$$^{13}N \longrightarrow {}^{13}C + e^+ + \nu_e$$
$$^{13}C + p \longrightarrow {}^{14}N + \gamma$$
$$^{14}N + p \longrightarrow {}^{15}O + \gamma$$
$$^{15}O \longrightarrow {}^{15}N + e^+ + \nu_e$$
$$^{15}N + p \longrightarrow {}^{12}C + {}^{4}He$$



The final result is:

$$4\,p \longrightarrow {}^{4}He + 2\nu_e + 2e^+ + \gamma\text{'s}$$

Main sequence stars

Most stars spend the bulk of their lifecycle in the main sequence. Assuming that the star is quasi-static (time independent):

$$\frac{dP}{dr} = -G\frac{M_r \rho}{r^2}$$

Hydrostatic equillibrium

$$\frac{dM_r}{dr} = 4\pi r^2 \rho$$

Mass conservation

$$\frac{dL_r}{dr} = 4\pi r^2 \rho \epsilon$$

Fusion energy production

For T ~ 1.5 10^7 K

$$\epsilon_{pp} \propto (T/10^6\mathrm{K})^4$$

$$\epsilon_{CNO} \propto (T/10^6\mathrm{K})^{19.9}$$

$$\frac{dT}{dr} = -\frac{3}{4ac}\frac{\bar{\kappa}\rho}{T^3}\frac{L_r}{4\pi r^2}$$

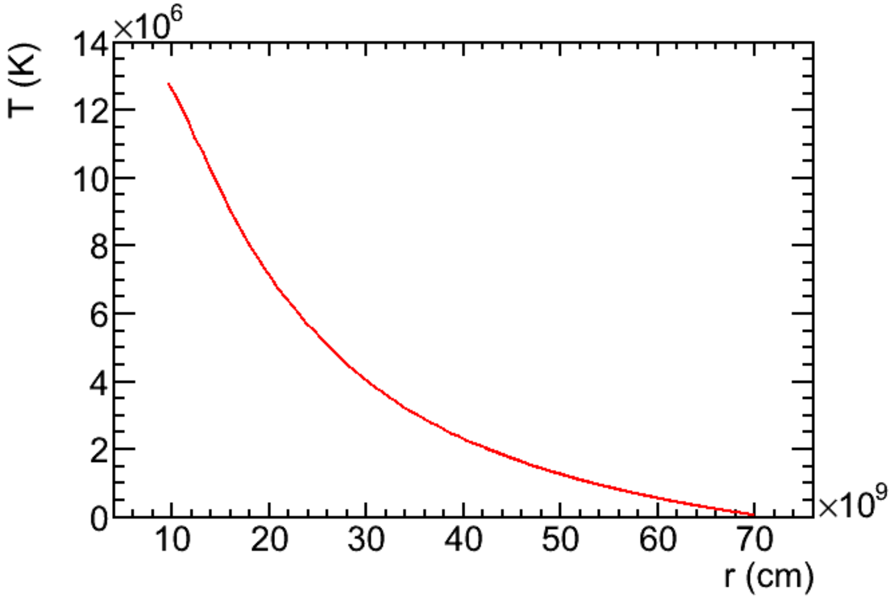
Radiative transport

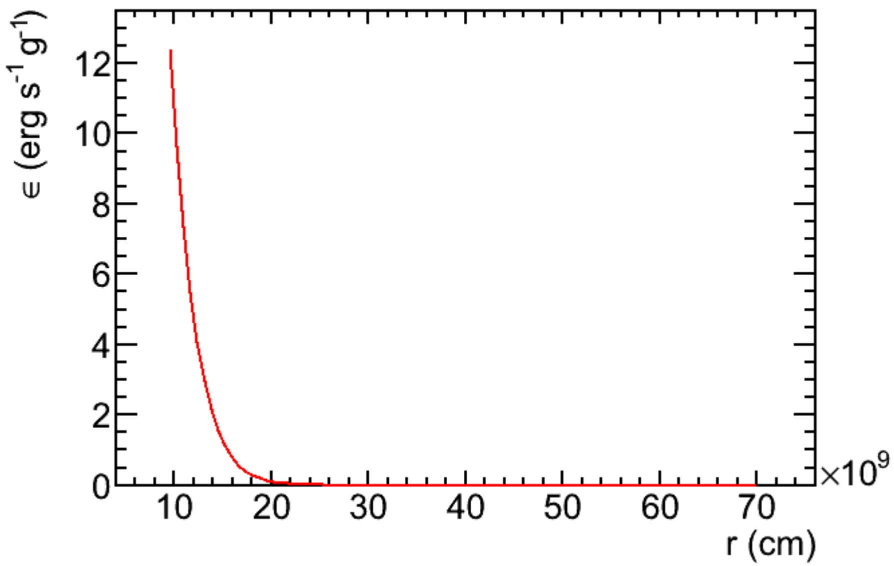
$$\frac{dT}{dr} = (1\frac{1}{\gamma})\frac{\mu m_p}{k_B}\frac{GM_r}{r^2}$$

Convection

This goes beyond this course … Check Carrol & Ostlie. This book includes cool stellar model simulations, that you can run yourself (google runstatstar)

The solar interior





Using the simulation in Carrol & Ostlie

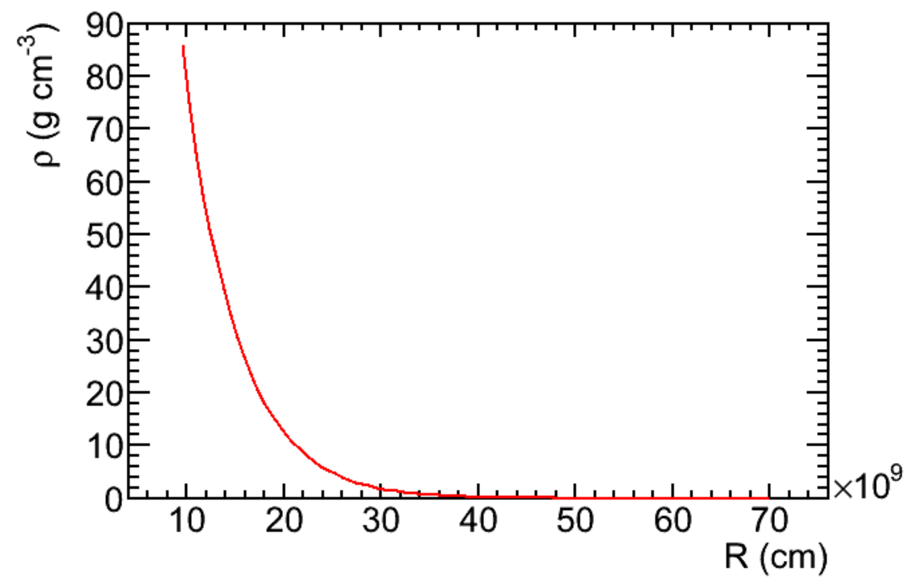
$M = 1\ M_{sun}$

$R = 1.024\ R_{sun}$

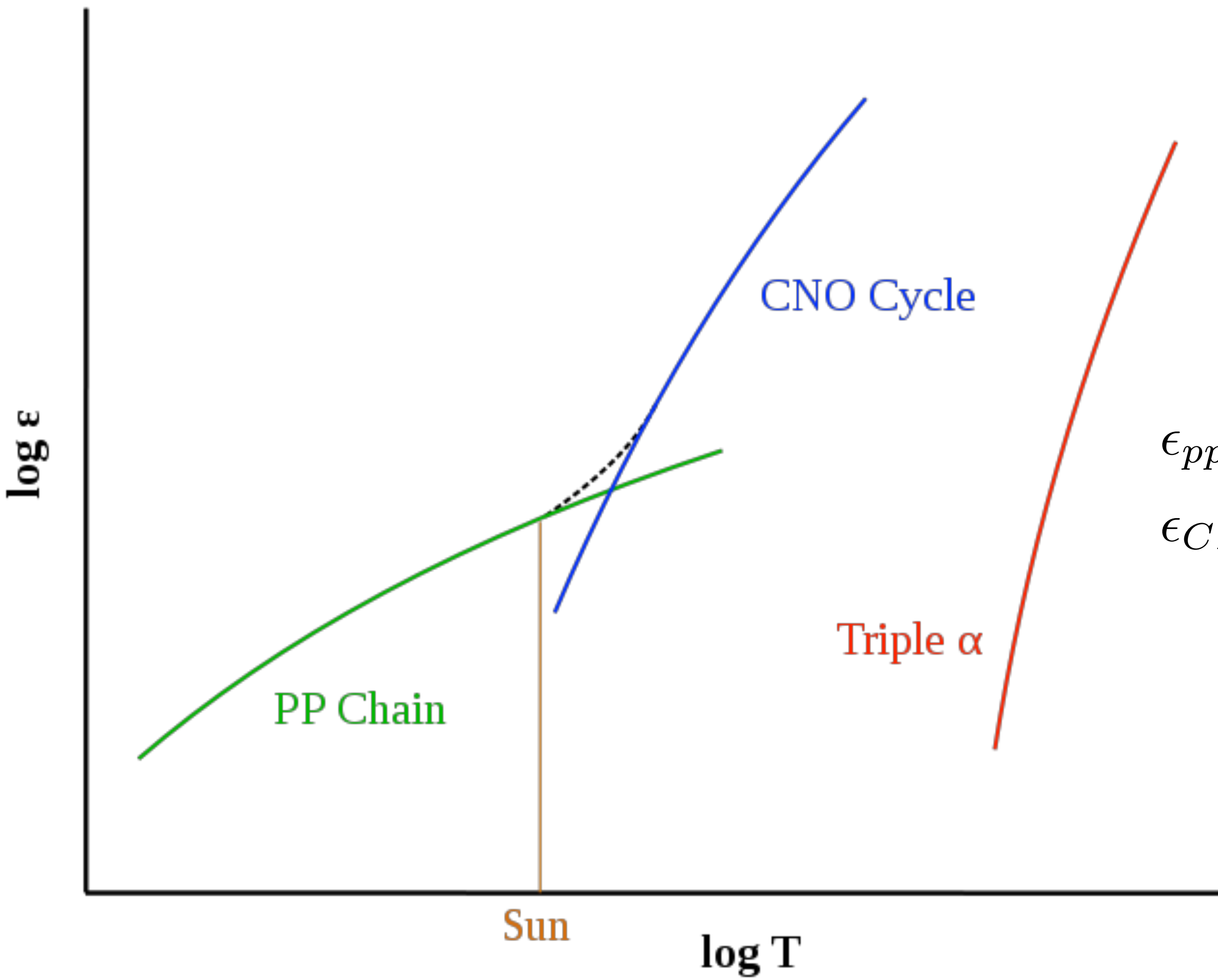
$X=0.73,\ Z=0.02.$

$L = 1\ L_{sun}$

$T_{eff} = 5700$ K



Hydrogen fusion in main sequence stars



$$\epsilon_{pp} \propto (T/10^6\mathrm{K})^4$$

$$\epsilon_{CNO} \propto (T/10^6\mathrm{K})^{19.9}$$

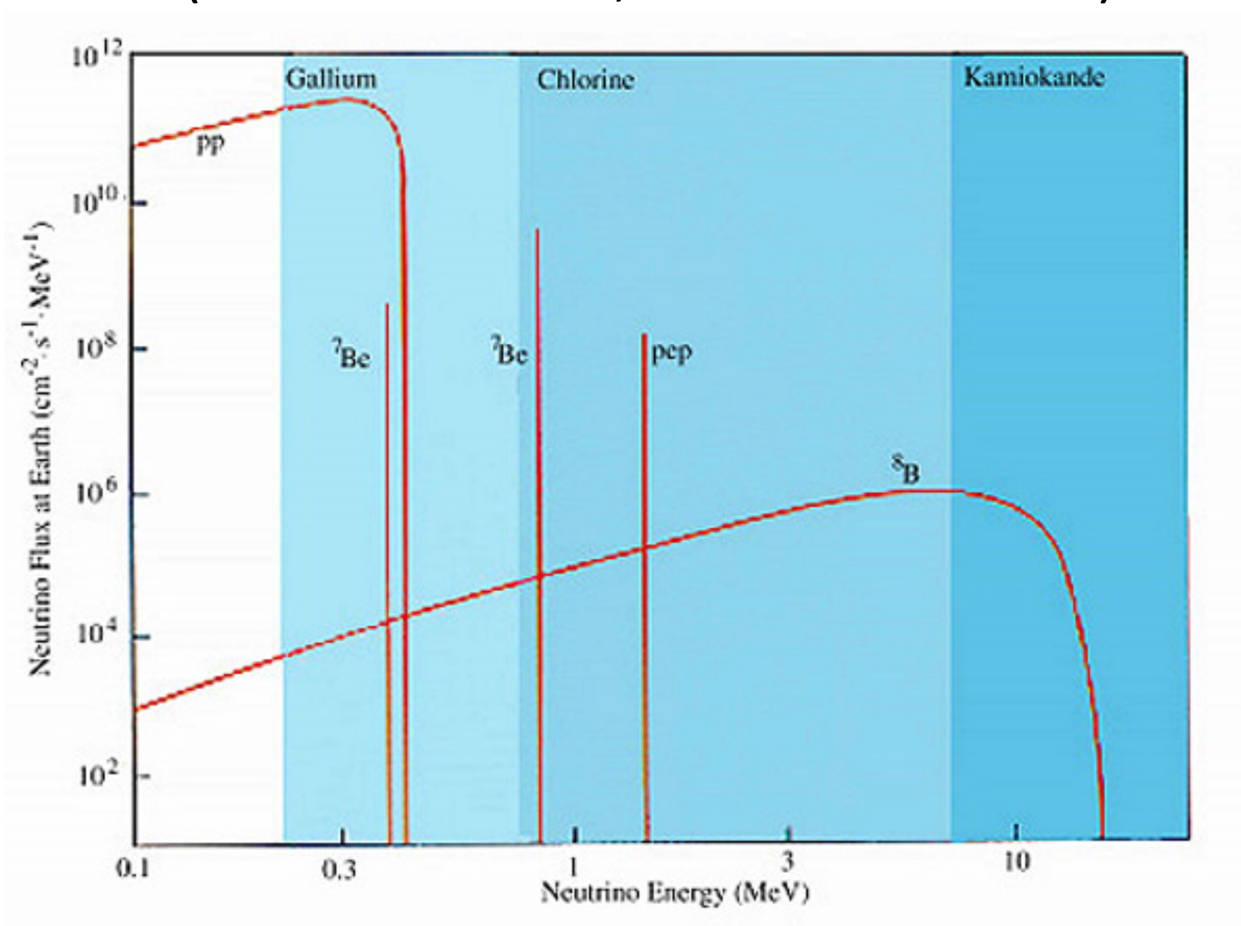
Some properties of main sequence stars

Low mass: long life <-> High mass: short life. Very massive stars can be in the main sequence for as little as $10^5 – 10^6$ yr. This is important, because very massive stars turn into core collapse supernovae. A high rate of CC SNe should be an indicator of high star formation rate.

High mass: high surface temperature (blue) <-> low mass: low surface temperature (red)

Solar Standard Model Prediction

Only electron neutrinos are produced
(no other flavors, no anti-neutrinos)



Total solar neutrino flux at Earth ~10^{10} ν cm^{-2} s^{-1}

Homestake Experiment

(late 1960s)

$$\nu_e + {}^{37}Cl \longrightarrow e^- + {}^{37}Ar$$

615 tons of tetrachloroethylene
(dry cleaning fluid)
Radiochemical extraction of Argon

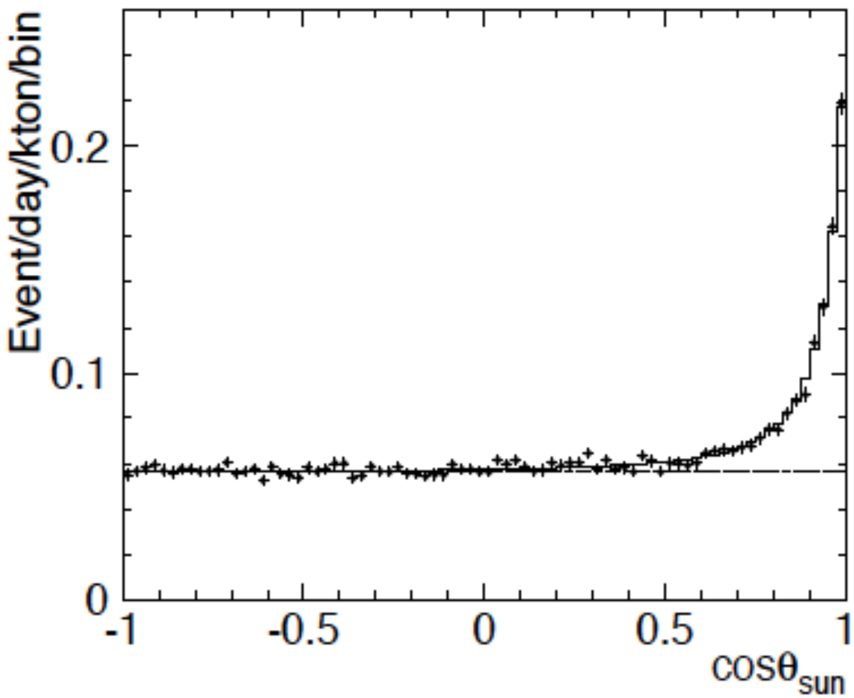
Experiment / Theory = 0.31

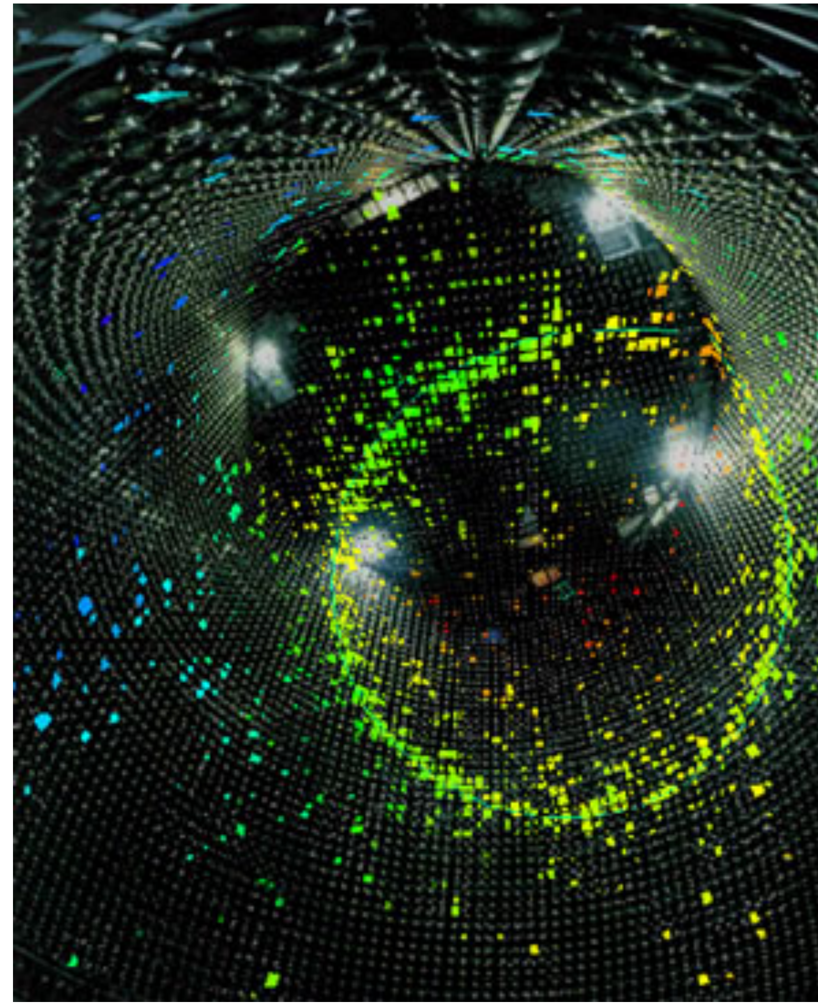
This is the Solar Neutrino Problem

Kamiokande / Super-Kamiokande

$\nu_e + e- \longrightarrow \nu_e + e^-$

1987 (K) / 1998 (SK)

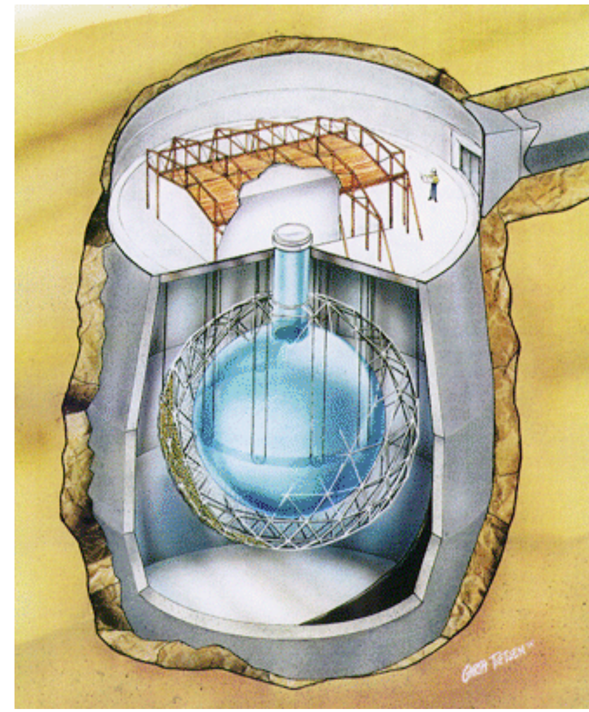




Experiment / Theory = 0.48

Sudbury Neutrino Observatory

1 kton of D_2O
10000 PMTs



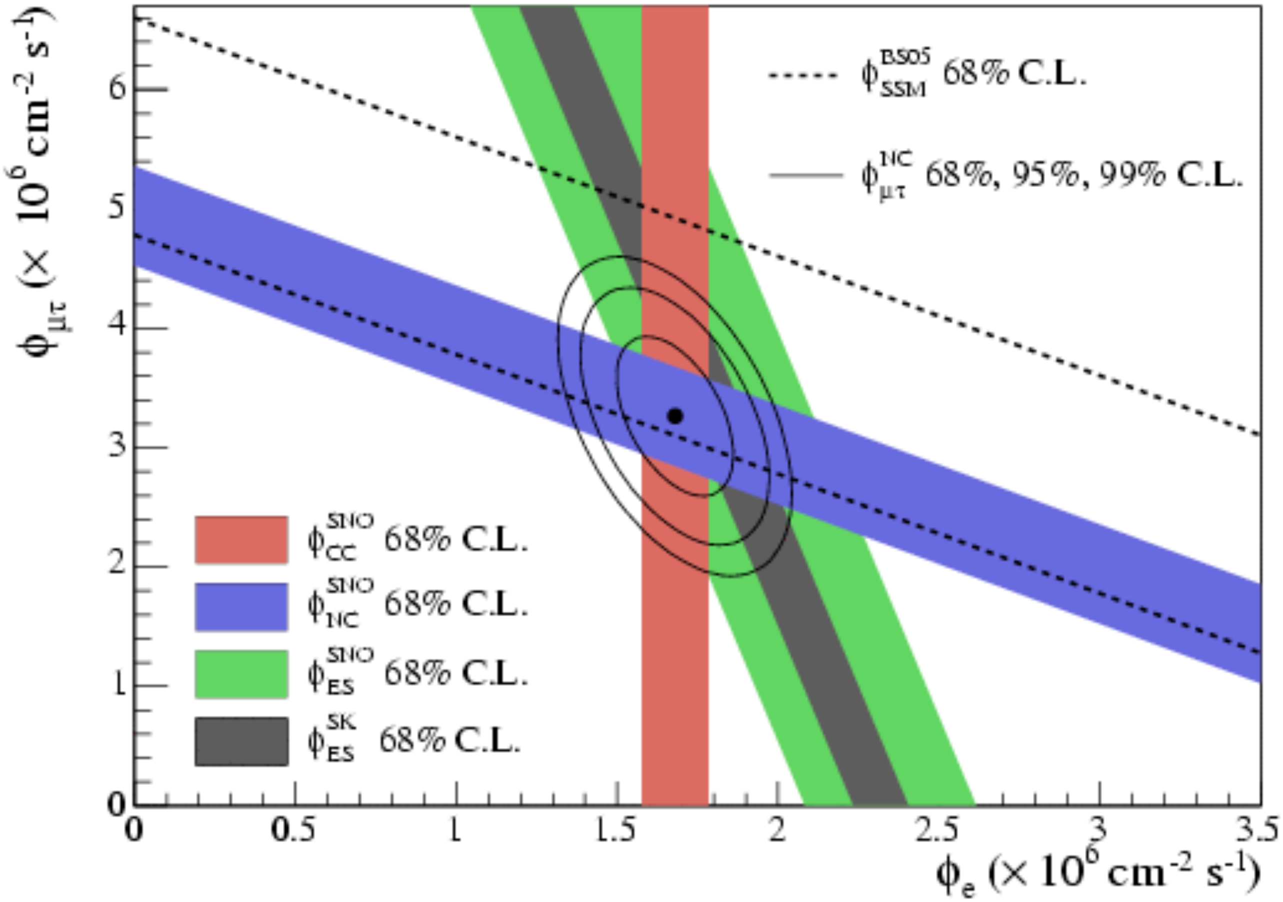
$\nu_e + e^- \longrightarrow \nu_e + e^-$ (Tiny for SNO)

$\nu_e + {}^2H \longrightarrow p + p + e^-$ (CC)

$\nu_x + {}^2H \longrightarrow p + n + \nu_x$ (NC)

$n + d \longrightarrow {}^3H + \gamma$ (6.8 MeV)

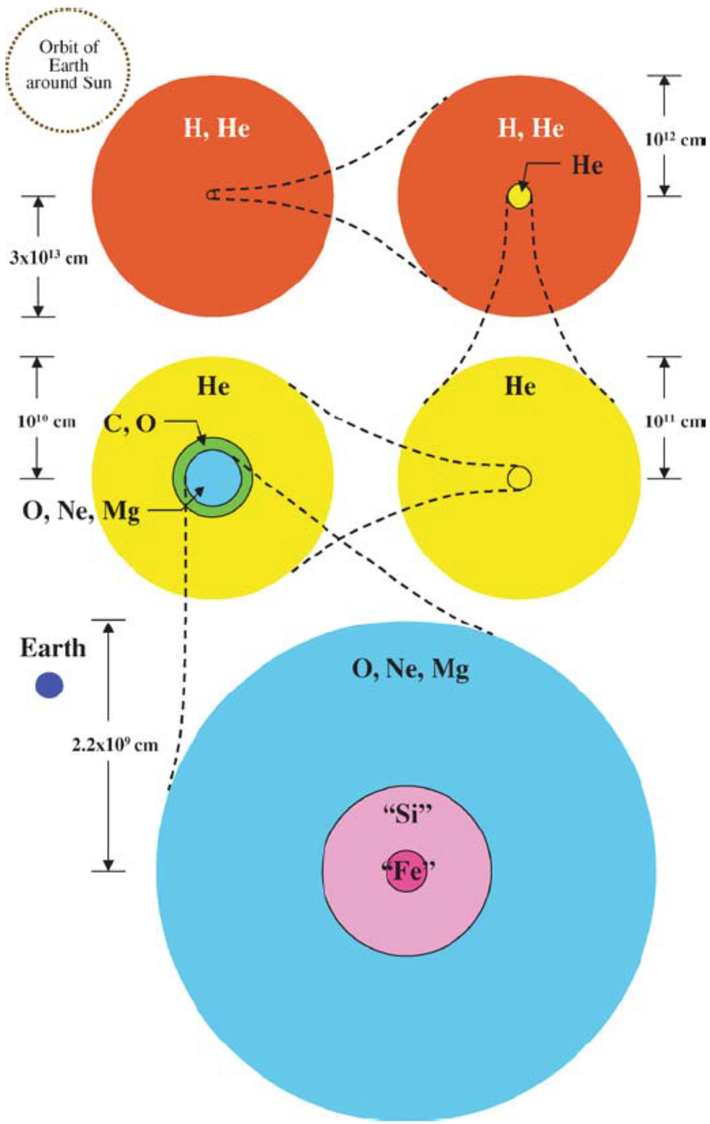
SNO + Super-K results on Solar Neutrinos

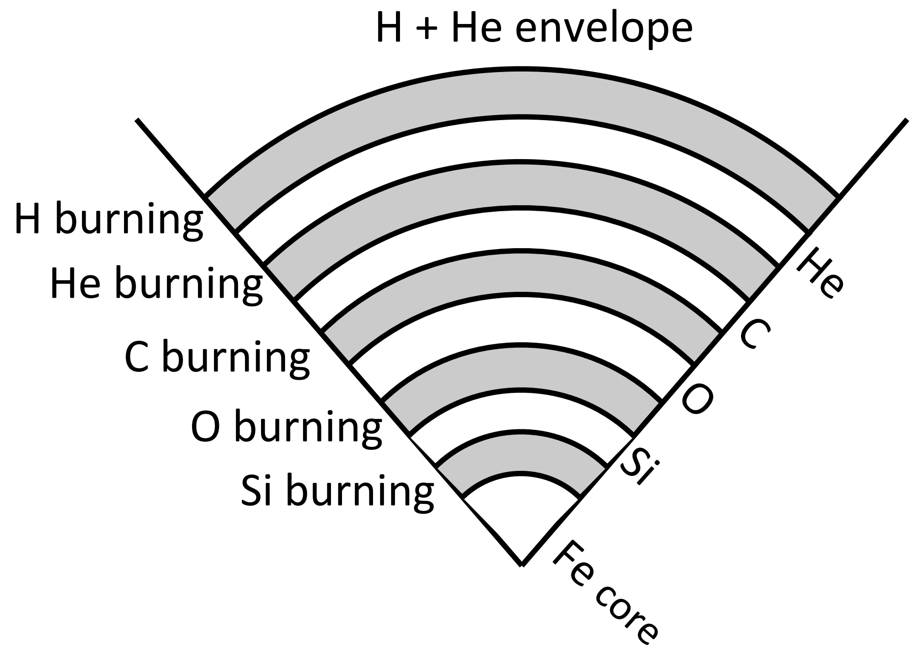


SNO. Phys.Rev.Lett.89:011301,2002

After oscillations, total neutrino flux matches Standard Solar Model prediction

The fate of the most massive stars



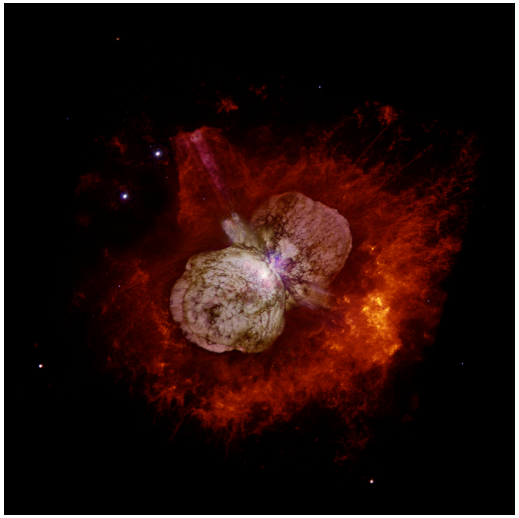


Onion structure

Outer H/He envelope may be absent if blown away by stellar wind

Supernova types

Initial Mass (M_{sun})	Progenitor	SN type
> 60	Wolf Rayet	Ib/Ic or IIn
40 - 60	Wolf Rayet	Ib/Ic
30 - 40	Wolf Rayet	Ib
20-30	Red Supergiant	II-L or II-b
10 -20	Red Supergiant	II-P

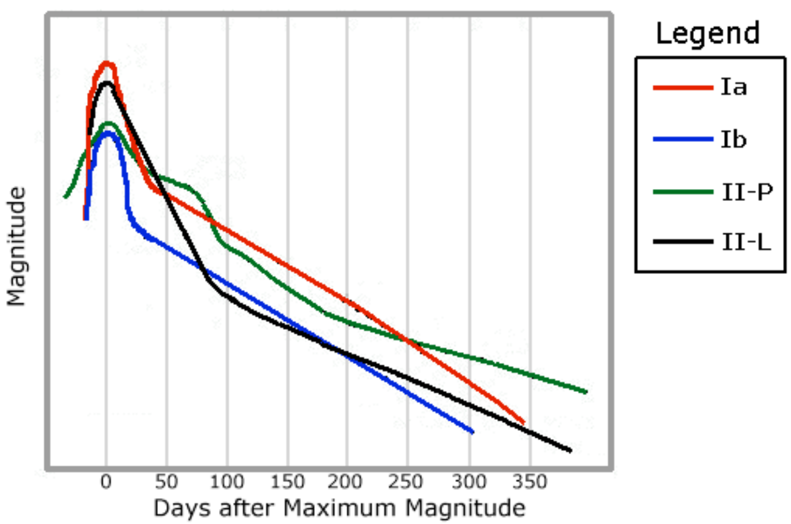


Eta Carinae

WR stars: H/He envelope lost to strong winds

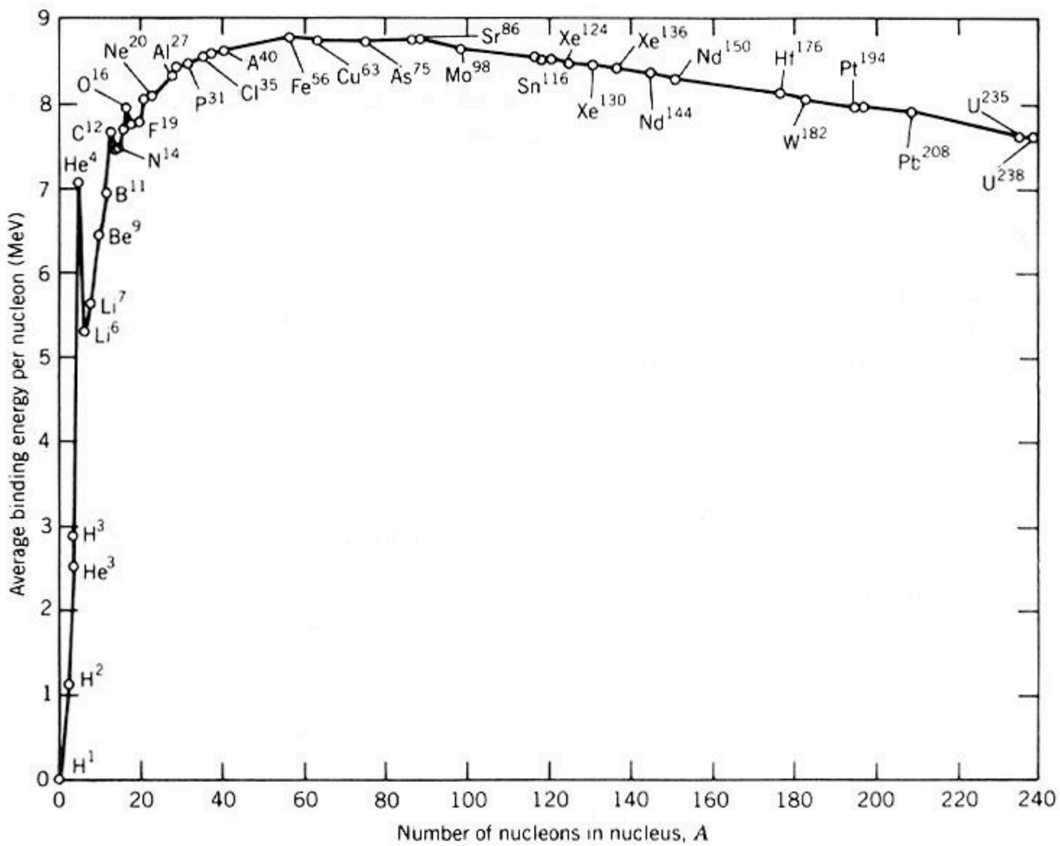
Type I: no hydrogen lines
- Ia: Not due to core collapse
- Ib: no hydrogen lines
- Ic: no helium lines (assoc. with GRBs)

Type II: hydrogen lines
- II-L: “Linear decline”
- II-P: “plateau”
- II-n: narrow hydrogen lines



The fate of the most massive stars

Massive stars burn heavy elements. Because heavier elements are closer to the peak in binding energy per nucleon, less and less energy per gram of fuel is released



Core pressure is due to Fermi gas electrons

The fate of the most massive stars

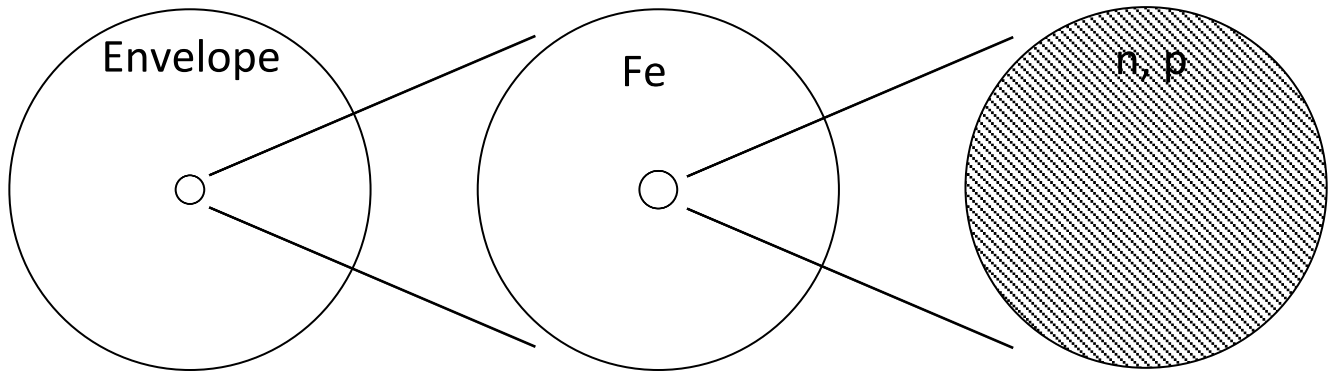
When the (isothermal) core is sufficiently large (Chandrasekhar limit, nominally 1.4 M_{sun}, range 1.2 – 2 M_{sun}), it can't provide enough pressure to overcome gravity and it collapses

For 8-9 M_{sun}, the core is O-C-Ne and it is believed that the explosion mechanism is driven by neutrino winds. These supernovae may have a kinetic energy of ~10^{50} erg.

Above ~10 M_{sun}, the iron core forms and neutrino wind is not enough to trigger the explosion. The explosion may be related to MHD instabilities. These supernovas have kinetic energy of ~10^{51} erg.

Note that the explosion mechanism is not completely understood.

Core collapse energetics



Post – pre collapse gravitational energy difference

$$\Delta E \approx \frac{3}{5}\frac{GM_{NS}^2}{R_{NS}} - \frac{3}{5}\frac{GM_{NS}^2}{R_{core}} \approx 3 \times 10^{53} \text{ erg}$$

Kinetic energy $\sim 10^{-2}\Delta E$ (10^{51} erg – C.R. connection)

E.M. radiation $\sim 10^{-4}\Delta E$

Most of the energy is released as neutrinos

Useful comparisons:

$M_{sun}c^2 = 1.79\times10^{54}$ erg $R_{sun} = 7\times10^5$ km

Total sun's EM output: ~10^{51} erg – Similar output in neutrinos

Core collapse

As core collapses, temperature increases past 10^9 K, triggering photo-disintegration

$$^{26}Fe + \gamma \rightarrow 13\,^4He + 4n$$
$$^4He + \gamma \rightarrow 2p^+ + 2n$$

After density reaches 10^{10} g.cm^{-3} free electrons (that provided pressure in the iron core) are captured by protons released in photo-disintegration

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

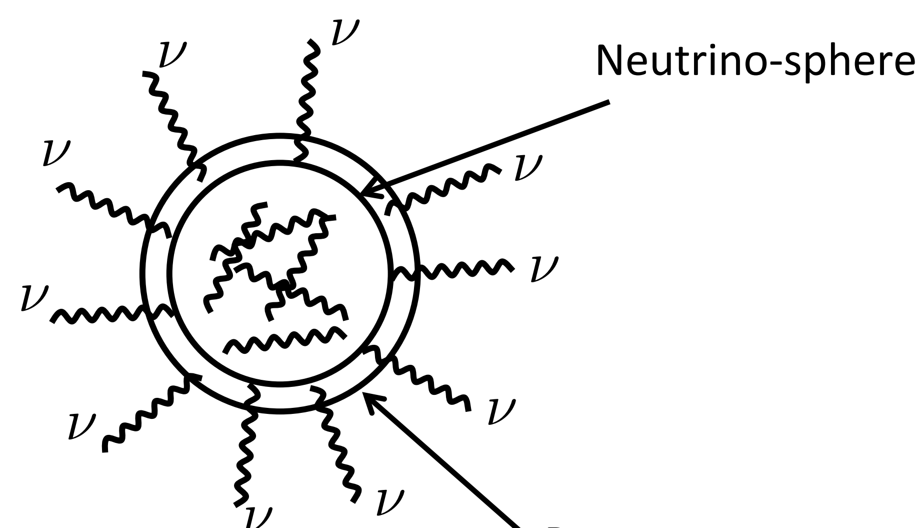
Collapse happens is about 1 s. Mechanical info travels at speed of sound, so outer layers don't *know* that core has collapsed. The dynamical time for the outer layers is ~1 day.

Core Stiffening, rebound and neutrino trapping

Collapse stops due to Pauli exclusion applied to neutrons at $8x10^{14}$ $g.cm^{-3}$ (x3 nuclear density). The strong force becomes repulsive. This process takes ~1 ms. The core rebounds triggering a shock wave.

Neutrinos are now trapped inside a proto-neutron star when the density is higher than 10^{11} $g.cm^{-3.}$ Neutrino trapping happens <u>before</u> electron capture is over.

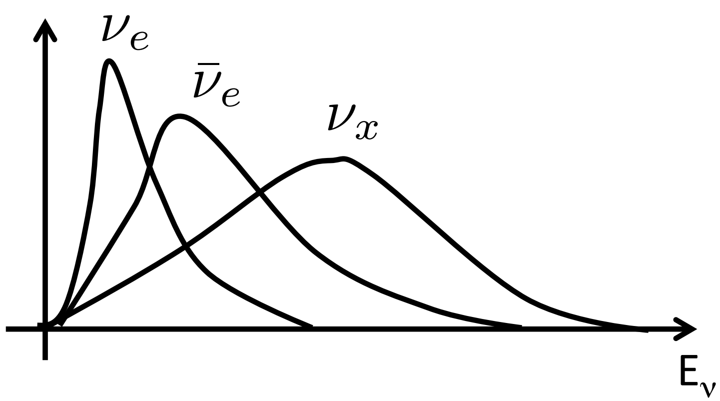
Neutrino trapping explains the ~10 s duration of the ν burst.

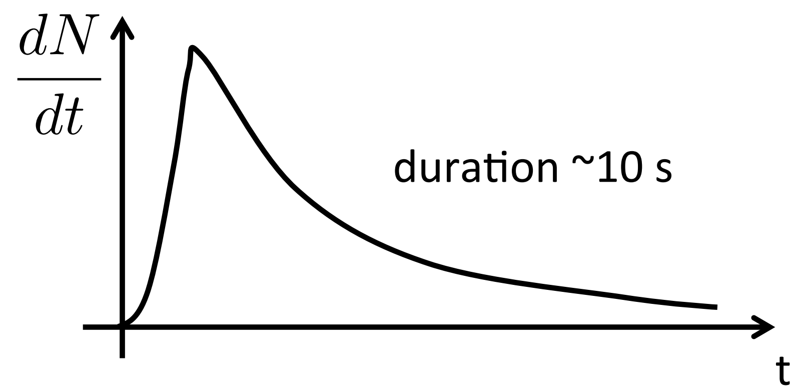


Neutrino emission by CC Supernovae

Neutrinos may also be produced via

$$e^+ + e^- \rightarrow \nu_e + \bar{\nu}_e, \nu_\mu + \bar{\nu}_\mu, \nu_\tau + \bar{\nu}_\tau$$





$$< E_{\nu_e} > \sim 11 \text{ MeV}$$

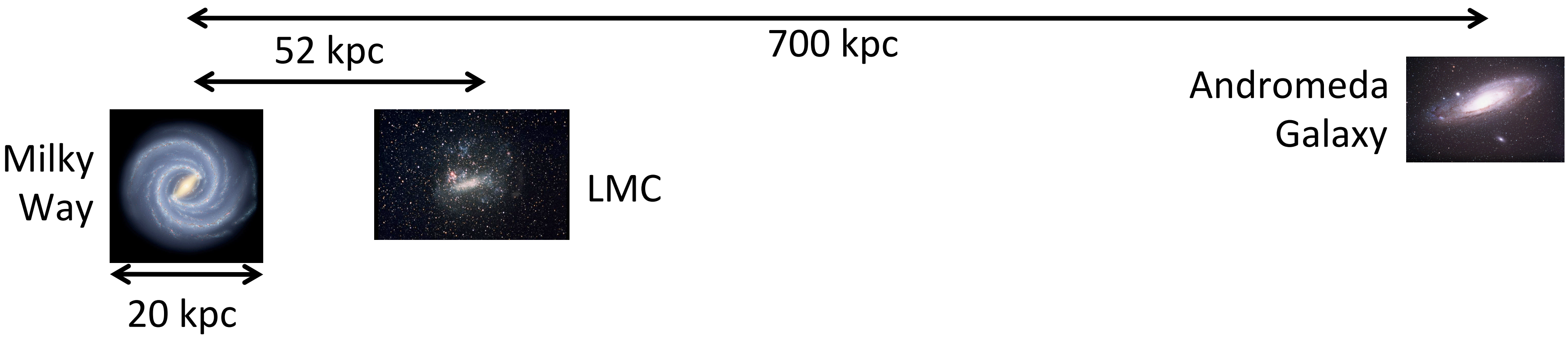
$$< E_{\nu_\mu} > \sim 16 \text{ MeV}$$

$$< E_{\nu_\tau} > \sim 25 \text{ MeV}$$

$$L_{\nu_e}(t) \sim L_{\bar{\nu}_e}(t) \sim L_{\nu_x}(t)$$

Supernova SN1987A and ν detectability

How big does a neutrino detector need to be to see a supernova?



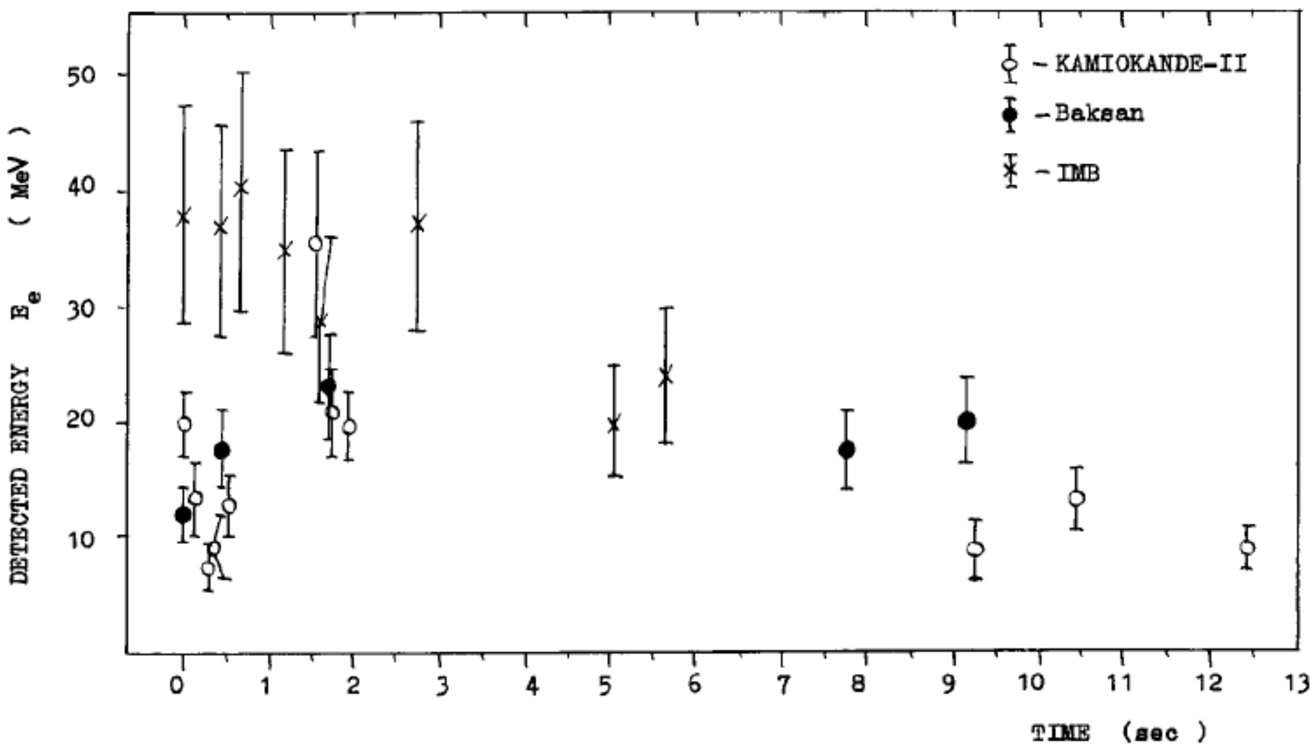
Kamiokande, with 2.14 active ktons, saw 11 neutrinos from SN1987A

$$N_\nu \approx 11 \left[\frac{M}{2.14\mathrm{kton}}\right]\left[\frac{52kpc}{d}\right]^2$$

To detect <u>one</u> neutrino at 1 Mpc you need ~700 ktons

N.B. SN1987A was type IIp and had an unusual Blue Giant progenitor

Neutrinos from SN1987A



SNEWS: A fast alert system that links neutrino detectors worldwide and provides information to astronomers

Some detectors capable of detecting SNe in the Milky Way now

- Super K Fiducial mass ~22.5 kton
- IceCube. Effective 3.5 Mton (high noise rate)
- HALO: 79 ton Lead target with ^{3}He proportional counters
  Objective 1 kton if first phase is successful
- Borexino Fiducial mass ~100 ton

SNEWS: SuperNova Early Warning System: consortium of neutrino detectors that alerts astronomers to a galactic supernova

Sholberg, Ann. Rev. Nucl. Part Phys. (2012)

Diffuse flux of neutrinos from SNe

All core collapse supernovae in the history of the Universe contribute to a MeV diffuse flux of neutrinos. I'll keep it simple, ignore describing neutrino oscillations and describe $\bar{\nu}_e$

This flux is isotropic and time constant. The energy density of these neutrinos is 10^{-2} eV.cm^{-3} (CMB is ~10^{-3} eV.cm^{-3})

Detecting the DSNB will help us:

1) To understand CC SNe.
2) Help understand neutrino properties
3) Supernova rate traces star formation rate. DSNB provides an integrated measurement of star formation in the Universe.

Super-K is big enough to have a few DSNB neutrinos in its data, but they are hidden by background (e.g. solar/atmospheric ν)

Beacom Annu. Rev. Nucl. Part. Sci. (2010)

Diffuse flux of neutrinos from SNe

Rate estimate. Again, use SN1987A

$$\left[\frac{dN_\nu}{dt}\right]_{DSNB} = \left[\frac{dN_\nu}{dt}\right]_{1987A} \left[\frac{N_{SN} M_{det}}{4\pi d^2}\right]^{-1}_{1987A} \left[\frac{N_{SN} M_{det}}{4\pi d^2}\right]_{DSNB}$$

For SN1987A N_{SN} = 1; dN_ν/dt = 1/s (12 neutrinos in 10 s for Kamionkande; M_{det} = 2.14 kton; d = 52 kpc

For all C.C. SNe in the Universe, N_{SN} = 10 SNe/s (our frame). This last number can be calculated assuming 1 SNe/century/galaxy (now). A galaxy density of 10^{-2} Mpc^{-3} and a SNe rate that was x10 higher in the past (redshift 1-2). The typical distance to a Sne is z=1, or 4 Gpc.

Putting all this together for Super-K (22.5 kt) results in 3 DSNB ν yr^{-1}

DSNB spectrum

A line of sight integration gives:

$$\frac{dN_{DSNB}}{dE_\nu} = \int_0^\infty (1+z)\frac{dN_{SN}}{dE_\nu}(E_\nu(1+z))R_{SN}(z)\left|\frac{cdt}{dz}\right|dz$$

Where

$$\left|\frac{dt}{dz}\right|^{-1} = H_0(1+z)\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}$$

(we will review cosmology later in the course) and
H_0 = 70 km.s^{-1}.Mpc^{-1}, Ω_Λ = 0.7 and Ω_m = 0.3

Here it is assumed that the flux from all SNe is the same (in the rest frame).

Individual neutrino spectrum

The neutrino spectrum can be parameterized (from simulations) as:

$$\frac{dN_{SN}}{dE_\nu}(E_\nu) = \frac{(\alpha+1)^{\alpha+1}}{< E_\nu > \Gamma(\alpha+1)} \left(\frac{E_\nu}{< E_n u >}\right)^\alpha e^{-(\alpha+1)\frac{E_\nu}{< E_\nu >}}$$

Here a is known as the *pinching* parameter. Different flavors have different average energies and different pinching parameters. (Pinching describes whether the spectrum is wider or narrower than a Fermi Dirac spectrum)

Matter effect (MSW) in supernovae is critical. Moreover, the neutrino density is so high that ν-ν interactions also need to be taken into account.

Supernova rate

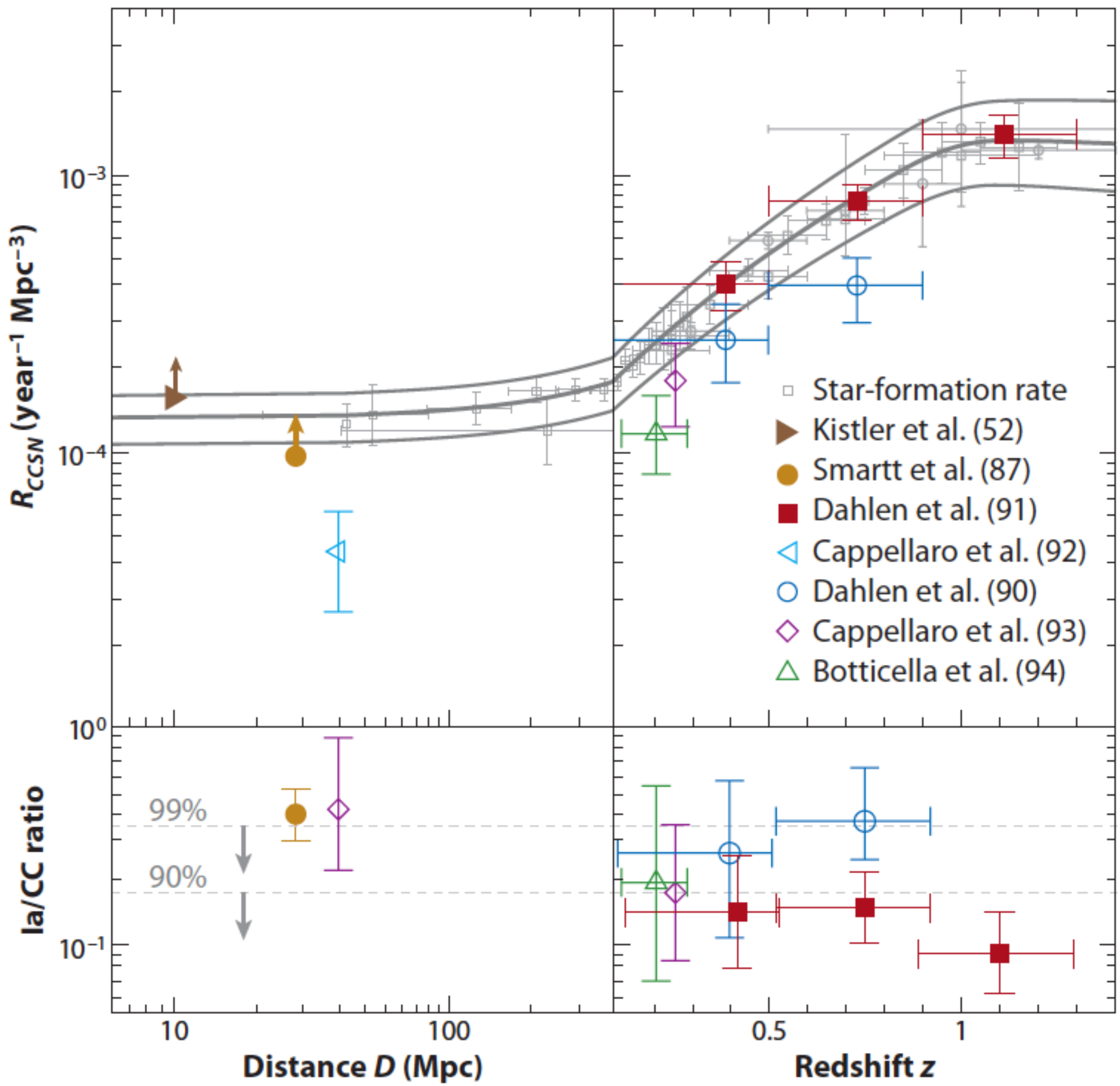
SN rate traces star formation rate. To correlate the most massive stars with all stars an IMF (initial mass function) is needed. Saltpeter assumes $dn/dm \propto M^{-2.35}$ between 0.1 and 100 $M_{sun.}$ At the low mass end, there's an uncertainty of x2 in the star formation rate due to lack of knowledge of the IMF.

$$R_{SN}(z) = R_{SF}(z) \frac{\int_8^{50} \frac{dn}{dM} dM}{\int_{0.1}^{100} M \frac{dn}{dM} dM} \approx \frac{R_{SF}(z)}{143 M_\odot}$$

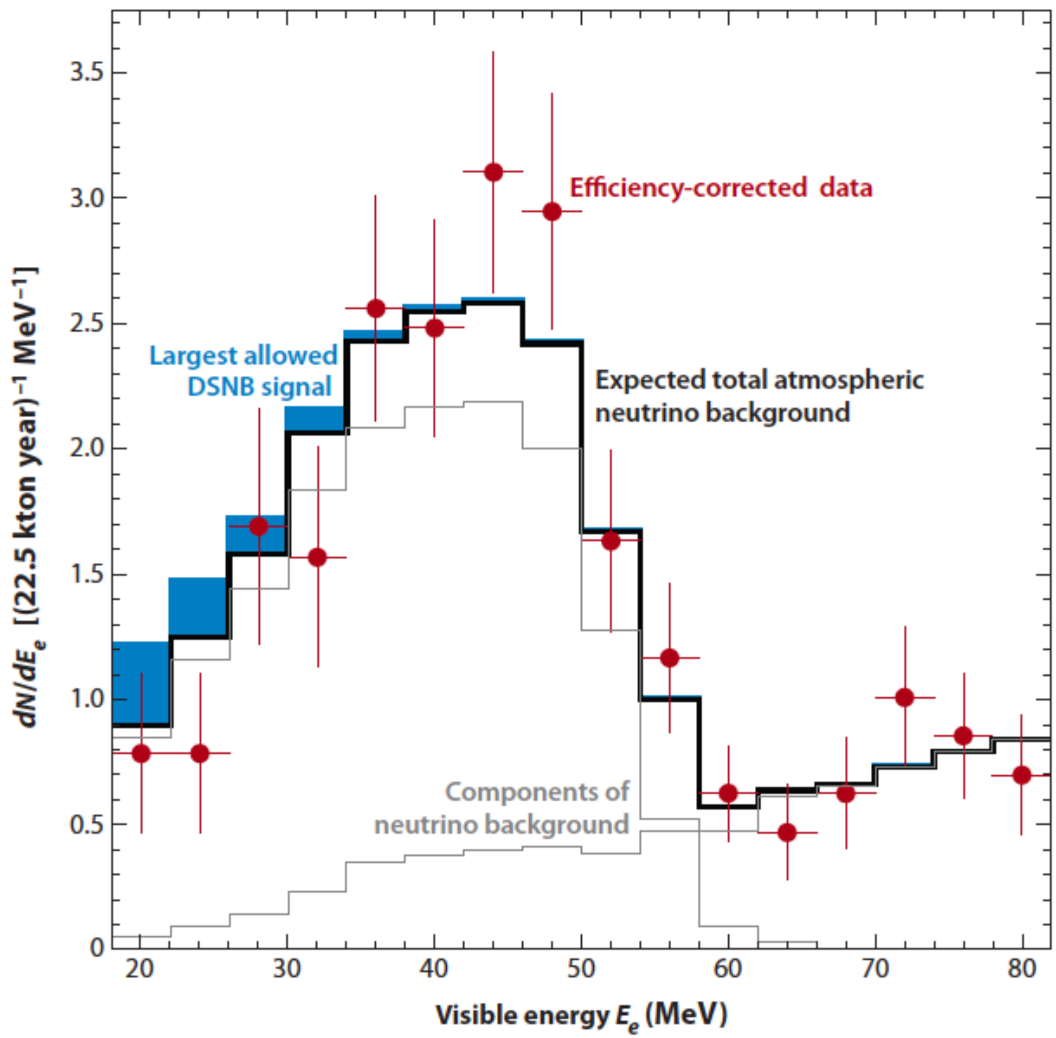
N.B. R_{SN} is in $Mpc^{-3}yr^{-1}$ and R_{SF} is in $M_{sun}Mpc^{-3}yr^{-1}$

Note that the rate of Supernova is insensitive to the choice of IMF at low energy.

Supernova rate



Super K limit on DSNB

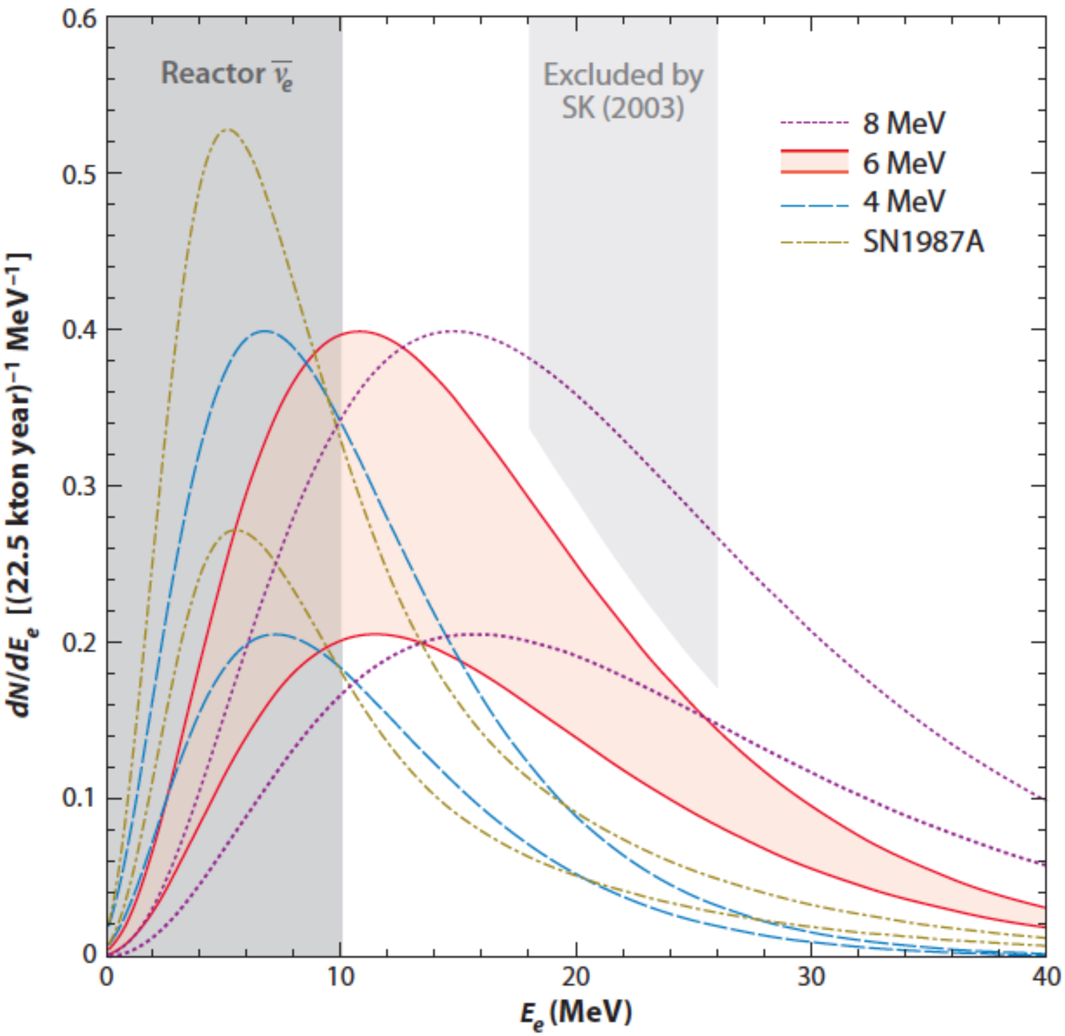


Low energy bckg are solar and reactor neutrinos. So the search is performed above a visible (e^+ or e^-) energy of 18 MeV

Main background are atmospheric neutrinos.

Bump is due ν_μ CC interactions that produce a sub-Cherenkov μ that decays inside the detector.

Super K limit on DSNB



Various $\bar{\nu}_e$ temperatures are considered. The width of the band is due to uncertainty in the Universe SN rate.

Low energy bckg are solar neutrinos, high energy bckg are atmospheric neutrinos.

Detecting the DSNB with Gadolinium

Beacom & Vagins PRL (2004)

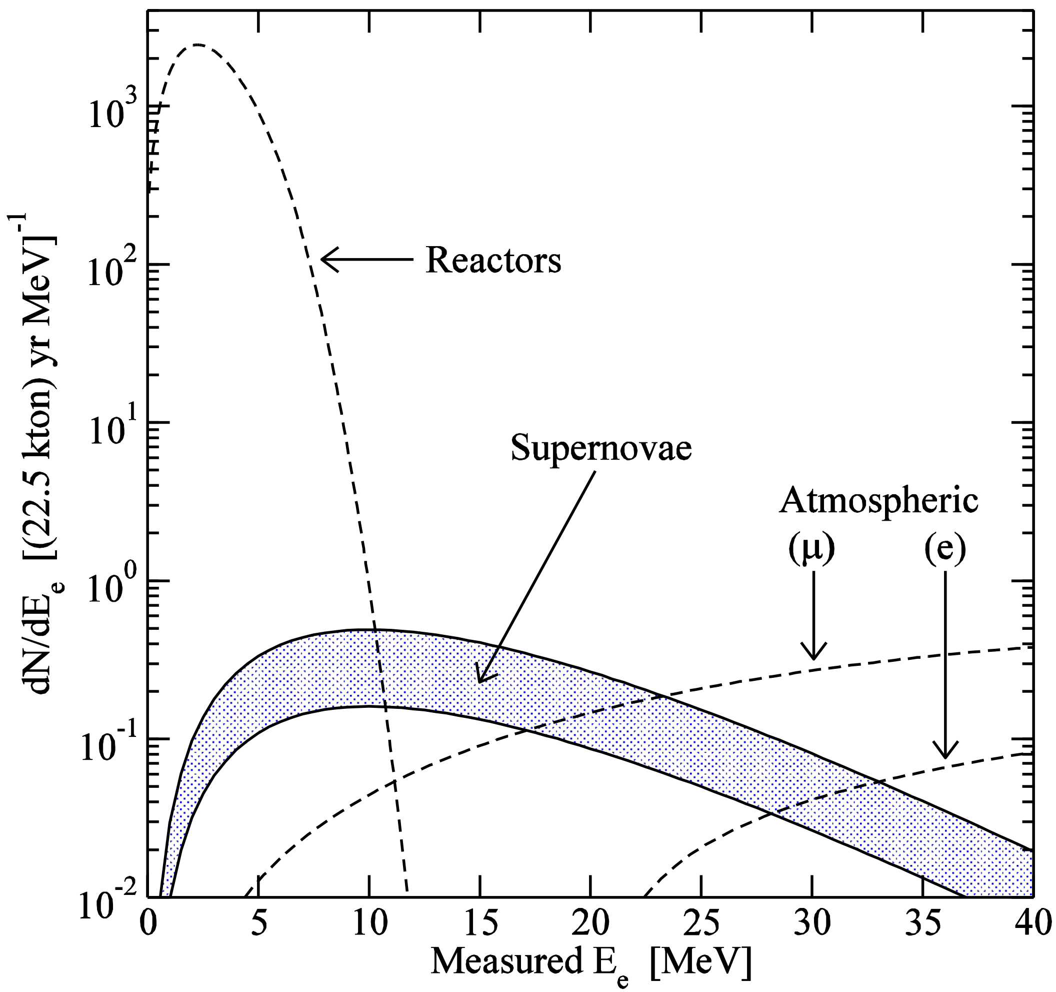
Gadolinium has a very high neutron capture cross section. Also, the resulting Gd isotopes decays alpha with a γ energy of 8 MeV. Thus in $\bar{\nu}_e$ interactions, both the positron and the neutron are visible:

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

The characteristic delay between neutron and positron is about 10 μs and the positron and neutron should have vertices close to each other.

Several Gadolinium salts are soluble in water ($GdCl_3$, $Gd_2(SO_4)_3$).

DSNB detection with Gadolinium

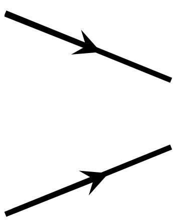
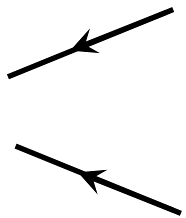
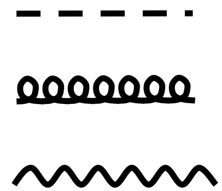


Event rate would still be a few events per year, but they would be very clean events.

This requires ~100 kg of Gd dissolved into Super-K water.

Vagins working on prototype detector (EGADS). Targeting 2016 for adding Gd to Super K.

Feynman diagram toolkit

Particles	Anti Particles	Bosons
		
n		W
p		Z^0
l^-	l^+	γ
ν_l	$\bar{\nu}_l$	

White Dwarfs

Sirius (A) is the brightest star in the sky after the Sun.

Distance to Sirius (2.65 pc) was measured by Bessel via parallax. In the process a binary is found (Sirius B).

$M_{siriusB}$ = 1.053 M_{sun} $T_{siriusB}$ = 27,000 K $L_{siriusB}$ = 0.003 L_{sun}

From Stefan-Boltzman law, $L = 4\pi R^2 \sigma T^4$, we find

$R_{siriusB}$ = 0.008 R_{sun} (R_{earth} = 0.009 R_{sun})

Clearly WD can't have hydrogen in the core (otherwise pp or CNO would produce energy furiously).

Pressure inside a WD is due to electrons that form a Fermi gas. Above "1.44 M_{sun}", the gravitation overcomes this pressure (Chandrasekhar limit)

Type Ia supernovae

Type Ia supernovae lack hydrogen lines

Potential progenitors involve Carbon-Oxygen White Dwarfs

Single WD. Material is transferred from binary companion to WD until Chandrasekhar limit is reached

Double WD. A pair of WD loose orbital angular momentum to GW and eventually merge, forming a super-Chandrasekhar object

Energy released is approximately constant (standard candles)

Type Ia supernovae do not produce MeV neutrinos and they don't leave a compact object (neutron star) behind.

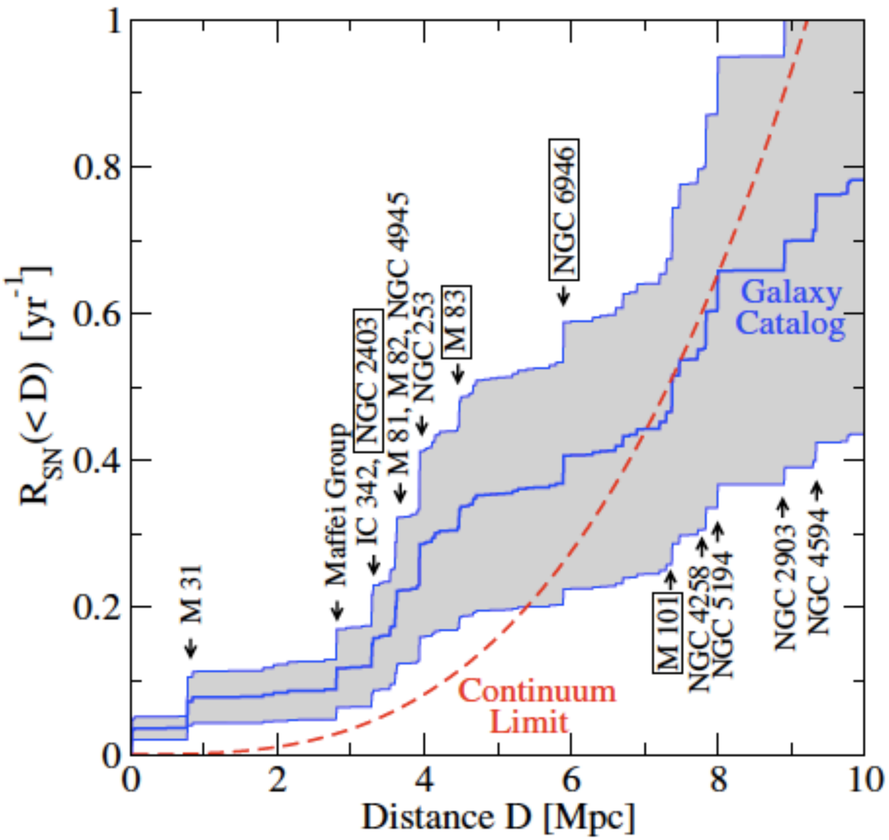
What do we learn from understanding CC SNe?

- Neutron star mass distribution – nominally and observationally close to Chandrasekhar limit
- Nucleosynthesis yields
- Neutron star proper speeds (Asymmetric explosions)
- Energetics

Though computer simulations (hydrodynamics, nuclear physics, neutrino physics, shock physics, etc) have successfully made supernovae explode on simulations, there isn't a complete description of the explosion mechanism.

Local Supernova Rate

CC SN rate within 10 Mpc ~1/yr (from star formation rate) to ~2/yr (from direct counts)



Ando, Beacom, Yuksel PRL (2005)
Kistler, et al PRD (2011)

In our galaxy the C.C. SNe rate is 1.9±1.1 / century

SNe rate measured with ^{26}Al by Integral
R Diehl *et al*. Nature (2006)

Galactic Sne are distributed:

20% Type Ia

10% Type Ib/c

70% Type II