Extra-terrestrial Neutrinos

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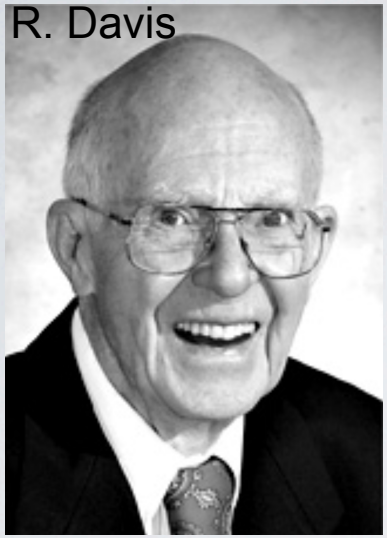
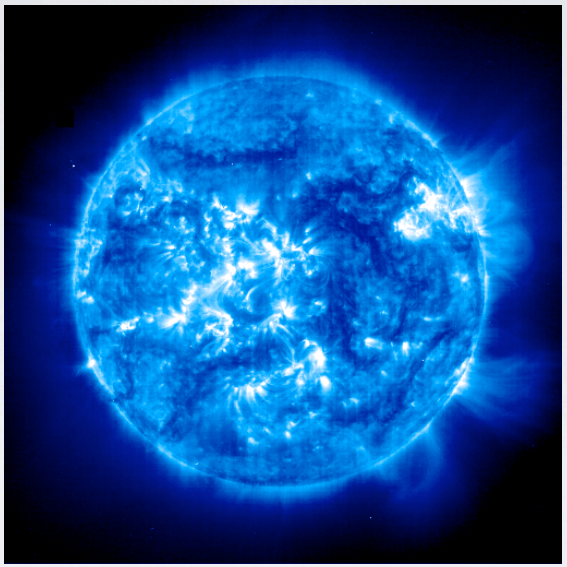
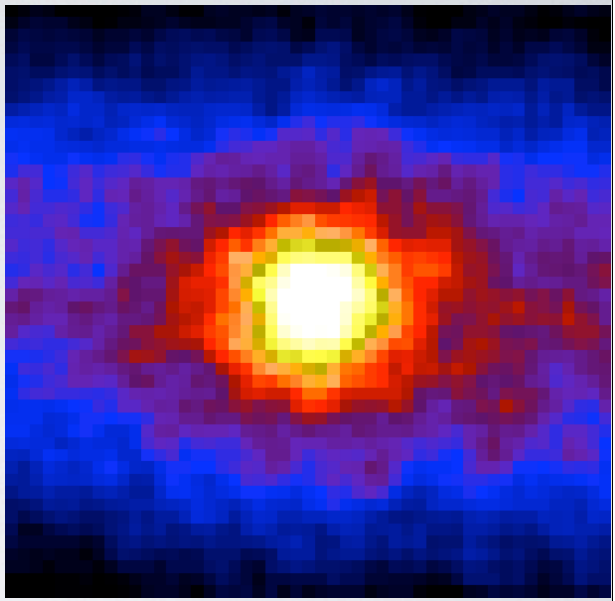
THE BIRTH OF NEUTRINO ASTRONOMY

First extra-terrestrial neutrino signals (~10 MeV range)



solar neutrinos





Nobel Prize in Physics 2002

SN1987A

THIS LECTURES CONTENTS

Solar neutrinos

What we learnt: solar model & oscillations (radiochemical, SNO, SK, Borexino mainly) => oscillation parameters, SSM understanding
Future of solar neutrinos: solar physics, magnetic interaction properties with plasma, solar dynamics

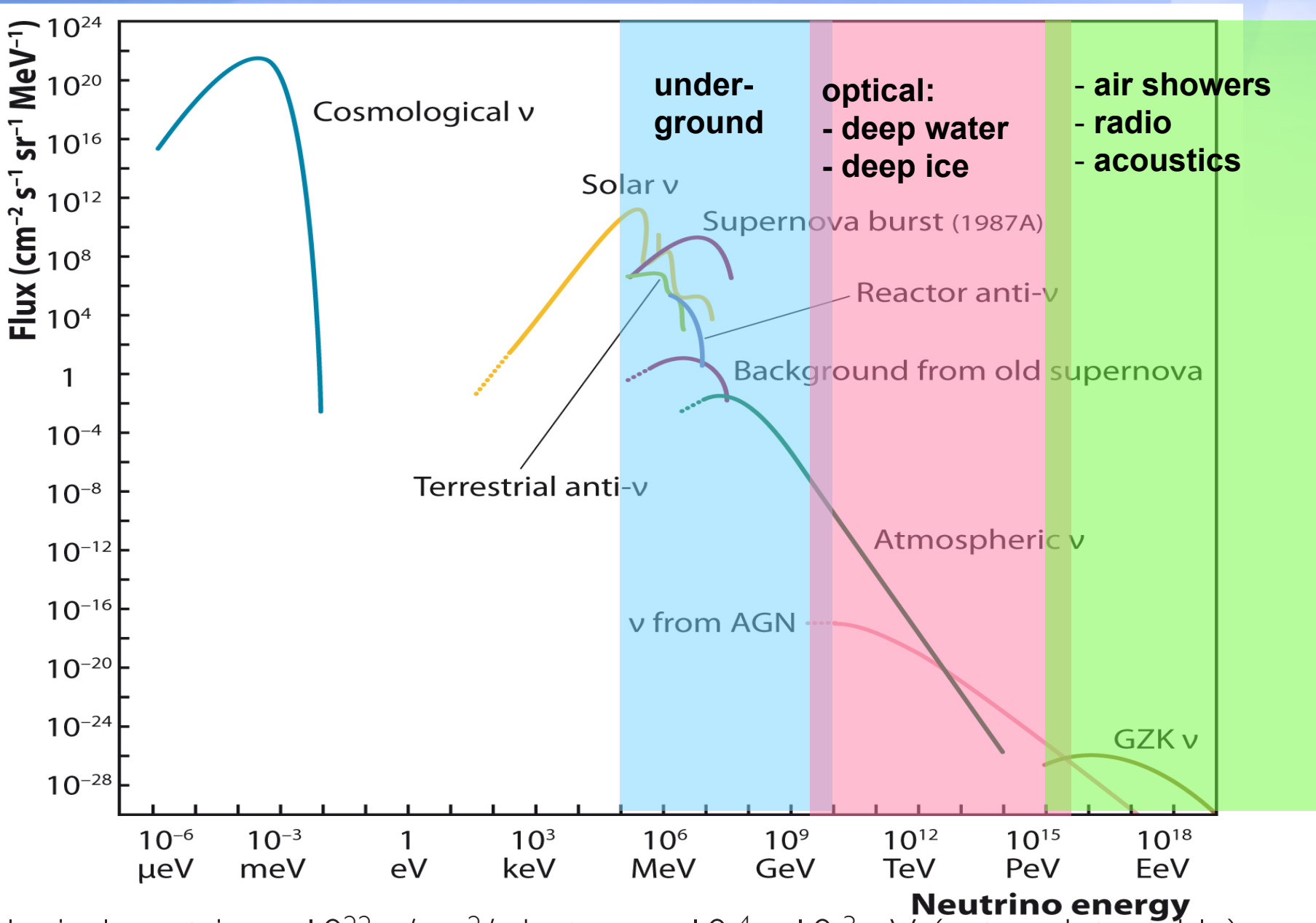
SN Neutrinos

Core Collapse SN
SN 1987: what we learnt
What could IceCube tell us if we had such a SN?

VHE and UHE Neutrinos

Multi-messenger Astronomy: gamma-UHECRs-neutrinos
Extra-galactic and Galactic sources

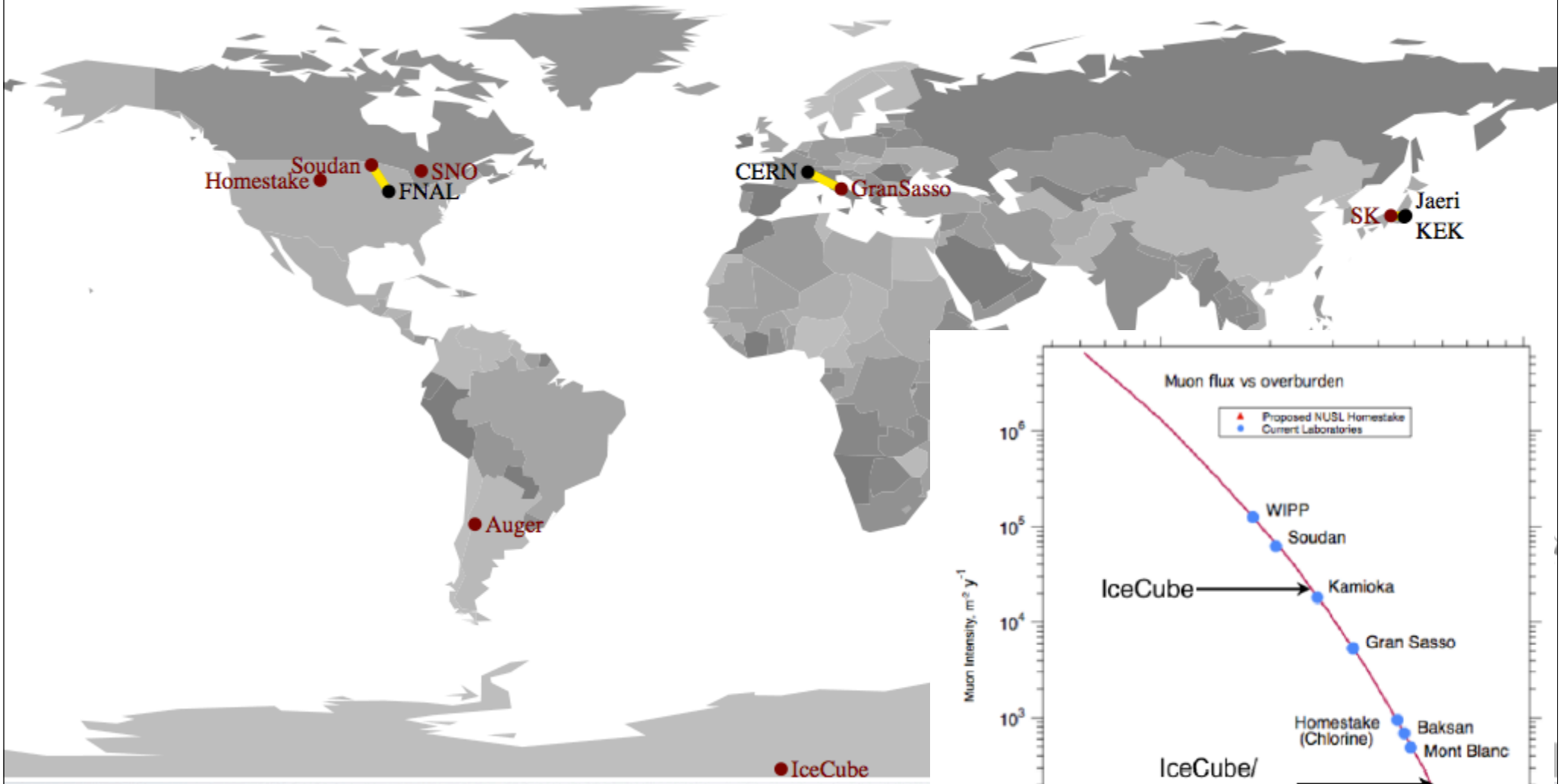
SUMMARY OF NEUTRINO FLUXES

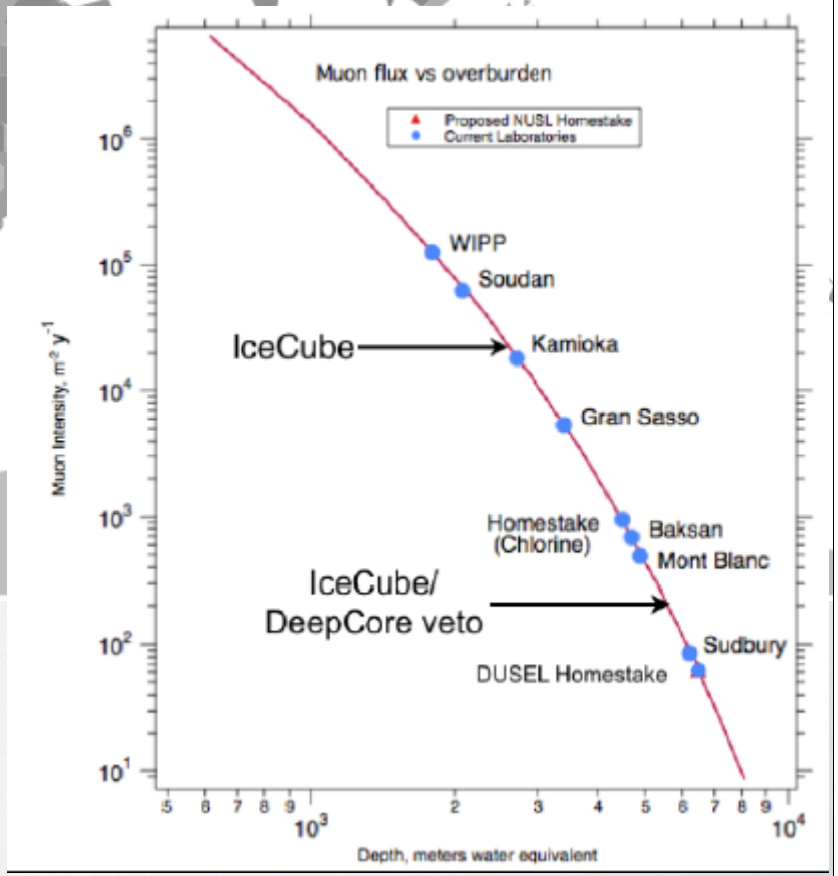


Cosmological neutrinos: 10^{22} ν/cm²/s between 10^{-4} - 10^{-3} eV (yet undetectable)

Solar neutrinos: 6.7 x 10^{10} ν/cm²/s between 0.1-20 MeV

UNDERGROUND OBSERVATORIES





HOW LONG COULD THE SUN SHINE?

Helmholtz and Kelvin at the end of 1800...
Power radiated by the Sun at Earth: P = 8.53 x 10^{11} MeV cm^{-2} s ≈ 1400 W/m^2
which implies for isotropic emission a luminosity of:

$$L_{Sun} = 4\pi d^2_{Sun-Earth} P \sim 4 \times 10^{26} W$$

If all the gravitational energy is radiated the Sun can shine for:

$$T = \frac{U_{grav}}{L_{Sun}} = \frac{\frac{3}{5}\frac{GM^2}{R}}{L_{Sun}} \sim 20 Myr$$

$$d^2_{Sun-Earth} = 1 A.U. = 149.6 \times 10^9 m$$

$$R \sim 7 \times 10^8 m$$

$$M \sim 2 \times 10^{30} kg$$

Nuclear processes in the sun

Flux	Reaction	Φ_ν $10^{10}/\,\mathrm{cm^2\,s}$	$\langle E_\nu \rangle$ MeV	$E_\nu^{\max}$ MeV	Q MeV
pp	$pp \to {}^2\mathrm{H}\ \bar{e}\ \nu_e$	$6.0 \pm 1\%$	0.267	0.423	13.10
pep	$pep \to {}^2\mathrm{H}\ \nu_e$	$0.014 \pm 1\%$	1.445		11.92
hep	${}^3\mathrm{He}\ p \to {}^4\mathrm{He}\ \bar{e}\ \nu_e$	$\sim 10^{-6}$	9.628	18.8	3.737
Be	${}^7\mathrm{Be}\ e \to {}^7\mathrm{Li}\ \nu_e$	$0.477 \pm 9\%$	0.814	0.863	12.60
B	${}^8\mathrm{B} \to {}^8\mathrm{Be}\ \bar{e}\ \nu_e$	$0.00050 \pm 20\%$	6.735	16.3	6.630
N	${}^{13}\mathrm{N} \to {}^{13}\mathrm{C}\ \bar{e}\ \nu_e$	$0.033 \pm 20\%$	0.706	1.20	3.456
O	${}^{15}\mathrm{O} \to {}^{15}\mathrm{N}\ \bar{e}\ \nu_e$	$0.026 \pm 20\%$	0.996	1.73	21.57
all	$4p\ 2e \to {}^4\mathrm{He}\ 2\nu_e$	—	—	—	26.7

energy released in the nuclear reactions

pp chain 98.8% of tot energy

CNO chain 1.2%

The Sun shines thanks to nuclear fusion:

$$4\mathrm{p} \to {}^4\mathrm{He} + 2\mathrm{e}^+ + 2\nu_\mathrm{e} + \mathrm{Q} \qquad - \mathrm{E}_\nu$$

average 0.6 MeV

$$Q = [4 \times 1.007825u - 4.002603u][931MeV/u] = 26.7MeV$$

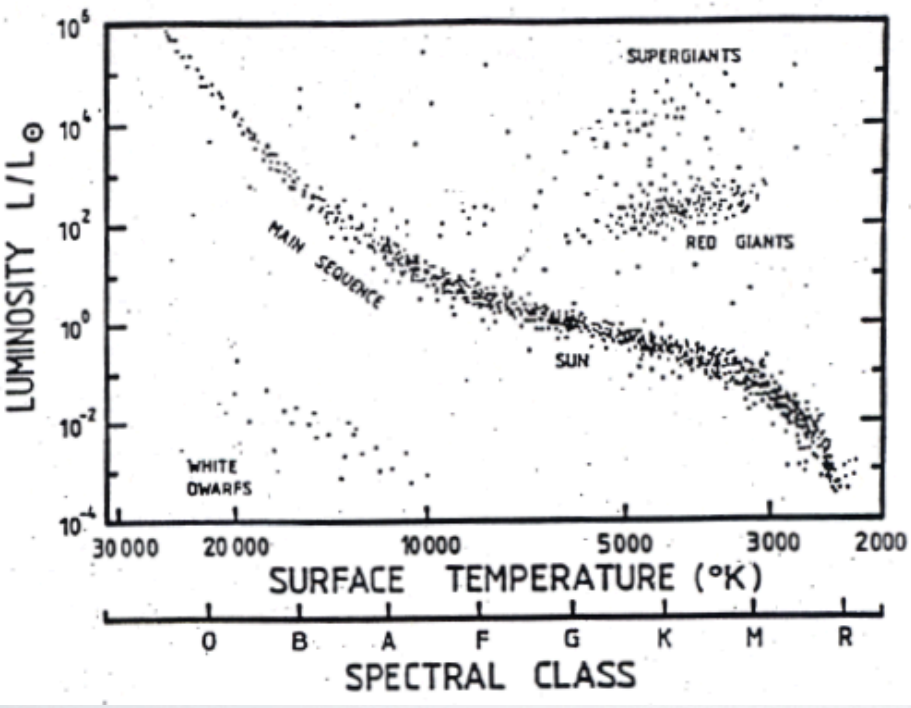
H atomic mass

^{4}He atomic mass

From this information you can estimate 6.5 x 10^{10} neutrinos/cm^2/s

HERTZSPRUNG-RUSSELL DIAGRAM OF STARS

HR diagram dominated by one path in the (L, $T_{surface}$) diagram corresponding to 80% of "**main sequence**" stars powered by H burning (mainly from pp chain, and CNO cycle). The Sun is a good test case for understanding the main-sequence evolution because its proximity allows to determine well relevant parameters.



- $L \sim 10^{-4} - 10^{6} L_{\odot}$ and $T \sim 2000 - 50000K$
- Simplest possible model might be a radiating blackbody

$$L = 4\pi R^2 \sigma T_s^4 \Rightarrow \frac{L}{L\odot} = (\frac{R}{R_{\odot}})^2 (\frac{T_s}{T_{\odot}})^4$$

suggests a path in the (L,Ts) plane

THE STANDARD SOLAR MODEL

More than 40 yrs of effort lead by J. Bahcall lead to remarkable agreement with observations (J.N. Bahcall and M. H. Pinsonneault, Phys. Rev. Lett. **92**, 121301 (2004), astro-ph/0402114) SSM traces the solar evolution for 4.9Byr and predicts the **present temperature and composition profile of the solar core.** It is constrained to produce today's radius, mass, luminosity. Basic assumptions:

1) **local hydrostatic equilibrium:** each shell is balanced by outward gas pressure counteracting gravitational force

$$\frac{dP}{dr} = -\frac{M(r)G}{r^2}\rho \text{ and } \frac{dM}{dr} = 4\pi r^2\rho$$

2) **Thermal equilibrium:** the **energy produced by nuclear reactions** ($4\pi r^2\rho\epsilon$) balances the **energy flux L(r) radiated from the spherical shell** of radius r and thickness dr and a heat transfer term needs to be accounted for:

$$\frac{dL}{dr} = 4\pi r^2\rho\left(\epsilon - \frac{TdS}{dt}\right)$$

nuclear production rate

heat transfer term

S = entropy of gas

In a star like the Sun the processes that dominate the energy transport are radiation and convection. In a **radiative region** of the star the **diffusion approximation** applies:

$$\frac{dT}{dr} = \frac{-3}{4ac}\frac{\kappa\rho}{T^3}\frac{L(r)}{4\pi r^2}$$

radiative opacity coefficient

NUCLEAR REACTIONS

For a nuclear reaction: $a + X \rightarrow b + Y$

The gain or loss of energy is: $Q = \Delta E = (M_X + M_a - M_Y - M_b)c^2$

Total rate of reactions/volume $r = N_a N_X v\sigma(v)$ units 1/(m^3 s)

number densities

x-section = prob that a projectile a with speed v collides with a fixed nucleus X

More precisely, the relative velocities are distributed according a Maxwell distribution f(v) because matter in the stellar interior is in local thermal equilibrium:

$$r = N_a N_X \int v\sigma(v) f(v) dv$$

The total energy generated per unit mass and unit time (**nuclear production rate**) is

$$\epsilon = \frac{rQ}{\rho}$$

1/(m^3 s) x energy x m^3/mass = energy/(mass x s)

COULOMB BARRIERS

In the Sun interior atoms are almost all ionized since the energy corresponding to the core

$$T_c \sim 1.5 \times 10^7 K \rightarrow \frac{3}{2} k_B T_c \sim \frac{3}{2} \times 8.6 \times 10^{-8} \frac{keV}{T} \times 1.5 \times 10^7 K \sim 2keV$$ >> 13.6 eV

Charges are free. This energy of thermal motion is << Coulomb barrier (energy barrier that 2 nuclei need to overcome for fusion to happen) ~ MeV

Eg. $$^3He + ^3He \Rightarrow U_C = \frac{Z_1 Z_2 e^2}{4\pi\epsilon_0 r} \sim \alpha\hbar c \frac{Z_1 Z_2}{r} \sim \frac{197\text{MeVfm}}{137} \frac{4}{10\text{fm}} \sim 575\text{keV}$$

From a **classical** point of view **no reaction can take place at typical stellar temperatures**. Eg. pp interaction could only occur for T ~10^{10} K (corresponding to the Coulomb barrier) but at this temperature nuclear reactions would be so strong that the star would experience a catastrophic explosion. Since particles velocities are distributed according to a Maxwell-Boltzmann, nuclear reactions could also occur in its high energy tail but the number of participating particles would be very small.

- Reduced Planck's constant × speed of light in vacuum
  $\hbar c = 197 \text{ MeV} \cdot \text{fm} \approx 200 \text{ MeV} \cdot \text{fm}$
- Fine structure constant
  $\alpha = \frac{e^2}{4\pi\varepsilon_0} \frac{1}{\hbar c} = \frac{1}{137}$
- Classical electron radius
  $r_e = \frac{e^2}{4\pi\varepsilon_0} \frac{1}{m_e c^2} = 2.818 \text{ MeV}$

Gamov (1928) showed that **quantum mechanics** would allow nuclear reactions to happen through tunneling. showed that H is the most abundant element in stars and it is the 1st element to be converted because it has the lowest Coulomb barrier. He

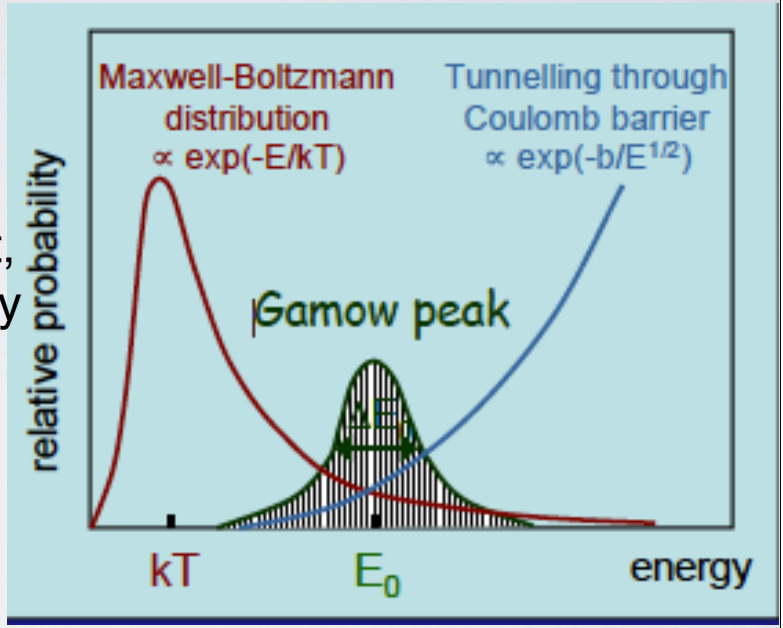
TUNNELING

In quantum mechanics there is a finite tunneling probability through the Coulomb barrier proportional to:

$$\exp[-2\pi a Z_1 Z_2 (\frac{mc^2}{2E})^{1/2}] = \exp(\frac{-b}{E^{1/2}})$$

$$a = \frac{e^2}{hc}$$

The competition between the decrease of the Maxwellian distribution with E and the increase of the penetration effect, leads to an increase in the x-section in a rather small energy range around $E_0 = (bkT/2)^{2/3}$, known as the Gamow peak.



E_0 increases with the charge of the particle and is typically between 10 to 50 keV for H burning at

$$T_c \sim 1.5 \times 10^7 K$$

$$\epsilon = \frac{N_a N_X Q}{\rho} (\frac{8}{m\pi})^{1/2} (kT)^{-3/2} \int_0^\infty S(E) \exp(\frac{-E}{kT} - \frac{b}{\sqrt{E}}) dE$$

S(E) gives the variation of the x-section with energy and must be determined from laboratory measurements for the reactions involved (eg LUNA at Gran Sasso). Extrapolations of x-section measurements at higher energies are needed since below the Coulomb barrier x-sections are small at the relevant energies.

This is a source of uncertainty in the SSM, together with the opacity, initial composition and He/H mass ratio.

HEAVY ELEMENTS ABUNDANCES

While the solar envelope is convective, radiative transport dominates in the core region where thermonuclear reactions take place. The **opacity** depends sensitively on the **solar composition**, particularly the **abundances of heavier elements.**

The agreement with **helioseismology** was **worsened** by the decrease of about 30% of the heavy element photospheric abundance estimate. A 3D solar model simulation was done to using them. This has consequences on the sound speed in the radiative zone. Three different sets of solar abundances of heavy elements: AG89 (Anders&Grevesse 89), AGS05 (Asplund et al, 2005) and AGS09 (Asplund et al. 2009) have been used originating 2 different, **low metallicity** or **high metallicity** versions of the SSM. High metallicity produces slightly higher rates.

Table 5. Abundances of the elements used in a solar model derived from the solar Photosphere (from Anders & Grevesse (1989): AG, from Asplund et al. (2005): AGS and from Asplund et al. (2009) and compared to meteoritic values from Lodders (2003). They are given in fraction number normalised such that log $N_H = 12$. The main changes are a strong reduction for the C, N, and O abundances (see text). Indirect solar estimates are mentioned in parentheses.

Elements	Photosphere AG	Meteorites	Photosphere AGS	Asplund et al. (2009)
^{1}H	12.00	8.25 ± 0.05	12.00	12.00
^{2}He	$[10.99 \pm 0.035]$	1.2900	$[10.93 \pm 0.01]$	$[10.93 \pm 0.01]$
^{7}Li	1.16 ± 0.1	3.25 ± 0.06	1.05 ± 0.1	1.05 ± 0.1
^{4}Be	1.15 ± 0.1	1.38 ± 0.08	1.38 ± 0.09	1.38 ± 0.09
^{6}C	8.56 ± 0.04	7.40 ± 0.06	8.39 ± 0.05	8.43 ± 0.05
^{7}N	8.05 ± 0.04	6.25 ± 0.07	7.78 ± 0.06	7.83 ± 0.05
^{8}O	8.93 ± 0.035	1.38 ± 0.08	8.66 ± 0.09	8.69 ± 0.05
^{10}Ne	$[8.09 \pm 0.1]$	-	$[7.84 \pm 0.06]$	$[7.93 \pm 0.1]$
^{11}Na	6.33 ± 0.03	6.27 ± 0.03	6.17 ± 0.04	6.24 ± 0.04
^{12}Mg	7.58 ± 0.05	7.53 ± 0.03	7.53 ± 0.09	7.60 ± 0.09
^{13}Al	6.47 ± 0.07	6.43 ± 0.02	6.37 ± 0.06	6.45 ± 0.06
^{14}Si	7.55 ± 0.05	7.51 ± 0.02	7.51 ± 0.04	7.51 ± 0.03
^{15}P	5.45 ± 0.04	5.40 ± 0.04	5.36 ± 0.04	5.41 ± 0.03
^{16}S	7.21 ± 0.06	7.16 ± 0.04	7.14 ± 0.05	7.12 ± 0.05
^{17}Cl	5.5 ± 0.3	5.23 ± 0.06	5.50 ± 0.3	5.50 ± 0.3
^{18}Ar	$[6.56 \pm 0.1]$	-	$[6.18 \pm 0.08]$	$[6.40 \pm 0.08]$

Three sources are normally used: the Earth, the solar photosphere and meteorites. The Earth is useful to determine isotopic ratios, but preferred sources are the other 2.

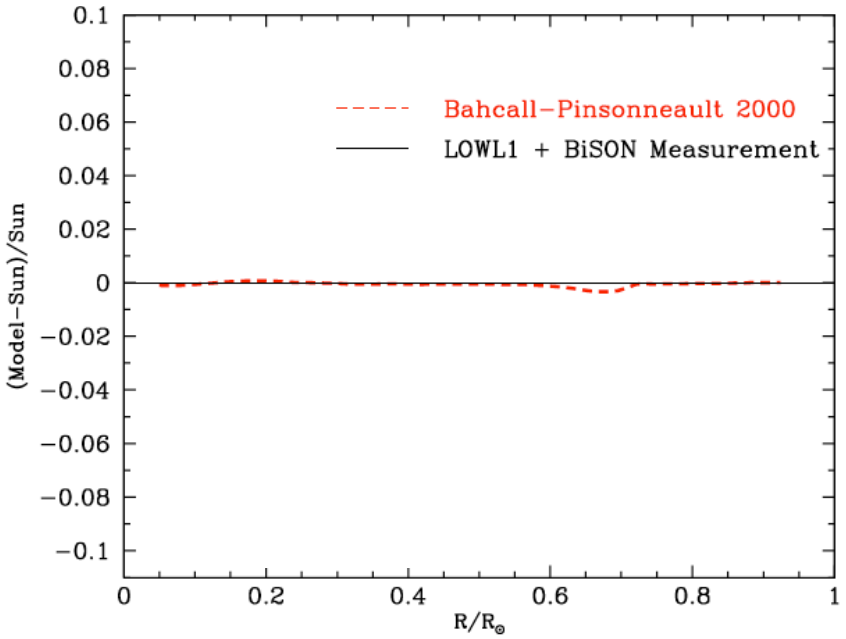
The C, N, and O elements are the main contributors to the heavy element category. These major volatile elements can only be studied in the solar photosphere.

HELIOSEISMOLOGY

The Sun, as a self-graviting sphere of compressible gas, oscillates around its equilibrium state with a period of about 5 min. These oscillations are interpreted as a superposition of waves propagating inside the star (acting as a resonant cavity), and forming standing waves: the eigenmodes of vibration. They can be use to measure properties of the Sun interior.

The sound velocity measurement within the Sun, deduced from observations of surface oscillations, is a powerful check for SSM.

comparison of observed and predicted sound speed profiles

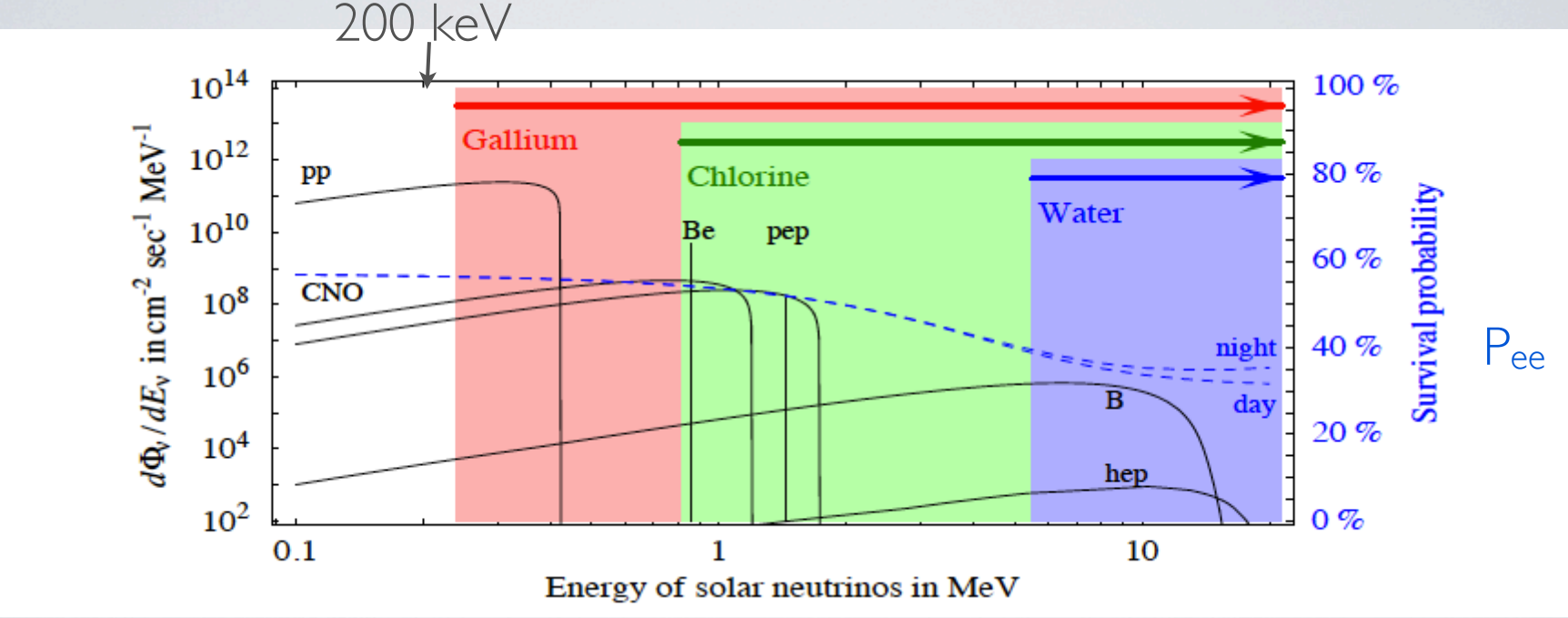


Bahcall: agreement at 0.2% over 80% of Sun a more severe test than the Vs

Table 7. Sensitivity of the sound speed to the physical processes

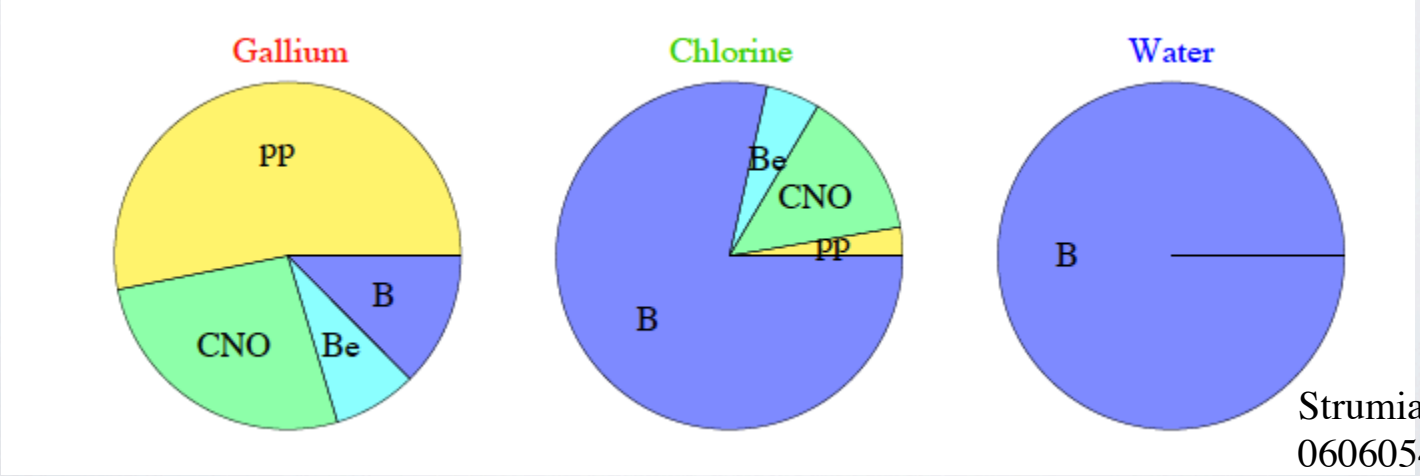
Quantity	variation	$\Delta c^2/c^2$ variation
T Temperature	1 %	1%
κ opacity	1 %	0.1 %
X_c ^{56}Fe abundances	4 %	0.1 %
X ^{3}He	25%	0.1 %
(p,p) reaction rate	1%	± 0.1%
(^{3}He, ^{3}He) reaction rate	- 25 %	- 0.1 %
(^{3}He, ^{4}He) reaction rate	-25%	+0.2%
(p, ^{7}Be) reaction rate	10%	none
(p, ^{16}O) reaction rate	-50%	- 0.1-0.2 % just at the center

SPECTRA



P_{ee}

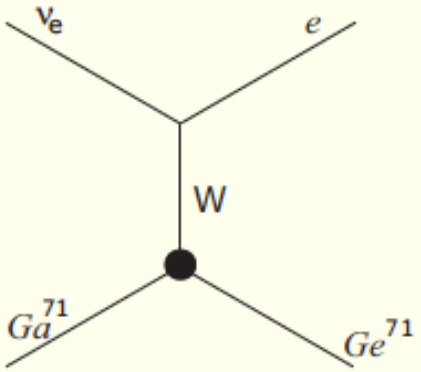
Now we know: suppression is not flat as would be expected by vacuum oscillations.
Fractions of neutrinos seen with different techniques assuming energy independent oscillations



Strumia & Vissani arXiv: 0606054

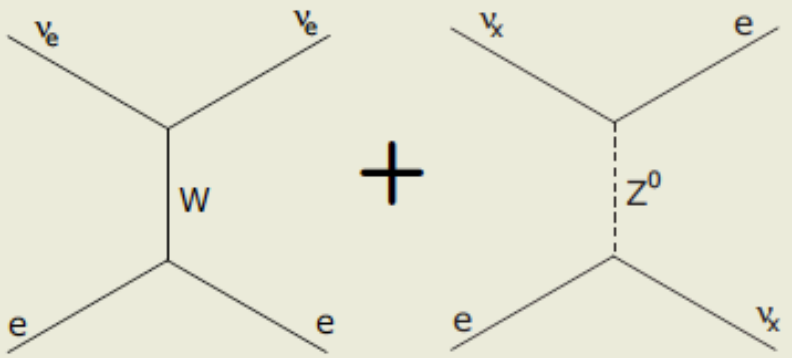
SOLAR NEUTRINO INTERACTIONS

Radiochemical



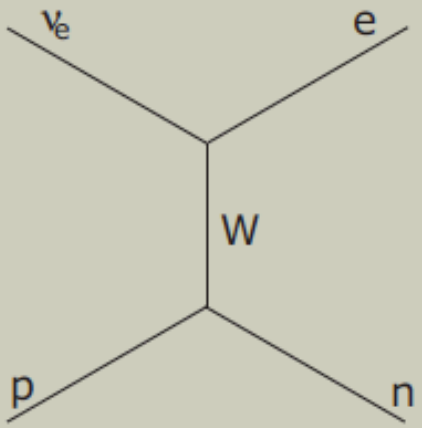
$$\nu_e + n \rightarrow e^- + p$$

Elastic scattering

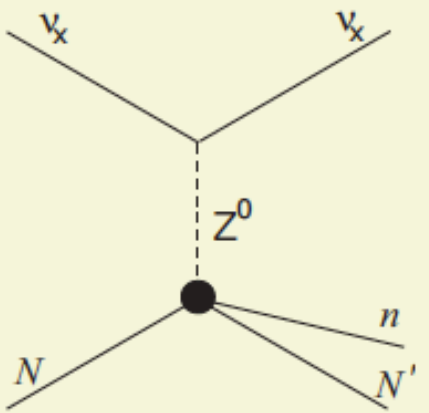


$$\frac{\sigma(\nu_{\mu,\tau})}{\sigma(\nu_e)} \simeq 0.15$$

Charged currents



Neutral currents



sensitive to all flavors

RADIOCHEMICAL DETECTION

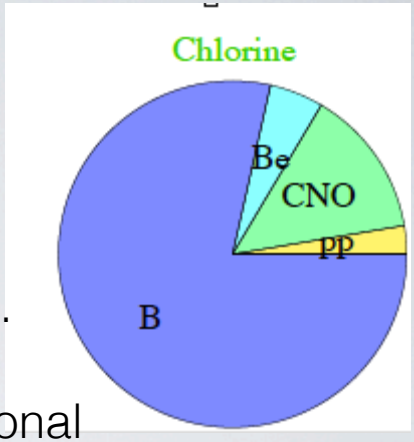
Davis decided in 1951 to follow the idea suggested by Pontecorvo to capture neutrinos through the inverse β reaction:

$$E_{\nu_e} > 0.814\,\mathrm{MeV}$$

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

$$\text{then } e^-_{1s} + {}^{37}\mathrm{Ar} \rightarrow {}^{37}\mathrm{Cl} + \nu_e, \quad \tau_{1/2} \sim 35\ \mathrm{d}$$

electron capture



390 m^3 tank with 0.615 kton of tetrachloroethylene C_2Cl_4 at Homestake Mine.
Main sources of detectable neutrinos are ^{8}B (78%) and ^{7}Be (15%).
1.5/d ^{37}Ar atoms expected and they were extracted flowing He and proportional chambers were filled with the gas to measure the time distribution of Ar decays.
Auger electrons and X-rays are observed in the counter: 81.5% are K orbital electron capture and deposition of 2.82 keV in Auger electrons.

Syst. error 6%: 1.3% extraction eff, 2.8% detection eff, 5% n backgrounds by atm muons

The measured Cl rate by Homestake (1966) was found to be **about 3 times lower** than the predicted value, suggesting an intriguing discrepancy between a pioneering experiment and supposedly accurate enough solar models.

A. Marchionni's lecture

30-year rate: 2.56 ± 0.16 ± 0.16 SNU

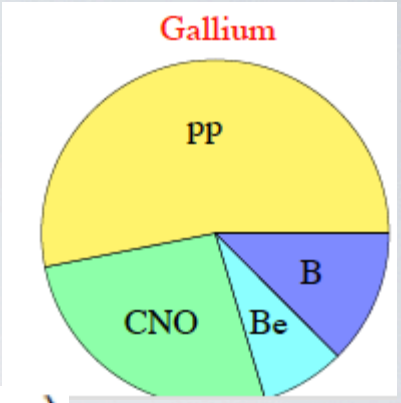
SSM prediction: 8.1 ± 1.3 SNU (SNU = captures/10^{36} atoms/s)

http://iopscience.iop.org/0004-637X/496/1/505/pdf/0004-637X_496_1_505.pdf

THE GALLIUM EXPERIMENTS

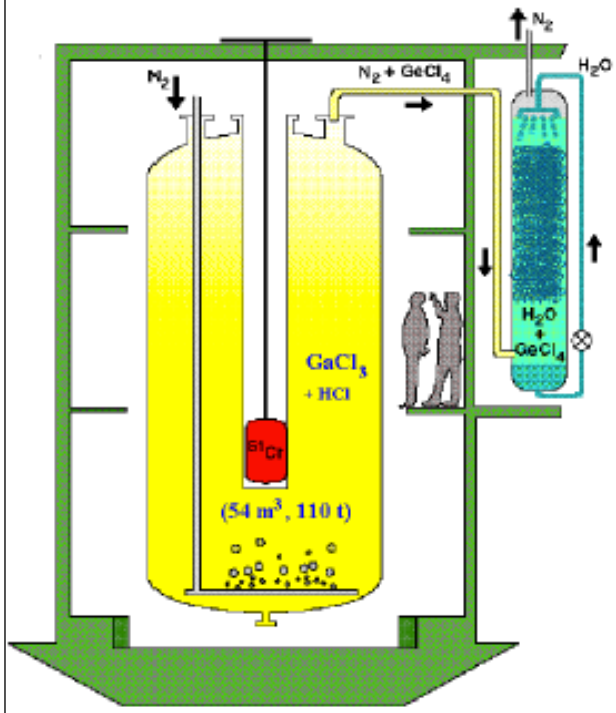
Only technique sensitive to pp

Gallex-GNO Laboratori Nazionali del Gran Sasso (LNGS)
30.3 ton of gallium under in $GaCl_3 - HCl$ solution.
Neutrino reaction: $\nu_e + Ga^{71} \rightarrow Ge^{71} + e^-$ Threshold: $E_\nu = 233\ keV$ sensitive to the pp cycle neutrinos.



- Every 3 weeks ^{71}Ge atoms produced by neutrinos are extracted with N_2
- N_2 is separated and $GeCl_4$ converted in GeH_4 and inserted in proportional counters
- ^{71}Ge detected thanks to X-rays of $e^- + Ge^{71} \rightarrow Ga^{71} + \nu.\ (\tau_{1/2} = 11.43\ \text{days})$
- temporal dr and energy of X-rays are the signature for ^{71}Ge
- detector eff with Cr source 95 ± 8%

Cr^{51} source! $\rightarrow e^- + Cr^{51} \rightarrow \nu_e + V^{51}$



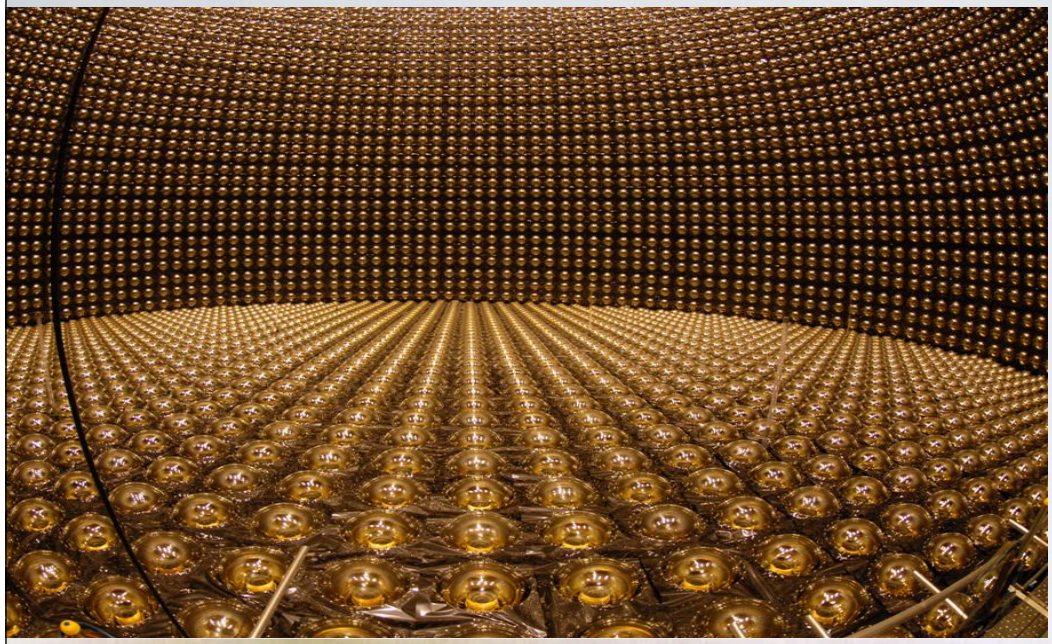
GALLEX	65 Runs	$77.5 \pm 6.2(\text{stat}) \pm 4.5(\text{sys})$ SNU
GNO	58 Runs	$62.9 \pm 5.4(\text{stat}) \pm 2.5(\text{sys})$ SNU
GNO+GALLEX	123 Runs	$69.3 \pm 4.1(\text{stat}) \pm 3.6(\text{sys})$ SNU
SSM		129^{+8}_{-6} SNU

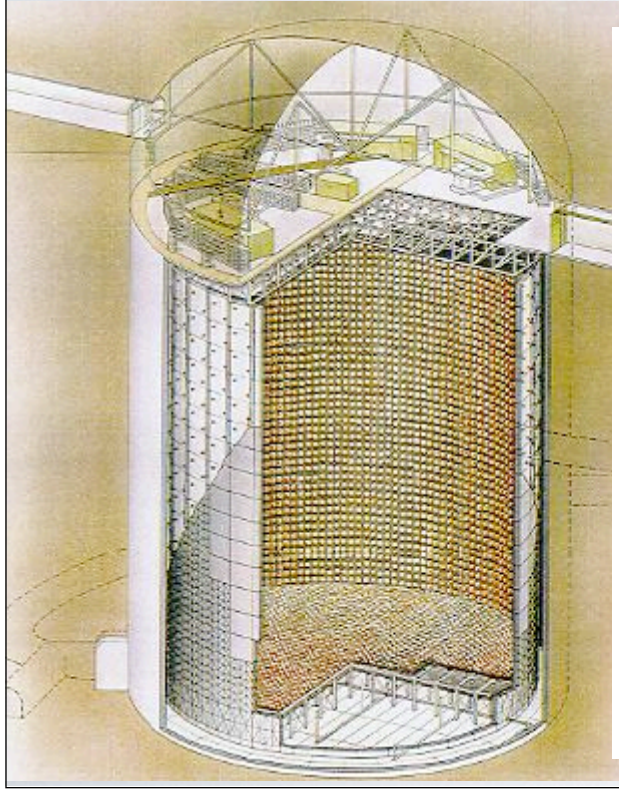
SAGE: 57 ton of metallic Ga at Baksan

Overall: 69.1 +4.3/-4.2 SNU

Observe about 0.5 of standard model .

SUPER-KAMIOKANDE





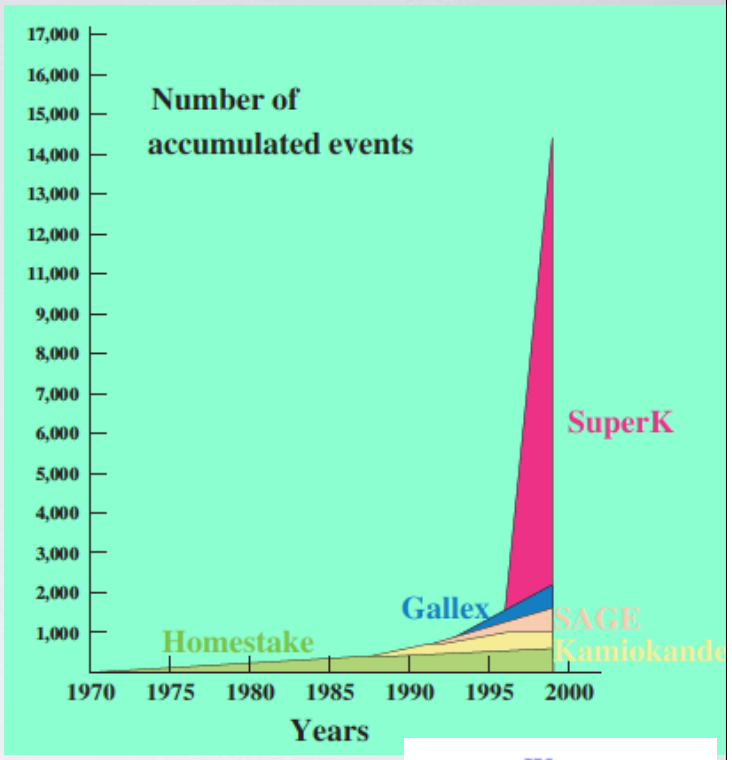
50 kton water Cherenkov
22.5 kton fiducial volume

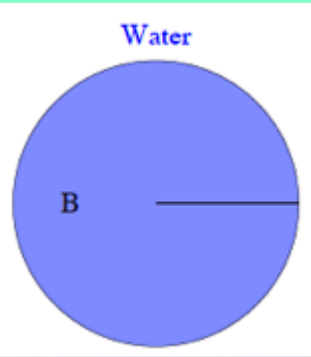
2700 m.w.e overburden
~3 Hz cosmic ray BG
~10 Solar ν /day
~10 Atmospheric ν / day

Inner detector (ID):
~11,100 50 cm PMTs (40% coverage)
~ 2ns timing resolution
~ 4.5MeV threshold

Outer detector (OD):
water layer ~ 2m thick,
1,885 20 cm PMTs

$\nu + e^- \rightarrow \nu + e^-$
some directional sensitivity





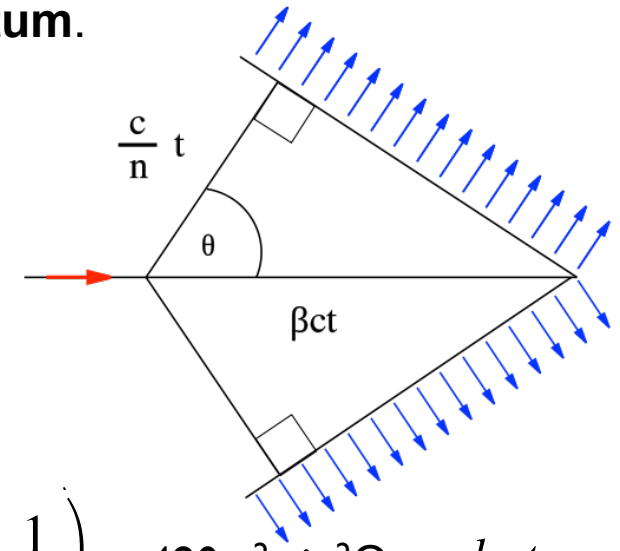
real time detection

The Cherenkov effect

1937 Frank and Tamm: a charged particle traveling in a dielectric medium with n>1 radiates **Cherenkov radiation** if its velocity is larger than the phase velocity of light **v>c/n or** β **> 1/n.** A coherent wave front is generated moving at velocity v at an angle Θc.
The emission is due to an asymmetric polarization of the medium in front and at the rear of the particle, giving rise to a **time-varying electric dipole momentum**.

In water $\Theta_c = 43^\circ$,
in ice 41°

$$\cos\theta_c = \frac{AB}{AC} = \frac{\frac{c}{n}t}{\beta ct} = \frac{1}{\beta n}$$



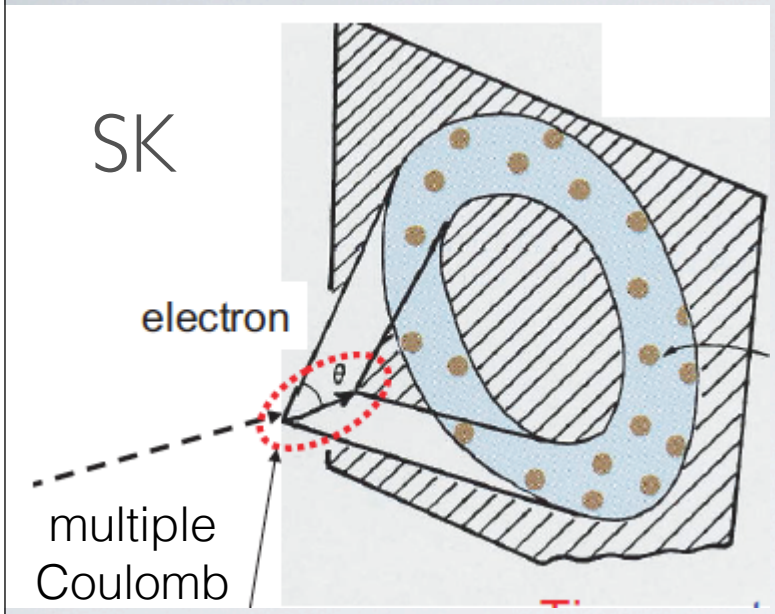
$$\frac{d^2N}{dxd\lambda} = \frac{4\pi^2 z^2 e^2}{hc\lambda^2}\left(1 - \frac{1}{n^2\beta^2}\right) = \frac{2\pi z^2}{\lambda^2}\alpha\sin^2\Theta_C$$

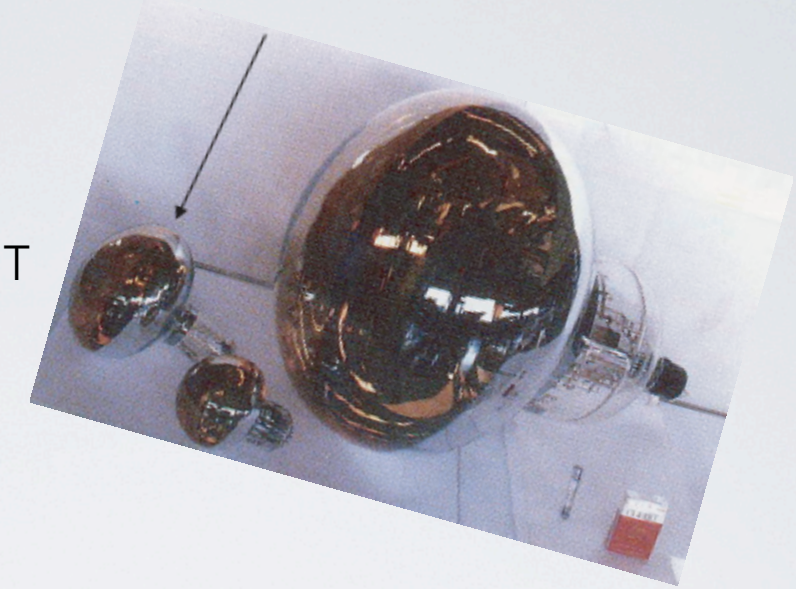
$$\alpha = \frac{2\pi e^2}{}$$

$$\frac{dN_\gamma}{dx} = \int_{\lambda_1}^{\lambda_2} d\lambda \frac{d^2N_\gamma}{dxd\lambda} = 2\pi z^2\alpha\sin^2\Theta_C \int_{\lambda_1}^{\lambda_2}\frac{d\lambda}{\lambda^2} = 2\pi z^2\alpha\sin^2\Theta_C\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) = 490\ z^2\sin^2\Theta_c \quad photons/cm$$

Integrating in the range of sensitivity of photomultipliers (400-700 nm) and for 20% QE: 40 photons/cm in ice

CHERENKOV LIGHT DETECTION

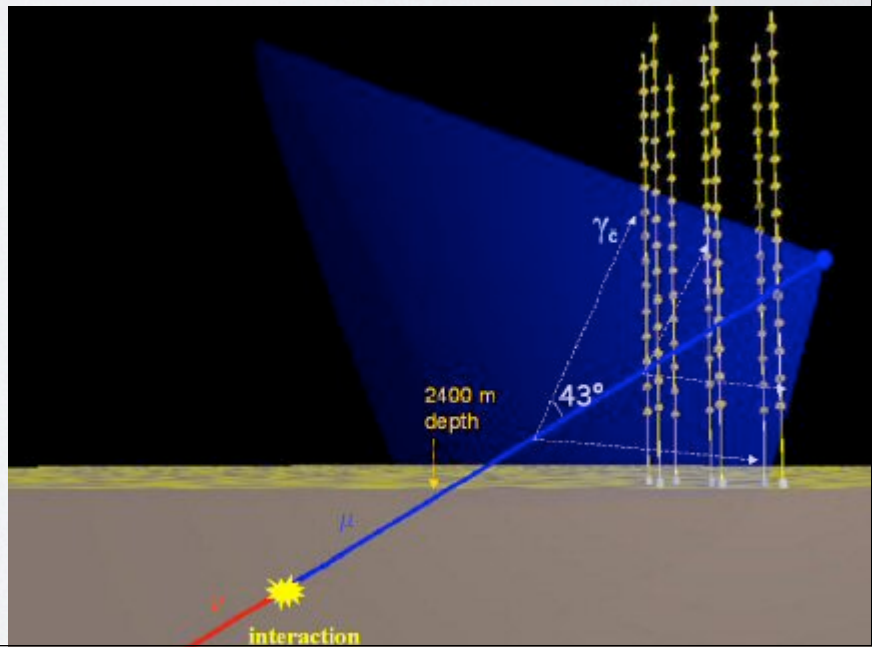




PMT diameter:
SK 50 cm
IceCube 25 cm
SNO 20 cm

Leading edge of PMT pulses: direction
Integrated charge: energy
IceCube: full waveform (time and charge of each PE signal)

Particle	Cerenkov threshold (Energy (MeV))
e	0.768
μ	158.7
π	209.7



THE SOLAR NEUTRINO PROBLEM

Experiment	Reaction	$E_{\rm th}$ (MeV)	ν fluxes	Running time	$R^{\rm exp}$	$R^{\rm BP00}$
Homestake	$\nu_e\,^{37}\mathrm{Cl} \to\, ^{37}\mathrm{Ar}\, e$	0.814	mainly ^{8}B	1970 – 1994	2.56 ± 0.23	7.6 ± 1.3
SAGE	$\nu_e\,^{71}\mathrm{Ga} \to\, ^{71}\mathrm{Ge}\, e$	0.233	all	1990 – 2003	69.1 ± 5.7	128 ± 9
GALLEX				1991 – 1997	77.5 ± 7.7	
GNO				1998 – 2003	62.9 ± 5.9	
Borexino	$\nu e \to \nu e$	0.862	^{7}Be	2007 – 2008	49 ± 5	74 ± 4
		3.0	^{8}B, *hep*	2007 – 2009	2.4 ± 0.4	5.05 ± 0.9
Kamiokande		6.75		1987 – 1995	2.80 ± 0.36	
SK		4.75		1996 – 2001	2.35 ± 0.06	
SNO		5.2		1999 – 2003	2.31 ± 0.21	
	$\nu_e d \to ppe$	6.9			1.67 ± 0.08	
	$\nu d \to pn\nu$	2.2			5.17 ± 0.38	

Table 6.2: *Solar neutrino experiments. Rates measured by radiochemical experiments are expressed in* SNU $\equiv 10^{-36}$ *interactions per target atom and per second, while SK and SNO report neutrino fluxes in* $10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$*, and Borexino gives the* ^{7}Be *rate in interactions per day per 100 ton.*

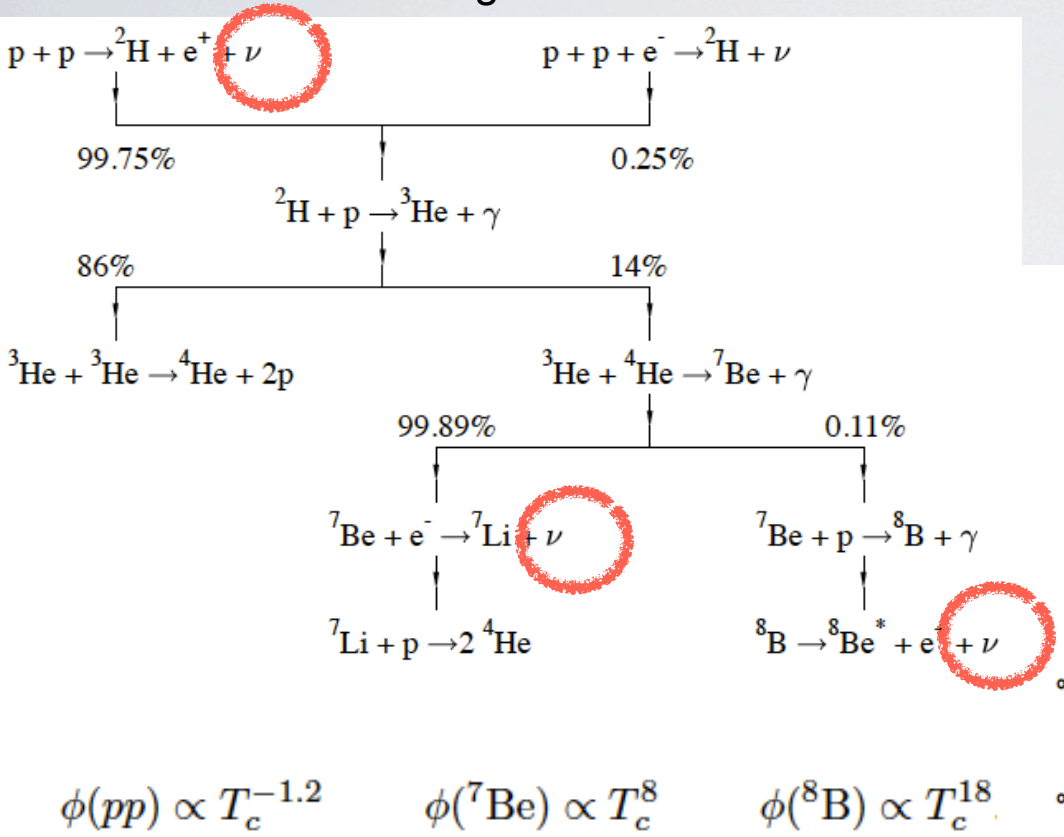
An interpretation to explain observations not invoking oscillation required:

$$\phi(pp) \sim 0.9\,\phi^{\rm SSM}(pp)$$
$$\phi(^7\mathrm{Be}) \sim 0$$
$$\phi(^8\mathrm{B}) \sim 0.43\,\phi^{\rm SSM}(^8\mathrm{B})$$

Before Borexino the only experiment also sensitive to the ^{7}Be flux were Ga experiments (Cl exp. had small sensitivity).
In the SSM a suppression of the ^{8}B flux could be obtained lowering T_c. But then the ^{7}Be/^{8}B would increase. Variations of the SSM parameters could not decrease both.

TEMPERATURE DEPENDENCIES

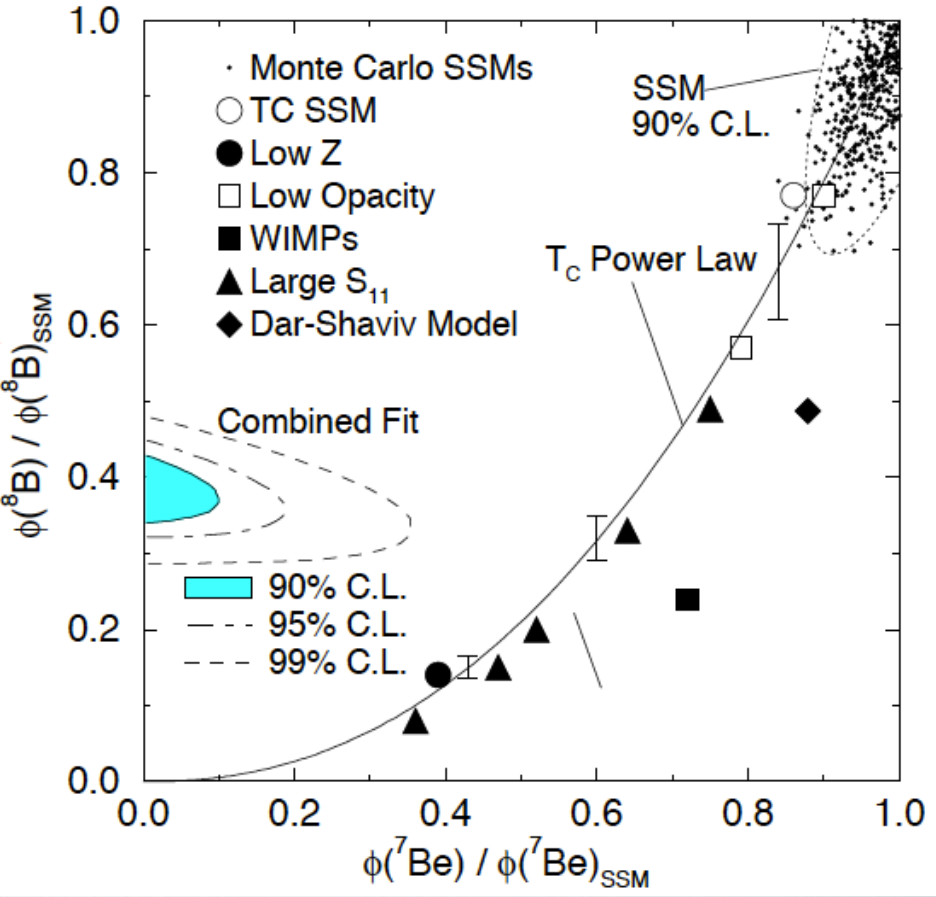
Neutrinos from various cycles are produced in different zones of the Sun and have different dependency on T_{core} because there are different Coulomb barriers to overcome. **^{8}B neutrinos are produced in the Sun core, ^{7}Be neutrinos appear in a wider domain, and the pp neutrinos originate from the whole nuclear region.**



$$\phi(pp) \propto T_c^{-1.2} \qquad \phi(^7\mathrm{Be}) \propto T_c^{8} \qquad \phi(^8\mathrm{B}) \propto T_c^{18}$$

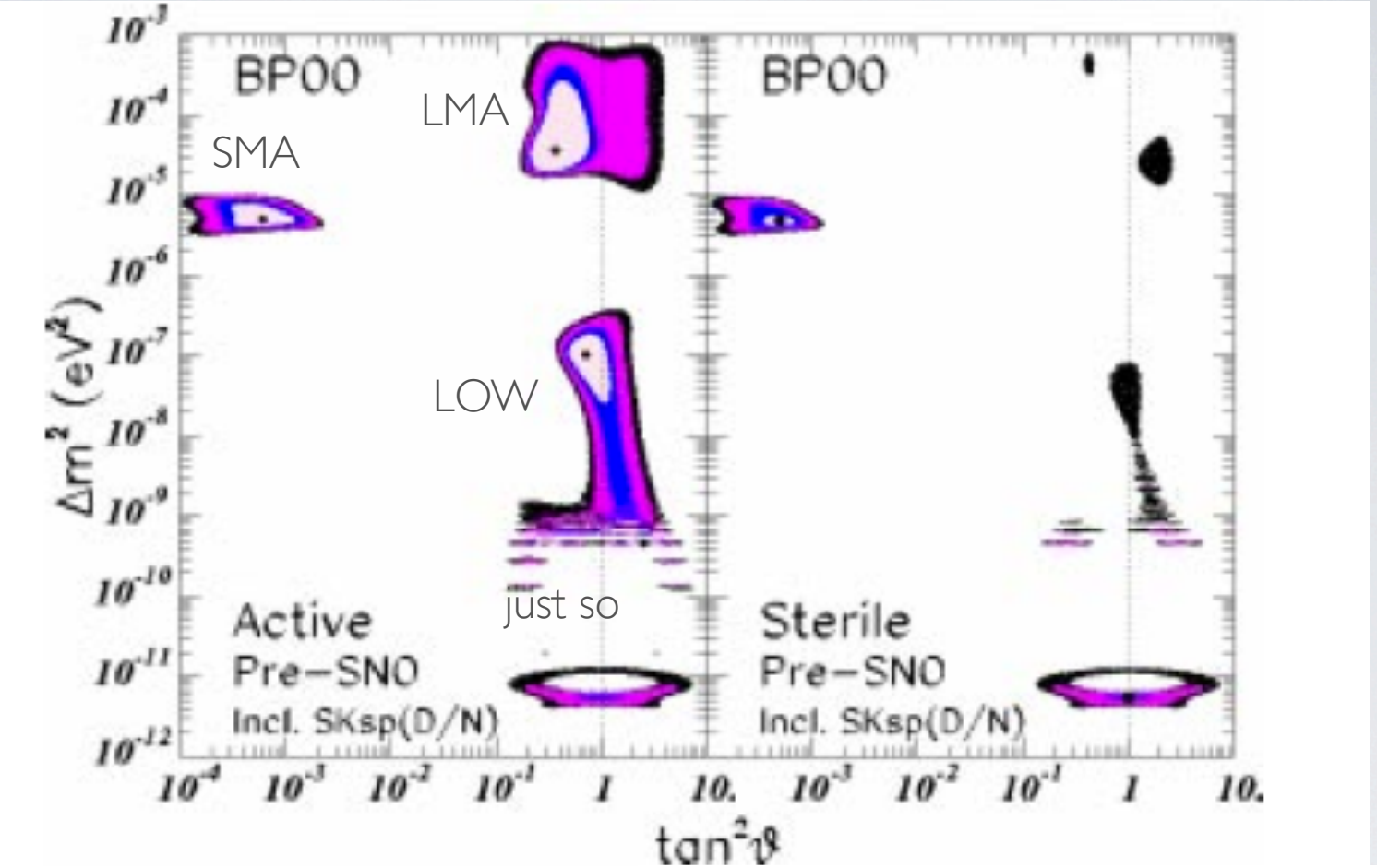
$$\Phi(^8B) \sim T_c^{18}$$

$$\frac{\Phi(^7Be)}{\Phi(^8B)} \sim T_c^{-10}$$



Simulating SSM varying parameters (under the constraint of actual solar luminosity) a strong correlation with the core T is found of the fluxes.

OSCILLATION PLOT AROUND 2001 (PRE-SNO)



Solution	Δm^2	$\tan^2(\theta)$	$\chi^2_{\min}$	g.o.f.
LMA	4.5×10^{-5}	4.1×10^{-1}	35.3	59%
LOW	1.0×10^{-7}	7.1×10^{-1}	38.4	45%
VAC	4.6×10^{-10}	2.4×10^{0}	39.0	42%
SMA	4.7×10^{-6}	3.9×10^{-4}	45.4	19%
Just So^2	5.5×10^{-12}	$0.67(1.5) \times 10^{0}$	45.7	18%
Sterile Just So^2	5.5×10^{-12}	$0.67(1.5) \times 10^{0}$	45.8	18%
Sterile SMA	4.5×10^{-6}	3.1×10^{-4}	46.6	16%
Sterile VAC	4.7×10^{-10}	2.7×10^{-1}	47.2	15%

In vacuum $\sin^2 2\theta$ is a good variable because θ and $\pi/2-\theta$ give same P =>reflection symmetry around $\tan^2\theta = 1$ if plotted in log scale.

Matter effects in the Sun and during night in the Earth distinguish between θ and $\pi/2-\theta$, $\tan^2\theta$ is better since it covers the whole range $[0,\pi/2]$

Bahcall et al., JHEP 08 (2001)

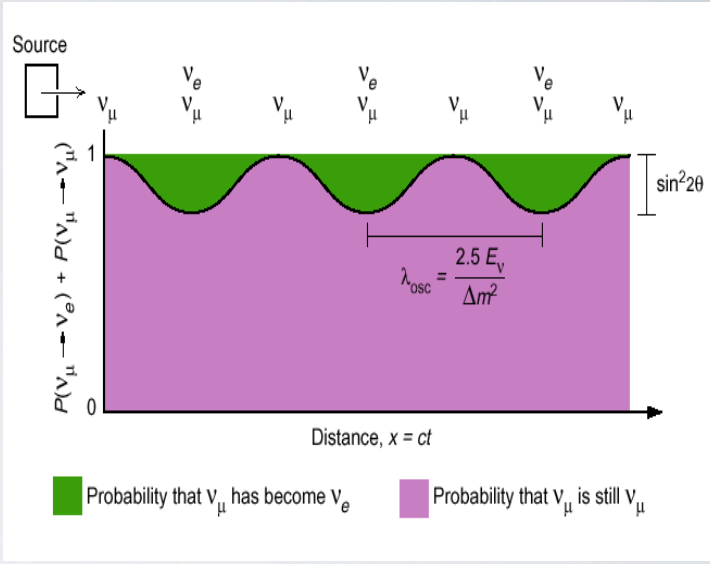
SHORT REMINDER ON OSCILLATIONS

Neutrinos are created and detected in definite flavor states (weak interactions only!) eg. in decays with the corresponding lepton

$$A \rightarrow B + \alpha^+ + \nu_\alpha$$

A state of defined flavor is a linear combination of mass eigenstates (states of definite mass)

$$|\nu_\ell\rangle = \sum_\alpha U_{\ell\alpha} |\nu_\alpha\rangle$$



Since ν_α have different masses their energies are different:

$$E_\alpha = \sqrt{|\mathbf{p}|^2 + m_\alpha^2}$$

Notice that if $p \gg m_\alpha$

$$E_\alpha = \sqrt{|\mathbf{p}|^2 + m_\alpha^2} \approx p\sqrt{1 + \frac{m_\alpha^2}{p^2}} \approx p + \frac{m_\alpha^2}{2p}$$

Let's consider at t = 0 a beam of flavor ℓ and momentum p. After a time t the evolution of the beam is described by:

$$|\nu_l(t)\rangle = \sum_\beta e^{-iE_\beta t} U^*_{l\beta} |\nu_\beta\rangle$$

The probability of finding a ν'_l in a beam originally made of ν_l is

$$P_{\nu_{\ell'};\nu_\ell}(t) = |\langle \nu_{\ell'} | \nu_\ell(t) \rangle|^2 = \sum_{\alpha,\beta} U_{\ell\alpha} U^*_{\ell'\alpha} U_{\ell\beta} U^*_{\ell'\beta} e^{i(E_\alpha - E_\beta)t}$$

where we used the fact that mass eigenstates are orthonormal

$$\langle \nu_\alpha | \nu_\beta \rangle = \delta_{\alpha\beta}$$

SHORT REMINDER

After a distance x t for ultrarelativistic νs

$$P_{\nu_\ell \nu_{\ell'}}(x) = \sum_{\alpha\beta} U_{\ell\alpha} U^*_{\ell'\alpha} U_{\ell\beta} U^*_{\ell'\beta} e^{i\left(\frac{2\pi x}{L_{\alpha\beta}}\right)}$$

oscillation length

$$L_{\alpha\beta} \equiv \frac{4\pi\,|\mathbf{p}|}{\Delta m^2_{\alpha,\beta}} = 2.5\,\frac{p(GeV)}{\Delta m^2_{\alpha,\beta}(eV^2)}(km)$$

2 family and vacuum case: the mixing matrix is

$$\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

θ mixing angle

$$|\nu_\ell\rangle = \sum_\alpha U_{\ell\alpha} |\nu_\alpha\rangle$$

$$\nu_\ell = \nu_1 \cos\theta + \nu_2 \sin\theta$$
$$\nu_{\ell'} = -\nu_1 \sin\theta + \nu_2 \cos\theta$$

$$P_{\nu_\ell;\nu_{\ell'}} = \sin^2 2\theta \sin\left(\frac{\Delta m^2}{4\,|\vec{p}|} x\right) \quad \ell \neq \ell'$$

$$P_{\nu_\ell;\nu_\ell} = 1 - \sin^2 2\theta \sin\left(\frac{\Delta m^2}{4\,|\vec{p}|} x\right) .$$

oscillation prob

survival prob

$$\Delta m^2 = |m_1^2 - m_2^2|$$

if θ =π/4 maximal mixing

$$P_{\nu_\alpha \to \nu_\beta}(L) = \sin^2 2\vartheta \sin^2\left(1.27\,\frac{(\Delta m^2/\mathrm{eV}^2)\,(L/\mathrm{km})}{(E/\mathrm{GeV})}\right)$$

Appearance or disappearance experiments

Flavor transitions are observable when

$$\frac{\Delta m^2 L}{4E} \gtrsim 0.1 - 1$$

EXPERIMENTAL SENSITIVITIES

Hence we can classify based on L/E the range of Δm^2 to which experiments are sensitive:

Short BaseLine experiments $L/E \le 1\ \mathrm{eV}^{-2} \Rightarrow \Delta m^2 \ge 0.1\mathrm{eV}^2$

L <~1km and E >~1 GeV

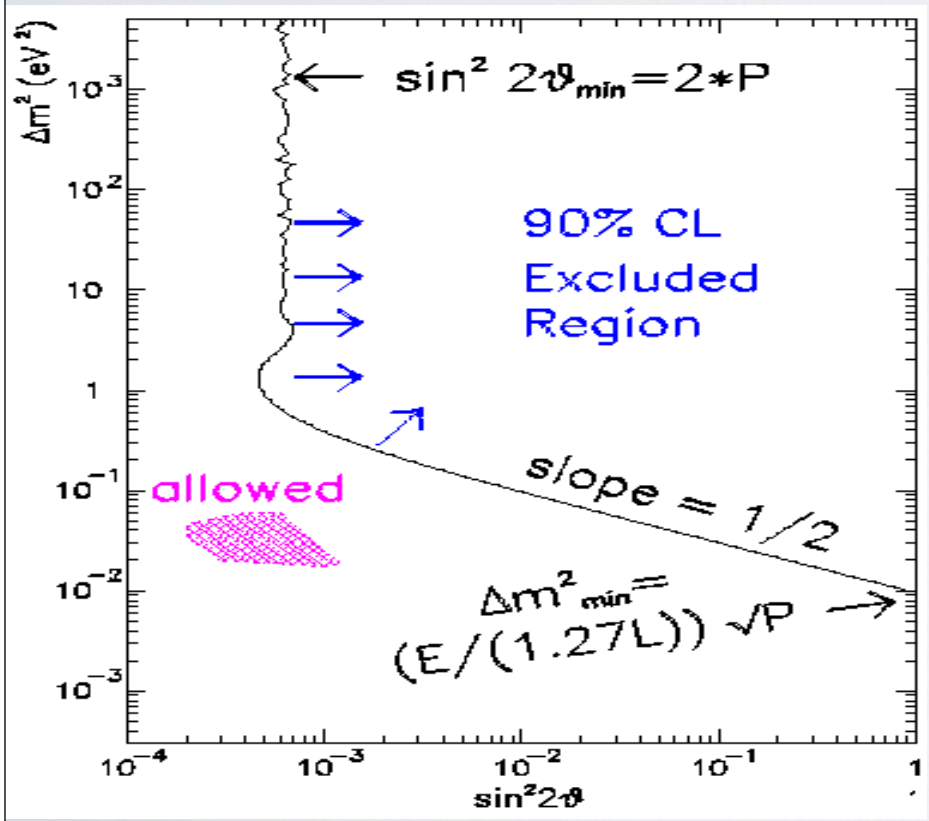
Long BaseLine and atmospheric neutrino experiments: $L/E \le 10^4\ \mathrm{eV}^{-2} \Rightarrow \Delta m^2 \ge 10^{-4}\mathrm{eV}^2$

LBL: L <~1000km and E >~10 GeV

Eg atmospheric neutrinos: L ~20-13000 km and E~300 MeV - 100 GeV

LBL reactor (KAMLAND) and solar ν experiments (vacuum):

L <~100 x 10^6 km and E >~10 MeV $\Delta m^2 \gtrsim L/E \sim 10^{-10} eV^2$



$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \sin^2\left(\frac{1.27(\Delta m^2/eV^2)(L/km)}{E/GeV}\right)$$

- ***large*** Δm^2 $Posc = \dfrac{\sin^2(2\theta)}{2}$
- ***small*** Δm^2 $Posc = \sin^2(2\theta)\left(1.27\Delta m^2 \dfrac{L}{E}\right)^2$

The minimum value of $\sin^2 2\theta$ observable depends on the observable statistics of events:

$$N_{\nu_\ell} \propto (1 - P_{\nu_\ell \nu'_\ell}) \propto (1 - \frac{1}{2}\sin^2 2\theta)$$

$$N_{\nu_{\ell'}} \propto P_{\nu_\ell \nu_{\ell'}} \propto \frac{1}{2}\sin^2 2\theta$$

$\sin^2\theta \ll 1$

$$\frac{1}{2}\sin^2 2\theta = K\frac{N_{\nu_{\ell'}}}{N_{\nu_\ell}}$$

NEUTRINO OSCILLATION REMINDER

Conversion probability (3 neutrino flavors and in vacuum):

Kayser's lectures

$$P(\nu_\alpha \to \nu_\beta; L) = \delta_{\alpha\beta} - \sum_{j \neq k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \left(1 - e^{-i\Delta E_{jk} L}\right)$$

Where the MSP mixing matrix is:

B. Pontecorvo, Sov. Phys. JETP 7, 172 (1958) [Zh. Eksp. Teor. Fiz. **34**, 247 (1957)].
Z. Maki, M. Nakagawa and S. Sakata, Prog. Theor. Phys. **28** 870 (1962)

solar U_{e1}, $U_{e2} \leftrightarrow \theta_{12}$ CHOOZ $U_{e3} \leftrightarrow \theta_{13}$

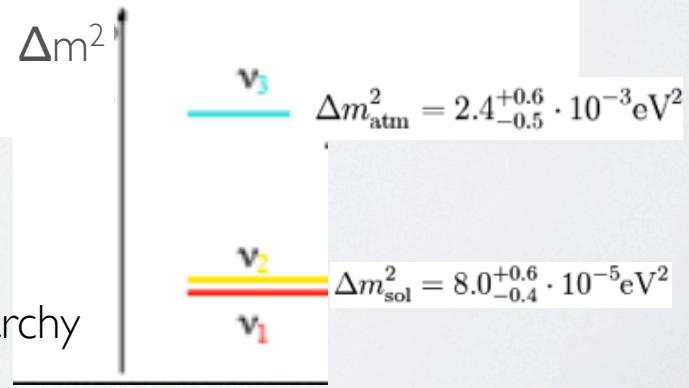
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

atmospheric $U_{e3} \leftrightarrow \theta_{13}$ $U_{\mu 3}, U_{\tau 3} \leftrightarrow \theta_{23}$

$$s_{ij} \equiv \sin\theta_{ij},\ c_{ij} \equiv \cos\theta_{ij}.$$

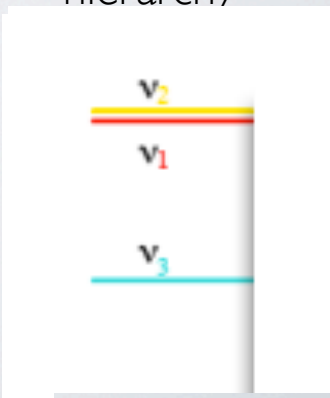
Observed values of oscillation parameters

- $\sin^2(\theta_{13}) < 0.032$ at 95% confidence level ($\theta_{13} < 10.3°$) [4] CHOOZ
- $\tan^2(\theta_{12}) = 0.45^{+0.09}_{-0.07}$. This corresponds to $\theta_{12} \equiv \theta_{\text{sol}} = 33.9°^{+2.4°}_{-2.2°}$ ("sol" stands for solar) [6]
- $\sin^2(2\theta_{23}) = 1^{+0}_{-0.1}$, corresponding to $\theta_{23} \equiv \theta_{\text{atm}} = 45 \pm 7°$ ("atm" for atmospheric)[7]
- $\Delta m^2_{21} \equiv \Delta m^2_{\text{sol}} = 8.0^{+0.6}_{-0.4} \cdot 10^{-5}\text{eV}^2$ [6]
- $|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \equiv \Delta m^2_{\text{atm}} = 2.4^{+0.6}_{-0.5} \cdot 10^{-3}\text{eV}^2$[7]



direct hierarchy

inverted hierarchy



MATTER EFFECTS

While ν_e has NC and CC interactions with the electrons in the medium, ν_μ and ν_τ have only CC int. The effect can be described by a potential in which ν propagate

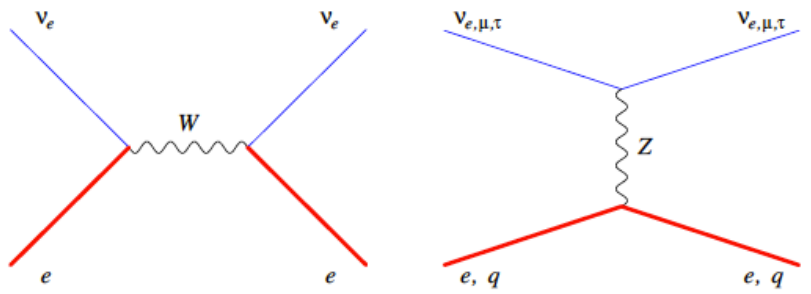
L. Wolfenstein, Phys. Rev. **D17** (1978) 2369-2374.

$$V_e = \frac{G_F}{\sqrt{2}}[(1+4\sin^2\theta_W)N_e + (1-4\sin^2\theta_W)N_p - N_n] =$$

$$\frac{G_F}{\sqrt{2}}[2N_e - N_n]$$

$$V_\mu = V_\tau = \frac{G_F}{\sqrt{2}}[(-1+4\sin^2\theta_W)N_e + (1-4\sin^2\theta_W)N_p - N_n]$$

$$= \frac{G_F}{\sqrt{2}}[-N_n]\,,$$



$N_e = N_p$ matter is neutral

For anti-neutrinos $V_\alpha = -V_\alpha,\ \alpha = e,\ \mu,\ \tau$

The same formalism than in vacuum is obtained using

$$v_{\alpha,\beta} = V_{\alpha,\beta}(2E/\Delta m^2)$$

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{[(v_\alpha - v_\beta) - \cos 2\theta]^2 + \sin^2 2\theta}$$

$$\ell_m = \frac{\ell}{\{[(v_\alpha - v_\beta) - \cos 2\theta]^2 + \sin^2 2\theta\}^{\frac{1}{2}}}$$

$$v_\alpha - v_\beta = \cos 2\theta \quad \Rightarrow \sin^2 2\theta_m = 1$$

$$\Delta m^2 \cos 2\theta = 2\sqrt{2} G_F E N_e \quad \text{critical density}$$

Mikheyev Smirnov Wolfenstein resonance condition: matter can lead to a strong enhancement of the osc. prob. even if the vacuum mixing angle is small. No matter effect for $\nu_\mu \leftrightarrow \nu_\tau$

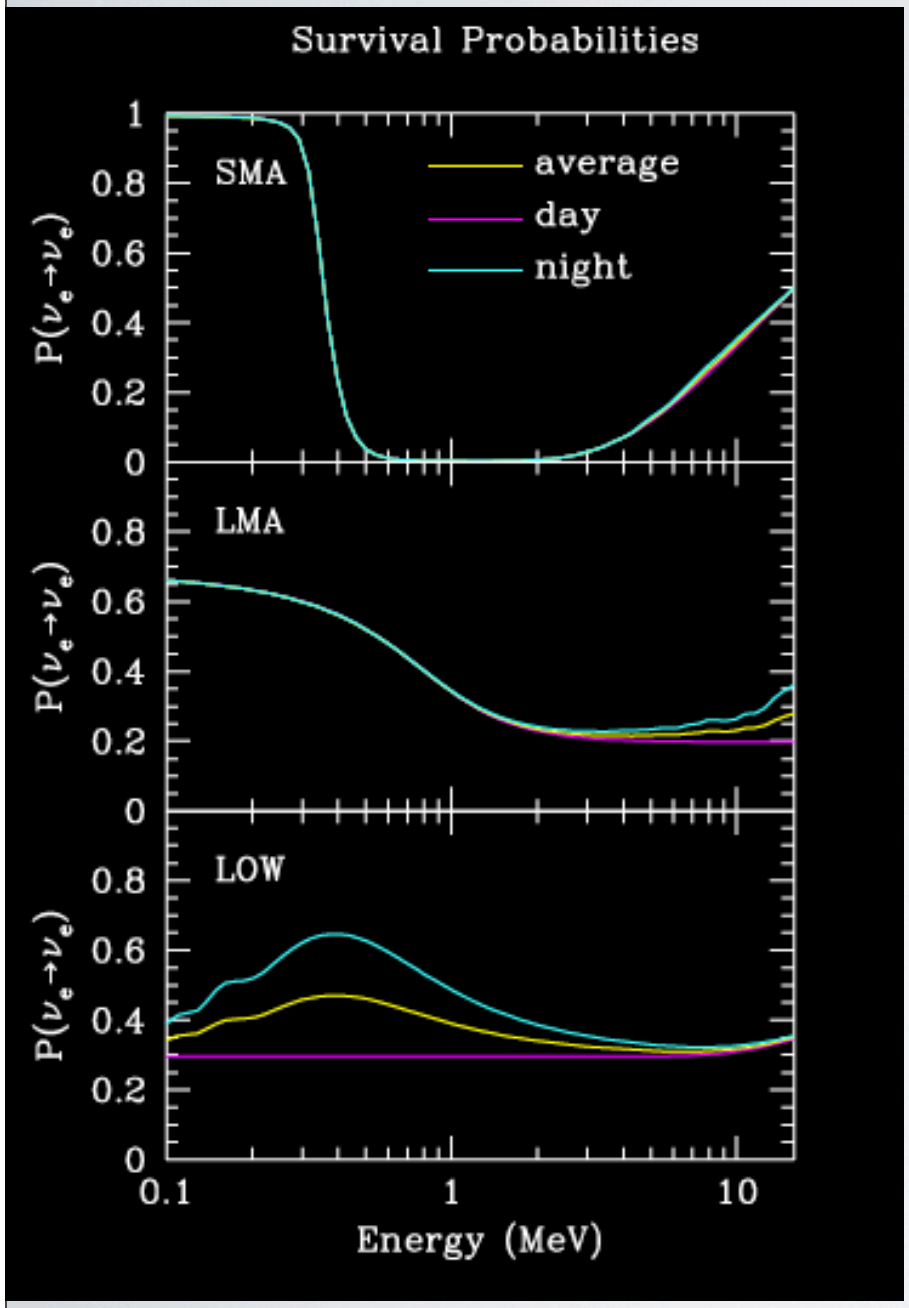
matter oscillations introduce a dependency of the electron neutrino mass on the solar density.

changes sign for anti-neutrinos

Electrons neutrinos from the Sun and we see LMA => $\Delta m^2 > 0$ (normally taken as Δm^2_{12})

SOLAR NEUTRINO OSCILLATIONS

Observables



1) **Spectral modulation:** The electron energy spectrum is consistent **with an energy-independent reduction in the flux of B neutrinos.** Excludes SMA and part of Just so (VAC).

2) VAC oscillations $\Delta m^2 \sim 10^{-10}\,\mathrm{eV}^2$ have baseline $\approx d_{\text{Sun-Earth}}$ and predict larger **seasonal variation** than $1/d^2$ geometrical factor (not seen by SK) => excluded;

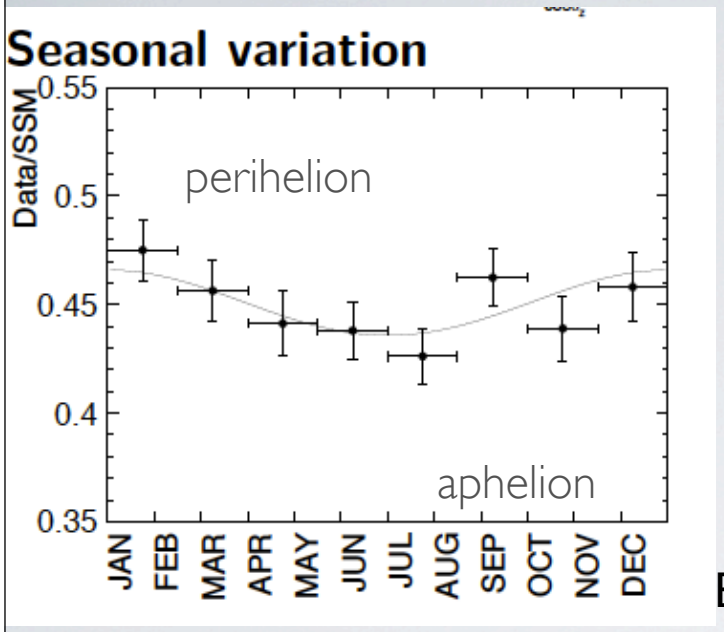
3)During the night neutrinos cross the Earth before reaching the detector ⇒resonance energy for matter oscillations:

$$E_\nu^{\mathrm{res}} = \frac{\Delta m^2}{2\sqrt{2} G_{\mathrm{F}} N_e^{\oplus}} \approx 200\,\mathrm{MeV}\,\frac{\Delta m^2}{10^{-4}\,\mathrm{eV}^2}$$

The absence of a strong **asymmetry day/night** excluded LOW (about 20%) and favor LMA (0-2%);

SK RESULTS

A. Marchionni's lecture

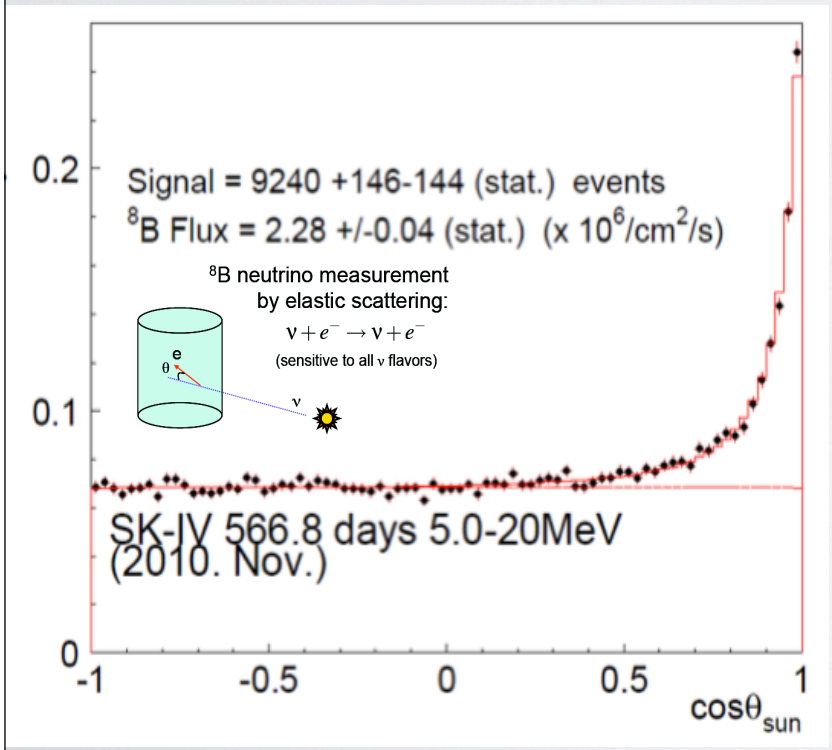


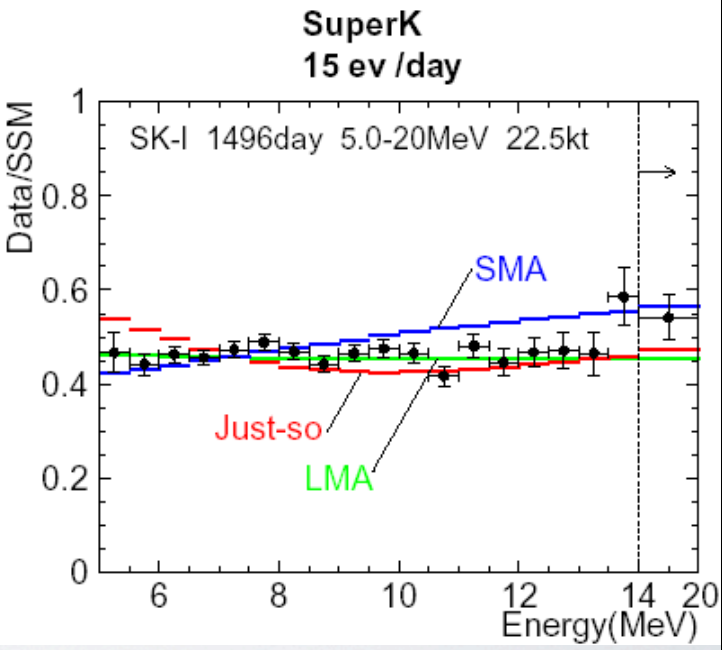
SKI (1996 →), SKII (2002 →), SKIII (2006 →), SKIV (2008 →)

	11146 ID PMTs (40% coverage)	5182 ID PMTs (19% coverage)	11129 ID PMTs (40% coverage)	Electronics Upgrade
Threshold:		7.0 MeV	5.0 MeV	~4.5 MeV
(Total energy)		~6.5 MeV	~4.5 MeV	~4.0 MeV
(Kinetic energy)				

B Flux:

- SK-I: 2.38+/-0.02(stat.)+/-0.08(syst.)
- SK-II: 2.41+/-0.05(stat.)+0.16/-0.15(syst.)
- SK-III: 2.32 ± 0.04(stat.) ± 0.05(syst.)
- SK-IV: 2.28 ± 0.04



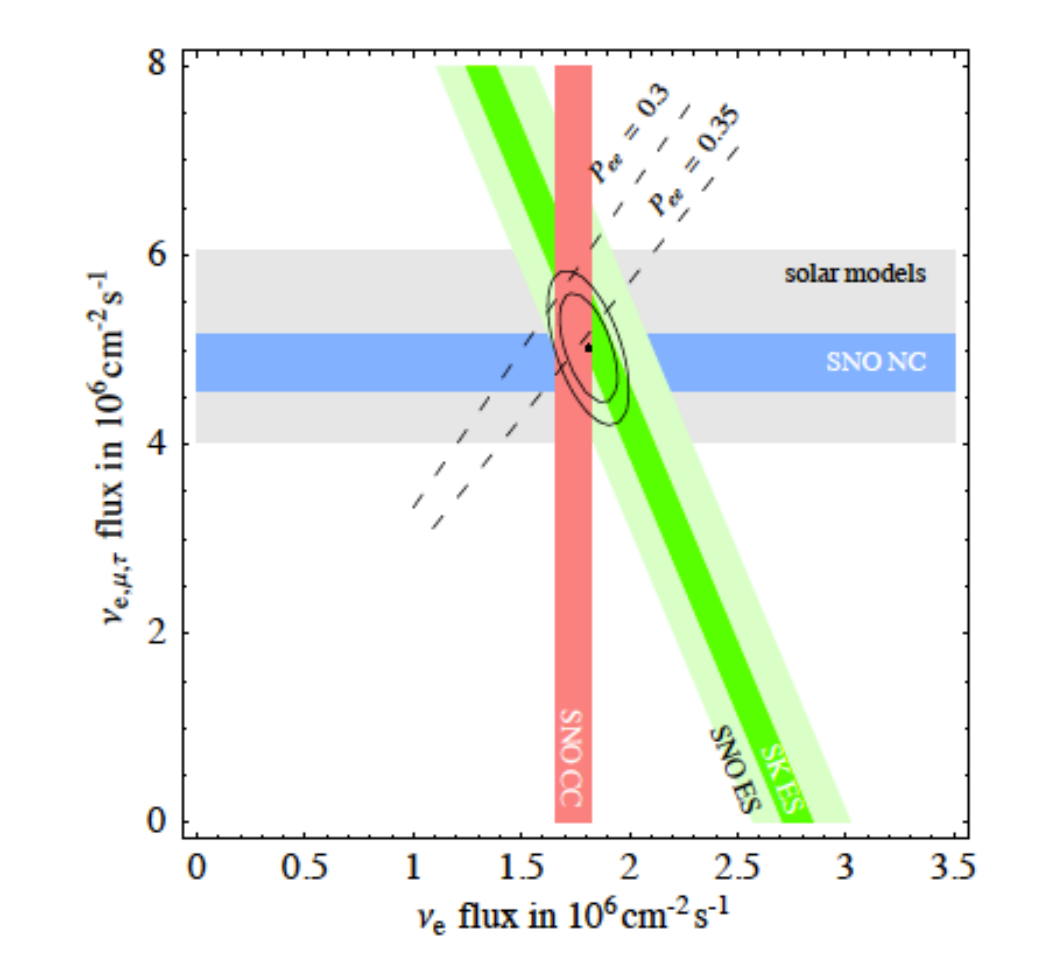


$$A_{DN} = \frac{(\Phi_{Day} - \Phi_{Night})}{(\Phi_{Day} + \Phi_{Night})/2} = -0.056 \pm 0.031(\text{stat.}) \pm 0.013(\text{syst.})$$

http://arxiv.org/pdf/1010.0118

SNO: Direct evidence of oscillations

NC/CC or ES/CC ratio: ν_e transform into ν_μ and ν_τ or sterile neutrinos. NC rate must remain constant except for sterile neutrino oscillations. A detector sensitive to NC can normalize the overall neutrino flux while the CC flux gives the ν_e flux. A difference of these 2 fluxes is the oscillation signature ⇒ SNO



Original result in Phys. Rev. Lett. 89, 011301 (2002)

SNO (unlike SK sensitice only to ES) measured for the 1st time all the neutrino species which corresponds to the number of electron neutrinos really emitted by the Sun

ν Reactions in SNO

CC $\nu_e + d \Rightarrow p + p + e^-$

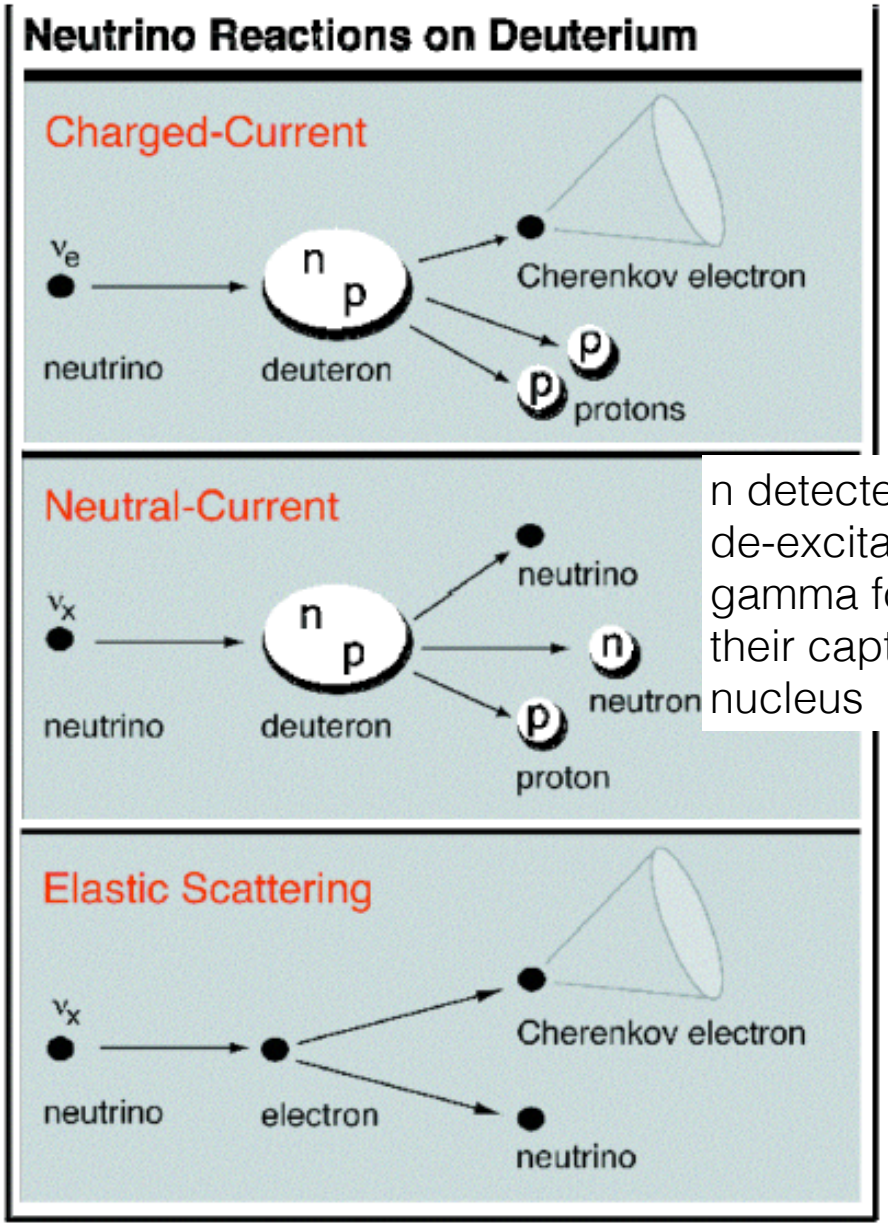
-Gives ν_e energy spectrum well
-Weak direction sensitivity $\propto$ 1-1/3cos(θ)
- ν_e only.

NC $\nu_x + d \Rightarrow p + n + \nu_x$

-Measure total ^{8}B ν flux from the sun.
- Equal cross section for all ν types

ES $\nu_x + e^- \Rightarrow \nu_x + e^-$

-Low Statistics
-Mainly sensitive to ν_e, some
-sensitivity to ν_μ and ν_τ
-Strong direction sensitivity



n detected thru de-excitation gamma following their capture in a nucleus

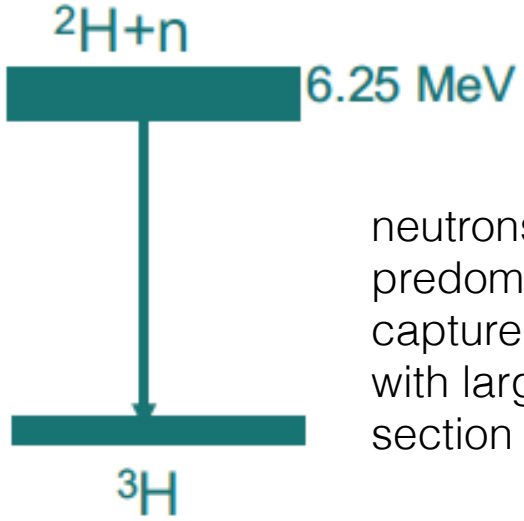
SNO PHASES

Phase I (D_2O)

Nov. 99 - May 01

n captures on
$^2H(n, \gamma)^3H$
$\sigma = 0.0005$ b
Observe 6.25 MeV γ
PMT array readout

neutrons predominantly captured on d

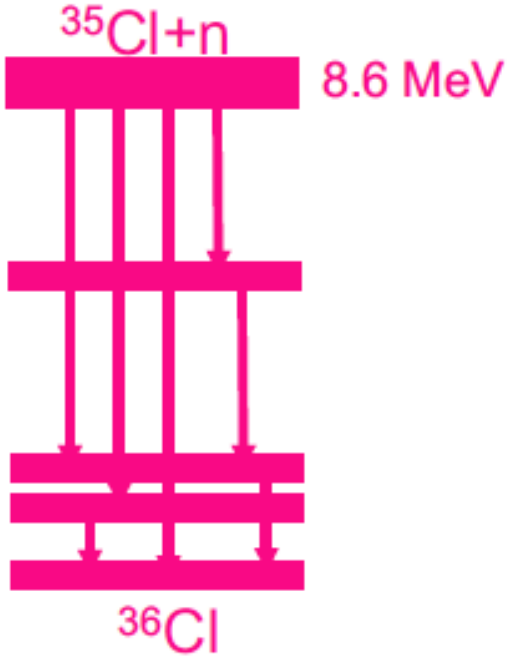


Phase II (salt)

July 01 - Sep. 03

2 t NaCl. n captures on
$^{35}Cl(n, \gamma)^{36}Cl$
σ= 44 b
Observe multiple γ
PMT array readout
Enhanced NC

neutrons predominantly captured on ^{35}Cl with larger x-section than d

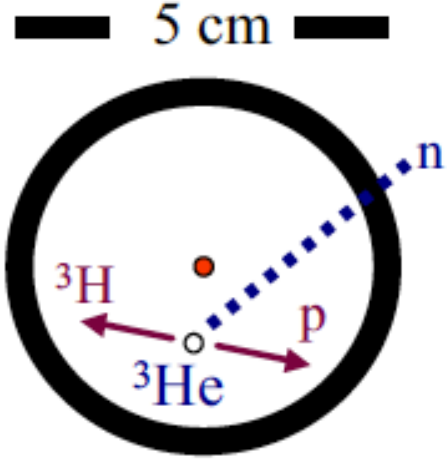


Phase III (^3He)

Summer 04 - Dec. 06

40 proportional counters
$^3He(n, p)^3H$
$\sigma = 5330$ b
Observe p and ^3H
PC independent readout
Event by Event Det.

NC detected by ^3He proportional counters



$n + {}^3He \rightarrow p + {}^3H$

MAXIMUM LH SELECTION

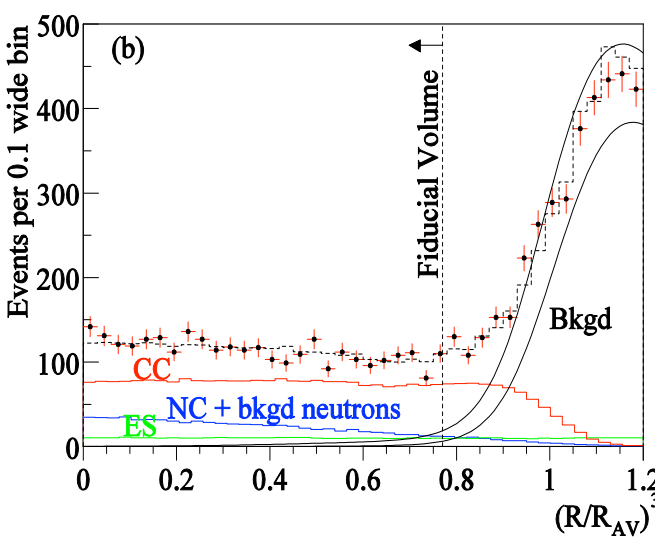
Major challenge: reduce radioactive backgrounds to $<10^{-14}$ g/g of U and Th in the heavy water; the high energy rays from the U and Th chains can photodissociate the deuterium, emitting a neutron which can simulate a Z exchange process.

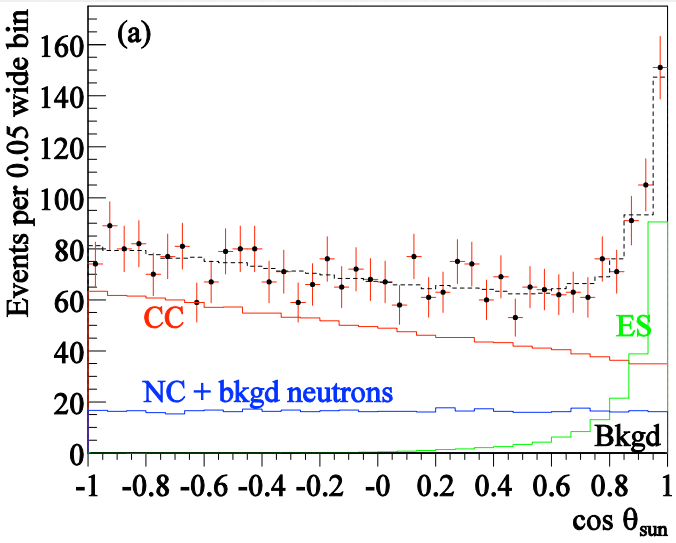
In Phase I and II neutrinos cannot be separated on an event-by-event basis from each other or from backgrounds arising from radioactivity in the detector materials. Signals and backgrounds are statistically extracted using the observables:

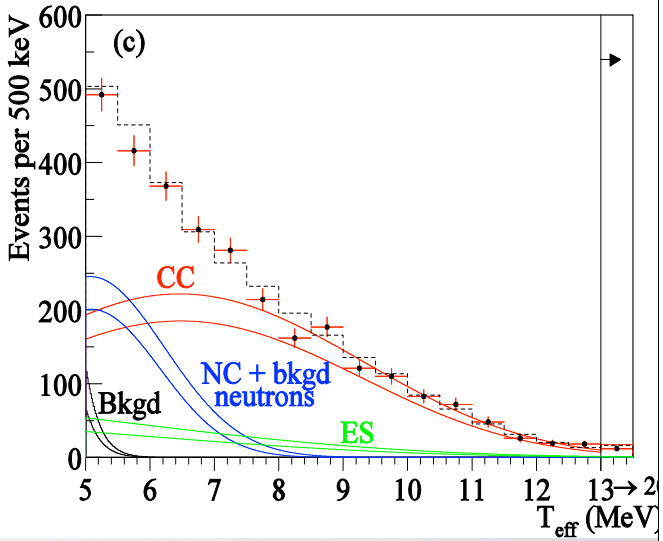
reconstructed radial position of the event

reconstructed direction of the event relative to the direction of a neutrino arriving from the Sun

estimated energy assuming the event consisted of a single electron







RESULTS

$$\Phi_{^8\mathrm{B}} = 5.046\,^{+0.159}_{-0.152}(\mathrm{stat})\,^{+0.107}_{-0.123}(\mathrm{syst}) \times 10^6\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

no spectral distortion

BS05(OP) SSM of $5.69\times10^6\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

16% error on prediction

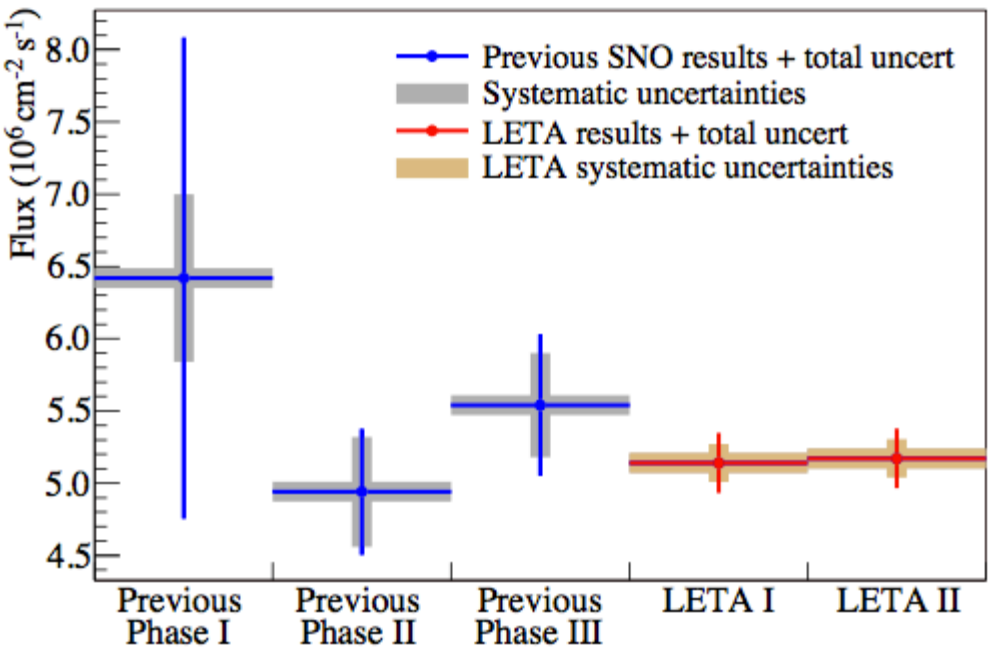
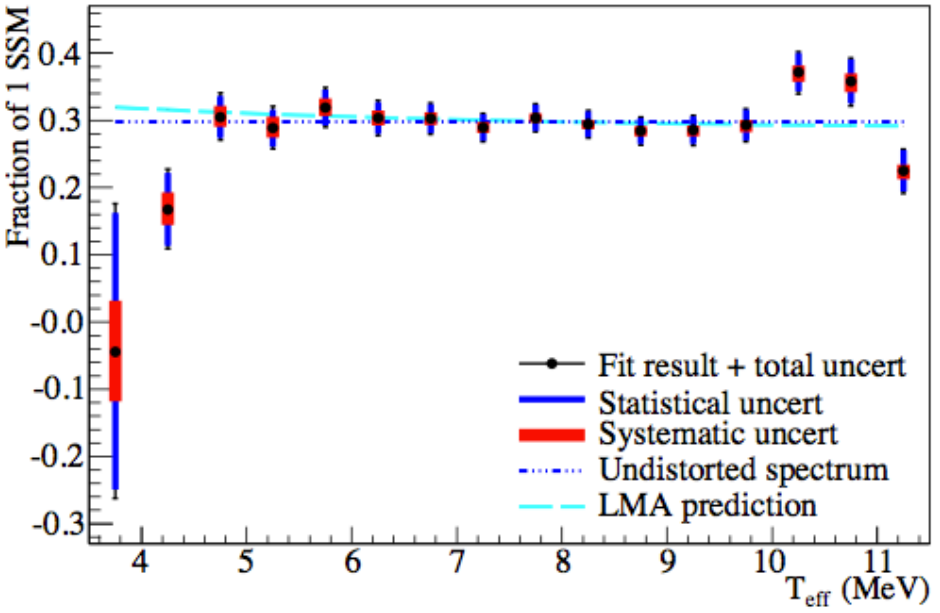
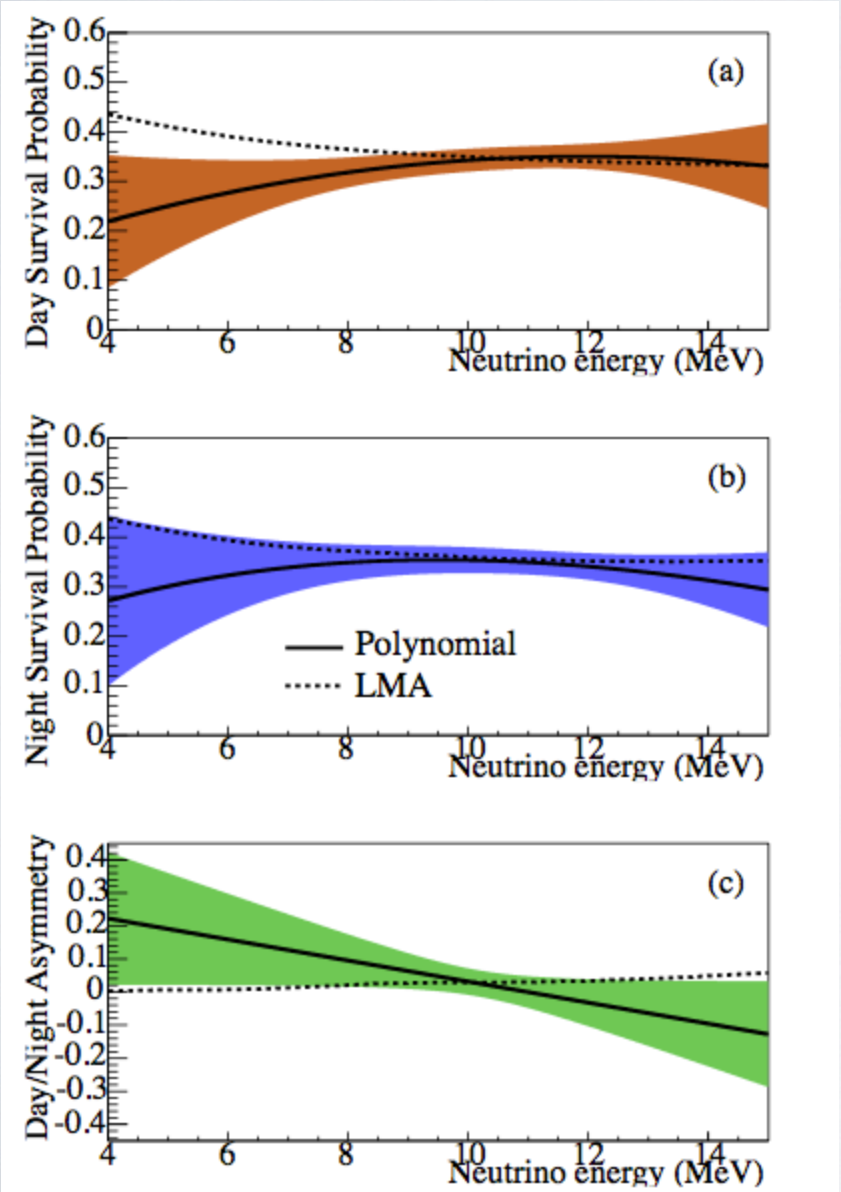


FIG. 27: (Color online) Total ^{8}B neutrino flux results using the NC reaction from both unconstrained signal extraction fits in comparison to unconstrained fit results from previous SNO analyses. 'LETA I' refers to the binned-histogram method and 'LETA II' to the kernel estimation method.



ASYMMETRY

The survival probability was parametrized as a second order polynomial, allowing for a linear energy-dependent asymmetry between day and night spectra. The polynomial with best fit parameters is compared to the previous LMA best fit



LOW preferred by SNO alone compatible with LMA at 68.3% c.l.

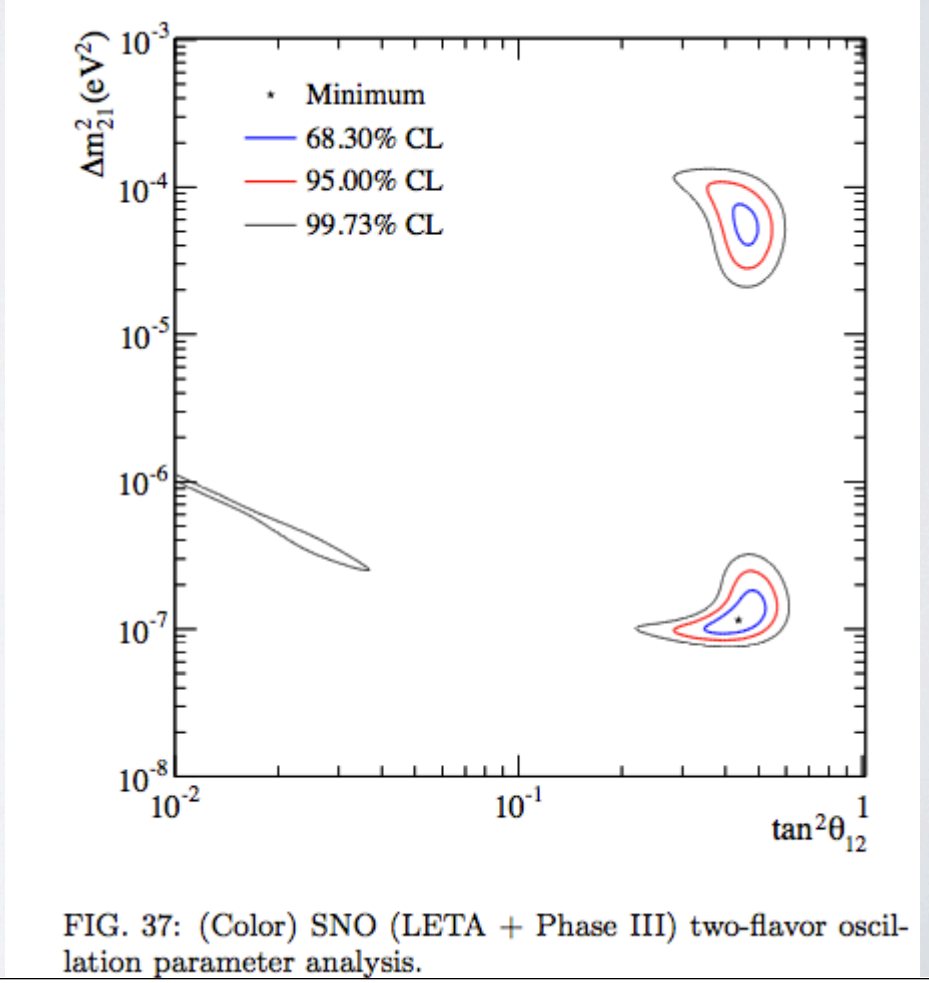
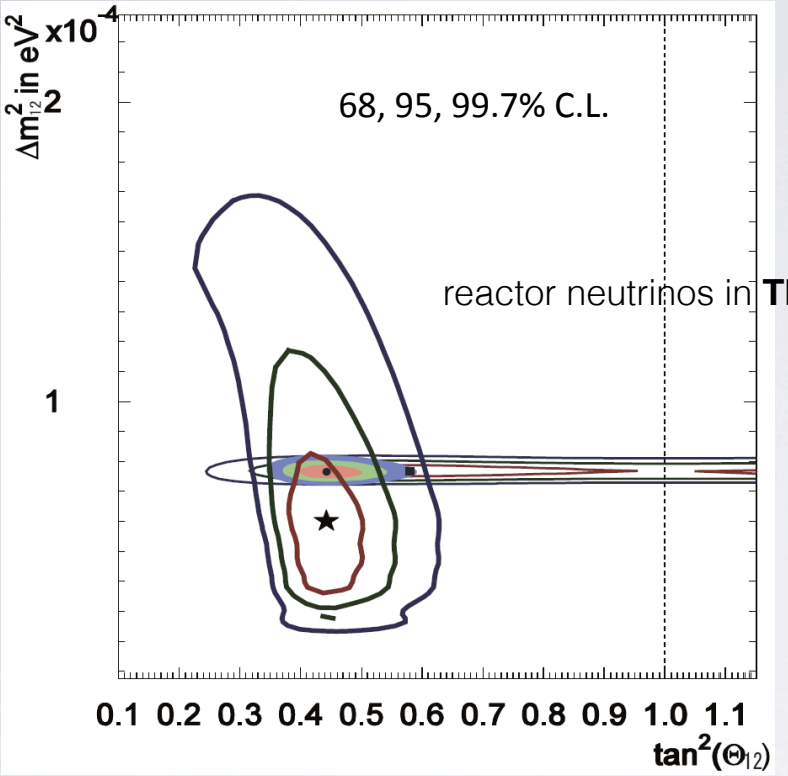
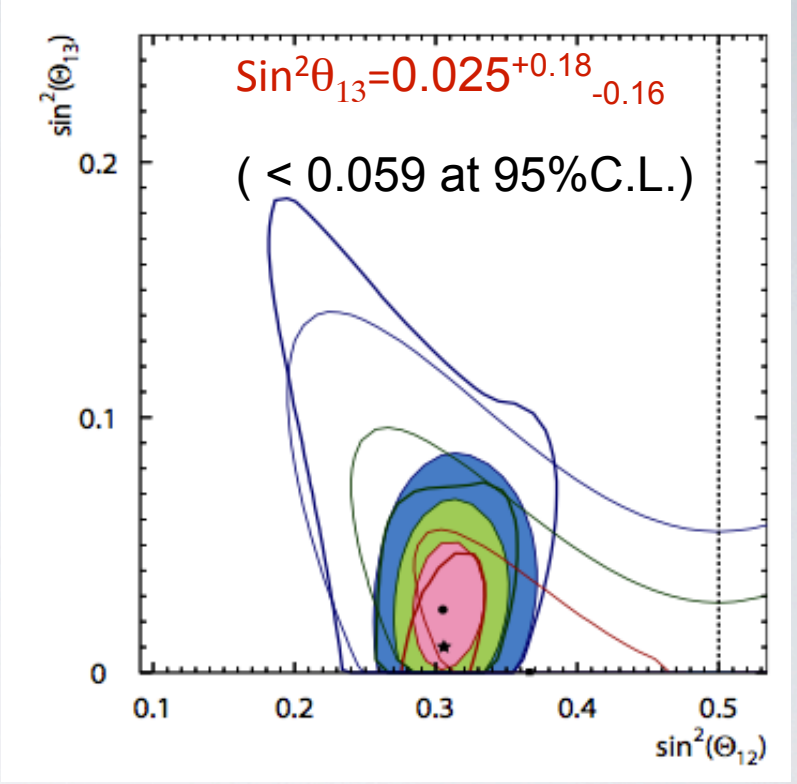


FIG. 37: (Color) SNO (LETA + Phase III) two-flavor oscillation parameter analysis.

OSCILLATIONS: SOLAR AND REACTORS

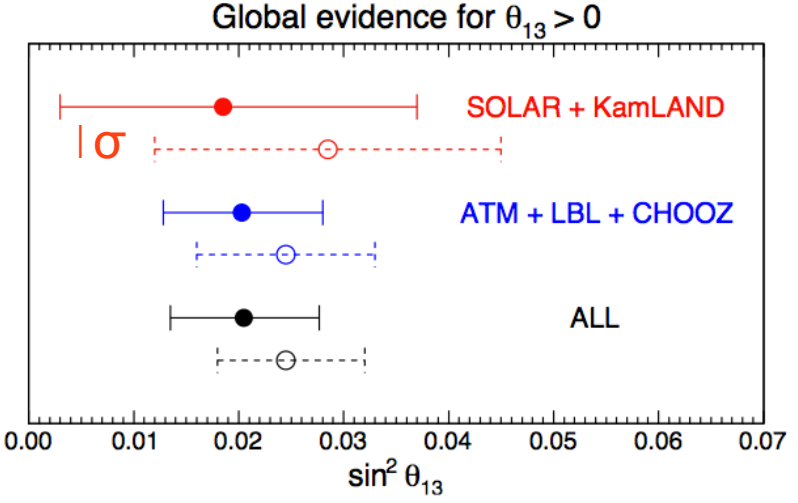




Fogli et al, http://arXiv.org/pdf/1106.6028

Large Mixing Angle solution favored

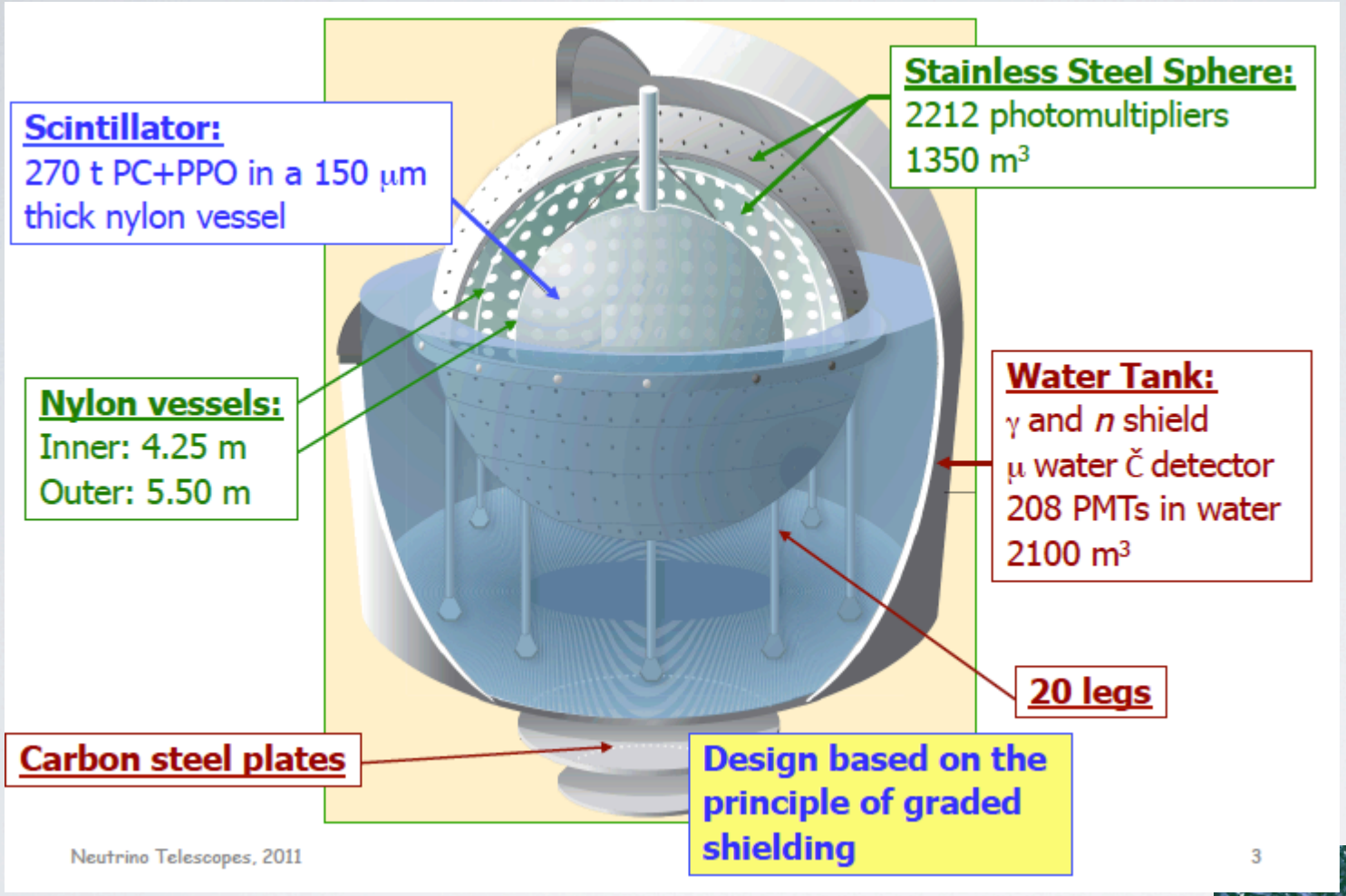
Global solar+KamLAND:
$\Delta m_{21}^2 = 7.6 \pm 0.2 \times 10^{-5}$ eV^2
$\tan^2\theta_{12} = 0.44 \pm 0.03$ (34°)
$\Phi_{B8} = 0.89 \times \Phi_{B8,SSM}$



T2K recent result:

0.03(0.04)< sin^2 2θ$_{13}$ < 0.28(0.34) for δCP = 0 and normal (inverted) hierarchy => preferred sin^2 2θ$_{13}$ = 0.028

BOREXINO @ GRAN SASSO



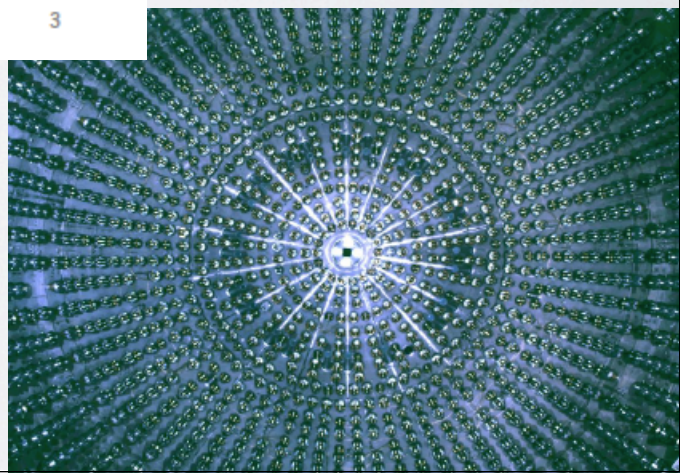
Triggers at 250 KeV

Good energy resolution (5% @ 1 MeV, uncertainty in energy scale in 0-2 MeV = 1.3%), position resolution (10 cm at 1 MeV) => sys error on fiducial volume 1.3%

Main target: detection of **0.862 MeV ^{7}Be neutrinos through ES** in a volume of highly purified scintillator.

Drawbacks: neutrinos cannot be distinguished from β-decay due to natural radioactivity (< 10^{-17} g/g achieved for ^{238}U, ^{232}Th) and long-lived activities induced by CR muons

Aims at precise measurement of P_{ee} and confirmation of MSW-LMA scenario



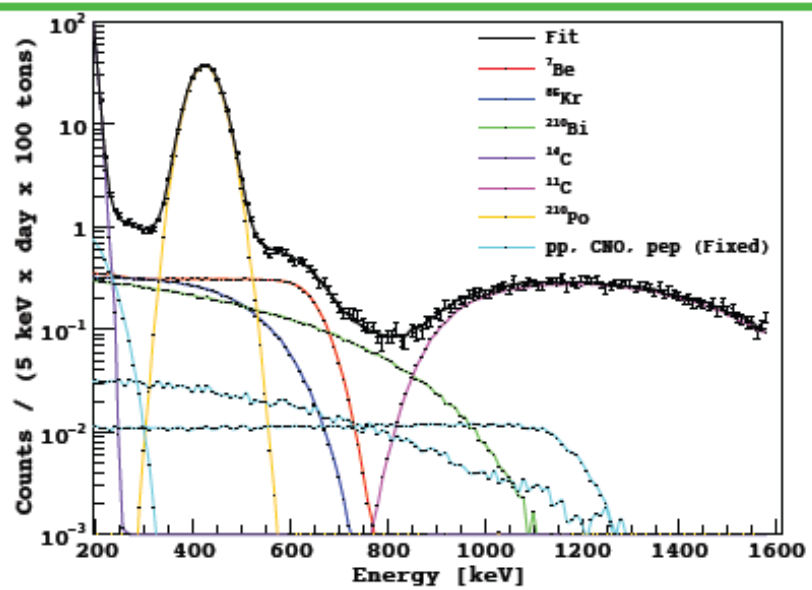
RESULTS

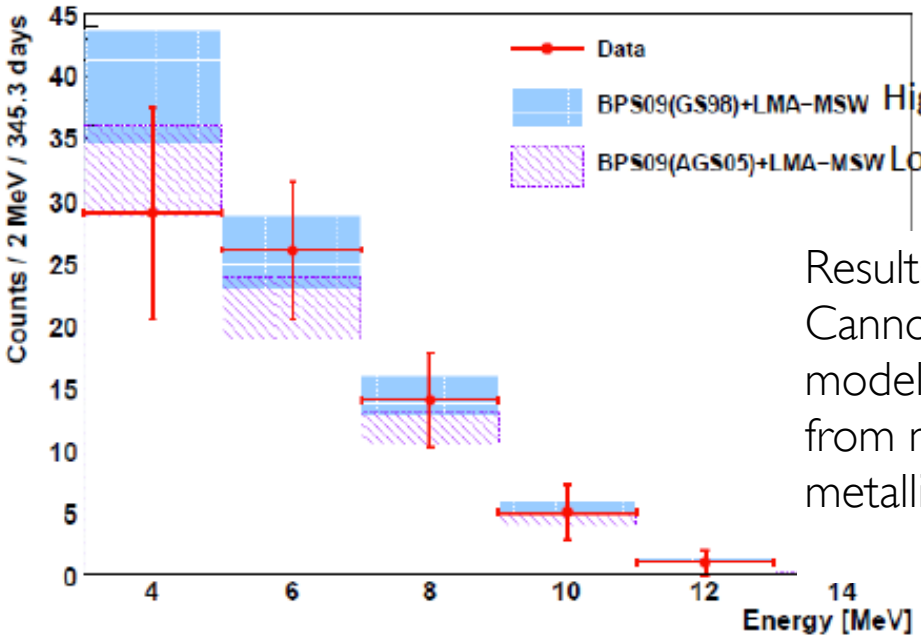
Nutel2011

^{7}Be ν Rate:
$46 \pm 1.5_{STAT} \pm 1.3_{SYS}$ c/d/100 t
in 750 days of data

Hypothesis	Expected rate (cpd/100t)
No oscillation +High Metallicity	74±4
No oscillation + Low Metallicity	67±4
Oscillation MSW + High Metallicity	48±4
Oscillation MSW + Low Metallicity	44±4

A spectral fit based on MonteCarlo





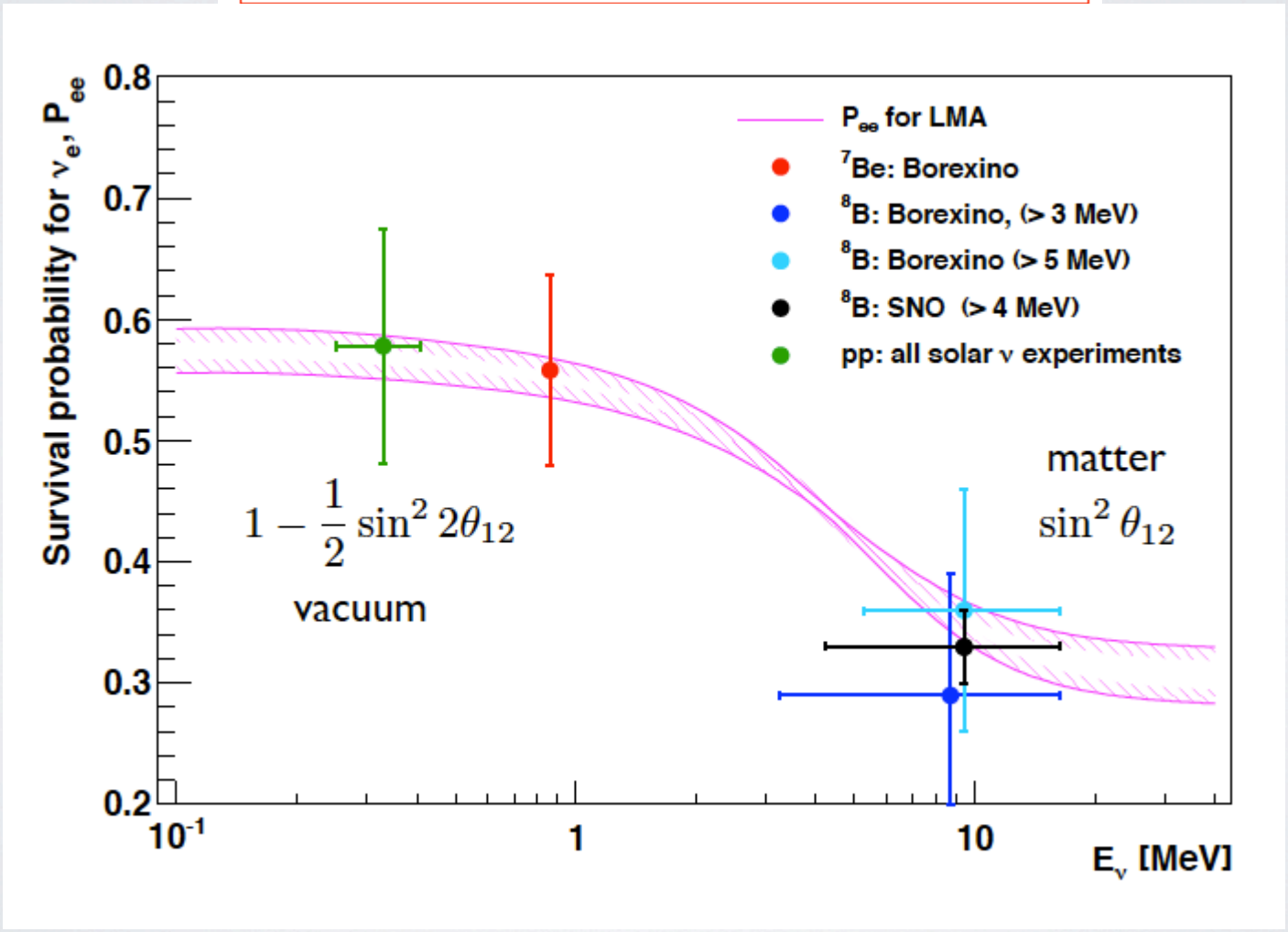
Results in agreement with SSM + LMA.
Cannot discriminate between low and high metallicity in solar model. SSM requires at input core metallicity at t =0, taken from meteorites or photospheric absorption lines. High metallicity has better agreement with helioseismology

PLB 658 (2008), PRL 101 (2008)

$$A_{DN} = 2\frac{\Phi_n - \Phi_d}{\Phi_n + \Phi_d} = 0.007 \pm 0.073(stat)$$

RESULTS

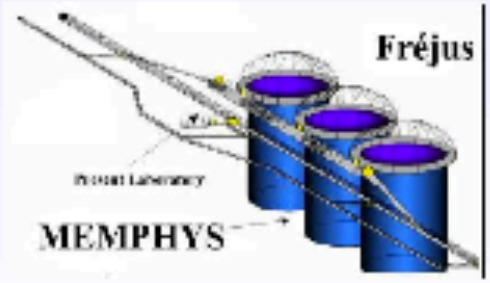
Probing for the first time with the same experiment the Pee in the vacuum regime (^{7}Be neutrinos) and in the matter-enhanced regime (^{8}B neutrinos);



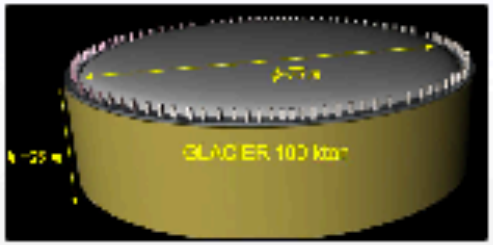
CONCLUSIONS

- The **solar neutrino puzzle** was posed by **radiochemical experiments** and **solved mainly by real time experiments** (SK, SNO and Borexino)
- Strong constraints have been set on θ_{12}, Δm_{12} **(>0)**, P_{ee}
- All solar+reactor neutrino experiments support the **MSW-LMA solution**
- Day-night variability in the neutrino detection can unveil oscillation characteristics and longer term variability can be the signature for magnetic moment of the neutrino
- The sensitivity to $\sin^2\theta_{13}$ can be improved to 0.01-0.02 by precise measurement of the **pp flux measurement, CC/NC ratio and spectrum distortions**
- Despite the good agreement, i**t is not totally established that the SSM** is the appropriate picture or if dynamical effects play crucial roles. The measurements of pp, pep and CNO are relevant.
- Future experiments aim at lowering the energy threshold (SNO+ scintillator, also double beta decay and SN neutrinos), LENS (neutrino capture in ^{115}In), LAGUNA

LAGUNA detector concepts



- MEMPHYS - MEgaton Mass PHYSics
  - 80 m heigth ×65 m ⌀
  - ∼500 kt water Cherenkov detector
  - 81 000 PMTs per shaft (30% coverage)



- GLACIER - Giant Liquid Argon Charge Imaging ExpeRiment
  - 20 m heigth ×70 m ⌀
  - ∼ 100 kt liquid Ar TPC
  - Light (28 000 PMTs) + charge readout

- LENA - Low Energy Neutrino Astronomy
  - 100 m long × 30 m ⌀
  - ∼ 50 kt liquid scintillator
  - 13 500 PMTs for 30% covera

Rates of solar neutrino events

In the LENA fiducial volume:

$18 \cdot 10^3$ m^3

- ^{7}Be ν's: ∼ 5400 d^{-1}
  - Small time fluctuations (1-2 % amplitude detectable at 3σ)
- pep ν's: ∼ 150 d^{-1}
  - Information about the pp-flux → Solar luminosity in ν's
- CNO ν's: ∼ 210 d^{-1}
  - Important for heavy stars
- ^{8}B ν's: CC on ^{13}C: ∼ 360 y^{-1}

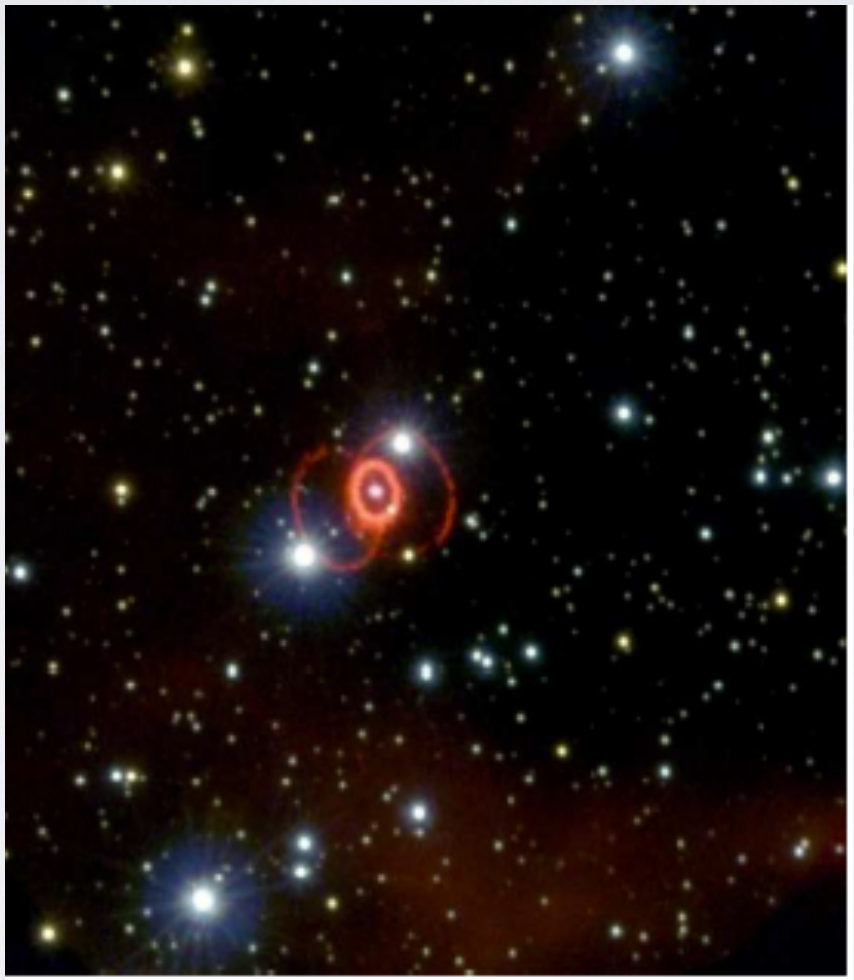
References

Reviews

- Balentekin & Haxton, nucl-th/9903038
- A. Strumia & F. Vissani, hep-ph/0606054v3 (updated Apr 2010)
- **S. Turck-Chièze & S. Couvidat,** arXiv:1009.0852
- See experimental and theory references in http://www.nu.to.infn.it/

NEUTRINOS FROM SN COLLAPSE

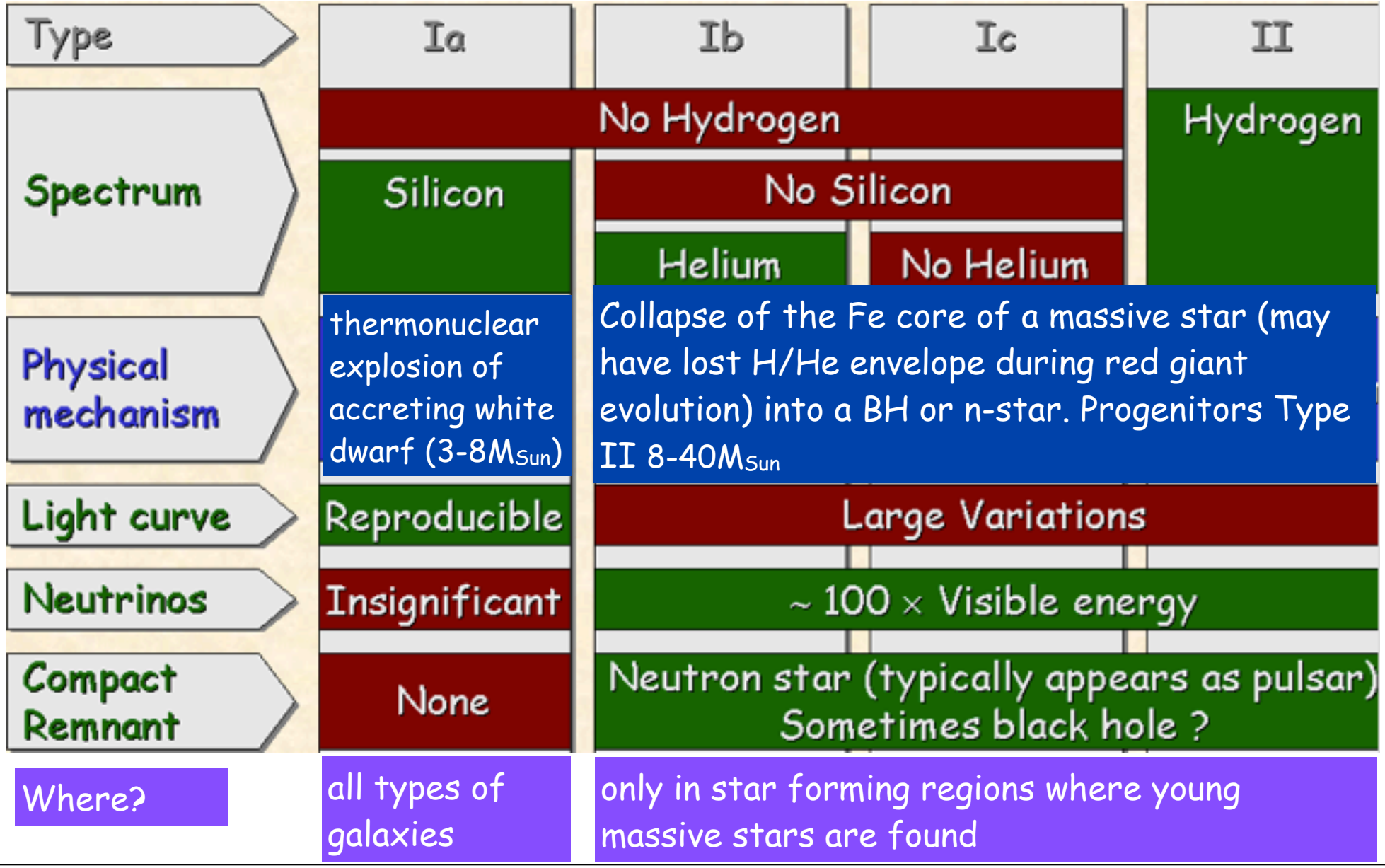
Neutrino collapse and neutrino production
Detection of a galactic supernova: SN 1987A
Current detectors



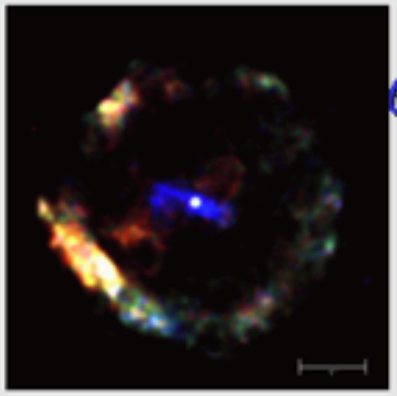
(Hubble image)

CLASSIFICATION

Focus on core collapse SN

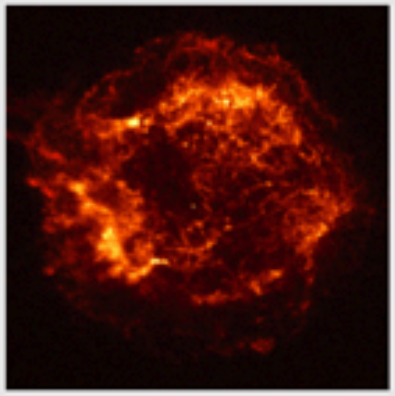


HISTORICAL SUPERNOVAE IN THE LOCAL GROUP

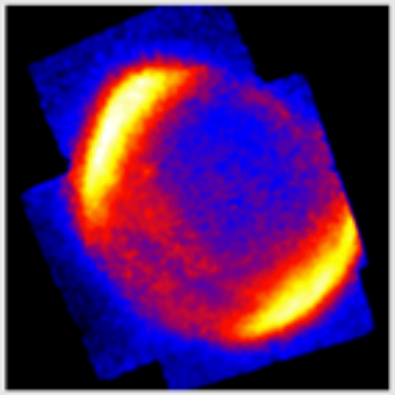


386
G11.2-0.3
5 kpc
Pulsar ?
Type II ?
Chandra

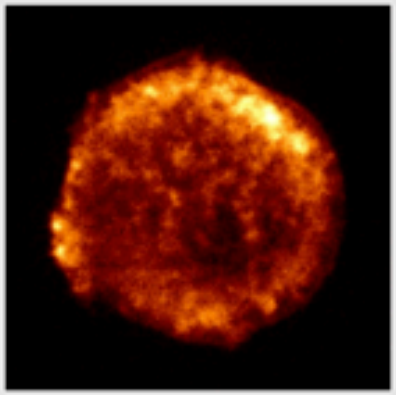
1054
Crab
2 kpc
Pulsar
Type II
ESO



~ 1667
Cas A
2.8 kpc
Neutron
Star
Chandra



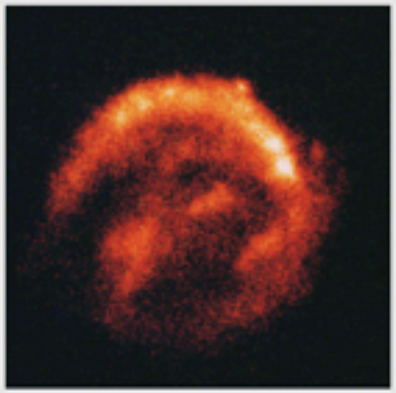
1006
1.5 kpc
ASCA



1572
Tycho
3 kpc
Type Ia
Rosat

1885
SAndro-
medae
900 kpc

1181
3C 58
8 kpc



1604
Kepler
4-8 kpc
Type II ?
Rosat

1987
LMC
50 kpc
No pulsar
Type II
HST

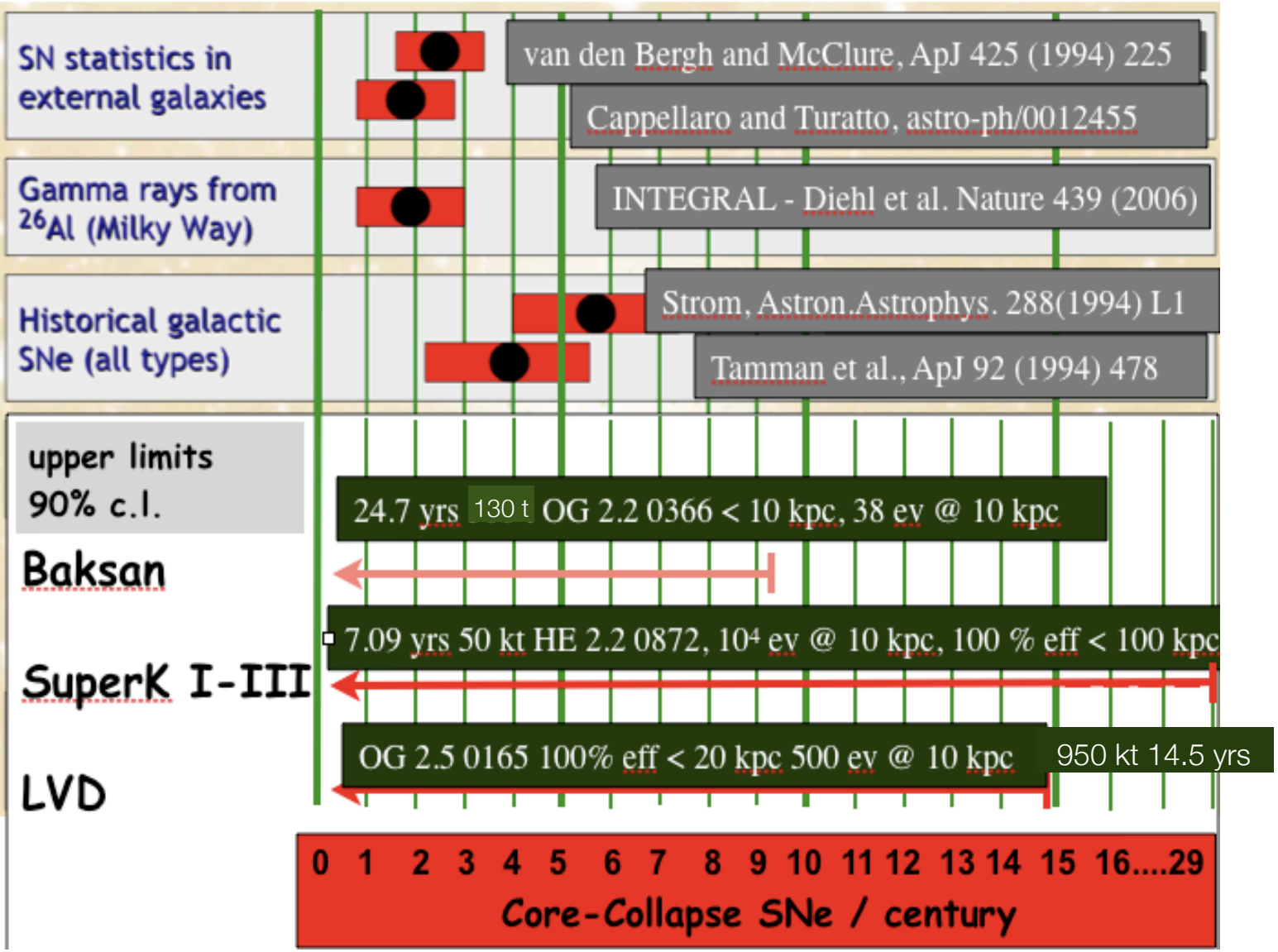
http://arxiv.org/pdf/astro-ph/0301603

CORE-COLLAPSE SN RATES

Galaxy: compilation of results: 1.7 - 2.5/century

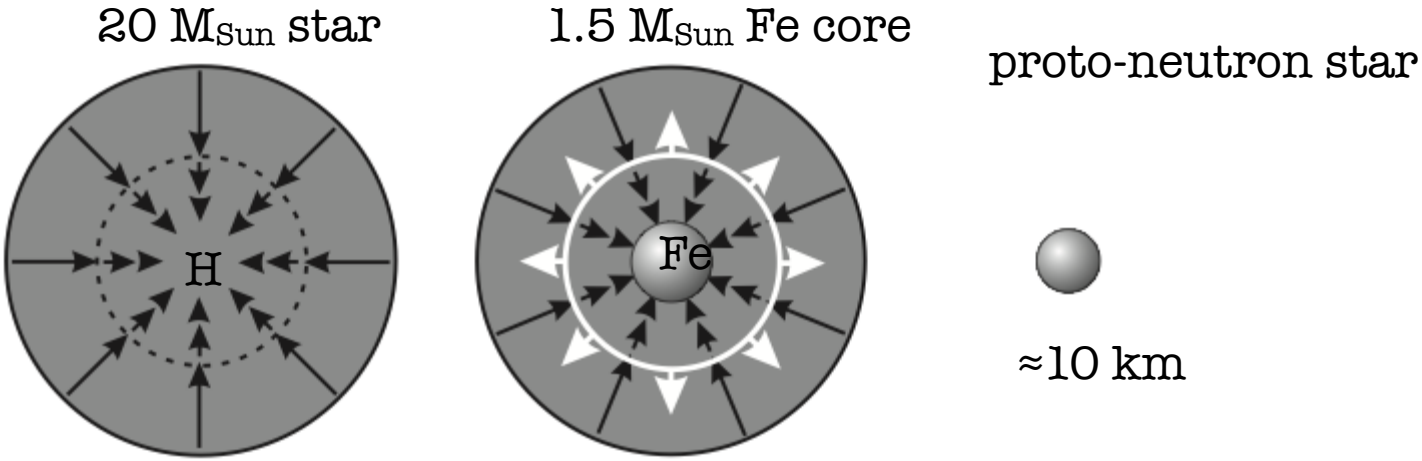
Best limit: 9.3/century (Baksan)

Giunti & Kim, Fundamental of neutrino physics and astronomy 2007



ICRC 2009

SN ENERGETICS



Baade & Zwicky (1939): SN are energized by the collapse of an ordinary star to a neutron star.

mass and radius of collapsing core

$$\Delta E_B \simeq \frac{3}{5}\frac{G M_{NS}^2}{R_{NS}} - \frac{3}{5}\frac{G M_{NS}^2}{R_{core}} \simeq 3\times10^{53}\ ergs \simeq 2\times10^{59}\ MeV$$

radius of collapsed core

This shows up as

99%	Neutrinos
1%	Kinetic energy of explosion
	10% of this into CRs
0.01%	Photons (outshine host galaxy)

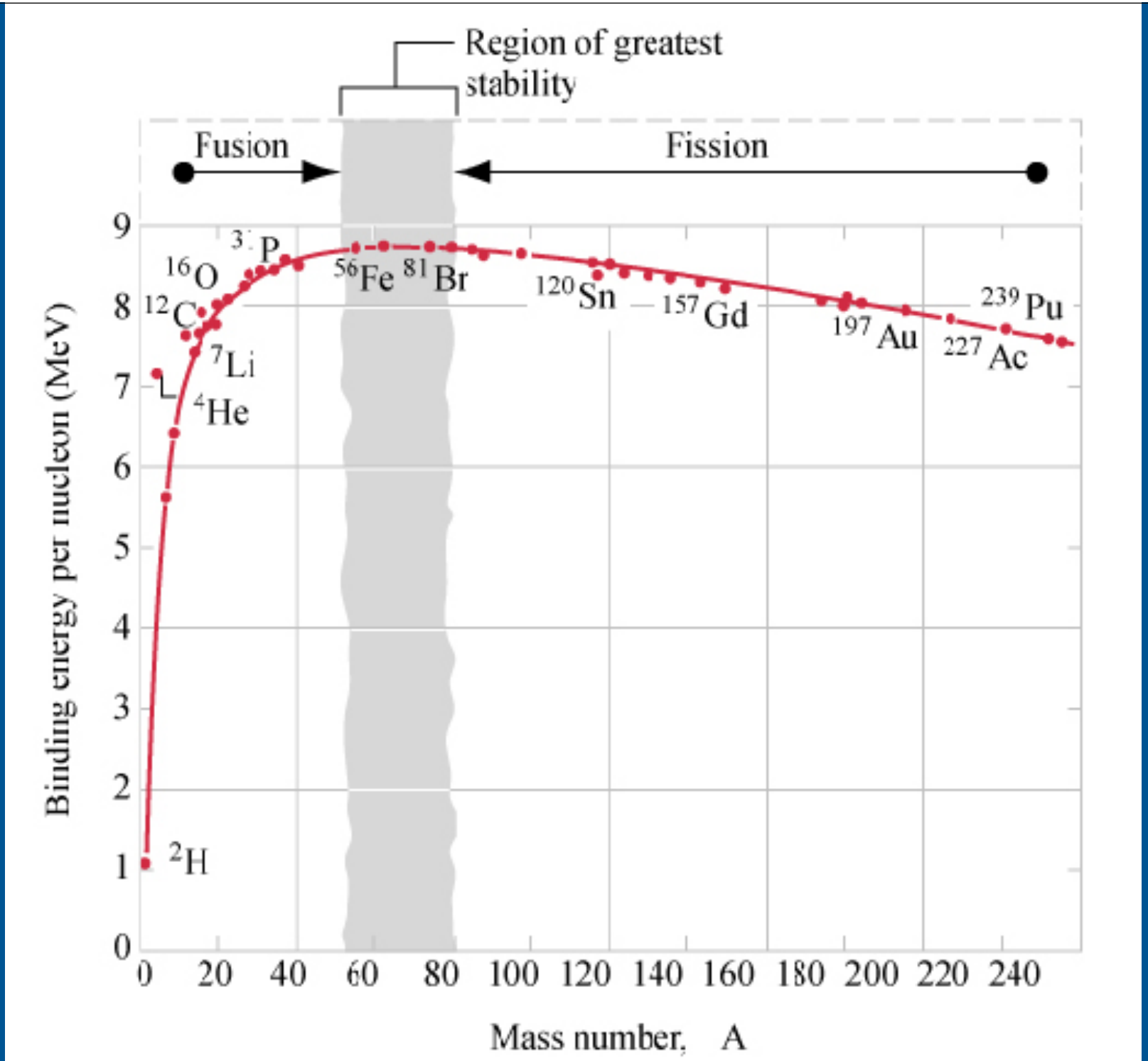
IN SUMMARY...

1. Nuclear fusion ends with Fe
2. Gravity wins: collapse into core of *nuclear density* ($\rho \sim 10^{14}$ g cm $^{-3}$, R~ 20 Km)
3. Bounce back, shock, explosion
4. Energy emitted (light, neutrinos, explosion)
5. Small, cold neutron star remains, M~ (1.35 -2.1) M_{sun}

Star formation: large enough cloud of particles contracts => gravitational potential energy is converted into kinetic energy that heats the gas. Nuclear reactions start and H is converted into He.

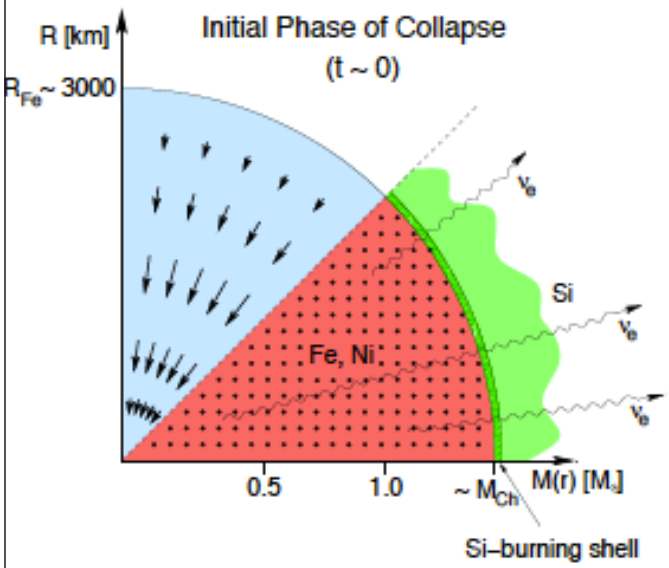
Star life: balance between **pressure from nuclear fusion and gravity**. When H in the core has burned, a massive enough star (> 8 M_{Sun}) contracts and become hot enough so He burns into C. Very massive stars can form a core of ^{56}Fe, the most stable nucleus. Fe has the **highest binding energy so the synthesis of a heavier element from a lighter one does not produce anymore energy and the star collapses.** The star is formed by `onion layers' of unburned lighter nuclei. The Fe core, is sustained by the degeneracy pressure of its electrons until until it reaches the Chandrasekar mass of 1.4 M_{Sun} and the SN core collapse process starts.

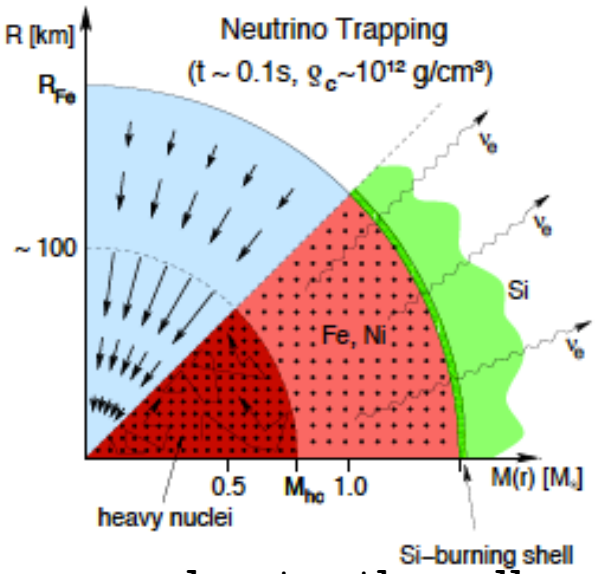
Janka et al, http://arxiv.org/abs/astro-ph/0612072v1


Region of greatest stability
Fusion
Fission
Binding energy per nucleon (MeV)
Mass number, A
0
1
2
3
4
5
6
7
8
9
0
20
40
60
80
100
120
140
160
180
200
220
240
^{2}H
^{4}He
^{7}Li
^{12}C
^{16}O
^{31}P
^{56}Fe
^{81}Br
^{120}Sn
^{157}Gd
^{197}Au
^{227}Ac
^{239}Pu

Neutrino Emission and trapping

Once the contraction of the Fe core starts, electron capture starts that produce many electron neutrinos (electrons decrease and n increase).





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

Neutronization or deleptonization (time scale of ms)

The decreases the electron pressure accelerates the collapse. The core density reaches 10^{13} g/cm^3. **Neutrinos are trapped** due to scattering processes on nucleons in the collapsing core $\nu + A \rightarrow \nu + A$
and the collapse proceeds to densities of about 10^{14} g/cm^3.

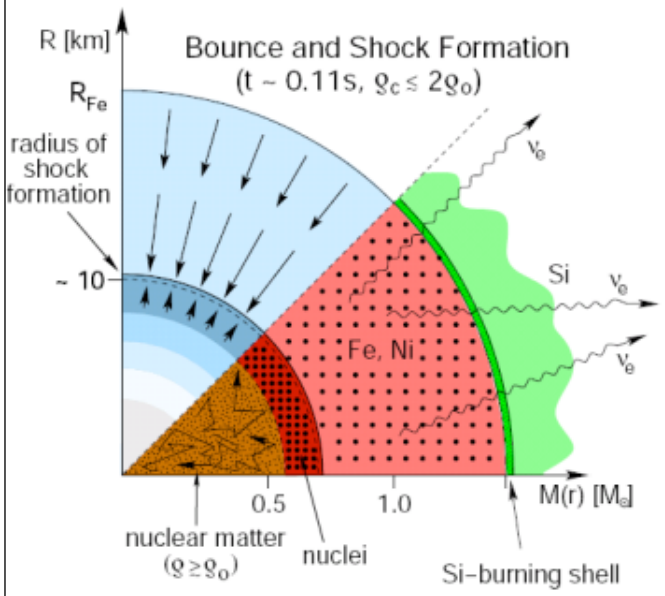
Neutrino are in thermal equilibrium and they form a Fermi-Dirac gas.

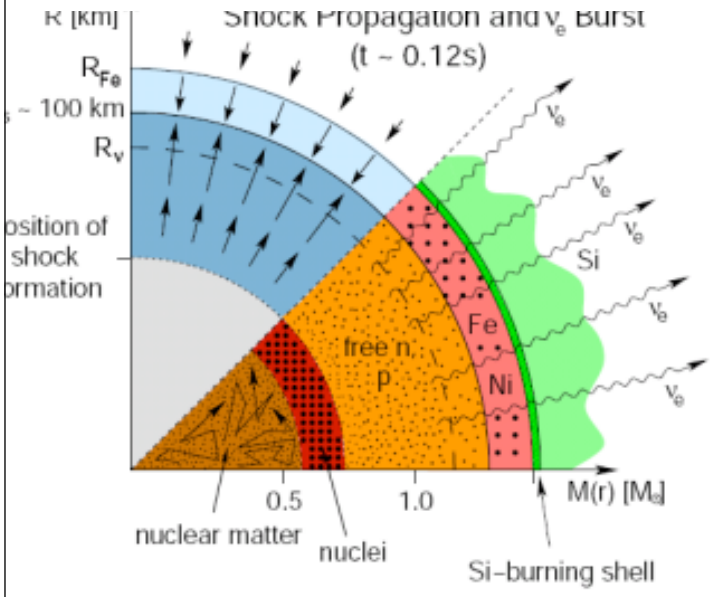
T ~ 5-30 MeV, ϱ ~ 10^8-10^{14} g/cm^3

Mean free path: $\sim \frac{m_n}{G_F^2 E^2 \rho} \sim 10$ cm - 100 km << size of star

Duration of neutrino burst: time $\sim$ (size)^2/m.f.p $\sim$ 10 s

The core collapse is stopped by the nuclear force when it becomes incompressible due to the increased nuclear matter pressure (**core bounce**). This drives a **shock wave into the outer core** that has continued to fall inwards supersonically (faster than mechanic waves from the core). **The core bounce triggers the explosion.**





After the core bounces a compact remnant remains rich of protons at the center of the exploding star (**proto-neutron star ≈ 20 km radius**) that will evolve into a n-star or BH (M> 25 M_{Sun}).

The proto-neutron star contains also electrons and neutrinos that are trapped. Many electron neutrinos are produced

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

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

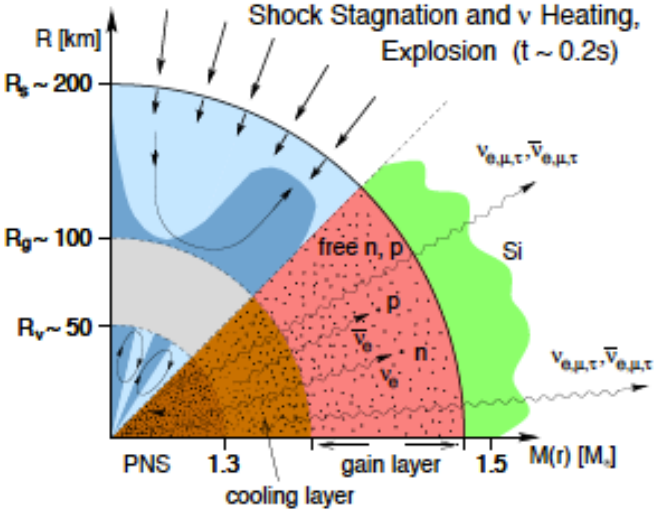
deleptonization burst

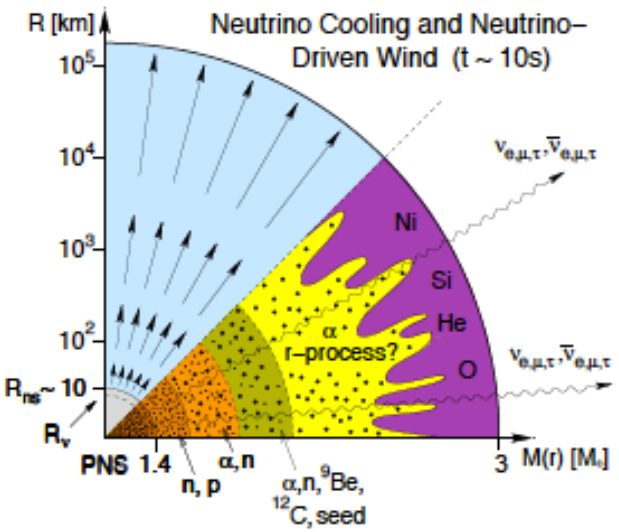
until the density reaches 10^{14} g/cm^3

This many electron neutrinos and antineutrinos carry away energy and lead to further neutronization. The shock is weakened and stalls. Neutrinos cool the surface of the proto-neutron star due to pair production and diffusive loss of neutrinos of all flavors:

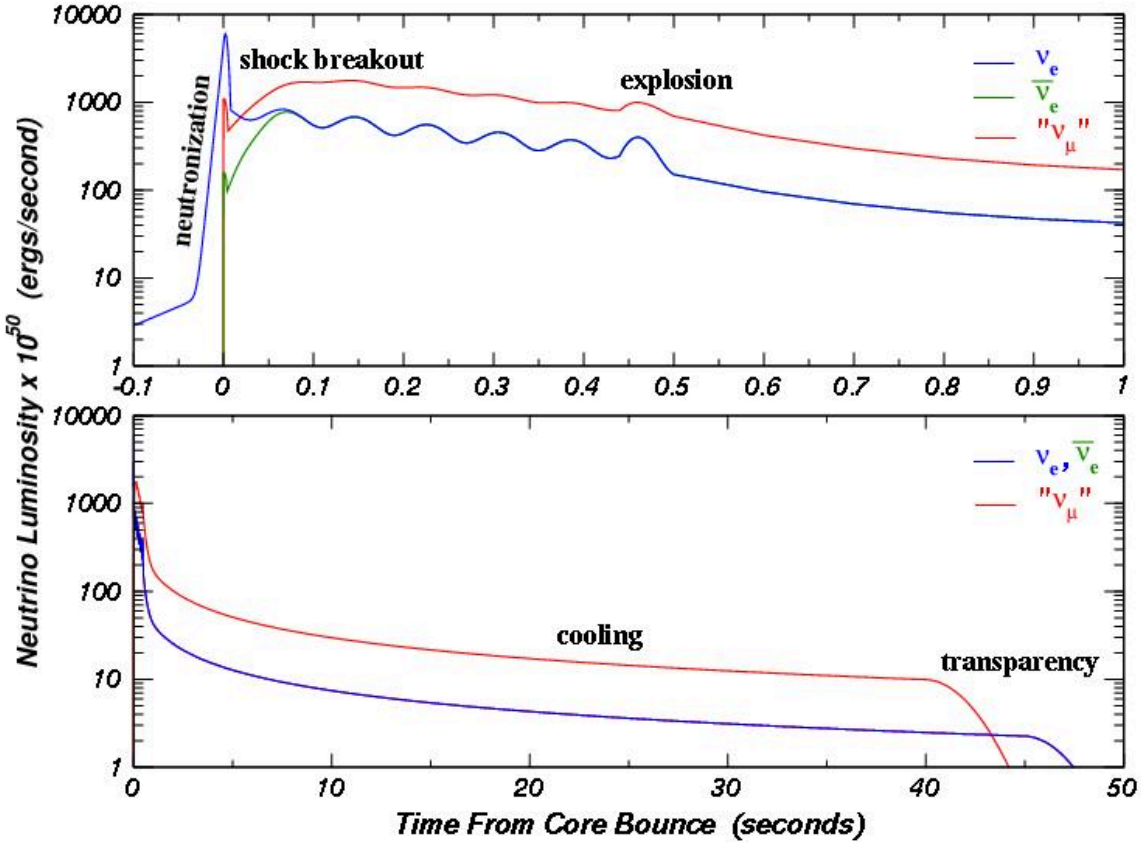
$$e^+ + e^- \rightarrow \nu_j + \bar{\nu}_j$$ thermalization

This is called Kelvin-Helmholtz-cooling phase.





The shock starts again moving being revived by the energy of outgoing neutrinos. In the case of a very massive star a BH forms and neutrino emission stops soon.



http://nu.phys.laurentian.ca/~fleurot/supernova

NEUTRINO EMISSION

Spectra follow approximately a Fermi Dirac distribution

$$f_t(E) = \frac{E_\nu^2}{1 + e^{\frac{E_\nu}{T}}}$$

$$\langle E_\nu \rangle = \frac{\int_0^\infty dE_\nu E_\nu f_t(E)}{\int_0^\infty dE_\nu f_t(E)}$$

$$\Phi_0 = \frac{1}{4\pi D^2} \frac{L}{\langle E_\nu \rangle}$$

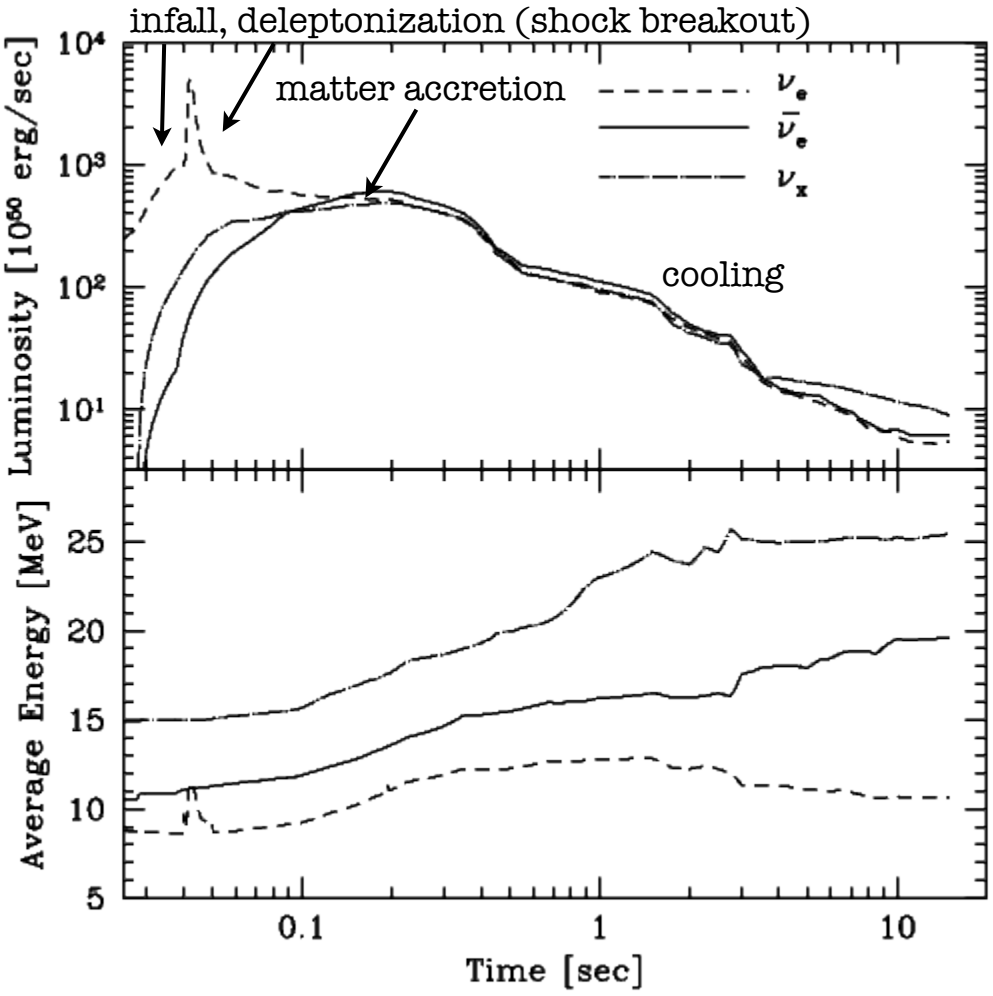
<Eν>∝ T

$$\langle E_{\nu_e} \rangle \approx 10\,\mathrm{MeV}, \quad \langle E_{\bar{\nu}_e} \rangle \approx 15\,\mathrm{MeV}, \quad \langle E_{\nu_x} \rangle \approx 20\,\mathrm{MeV}.$$

The most strongly coupled particle decouples at lower density where matter is colder ➜ colder spectrum:
- ν_X have NC coupling
- ν_e and anti-ν_e have NC + CC
- There are more n than p➜ ν_e more strongly coupled than anti-ν_e

Garching group http://arxiv.org/abs/astro-ph/0308228)

Livermore group (Totani et al, 1998)



(α∈ [2,5])

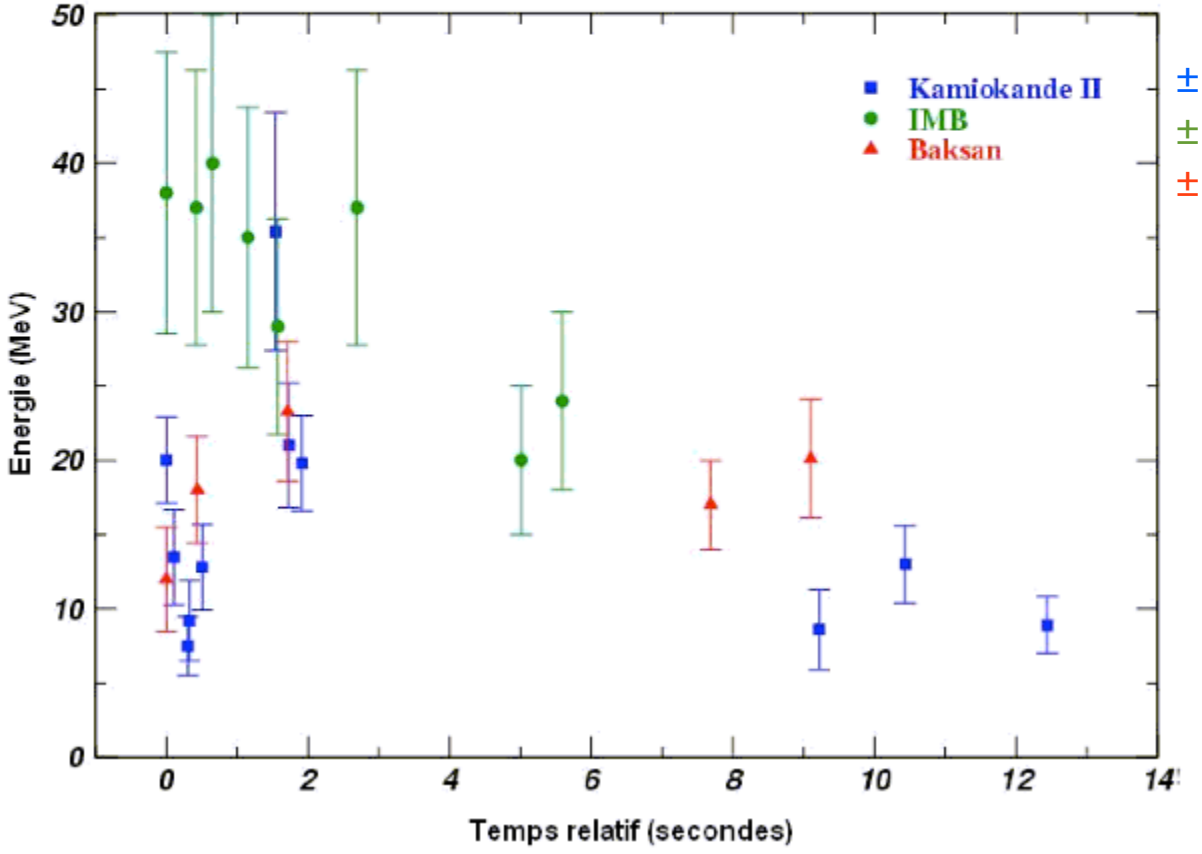
$$f(E_\nu, \langle E_\nu \rangle, \alpha) = \frac{(1+\alpha)^{(1+\alpha)}}{\Gamma(1+\alpha)} \frac{E_\nu^\alpha}{\langle E_\nu \rangle^{(1+\alpha)}} e^{-(1+\alpha)\frac{E_\nu}{\langle E_\nu \rangle}}$$

SN1987A

23 february 1987 7:36 UT. Neutrinos detected roughly 3 hrs before the optical signal
Progentor: Blue SuperGiant Sanduleak-69 in the Magellanic cloud ~50 kpc

- ~ 1 Kt water/scintillator detectors
  - Inverse beta decay: anti-$\nu_e + p \rightarrow n + e^+$

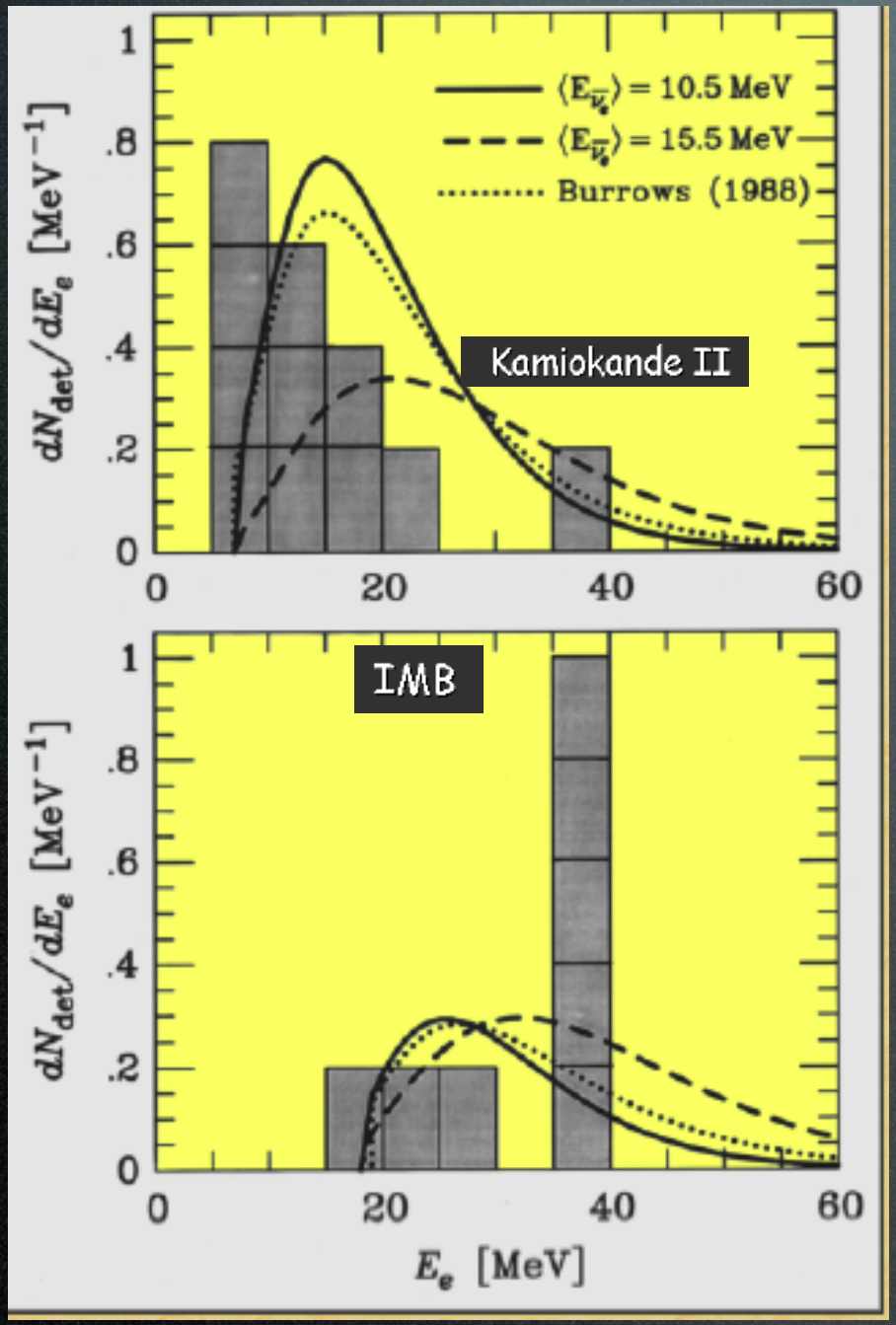
clock uncertainties

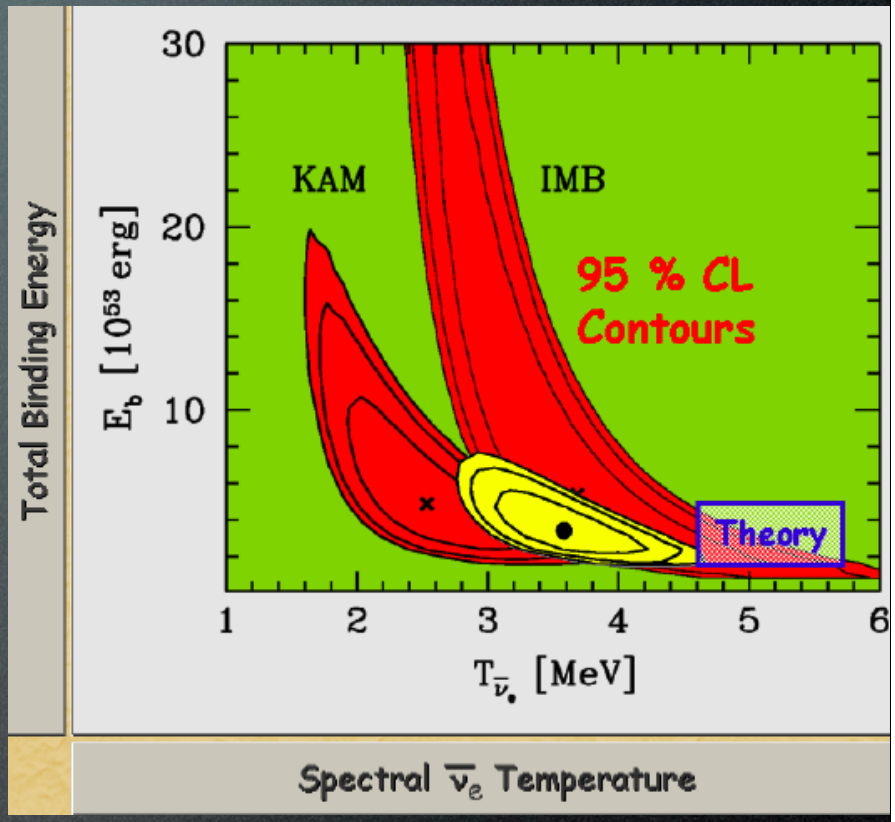


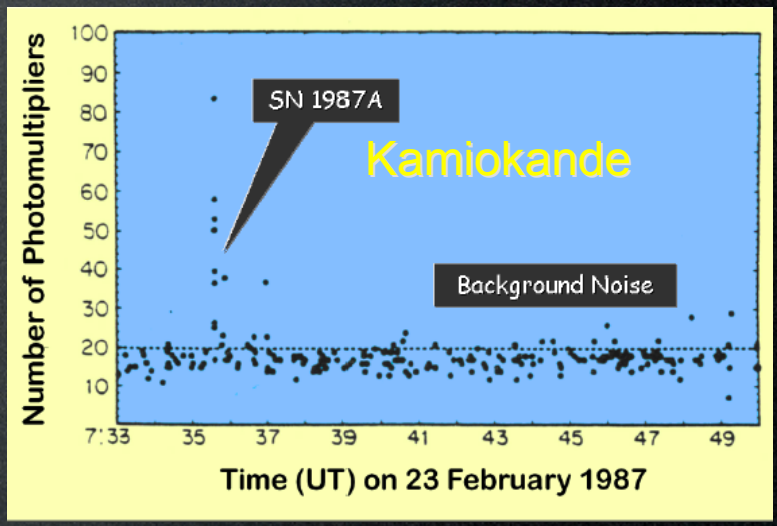
± 1 min
± 50 ms
± 1 min

http://astro.berkeley.edu/~bmetzger/

Energy distribution







What did we learn?

- Luminosity ≈ total energy budget
  - Energy emitted is of *gravitational* nature:

    $L_\nu \approx G\,M^2_f/R_f - G\,M^2_i/R_i \sim 3\,10^{53}$ ergs ✓ ($R_f \sim 10$ Km)

- Energy spectrum: ~ *Fermi Dirac (thermal)*
  - $E \approx 3.15\,T \sim$ 15-20 MeV ✓

- Duration of neutrino burst ~ diffusion time
  - Time ≈ (size^2)/(mean free path) ~ 10 s ✓

Limit on neutrino masses now well overcome:

$$v = \frac{p}{E} = \frac{\sqrt{E^2 - m^2}}{E} \approx 1 - \frac{1}{2}\frac{m_\nu^2}{E_\nu^2} \qquad t_a - t_e = d \times (1 + \frac{1}{2}\frac{m_\nu^2}{E_\nu^2}) \qquad |\Delta t_a - \Delta t_e| = \frac{1}{2} d\, m_\nu^2 \frac{|E_1^2 - E_2^2|}{E_1^2 E_2^2}$$

propagation time = arrival - emission time

Measure energy of 2 events and the tim
dispersion between the 2 events =>

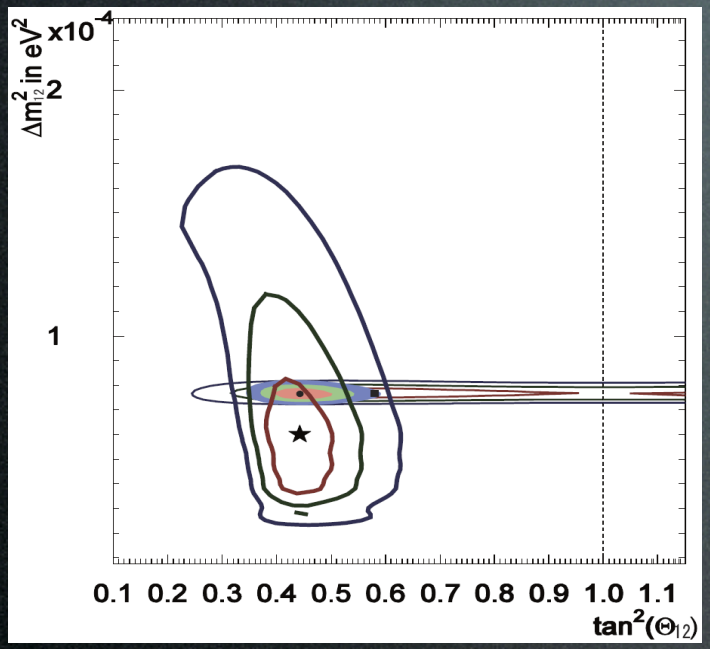
$$m_{\nu_e} \lesssim 20\,eV$$

$$F(\bar{\nu}_e) = (1-p)\cdot F_0(\bar{\nu}_e) + p \cdot F_0(\bar{\nu}_\mu).$$

http://arXiv.org/pdf/hep-ph/9305204

The final anti-ν_e spectrum is a mixture of the 2 original spectra for anti-ν_e,ν_μ
permutation factor < 35% (99%CL)

Limits on parameter space from SN1987A



$$F(\bar{\nu}_e) = (1-p)\cdot F_0(\bar{\nu}_e) + p\cdot F_0(\bar{\nu}_\mu).$$

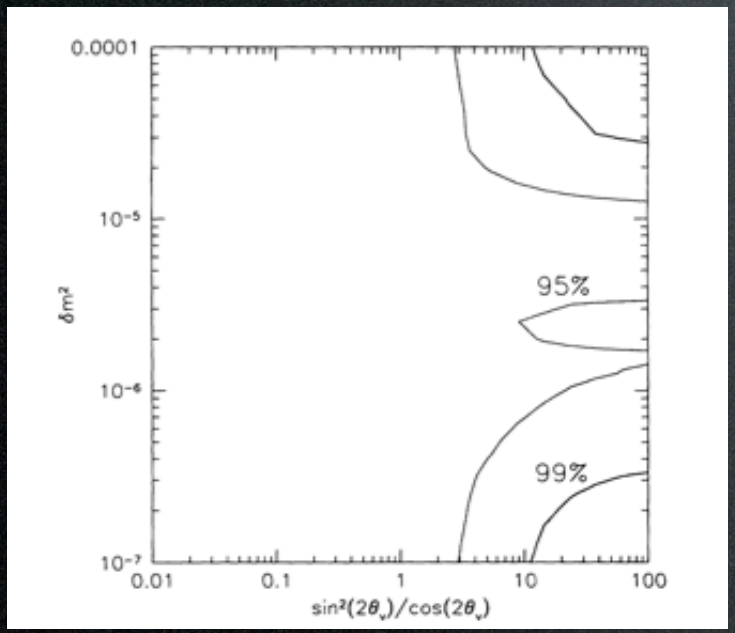
The final anti-ne spectrum is a mixture of the 2 original spectra for anti-ν_e, ν_μ
permutation factor < 35% (99%CL)

$$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$$

would have produced un-observed high energy events

$$\sin^2 2\theta \leq \begin{cases} 0.9 & (\Delta m^2 \gg 10^{-9}\ \mathrm{eV}^2), \\ 0.7 & (\Delta m^2 \ll 10^{-9}\ \mathrm{eV}^2). \end{cases}$$

<36°



Energy measurements were not good enough

http://arXiv.org/pdf/hep-ph/9305204

Open questions

Measure

- Exact time structure for neutronization, accretion, cooling
- Total energy (NC, all flavors)

To determine:

- Astrophysical model for collapse
- Oscillations (MSW, neutrino self-interactions, Θ_{13})
- New physics?