XII.

Low-Energy Neutrino Physics and Astrophysics

Astroparticle Physics a.a. 2021/22

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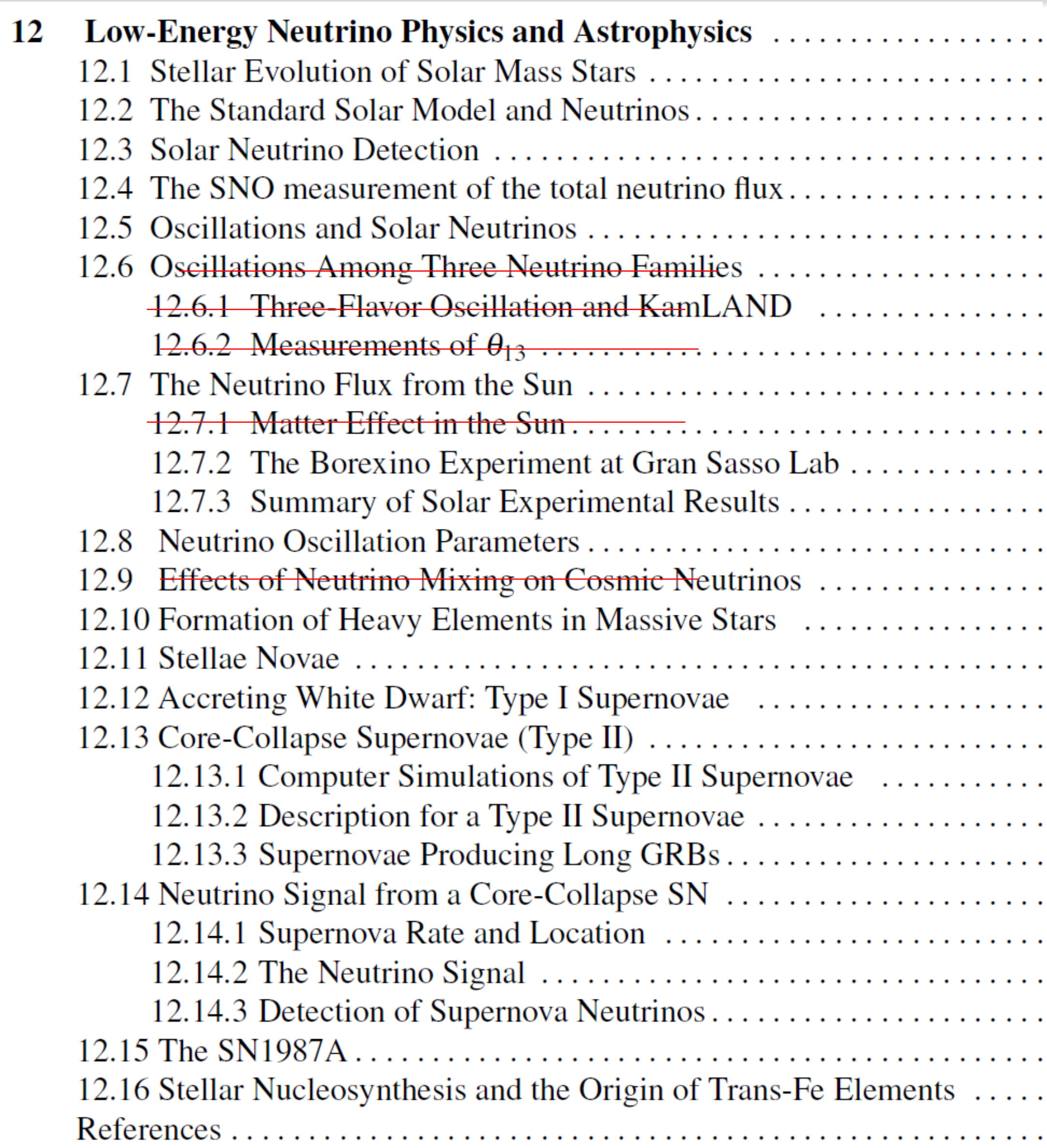
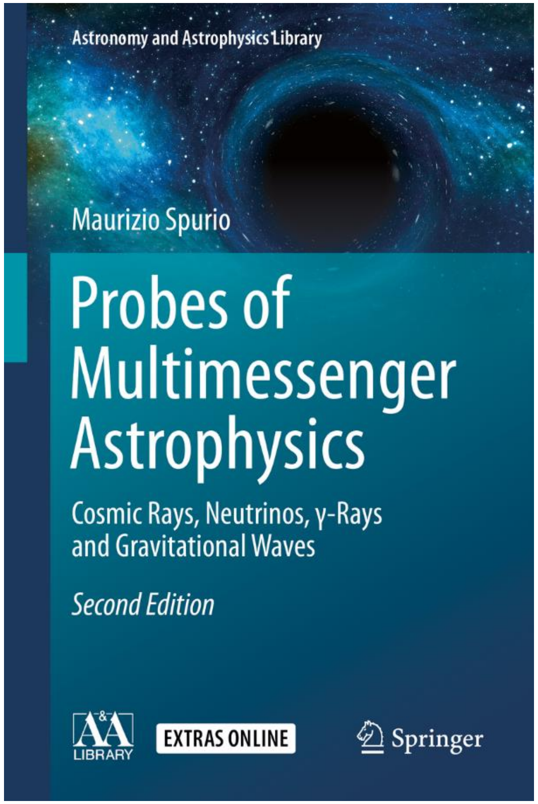
Content





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Probes of Multimessenger Astrophysics

Cosmic Rays, Neutrinos, γ-Rays and Gravitational Waves

Second Edition

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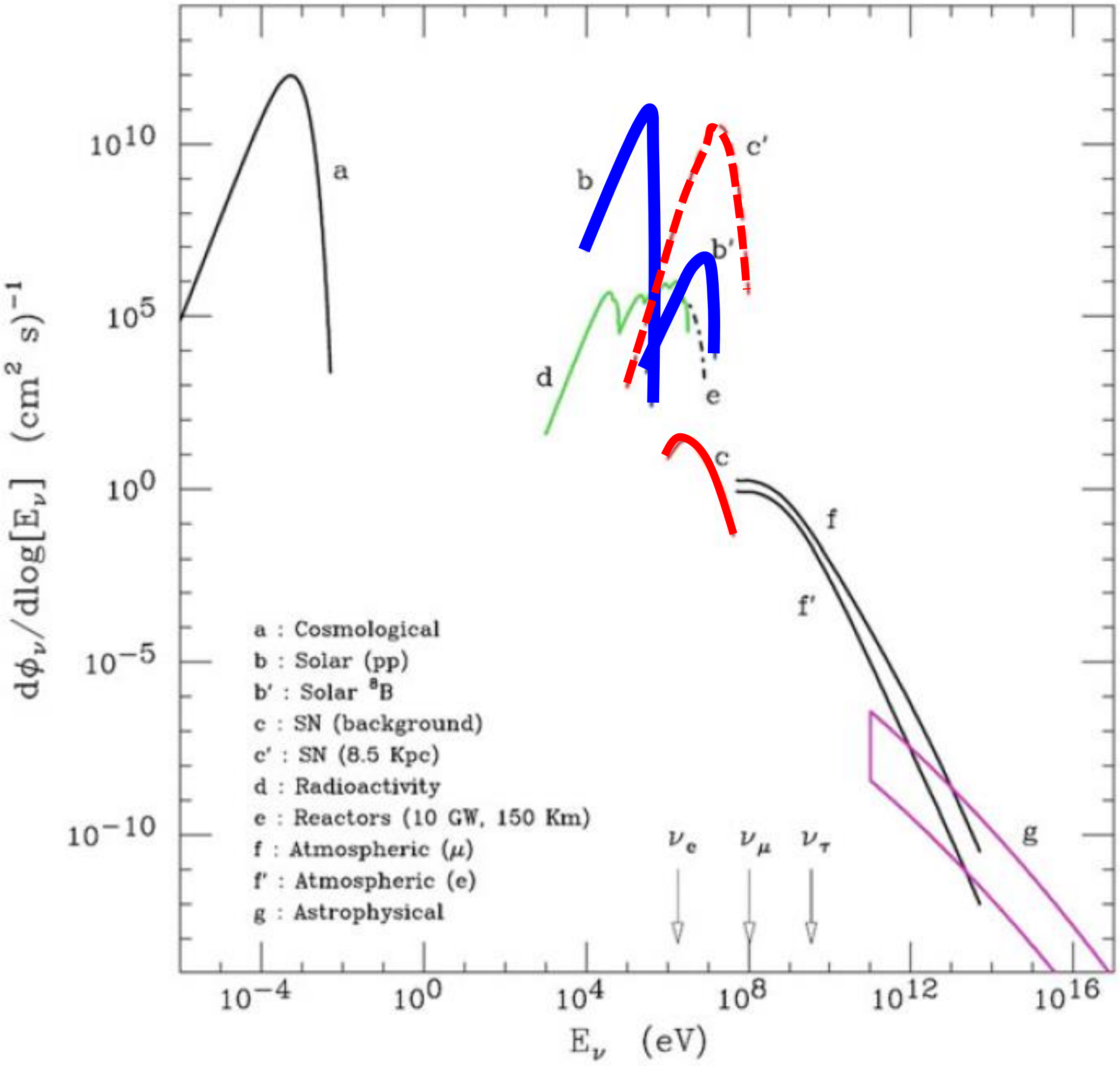
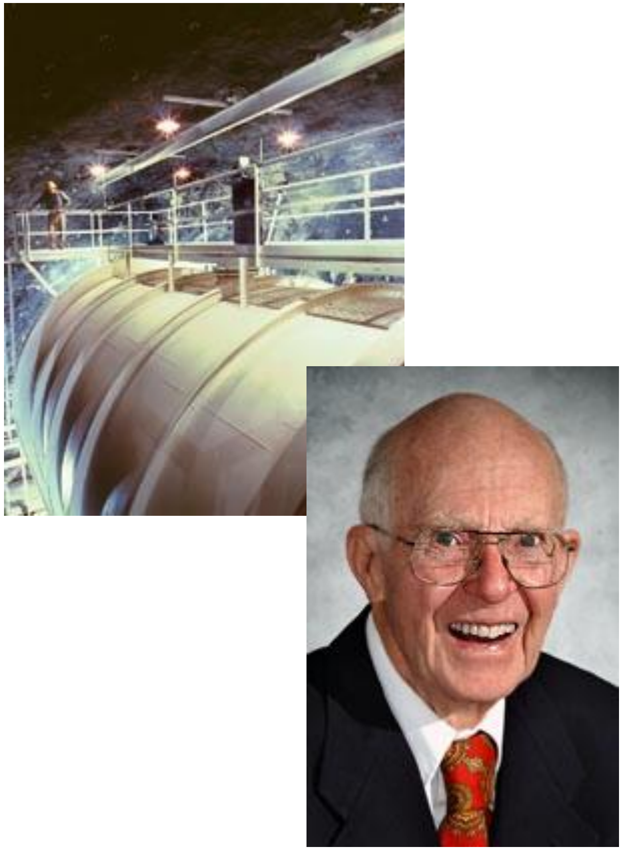
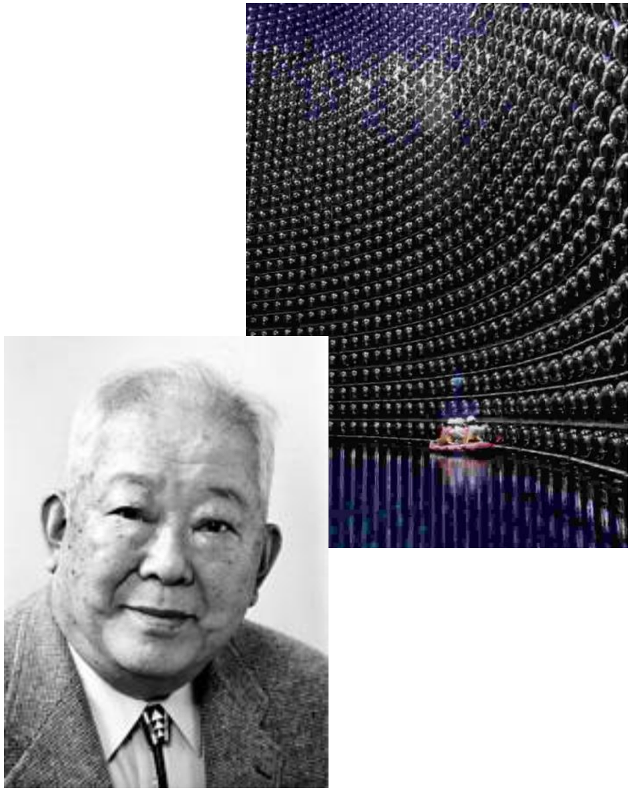
Neutrinos from the Cosmos



- Flux of neutrinos at the surface of the Earth.
- The three *arrows* near the *x*-axis indicate the energy thresholds for CC production of the charged lepton

The 2002 Nobel Prize for the Solar Neutrinos





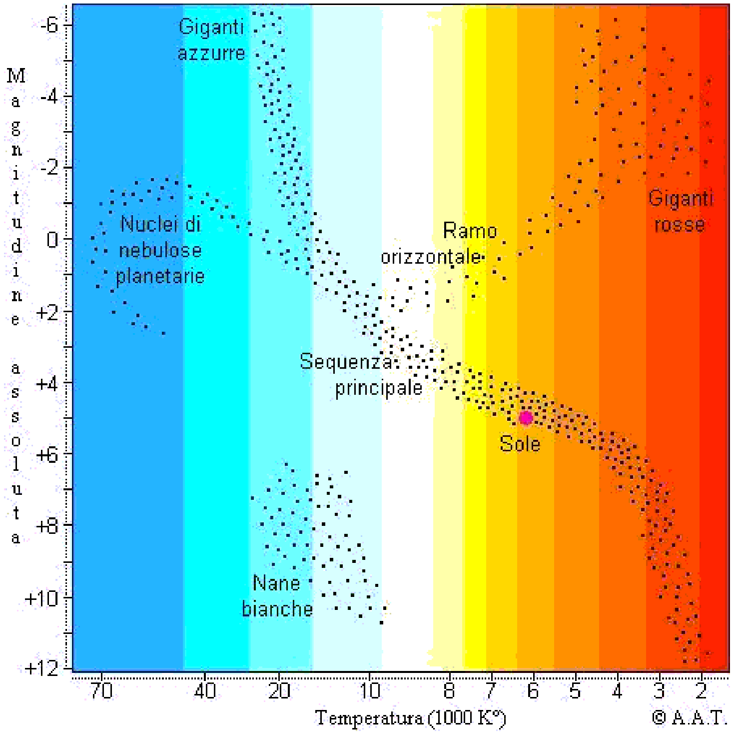
Masatoshi Koshiba

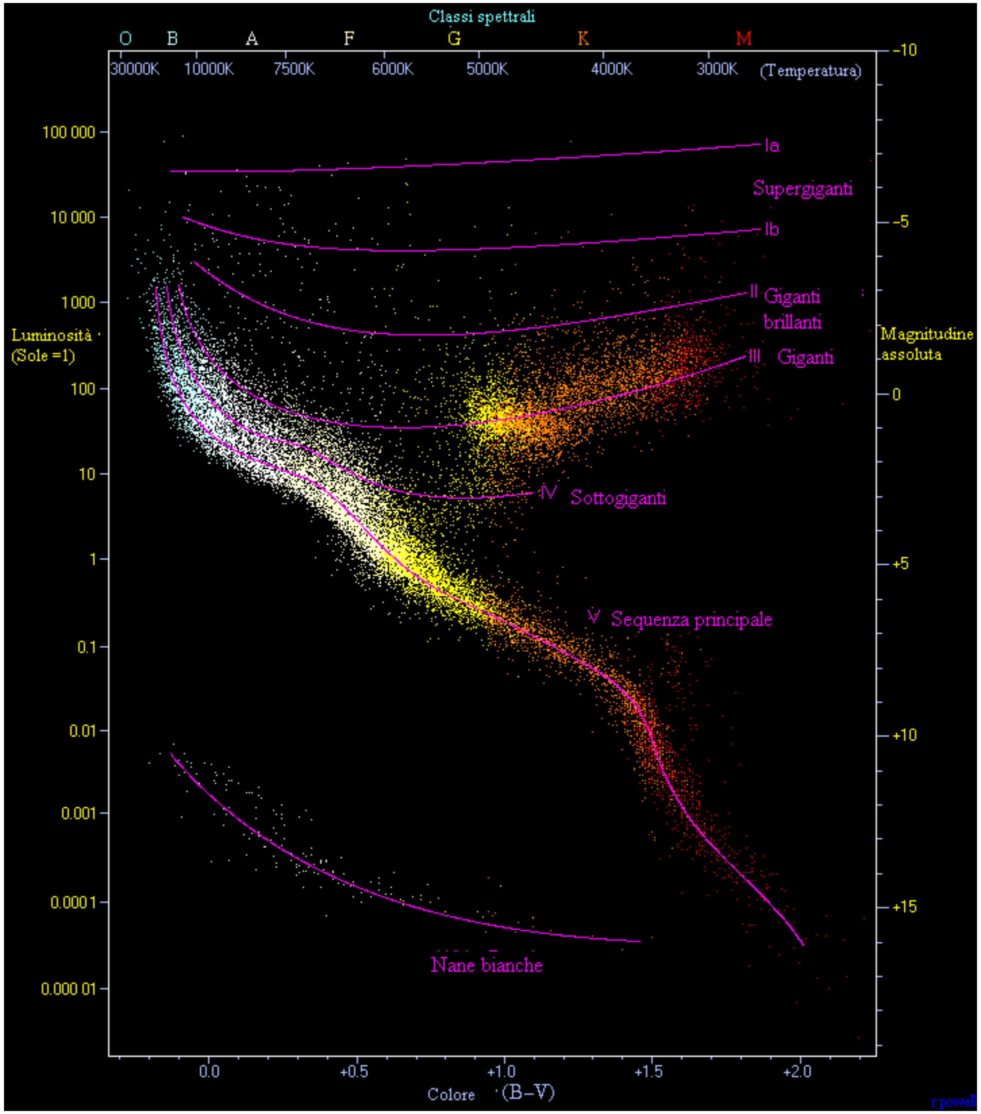
http://nobelprize.org/nobel_prizes/physics/laureates/2002/koshiba-lecture.pdf

Raymond Davis Jr.

http://nobelprize.org/nobel_prizes/physics/laureates/2002/davis-lecture.pdf

The HR diagram





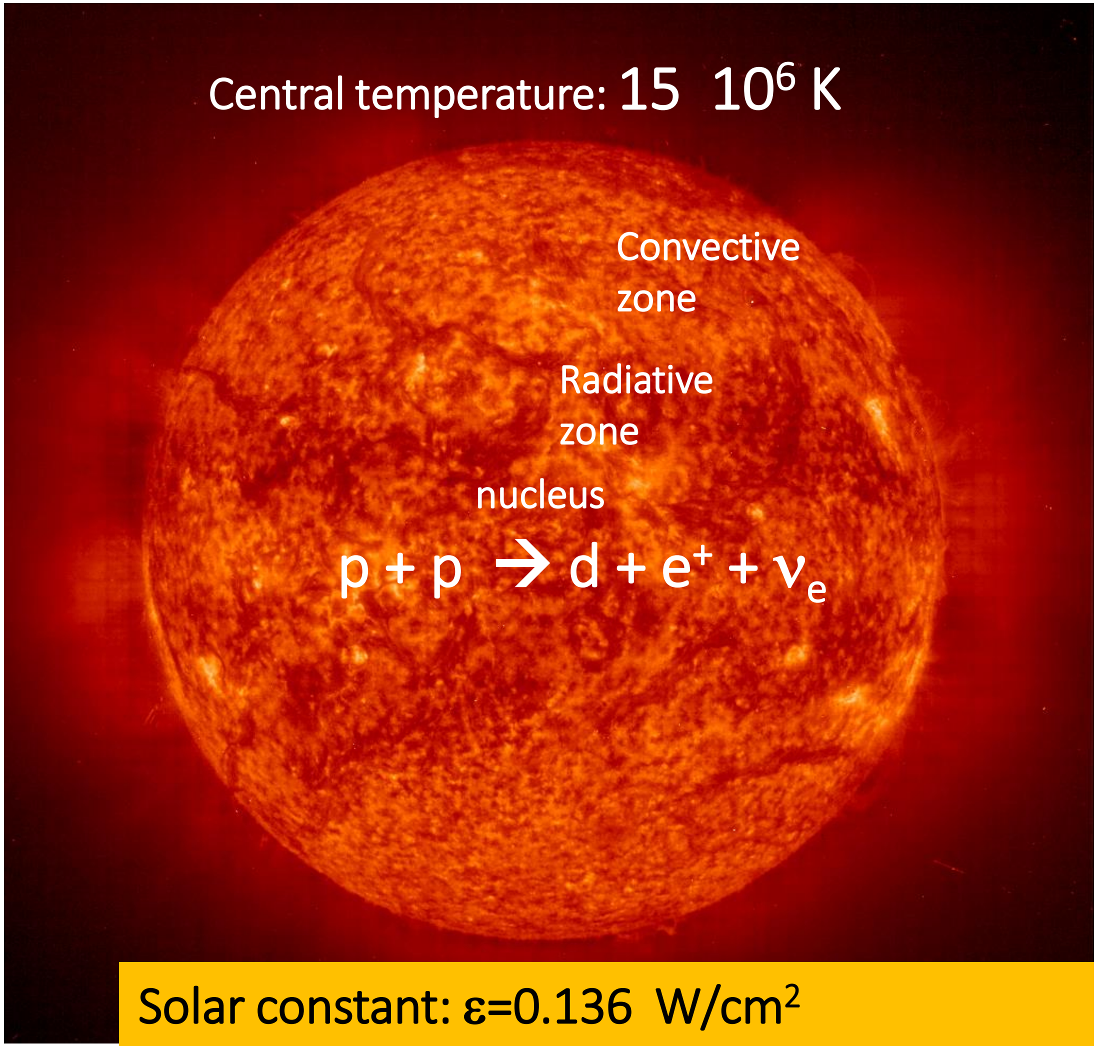
The Sun

Composition :

- **73% hydrogen (H)**
- **25% helium (He)**
- **2% heavier elements (= "metals")**

Question 1: Compute the Sun age assuming electromagnetic burning

Question 2.2: Compute the Sun age assuming the Lord Kelvin model (gravitational energy source of radiation)



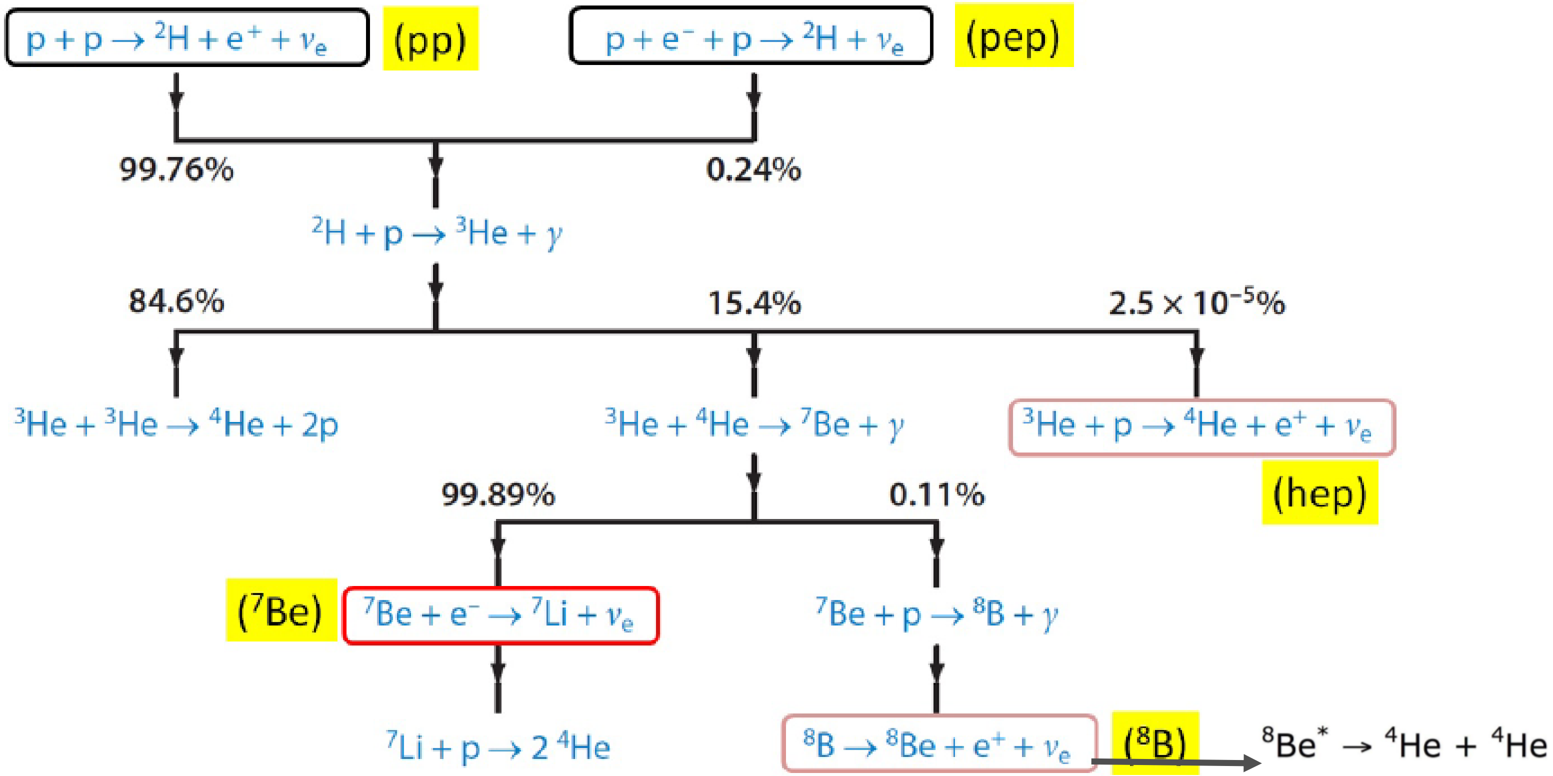
Central temperature: 15 10^6 K

$p + p \rightarrow d + e^+ + \nu_e$

Solar constant: ε=0.136 W/cm^2

→ Luminosity: L_{sun}= 3,84 10^{26} W

ν from the Sun: the pp chain



$p + p \rightarrow {}^2H + e^+ + \nu_e$ **(pp)**

$p + e^- + p \rightarrow {}^2H + \nu_e$ **(pep)**

99.76%

0.24%

${}^2H + p \rightarrow {}^3He + \gamma$

84.6%

15.4%

$2.5 \times 10^{-5}\%$

${}^3He + {}^3He \rightarrow {}^4He + 2p$

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$ **(hep)**

99.89%

0.11%

(${}^7Be$) ${}^7Be + e^- \rightarrow {}^7Li + \nu_e$

${}^7Be + p \rightarrow {}^8B + \gamma$

${}^7Li + p \rightarrow 2\,{}^4He$

${}^8B \rightarrow {}^8Be + e^+ + \nu_e$ **(${}^8B$)**

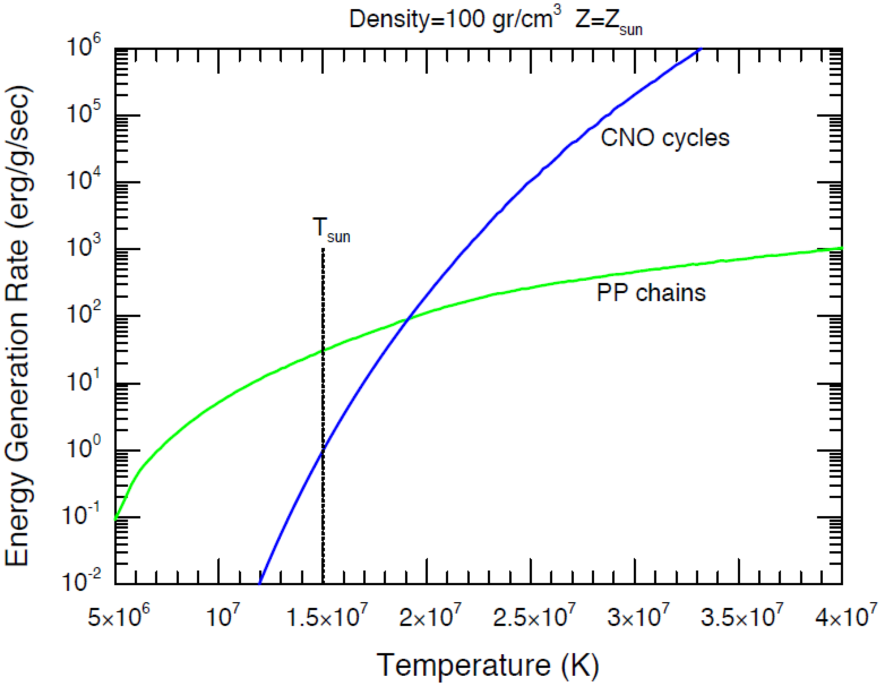
${}^8Be^* \rightarrow {}^4He + {}^4He$

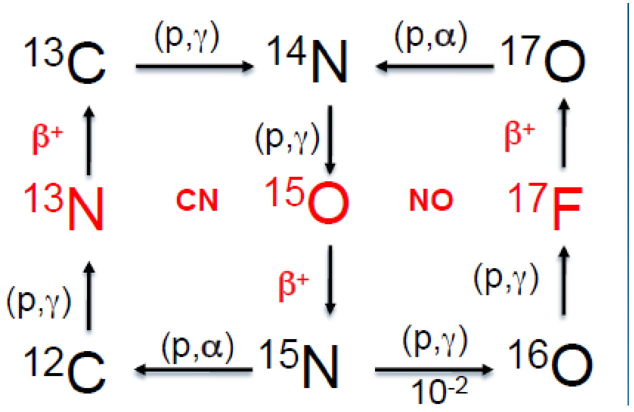
$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e \qquad Q = 26.73\ \text{MeV} \quad \langle E_\nu \rangle \cong 0.53\ \text{MeV}$$

$$\Phi_{\nu_e} \simeq \frac{1}{4\pi D_\odot^2} \frac{2L_\odot}{(Q - \langle E_\nu \rangle)} = 6 \times 10^{10}\ \text{cm}^{-2}\text{s}^{-1}$$

ν from the Sun: the CNO chain

Reaction	Q (MeV)
$p + ^{12}\mathrm{C} \to ^{13}\mathrm{N} + \gamma$	1.94
$^{13}\mathrm{N} \to ^{13}\mathrm{C} + e^+ + \nu_e$	1.20
$p + ^{13}\mathrm{C} \to ^{14}\mathrm{N} + \gamma$	7.55
$p + ^{14}\mathrm{N} \to ^{15}\mathrm{O} + \gamma$	7.29
$^{15}\mathrm{O}_8 \to ^{15}\mathrm{N} + e^+ + \nu_e$	1.73
$p + ^{15}\mathrm{N} \to ^{12}\mathrm{C} + ^{4}\mathrm{He}$	4.96





- Solar ν's are a **unique probe** for understanding the interior of the Sun and its energy source
- The Sun can be used to calibrate stellar models
- Probing ν propagation (physics) in a high density medium (~100 g/cm^3)

The Standard Solar Model (SSM)

- **J. Bahcall**: The initial author of the SSM
- Derived from the conservation laws and energy transport equations of physics, applied to a spherically symmetric gas (plasma) sphere

- **Input of the SSM:**
  - Mass, Age, Luminosity, Radius
- **Assumptions of the SSM**
  - Hydrostatic equilibrium
  - Spherical symmetry, no rotation, no magnetic field
  - Energy generation by H burning
- **Free parameters**:
  - initial relative mass abundances:

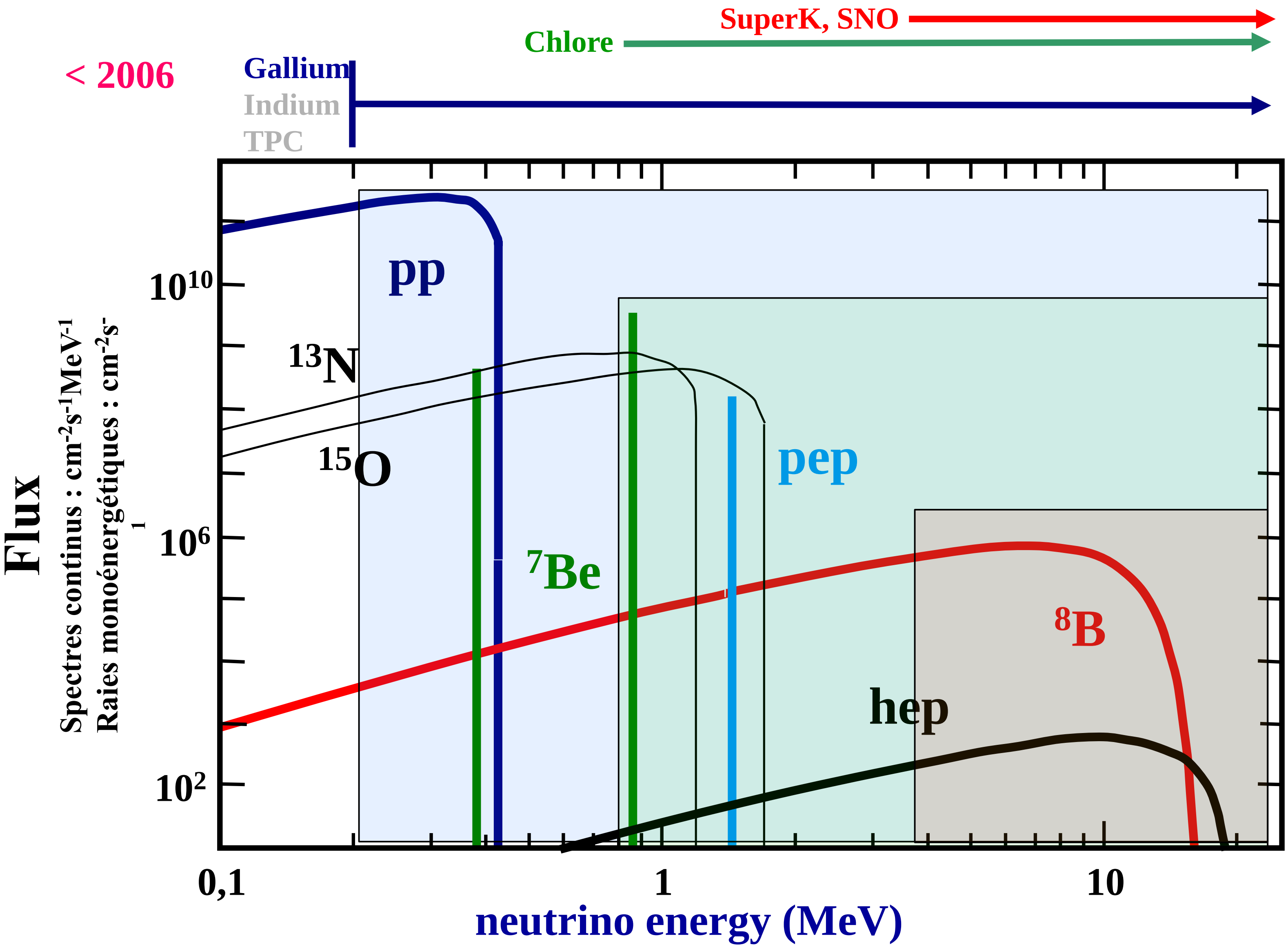
X_{in} (H), Y_{in}(He), Z_{in}(metals)=$1-X_{in} - Y_{in}$

- **Tested by helioseismology**

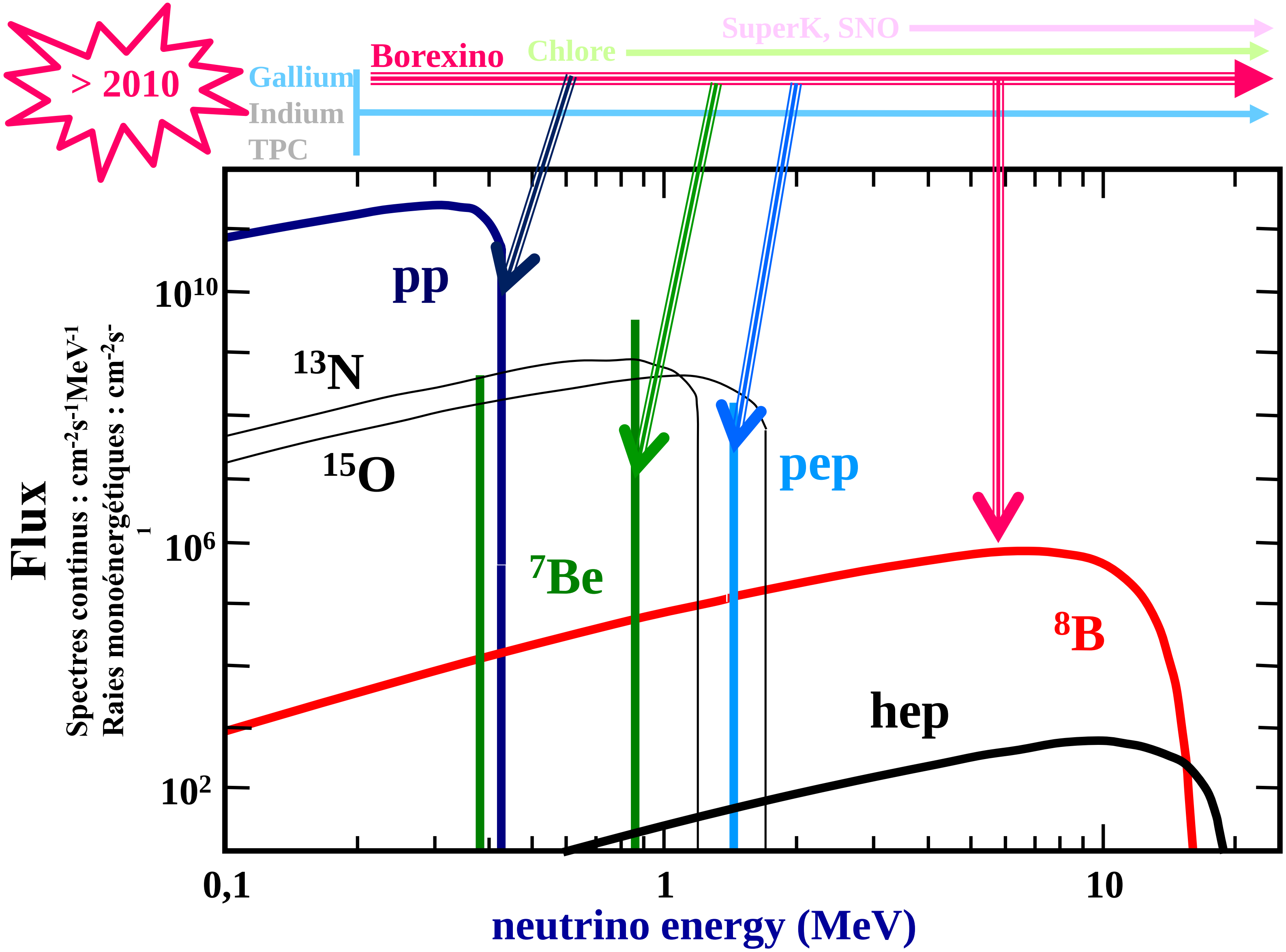
http://www.sns.ias.edu/~jnb/

Note: Read the paper (anche in italiano)
http://www.sns.ias.edu/~jnb/Papers/Popular/Nobelmuseum/italianmystery.pdf

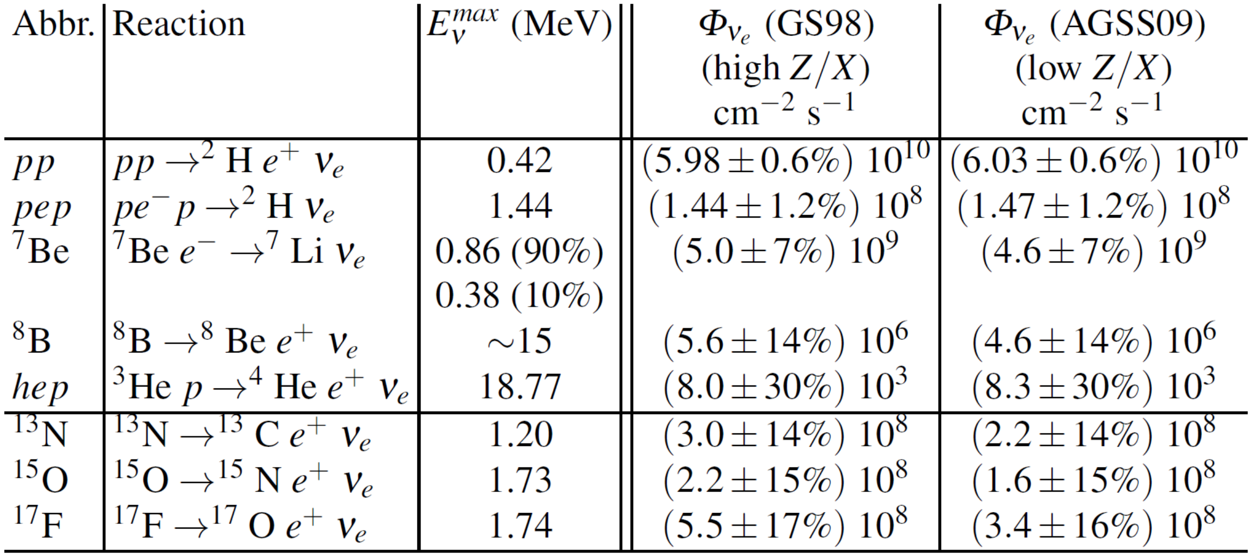
Output: differential ν_e flux



Differential ν_e flux



The predictions of the SSM



Abbr.	Reaction	E_ν^{max} (MeV)	Φ_{ν_e} (GS98) (high Z/X) $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	Φ_{ν_e} (AGSS09) (low Z/X) $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
pp	$pp \rightarrow {}^2\mathrm{H}\ e^+\ \nu_e$	0.42	$(5.98 \pm 0.6\%)\ 10^{10}$	$(6.03 \pm 0.6\%)\ 10^{10}$
pep	$pe^-p \rightarrow {}^2\mathrm{H}\ \nu_e$	1.44	$(1.44 \pm 1.2\%)\ 10^{8}$	$(1.47 \pm 1.2\%)\ 10^{8}$
^{7}Be	$^7\mathrm{Be}\ e^- \rightarrow {}^7\mathrm{Li}\ \nu_e$	0.86 (90%) 0.38 (10%)	$(5.0 \pm 7\%)\ 10^{9}$	$(4.6 \pm 7\%)\ 10^{9}$
^{8}B	$^8\mathrm{B} \rightarrow {}^8\mathrm{Be}\ e^+\ \nu_e$	~15	$(5.6 \pm 14\%)\ 10^{6}$	$(4.6 \pm 14\%)\ 10^{6}$
hep	$^3\mathrm{He}\ p \rightarrow {}^4\mathrm{He}\ e^+\ \nu_e$	18.77	$(8.0 \pm 30\%)\ 10^{3}$	$(8.3 \pm 30\%)\ 10^{3}$
^{13}N	$^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C}\ e^+\ \nu_e$	1.20	$(3.0 \pm 14\%)\ 10^{8}$	$(2.2 \pm 14\%)\ 10^{8}$
^{15}O	$^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N}\ e^+\ \nu_e$	1.73	$(2.2 \pm 15\%)\ 10^{8}$	$(1.6 \pm 15\%)\ 10^{8}$
^{17}F	$^{17}\mathrm{F} \rightarrow {}^{17}\mathrm{O}\ e^+\ \nu_e$	1.74	$(5.5 \pm 17\%)\ 10^{8}$	$(3.4 \pm 16\%)\ 10^{8}$

- Most of the Sun ν's from the first step of the pp chain.
- These ν's have energy very low (<0.425 MeV) → very difficult to detect.
- A rare side branch produces the "^{8}B" ν's with a maximum energy of ~15 MeV
- ^{8}B are the easiest ν's to observe, because the cross section increases with energy.
- A very rare interaction in the pp chain produces the "hep" neutrinos.
- All of the interactions described above produce ν's with a spectrum of energies. The inverse beta decay of ^{7}Be produces mono-energetic ν's at either ~ 0.9 or ~ 0.4 MeV.

Experimental Methods

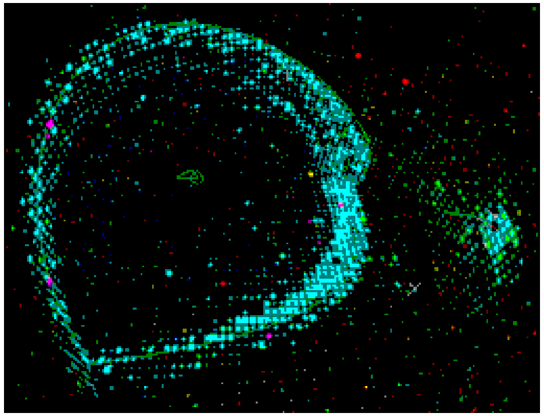
Detection methods for detecting solar neutrinos:

1- elastic scattering (*)

$$\nu_x + e \rightarrow \nu_x + e$$

(* ν_e channel dominant due to W exchange)

SK



2- Neutron capture on nuclei

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

No free neutrons in nature:

$$(Z,A) + \nu_e \rightarrow e + (Z+1,A)$$

Examples:

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

$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e$

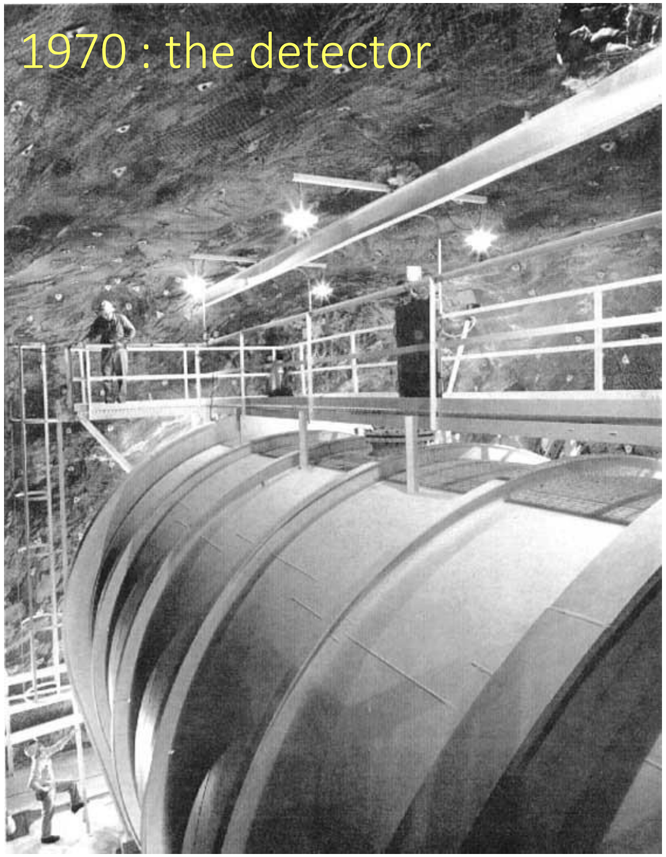
3- The SNO way:

- $\nu_e + d \rightarrow e + p + p$
- $\nu_x + d \rightarrow \nu_x + n + p$

Solar ν_e experiments

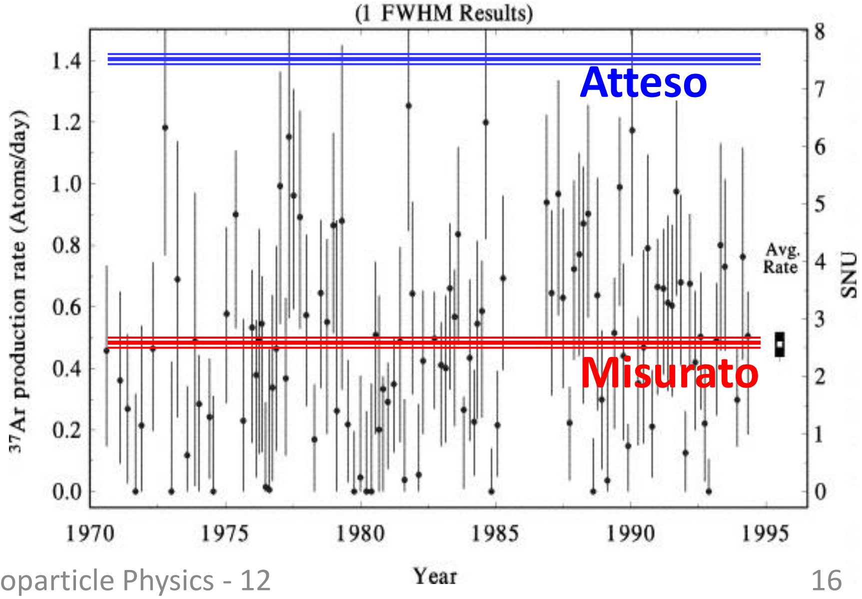
Detector	Target mass	Threshold [MeV]	Data taking
Homestake	615 tons C_2Cl_4	0.814	1970-1994
Kamiokande II/III	3ktons H_2O	7.5 / 7.0	1983-1995
SAGE	50tons molted metal Ga	0.233	**1989-pre** **>2019 ?**
GALLEX	30.3tons $GaCl_3$-HCl	0.233	1991-1997
GNO	30.3tons $GaCl_3$-HCl	0.233	1998-2003
Super-Kamiokande	22.5ktons	5 7 4.5 3.5	1996-2001 2003-2005 2006-2008 **2008-present**
SNO	1kton D_2O	3.5	1999-2006
Borexino	300ton C_9H_{12}	0.2 MeV	**2007-** **2022**

Clorine (Davis) pioneering experiment (1970-94)



- Pioneering experiment by Ray Davis at Homestake mine (S. Dakota) began in 1967
- Threshold: 0.8 MeV
- Consisted of a 600 ton chlorine tank
- Measured rate: 0.48 counts/d (bck:0.09/d)
- Experiment was carried out over 20 year
- The Ar returns to Cl (electron capture). The new Cl atom has one electron missing → X-ray cascade

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



SNU= 10^{-36} (interactions/s · nucleus)

1/3 of expected from Sun models (7.6 ± 1.2 SNU)

B.T.Cleveland et al., Ap. J. 496 (1998) 505

The Solar Neutrino Problem, after *Clorine* (1980)

How can this deficit be explained?

1. The Sun's reaction mechanisms are not fully understood

   NO! *new measurements (~1998) of the sun resonant cavity frequencies*

2. The experiment is wrong –

   NO! *All the forthcoming new experiments confirmed the deficit!*

3. Something happens to the neutrino as it travels from the Sun to the Earth

   YES! *Oscillations of electron neutrinos!*

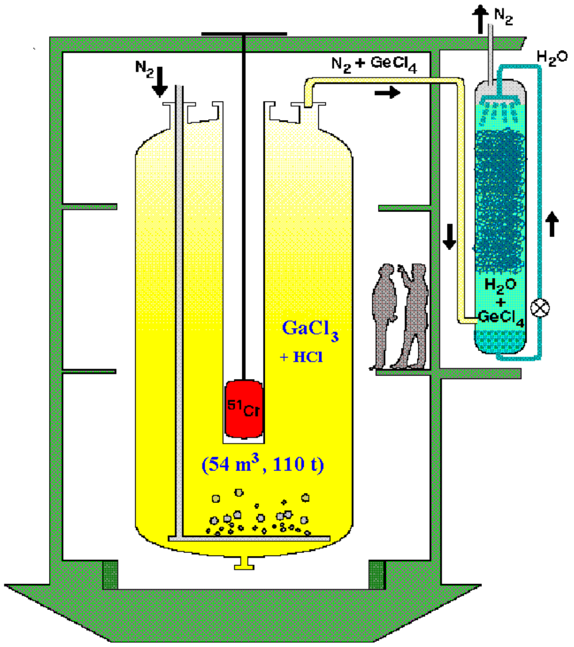
GALLEX/GNO (1991- 2003) and SAGE (1989-2019?)

- The main solar neutrino source is from the p-p reaction:
  - $p + p \rightarrow d + e^+ + \nu_e + 0.42\mathrm{MeV}$
- Experiments based on the reaction: $^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$

- Radiochemical experiments, like Homestake
- Energy threshold: (233.2 ± 0.5) keV, below the p-p neutrino (420 keV)
- **SAGE**: Located at the Baksan Neutrino Observatory in the Caucasus mountains of Russia (1990-2000); Used 50 t of Ga (molten metal at 30^o)
- **GALLEX/GNO**: Located at the Gran Sasso; 30 t of Ga in the form of $\mathrm{GaCl_3}$
- The produced ^{71}Ge has half-life of 11.4 d; in GALLEX the $\mathrm{GeCl_4}$ molecule was recovered by bubbling Ni through the solution and scrubbing the gas

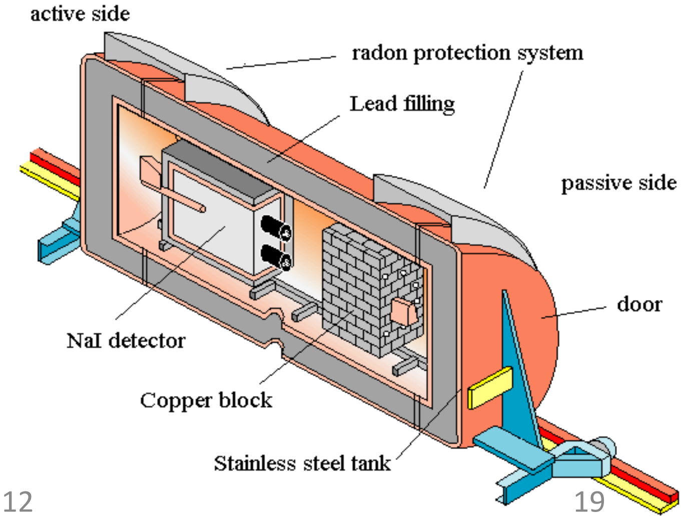
GALLEX/GNO @ LNGS (1991- 2003)

- 30.3 tons of gallium in form of a concentrated $GaCl_3$-HCl solution
- Neutrino induced ^{71}Ge forms the volatile compound $GeCl_4$
- Nitrogen gas stream sweeps $GeCl_4$ out of solution
- $GeCl_4$ is absorbed in water $GeCl_4 \rightarrow GeH_4$ and introduced into a proportional counter

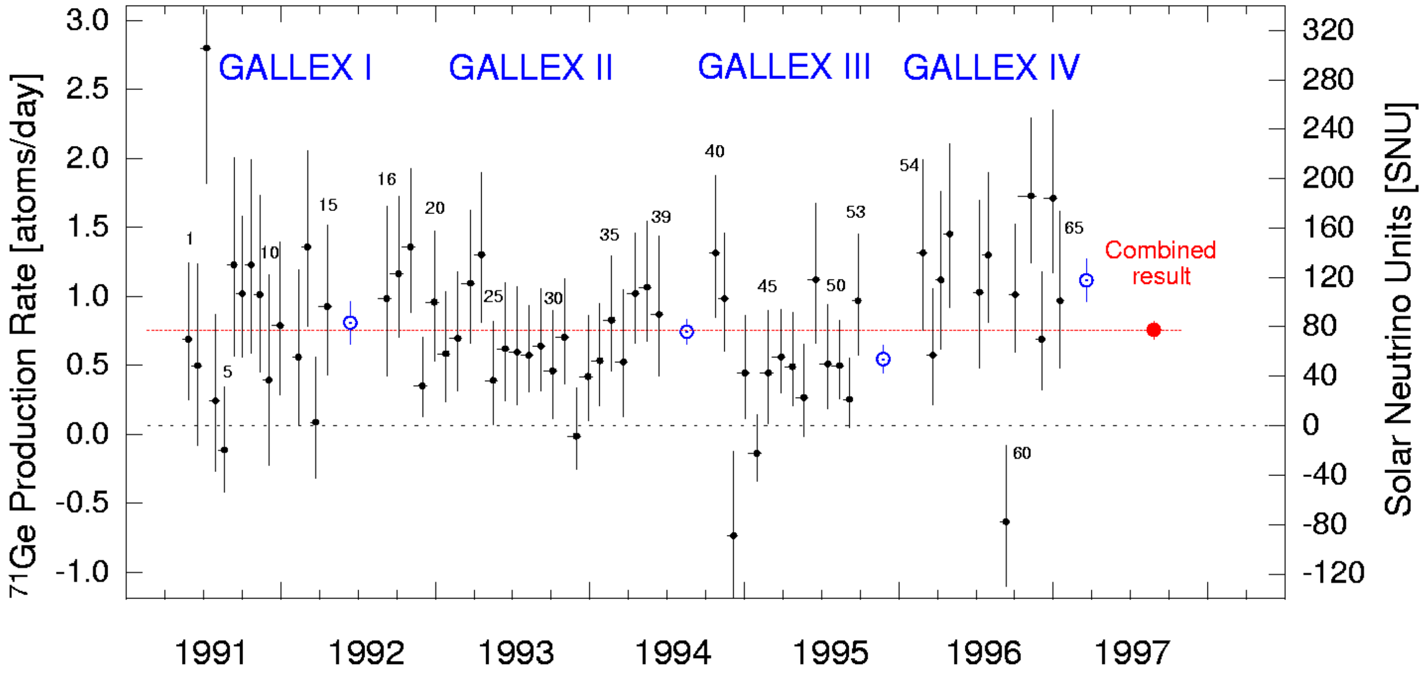


Calibration

- Important improvement w.r.t. Homestake:
- Number of ^{71}Ge atoms evaluated by their radioactive decay



GALLEX-SAGE results

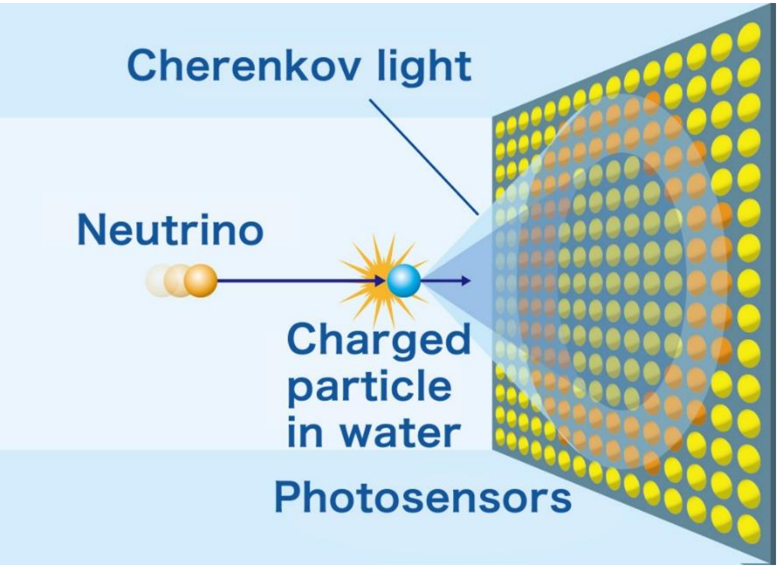


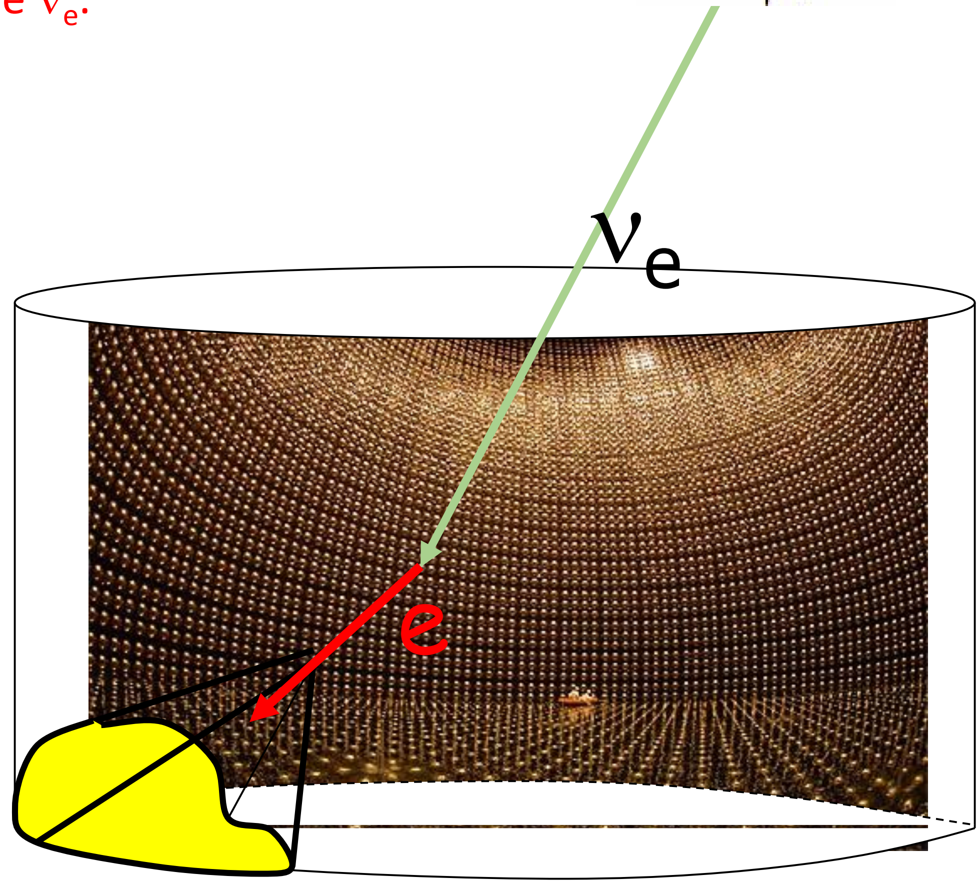
	GALLEX+GNO (SNU)	SAGE (SNU)
Measured	71 ± 5	66 ± 5
Expected	128 ± 8	128 ± 8

SNU= 10^{-36} (interactions/s · nucleus)

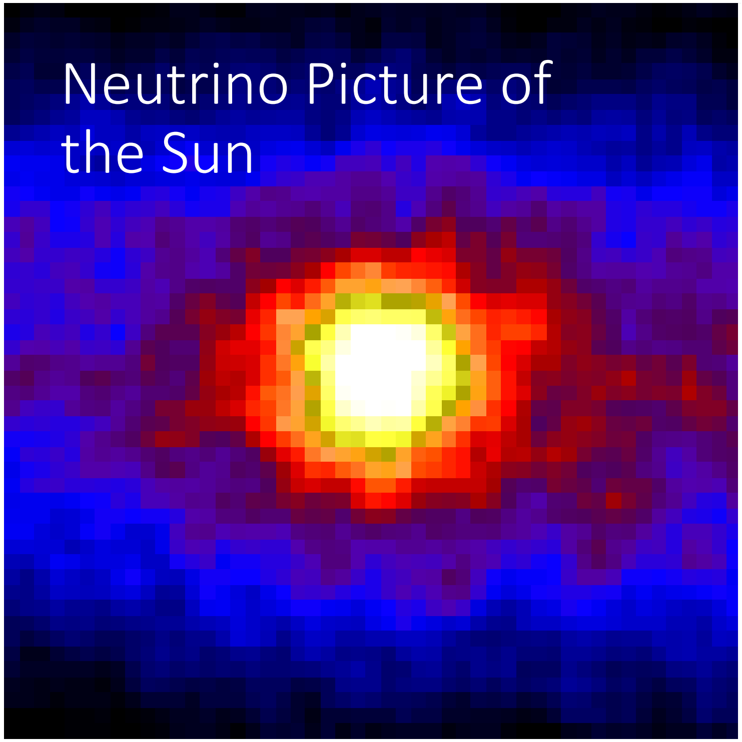
SuperKamiokande (1996→): ES $\nu_x\, e \rightarrow \nu_x\, e$

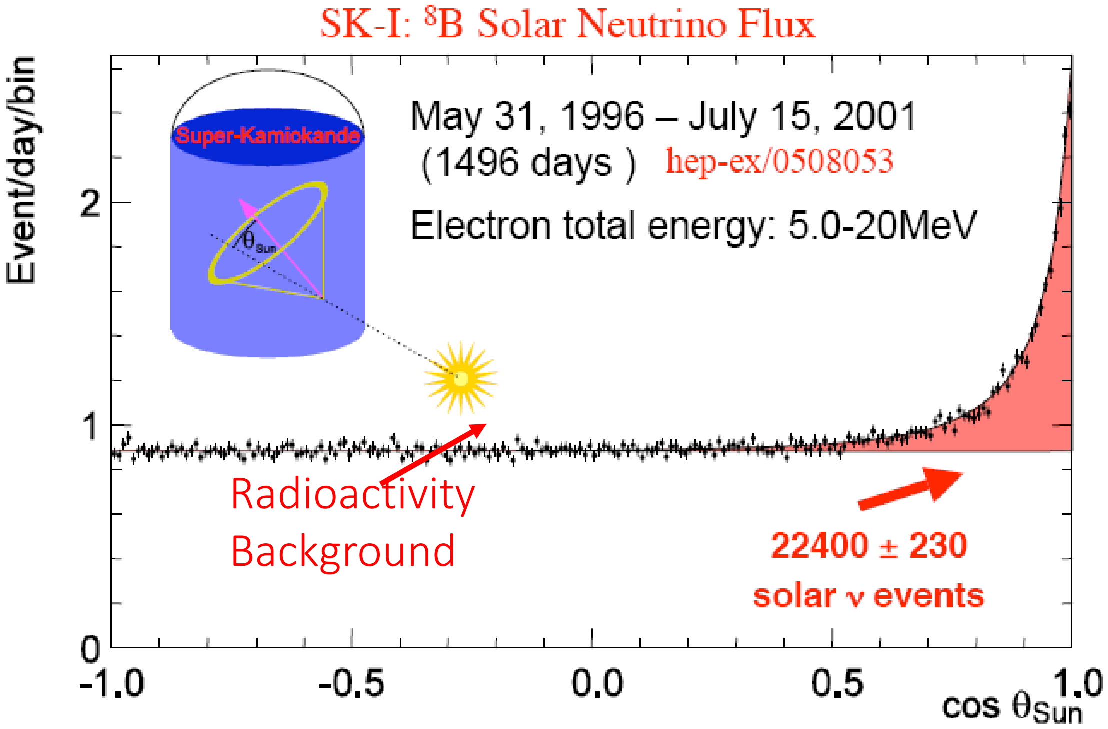
Question 3: Explain why in the Elastic Scattering (ES) reaction the contribution of the $\nu_\mu+\nu_\tau$ flux on the event rate is only 1/6 of that of the ν_e.
(Note: the same is valid for SNO)





SuperKamiokande: ES $\nu_x\, e \rightarrow \nu_x\, e$


Neutrino Picture of the Sun


SK-I: ^{8}B Solar Neutrino Flux

May 31, 1996 – July 15, 2001 (1496 days) hep-ex/0508053

Electron total energy: 5.0-20MeV

Radioactivity Background

22400 ± 230 solar ν events

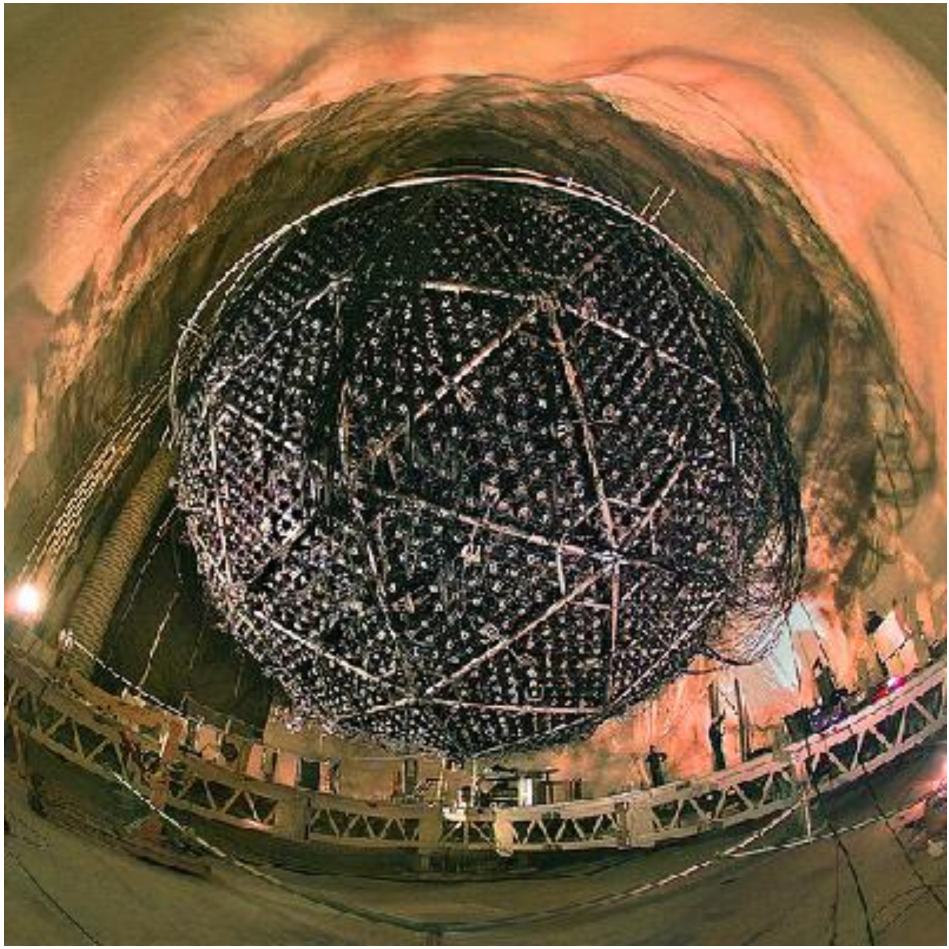
$$\phi_{ES} = 2.35 \pm 0.02 \pm 0.08 \ [\times 10^6/\mathrm{cm}^2/\mathrm{s}]$$

- SK measured a flux of solar neutrinos with energy > 5 MeV (from B^8) about 40% of that predicted by the SSM
- The reduction is almost constant up to 18 MeV

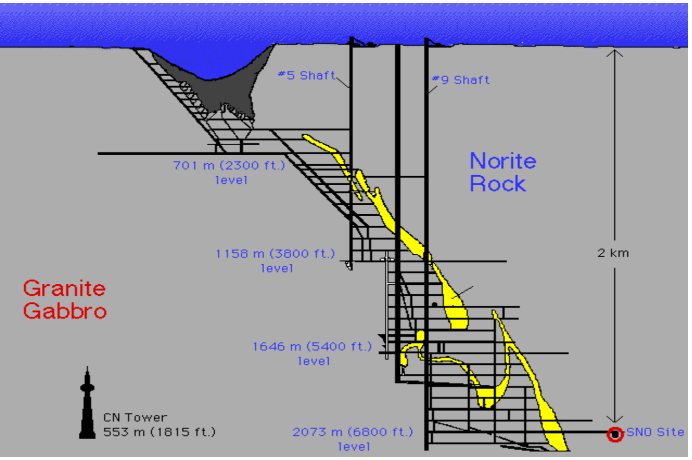
The decisive results: SNO (1999 –2006)

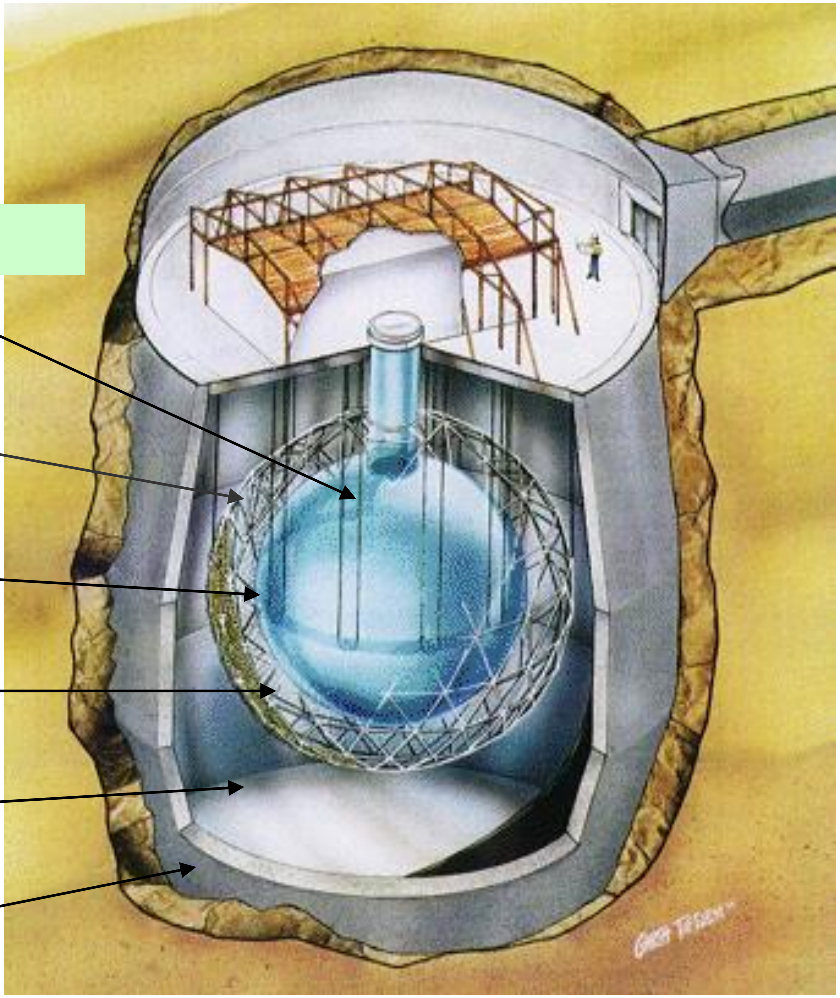
- 18 m sphere underground (~2.5km), in Ontario - Canada
- Heavy water (D_2O) inside a transparent acrylic sphere (12m diameter)
- 10,000 photomultiplier tubes (PMTs)
- PMTs collect Cherenkov light photons
- Pure salt is added to increase sensitivity of NC reactions (≥2002)
- SNO measure the flux of all flavors '$\Phi(\nu_x)$' from NC and electron neutrinos '$\Phi(\nu_e)$' with CC
- The flux of non-electron neutrinos is

$$\Phi(\nu_\mu, \nu_\tau) = \Phi(\nu_x) - \Phi(\nu_e)$$



Sudbury Neutrino Observatory (SNO)





1000 tons D_2O

Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

Urylon Liner and Radon Seal

ν Reactions in SNO

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

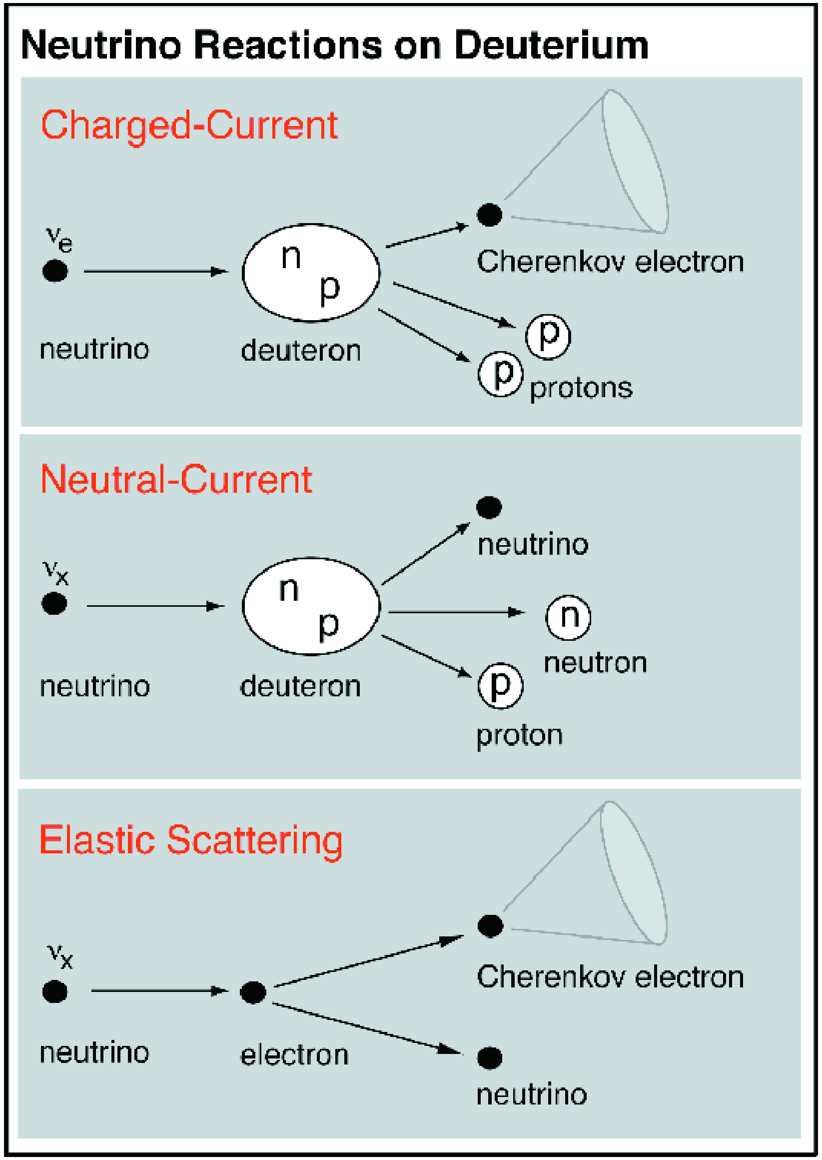
- Gives ν_e energy spectrum well
- Weak direction sensitivity ∝ 1-1/3cos(θ)
- ν_e only.
- SSM: 30 CC events day^{-1}

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

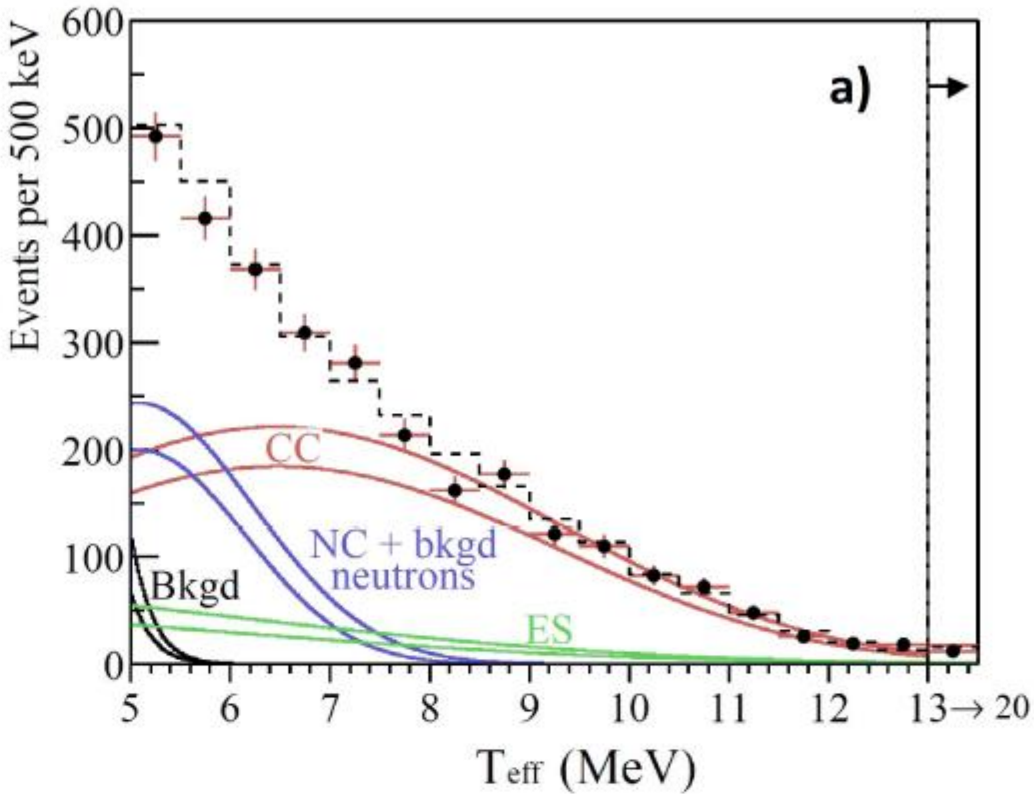
- Measure total ^{8}B ν flux from the sun.
- Equal cross section for all ν types
- SSM: 30/day

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

- Low Statistics (3/day)
- Mainly sensitive to $\nu_{e,}$, some
  - sensitivity to ν_μ and ν_τ
- Strong direction sensitivity



2001- Total spectrum (NC + CC + ES)



Pure D_2O

Nov 99 – May 01

$n + d \rightarrow t + \gamma$

(E_γ = 6.25 MeV)

PRL **87**, 071301 (2001)

PRL **89**, 011301 (2002)

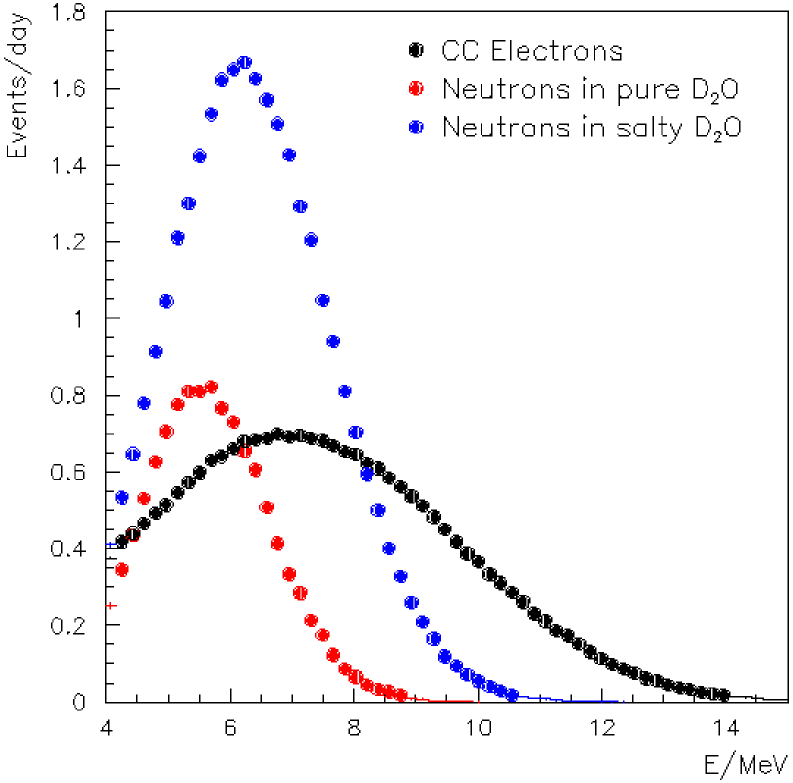
PRL **89**, 011302 (2002)

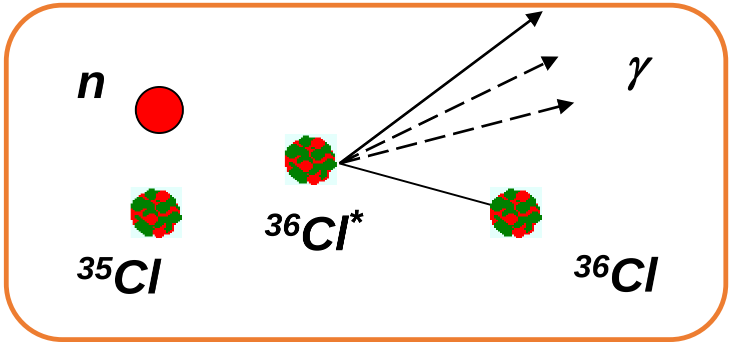
PRC **75**, 045502 (2007)

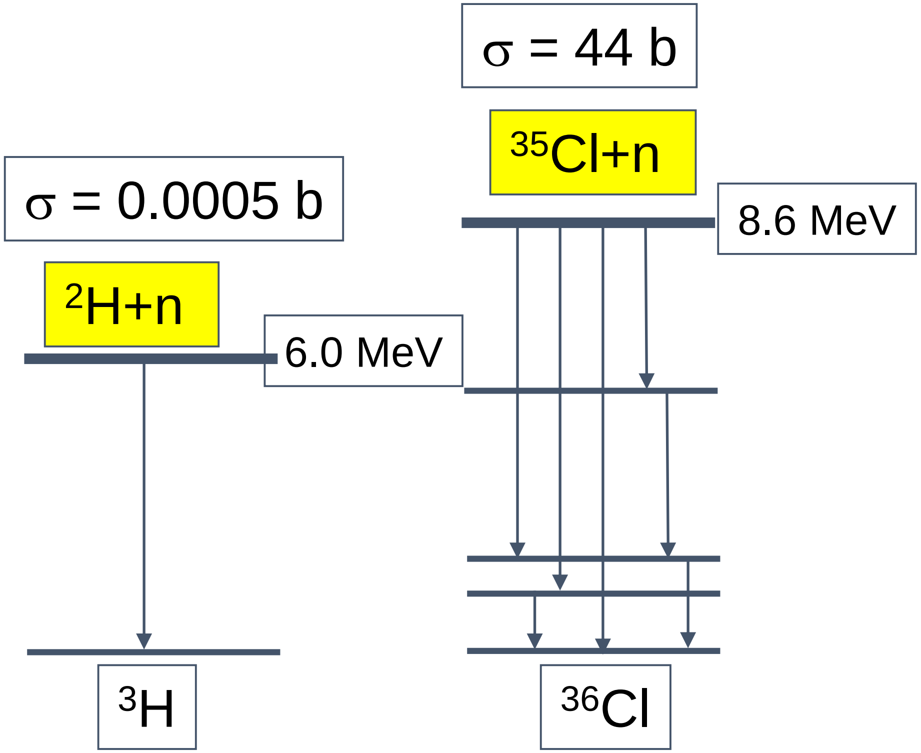
Kinetic energy spectrum (points) for events with measured energy T_{eff}> 5MeV occurring inside the fiducial region (R < 550 cm) in the SNO-I. Also shown are the Monte Carlo predictions for charged-current (CC = red lines), elastic scattering (ES = green lines), and neutral current (NC) and background (bkgd) neutron events (blue lines). The simulations are scaled to fit the results. The dashed line represents the summed components, and the bands show the statistical uncertainties from the signal-extraction fit.

2002 (Salt): increased *neutron* capture

- Higher capture cross section of ν on Cl
- Higher energy release
- Many gammas







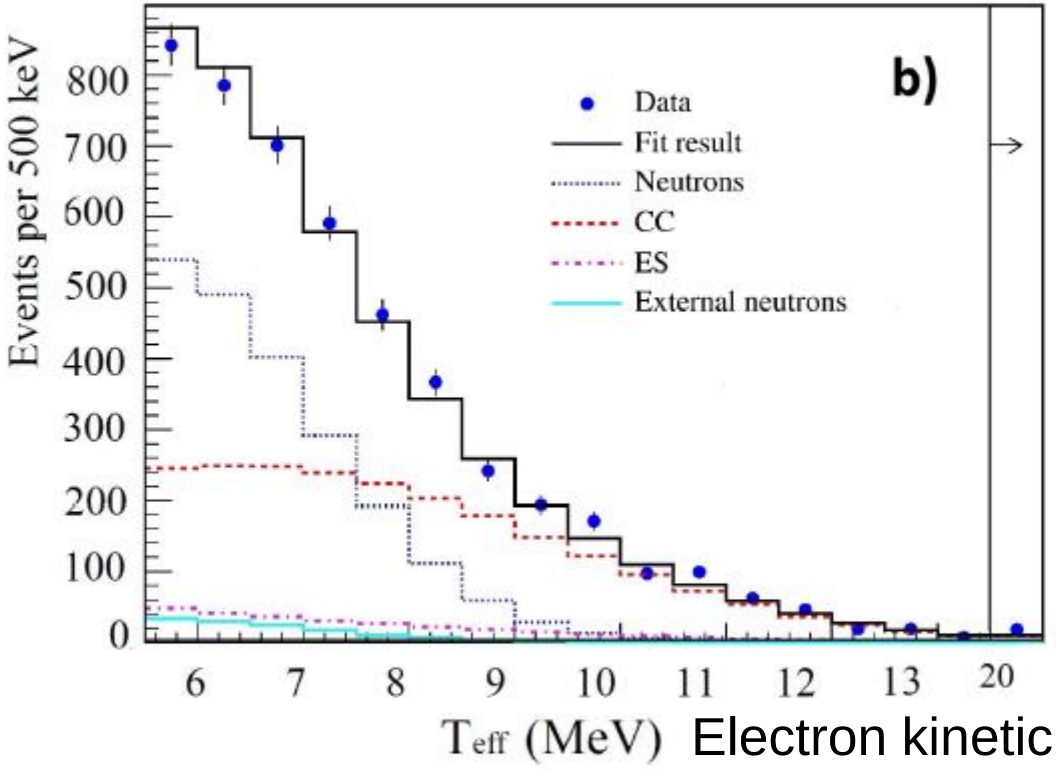
2003: SNO Energy spectra (Salt data)

UNITS:
x 10^6 cm^{-2} s^{-1}

$$\phi_{CC}^{SNO} = 1.59^{+0.08}_{-0.07}(\mathrm{stat})^{+0.06}_{-0.08}(\mathrm{syst})$$

~~$\phi_{ES}^{SNO} = 2.21^{+0.31}_{-0.26}(\mathrm{stat}) \pm 0.10\ (\mathrm{syst})$~~

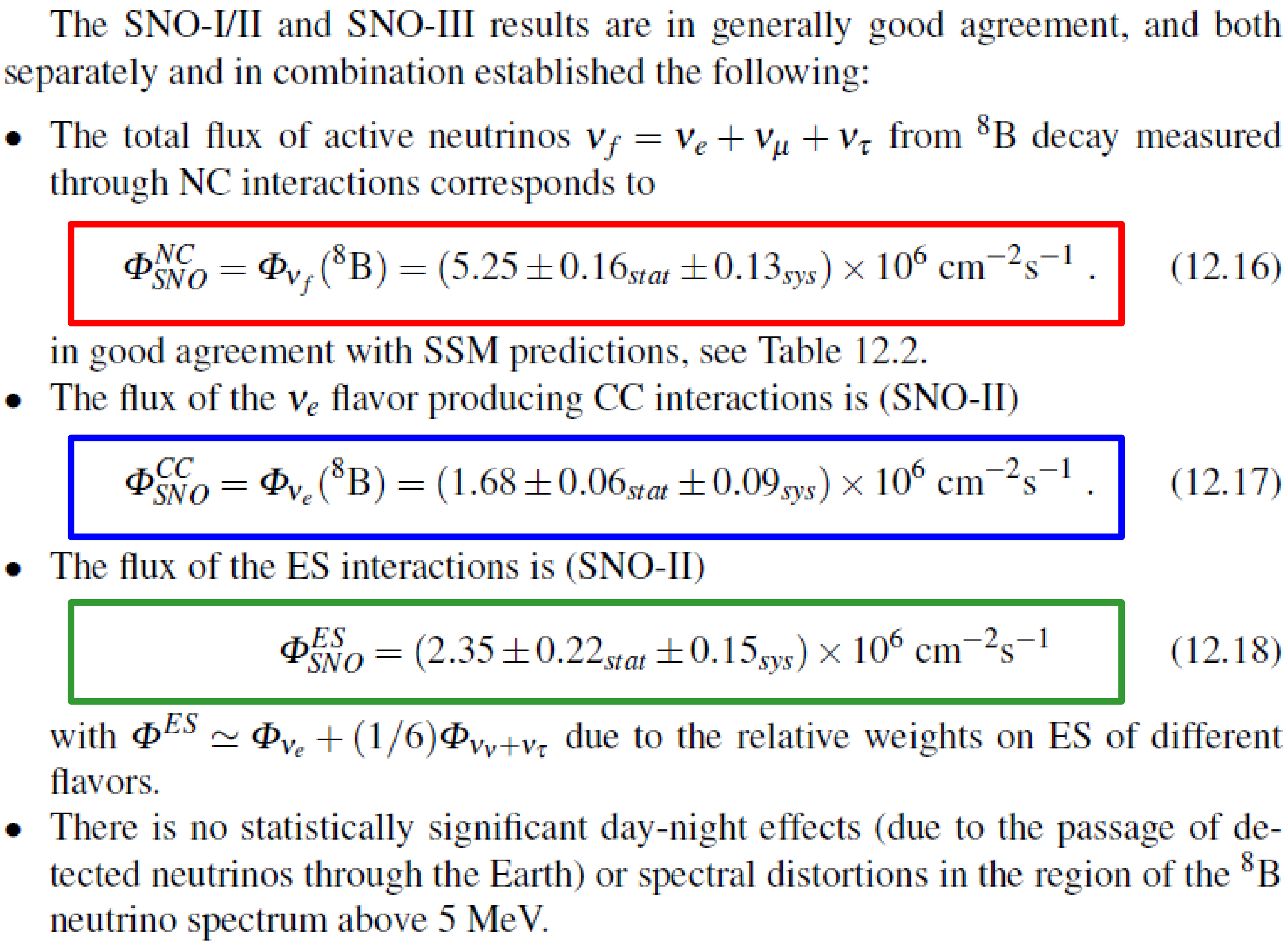
$$\phi_{NC}^{SNO} = 5.21 \pm 0.27\ (\mathrm{stat}) \pm 0.38\ (\mathrm{syst})$$



Electron kinetic energy

ATTESO:
Bahcall et al. – SSM= **5.05±0.8**

Final SNO Solar ν Results



The SNO-I/II and SNO-III results are in generally good agreement, and both separately and in combination established the following:

- The total flux of active neutrinos $\nu_f = \nu_e + \nu_\mu + \nu_\tau$ from ^{8}B decay measured through NC interactions corresponds to

$$\boxed{\Phi^{NC}_{SNO} = \Phi_{\nu_f}(^8\mathrm{B}) = (5.25 \pm 0.16_{stat} \pm 0.13_{sys}) \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\ .} \tag{12.16}$$

  in good agreement with SSM predictions, see Table 12.2.

- The flux of the ν_e flavor producing CC interactions is (SNO-II)

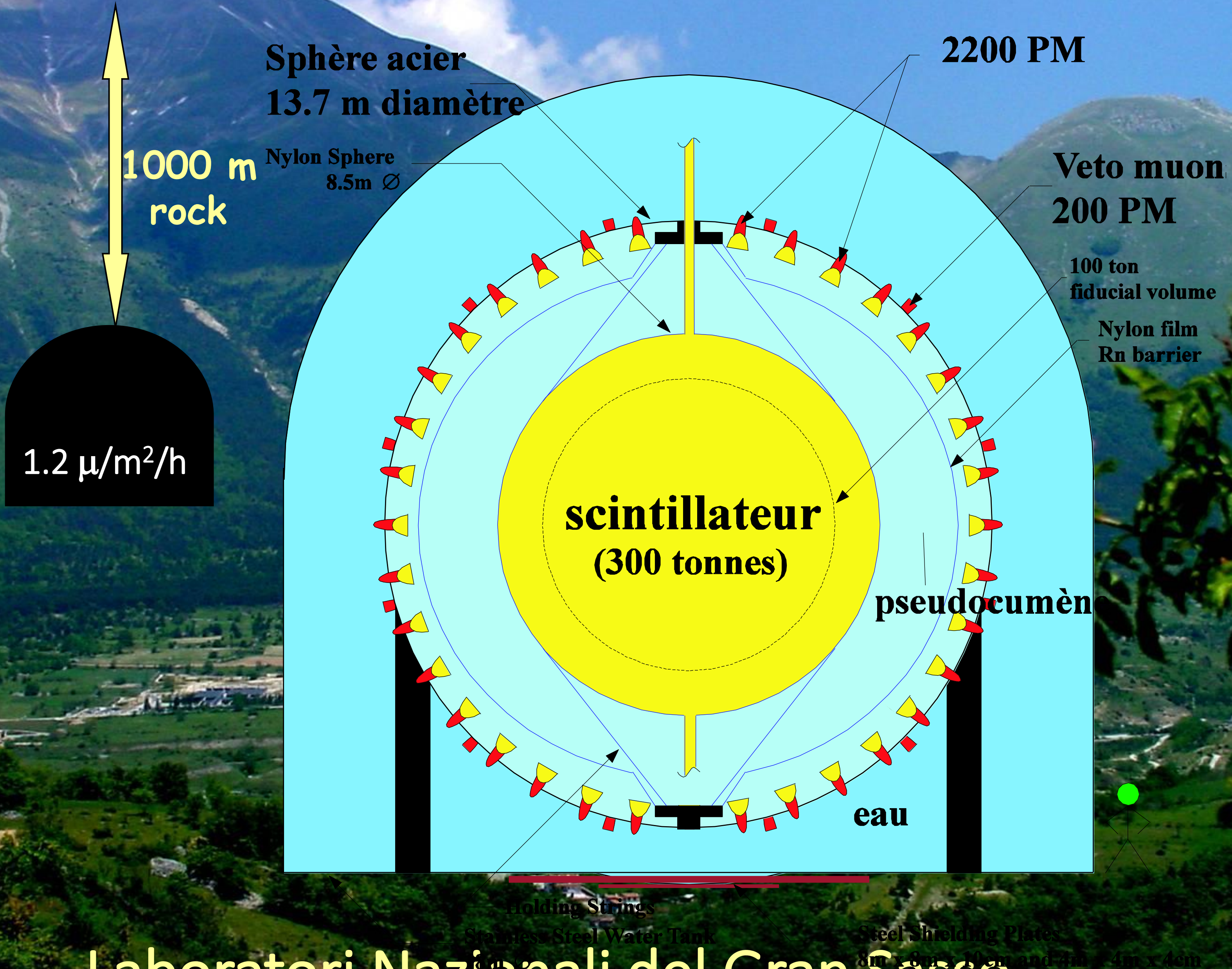
$$\boxed{\Phi^{CC}_{SNO} = \Phi_{\nu_e}(^8\mathrm{B}) = (1.68 \pm 0.06_{stat} \pm 0.09_{sys}) \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\ .} \tag{12.17}$$

- The flux of the ES interactions is (SNO-II)

$$\boxed{\Phi^{ES}_{SNO} = (2.35 \pm 0.22_{stat} \pm 0.15_{sys}) \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}} \tag{12.18}$$

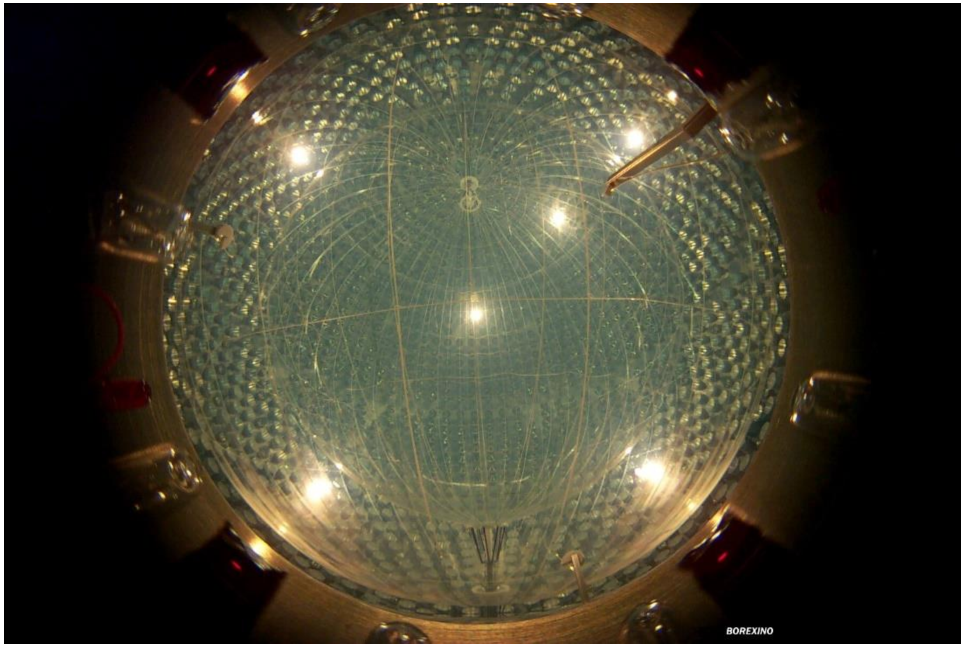
  with $\Phi^{ES} \simeq \Phi_{\nu_e} + (1/6)\Phi_{\nu_\nu + \nu_\tau}$ due to the relative weights on ES of different flavors.

- There is no statistically significant day-night effects (due to the passage of detected neutrinos through the Earth) or spectral distortions in the region of the ^{8}B neutrino spectrum above 5 MeV.



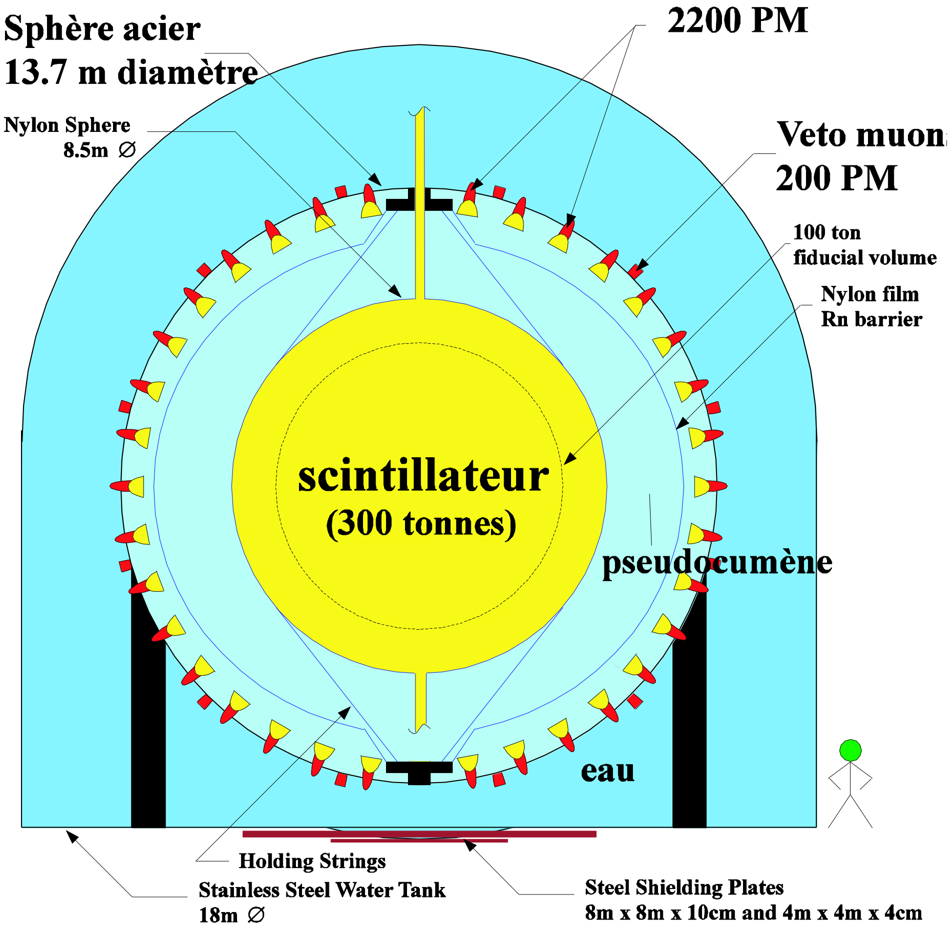
Laboratori Nazionali del Gran Sasso

Borexino filled with scintillator (2007-2022)



- Borexino has a layout similar to SNO, but it measures the ν_ee elastic scattering (ES) using a liquid scintillator as the active target.
- It is located at the Laboratori Nazionali del Gran Sasso, and started its data-taking in 2007.
- The suppression of the radioactivity of the scintillator itself has been achieved using several radio-purification techniques.
- This allows Borexino to test the SSM using neutrinos of lower energy than the 8B.
- The detector consists of 278 tons of a high-purity liquid scintillator. The scintillation light yield is a measure of the energy imparted to the electron of the ES, but has no sensitivity to direction.
- The scintillation photons are detected with an array of 2,200 PMTs mounted on the inside surface of the stainless-steel sphere (light-yield ~500 photons/MeV, energy resolution is ~ 5% at 1MeV, and the position resolution is ~10–15 cm.

Borexino@LNGS (ES)



Elastic scattering

$$\nu e \rightarrow \nu e$$

Goal n° 1 : ^{7}Be neutrinos

Proposal :
60 event/ day (without oscillation)
10-40 (if oscillation)

$5\ 10^{-9}$ Bq/kg
1 water glass : 10 Bq

Background suppression (10 Orders of magnitude)

- ☺ x 50 times light w.r.t. Cherenkov
- ☹ No direction
- 💣 No distinction e^- Sun from e^- radioactivity

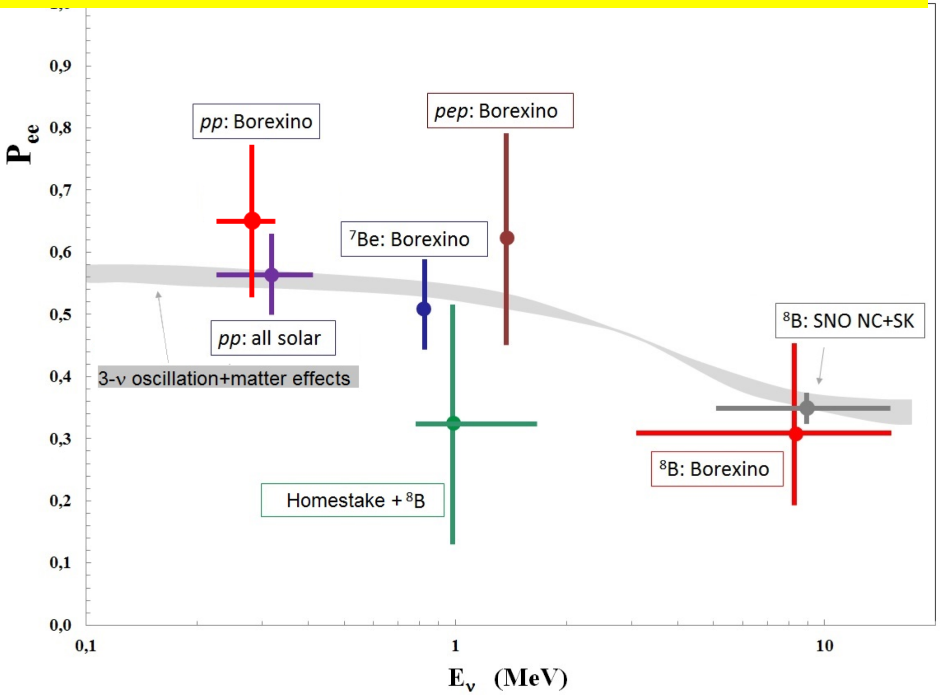
Neutrino oscillations and the Sun

ν React.	Interaction rate counts (day 100 ton)$^{-1}$	$(\frac{Data}{SSM})$ ratio	$\Phi_{\nu_e}(E)$ (10^8 cm^{-2} s^{-1})	$(\frac{Data}{SSM})/P_{ee}$ ratio
pp	$144 \pm 13 \pm 10$	0.64 ± 0.12	$(6.6 \pm 0.7) \times 10^2$	1.10 ± 0.22
^{7}Be	$46.0 \pm 1.5 \pm 1.6$	0.51 ± 0.07	48.4 ± 2.4	0.97 ± 0.09
pep	$3.1 \pm 0.6 \pm 0.3$	0.62 ± 0.17	1.6 ± 0.3	1.1 ± 0.2
^{8}B	$0.22 \pm 0.04 \pm 0.01$	0.31 ± 0.15	0.05 ± 0.01	0.91 ± 0.23
~~CNO~~	~~< 7.9~~	~~-~~	~~< 7.7~~	~~< 1.5~~
CNO	$\mathbf{7.2^{+3.0}_{-1.7}}$		$\mathbf{7.0^{+3.0}_{-2.0}}$	*Nature* **587** (2020) 577

Table: *Interaction rates of different ν measured by Borexino and the ratios w.r.t. SSM (column 3)*

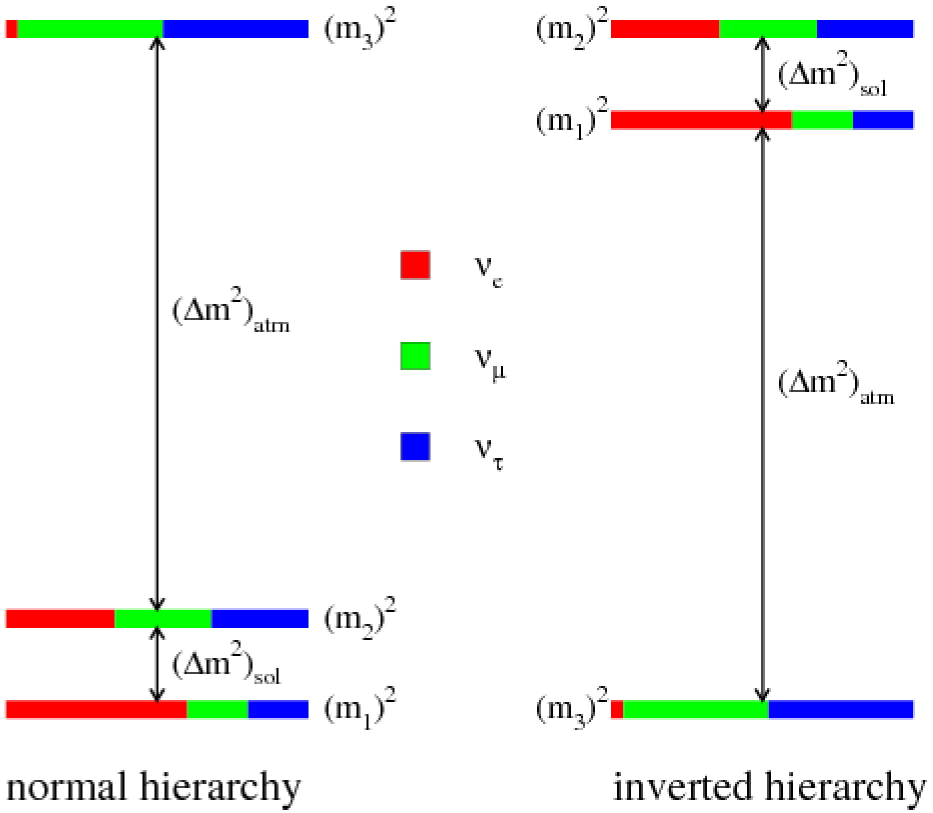
Figure:

- *Survival probability as a function of E_ν produced by the different reactions.*
- *The gray band represents the ratio between the expected flux on Earth and the SSM prediction when neutrino oscillations in the Sun matter are considered.*
- *Points with error bars represent measurements from different experiments..*

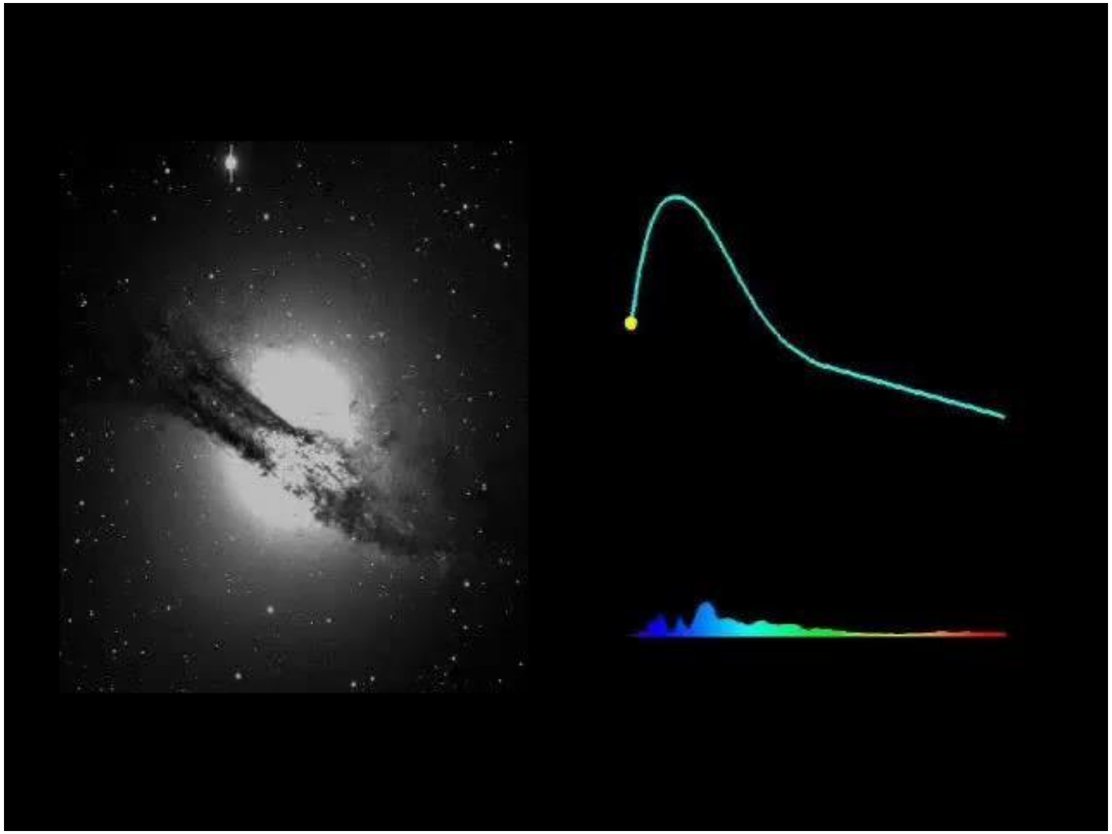


Neutrino oscillation parameters

Parameter	best-fit value ($\pm 1\sigma$)
$\Delta m^2_\odot$	$(7.58^{+0.22}_{-0.26}) \times 10^{-5}$ eV^2
Δm^2_{atm}	$(2.35^{+0.12}_{-0.09}) \times 10^{-3}$ eV^2
$\sin^2\theta_{12}$	$0.306^{+0.018}_{-0.015}$
$\sin^2\theta_{23}$	$0.42^{+0.08}_{-0.03}$
$\sin^2\theta_{13}$	0.0251 ± 0.0034



Neutrinos from a Stellar Gravitational Collapse



Three representations of a SN occurred in the Centaurus A galaxy.

The clip was prepared by the Supernova Cosmology Project (P. Nugent: spectral sequence; A. Conley: image sequence) with the help of Lawrence Berkeley National Laboratory's Computer Visualization Laboratory (N. Johnston: animation) at the National Energy Research Scientific Computing Center.

For a recent review: Supernova neutrinos: Production, oscillations and detection
A. Mirizzi, et al. Rivista del Nuovo Cimento 39, N1-2: https://arxiv.org/pdf/1508.00785.pdf

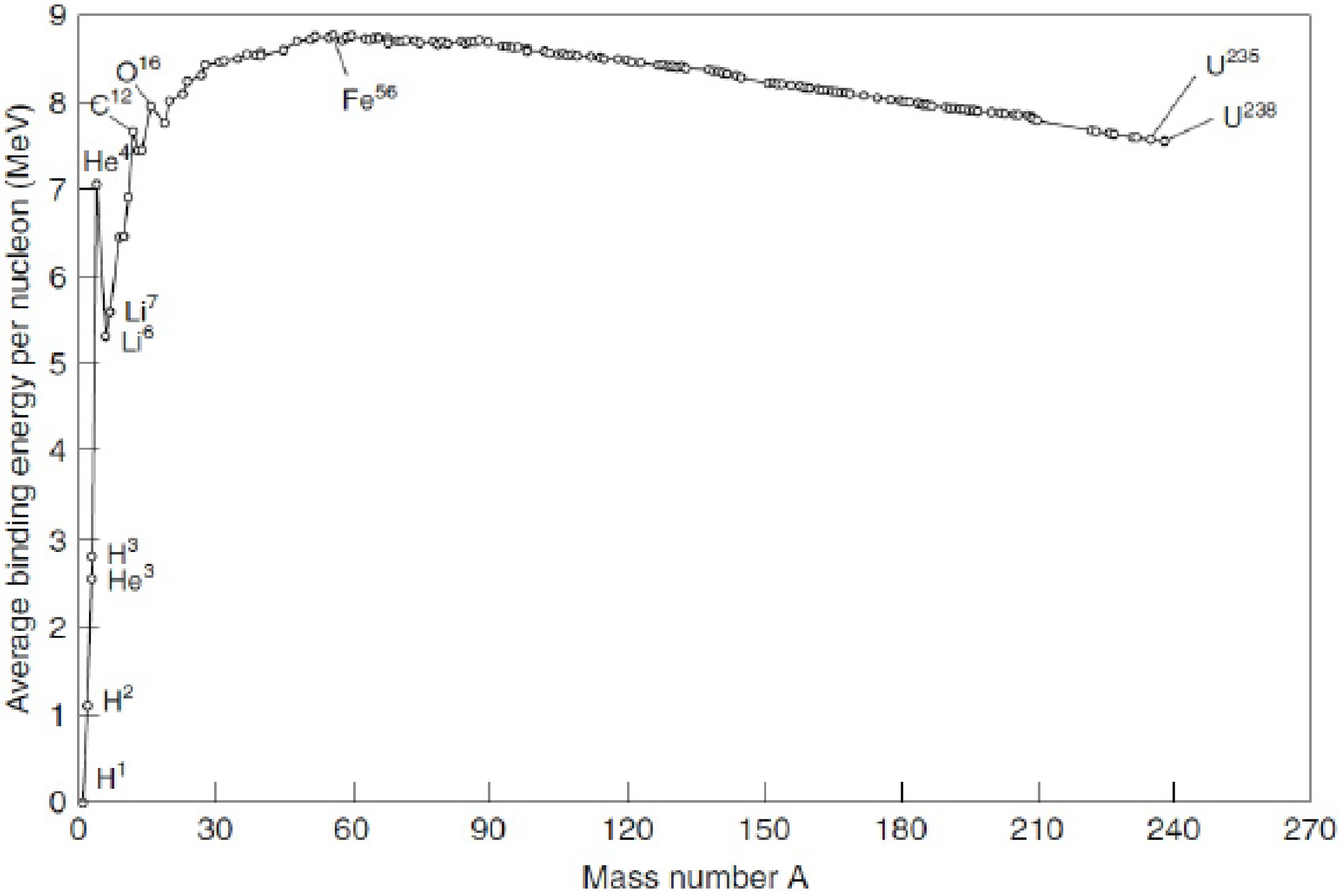
Recorded explosions visible to naked eye

SN1987A

Year (A.D.)	Where observed	Brightness
185	Chinese	Brighter than Venus
369	Chinese	Brighter than Mars or Jupiter
1006	China, Japan, Korea, Europe, Arabia	Brighter than Venus
1054	China, SW India, Arabia	Brighter than Venus
1572	Tycho	Nearly as bright as Venus
1604	Kepler	Brighter than Jupiter
1987	Ian Shelton (Chile)	

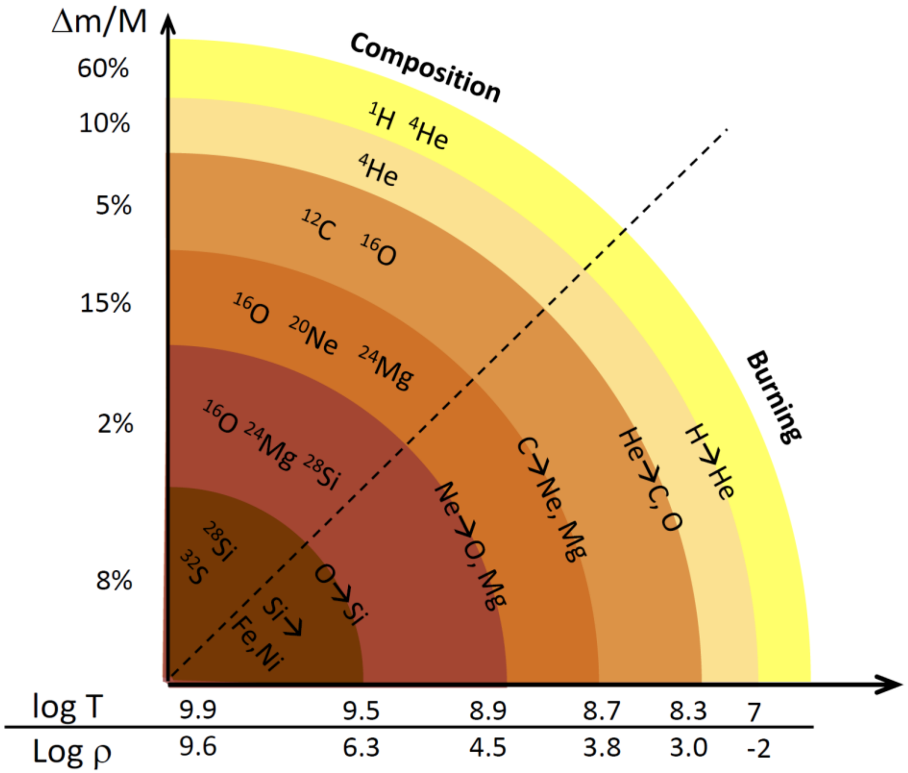
The nuclear binding energy

- H and He (produced after the Big Bang) are the most abundant elements
- The remaining elements, making up only about 2% of the Universe, have been produced as the result of stellar activities.
- Nuclear fusion in stars synthetize elements with mass number A up to 56.
- ^{56}Fe is one of the highest binding energies of all of the isotopes, and is the last element that releases energy by fusion.



Heavy elements in massive stars

- The onion-like structure in the final stage of a massive (25 M_s) star.
- The outermost envelope is composed of H and He, and progressively heavier nuclei (up to Fe) are layered, due to successive fusion reactions.
- Typical values of the mass, density ρ (in g/cm^3) and temperature T (in K) of the different shells are indicated along the axes



- Once the star's inner region is made primarily of Fe, further compression of the core no longer ignites nuclear fusion;
- the star is unable to thermo-dynamically support its outer envelope of concentric shells.
- The rest of the star, without the support of the radiation, collapses, compressing the nucleus, producing a **core-collapse supernova.**

Core-Collapse Supernovae (Type II)

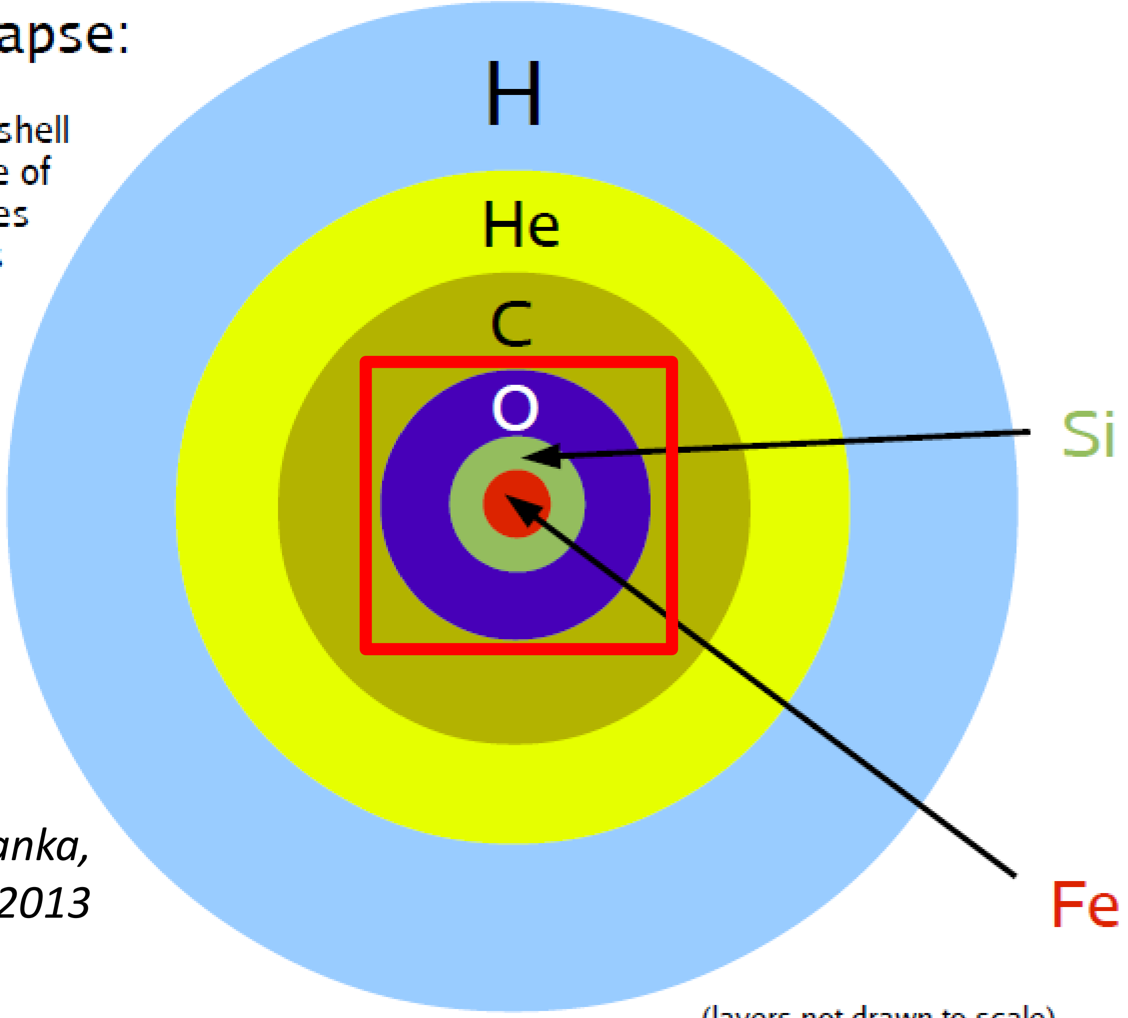
(see the details on the figures in the following slides)

- Stars with masses above eight solar masses undergo ***gravitational collapse***.
- Once the star’s core becomes constituted primarily of iron, further compression does not ignite nuclear fusion and the star is unable to support its outer envelope.
- As the surrounding matter falls inward under gravity, the temperature of the core rises and iron dissociates into α particles and nucleons.
- Electron capture on protons becomes heavily favored and electron neutrinos are produced as the core gets neutronized (a process known as ***neutronization***).
- When the core reaches densities above 10^{12} g/cm^3, neutrinos become trapped (in the so-called neutrinosphere).
- The collapse continues until 3 – 4 times nuclear density is reached, after which the inner core rebounds, sending a shock-wave across the outer core and into the mantle.
- This shock-wave loses energy as it heats the matter it traverses and incites further electron-capture on the free protons left in the wake of the shock.
- During the few milliseconds in which the shock-wave travels from the inner core to the neutrinosphere, electron neutrinos are released in a pulse. This neutronization burst carries away approximately **10^{51} ergs of energy**.

Description for a Type II Supernovae (I)

Evolved massive star
prior to its collapse:

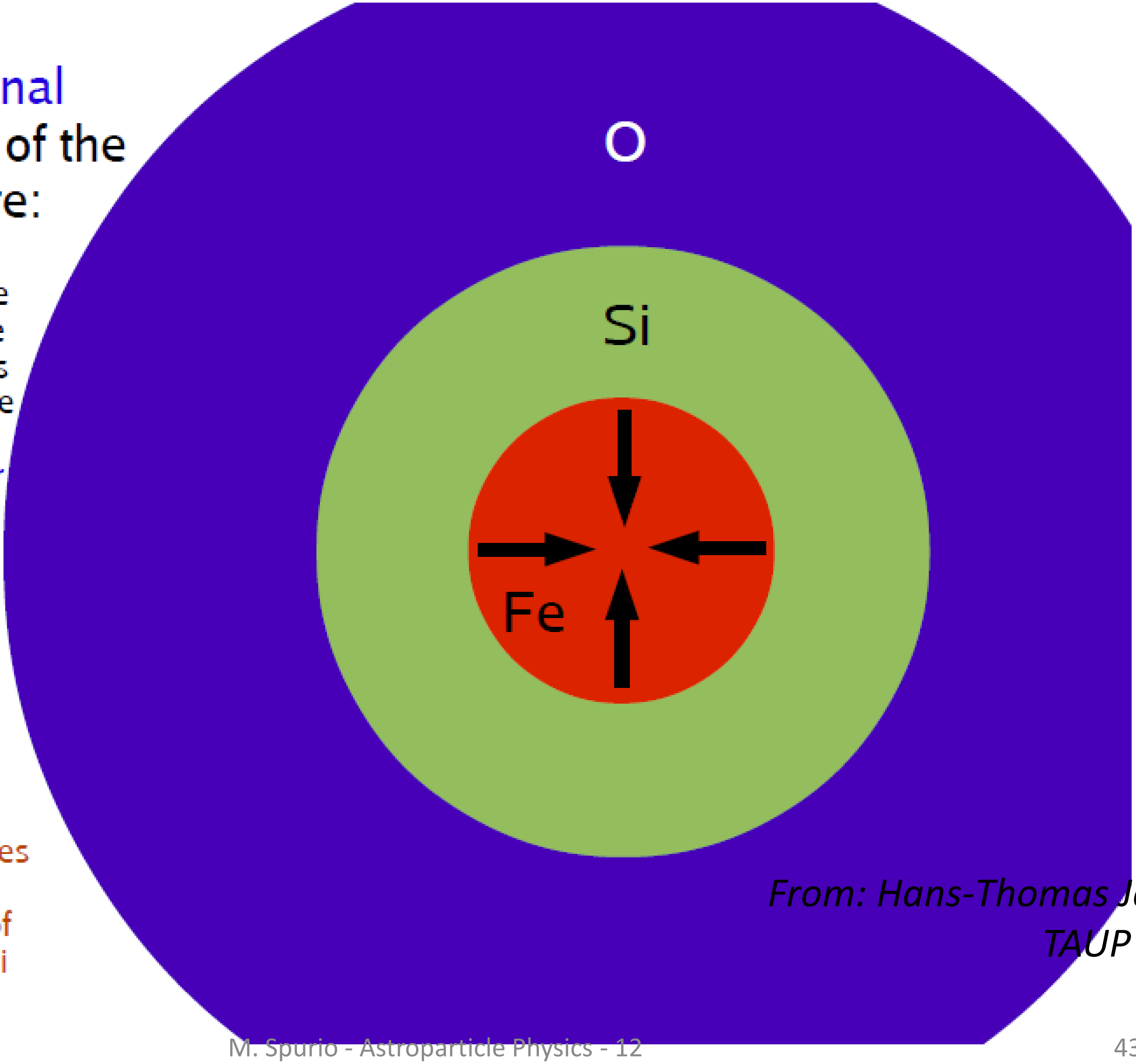
Star develops onion-shell structure in sequence of nuclear burning stages over millions of years



(layers not drawn to scale)

From: Hans-Thomas Janka, TAUP 2013

Description for a Type II Supernovae (II)



Gravitational instability of the stellar core:

Stellar iron core begins collapse when it reaches a mass near the critical Chandrasekhar mass limit

Collapse becomes dynamical because of electron captures and photo-disintegration of Fe-group nuclei

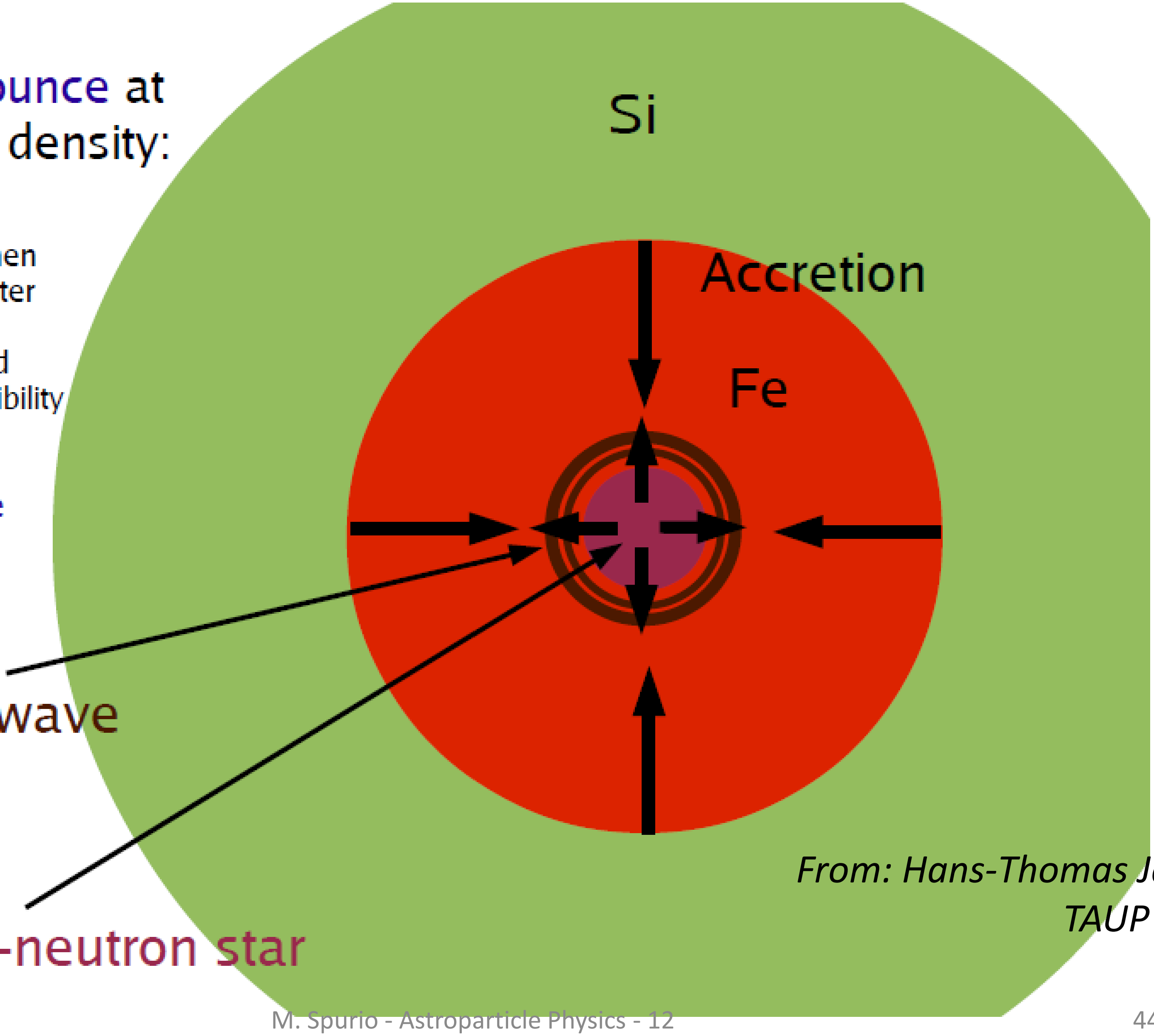
From: Hans-Thomas Janka, TAUP 2013

Description for a Type II Supernovae (III)

Core bounce at nuclear density:

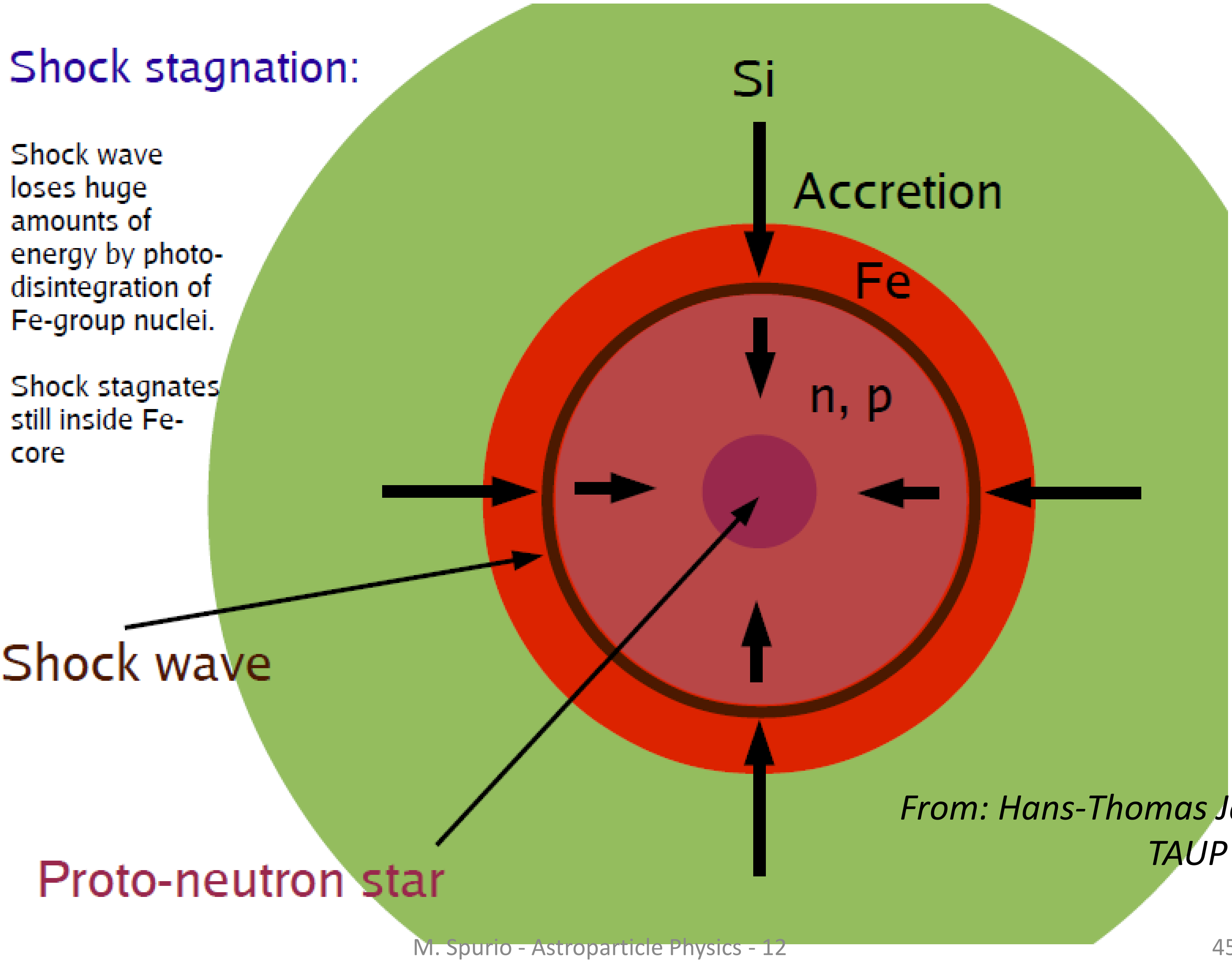
Inner core bounces when nuclear matter density is reached and incompressibility increases

Shock wave forms



From: Hans-Thomas Janka, TAUP 2013

Description for a Type II Supernovae (IV)



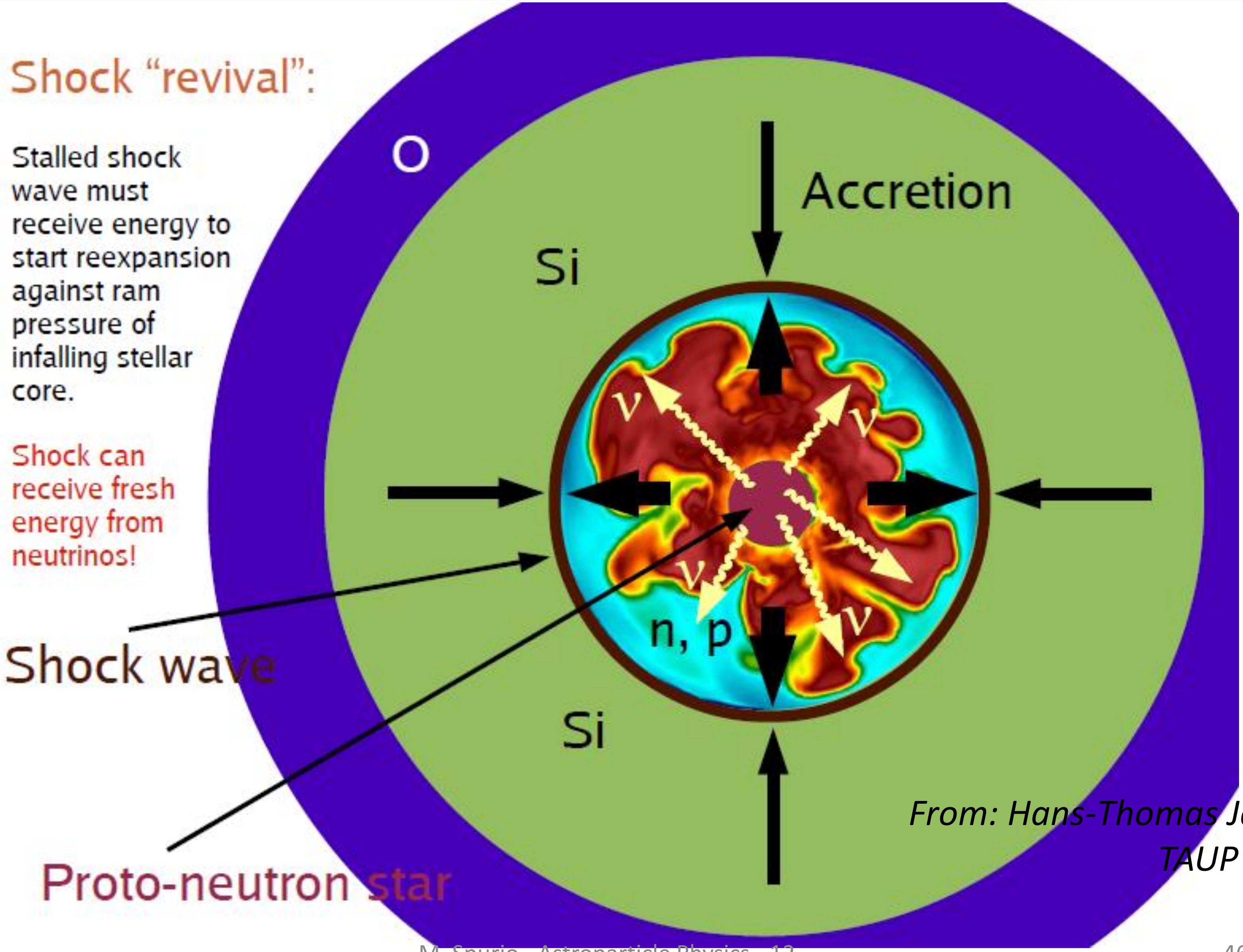
Shock stagnation:

Shock wave loses huge amounts of energy by photo-disintegration of Fe-group nuclei.

Shock stagnates still inside Fe-core

From: Hans-Thomas Janka, TAUP 2013

Description for a Type II Supernovae (V)



Shock “revival”:

Stalled shock wave must receive energy to start reexpansion against ram pressure of infalling stellar core.

Shock can receive fresh energy from neutrinos!

From: Hans-Thomas Janka, TAUP 2013

Core-Collapse Supernovae (Type II)

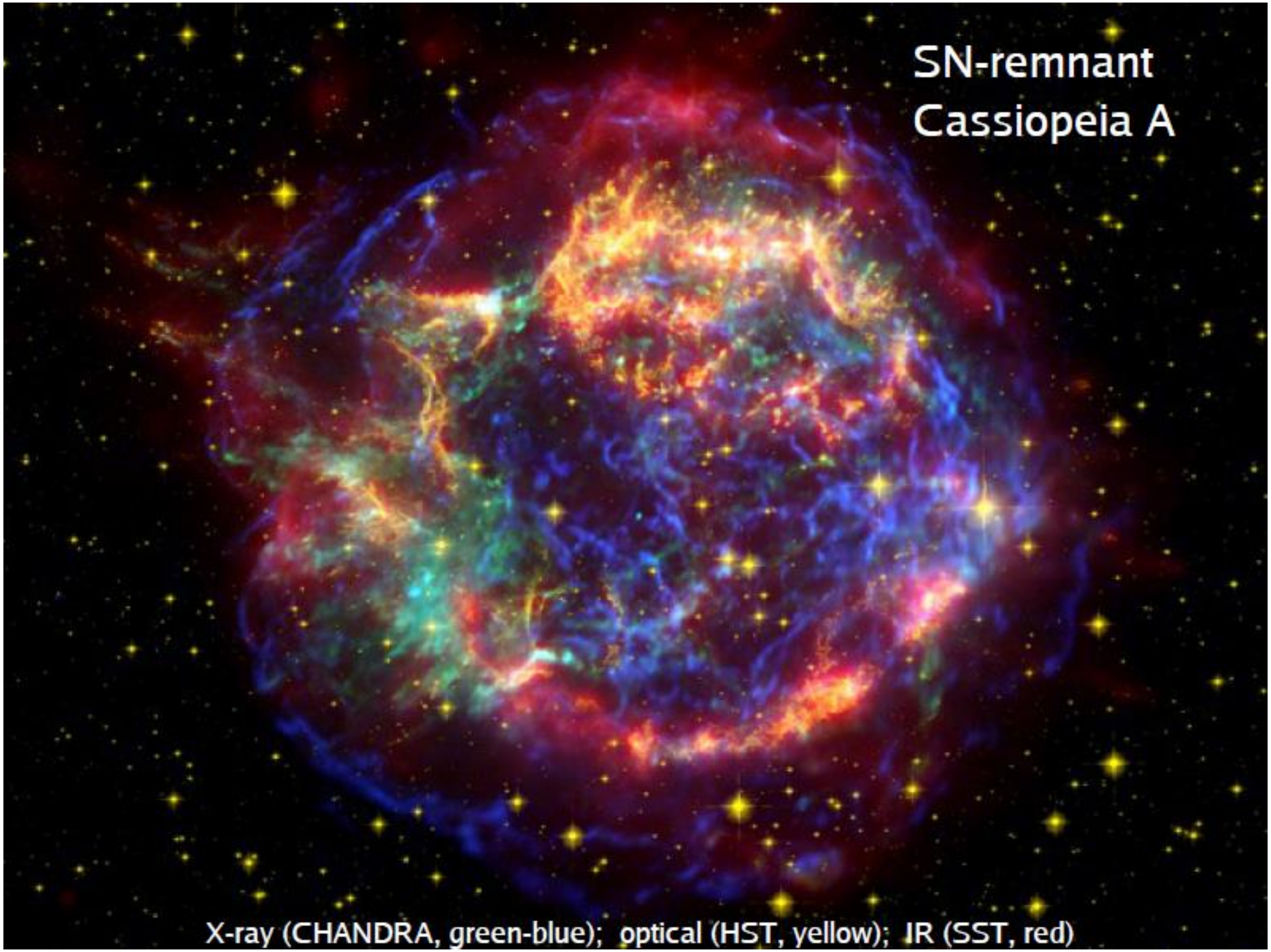
- The work U done by gravity in compressing a star of mass M and radius R in the core (neutron star) of radius R_{NS} and mass M_{NS} is given by

$$U = \left|\frac{3GM^2}{5R} - \frac{3GM_{NS}^2}{5R_{NS}}\right| \simeq \frac{3GM_{NS}^2}{5R_{NS}} \simeq 3 \times 10^{53}\mathrm{erg}$$

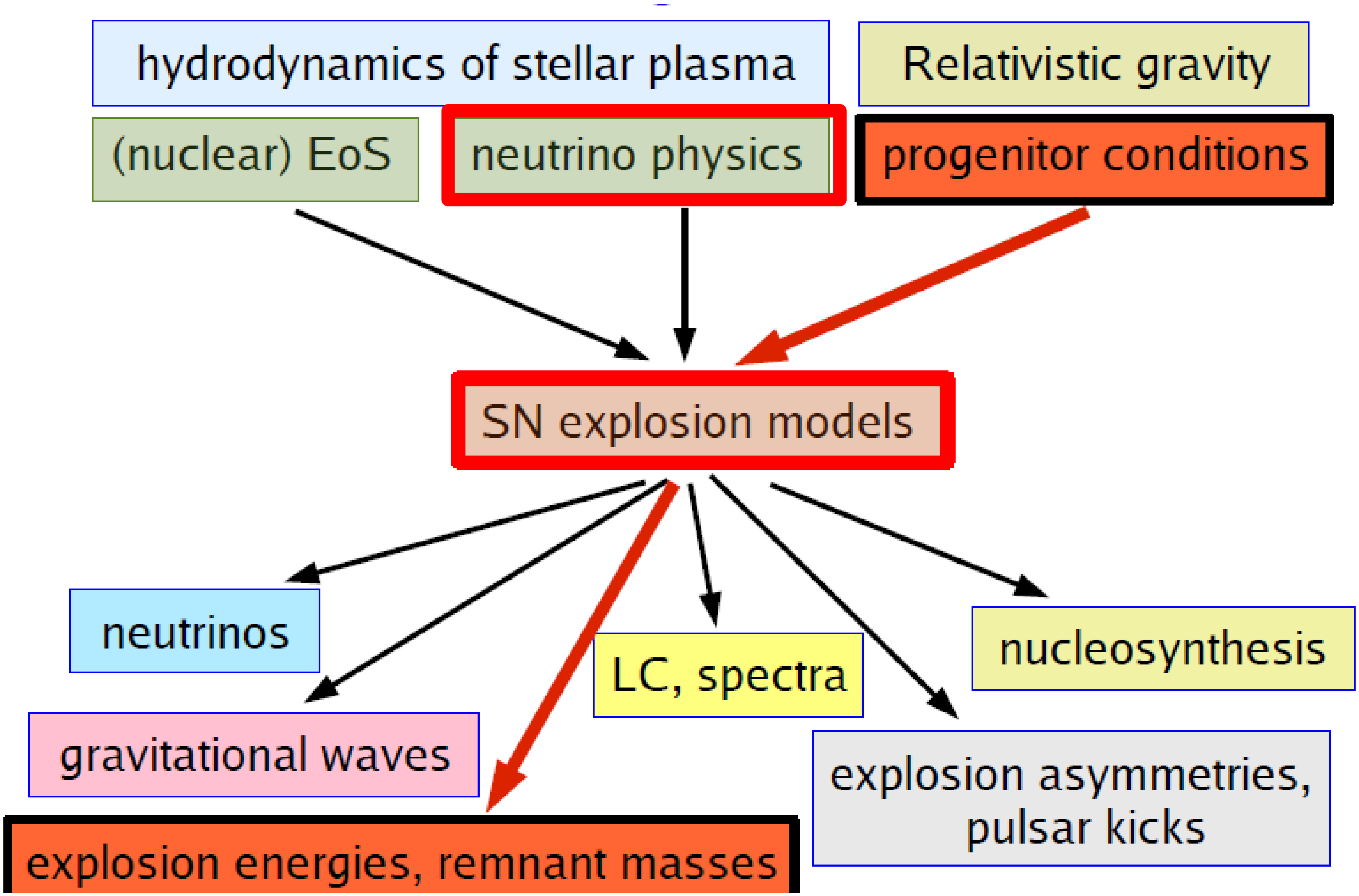
- This shows up as
- **99% Neutrinos**
- **1% Kinetic energy of the explosion**
  (few % of this into Cosmic Rays)
- **0.01% Photons (outshine host galaxy)**

The Crab Nebula (derived from SN1054)

SN1572 (Tycho)



Predictions from SN Core



hydrodynamics of stellar plasma

Relativistic gravity

(nuclear) EoS

neutrino physics

progenitor conditions

SN explosion models

neutrinos

LC, spectra

nucleosynthesis

gravitational waves

explosion asymmetries, pulsar kicks

explosion energies, remnant masses

The SN neutrino fluence

- *Neutronization (burst)*, ~10 ms

10^{51} erg, ν_e only

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

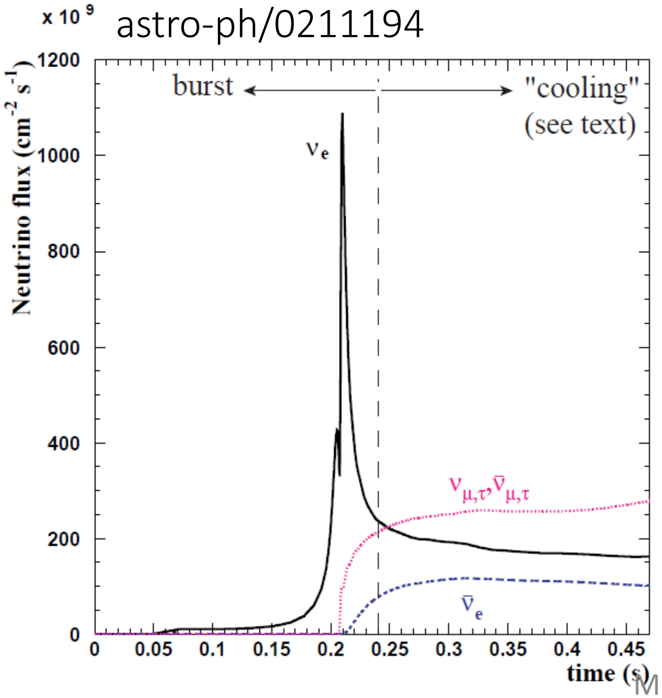
t=0

- *Thermalization (cooling):* ~10 s
- 3×10^{53} erg
- $L_{\nu_e}(t) \approx L_{\bar{\nu}_e}(t) \approx L_{\nu_x}(t)$

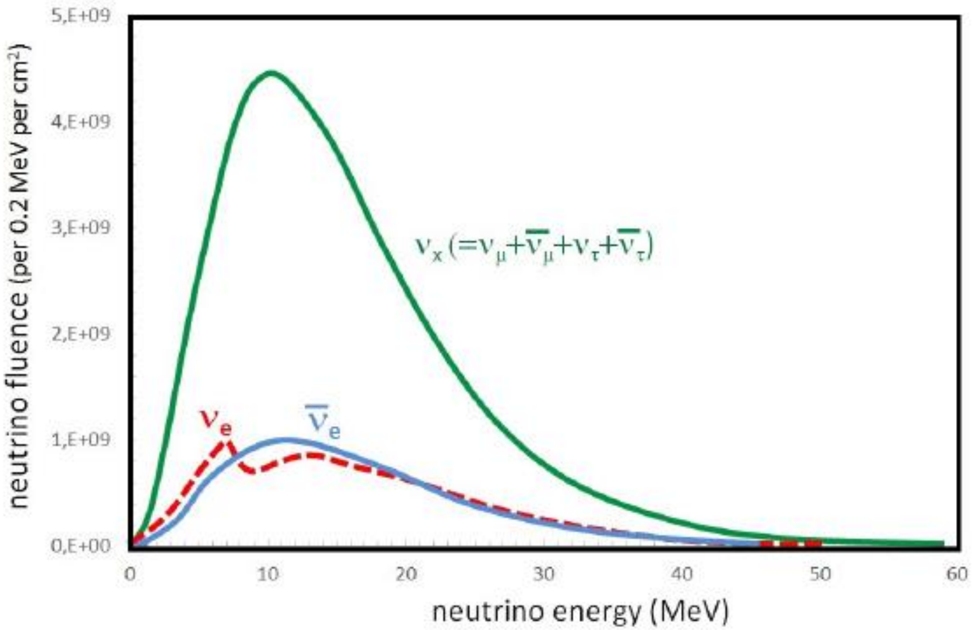
$$e^- + e^+ \rightarrow \bar{\nu} + \nu$$

Δt=3-10 s

- **Exercize:** evaluate the $\bar{\nu}_e$ fluence [cm^{-2}] on Earth for a SN burst occurred at the Galactic Center (GC, 8.5 kpc) using the above information



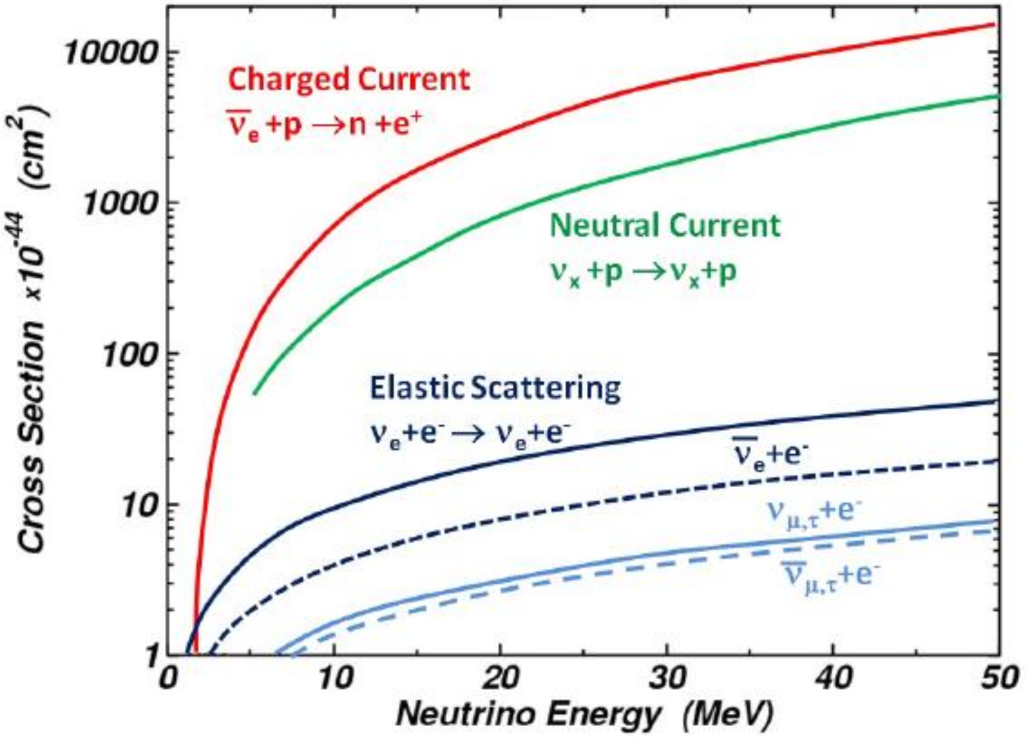
astro-ph/0211194



The SN neutrino signal **on detectors**

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

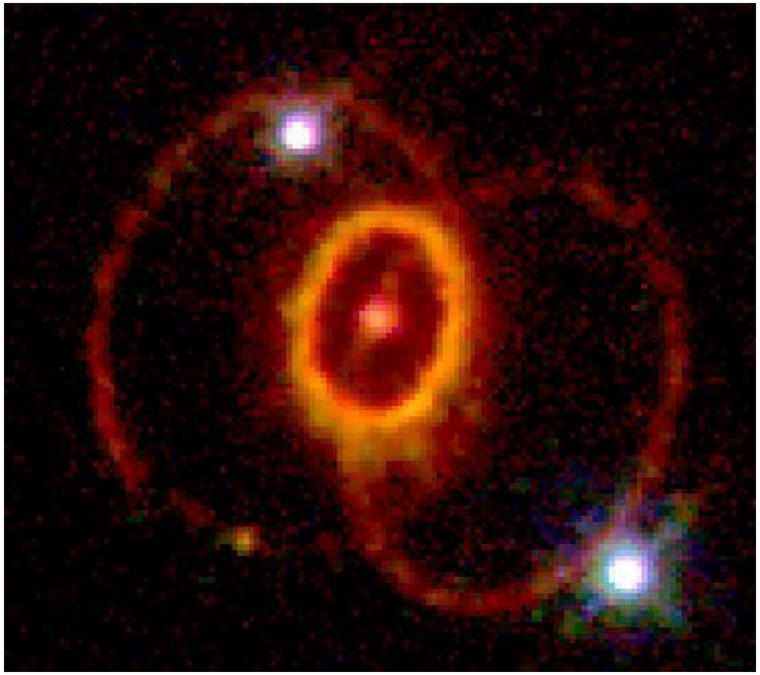
- **Electron scattering (ES).** Sensitive to all flavors, with pointing capabilities
- The $\overline{\nu}_e$ CC (inverse beta decay). Dominant cross section; threshold at 1.8 MeV. Easy to detect (delayed coincidence)
- **Neutral current on p.** Smaller σ than CC, but sensitive to all flavors. Difficult to detect.
- CC ν_e, $\overline{\nu}_e$ with nuclei (as in solar experiments). Only in dedicated experiments



- **Exercize:** evaluate the number of $\bar{\nu}_e$ interaction in 1 kton of material (=water) using the fluence and the cross-section reported in figure for a SN burst in the GC.
- **Answer**: about 250 positrons/kton are expected (see solution in Question 4)

The SN1987A

- SN1987A was the first SN since 1604 visible with the naked eye
- The progenitor was a main-sequence star of mass $M = (16-22)M_{sun}$
- Located in the Large Magellanic Cloud at a distance of about 50 ± 5 kpc
- Two water Cherenkov detectors, Kamiokande-II (2.2 kton) and IMB (5 kton in USA), observed 12 and 8 neutrino interactions respectively, over a 13 s interval
- The signals of the two experiments were simultaneous (for the technology of 1987)



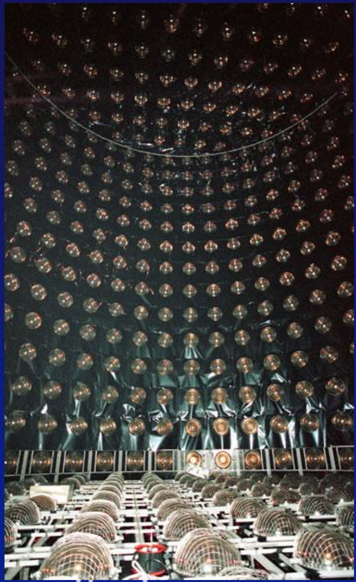
- Two smaller scintillator detectors, LSD and Baksan also reported observations
  - Baksan reported five counts
  - The LSD is controversial because the events were recorded several hours early

- **Question 4**: Evaluate the expected signal in Kamiokande for the SN1987A
- **Question 5**: Why IMB (larger) detected fewer events than Kamiokande?

The Detectors

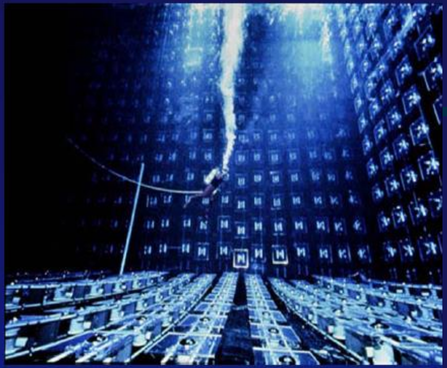
- Water Cherenkov detectors
  - Kamiokande (Japan)
  - IMB (Ohio)
- Liquid scintillation telescopes
  - Baksan – USSR Academy of Sciences, in North Caucasus Mountains, Russia
  - Mont Blanc – Italian Soviet collaboration, in Mont Blanc Laboratory, France

Kamiokande II



- Located in the Kamioka mine in Japan
- 1000m underground
- Cylindrical tank
  - d = 15.6m, h = 16m
- Large (D = 20 inches) photomultipliers
- Volume of water weighs 3000 metric tons

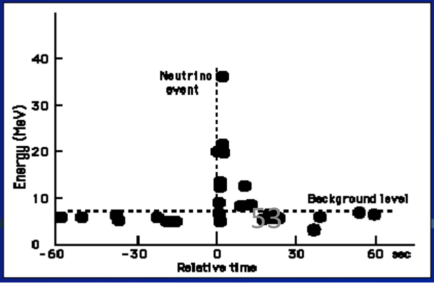
IMB



- Located in the Morton Thiokol mine in Ohio
- 580m underground
- Rectangular tank
  - 18 by 17 by 23 m
- 2048 8” photomultipliers
- 2.5 million gallons of water
- Compared to Kamiokande II: Larger volume, but not as deep

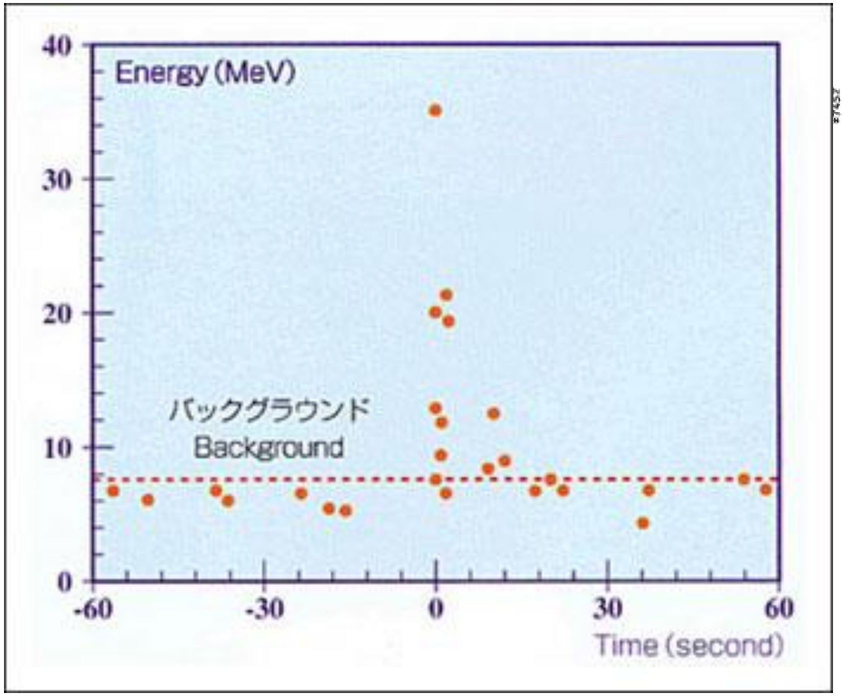
Results

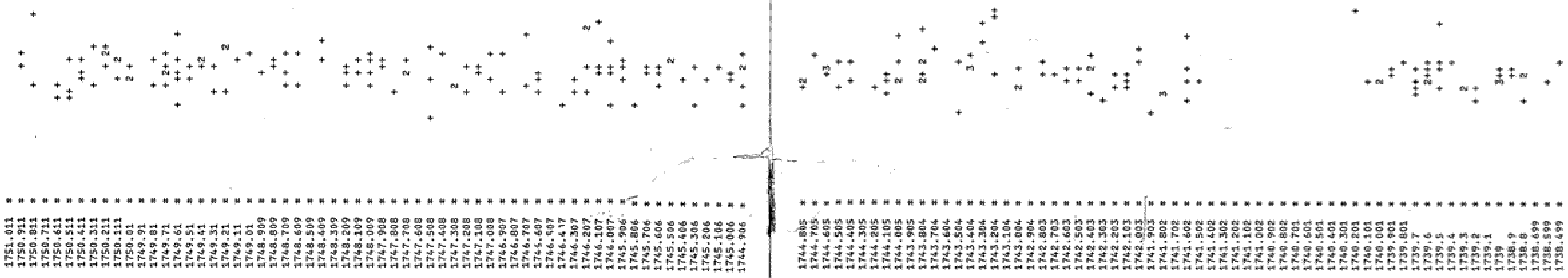
- Feb 23, 7:36 UT:
  - K II records 9 neutrinos within 2 sec, 3 more neutrinos 9-13 seconds later
  - IMB records 8 neutrinos within 6 seconds
  - Baksan records 5 neutrinos within 5 seconds
- 25 neutrinos detected!



The KamiokaNDE events

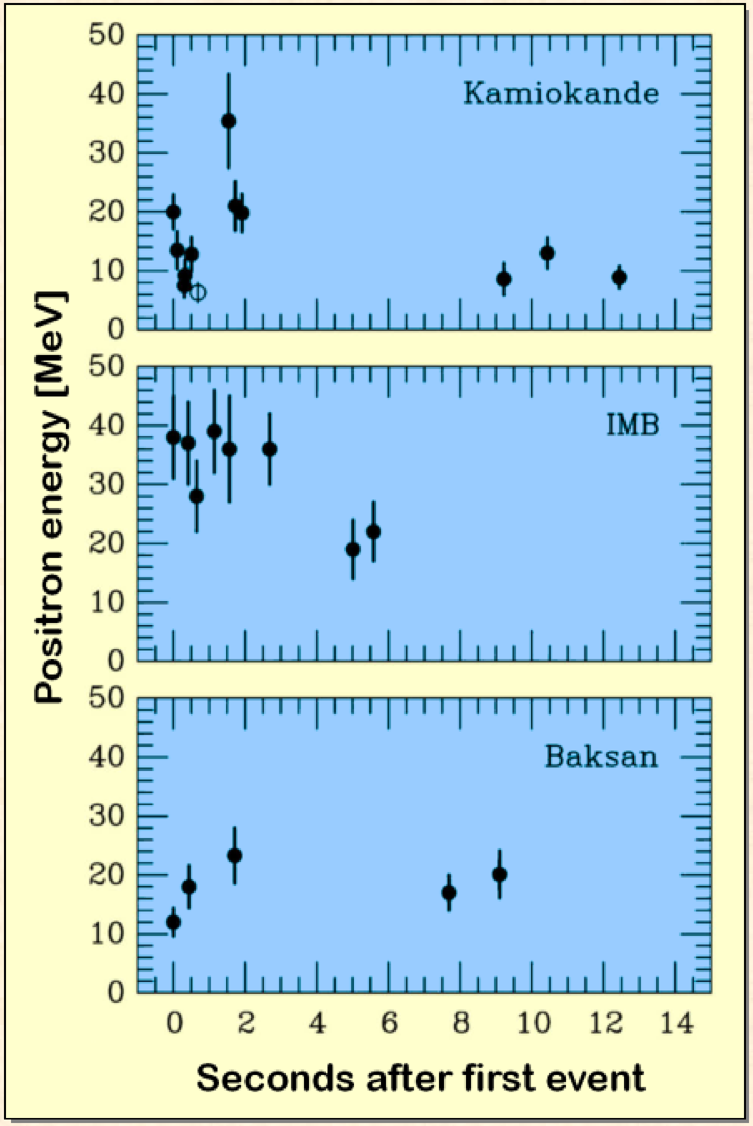
http://www-sk.icrr.u-tokyo.ac.jp/sk/news/2017/02/SN1987A-en.html





The printout of the data. Horizontal axis shows time (from right to left and one line as 10 seconds) and the vertical axis shows the number of hit (proportional to the energy of the event). The peak is the signal of neutrinos from SN1987A. The blank period due to the detector maintenance was recorded a few minutes before the signal.

Neutrino signal from SN1987A



Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (USA)
Water Cherenkov detector
Clock uncertainty ±50 ms

Baksan Scintillator Telescope (Soviet Union)
Clock uncertainty +2/-54 s

Within clock uncertainties, signals are contemporaneous

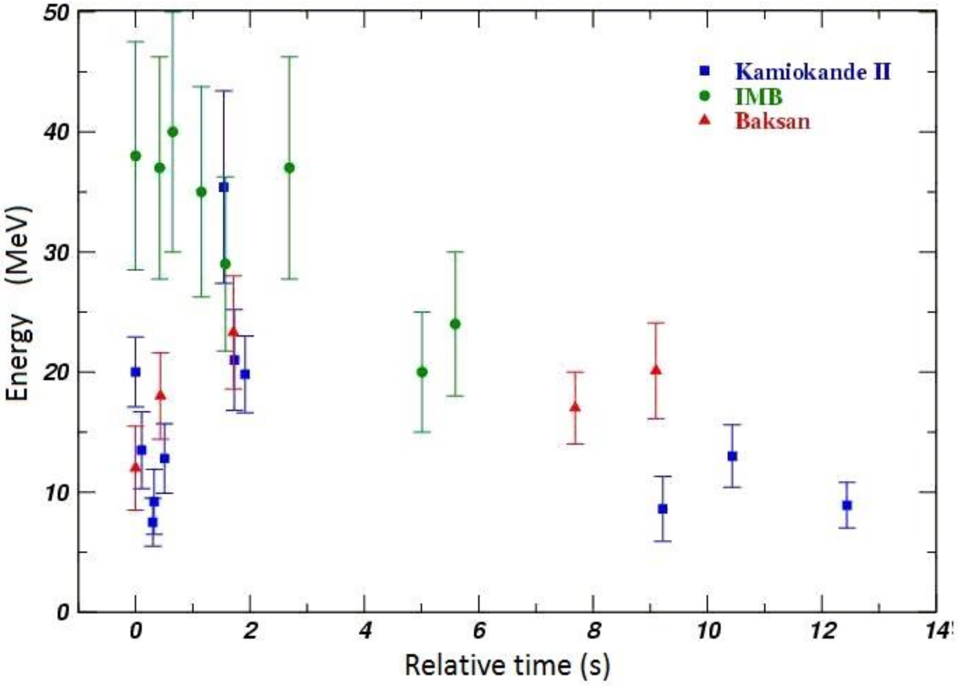
Georg Raffelt, Max-Planck-Institut für Physik (München)

Neutrino signal from SN1987A

Although Kamiokande, IMB and Baksan collected a small sample of ν's, they were sufficient to give an exact time for the start of the explosion to which the light curve can be normalized and to confirm the baseline model of core-collapse. In particular:

- the time distribution of the observed events is in agreement with predictions of a ~10 s burst;
- their energy distribution gives a measure T ~ 4.2MeV of the ν-sphere and an average energies of detected neutrinos of~15MeV;
- the number of the observed events is in agreement with ~ 3 × 10^{53} erg luminosity of a core-collapse burst

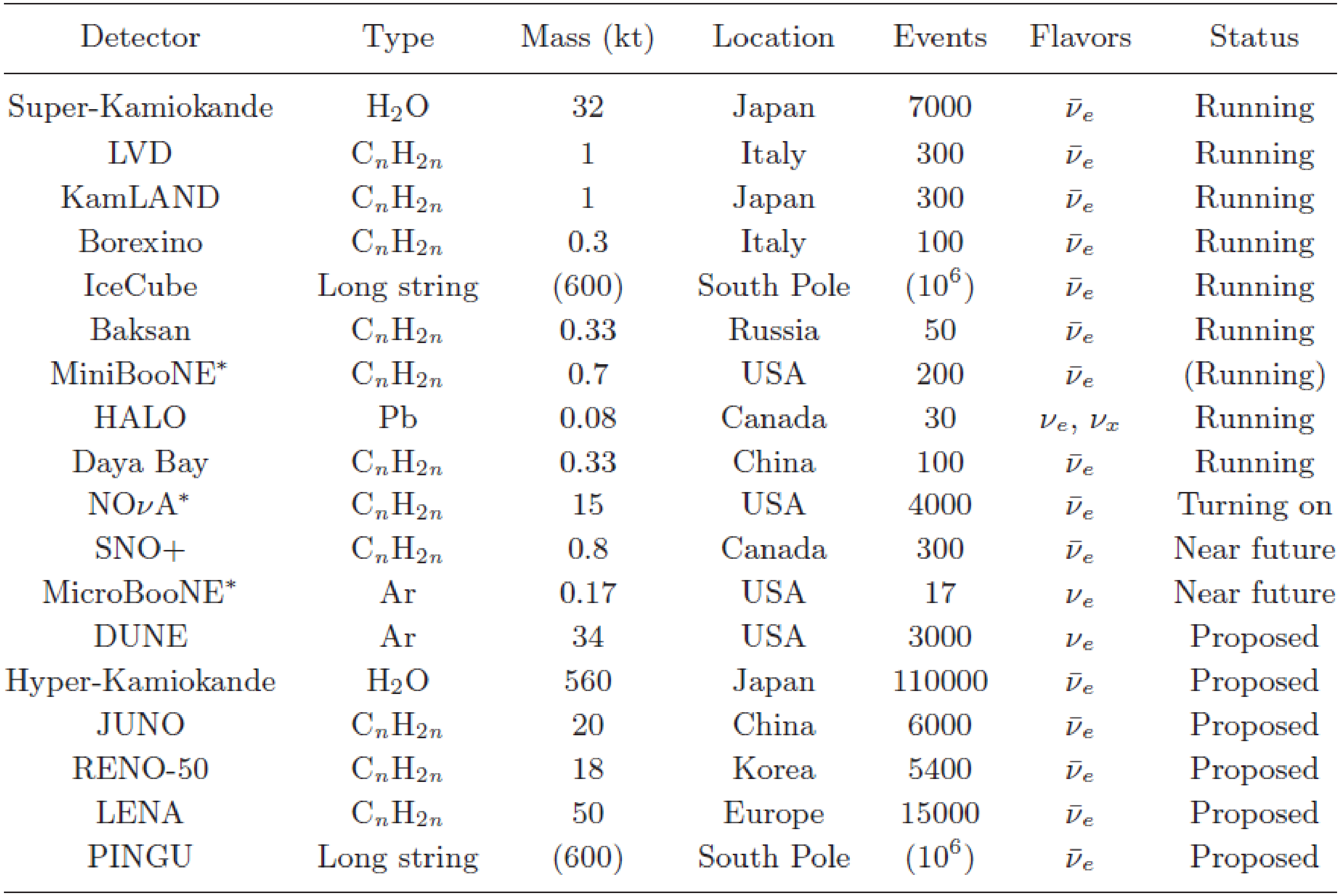
Relative time and energy of SN1987A neutrinos observed by Kamiokande, IMB and Baksan.
The time of the first event was arbitrarily set = 0



- **Question 6**: Estimate an upper limit on the neutrino mass from SB1987A

Present and future detectors

- ***Current and proposed SN neutrino detectors***. *Not included are smaller detectors and detectors sensitive primarily to coherent elastic neutrino-nucleus scattering.*
- *An * indicates a surface detector, which may not be self-triggering due to background.*
- *Numbers in parentheses indicate that individual events will not be reconstructed.*

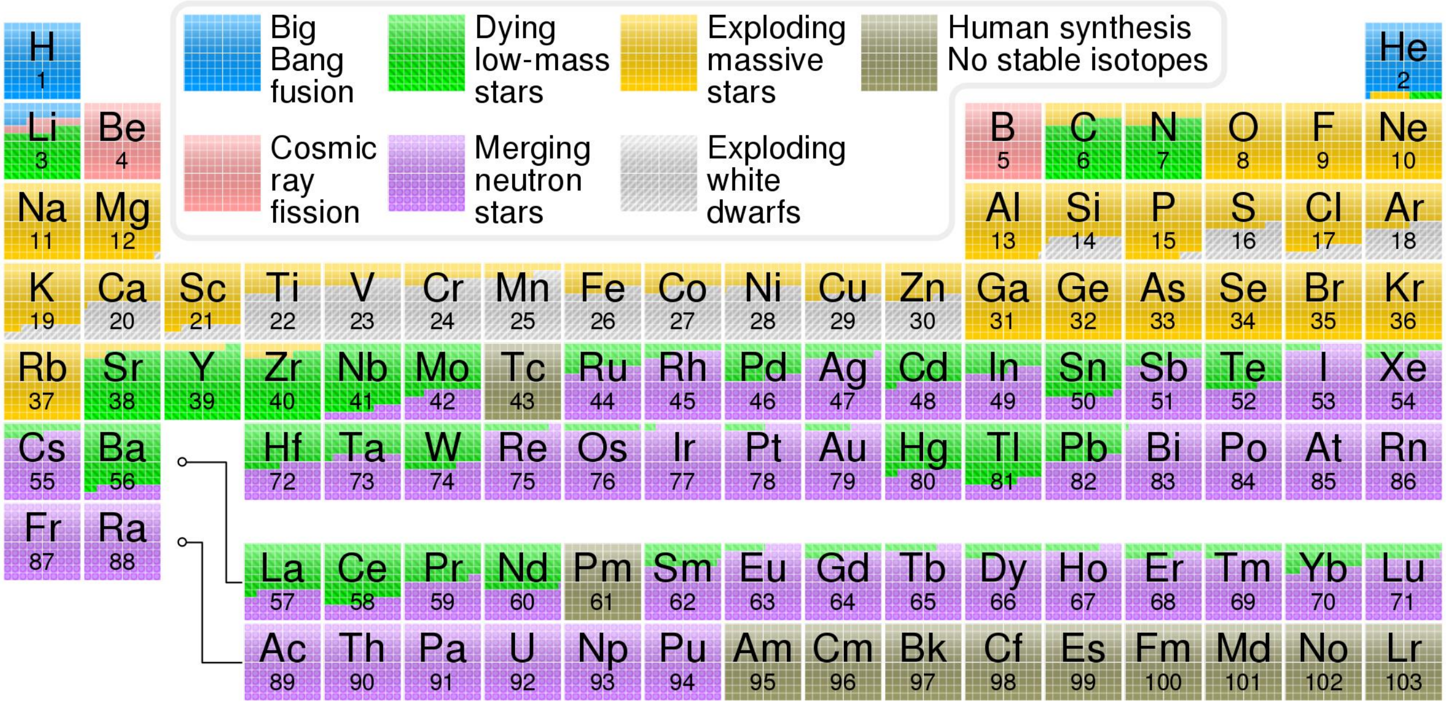


Detector	Type	Mass (kt)	Location	Events	Flavors	Status
Super-Kamiokande	H_2O	32	Japan	7000	$\bar{\nu}_e$	Running
LVD	C_nH_{2n}	1	Italy	300	$\bar{\nu}_e$	Running
KamLAND	C_nH_{2n}	1	Japan	300	$\bar{\nu}_e$	Running
Borexino	C_nH_{2n}	0.3	Italy	100	$\bar{\nu}_e$	Running
IceCube	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Running
Baksan	C_nH_{2n}	0.33	Russia	50	$\bar{\nu}_e$	Running
MiniBooNE*	C_nH_{2n}	0.7	USA	200	$\bar{\nu}_e$	(Running)
HALO	Pb	0.08	Canada	30	ν_e, ν_x	Running
Daya Bay	C_nH_{2n}	0.33	China	100	$\bar{\nu}_e$	Running
NOνA*	C_nH_{2n}	15	USA	4000	$\bar{\nu}_e$	Turning on
SNO+	C_nH_{2n}	0.8	Canada	300	$\bar{\nu}_e$	Near future
MicroBooNE*	Ar	0.17	USA	17	ν_e	Near future
DUNE	Ar	34	USA	3000	ν_e	Proposed
Hyper-Kamiokande	H_2O	560	Japan	110000	$\bar{\nu}_e$	Proposed
JUNO	C_nH_{2n}	20	China	6000	$\bar{\nu}_e$	Proposed
RENO-50	C_nH_{2n}	18	Korea	5400	$\bar{\nu}_e$	Proposed
LENA	C_nH_{2n}	50	Europe	15000	$\bar{\nu}_e$	Proposed
PINGU	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Proposed

LVD @LNGS

The Origin of Trans-Fe Elements

- Elements of higher mass number become progressively rarer, because they increasingly absorb energy in being produced.
- The abundance of elements in the Solar System is thought to be similar (Chap. 3)
- Supernova nucleosynthesis is the theory of the releasing in the Universe of elements up to iron (Z = 26) and nickel (Z = 28) in supernova explosions (F. Hoyle, 1954).
- Core-collapse supernovae are the main contributors of the heavy elements (A≥12) Elements heavier that iron are produced by neutron capture in neutron-rich



Slow (s) and Rapid (r) processes

- Elements heavier that iron are produced by neutron capture in neutron-rich astrophysical environments, followed by β decay of the forming nuclei.

$$n + {}^{A}_{Z}\mathrm{X} \rightarrow {}^{A+1}_{Z}\mathrm{X} + \gamma; \quad {}^{A+1}_{Z}\mathrm{X} \rightarrow {}^{A+1}_{Z+1}\mathrm{Y} + e^- + \nu_e \, . \qquad (12.49)$$

- The so-called **s-process is believed to occur mostly in asymptotic giant**.
- The s-process is believed to occur over time scales of thousands of years, passing decades between successive neutron captures.
- The **r-process** also involves neutron capture, as in (12.49) but the neutron capture time is much smaller than the nucleus decay time, due to the high neutron density.
- The newly formed nucleus does not decay immediately; after subsequent captures, the isotopes move away from the stability valley: ${}^{A}_{Z}X \rightarrow {}^{A+1}_{Z}X \rightarrow {}^{A+2}_{Z}X \rightarrow \ldots$
- The r-process occurs in astrophysical locations where there is a high density of free neutrons (astrophysical regions matter of ongoing researches).
- Until the observation of GW170817, the environment around core-collapse SN was the most plausible candidate.
- GW170817 showed that the most suited ambient for r-processes is probably the neutron-rich matter in a binary neutron star merger (the so-called kilonova).

Question 1)

- Potere calorifico carbone (lignite)= 24 MJ/kg, senza produzione di cenere
- Potere calorifico del Sole, immaginato come palla di carbone di massa 2x10^{30} kg → Q= 4 10^{37} J = 4 10^{44} erg
- (significa che la potenza per 1 ora di funzionamento equivale a 24 MJ/3600 s= 6600 W)
- Costante solare **ε= 1.4 10^6** erg/cm^2 s; Distanza Terra-Sole D= 1.5 10^{13} cm
- Potenza erogata dal sole dE/dt= $\varepsilon \times (4\pi D^2)$ = 4 10^{33} erg/s
- Tempo necessario a bruciare il Sole:
- **T_1= Q/(dE/dt) =4 10^{44} erg /(4 10^{33} erg/s) = 10^{11} s= 3300 y**

Question 2)

- Total gravitational potential energy of a sphere of mass M_{sun} of radius R is

$$U = \frac{3GM^2}{5R} \cong 10^{48}\ erg$$

- **$T_2 \cong$ U/(dE/dt)= 10^6 year**

Question 4) The SN1987A: how many events?

1- Energy released 2.5 10^{53} erg

2- Average $\bar{\nu}_e$ energy ≈ 16 MeV = 2.5 10^{-5} erg

3- N_{source}= (1/6) × 2.5 10^{53}/ (2.5 10^{-5})= 1.7 10^{57} $\bar{\nu}_e$

4- LMC Distance : D=52 kpc = 1.6 10^{23} cm

5- Fluency at Earth: F = $N_{Source}/4pD^2$ = 0.5 10^{10} cm^{-2}

6- Targets in 1 Kt water: N_t = 0.7 10^{32} protons

7- cross section: **$\sigma(\bar{\nu}_e$+p) ~ 2x10^{-41} cm^2**

8- N_e+ = F (cm^{-2})× σ (cm^2)× N_t (kt^{-1})= 0.5 10^{10} × 2x10^{-41}× 0.7 10^{32}

= 7 positrons/kt

9 – M(Kam II) = 2.1 kt, efficiency ε~ 80%

10 – Events in Kam II = 7 x 2.1 x e ~ 12 events

For a SN @ Galactic Center (8.5 kpc) :
N_{events}= 7x$(52/8.5)^2$ = 260 e^+/kt

Question 5)

IMB had smaller PMTs that Kamiokende, less covered area, thus an higher energy threshold (20 MeV) and a much smaller detection efficiency

Question 6) Neutrino mass from SN

- The observation of SN ν's brings a better understanding of the core collapse mechanism from the feature of the time and energy spectra;
- Moreover, an estimation of the neutrino masses could be done in the following manner. The velocity of a particle of energy *E* and mass *m*, with *E* >> *m*, is given by (with c = 1):

$$v_i = \frac{p_i c}{E_i} = \frac{\sqrt{E_i^2 - m^2\, c^4}}{E_i^2} \sim 1 - \frac{m^2 c^4}{2E_1^2}$$

- Thus, for a SN at distance *d*, the delay of a ν from the highest/lowest energy neutrino, ΔE, due to its mass is (in proper units)

$$\Delta t_{[s]} \sim 0.05\, \frac{m^2_{[eV^2]}}{\Delta E_{[MeV]}}\, d_{[kpc]}$$

- Therefore, neutrinos of different energies released at the same instant should show a spread in their arrival time. For SN1987A, assuming Kam data and Δt=13 s, ΔE=30 MeV and d=50 kpc, we get:

$$mc^2 < 12\ eV$$