Problemi correnti nella fisica dei neutrini

D.Orestano

AA2011/12

Riassunto delle puntate precedenti

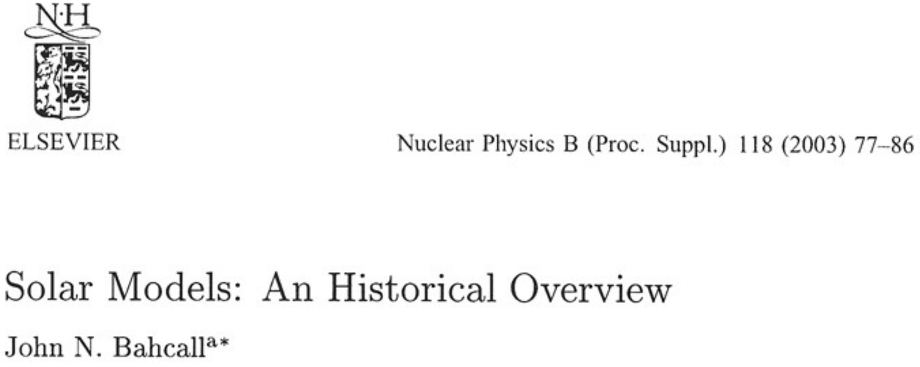
- Abbiamo ripercorso la storia della scoperta dei 3 neutrini e delle interazioni deboli
- Il neutrino con massa nulla puo' essere visto come un fermione di Dirac a due sole componenti, che interagisce solo se levogiro
- Ma se la massa non e' nulla ci sono due descrizioni possibili
  - Fermione di Dirac a 4 componenti
  - Neutrino di Majorana: neutrino e antineutrino sono la stessa particella in due diversi stati di elicita'
  - La coesistenza di neutrini di Dirac e di Majorana puo' generare neutrini molto piu' leggeri degli altri fermioni (meccanismo See-Saw)
  - L'osservazione del doppio decadimento beta senza neutrini darebbe l'evidenza di neutrini di Majorana

- Abbiamo introdotto due importanti sorgenti di neutrini:
  - I reattori nucleari, che producono un flusso elevato ed isotropo di anti-neutrini elettronici con energie tipiche del MeV
  - I fasci da acceleratori, che producono neutrini o anti-neutrini prevalentemente muonici (dai decadimenti di pioni e K) ma hanno piccole contaminazioni di neutrini elettronici (decadimento K3e) e piccolissime di neutrini tauonici (decadimento del Ds), ed energie dal GeV alle centinaia di GeV
- Abbiamo descritto due principali tecniche di rivelazione
  - Il processo beta inverso indotto da anti-neutrini, rivelato dalla coincidenza ritardata del segnale di annichilazione del positronio e di cattura neutronica. Questo processo e' tutt'ora il processo principale utilizzato nella rivelazione ai reattori
  - La diffusione di corrente carica, processo a soglia che consente l'identificazione del “sapore” del neutrino incidente. In particolare abbiamo parlato della rivelazione del neutrino tau tramite l'identificazione in emulsioni del decadimento del tau. Questa tecnica e comunue a molti altri esperimenti (CHORUS, OPERA).

Sommario III

- Il modello solare standard
- L’esperimento di Davis
- Il problema dei neutrini solari
- Oscillazioni

Seguirò però l’ordine cronologico, nel quale questi temi sono andati di pari passo, ed in particolare la divisione temporale usata da Bahcall in



ELSEVIER

Nuclear Physics B (Proc. Suppl.) 118 (2003) 77–86

Solar Models: An Historical Overview

John N. Bahcall[a]*

con l’ausilio di molte slides di L. Di Lella e G.Fiorentini

Non esiste idea sulla fisica del neutrino che non sia di Pontecorvo (V.Telegdi)

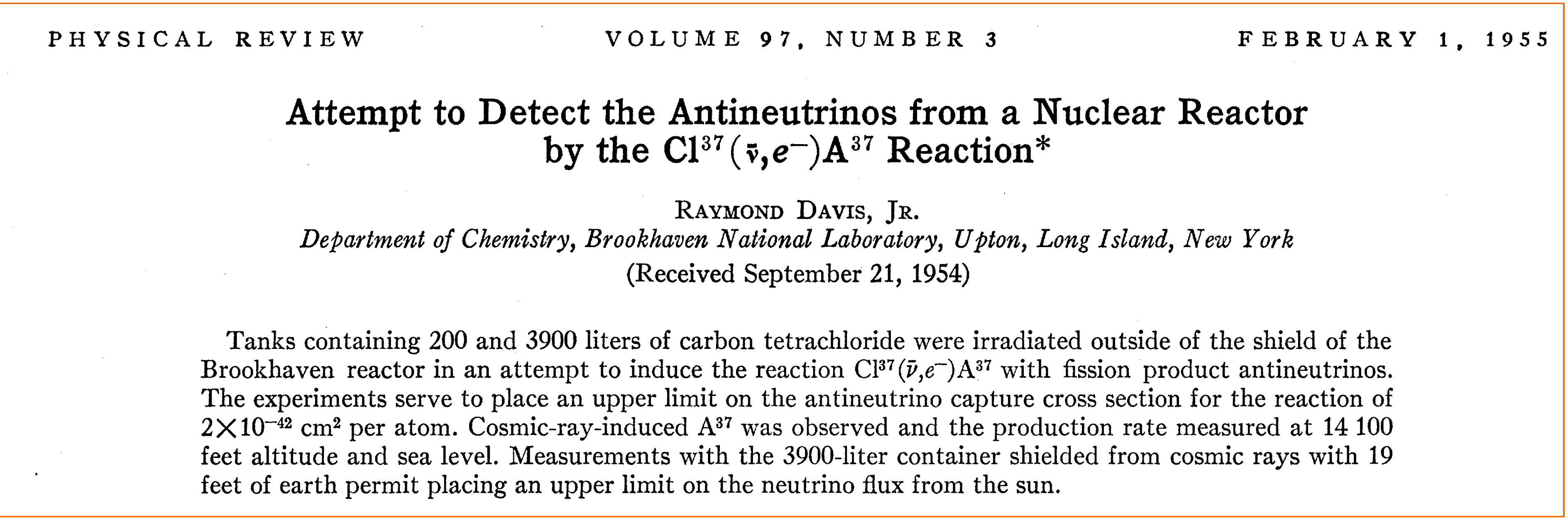
- **1946**: B.Pontecorvo, Chalk River Laboratory Report PD-205
  - Rivelazione dei neutrini da reattore (➔ esperimento di Reines e Cowan)
  - Proposta di rivelazione radiochimica dei neutrini (antineutrini?) solari
- **1957**: Oscillazioni di neutrino

BRUNO MAKSIMOVICH
PONTECORVO

Pontecorvo, B., J. Exp. Theor. Phys. **33**, 549 (1957) [Sov. Phys. JETP **6**, 429 (1958)].

Pontecorvo, B., J. Exp. Theor. Phys. **34**, 247 (1958) [Sov. Phys. JETP **7**, 172 (1958)].

1955



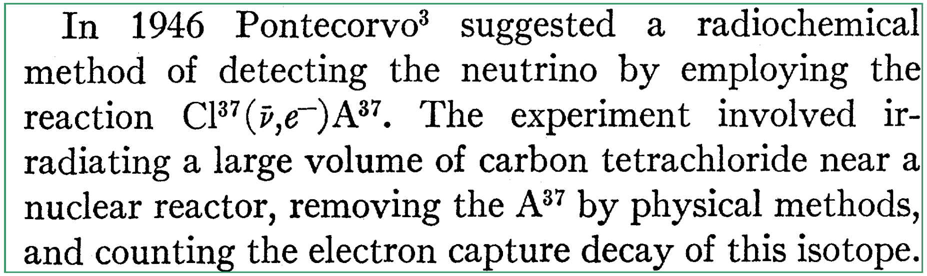
PHYSICAL REVIEW VOLUME 97, NUMBER 3 FEBRUARY 1, 1955

Attempt to Detect the Antineutrinos from a Nuclear Reactor by the $Cl^{37}(\bar{\nu},e^-)A^{37}$ Reaction*

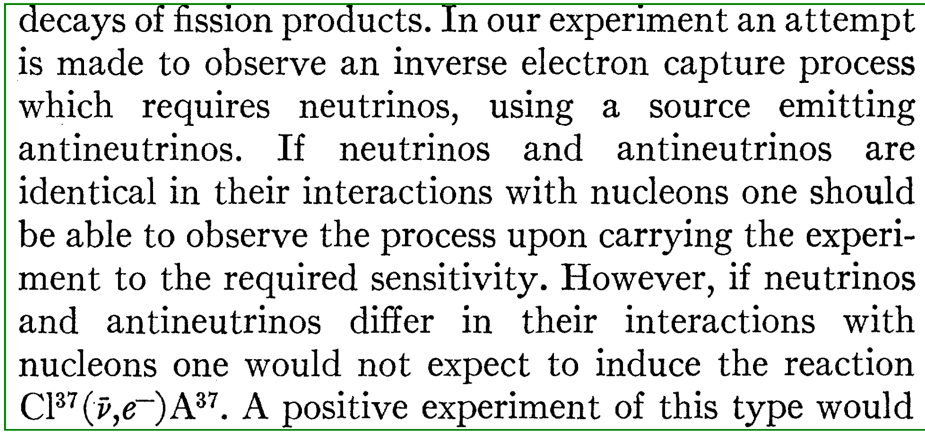
RAYMOND DAVIS, JR.
Department of Chemistry, Brookhaven National Laboratory, Upton, Long Island, New York

(Received September 21, 1954)

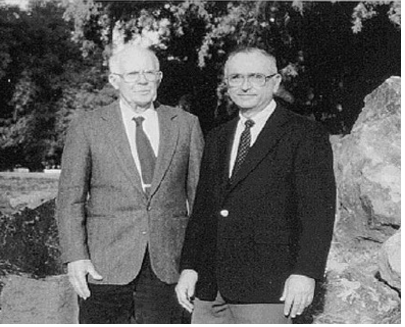
Tanks containing 200 and 3900 liters of carbon tetrachloride were irradiated outside of the shield of the Brookhaven reactor in an attempt to induce the reaction $Cl^{37}(\bar{\nu},e^-)A^{37}$ with fission product antineutrinos. The experiments serve to place an upper limit on the antineutrino capture cross section for the reaction of 2×10^{-42} cm² per atom. Cosmic-ray-induced A^{37} was observed and the production rate measured at 14 100 feet altitude and sea level. Measurements with the 3900-liter container shielded from cosmic rays with 19 feet of earth permit placing an upper limit on the neutrino flux from the sun.



In 1946 Pontecorvo[3] suggested a radiochemical method of detecting the neutrino by employing the reaction $Cl^{37}(\bar{\nu},e^-)A^{37}$. The experiment involved irradiating a large volume of carbon tetrachloride near a nuclear reactor, removing the A^{37} by physical methods, and counting the electron capture decay of this isotope.



decays of fission products. In our experiment an attempt is made to observe an inverse electron capture process which requires neutrinos, using a source emitting antineutrinos. If neutrinos and antineutrinos are identical in their interactions with nucleons one should be able to observe the process upon carrying the experiment to the required sensitivity. However, if neutrinos and antineutrinos differ in their interactions with nucleons one would not expect to induce the reaction $Cl^{37}(\bar{\nu},e^-)A^{37}$. A positive experiment of this type would

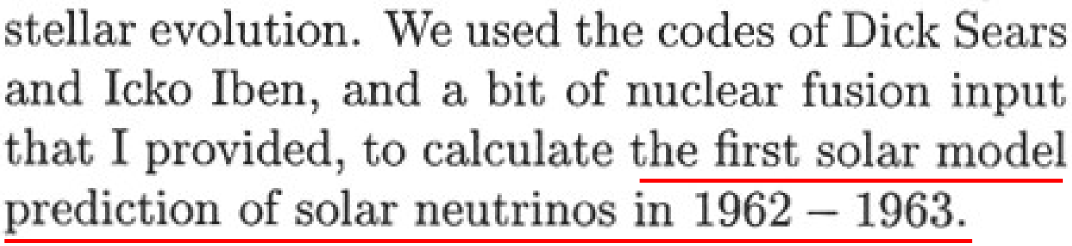


1962-1988

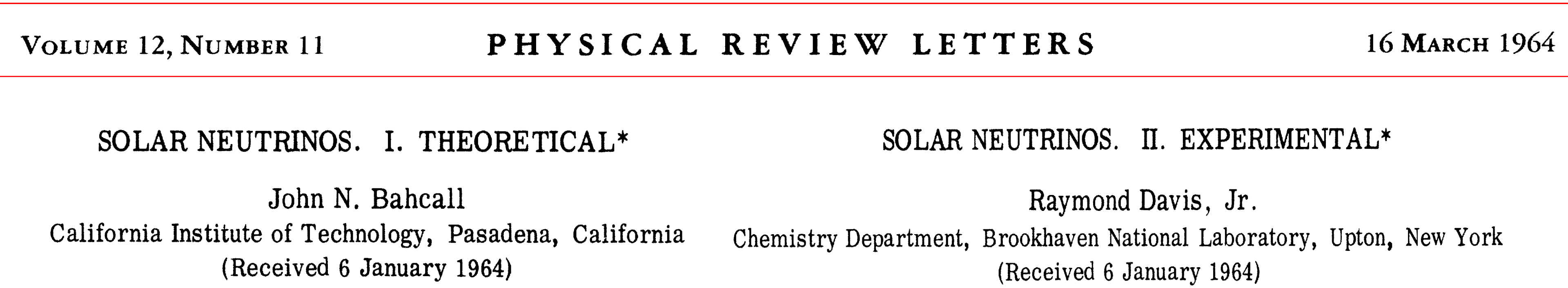
- 1962: Ray Davis & John Bahcall iniziano a discutere la possibilità di un esperimento per la rivelazione dei neutrini solari, in particolare l’esistenza di processi che generano neutrini “energetici”

Bahcall JN. *Phys. Rev.* 126:1143 (1962)

- Bahcall si convince che serve un modello solare vero e proprio per produrre una stima di flusso



stellar evolution. We used the codes of Dick Sears and Icko Iben, and a bit of nuclear fusion input that I provided, to calculate the first solar model prediction of solar neutrinos in 1962 – 1963.



VOLUME 12, NUMBER 11 PHYSICAL REVIEW LETTERS 16 MARCH 1964

SOLAR NEUTRINOS. I. THEORETICAL*

John N. Bahcall
California Institute of Technology, Pasadena, California
(Received 6 January 1964)

p.300

SOLAR NEUTRINOS. II. EXPERIMENTAL*

Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York
(Received 6 January 1964)

p.303

MODELLO SOLARE STANDARD (SSM)

(sviluppato nel 1960 e aggiornato frequentemente da J.N. Bahcall)

Ipotesi:

- equilibrio idrostatico
- produzione di energia da fusione
- equilibrio termico (potenza prodotta = luminosità)
- trasporto di energia all'interno del Sole per radiazione

Dati numerici:

- sezioni d'urto per reazioni di fusione
- opacità in funzione della distanza dal centro del Sole

Metodo:

- scelta dei parametri iniziali
- evoluzione all'epoca attuale ($t = 4.6 \times 10^9$ anni)
- confronto tra proprietà predette e misurate
- modifica dei parametri iniziali (se necessario)

IL SOLE OGGI: Luminosità $\mathcal{L}_\odot = 3.846 \times 10^{26}$ W

Raggio $R_\odot = 6.96 \times 10^{8}$ m

Massa $M_\odot = 1.989 \times 10^{30}$ kg

Temperatura del nucleo $T_c = 15.6 \times 10^{6}$ K

Temperatura alla superficie $T_s = 5773$ K

Idrogeno nel nucleo = 34.1% (inizialmente 71%)

Elio nel nucleo = 63. 9% (inizialmente 27.1%)

} da misure della superficie solare

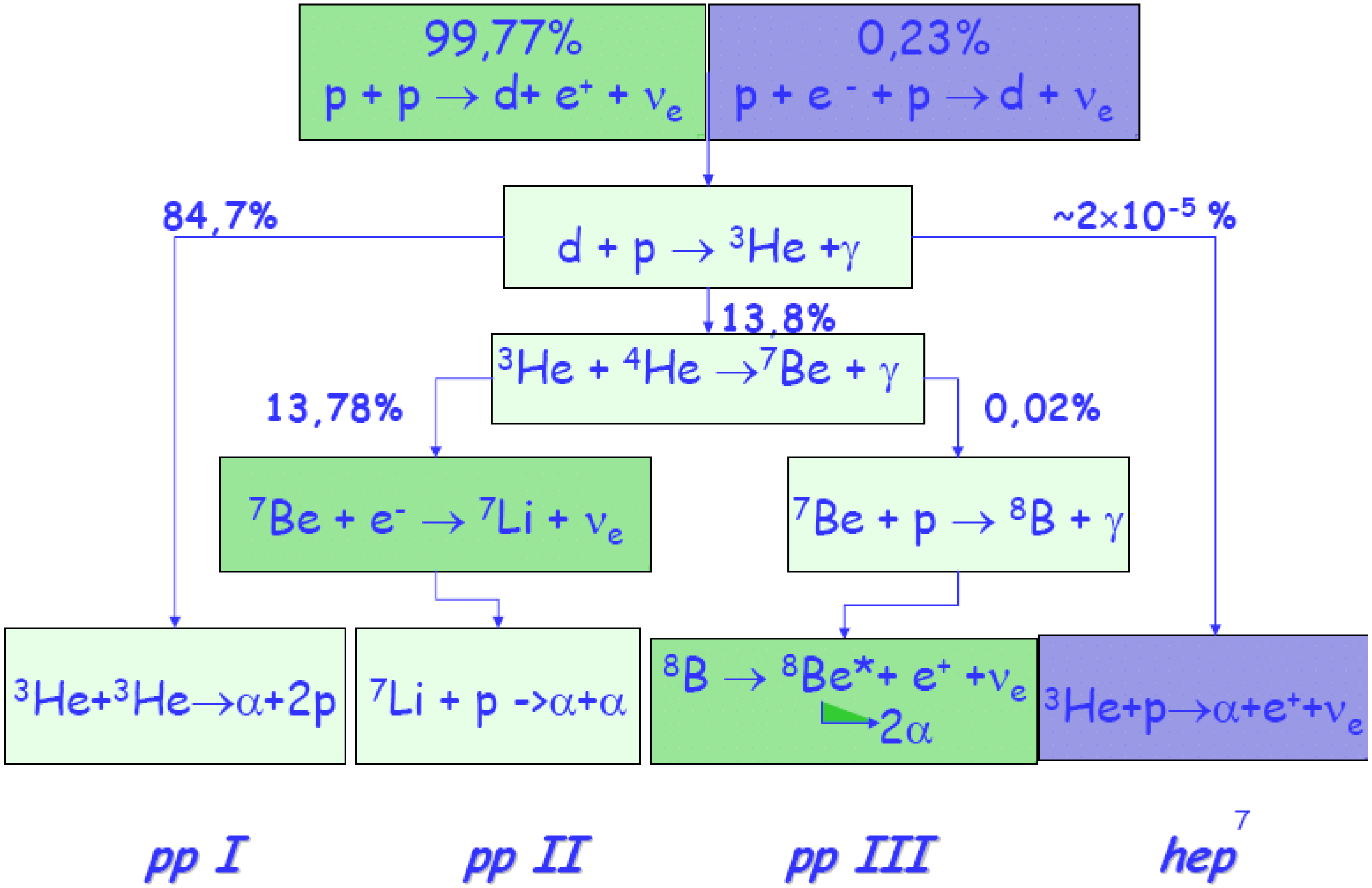
- 1962-1968: progressi nel modello solare standard legati ad una migliore conoscenza dei dati di input
  - Esempio: misura della sezione d’urto di fusione ^{3}He ^{3}He
  - Calcolo della sezione d’urto pp
  - Nuovi dati sulla composizione elementale del Sole
- Sfortunatamente tutte le migliorie andavano nella direzione di una riduzione del flusso atteso

Neutrini solari

- La prova che il Sole sia alimentato da reazioni nucleari deve provenire dall’osservazione dei prodotti di reazione
- Tra questi solo i neutrini possono uscire dalla regione di produzione indisturbati
- La loro rivelazione permette di studiare la regione di produzione che è quella più interna e non osservabile in altro modo

Reazioni di fusione nel Sole

The pp chain



99,77% $p + p \rightarrow d + e^+ + \nu_e$

0,23% $p + e^- + p \rightarrow d + \nu_e$

$d + p \rightarrow {}^3He + \gamma$

84,7%

~2×10⁻⁵ %

13,8%

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

13,78%

0,02%

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

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

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

${}^7Li + p \rightarrow \alpha + \alpha$

${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$, ${}^8Be^* \rightarrow 2\alpha$

${}^3He + p \rightarrow \alpha + e^+ + \nu_e$

pp I

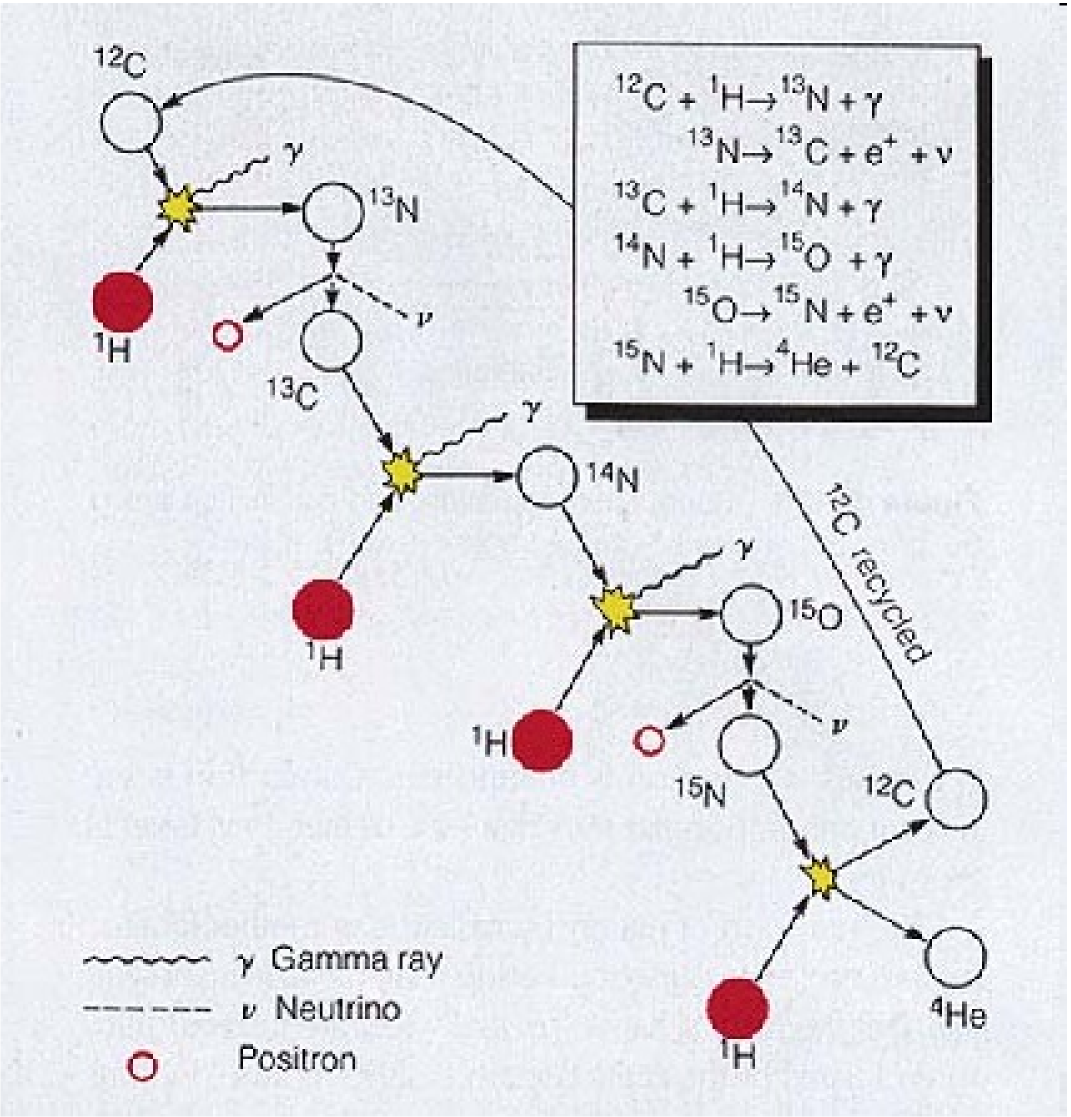
pp II

pp III

hep

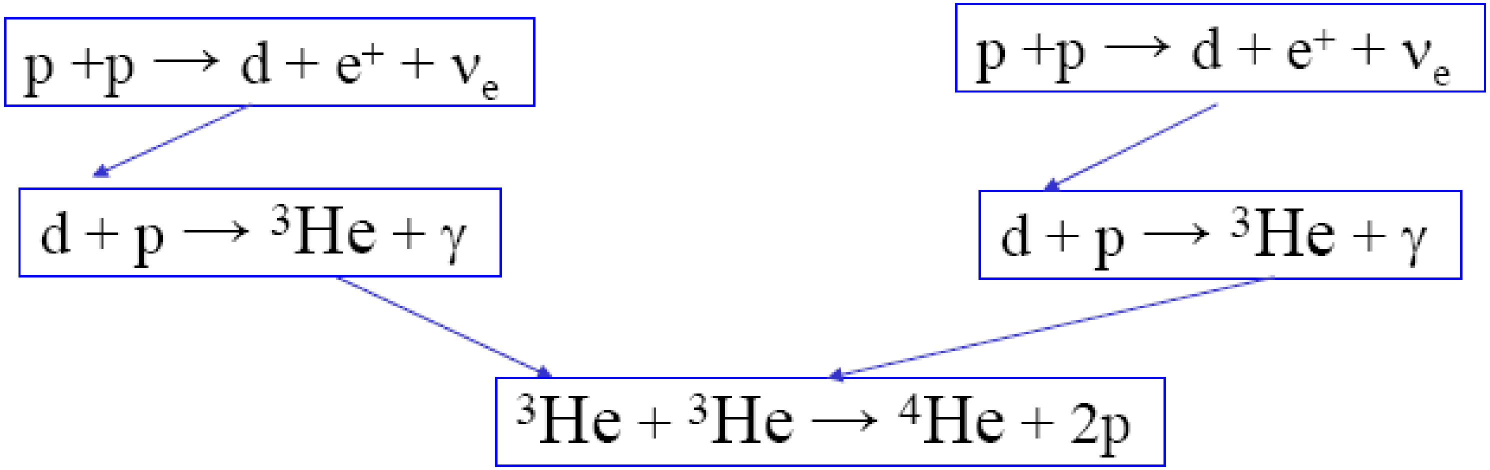
7

Ciclo CNO


$^{12}C + {}^{1}H \rightarrow {}^{13}N + \gamma$
$^{13}N \rightarrow {}^{13}C + e^{+} + \nu$
$^{13}C + {}^{1}H \rightarrow {}^{14}N + \gamma$
$^{14}N + {}^{1}H \rightarrow {}^{15}O + \gamma$
$^{15}O \rightarrow {}^{15}N + e^{+} + \nu$
$^{15}N + {}^{1}H \rightarrow {}^{4}He + {}^{12}C$
^{12}C
^{1}H
γ
^{13}N
ν
^{13}C
^{1}H
γ
^{14}N
^{1}H
γ
^{15}O
ν
^{15}N
^{12}C
^{1}H
^{4}He
^{12}C recycled
γ Gamma ray
ν Neutrino
Positron

The pp-I chain

- Reactions involving nuclei with the smallest charges are favoured, due to smaller Coulomb barrier. This is the reason why in the Sun we believe that pp-I is the dominant energy production mechanism, accounting for some 90% of the total energy production.
- It proceeds along the following steps



$$\boxed{p + p \longrightarrow d + e^+ + \nu_e} \qquad \boxed{p + p \longrightarrow d + e^+ + \nu_e}$$

$$\boxed{d + p \longrightarrow {}^3He + \gamma} \qquad \boxed{d + p \longrightarrow {}^3He + \gamma}$$

$$\boxed{{}^3He + {}^3He \longrightarrow {}^4He + 2p}$$

- Each e^+ will annhilate against e^- in the plasma
- The full result is

$$4p + 2e^- \longrightarrow {}^4He + 2\nu_e$$

Remarks on pp-I chain : pp neutrinos

$$\boxed{p + p \longrightarrow d + e^+ + \nu_e}$$

- Note that the first step is a weak interaction process,
- It transforms the *p*'s into *n*'s necessary to form ^{4}He; this is different from BBN, where free neutrons were available.
- The produced neutrinos (called pp-ν) have a continuous spectrum, with E_{max}=0.4 MeV and <E>=0.2 MeV

$$\boxed{d + p \longrightarrow {}^3He + \gamma}$$

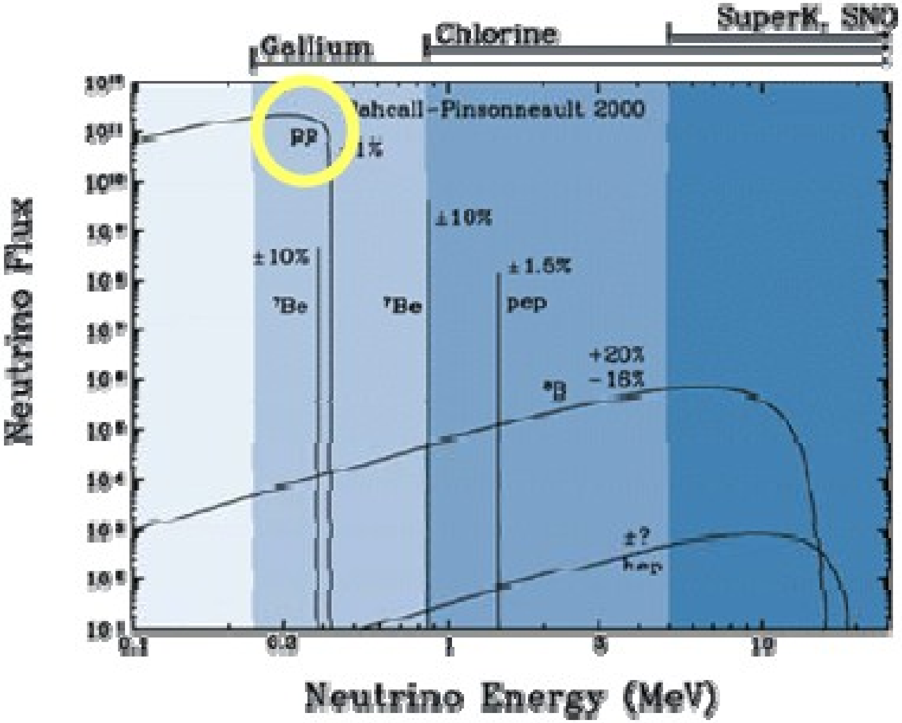
- This is an e.m process, which destroys *d*. This is generally the fate of *d* in stars and the reason why it is rare. It is formed by weak process where Hydrogen is present, and is destroyed by an e. m process which requires Hydrogen

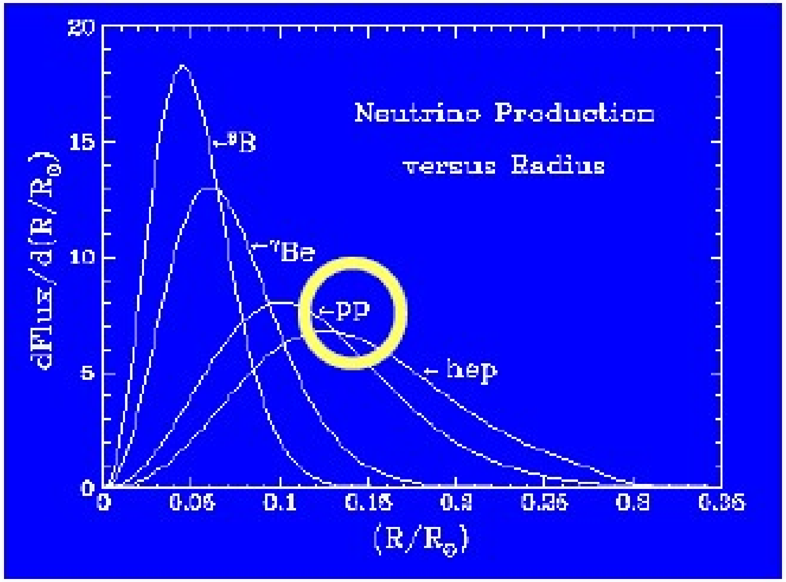
$$\boxed{{}^3He + {}^3He \longrightarrow {}^4He + 2p}$$

- It is a strong interaction process, which completes the chain.

pp neutrinos

- Energy spectra and production region is shown for pp neutrinos.
- pp neutrinos are :
  - the dominant component in number
  - the component with smallest energy
  - The component which is produced in a more extended area of the Sun, concentrated however within 1/3 of the solar radius and with a maximun at 1/10 of R_o





Equilibrium conditions and nuclear abundances

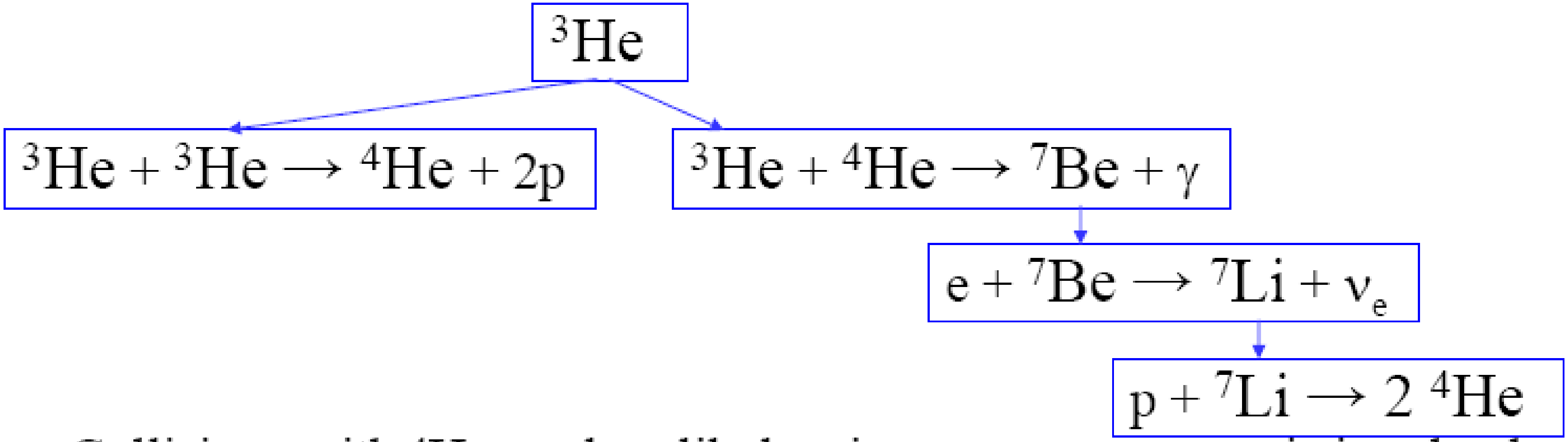
- In a large fraction of the energy prodution region the chain is equilibrated, i.e. at any point, the production rate of the intermediate products is equilibrated by their destruction rate.
- This can be used to derive the local densities of the different nuclei in temrs of that of hydorgen, n_1 *
- For d, by requiring that the formation rate ($1/2\ n_1^2\langle\sigma v\rangle_{11}$) equals the destruction rate ($n_1 n_2\langle\sigma v\rangle_{12}$) , one finds $n_2 = 1/2\ n_1\langle\sigma v\rangle_{11}/\langle\sigma v\rangle_{12}$, and for the mass abundances: $a(D)/a(H) = \langle\sigma v\rangle_{11}/\langle\sigma v\rangle_{12}$
- Deuterium abundance is very low with respect to that of Hydrogen as it involves the ratio of a weak to an e.m. process.
- Similarly, one can equate ^3He destruction rate ($2 \times \frac{1}{2}\ n_3^2\langle\sigma v\rangle_{33}$) to its formation rate, obtaining: $a(^3He)/a(H) = 3/\sqrt{2}\ (\langle\sigma v\rangle_{11}/\langle\sigma v\rangle_{33})^{1/2}$
- Also ^3He is very rare, for the same reasons as for deuterium
- Note that the ratio of abundances are determined by ratios of nuclear reaction rates, i.e. depend on the S-factors and temperature .

---

*) n_i is the number density of the nuclides with mass number *i* and $\langle\sigma v\rangle_{ij}$ is the collision rate between nuclei with mass numbers *i* and *j* .

The pp-II chain and Beryllium neutrinos

- Indeed, ^{3}He can be destroyed also in collisions with ^{4}He,



$^3\mathrm{He}$

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

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

$e + {}^7\mathrm{Be} \rightarrow {}^7\mathrm{Li} + \nu_e$

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

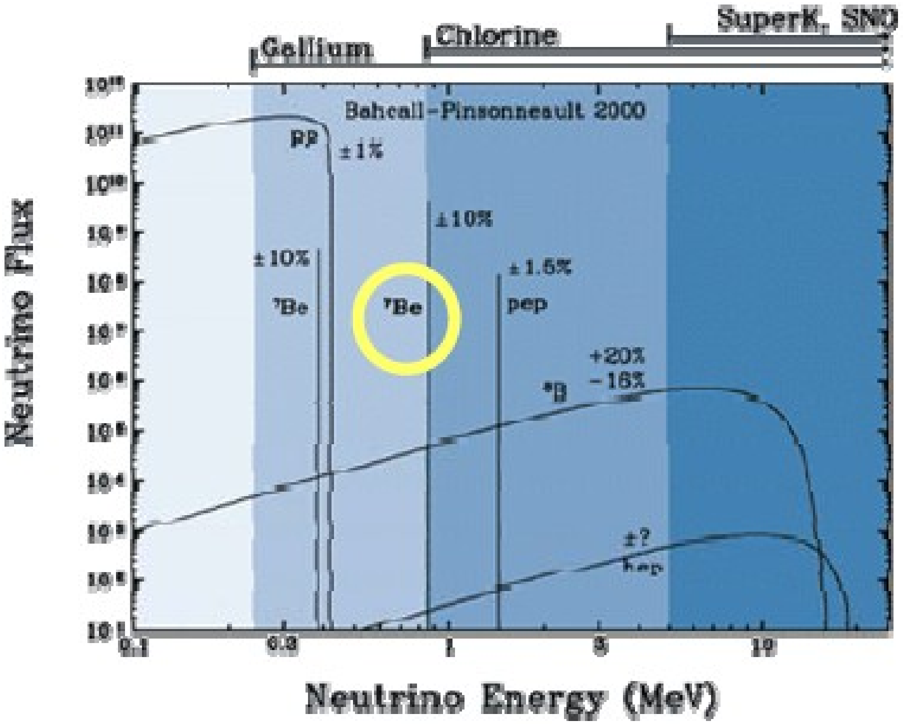
- Collisions with ^{4}He are less likely, since an e.m process is involved and more massive particles are involved in the tunneling.
- A (bare) nucleus of ^{7}Be, in vacuum is stable* but in the plasma an electron can be captured, with emission of a monochromatic Be-neutrino** with E=0.8 MeV.
- Be neutrinos are 10% with respect to pp neutrinos.

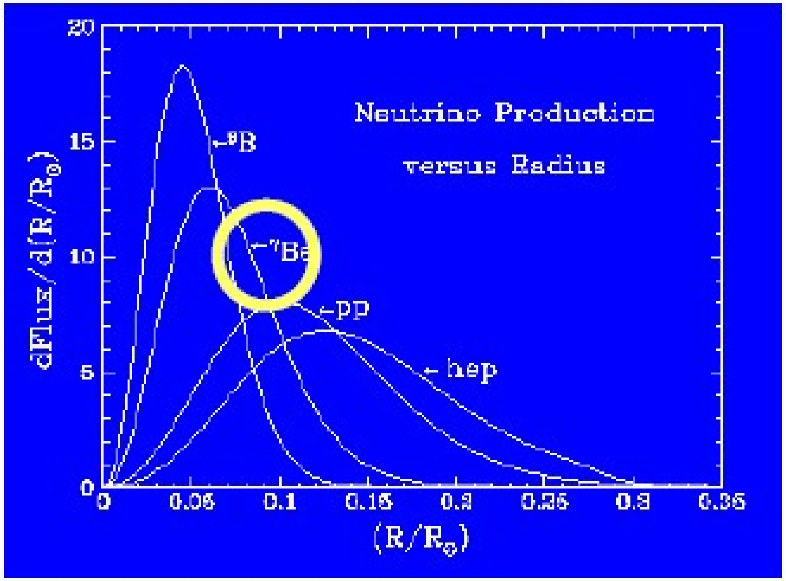
*) Exercise: One has: m(^{7}Be)- m(^{7}Li)=0.3 MeV. Prove that β^+ is forbidden whereas EC is allowed by energy conservation

**) In fact it is dichromatic, since also an excited state of ^{7}Li can also be produced, with 10% probability.

Be neutrinos

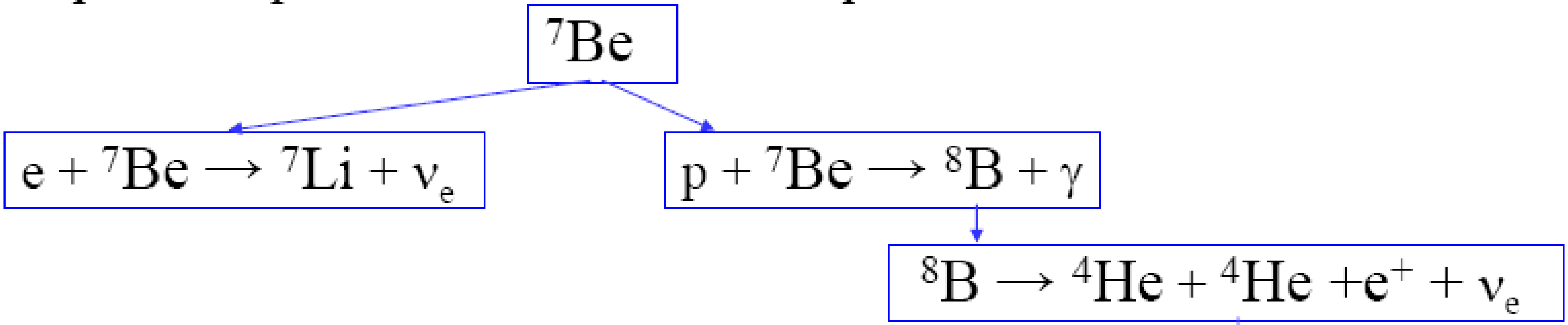
- Shape and production region are shown in the figures
- Be neutrinos are:
  - the second source in intensity, after pp
  - They are "intermediate energy neutrinos", in that their energy is in between that of pp and B.
  - They are produced in a more central region, where reaction with ^{4}He is more likely due to higher temperature.





The pp-III chain and Boron neutrinos

- Indeed, ^{7} Be can be destroyed also in collisions with protons, i.e proton capture instead of electron capture,



^{7}Be

$e + {}^{7}Be \longrightarrow {}^{7}Li + \nu_e$

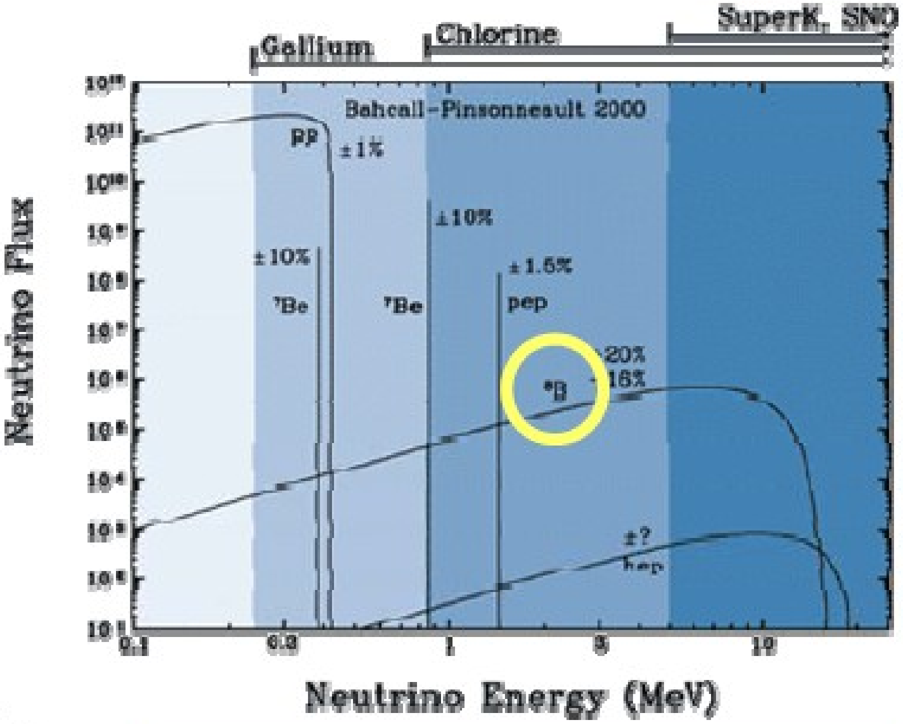
$p + {}^{7}Be \longrightarrow {}^{8}B + \gamma$

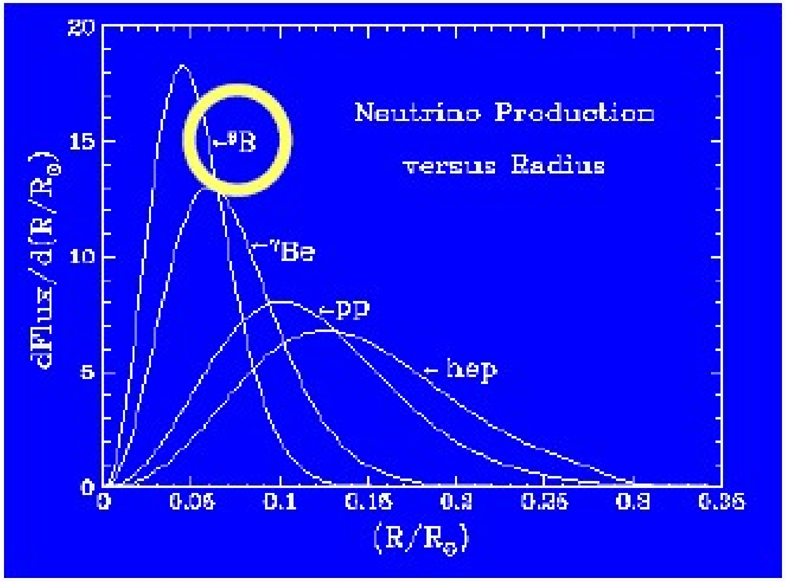
${}^{8}B \longrightarrow {}^{4}He + {}^{4}He + e^{+} + \nu_e$

- *p* capture is disfavoured with respect to *e* capture due to Coulomb repulsion, although the instrinsic strength of an e.m. process is larger than that of a weak process.
- Boron neutrinos have a continuous spectrum, extending to 14 MeV.
- Their intensity is about 10^{-4} with respect to pp
- Predictions on B neutrinos are affected by larger errors, due to the several branching involved an to marked temperature dependence.

Boron neutrinos

- Shape and production region are shown in the figures
- B- neutrinos are:
  - 10^{-4} in intensity with respect to pp
  - They are “high energy neutrinos”, in that their energy is higher than that of pp and of Be
  - They are produced in a more central region, where p capture on 7Be is more likely due to higher temperature.





Most studied solar neutrinos

name:	pp	^{7}Be	^{8}B
reaction:	$p+p \rightarrow d+e^+ +\nu_e$	$^7Be+e^- \rightarrow {}^7Li+\nu_e$	$^8B \rightarrow {}^8Be+e^+ +\nu_e$
energy: [MeV]	≤ 0.42	0.861 (90%) 0.383 (10%)	≤ 15
abundance: [cm $^{-2}$ s^{-1}]	$5.96 \cdot 10^{10}$	$4.82 \cdot 10^9$	$5.15 \cdot 10^6$
uncertainty: (1σ)	1%	10%	18%
production zone:	0.1 R_o	0.06 R_o	0.05 R_o

More neutrinos from the Sun:
pep neutrinos , a variant of pp-I chain :

- Whenever a β^+ decay is possible, $(Z,A) \longrightarrow (Z-1,A) + e^+ + \nu_e$ also Electron Capture is possibile, $e + (Z,A) \longrightarrow (Z-1,A) + \nu_e$, since $Q(EC) = Q(\beta^+) + 2m_e$, so if $Q(\beta^+) > 0$ then also $Q(EC) > 0$

- Thus *d* can be formed also through:

$$\boxed{e^- + p + p \longrightarrow d + \nu_e}$$

- This reaction is less likely (≈1%) , then $p + p \longrightarrow d + e^+ + \nu_e$ since having three particles on a region with nuclear dimension is more difficult than two.
- The reaction produces monochromatic neutrinos, with

$$E = E_{max} + 2m_e = 1.4 \text{ MeV}$$

The luminosity constraint (1)

- The total neutrino flux is immediately derived from the solar constant K_o:
- If one assumes that Sun is powered by transforming H into He with a heat release Q_H:

$$4p+2e^- \rightarrow 4He + \text{heat and particles}$$

- Due to L conservation, 2 neutrinos must appear on the r.h.s.
- If L_e also is conserved they must be of electron type:

$$4p+2e^- \rightarrow 4He + 2\nu_e + Q_H:$$

- Then one has $2\nu_e$ for each Q of radiated energy, and the total neutrino produced flux is:

$$\Phi_{TOT} = 2\,K_o / Q_H$$

The luminosity constraint (2)

- A more tedious but may be more transparent derivation is the following one
- From measurement of K_o on deduces the solar luminosity $L = 4\pi K_o D^2$ where D is the Sun Earth distance.
- If this energy is produced by nuclear fusion, with each fusion releasing an amount of heat Q_H, then one derives the fusion rate

  $dN_f/dt = L/Q_H = 4\pi K_o D^2 / Q_H$
- Since each fusion provides 2 neutrinos, the neutrino production rate is

  $dN_\nu/dt = 2dN_f/dt = 8\pi K_o D^2 / Q_H$
- The neutrino flux is then obtained by $\Phi_{TOT} = dN_\nu/dt / (4\pi D^2)$ which gives

$$\Phi_{TOT} = 2 K_o / Q_H$$

Heat release in $4p+2e^- \rightarrow {}^4He + 2\nu_e$

- The Q value of the reaction

$$Q = 4m_p + 2m_e - {}^4He = 26.7\ \text{MeV}$$

- is the energy which can be carried by the reaction products. Ultimately, this energy is in the form of photons (Heat) and neutrinos which escape from the Sun

$$Q = Q_H + 2\langle E_\nu \rangle$$

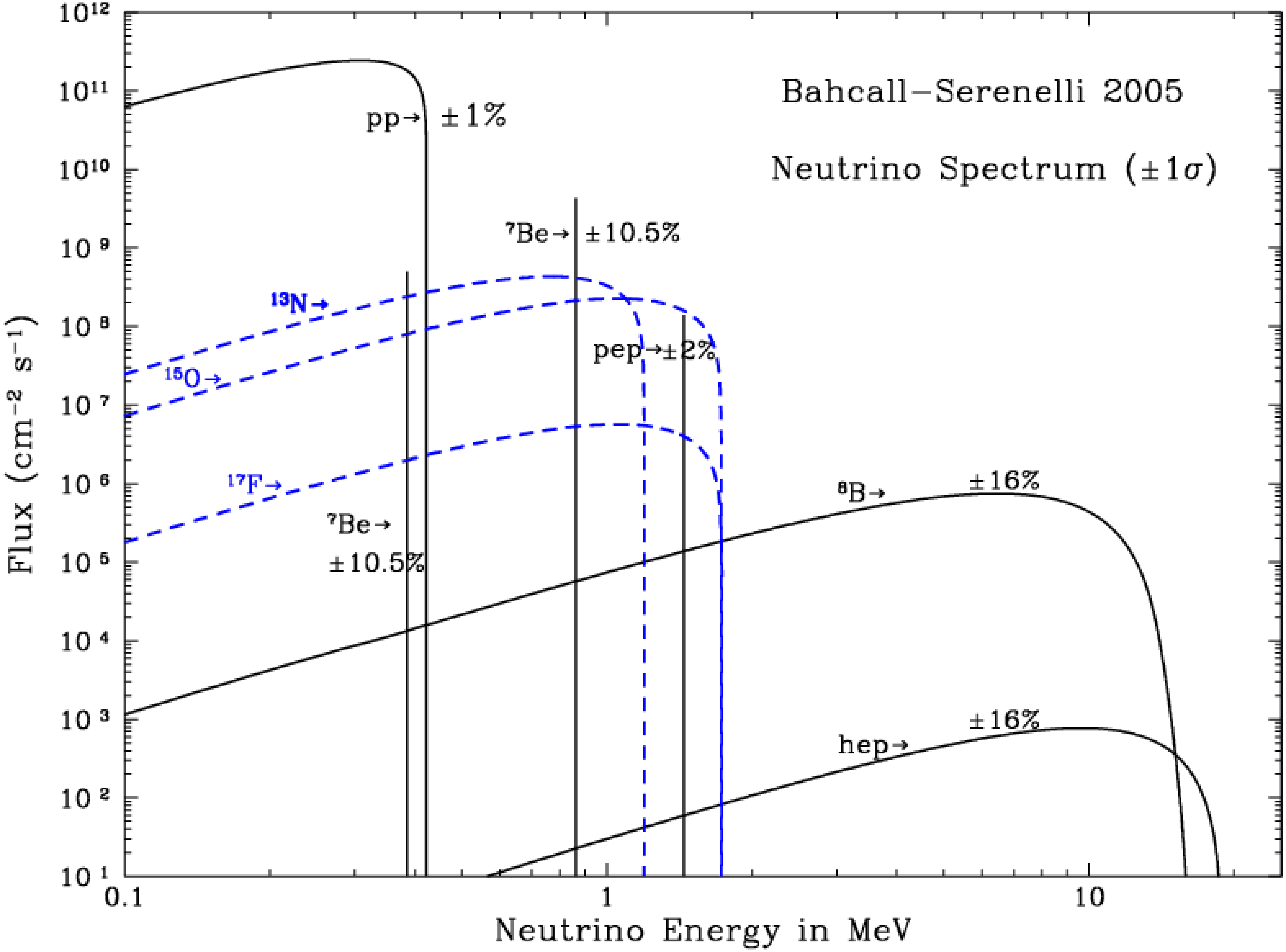
- where the average energy carried away by neutrinos is $\langle E_\nu \rangle = 0.2$ MeV, so that $Q_H = 26.3$ MeV. In practice, almost all the energy is carried by photons and little is "wasted" in neutrinos"*

- At this point one can easily estimate the total neutrino flux**

  $\Phi_{TOT} = 2\ K_o / Q_H = 6.4\ 10^{10}/\text{cm}^2/\text{s}$

**)Exercise: what is the photon flux form the sun? (photons//cm^2/s)

*) Note that the opposite occurr in a collapse supernova, where most of the energy is carried by neutrinos, and photons only account fo % of the total emitted energy


Bahcall−Serenelli 2005
Neutrino Spectrum (±1σ)
pp→ ±1%
⁷Be→ ±10.5%
¹³N→
¹⁵O→
¹⁷F→
pep→±2%
⁷Be→
±10.5%
⁸B→
±16%
hep→
±16%
Flux (cm⁻² s⁻¹)
10¹²
10¹¹
10¹⁰
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
10³
10²
10¹
0.1
1
10
Neutrino Energy in MeV

Dependence on T_c

- By building different solar models, with varied inputs parameters (within their uncertainties) and by using a power law parametrization, one finds (approximately):

$\boxed{\Phi_B \sim T_c^{20}}$ $\boxed{\Phi_{Be} \sim T_c^{10}}$ $\boxed{\Phi_{pp} \sim T_c^{-0.7}}$

- B neutrinos has the strongest dependence, due both to $^3He+^4He$ and (mainly) to ^7Be+p
- Be neutrinos strong depends on T_c, due to Gamow factor in $^3He+^4He$
- For the conservation of total flux, pp neutrinos decrease with increasing T_c

L'esperimento di Davis

Esperimento Homestake (1970 – 1998): prima rivelazione dei neutrini solari

Metodo radio-chimico (R. Davis, University of Pennsylvania)

$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$ **Energia alla soglia: E(ν_e) > 0.814 MeV**

Rivelatore: serbatoio contenente 390 m^3 C_2Cl_4 (percloroetilene) nella miniera di Homestake (South Dakota, U.S.A.). Profondità equivalente a 4100 m H_2O.

Contenuto di ${}^{37}Cl$ nel Cloro naturale = 24%

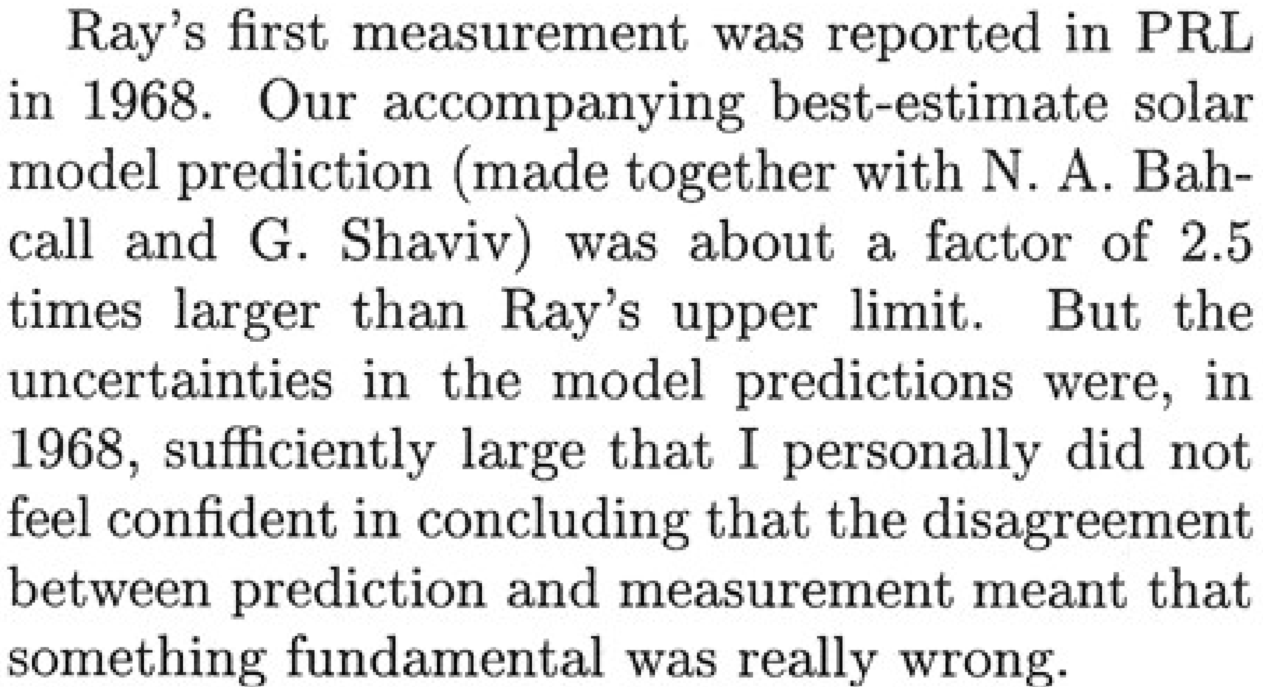
Frequenza di produzione di atomi di ${}^{37}Ar$ prevista ≈ 1.5 / giorno

Metodo sperimentale: ogni 2 – 3 mesi estrazione di ${}^{37}Ar$ mediante flusso di N_2 attraverso il serbatoio. Purificazione, miscelazione con Argon naturale, riempimento di un contatore proporzionale e rivelazione della cattura elettronica $e^- + {}^{37}Ar \rightarrow \nu_e + {}^{37}Cl$ (tempo di dimezzamento $\tau_{1/2} = 34$ giorni)

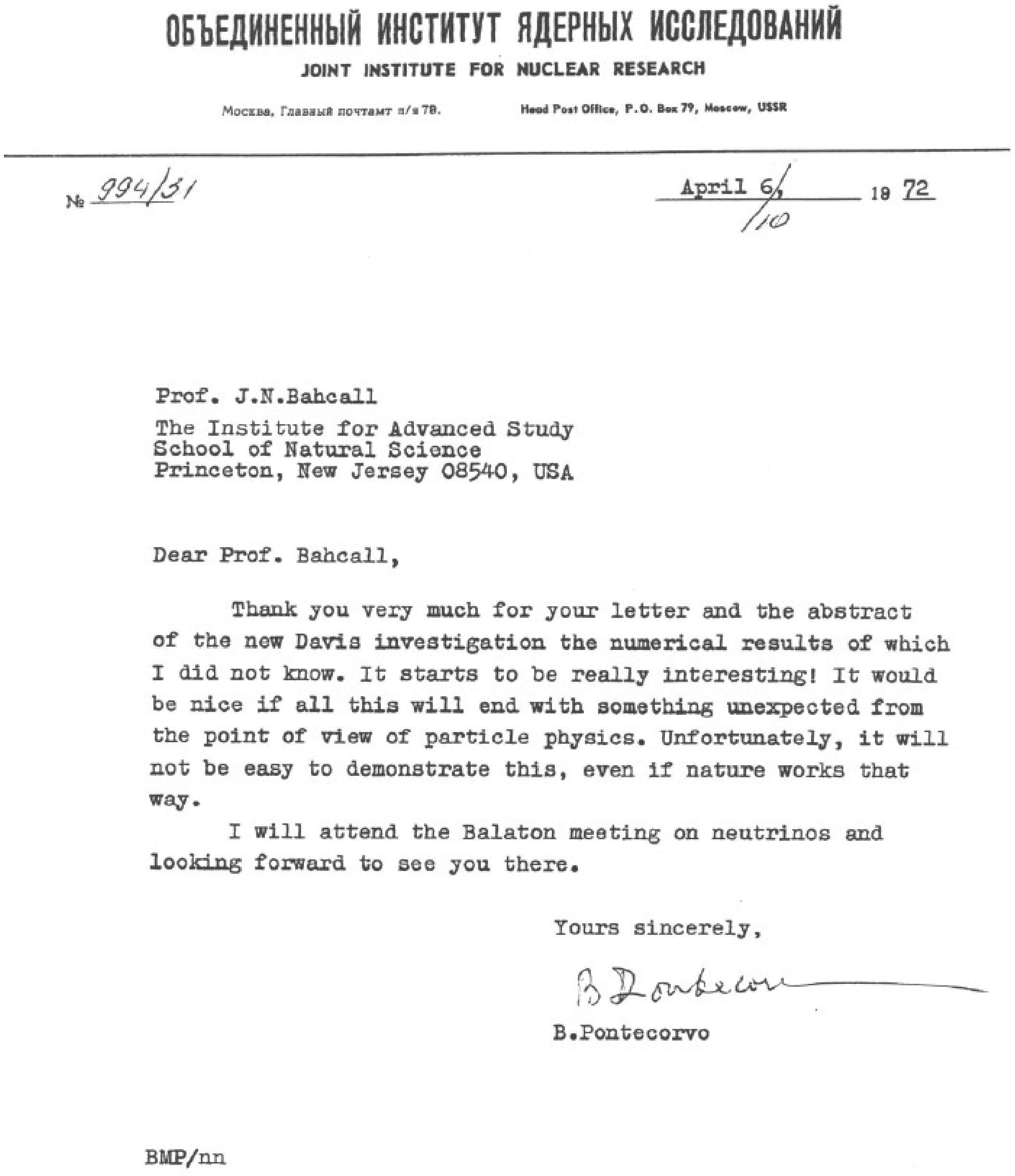
(Lo stato finale eccitato dell'atomo di ${}^{37}Cl$ emette elettroni Augier e/o raggi X)

Misura dell'efficienza mediante iniezione di quantità note di ${}^{37}Ar$ nel serbatoio.

Primo confronto dati/modello



Ray's first measurement was reported in PRL in 1968. Our accompanying best-estimate solar model prediction (made together with N. A. Bahcall and G. Shaviv) was about a factor of 2.5 times larger than Ray's upper limit. But the uncertainties in the model predictions were, in 1968, sufficiently large that I personally did not feel confident in concluding that the disagreement between prediction and measurement meant that something fundamental was really wrong.



ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ
JOINT INSTITUTE FOR NUCLEAR RESEARCH
Москва, Главный почтамт п/я 79. Head Post Office, P.O. Box 79, Moscow, USSR

№ 994/31 April 6/ 1972
/10

Prof. J.N.Bahcall
The Institute for Advanced Study
School of Natural Science
Princeton, New Jersey 08540, USA

Dear Prof. Bahcall,

Thank you very much for your letter and the abstract of the new Davis investigation the numerical results of which I did not know. It starts to be really interesting! It would be nice if all this will end with something unexpected from the point of view of particle physics. Unfortunately, it will not be easy to demonstrate this, even if nature works that way.

I will attend the Balaton meeting on neutrinos and looking forward to see you there.

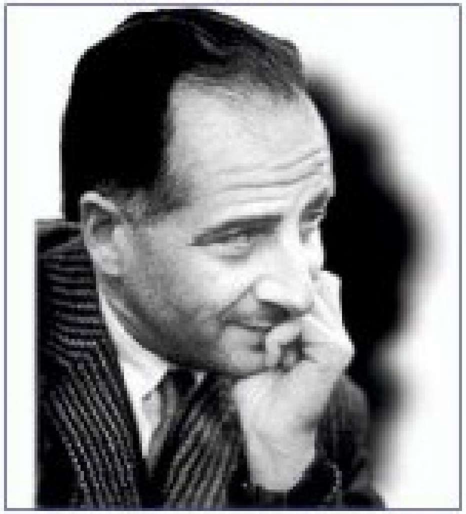
Yours sincerely,

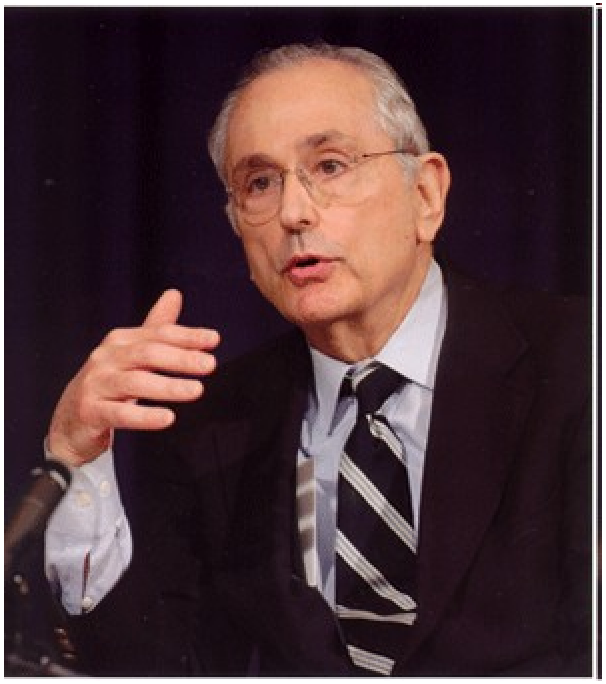
B Pontecorvo

B.Pontecorvo

BMP/nn

Bruno Pontecorvo





John Bahcall

Abbassare la soglia

- La soglia della reazione sul cloro è 814KeV, l’esperimento è sensibile solo ai neutrini del berillio e del boro, per i quali l’incertezza teorica è alta
- Si possono studiare altri processi a soglia più bassa che consentano di rivelare i neutrini pp

Esperimenti con Gallio: rivelazione radio-chimica della reazione

$$\nu_e + {}^{71}\mathrm{Ga}_{31} \rightarrow e^- + {}^{71}\mathrm{Ge}_{32}$$

Soglia energetica $E(\nu_e) > 0.233$ MeV $\Rightarrow$ reazione sensibile ai neutrini solari da $p + p \rightarrow e^+ + \nu_e + d$ (componente dominante)

Tre esperimenti:

- **GALLEX (Gallium Experiment, 1991 – 1997)**
- **GNO (Gallium Neutrino Observatory, 1998 –)**

$\}$ Nei Laboratori Nazionali del Gran Sasso. Profondità 3740 m H_2O eq.

- **SAGE (Soviet – American Gallium Experiment)**

Nel Laboratorio Sotterraneo di Baksan (Caucaso, Russia) Profondità 4640 m H_2O eq.

Rivelatore: 30.3 tonn. Gallio in soluzione di HCl (GALLEX, GNO)
50 tonn. Gallio metallico (liquido a 40°C) (SAGE)

Metodo sperimentale: ogni ~3 settimane estrazione di ${}^{71}Ge$ sotto forma di $GeCl_4$ (sostanza altamente volatile). Conversione chimica in gas GeH_4, iniezione del gas in un contatore proporzionale $\Rightarrow$ rivelazione della cattura elettronica $e^- + {}^{71}Ge \rightarrow \nu_e + {}^{71}Ga$ (tempo di dimezzamento $\tau_{1/2} = 11.43$ giorni)

(Rivelazione delle transizioni atomiche K , L nello stato finale eccitato dell'atomo ${}^{71}Ga$)

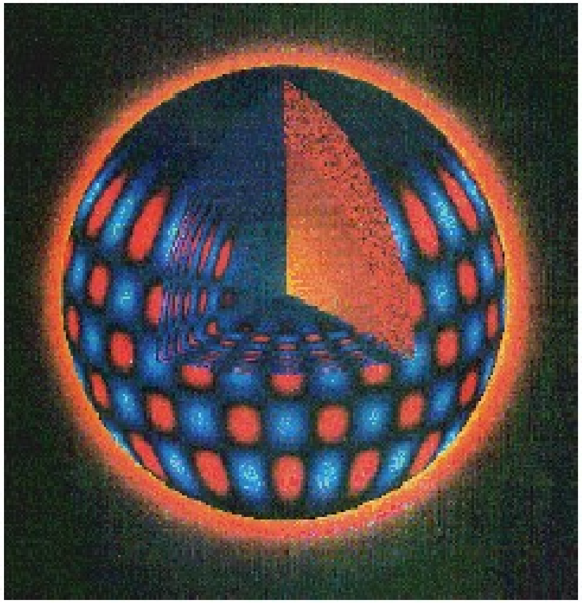
Misure dell'efficienza di rivelazione:

- **Iniezione di una quantità nota di ${}^{71}As$ (cattura $e^- + {}^{71}As_{33} \rightarrow {}^{71}Ge_{32} + \nu_e$)**
- **Uso di una sorgente artificiale intensa di ν_e mono-energetici ν_e : $e^- + {}^{51}Cr \rightarrow \nu_e + {}^{51}V$ preparata in un reattore nucleare, attività iniziale 1.5 MCurie equivalente a 5 volte il flusso di neutrini solari. $E(\nu_e) = 0.750$ MeV, $\tau_{1/2} = 28$ giorni**

Altre idee di esperimenti

- Sudbury Neutrino Observatory, 1983!

How to look into the solar interior? Helioseismology



- As one studies the deep Earth 's structure through hearthquakes or just like you can tell something about a material by listening to the sounds that it makes when something hits it, so one can study the solar interior by lookung at its vibrations.

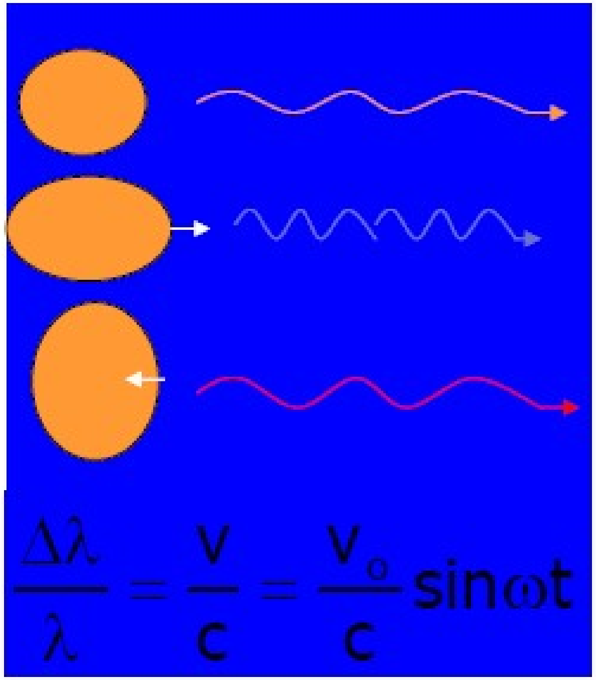
- Birth: in 1960 it was found that the solar surface vibrates with a period $T \approx 5$ min,

- Plan: reconstruct the properties of the solar interior by studying how the solar surface vibrates

Method

- By means of Doppler effect on the emitted radiation, one can measure oscillations of the solar surface with a very high accuracy

- Most recent measurements performed with SOHO satellite (SOlar and Heliospheric Observatory)

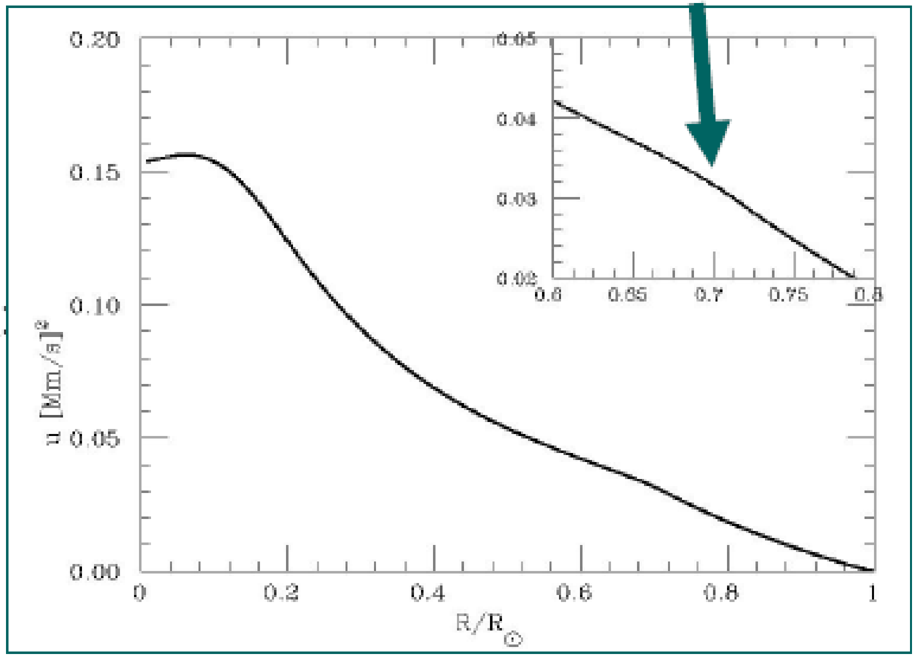


$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c} = \frac{v_o}{c}\sin\omega t$$

http://sohowww.nascom.nasa.gov/

Helioseismic inferences

By comparing the measured frequencies with the calculated ones (inversion method) one can determine:



- The sound speed profile (with accuracy of order 0.5%)
- Locate the transition between radiative transport and convection:

  R_b =0.711 (1 ± 0.14%) R
- The photospheric He abundance:

  Y_{photo}= 0.249 (1± 1.4%)
- Provide a benchmark for solar model builders.

1988-1995

- Confronto con dati eliosismologici ➔ accordo impressionantemente buono
- Inclusione nei modelli degli effetti di diffusione degli elementi
- Compare un secondo esperimento, realizzato per la ricerca del decadimento del protone, in grado di osservare i neutrini solari: Kamiokande

Esperimenti in "tempo reale" con contatori Čerenkov ad acqua per la rivelazione dei neutrini solari

Diffusione elastica neutrino – elettrone: $\nu + e^- \rightarrow \nu + e^-$

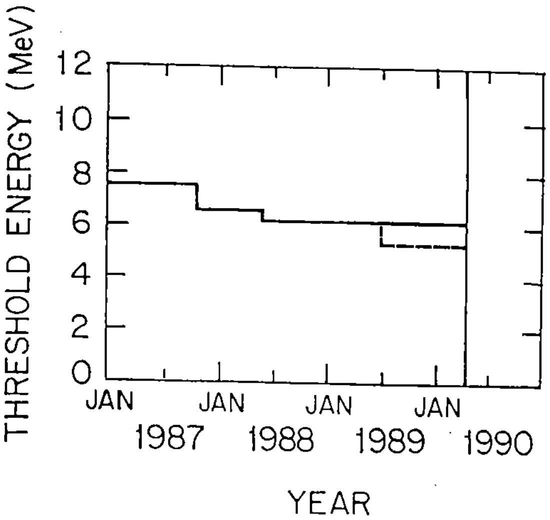
Rivelazione della luce Čerenkov emessa dagli elettroni in acqua

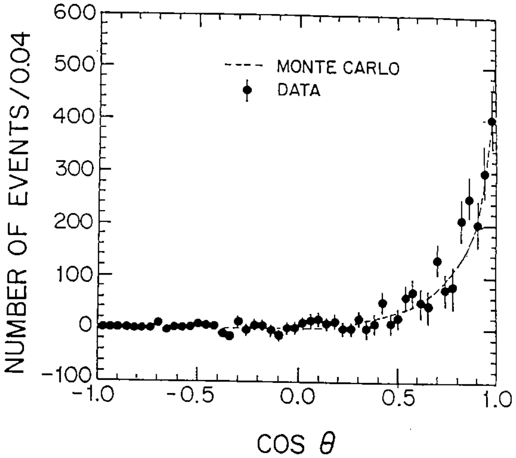
Soglia di rivelazione ~5 MeV (percorso residuo di elettroni da 5 MeV in $H_2O \approx 2$ cm)

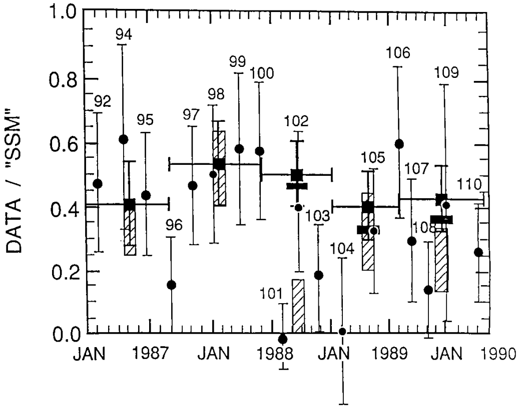
Sezioni d'urto: $\underset{\underset{\boxed{\text{scambio W , Z}}}{\uparrow}}{\sigma(\nu_e)} \approx 6\,\underbrace{\sigma(\nu_\mu) \approx 6\,\sigma(\nu_\tau)}_{\boxed{\text{Solo scambio Z}}}$

Kamiokande (1987-1994)

- Volume utile: 680m^3 di acqua
- Rivelazione in tempo reale: osservazione dei neutrini della supernova SN1987a, 11 eventi - Phys. Rev. Lett. **58** (1987) 1490-1493
- Flusso di neutrini solari (correlazione angolare) = 45% SSM







Phys. Rev. **D44** (1991) 2241-2260.

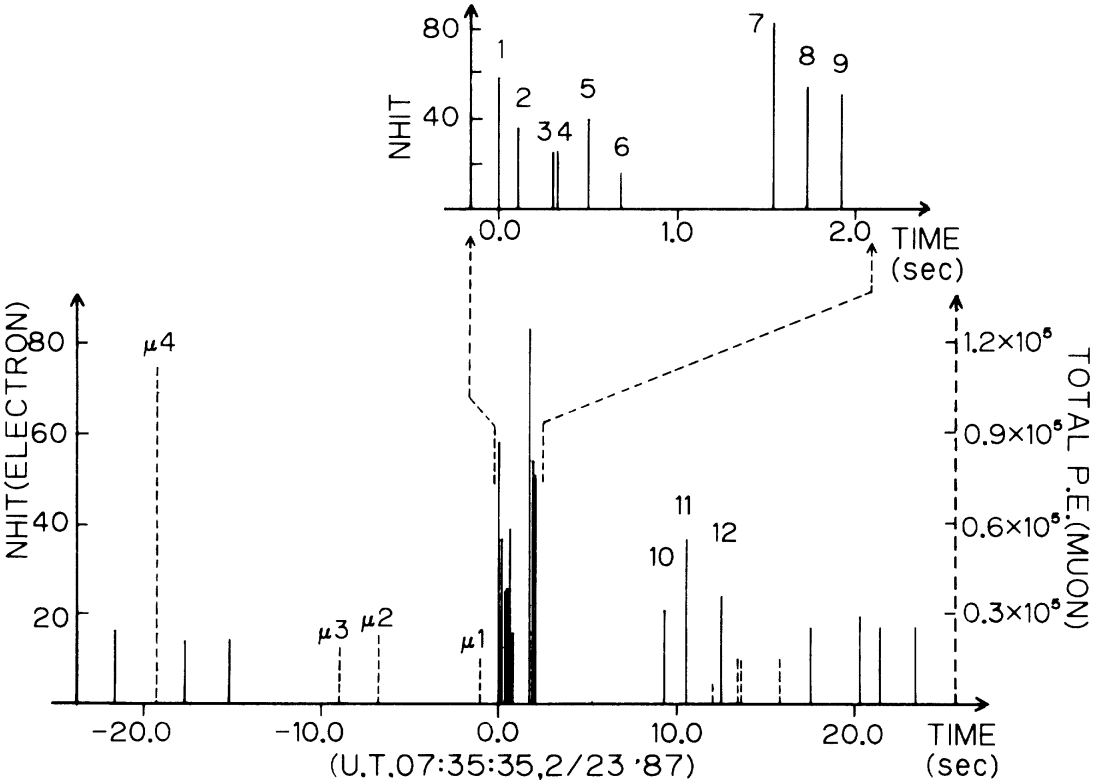
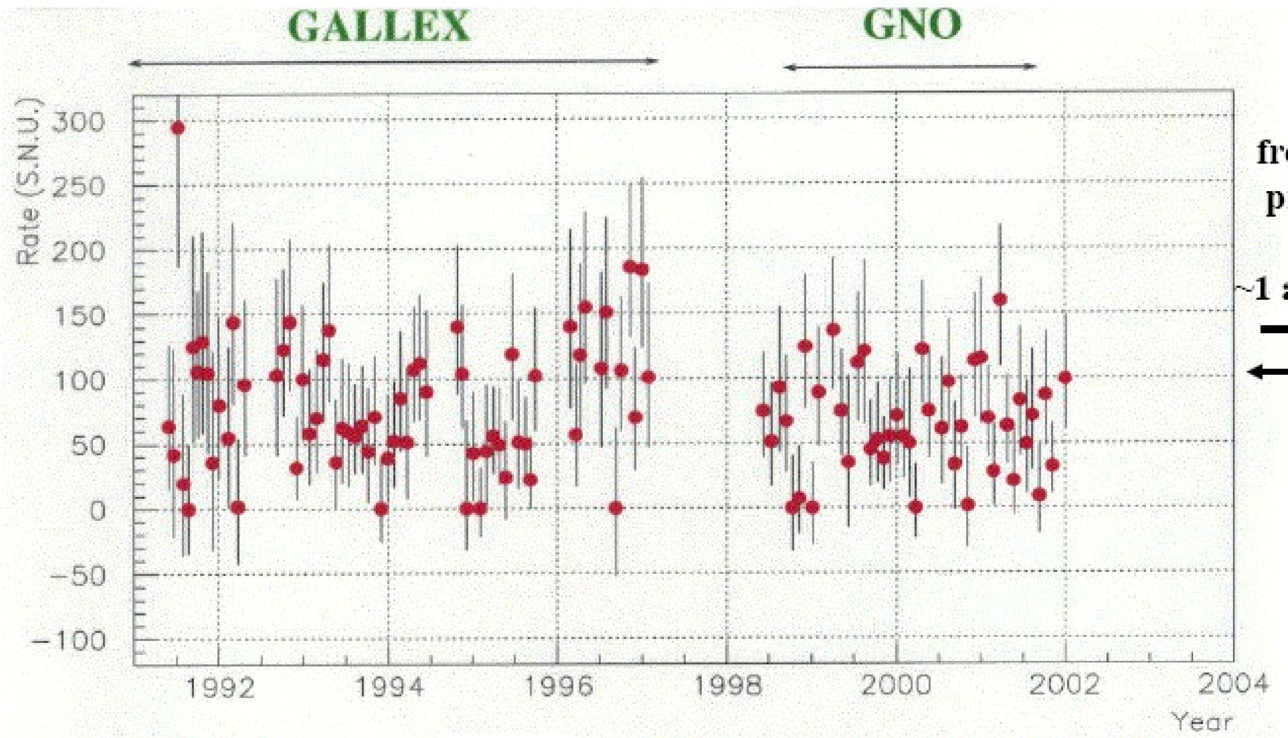


FIG. 2. The time sequence of events in a 45-sec interval centered on 07:35:35 UT, 23 February 1987. The vertical height of each line represents the relative energy of the event. Solid lines represent low-energy electron events in units of the number of hit PMT's, $N_{\rm hit}$ (left-hand scale). Dashed lines represent muon events in units of the number of photoelectrons (right-hand scale). Events $\mu 1-\mu 4$ are muon events which precede the electron burst at time zero. The upper right figure is the 0–2-sec time interval on an expanded scale.

Nel frattempo arrivano i risultati con il Gallio…



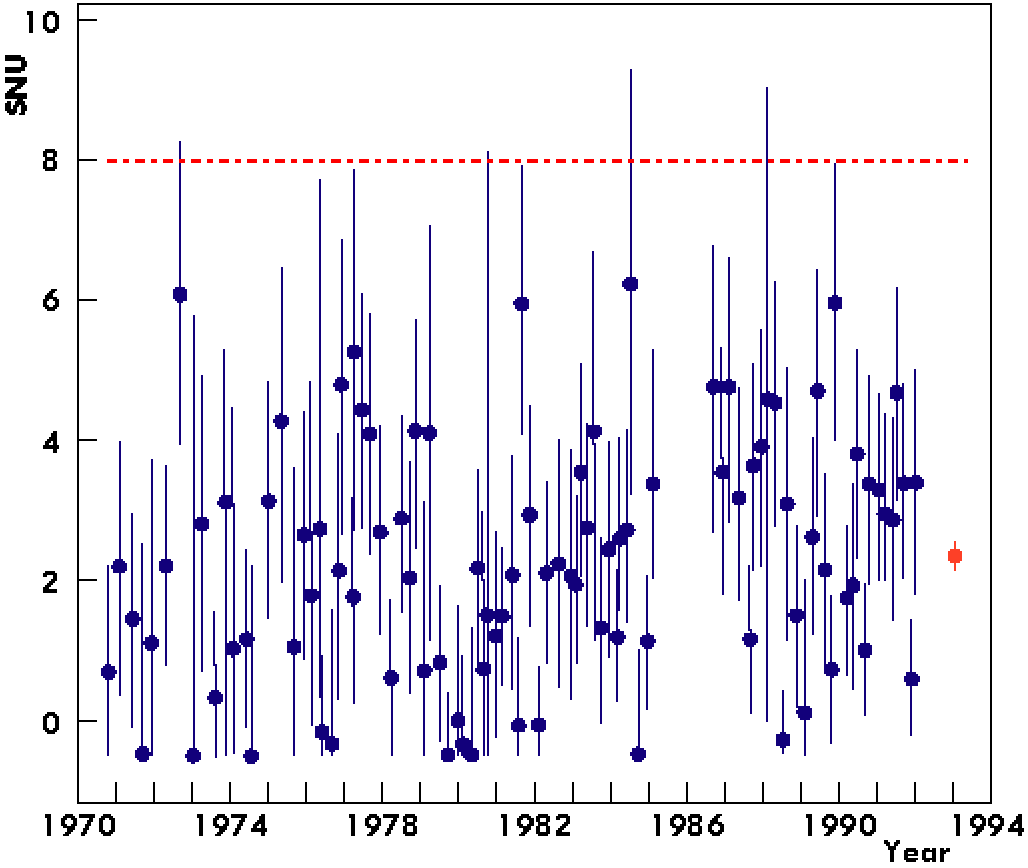
frequenza di
produzione
di ^{71}Ge
~1 atomo/giorno

GALLEX	77.5 +– 6.2 (stat) +– 4.5 (sys) SNU
GNO	65.2 +– 6.4 (stat) +– 3.0 (sys) SNU
GNO+GALLEX	70.8 +– 4.5 (stat) +– 3.8 (sys) SNU
SAGE (1990 – 2001)	$70.8^{+6.5}_{-6.1}$ SNU
PREDIZIONE SSM :	128^{+9}_{-7} SNU

Dati/SSM = 0.56 ± 0.05

SNU (Solar Neutrino Units): unità di misura della frequenza di eventi in esperimenti radio-chimici:
1 SNU = 1 evento s^{-1} per 10^{36} atomi

… si conclude Homestake…



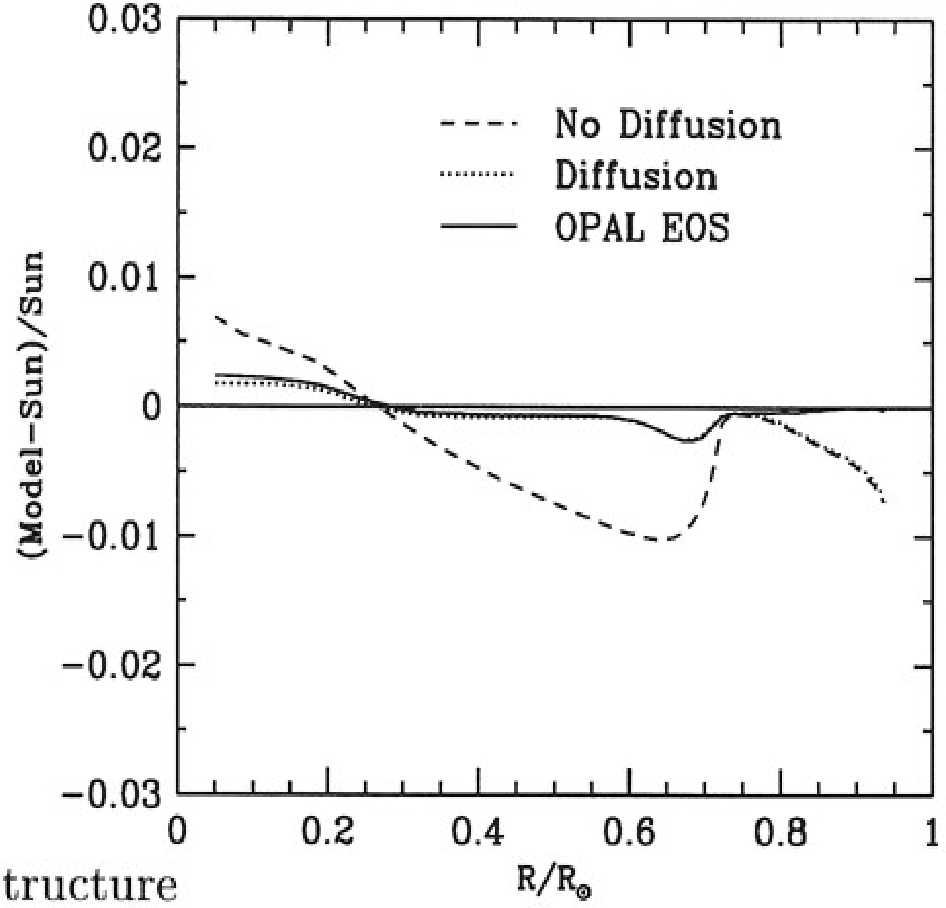
Ricostruzione (in tempo reale) dell’energia a bassa soglia?

- Borexino, proposto nel 1991

1995-1997

- Dati eliosismologici che consentono di sondare le regioni più profonde
- Nuovi valori di opacità
- Inclusione della diffusione dell’elio e degli elementi più pesanti

✂➔il problema dei neutrini solari non deriva da errori sul profilo di temperatura del Sole!

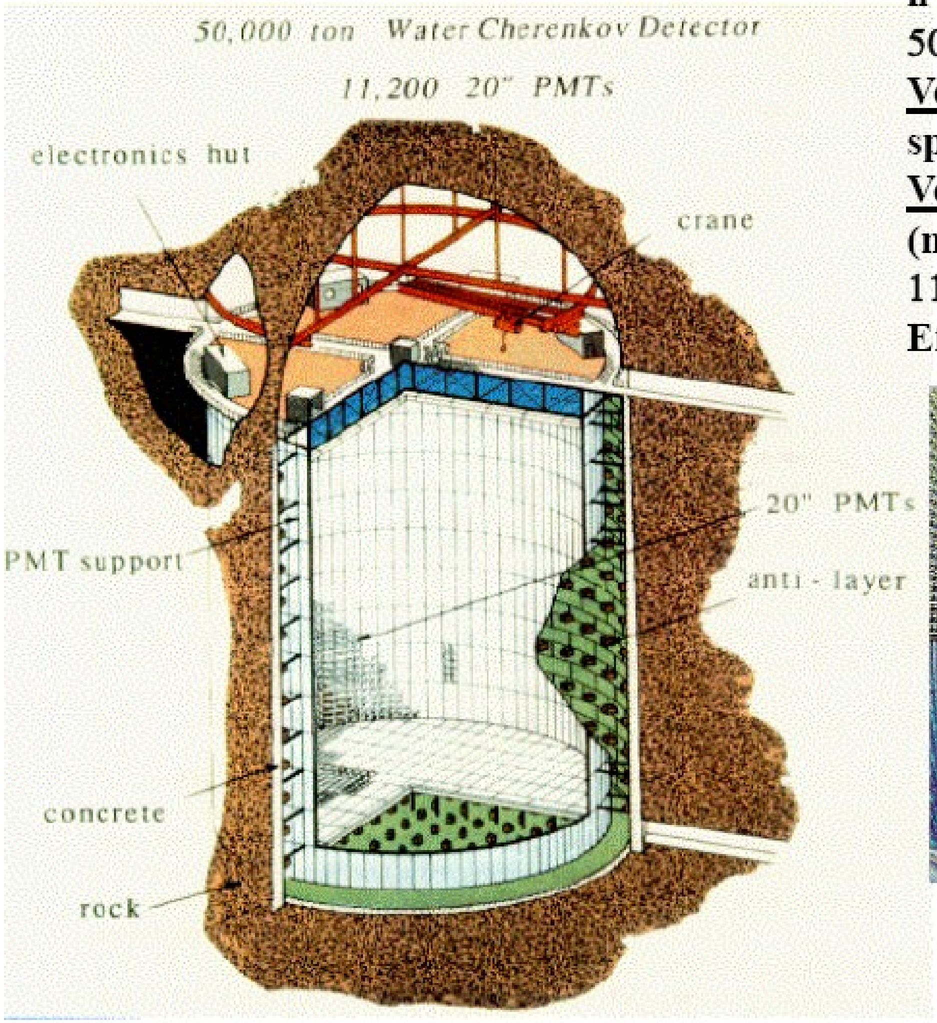


> “Standard solar models predict the structure of the Sun more accurately than is required for applications involving solar neutrinos.”

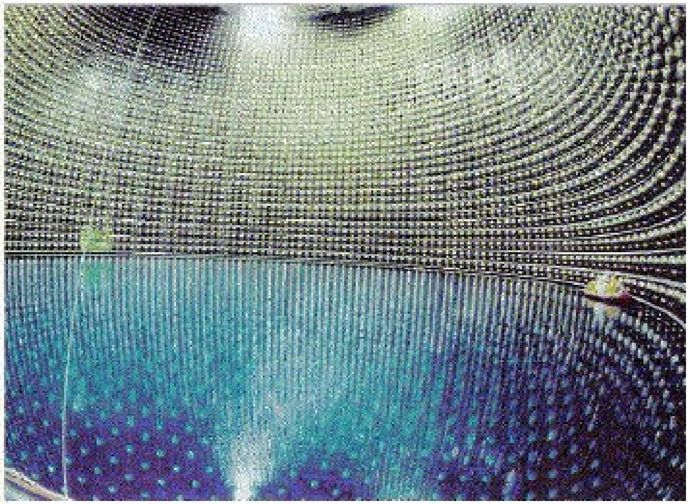
PRL vol 78, n 2, p 171 (1997)

…parte SuperKamiokande

Rivelatore Super-Kamiokande

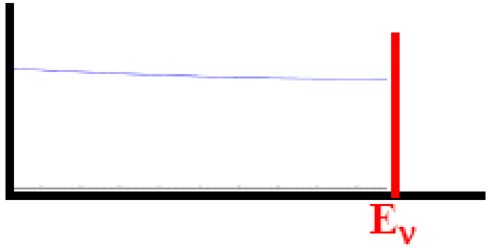


Serbatoio cilindrico
h = 41.4 m, diam. = 39.3 m
50 000 tonn. di H_2O pura
Volume esterno (anticoincidenza):
spessore ~2.7 m
Volume interno: ~ 32000 m^3
(massa fiduciale 22500 tonn.)
11200 fotomoltiplicatori, diam. = 50 cm
Efficienza di raccolta della luce ~ 40%

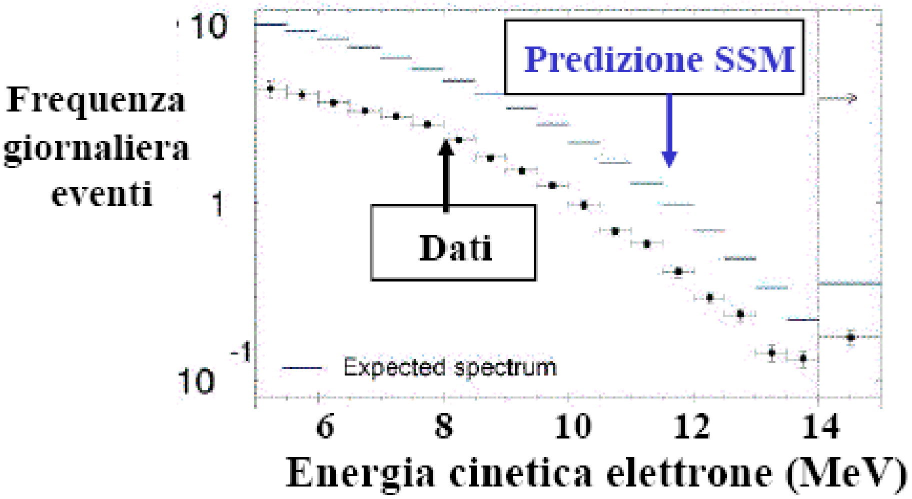


Volume interno durante il riempimento con acqua

Distribuzione dell’energia cinetica dell’elettrone da diffusione elastica $\nu_e - e$ di neutrini mono-energetici: →
praticamente piatta tra 0 and $2E_\nu/(2 + m_e/E_\nu)$



Convoluzione con lo spettro dei neutrini previsto
⇒ predizione SSM della distribuzione dell’energi degli elettroni



Risultati da 1496 giorni di presa – dati (22400 eventi)

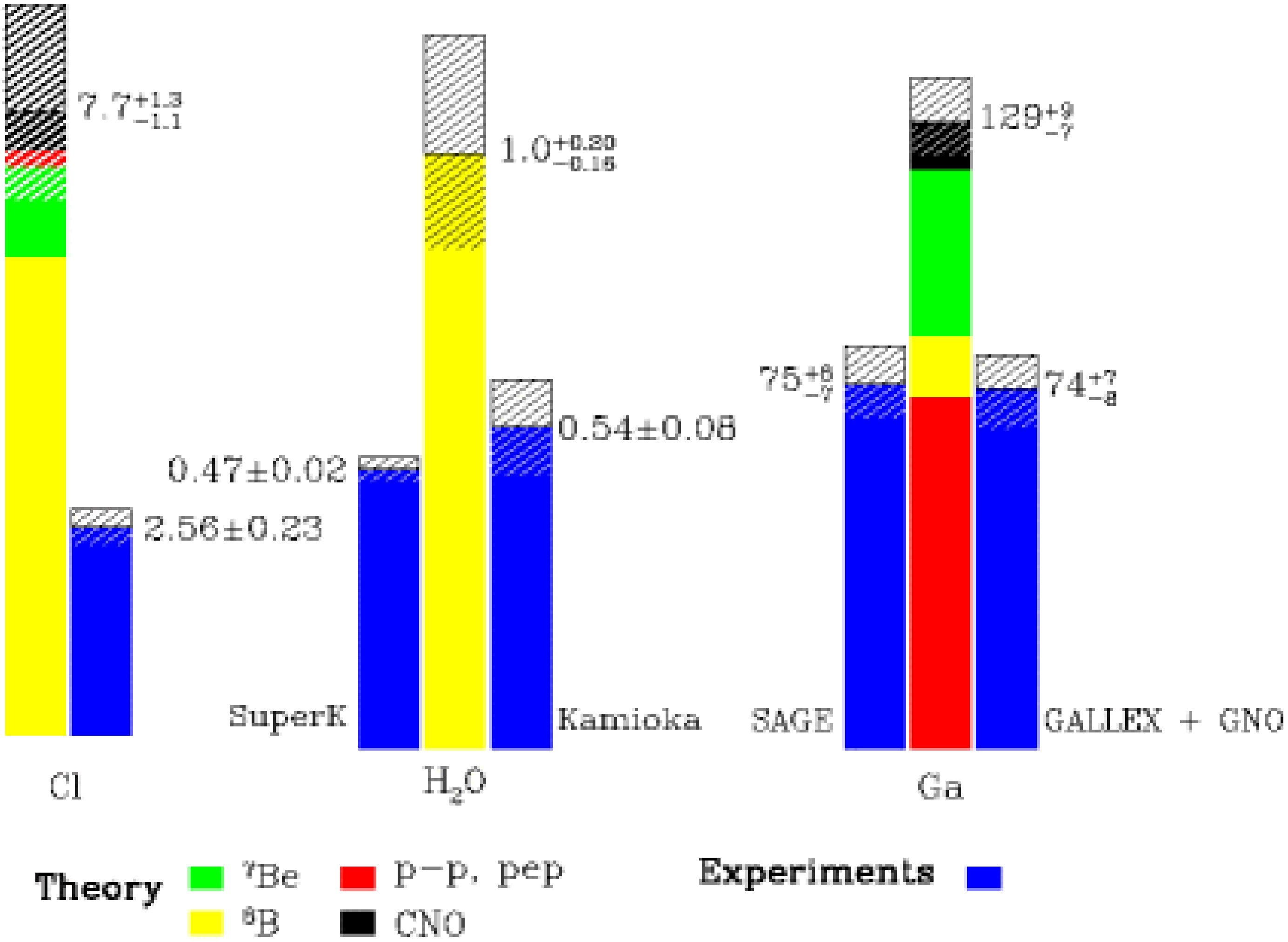
Flusso misurato (assumendo totalità di ν_e): $\Phi(\nu_e) = (2.35 \underset{\text{(stat)}}{\pm 0.02} \underset{\text{(sist)}}{\pm 0.08}) \times 10^{6}\ \text{cm}^{-2}\ \text{s}^{-1}$

Predizione SSM : $\Phi(\nu_e) = (5.05\ {}^{+1.01}_{-0.81}) \times 10^{6}\ \text{cm}^{-2}\ \text{s}^{-1}$

Dati/SSM = $0.465 \underset{\text{(stat)}}{\pm 0.005}\ {}^{+0.093}_{-0.074}$ (errore teorico incluso) ← DEFICIT DI ν_e

Total Rates: Standard Model vs. Experiment

Bahcall-Pinsonneault 2000



Il problema dei neutrini solari

- Inizialmente attribuito al modello, ormai comprovato dall’eliosismologia
- Deficit ossevato con diverse tecnologie e a diverse soglie

✂➔l’ipotesi di oscillazione, nell’aria fin dai primi anni ’70, prende decisamente corpo

- Ne parliamo solo adesso perché solo ora si dispone di abbastanza dati da poterla convalidare

Oscillazioni di neutrini

Ipotesi: "mixing" di neutrini

(Pontecorvo 1958; Maki, Nakagawa, Sakata 1962)

ν_e ν_μ ν_τ non sono autostati di massa ma combinazioni lineari di autostati di massa ν_1 ν_2 ν_3 con autovalori m_1 m_2 m_3

$$\boxed{|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle}$$

α = e, μ, τ (indice di "flavour")
i = 1, 2, 3 (indice di massa)

$U_{\alpha i}$: matrice unitaria di mixing

$$\boxed{|\nu_i\rangle = \sum_\alpha V_{i\alpha}|\nu_\alpha\rangle}$$

$$V_{i\alpha} = (U_{\alpha i})^*$$

Evoluzione temporale di un neutrino in un autostato dell’impulso creato nell’autostato di “flavour” ν_α all’istante $t = 0$

$$\boxed{\left|\nu(t)\right\rangle = e^{i\mathbf{p}\cdot\mathbf{r}} \sum_k U_{\alpha k} e^{-iE_k t} \left|\nu_k\right\rangle}$$

Nota: $\left|\nu(0)\right\rangle = \left|\nu_\alpha\right\rangle$

$E_k = \sqrt{p^2 + m_k^2}$ → le fasi $e^{-iE_k t}$ sono diverse se $m_j \neq m_k$

→ **apparizione di “flavour” $\nu_\beta \neq \nu_\alpha$ per $t > 0$**

Mixing di due neutrini

$$\boxed{\begin{aligned} \left|\nu_\alpha\right\rangle &= \cos\theta\left|\nu_1\right\rangle + \sin\theta\left|\nu_2\right\rangle \\ \left|\nu_\beta\right\rangle &= -\sin\theta\left|\nu_1\right\rangle + \cos\theta\left|\nu_2\right\rangle \end{aligned}}$$

$\theta \equiv$ angolo di mixing

Se $\nu = \nu_\alpha$ alla produzione ($t = 0$):

$$\left|\nu(t)\right\rangle = e^{i(\mathbf{p}\cdot\mathbf{r} - E_1 t)}\left[\cos\theta\left|\nu_1\right\rangle + e^{-i(E_2 - E_1)t}\sin\theta\left|\nu_2\right\rangle\right]$$

Per $m << p$ $\quad E = \sqrt{p^2 + m^2} \approx p + \dfrac{m^2}{2p}$ **(nel vuoto!)**

$$\Rightarrow E_2 - E_1 \approx \frac{m_2{}^2 - m_1{}^2}{2p} \approx \frac{m_2{}^2 - m_1{}^2}{2E} \equiv \frac{\Delta m^2}{2E}$$

Probabilità di rivelare ν_β all'istante t se $\nu(0) = \nu_\alpha$:

$$\boxed{\mathscr{P}_{\alpha\beta}(t) = \left| \langle \nu_\beta | \nu(t) \rangle \right|^2 = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 t}{4E}\right)}$$

$\hbar = c = 1$

$\Delta m^2 \equiv m_2{}^2 - m_1{}^2$

In unità più familiari:

$$\boxed{\mathscr{P}_{\alpha\beta}(L) = \sin^2(2\theta)\sin^2\left(1.267\,\Delta m^2 \frac{L}{E}\right)}$$

$L = ct$ distanza tra sorgente di neutrini e rivelatore

Unità: Δm^2 [eV^2]; L [km]; E [GeV] (oppure L [m]; E [MeV])

NOTA: $\mathscr{P}_{\alpha\beta}$ dipende da Δm^2 (non da m).

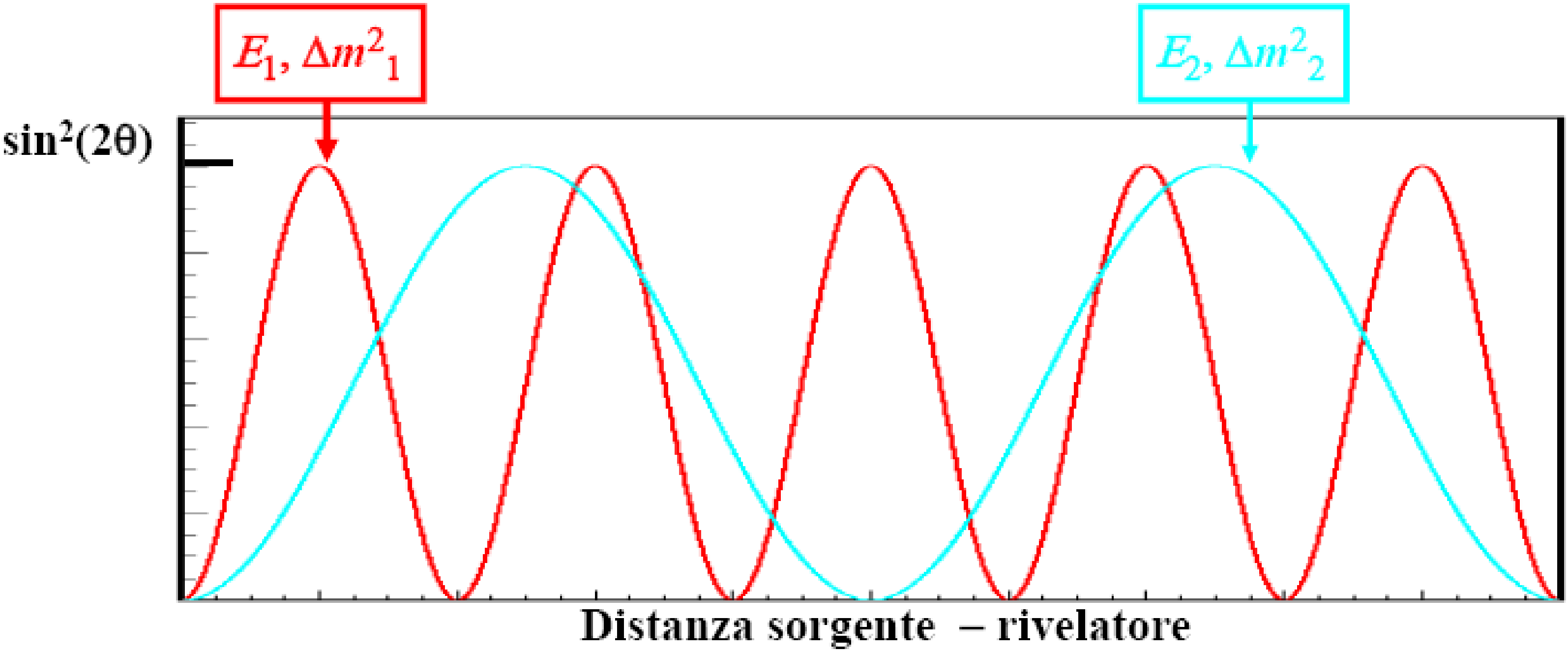
Se $m_1 << m_2$, $\Delta m^2 \equiv m_2{}^2 - m_1{}^2 \approx m_2{}^2$

Definizione di lunghezza d'oscillazione λ:

$$\boxed{\lambda = 2.48\frac{E}{\Delta m^2}}$$

Unità: λ [km]; E [GeV]; Δm^2 [eV^2]
(oppure λ [m]; E [MeV])

$$\Rightarrow \boxed{\mathcal{P}_{\alpha\beta}(L) = \sin^2(2\theta)\sin^2(\pi\frac{L}{\lambda})}$$



$E_1 < E_2$ e/o $\Delta m^2{}_1 > \Delta m^2{}_2$

Esperimenti di scomparsa

Sorgente di ν_α, misura del flusso di ν_α a distanza L dalla sorgente

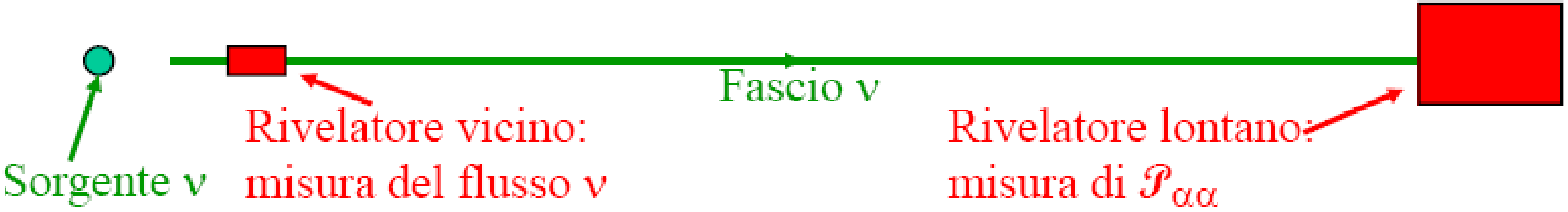
Quantità misurata:

$$\mathcal{P}_{\alpha\alpha} = 1 - \sum_{\beta \neq \alpha} \mathcal{P}_{\alpha\beta}$$

Esempi:

- **Esperimenti con $\bar{\nu}_e$ da reattori nucleari**
  ($E_\nu \approx$ pochi MeV: sotto soglia per produzione di μ o τ)
- **Rivelazione di ν_μ presso acceleratori o nella radiazione cosmica** (ricerca di oscillazioni $\nu_\mu \Rightarrow \nu_\tau$ se E_ν è inferiore alla soglia di produzione di τ)

Incertezza sistematica dominante: conoscenza del flusso di neutrini in assenza di oscillazioni $\Longrightarrow$ uso di due rivelatori (se possibile)



Fascio ν

Sorgente ν

Rivelatore vicino:
misura del flusso ν

Rivelatore lontano:
misura di $\mathcal{P}_{\alpha\alpha}$

Esperimenti di apparizione

Sorgente di ν_α , rivelazione di ν_β $(\beta \neq \alpha)$ a distanza *L* dalla sorgente

Esempi:

- **Rivelazione di $\nu_e + N \rightarrow e^- +$ adroni in un fascio di ν_μ**
- **Rivelazione di $\nu_\tau + N \rightarrow \tau^- +$ adroni in un fascio di ν_μ**
  (Energia alla soglia ≈ 3.5 GeV)

La contaminazione di ν_β alla sorgente deve essere conosciuta con precisione (tipicamente $\nu_e/\nu_\mu \approx 1\%$ in fasci di ν_μ da acceleratori di alta energia)

$$\mathcal{P}_{\alpha\beta}(L) = \sin^2(2\theta)\sin^2\left(1.267\Delta m^2 \frac{L}{E}\right)$$

RICERCHE DI OSCILLAZIONI: PARAMETRI SPERIMENTALI

Sorgente ν	Flavour	Distanza L	Energia ν	Minimo Δm^2 accessibile
Sole	ν_e	~1.5 x 10^8 km	0.2 –15 MeV	~10^{-11} eV^2
Raggi cosmici	ν_μ ν_e $\bar{\nu}_\mu$ $\bar{\nu}_e$	10 km – 13000 km	0. 2 GeV – 100 GeV	~10^{-4} eV^2
Reattori nucleari	$\bar{\nu}_e$	20 m – 250 km	<E> ≈ 3 MeV	~10^{-1} – 10^{-6} eV^2
Acceleratori	ν_μ ν_e $\bar{\nu}_\mu$ $\bar{\nu}_e$	15 m – 730 km	20 MeV – 100 GeV	~10^{-3} – 10 eV^2