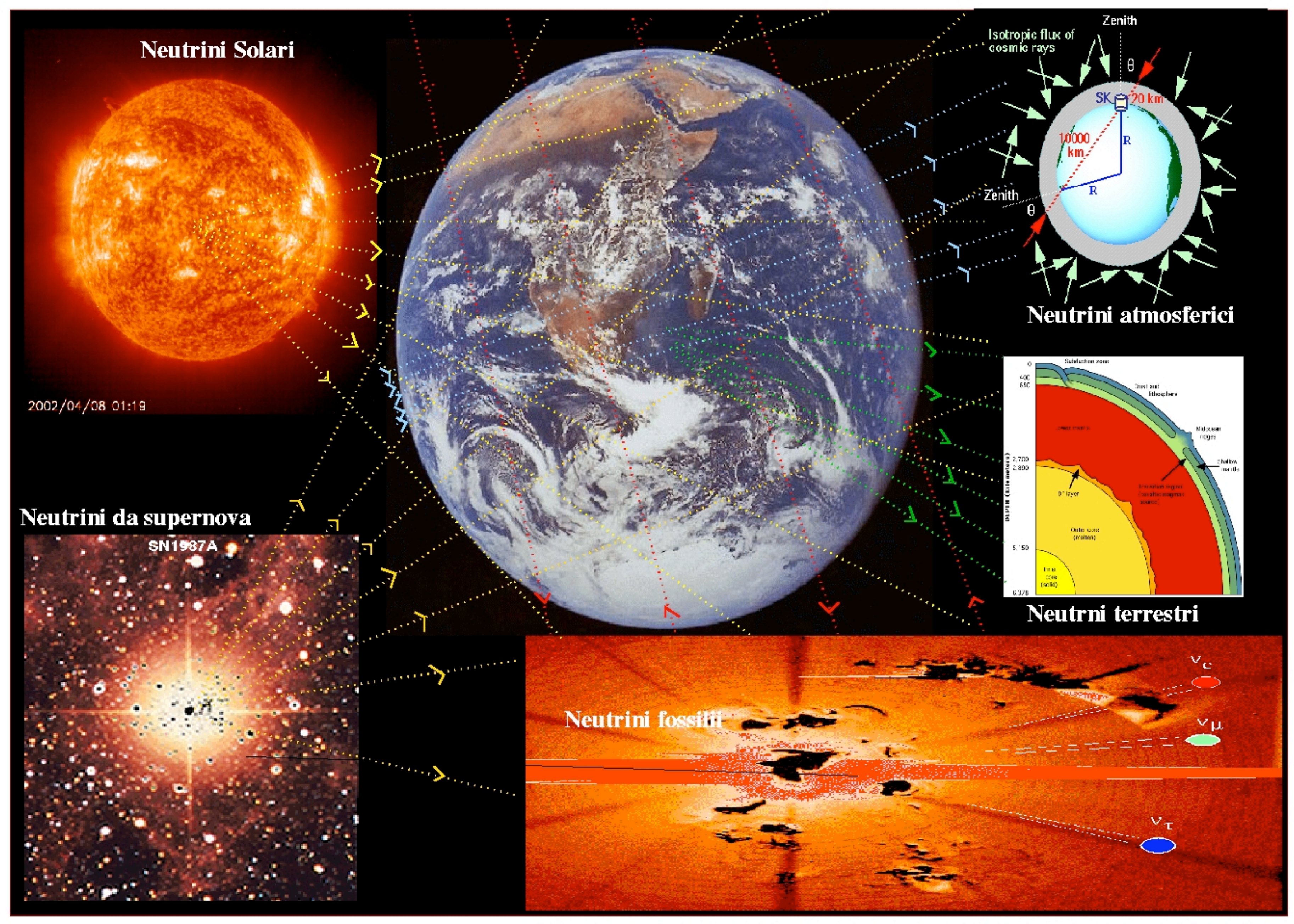
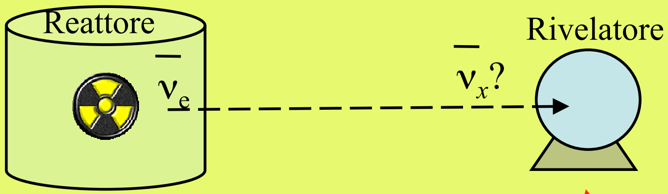
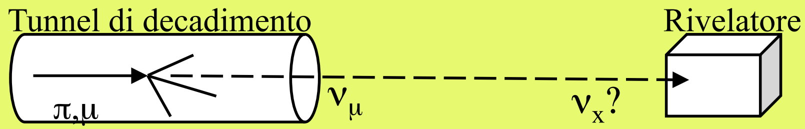
La luminosità in neutrini, circa 10^{53} erg/s durante l'esplosione, è superiore a quella dell'intero universo

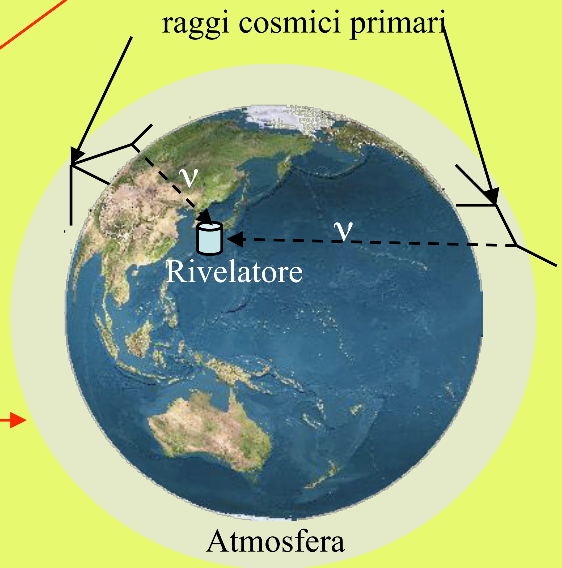
Sorgenti di neutrini naturali

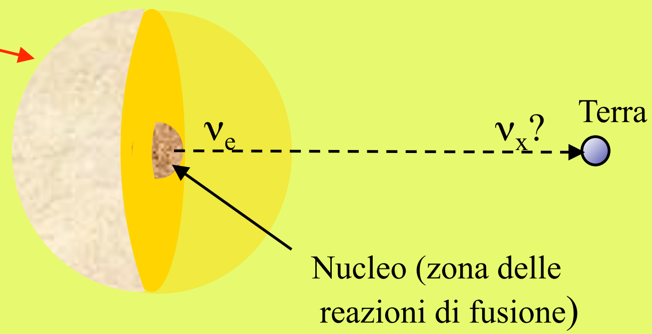






Principali sorgenti di neutrini			
Origine	**Sorgenti**		**E_ν**
"Terrestre"	Artificiali	Reattore	~O(MeV)
		Acceleratore	≥1GeV
	Atmosferici		1÷100GeV
	Geoneutrini		≈2MeV
"Astrofisica"	Solari		0÷15MeV
	Supernovae galattiche di tipo II		0÷30MeV
"Cosmica"	Di altissime energie (sorgenti ignote)		>>100GeV
	Primordiali (Big Bang)		<<1eV



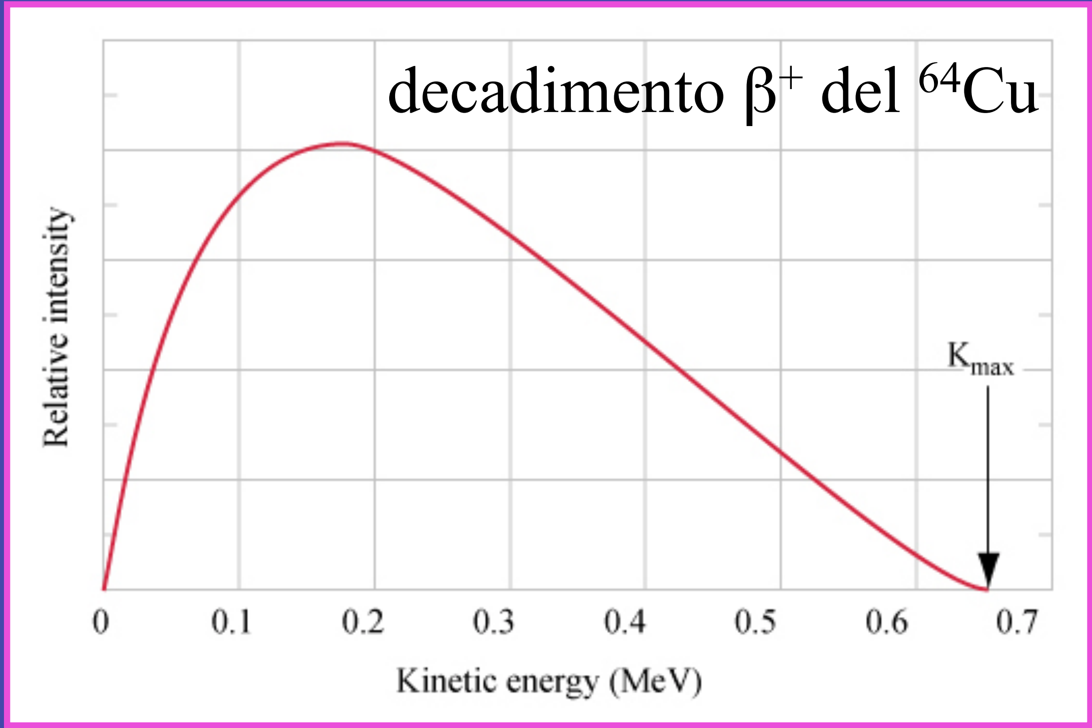


A livello nucleare i decadimenti β sono trasformazione di protoni in neutroni e viceversa: β^- β^+

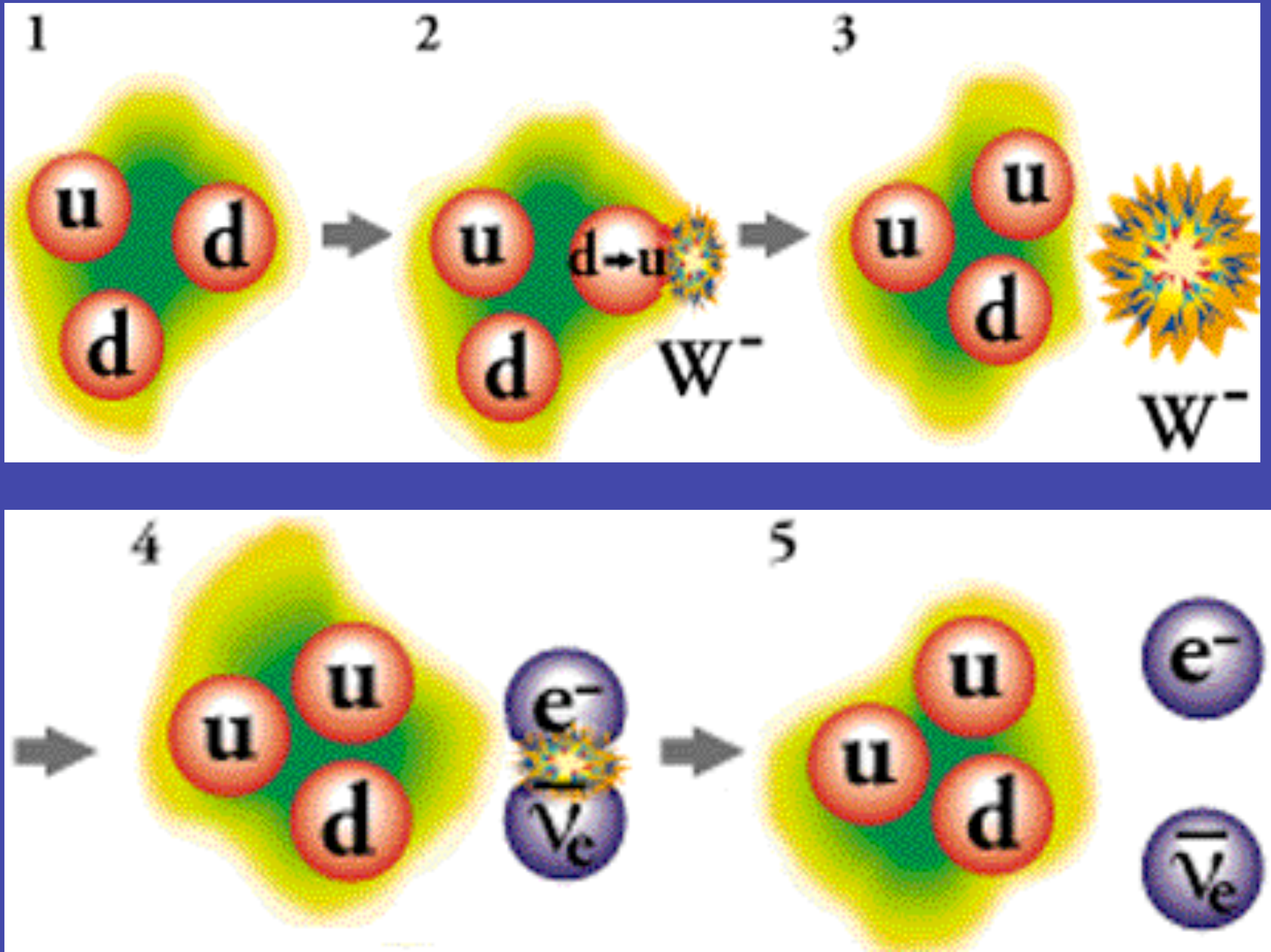
$$n \rightarrow p + e^- + \bar{\nu}_e$$

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

Nel 1930 Pauli ipotizzò l'esistenza del neutrino e nel 1934 Fermi formulò la teoria del decadimento β



Devono valere le leggi di conservazione:
dell'energia,
dell'impulso,
del numero barionico,
del numero leptonico.

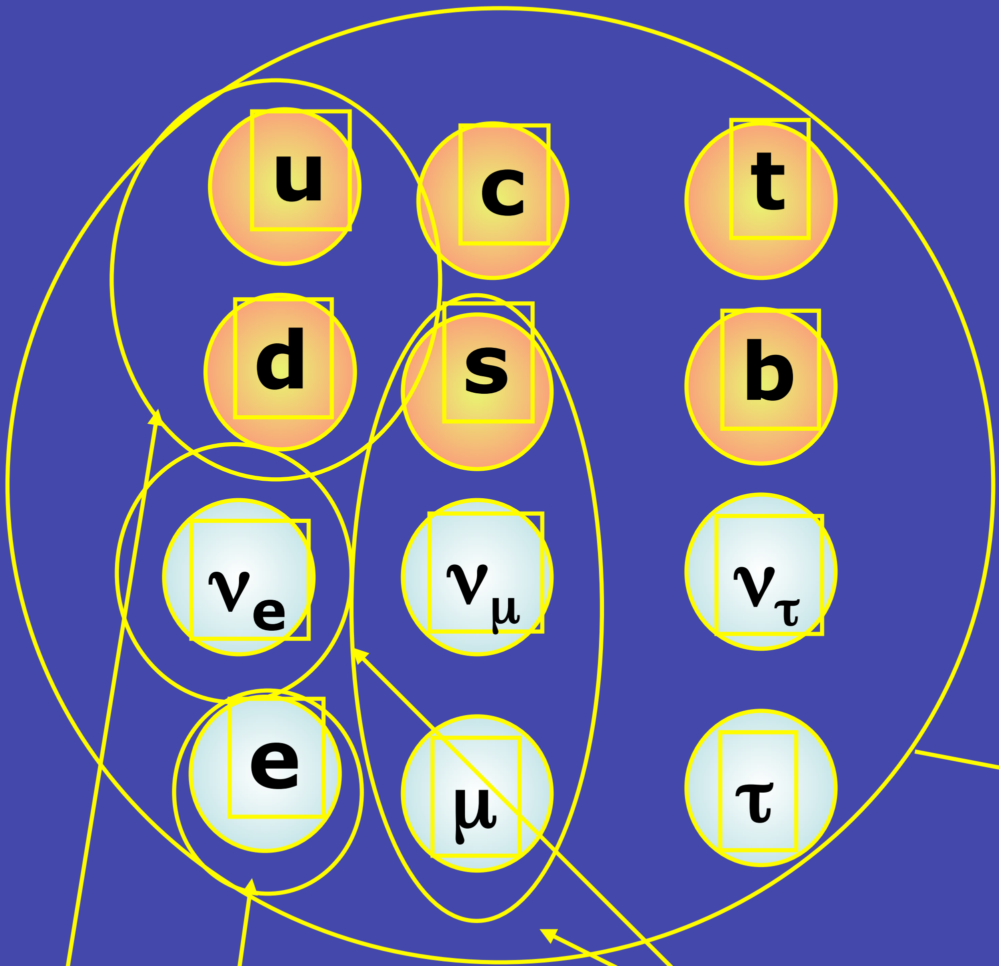

1
u
d
d
2
u
d→u
d
W-
3
u
u
d
W-
4
u
u
d
e-
$\bar{\nu}_e$
5
u
u
d
e-
$\bar{\nu}_e$

Particelle fondamentali

massa crescente →

Carica				
+2/3	u	c	t	quark
-1/3	d	s	b	quark
0	ν_e	ν_μ	ν_τ	leptoni
-1	e	μ	τ	leptoni

Il modello standard



Le particelle forza

g gluoni (8)

γ fotone

W^+, W^-, Z bosoni

H Higgs ??

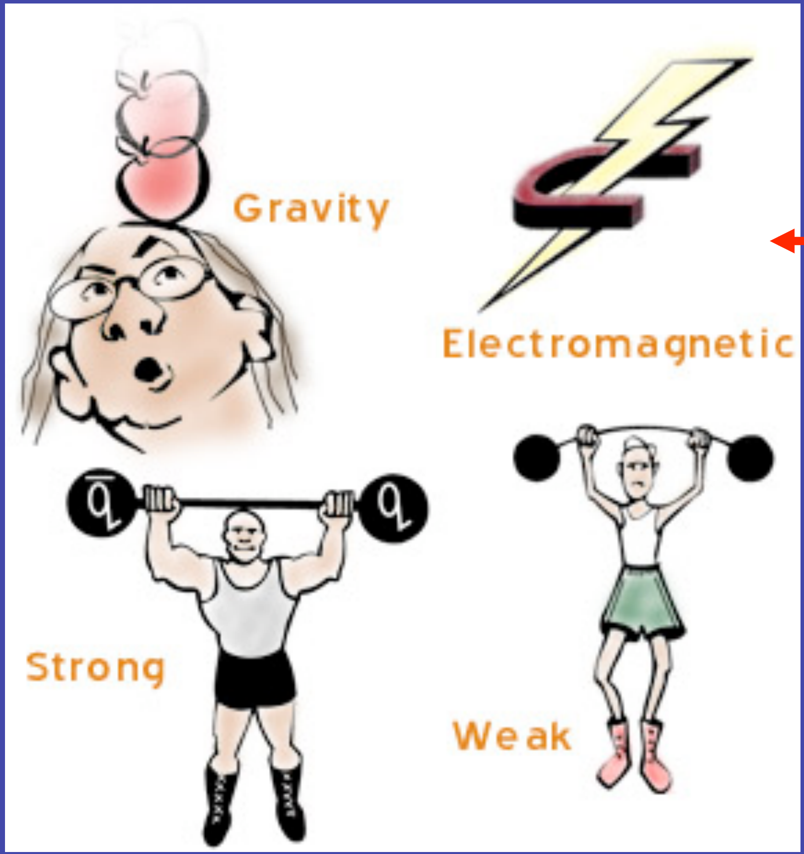
Si possono produrre in laboratorio

+ le antiparticelle ossia l'antimateria

Raggi cosmici

La materia di cui siamo fatti

Le interazioni fondamentali

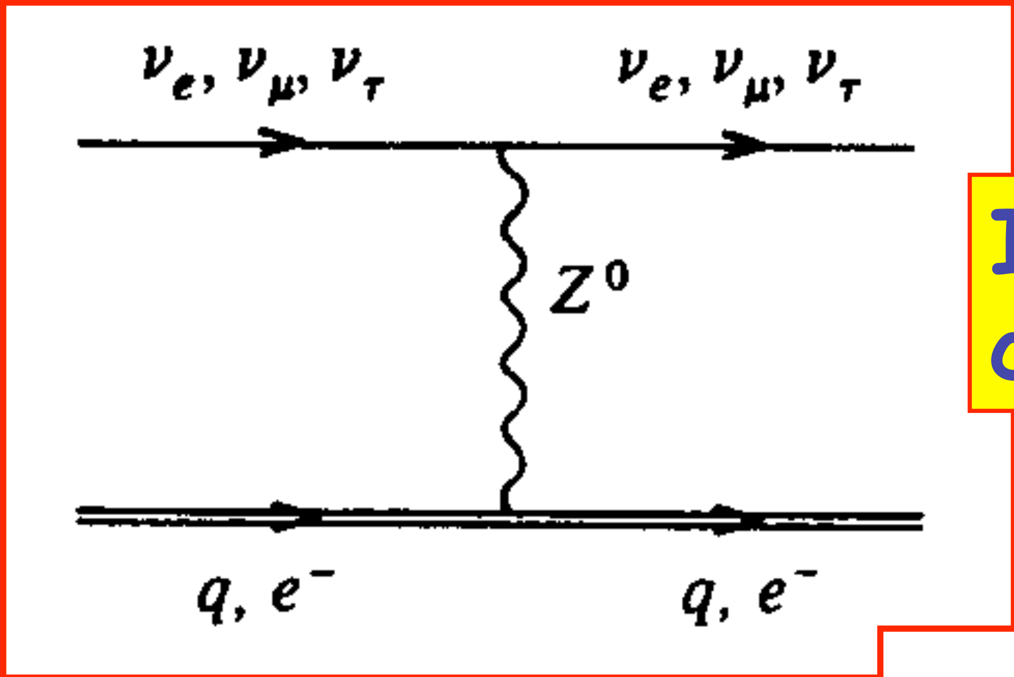


attive su tutte le distanze (*long range*)

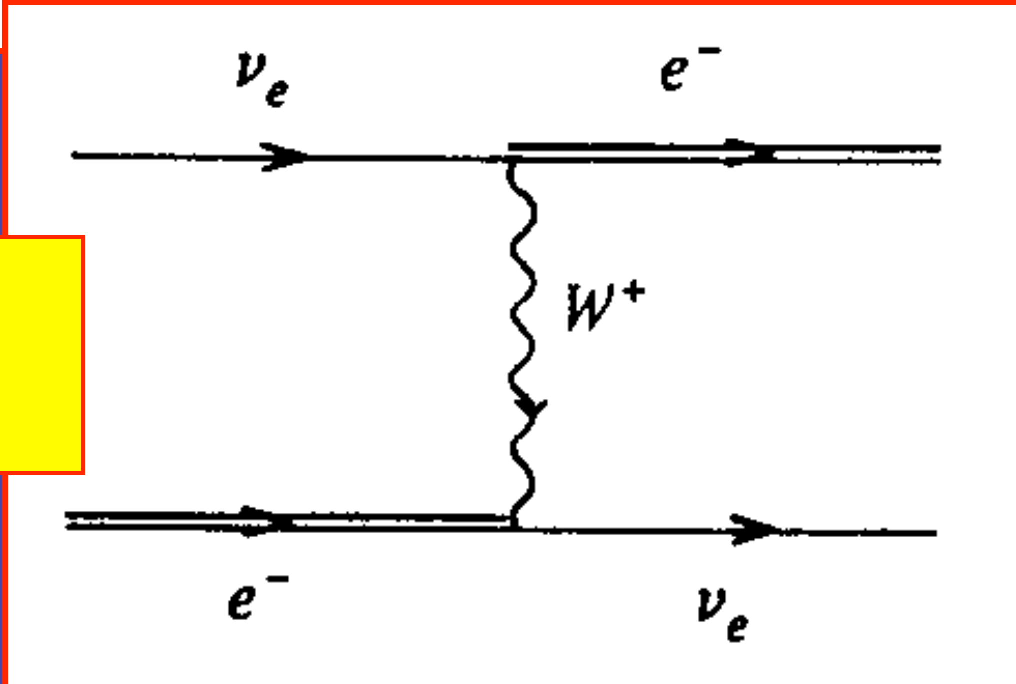
attive su d < 10^{-13} cm (*short range*)

Leptoni (e,ν) → sensibili a forza nucleare debole

Adroni (p,n) → sensibili a forza nucleare forte e debole



Interazioni a correnti neutre

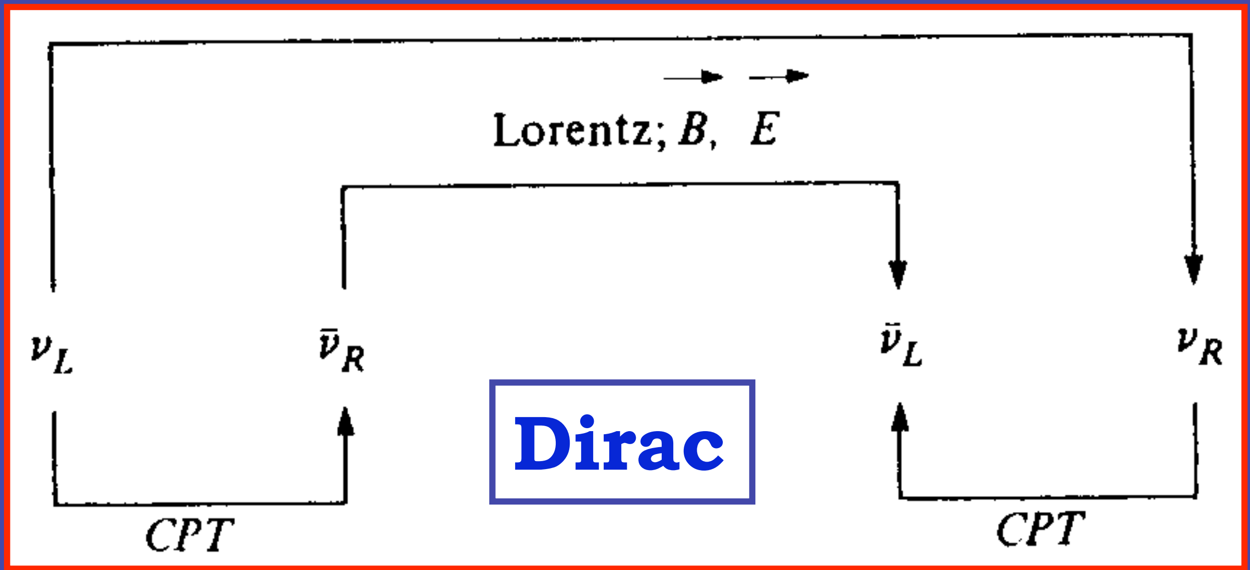


Interazioni a correnti cariche

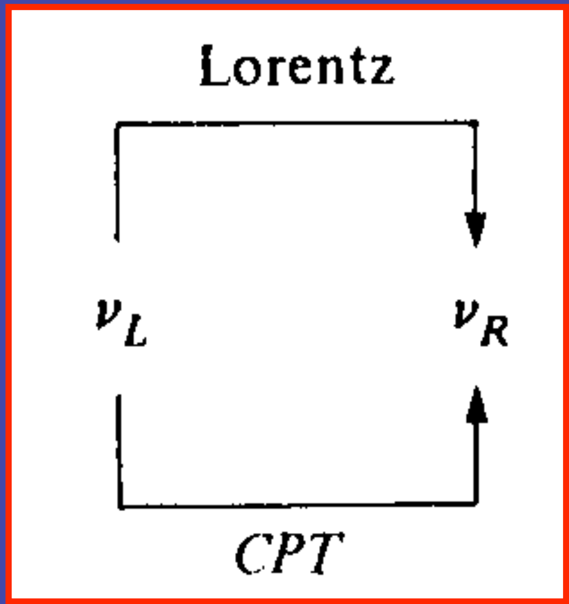
Neutrino spin 1/2

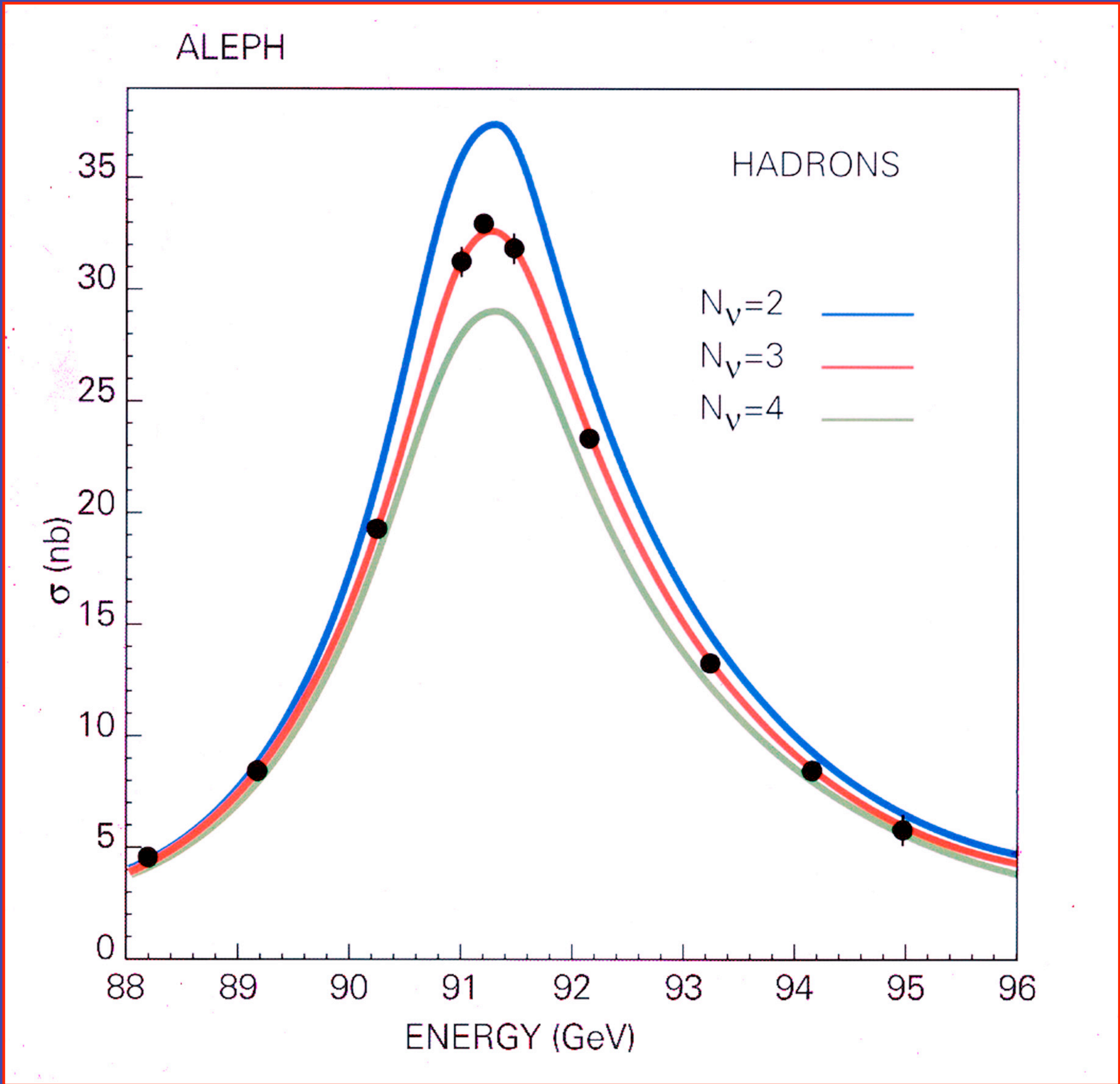
Anti-Neutrino spin 1/2

I neutrini sono particelle di Dirac o di Majorana?
Quante specie di neutrini esistono?
I neutrini hanno massa?
I neutrini oscillano?



Majorana

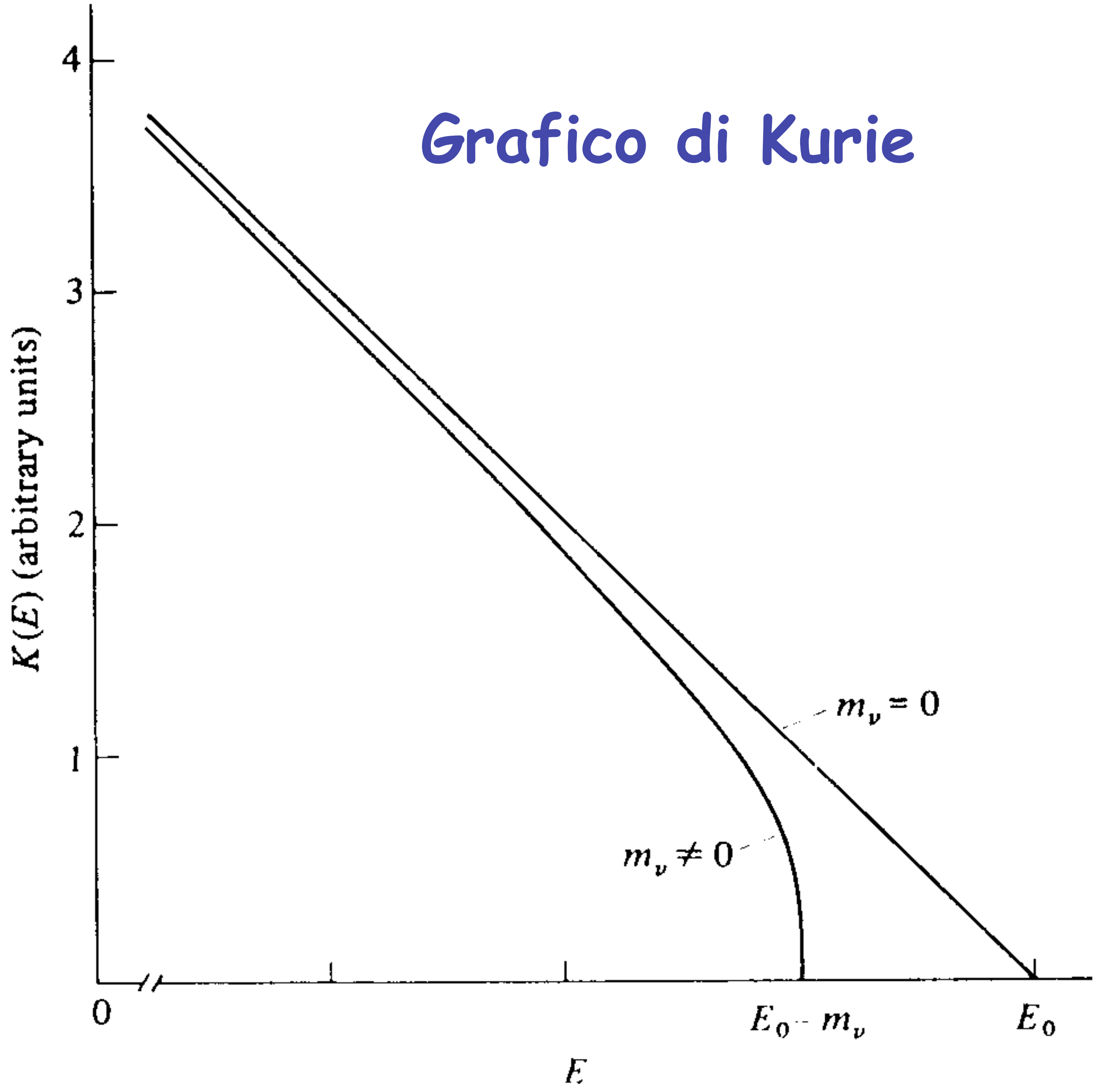




Dalla misura di precisione della massa della Z si è avuta conferma che le famiglie di quark sono 3

$$\Gamma_{totale} = \Gamma(Z_0 \rightarrow \text{adroni}) + 3\Gamma(Z_0 \rightarrow \text{leptoni}) + N_\nu \Gamma(Z_0 \rightarrow \text{neutrini})$$

Grafico di Kurie



The idea of neutrinos being massive was first suggested by Pontecorvo.
The prediction came from a proposal of ***neutrino oscillations***.

Neutrinos are created or annihilated as W.I. eigenstates

$|\nu_e\rangle$, $|\nu_\mu\rangle$, $|\nu_\tau\rangle$ = Weak Interactions eigenstates
$|\nu_1\rangle$, $|\nu_2\rangle$, $|\nu_3\rangle$ = Mass (Hamiltonian) eigenstates

Neutrinos propagate as a superposition of mass eigenstates

Per semplicità, consideriamo per ora due famiglie di neutrini

$$\begin{pmatrix} \nu_\mu \\ \nu_e \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Il segnale osservabile varia periodicamente con la distanza del rivelatore dalla sorgente, ripetendosi per multipli interi della lunghezza di oscillazione, che si ottiene ponendo la fase $\Phi = 2\pi$

$$L_{osc} = 2\pi \frac{2p_\nu}{|m_1^2 - m_2^2|} \approx 2\pi \frac{2E_\nu}{|m_1^2 - m_2^2|} = 2,48\,\mathrm{km}\ \frac{E_\nu(\mathrm{GeV})}{\Delta m^2(\mathrm{eV}^2)}$$

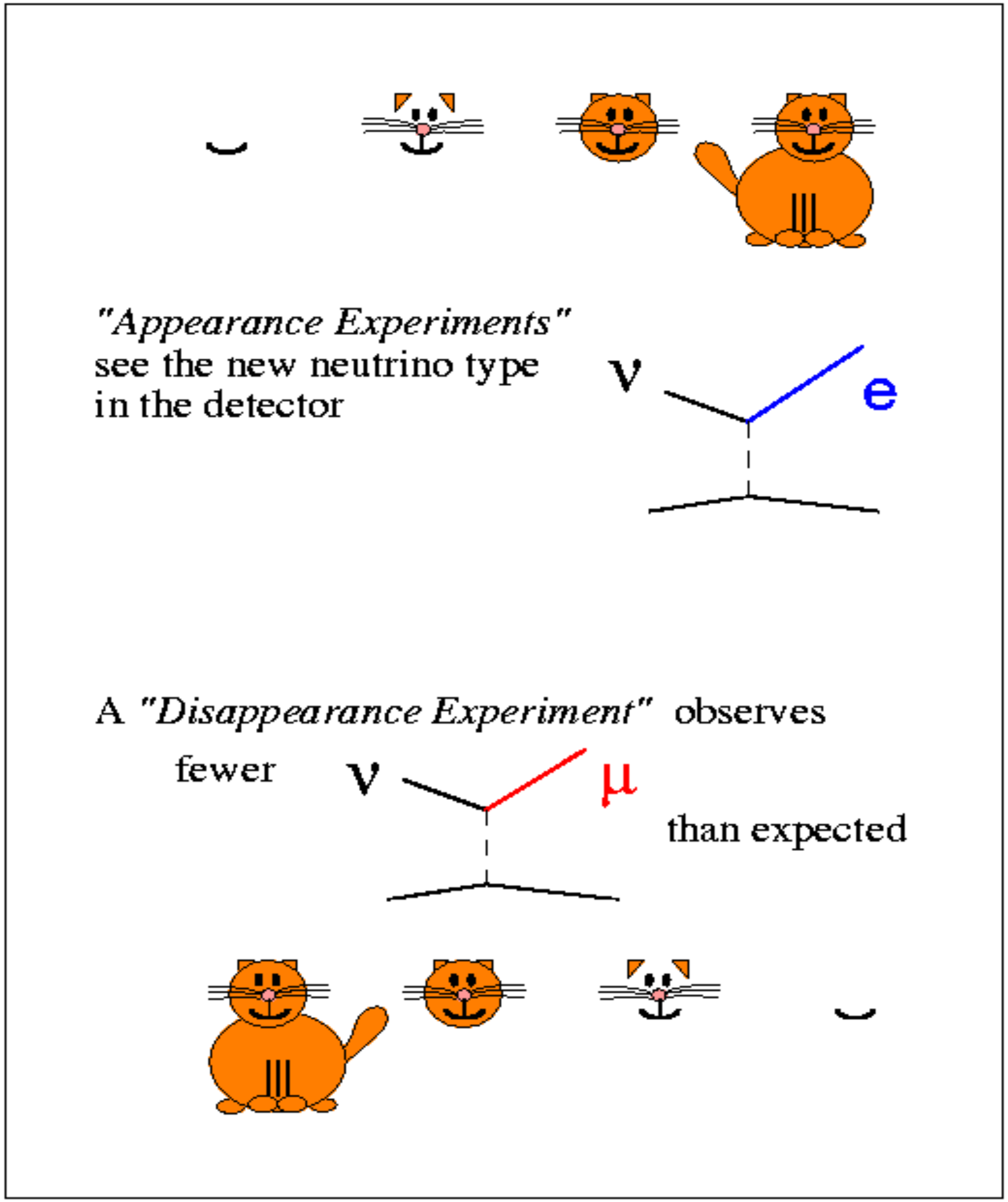
La probabilità di oscillazione è data da

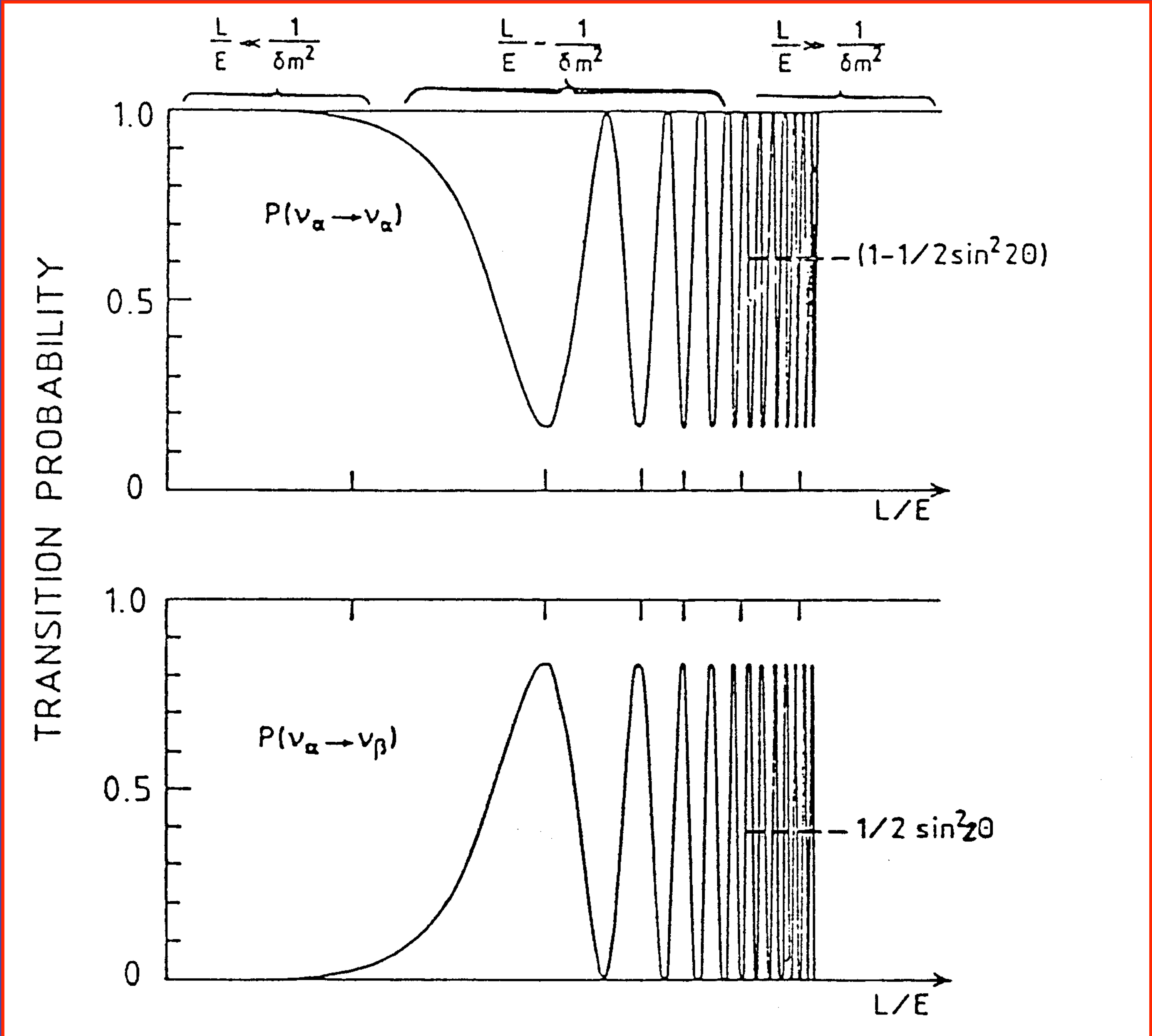
$$P_{\nu_\mu \to \nu_e} = \sin^2 2\vartheta \cdot \sin^2\left(1,27\frac{\Delta m^2 L}{E_\nu}\right)$$

e si hanno massimi di oscillazione per

$$1.27\frac{\Delta m^2 L}{E_\nu} = (2n+1)\frac{\pi}{2}$$

Appearance vs. Disappearance





L/E ≪ 1/δm²
L/E ~ 1/δm²
L/E ≫ 1/δm²
1.0
0.5
0
TRANSITION PROBABILITY
P(ν_α → ν_α)
(1-1/2sin²2Θ)
L/E
1.0
0.5
0
P(ν_α → ν_β)
1/2 sin²2Θ
L/E

In uno schema a 3 neutrini gli *autostati deboli* (o *di flavor*) *fenomenologici*, ossia ν_e, ν_μ, ν_τ sono legati agli *autostati di massa* ν_i aventi una massa definita m_i, da una relazione lineare del tipo:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathbf{U} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

dove la matrice unitaria U è detta *matrice di mixing*.

Di solito questa matrice viene parametrizzata come il prodotto di tre rotazioni, in analogia alla matrice di Cabibbo-Kobayashi-Maskawa nel settore adronico:

$$\mathbf{U}=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\cdot\begin{pmatrix}\cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13}\\ 0 & 1 & 0\\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13}\end{pmatrix}\cdot\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\cdot\begin{pmatrix}1 & & \\ & e^{i\varphi_2} & \\ & & e^{i\varphi_3}\end{pmatrix}$$

gli angoli θ_{ij} sono detti angoli di mixing, mentre le fasi δ (fase di Dirac), φ_2 e φ_3 (fasi di Majorana) sono legate alla violazione di CP nel settore leptonico. Le fasi di Majorana non sono osservabili nei fenomeni di oscillazione.

OSCILLAZIONI DI NEUTRINO

nel vuoto: $$P(\nu_\mu \to \nu_\tau) \approx \sin^2(2\vartheta)\sin^2\left(1.27\frac{\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

1. neutrini solari

L = 1.5 10^{11} m, E ~ 10 MeV.
da cui: L/E ~ 10^{10} km/GeV.

$$\nu_e \to \nu_x$$

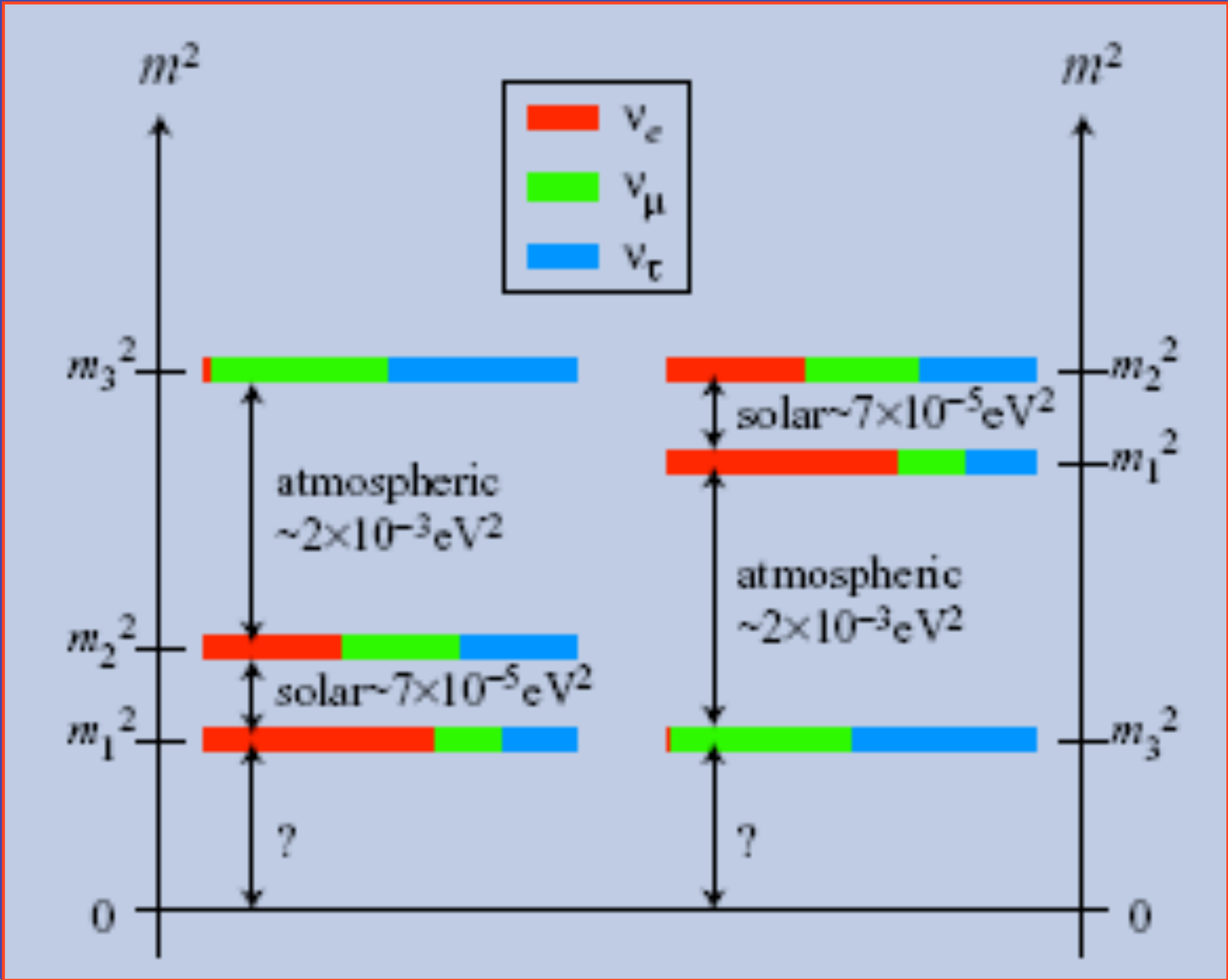
2. neutrini atmosferici (eventi confinati)

L = 30 km (dall'alto), E ~ 10 GeV
L = 10^4 km (dal basso), E ~ 10 GeV
da cui: L/E varia da ~ 1 a 10^4 km/GeV.

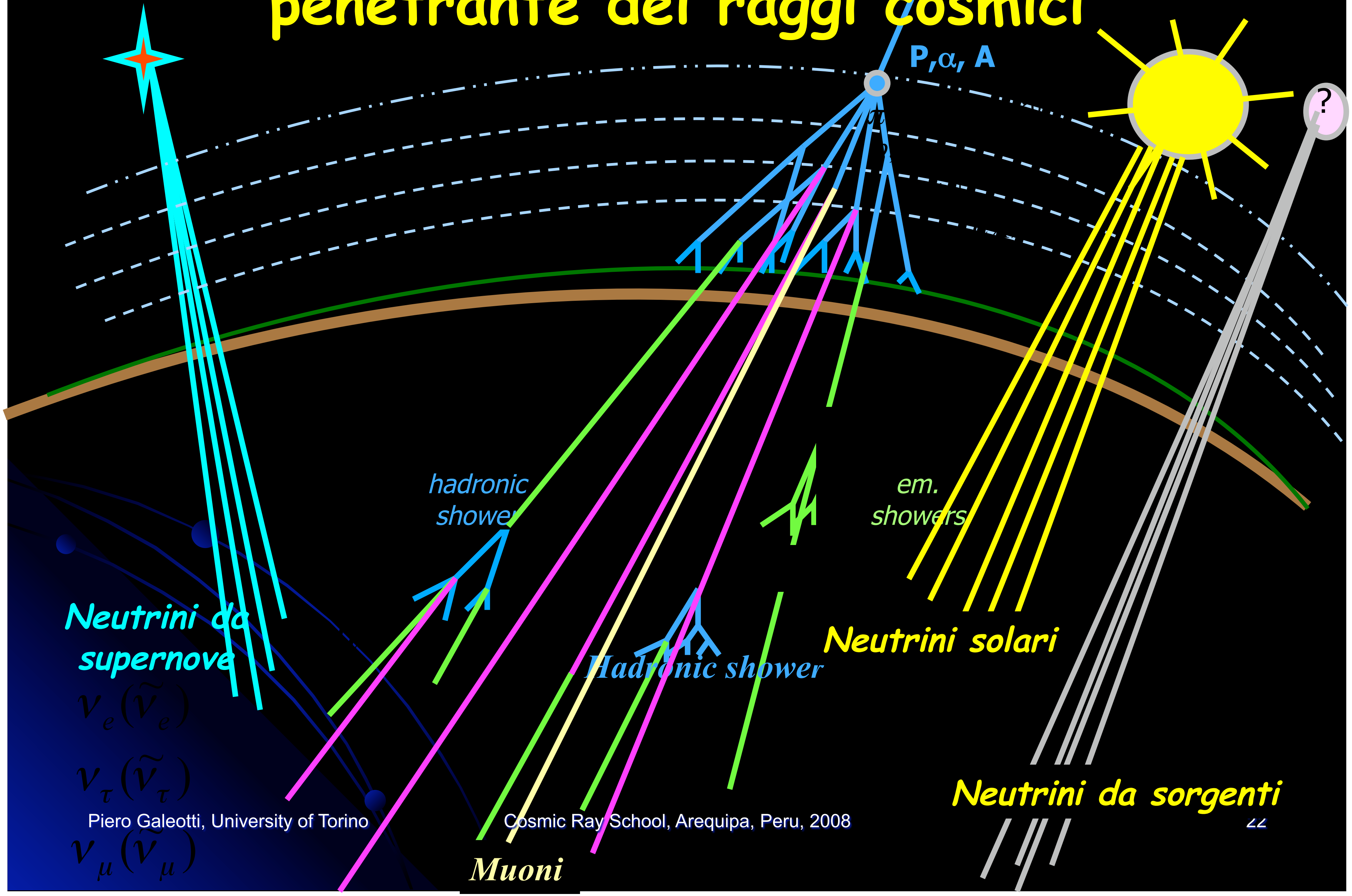
$$\nu_\mu \leftrightarrow \nu_\tau$$

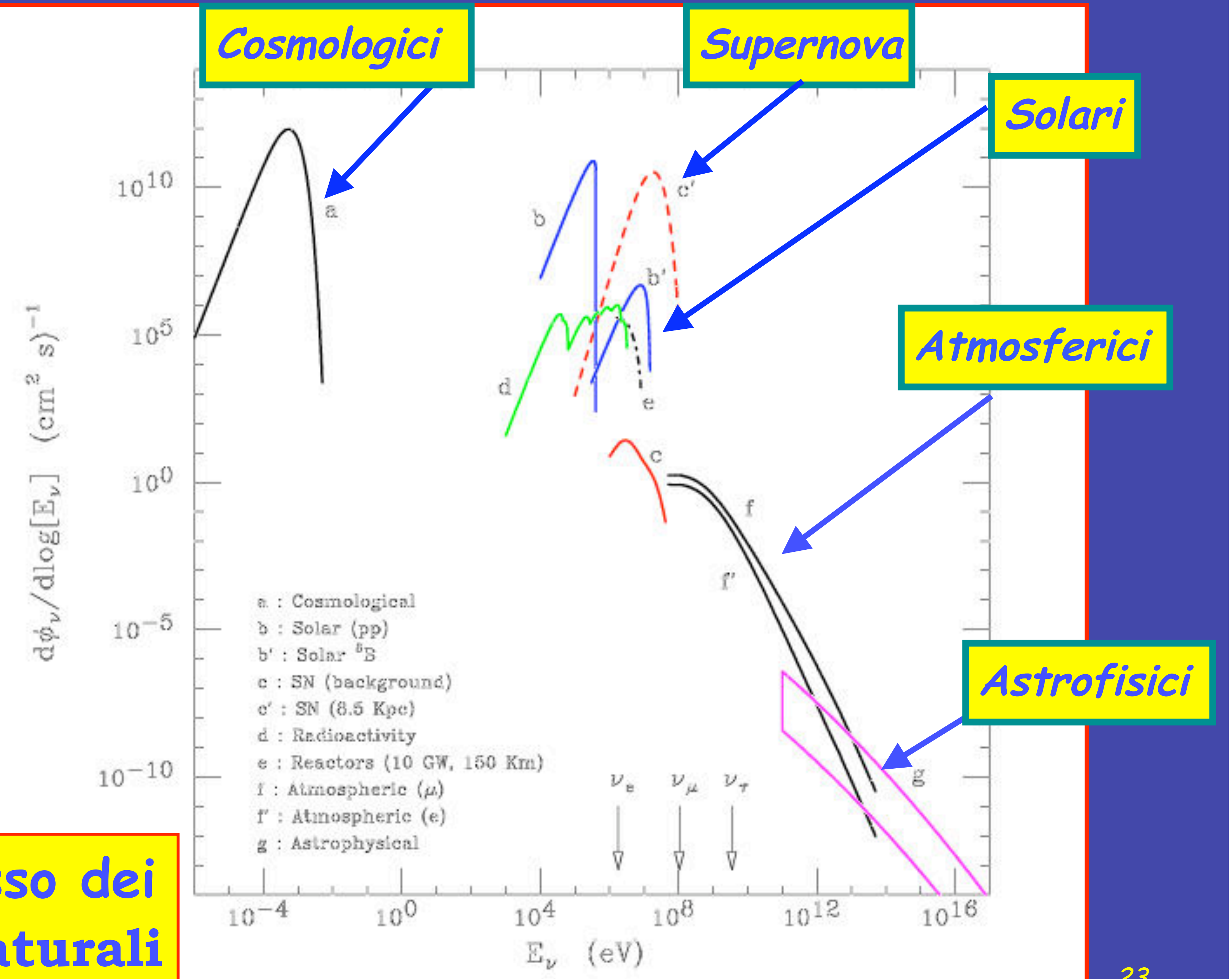
3. neutrini da sorgenti astrofisiche

L = $3 \cdot 10^{21}$ km (100 Mpc), E > 10^7 GeV
Sorgenti localizzate rispetto al fondo dei neutrini atmosferici


m^2
m^2
ν_e
ν_μ
ν_τ
m_3^2
atmospheric
$\sim 2\times10^{-3}eV^2$
m_2^2
solar$\sim 7\times10^{-5}eV^2$
m_1^2
?
0
m_2^2
solar$\sim 7\times10^{-5}eV^2$
m_1^2
atmospheric
$\sim 2\times10^{-3}eV^2$
m_3^2
?
0

Sottoterra si può studiare la componente penetrante dei raggi cosmici



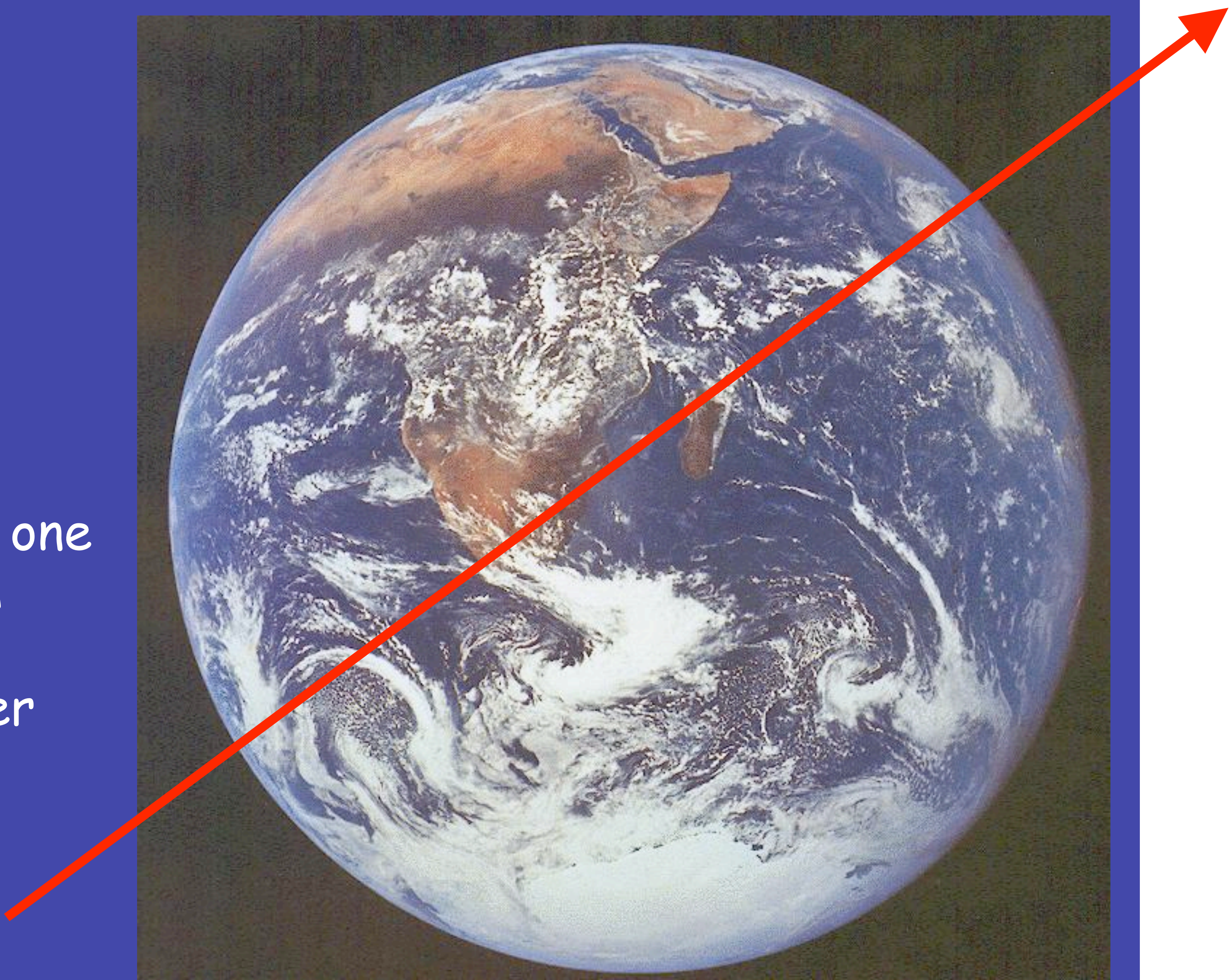


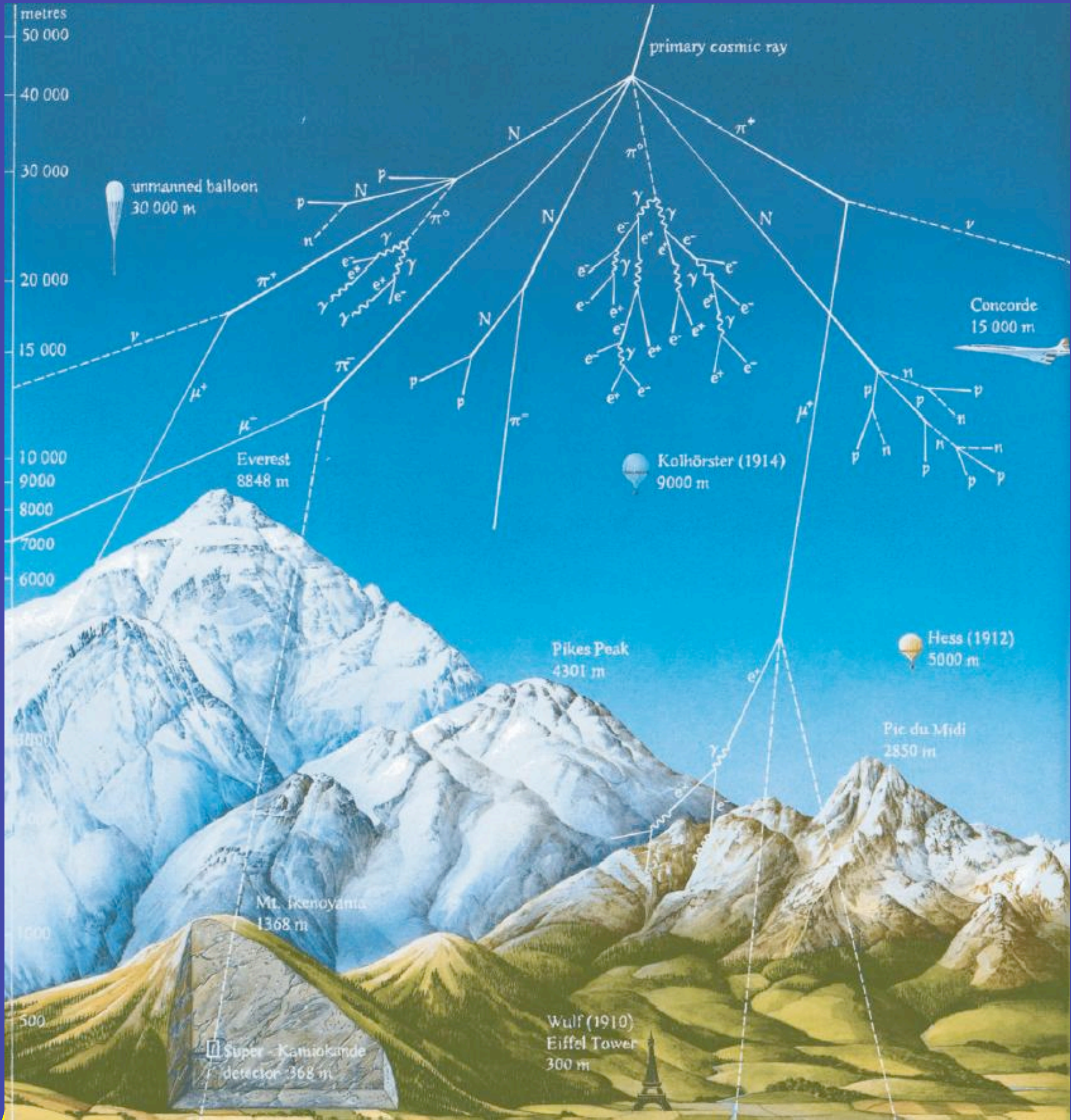
Flusso dei ν naturali

Neutrino energy
E = 1 MeV

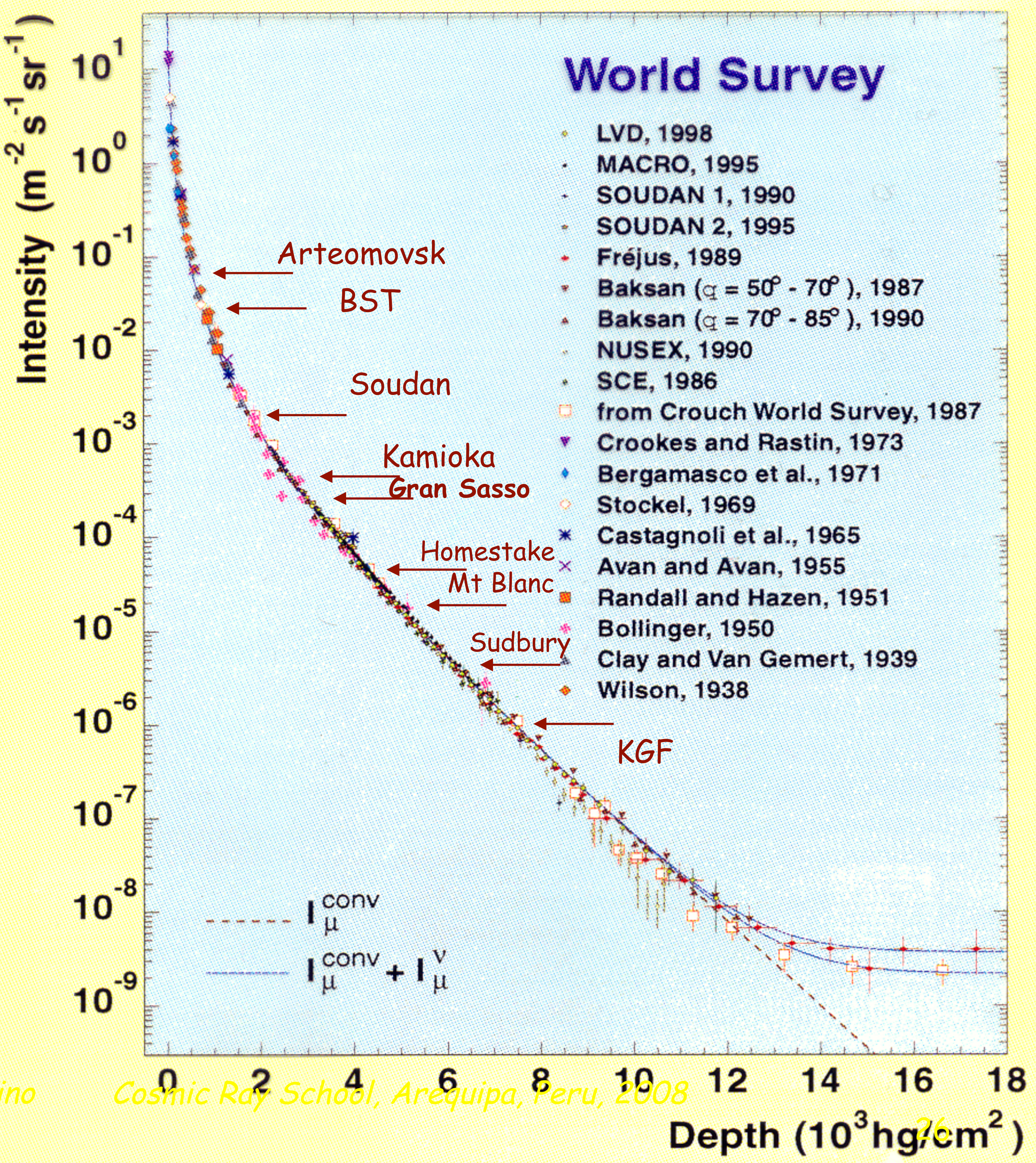
Neutrino cross-section
$\sigma = 10^{-44}$ cm^2

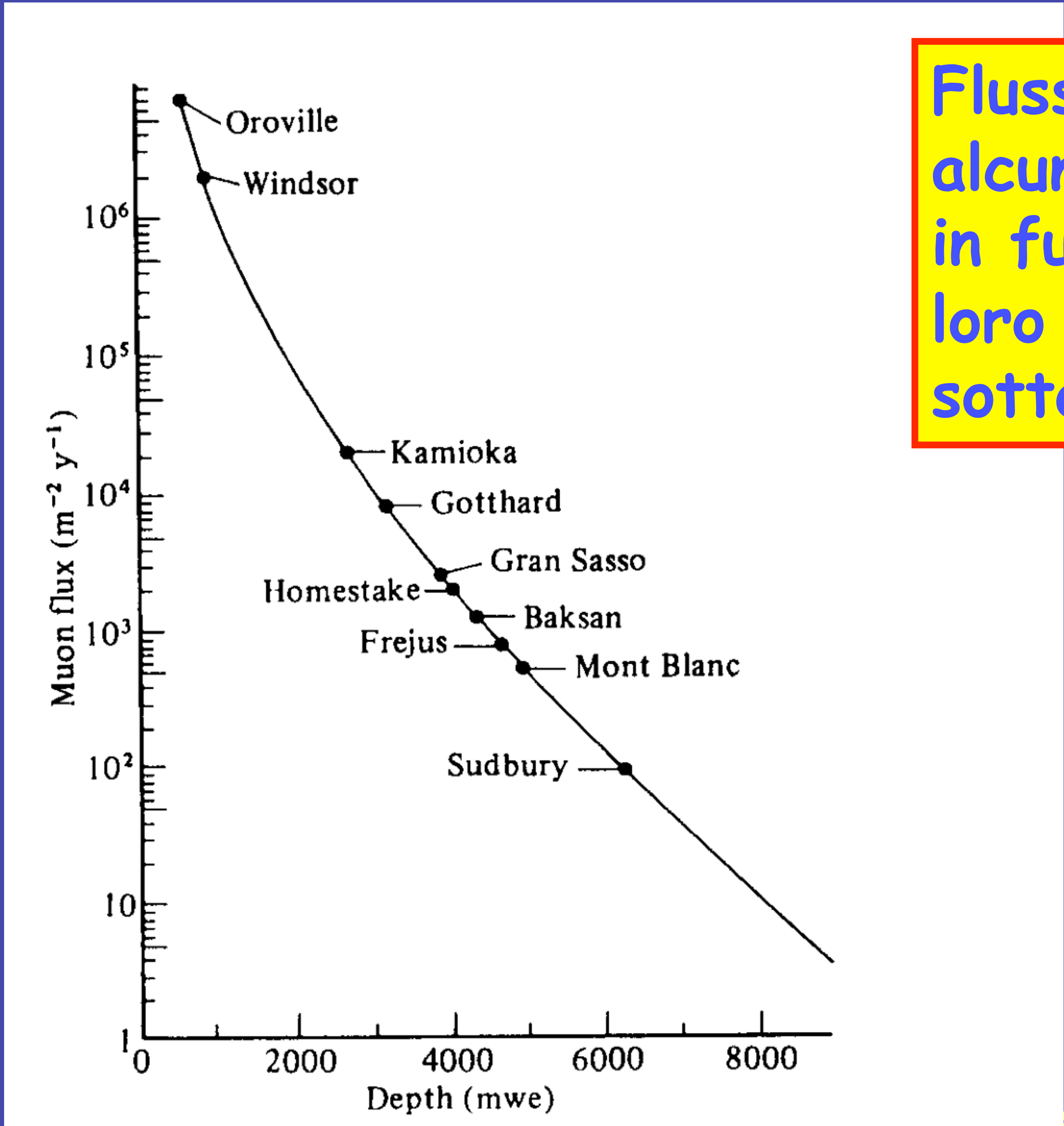
Probability of one interaction in crossing the Earth diameter
$P \sim 10^{-11}$




metres
50 000
40 000
30 000
20 000
15 000
10 000
9000
8000
7000
6000
500
primary cosmic ray
unmanned balloon
30 000 m
Concorde
15 000 m
Everest
8848 m
Kolhörster (1914)
9000 m
Pikes Peak
4301 m
Hess (1912)
5000 m
Pic du Midi
2850 m
Mt. Ikenoyama
1368 m
Super - Kamiokande
detector 368 m
Wulf (1910)
Eiffel Tower
300 m

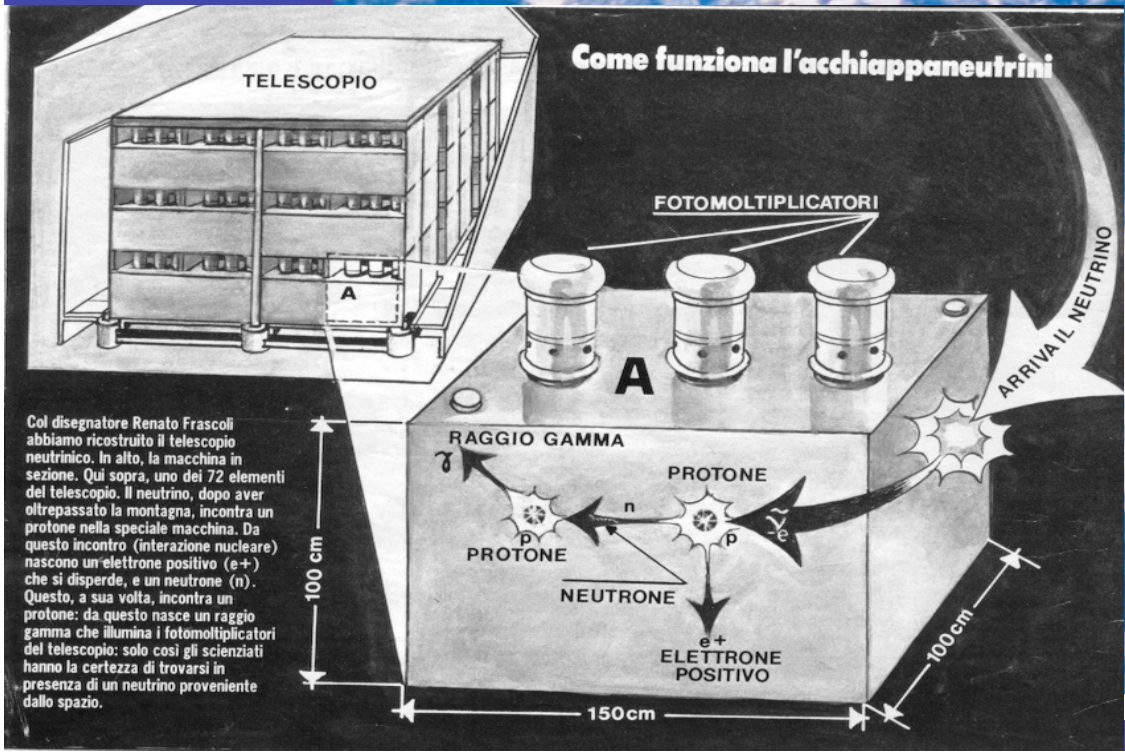
The muon depth-intensity curve (underground data): curves are calculated by Bugaev et al., 1998





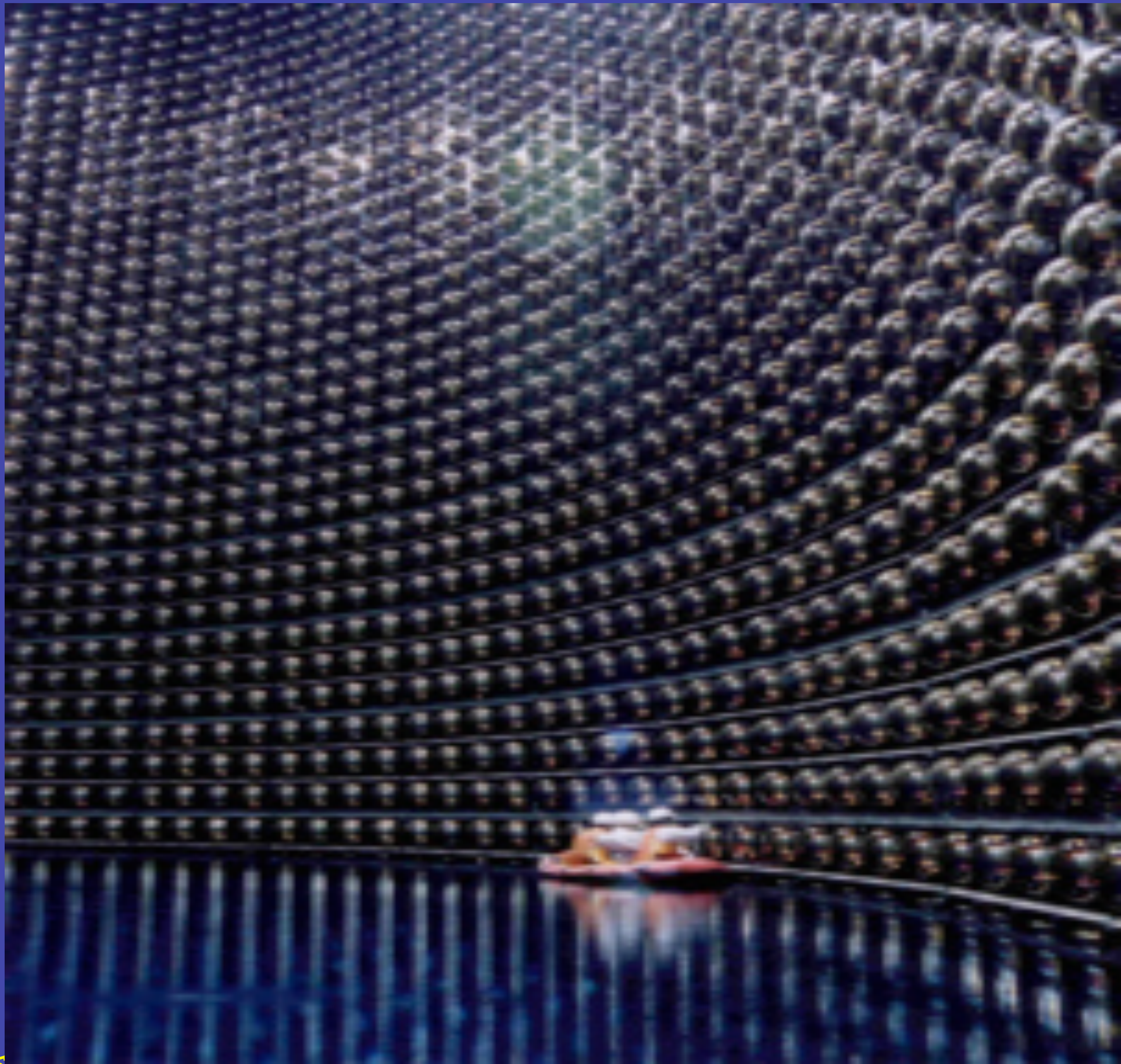
Flusso di μ in alcuni laboratori in funzione della loro profondità sottoroccia

Laboratorio del Monte Bianco

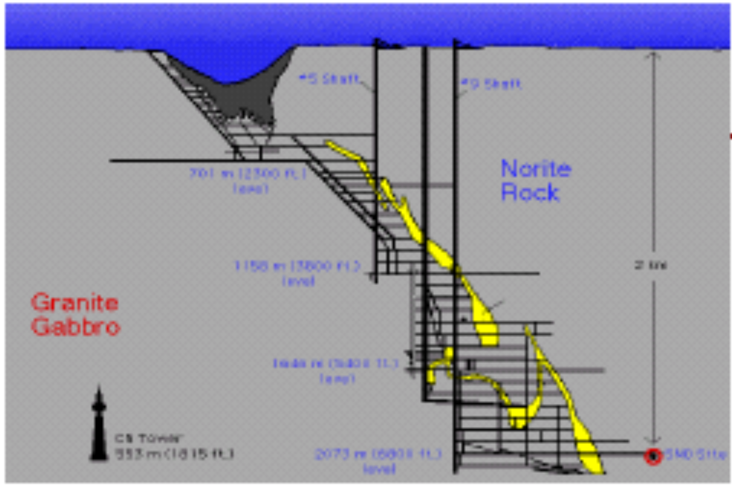


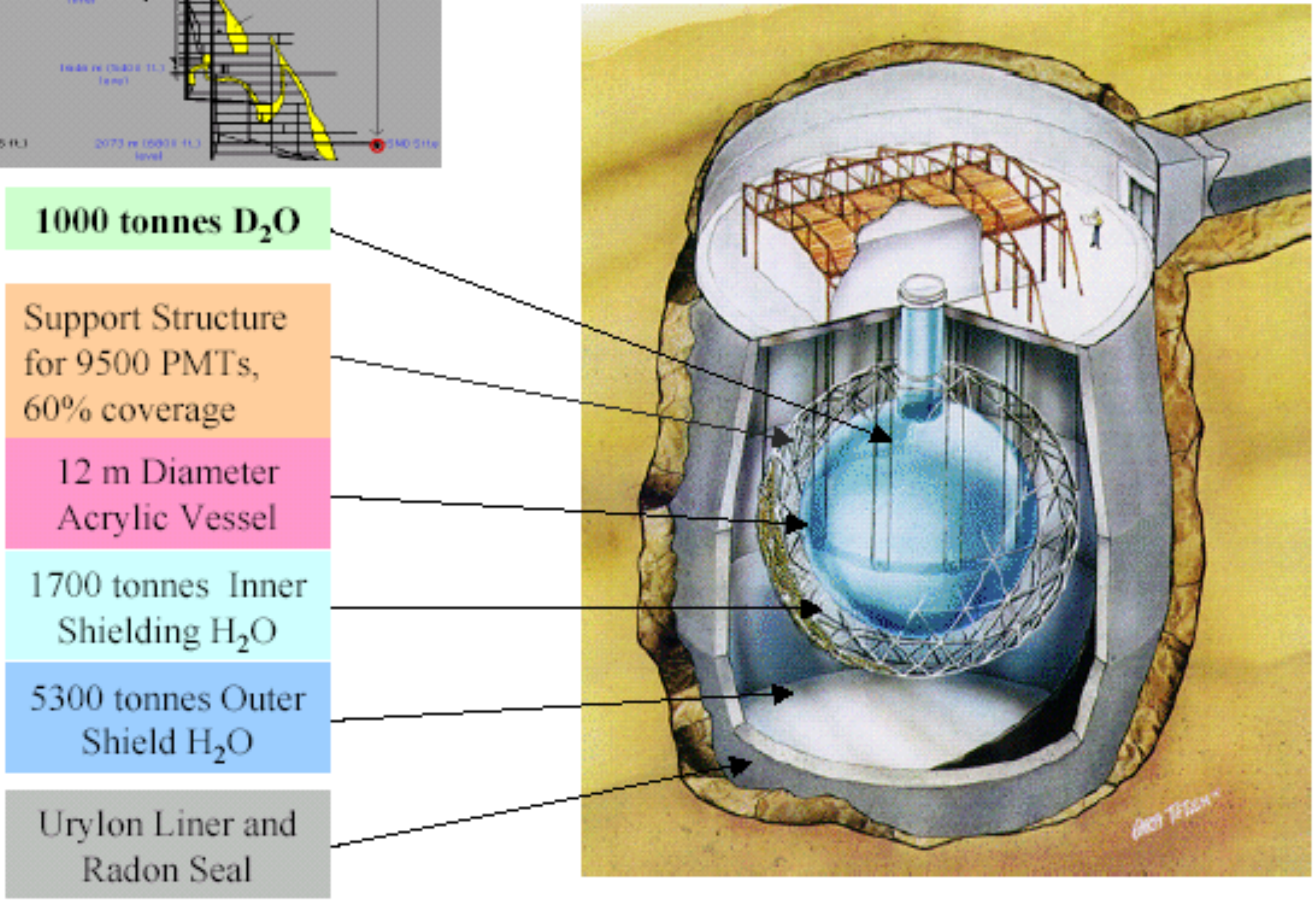
A massive (1 kton) scintillation detector for neutrino astronomy @ LNGS is running since 1992 (16 Years of data)

SuperK



Sudbury Neutrino Observatory





The Borexino detector

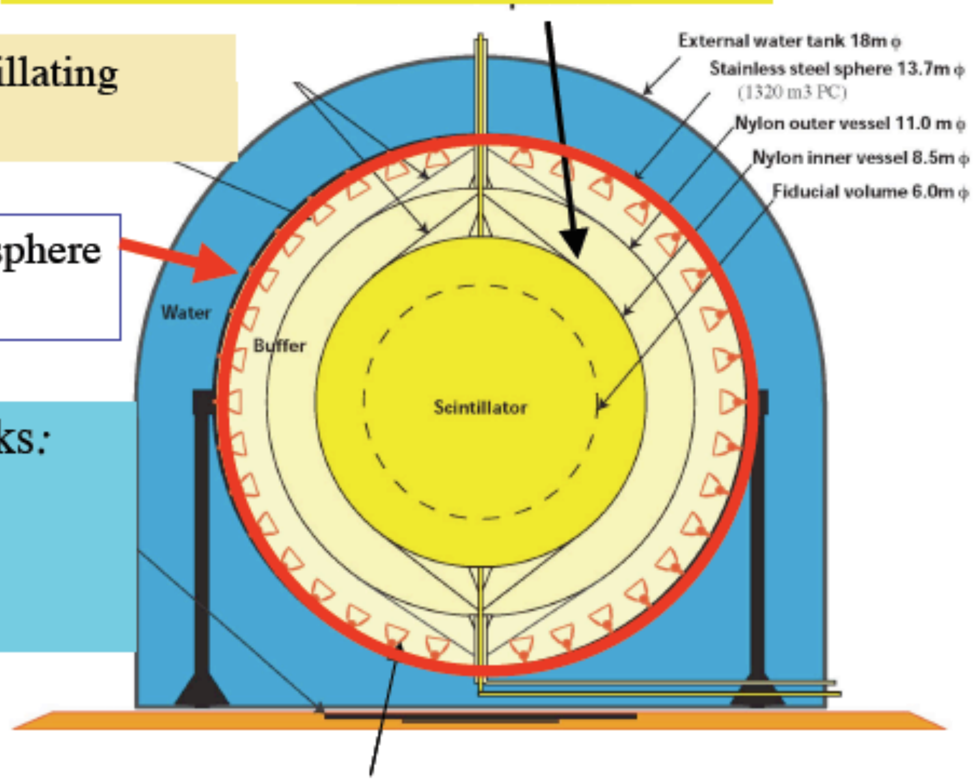
The Detector = 300 t (100 fid) of liquid scintillator : PC+PPO (1.5 g/l)

Suspended inside a nylon sphereØ=8.5m

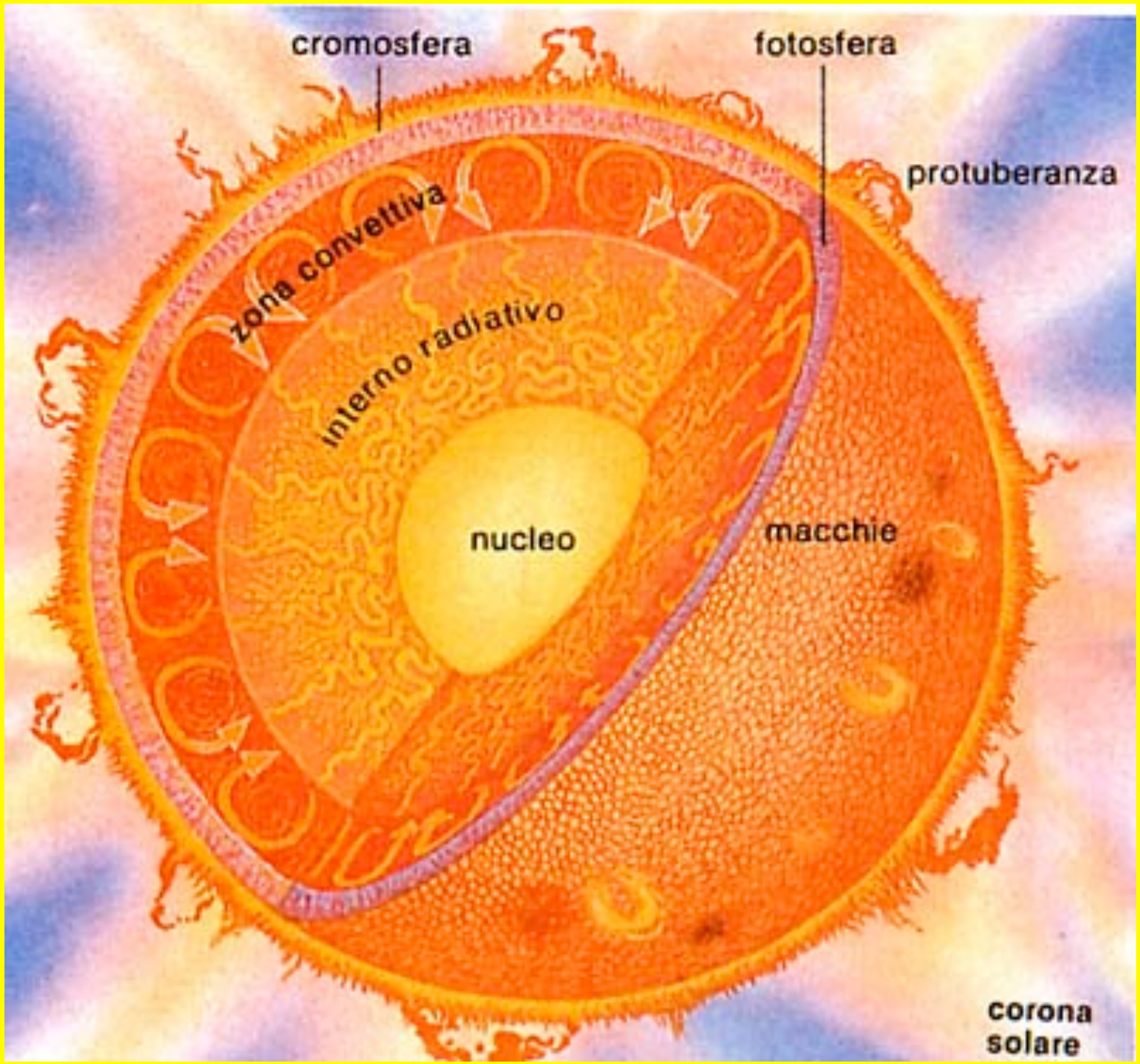
The buffer zone = 1040 t of non scintillating liquid: PC + DMP

All inside a SS sphere Ø=13.7m

The shielding of the γ from the rocks:
2m of ultrapure water
In a SS Water Tank
Ø= 18m



Sole



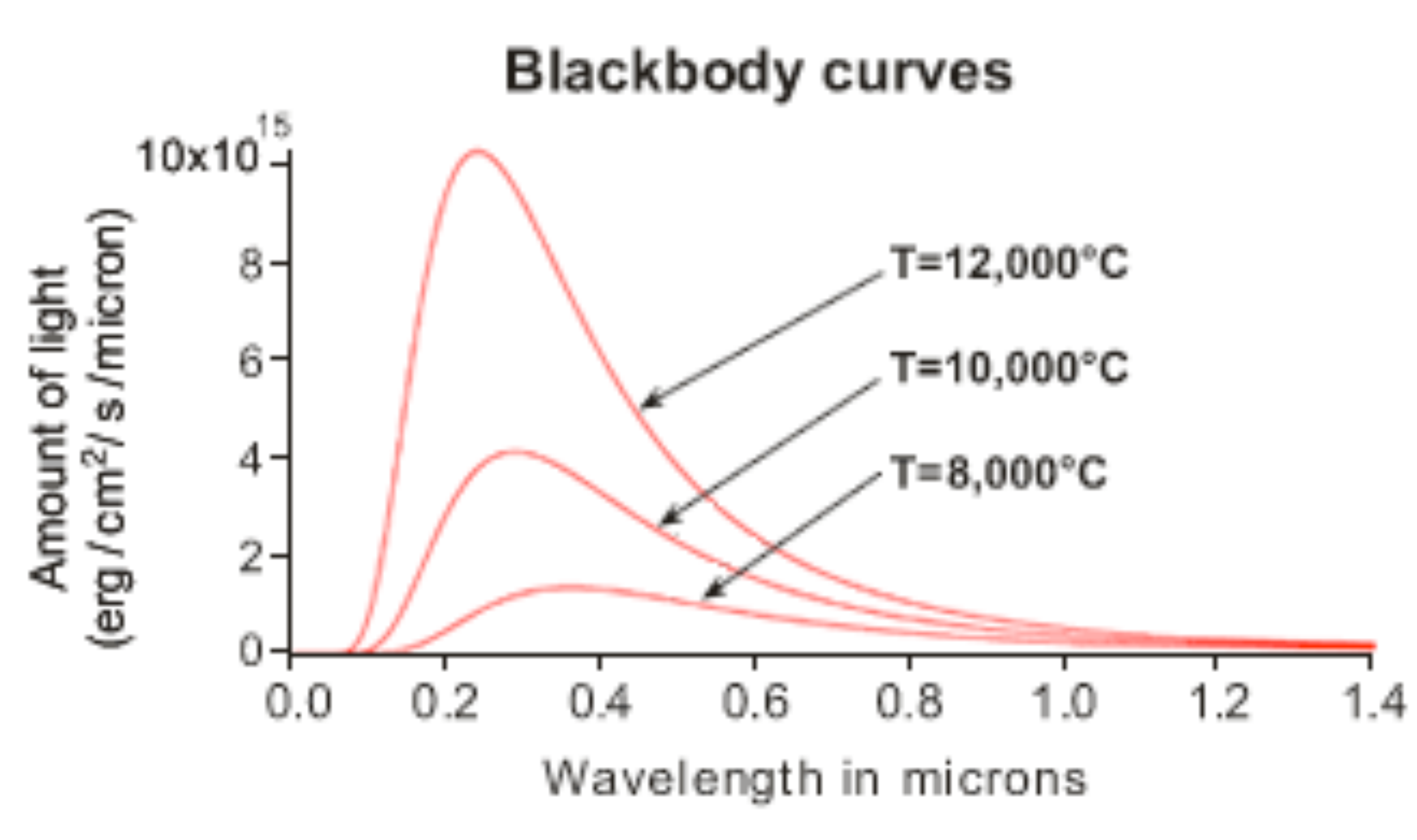
cromosfera
fotosfera
protuberanza
zona convettiva
interno radiativo
nucleo
macchie
corona solare

Struttura del Sole

Caratteristica	Valore
Distanza	$1.5 \cdot 10^{11}$ m
Raggio	$7 \cdot 10^{8}$ m
Massa	$2 \cdot 10^{30}$ Kg
Densità	$1.4 \cdot 10^{3}$kg/m^{3}
Luminosità	$3.8 \cdot 10^{26}$ W
Temperatura effettiva	5800 K
Densità centrale	$1.5 \cdot 10^{5}$ kg/m^{3}
Pressione centrale	$6 \cdot 10^{14}$ Pa
Temperatura centrale	$1.3 \cdot 10^{7}$ K
Età	$1.4 \cdot 10^{17}$ s

$$G\frac{m_P M_O}{d^2} = m_P a_c = \frac{m_P v^2}{d} = m_P\left(\frac{2\pi d}{T}\right)^2 \frac{1}{d}$$

$$M_O = \frac{4\pi^2 d^3}{GT^2}$$



Nelle stelle (e quindi anche nel Sole) avvengono spontaneamente le reazioni di fusione termonucleare che bruciano idrogeno trasformandolo in elio, l'unico processo in grado di spiegare la lunga esistenza delle stelle.
Due condizioni permettono di stimare le condizioni interne delle stelle:

equilibrio idrostatico (legge di Stevino)

$$dP = -\rho g \, dr$$

equazione di stato dei gas perfetti

$$P = \frac{nRT}{V} = NkT = \frac{k}{\mu m_H} \rho T$$

Dalla prima si ricava la pressione al centro del Sole:

$$\frac{dP(r)}{dr} = -\rho g = -\rho \frac{GM(r)}{r^2} = -\frac{4}{3}\pi G \rho^2 r$$

$$\int_r^{R_O} \frac{4}{3}\pi \bar{\rho}^2 G r\, dr = \frac{2}{3}\pi \bar{\rho}^2 G (R_O^2 - r^2) = P(r) - P(R_O)$$

$$P(r=0) = P_C = \frac{2}{3}\pi \bar{\rho}^2 G R_O^2 = \frac{3GM_O^2}{8\pi R_O^4} = \frac{\bar{\rho} G M_O}{2R_O} \approx 6 \cdot 10^{14}\,\mathrm{Pa}$$

Dalla seconda si ricava la temperatura al centro del Sole:

$T_C \sim 1{,}5 \cdot 10^7$ K ~ 1 keV

un valore circa 100 volte inferiore all'energia repulsiva elettrostatica tra 2 protoni alla distanza $r \sim 10^{-14}$ m.

Equilibrio idrodinamico ed energetico

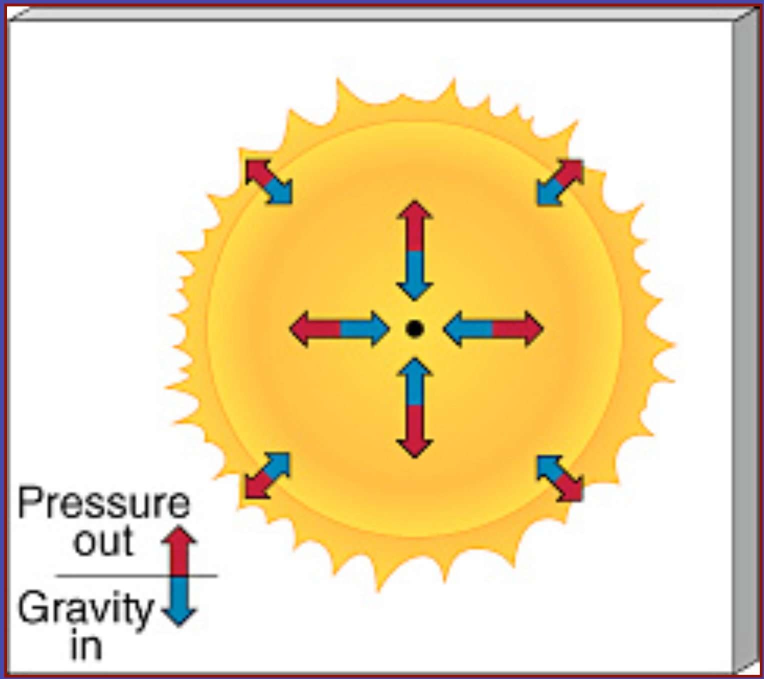
- Sfera di gas autogravitante in simmetria sferica
- Si trascurano effetti centrifughi e magnetici

$$\frac{dP}{dr} = -\frac{GM(r)\rho(r)}{r^2}$$

$$M(r) = 4\pi \int_0^r \rho(r')r^2 dr$$

$$L(r) = 4\pi \int_0^r \varepsilon(r')\rho(r')r^2 dr$$

$\varepsilon(r)$ = produzione di energia



Tempi evolutivi solari

Il Sole deve avere un'età almeno pari a quella della Terra ($4{,}5 \cdot 10^9$ anni) e non deve aver avuto variazioni troppo grandi di luminosità. Ciò vuol dire che, nel complesso, deve aver prodotto l'energia.

$$E = L\tau = 4 \cdot 10^{26} \cdot 4.5 \cdot 10^{9} \cdot 3.1 \cdot 10^{7} \approx 6 \cdot 10^{43}\ \mathrm{J}$$

corrispondente a $\varepsilon \sim 3 \cdot 10^{13}$ J/kg. L'ossidazione del carbonio fornisce solo $\varepsilon \sim 9 \cdot 10^{6}$ J/kg, mentre la contrazione gravitazionale può aver prodotto, in tutto l'energia:

$$E_P = -\int_0^R \left(\frac{4}{3}\pi r^3 \rho\right)(4\pi r^2 \rho\, dr)\frac{G}{r} =$$

$$= -\frac{1}{3}(4\pi\rho)^2 G \int_0^R r^4 dr = -\frac{3}{5}\frac{GM^2}{R} = 2 \cdot 10^{41}\ \mathrm{J}$$

Le reazioni di fusione di H in He sono invece in grado di produrre $\varepsilon \sim 6 \cdot 10^{14}$ J/kg e di garantire l'esistenza del Sole per oltre 10^{10} anni.

$$4p \rightarrow 1\alpha + 2e^{+} + 2\nu_{e} + \text{energia}$$

Quanta energia viene liberata?

- L'energia liberata è ~ 26 MeV
- = 4 x 10 $^{-12}$ Joule
- = 1 x 10 $^{-15}$ Calorie

- Il Sole libera questa energia 10^{38} volte al secondo
- ma ha 10^{56} atomi di H da bruciare

L'energia prodotta nelle parti interne del Sole è: $\frac{L}{M_C} \approx \frac{4 \cdot 10^{26}}{4 \cdot 10^{29}} = 10^{-3}\ \mathrm{W/kg} \approx 100\ \mathrm{W/m^3}$

Il processo di fusione dell'idrogeno nelle stelle avviene con emissione di γ e ν_e. Per definizione il loro libero cammino medio è:

$$\chi_f \leq \frac{1}{N_e \sigma_T} \approx 10^{-3} m \text{ per fotoni,} \quad \chi_\nu = \frac{1}{n\sigma} \approx 10^{18} m \text{ per neutrini}$$

quindi, mentre i fotoni diffondono lentamente verso la superficie del Sole, da cui vengono emessi dopo un tempo di oltre 10^{12} s (10^5 anni), i neutrini sfuggono immediatamente e sono rivelabili a Terra in esperimenti sotterranei.

Il flusso totale di ν_e a terra è:

$$\Phi_T(\nu_e) = \frac{2 \cdot 10^{38}}{4\pi d^2} \approx 10^{15} \nu_e \, \mathrm{m}^{-2}\mathrm{s}^{-1}$$

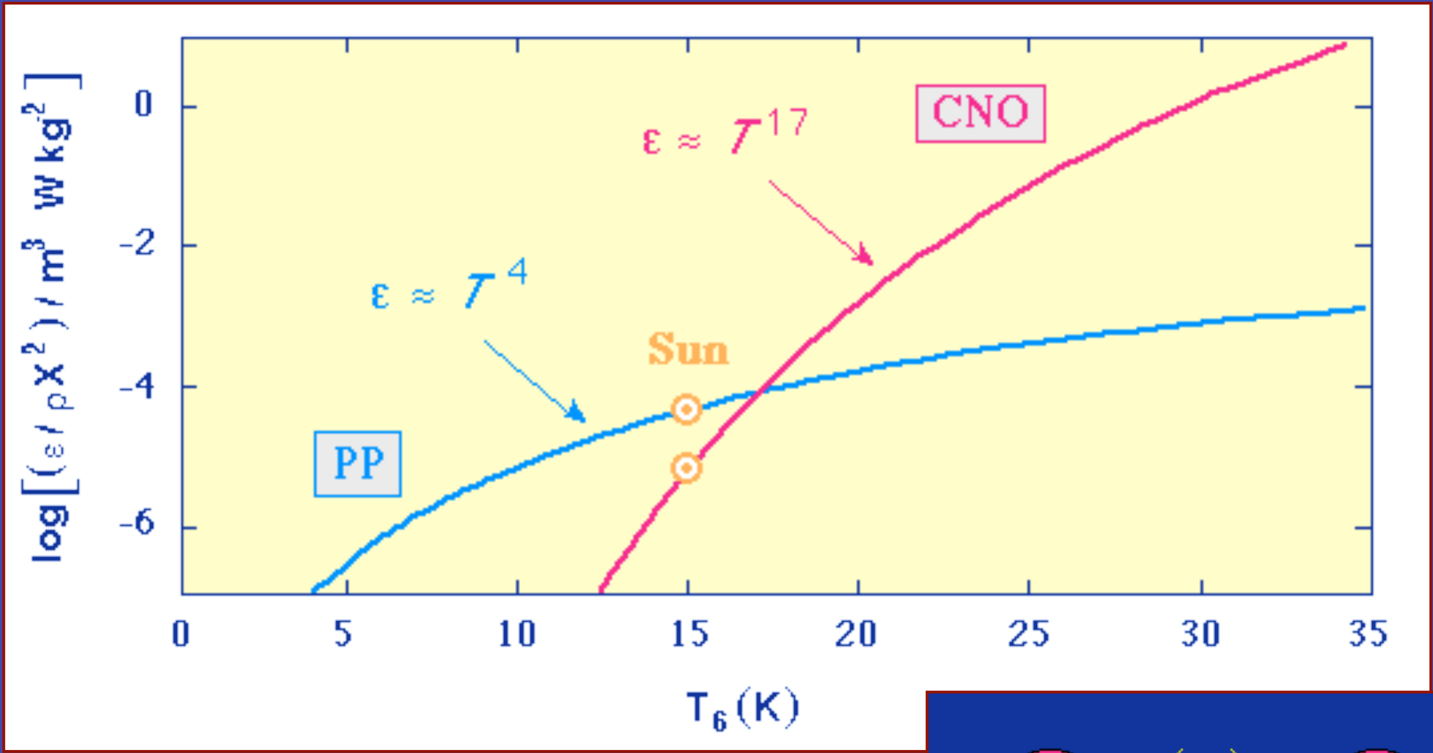
Il rate di eventi attesi per nucleo bersaglio si calcola con la relazione:

$$R = \sum_i \int_{E_{th}}^{E_{Max}} \Phi_i(E)\,\sigma(E)\,dE$$

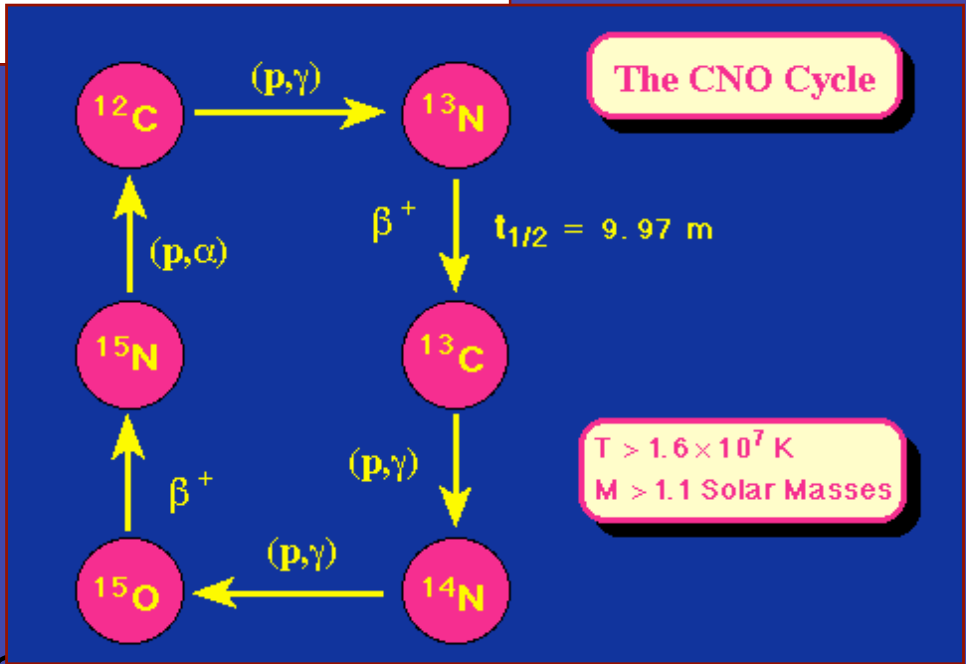
Per la rivelazione dei neutrini solari si usano nuclei in cui avvengono i processi di cattura:

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

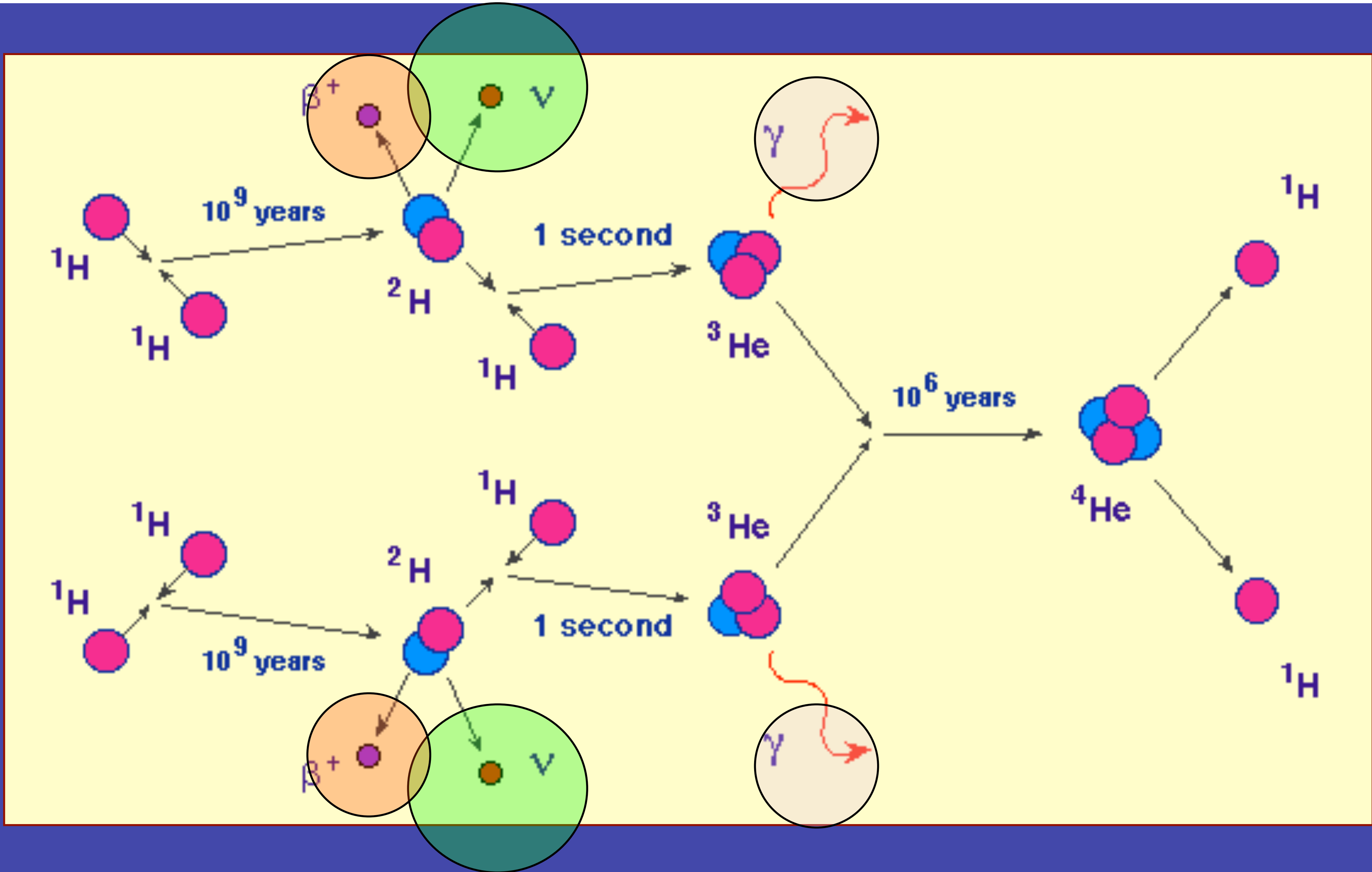
ossia, a livello elementare, $\nu_e + n \rightarrow p + e^-$. Il primo nucleo utilizzato è stato il ^{37}Cl che si trasforma in ^{37}A, in seguito è stato utilizzata la reazione ^{71}Ga $\rightarrow$ ^{71}Ge.

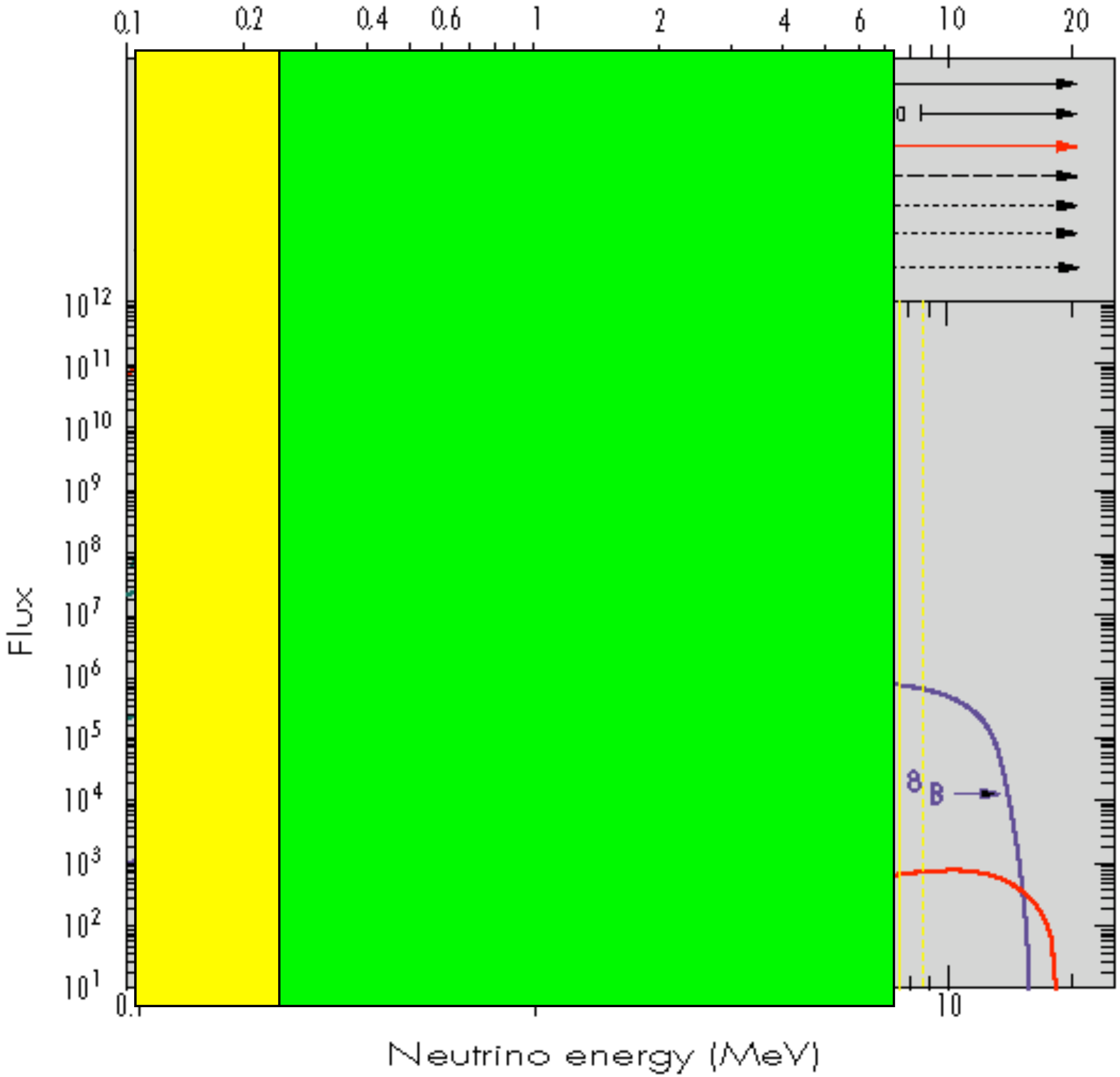


log[(ε/ρX²)/m³ W kg⁻²]
0
-2
-4
-6
0
5
10
15
20
25
30
35
T6 (K)
ε ≈ T^17
CNO
ε ≈ T^4
Sun
PP

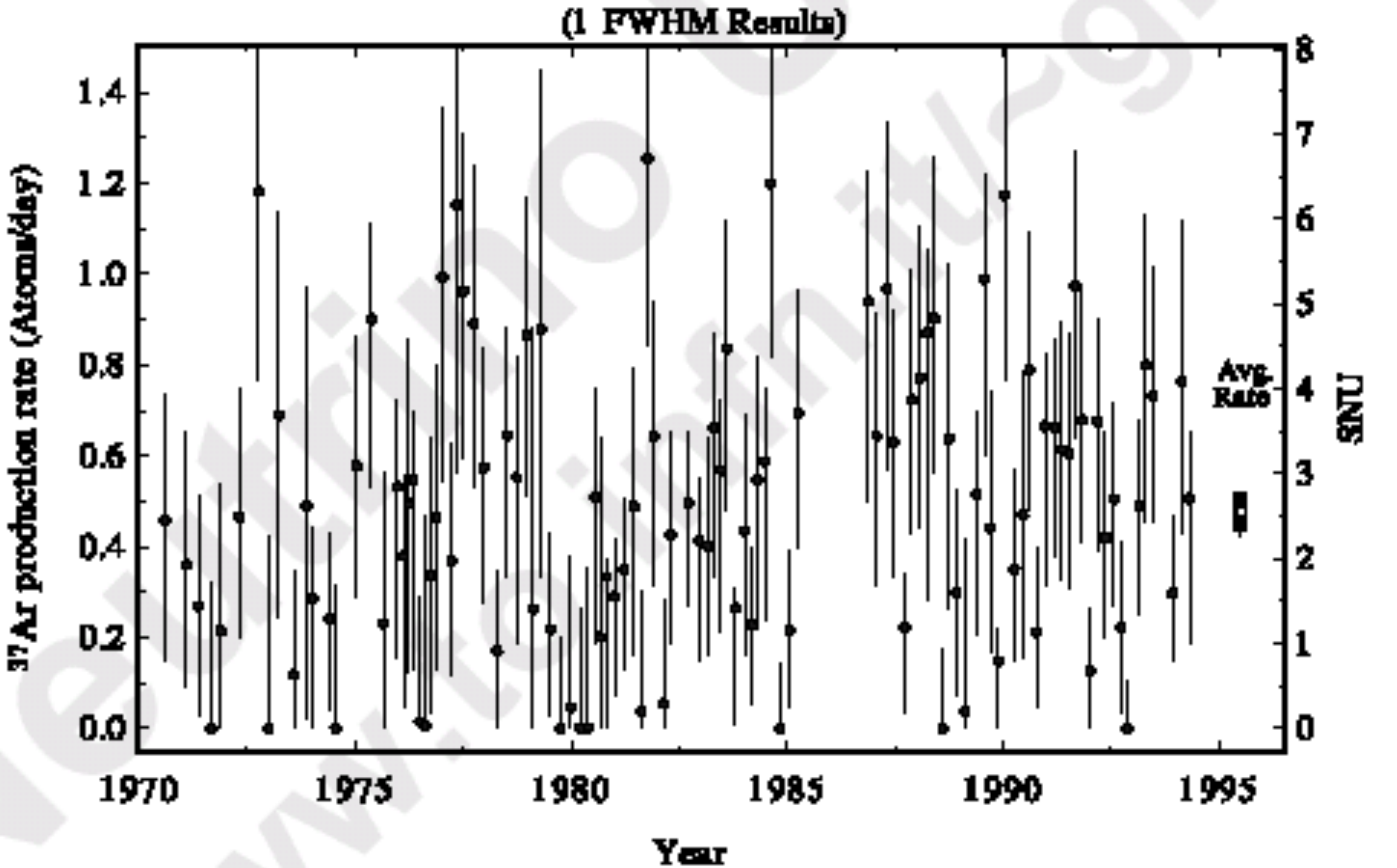


The CNO Cycle
12C
(p,γ)
13N
β+
t1/2 = 9.97 m
13C
(p,γ)
14N
(p,γ)
15O
β+
15N
(p,α)
T > 1.6×10⁷ K
M > 1.1 Solar Masses


β+
ν
γ
^{1}H
10^9 years
1 second
^{2}H
^{3}He
10^6 years
^{4}He
1 second
10^9 years
β+
ν
γ

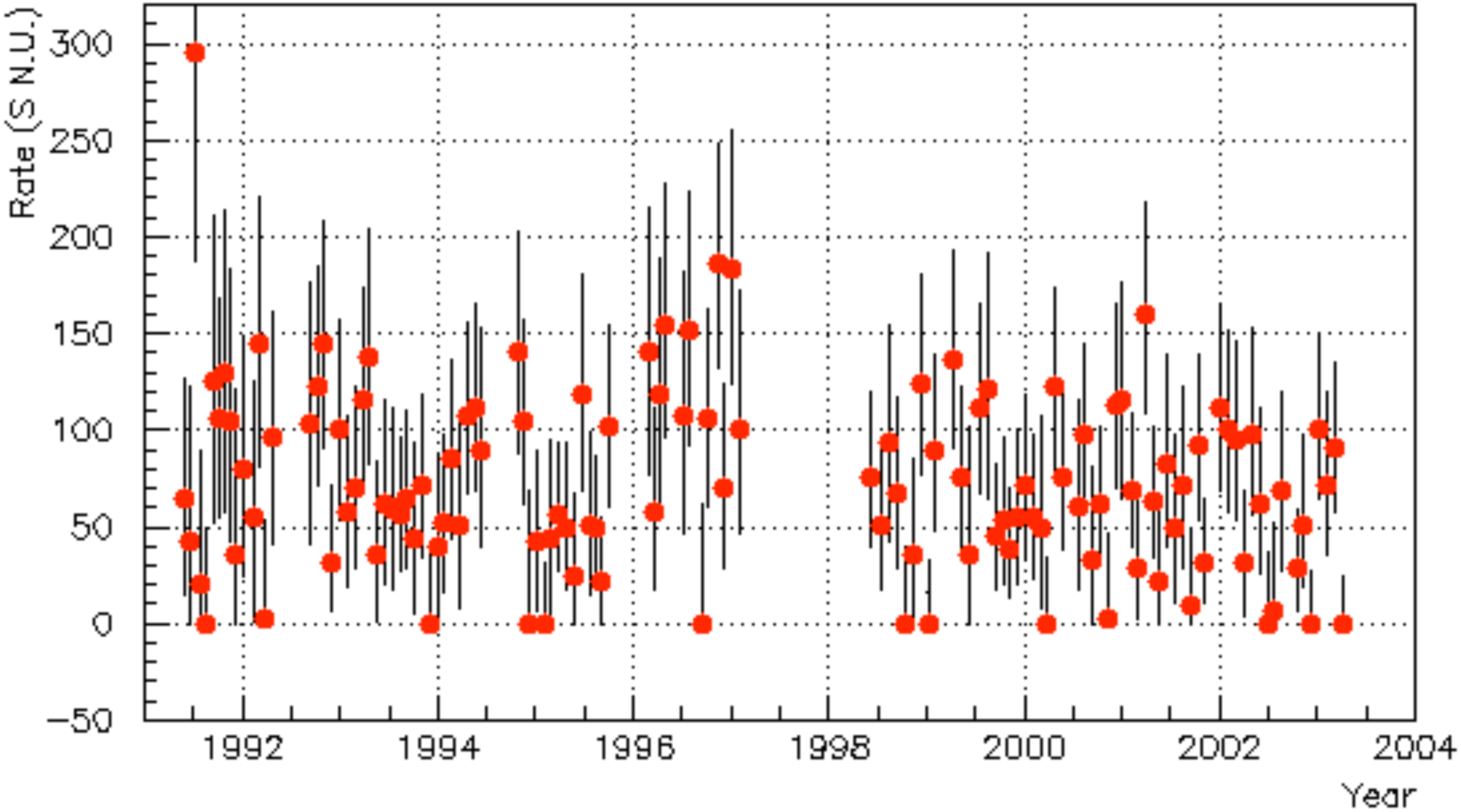

0.1
0.2
0.4
0.6
1
2
4
6
10
20
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
Flux
^{8}B
Neutrino energy (MeV)

$\nu_e + {}^{37}Cl \rightarrow {}^{37}A + e$

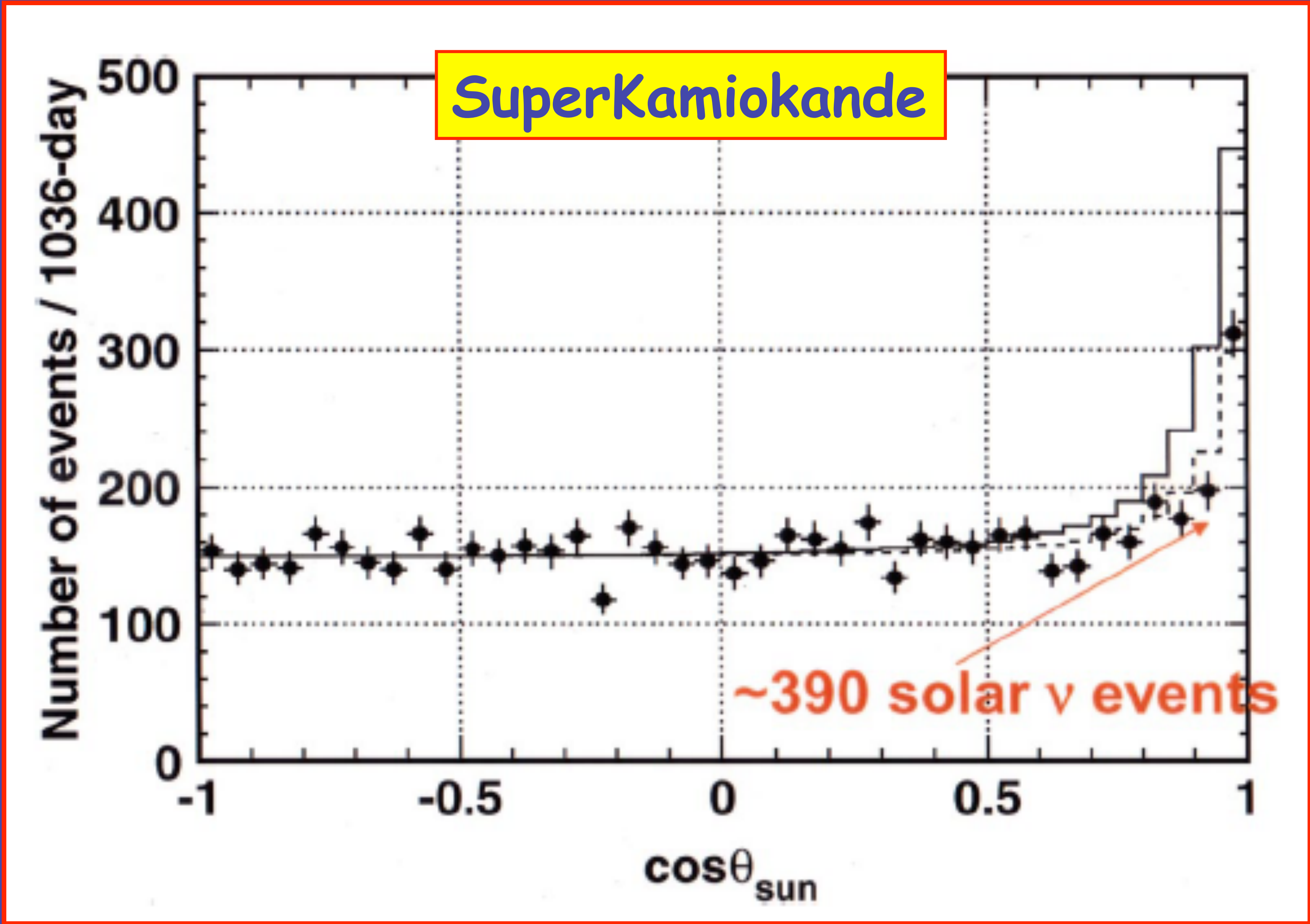


La piccola sezione d'urto, in media $\sigma \sim 10^{-46}$ m^2, richiede l'uso di grandi masse di rivelatore. Poichè il ^{37}Cl è sensibile quasi solo ai neutrini di alta energia prodotti dal decadimento del ^{8}B, il cui flusso a Terra è $\Phi(\nu_e) \sim 6 \cdot 10^{10}$ m^{-2}s^{-1}, il numero di eventi attesi è $R = \Phi(\nu_e)\sigma \sim 6 \cdot 10^{-36}$ per nucleo bersaglio.
Per avere valori R ~ 1, e` stata introdotta una unità di misura speciale per calcolare o per misurare il numero di catture di neutrini solari nei diversi rivelatori, lo SNU, dove 1 SNU equivale alla cattura di 1 ν_e s^{-1} in un bersaglio composto di 10^{36} atomi.

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



REAZIONE	^{37}Cl catture (SNU)		^{71}Ga catture (SNU)	
pp	0,0	0,0	70,8	71,1
pep	0,23	0,21	3,01	2,99
^{7}Be	1,12	0,99	34,4	30,9
^{8}B	6,15	4,06	14,1	10,77
^{13}N	0,10	0,10	3,77	2,36
^{15}O	0,34	0,37	6,03	3,66
^{17}F	0,003		0,06	
totale	7,9	5,8	132	122,5
misurato	$2,6 \pm 0,16 \pm 0,14$ (Homestake)		70 ± 8 (Gallex) 72 ± 10 (Sage)	


SuperKamiokande
Number of events / 1036-day
500
400
300
200
100
0
-1
-0.5
0
0.5
1
cosθ sun
~390 solar ν events

ν Reactions in SNO

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

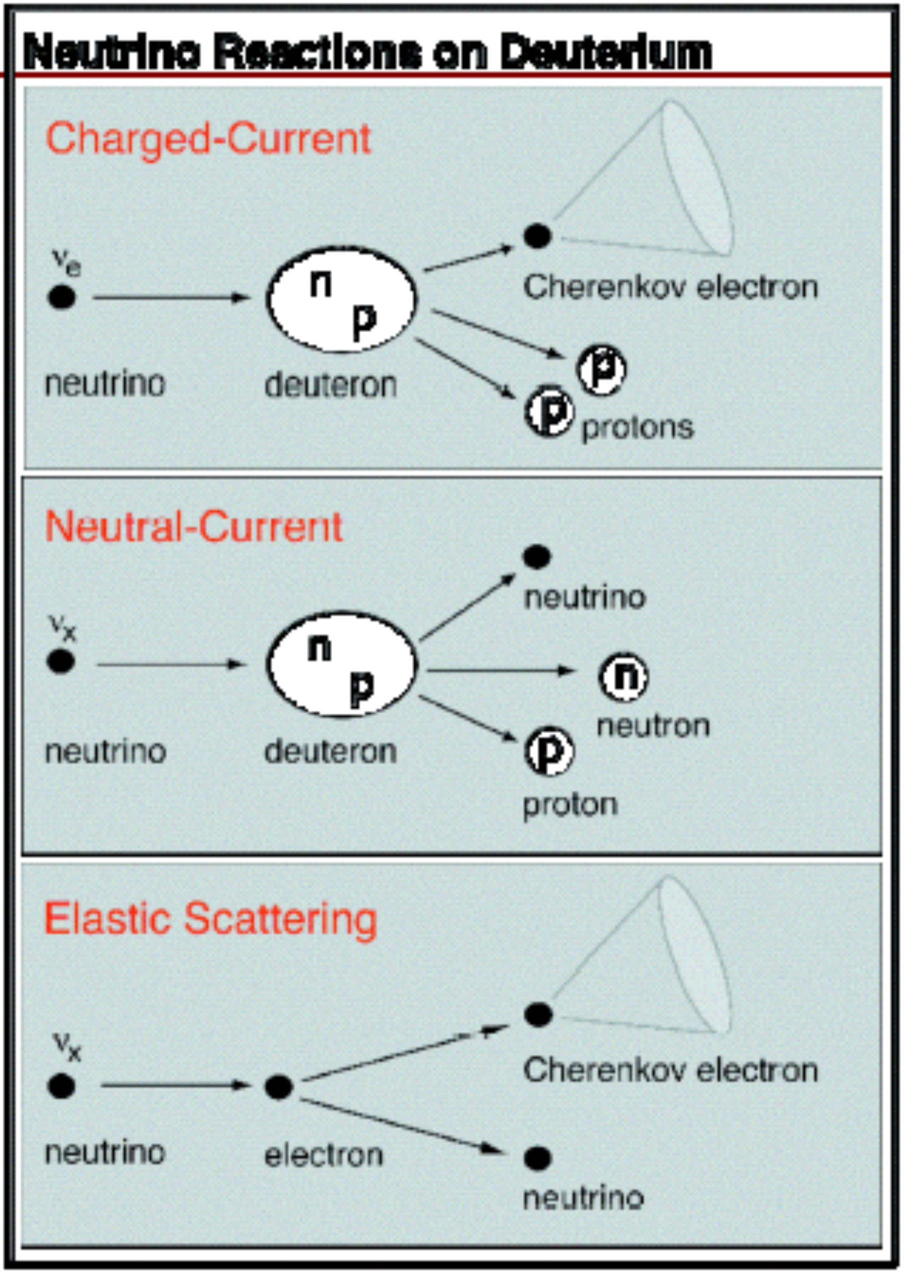
-Gives ν_e energy spectrum well
-Weak direction sensitivity ∝ 1-1/3cos(θ)
- ν_e only.

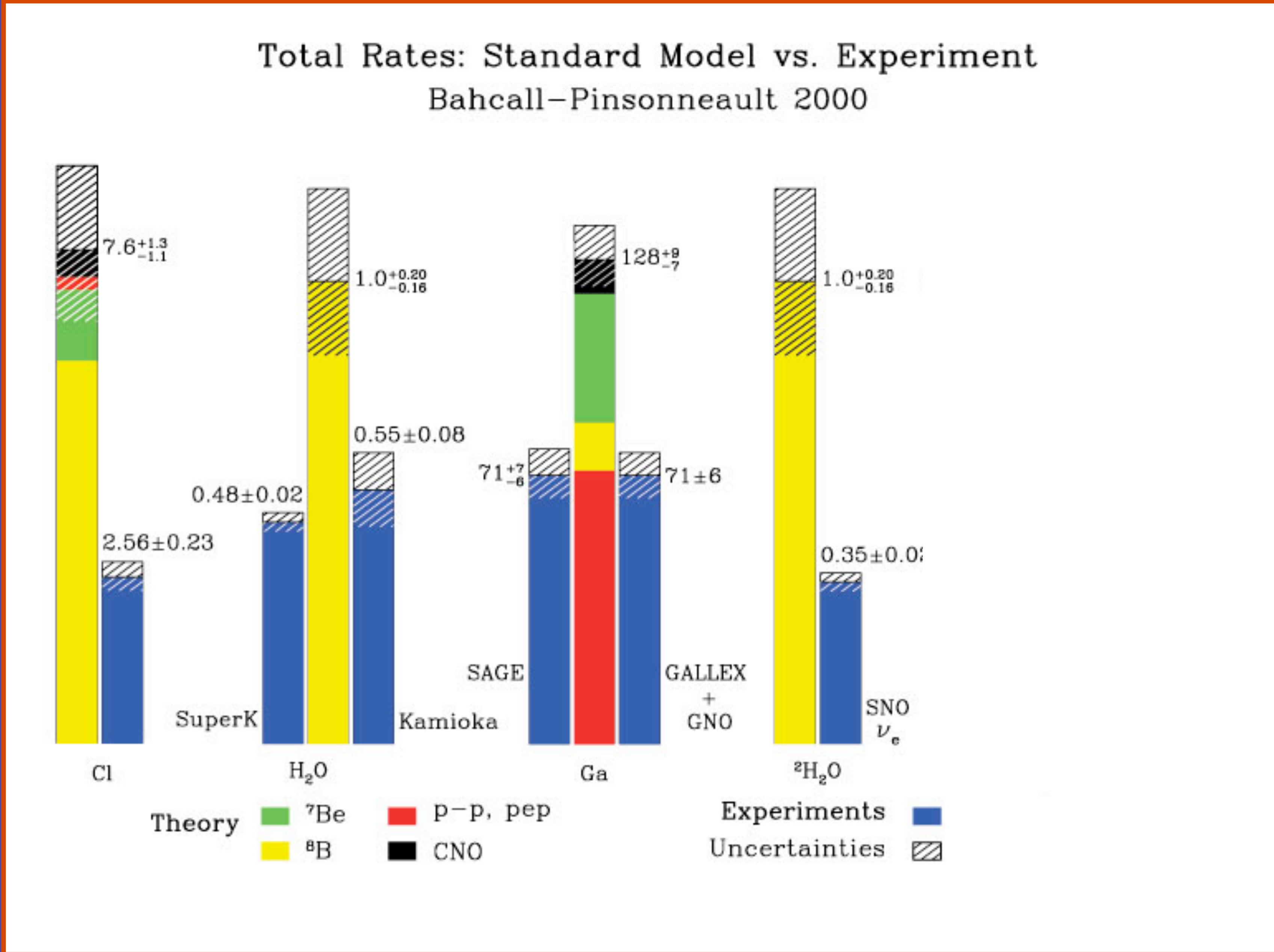
NC $\nu_x + d \Rightarrow p + n + \nu_x$

-Measure total ^8B 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





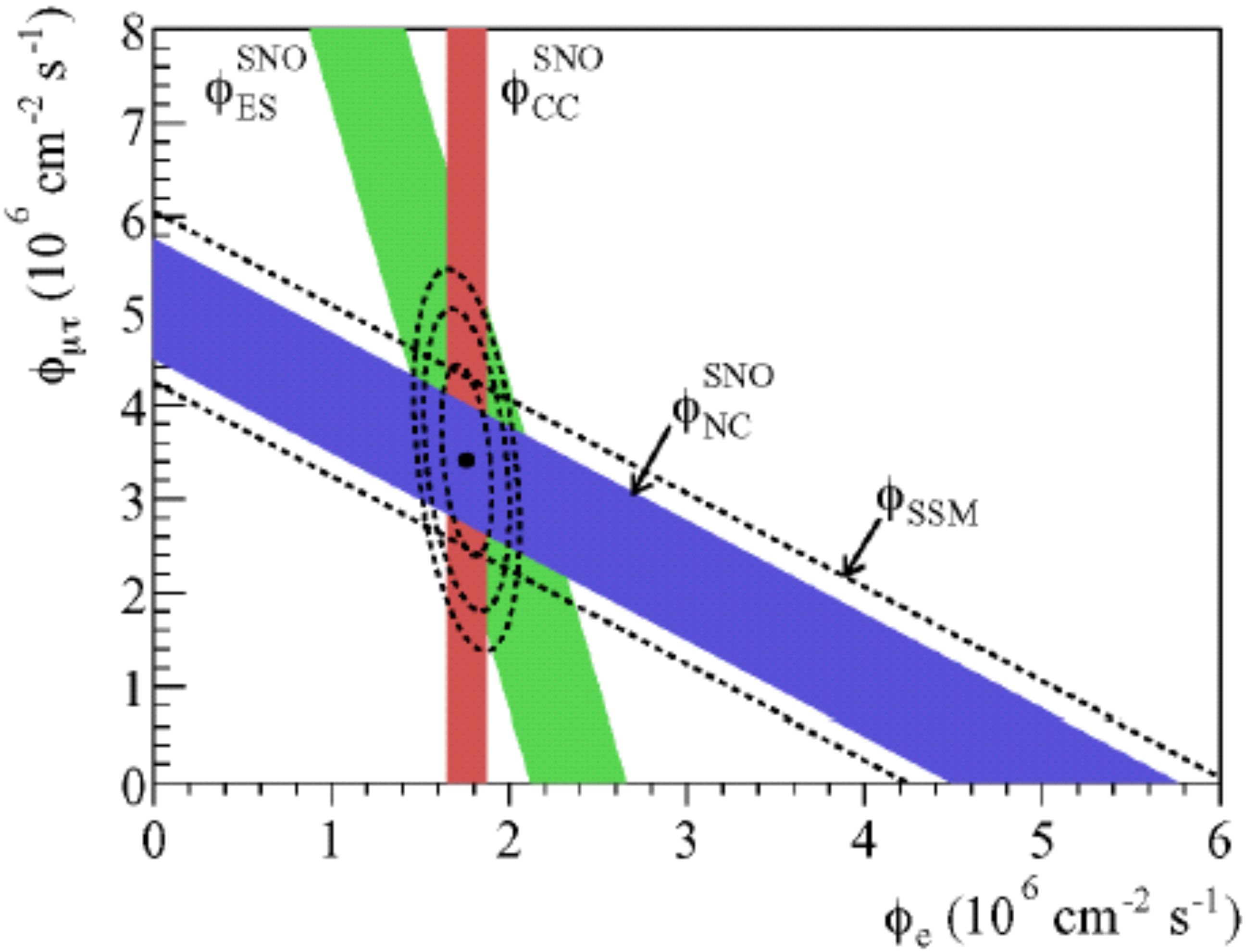
Total Rates: Standard Model vs. Experiment
Bahcall–Pinsonneault 2000
7.6+1.3 −1.1
2.56±0.23
0.48±0.02
1.0+0.20 −0.16
0.55±0.08
SuperK
Kamioka
128+9 −7
71+7 −6
71±6
SAGE
GALLEX + GNO
1.0+0.20 −0.16
0.35±0.0
SNO
Cl
H2O
Ga
2H2O
Theory
7Be
8B
p−p, pep
CNO
Experiments
Uncertainties

Neutrino Flavor Composition of ^{8}B Flux

Fluxes

(10^6 cm^{-2} s^{-1})

ν_e:	1.76(11)
$\nu_{\mu\tau}$:	3.41(66)
ν_{total}:	5.09(64)
ν_{SSM}:	5.05



Risultati di SNO

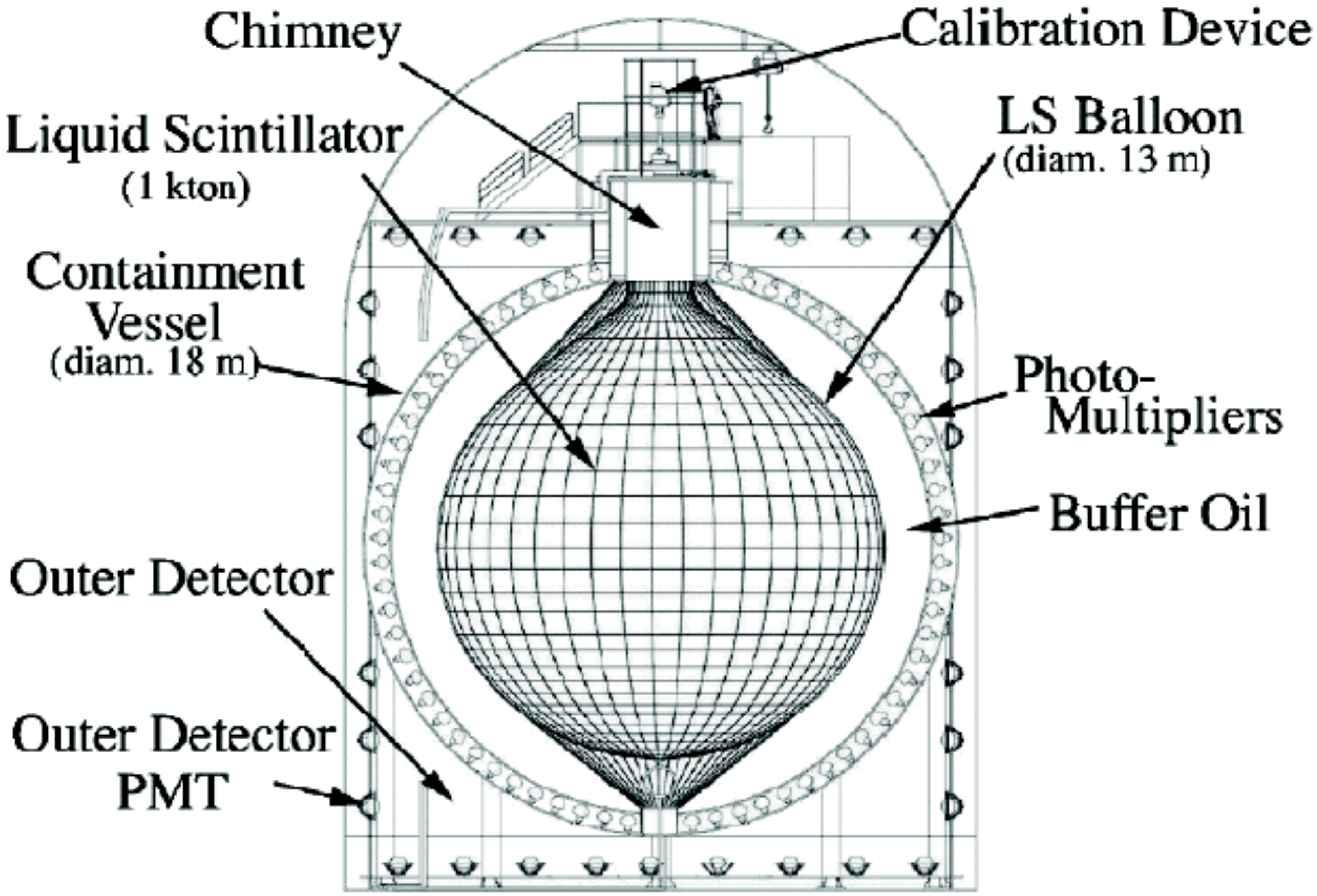
$$N_{cn} = 1344.2^{+69.8}_{-69.0} \qquad \Phi_{cn} = 5.21\times10^{6}\,\mathrm{cm^{-2}s^{-1}}$$

$$N_{cc} = 1339.6^{+63.8}_{-61.5} \qquad \Phi_{cc} = 1.59\times10^{6}\,\mathrm{cm^{-2}s^{-1}}$$

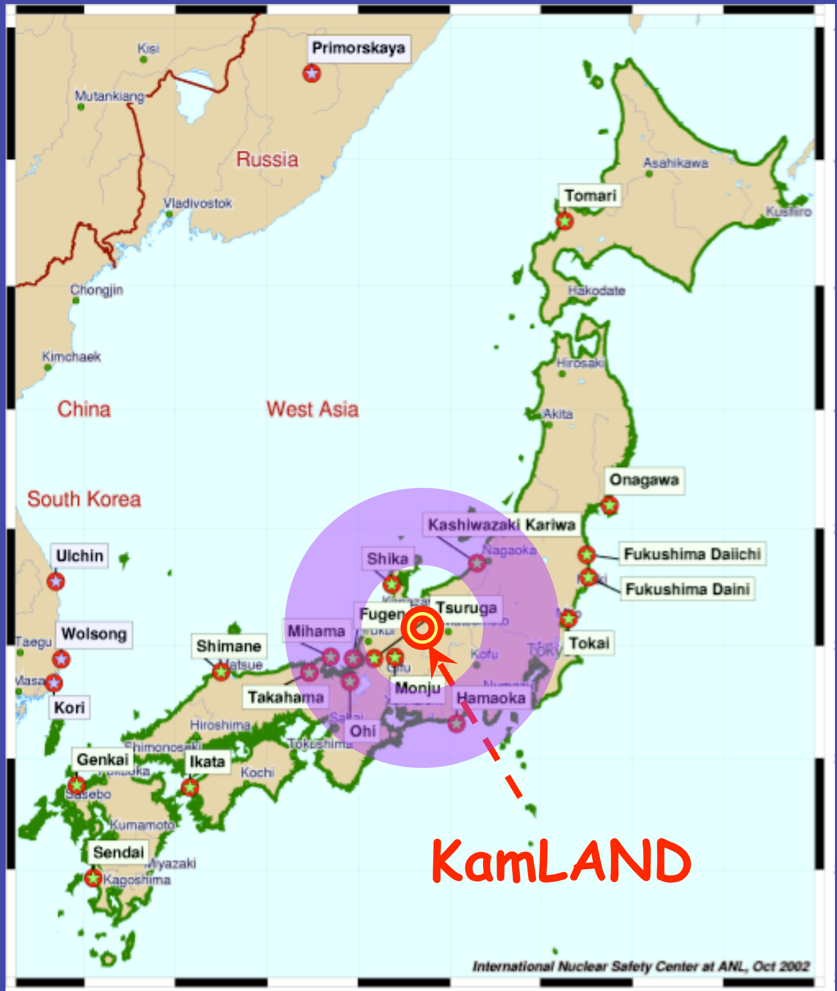
$$N_{es} = 170.3^{+23.9}_{-20.1} \qquad \Phi_{es} = 2.21\times10^{6}\,\mathrm{cm^{-2}s^{-1}}$$

$$\Delta m^2 = 7.1^{+1.0}_{-0.3}\times10^{-5}\,\mathrm{eV}^2,\;\; \vartheta = 32.5^{0}\,{}^{+1.7}_{-1.6}$$

KamLAND detector

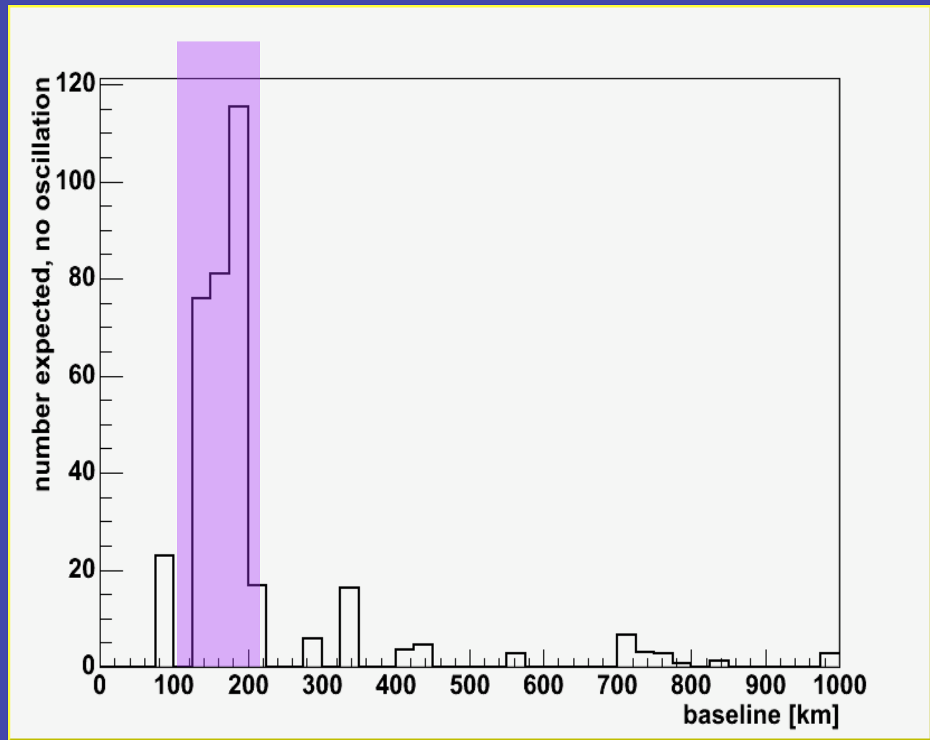


Reactor baseline



80 % of expected $\bar{\nu}_e$

from baselines 140-210 km

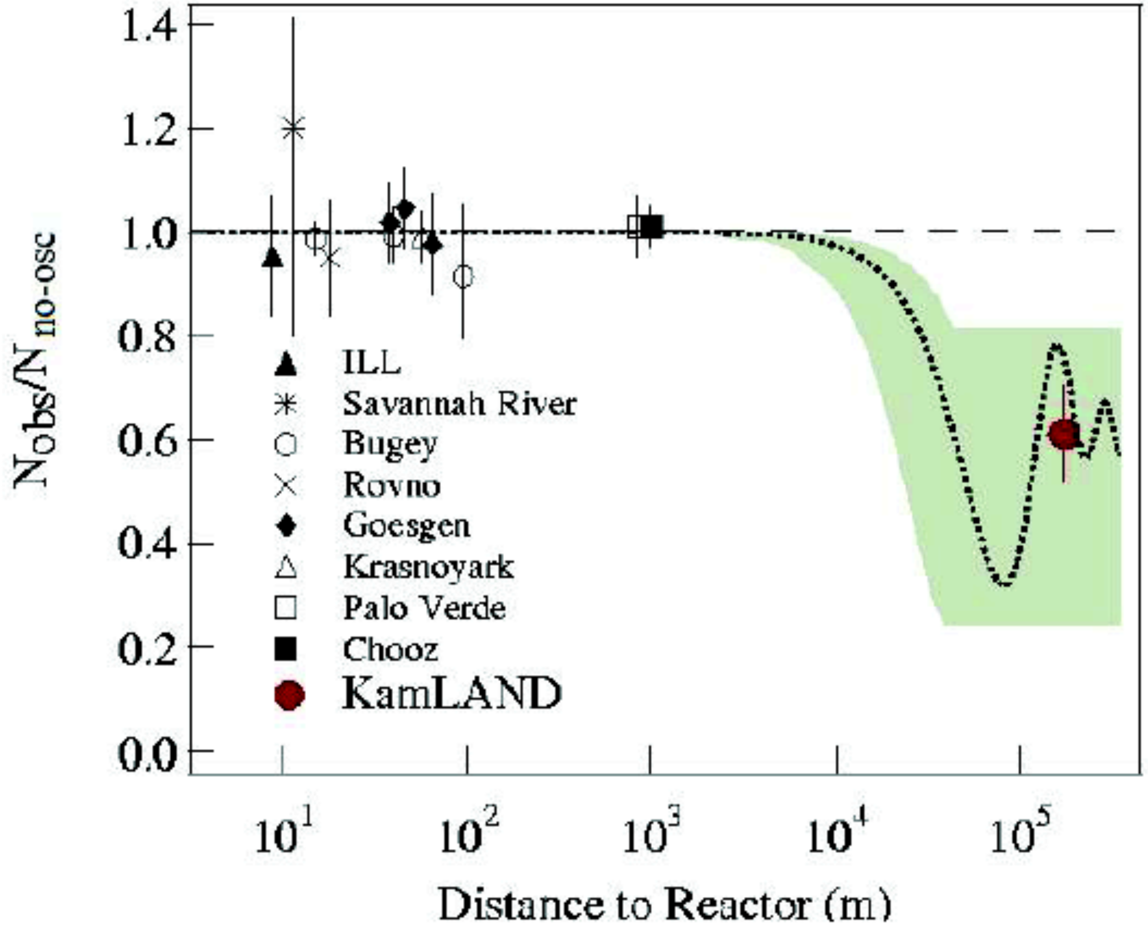


~ 5 x 10^6 $\bar{\nu}_e$ / cm^2 / sec

Few evts/day detected

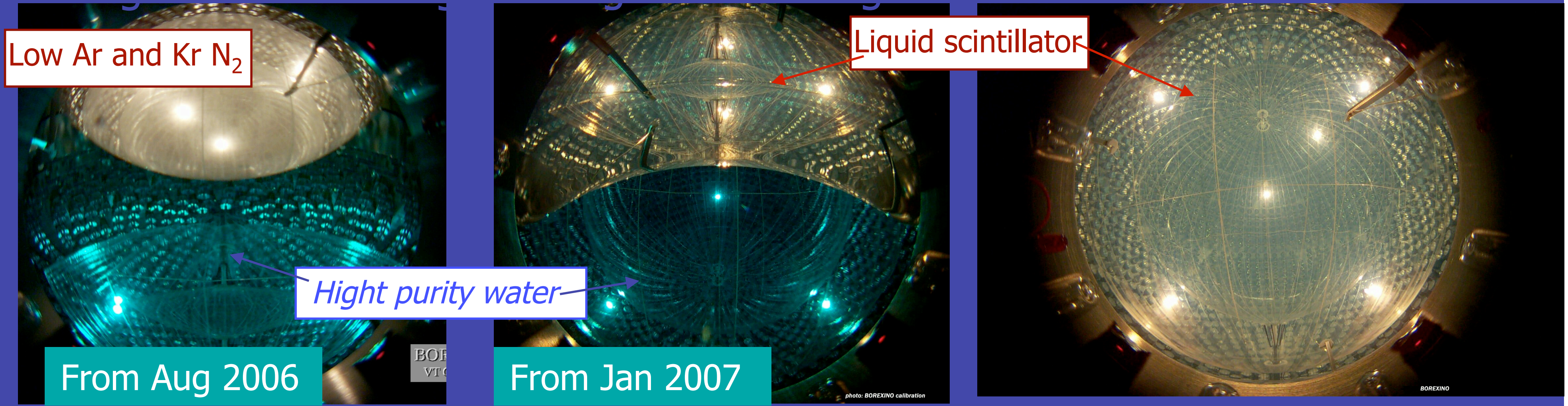
Rate suppression

$N_{obs}/N_{no\text{-}osc} = 0.611 \pm 0.085 \pm 0.041$



First result in August 2007

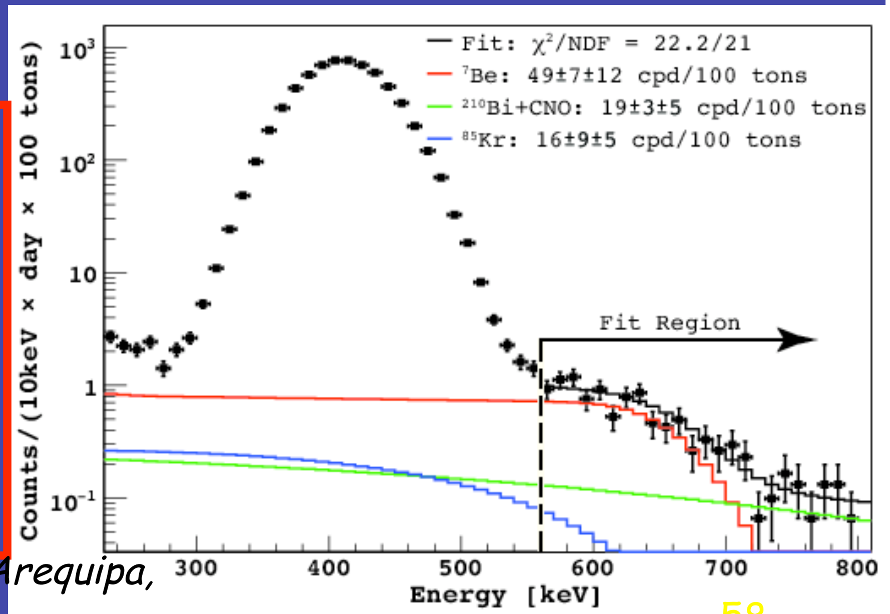
Finally, May 15th, 2007



We have measured the scattering rate of ^{7}Be solar νs on electrons

Rate 47 ± 7$_{STAT}$ ± 12$_{SYS}$ c/d/100 t

August 16(2007): PLB 658, 101(2008)



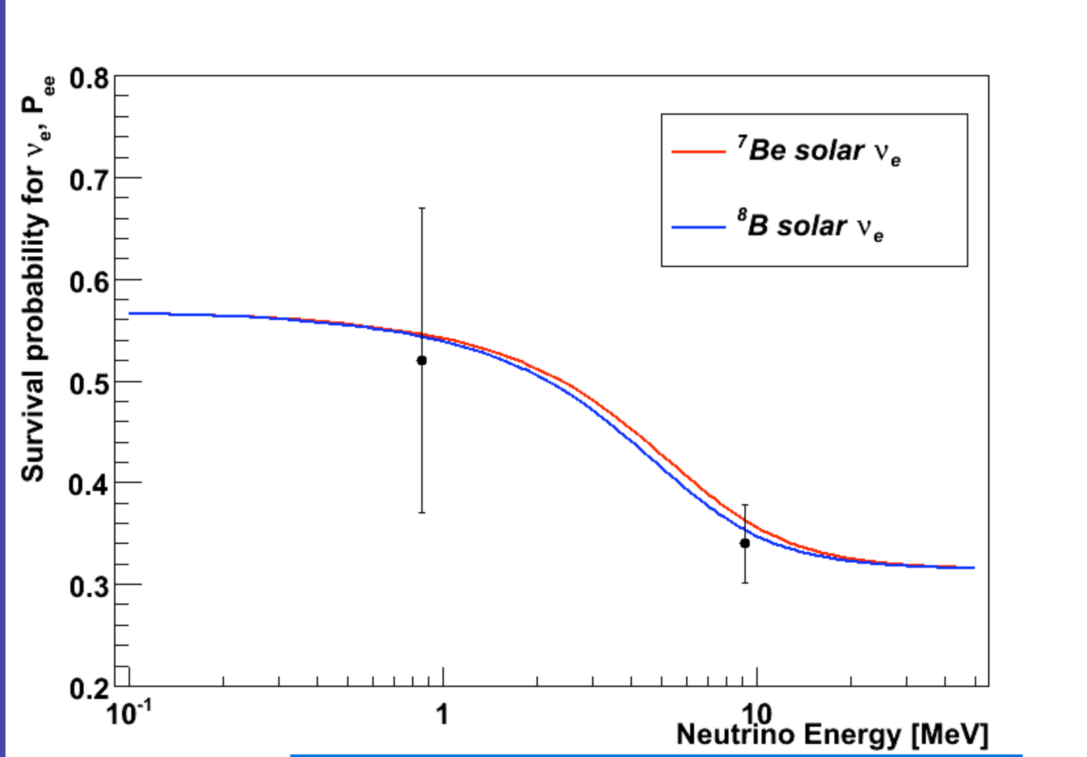
$47 \pm 7_{stat}$ cpd/100tons for 862 keV ^{7}Be solar ν

Using LMA with:

$\delta m_{12}^2 = 7.92 \cdot 10^{-5}\ eV^2$

$\sin^2\theta_{12} = 0.314$

and BPS07(GS98)



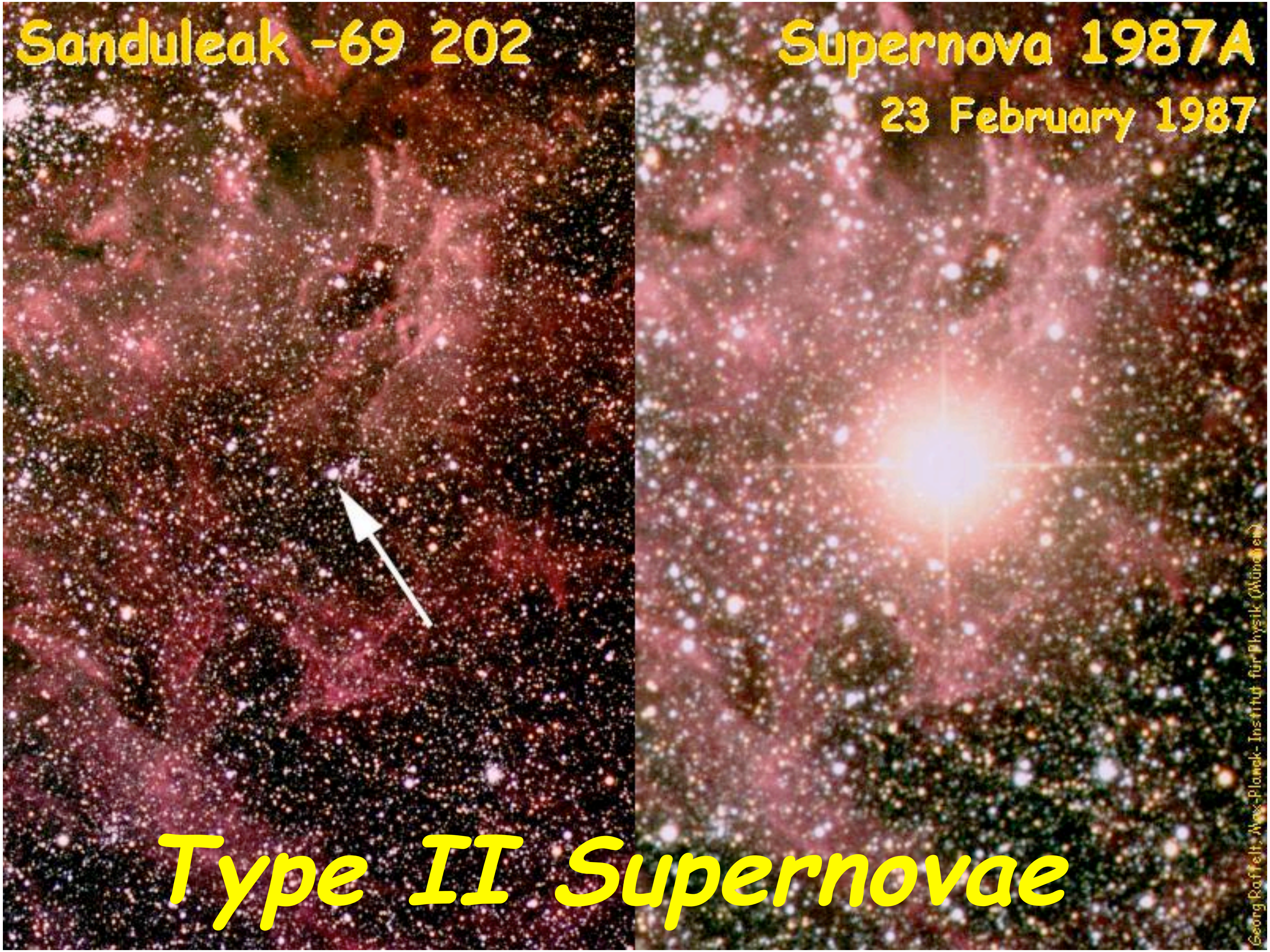
	Expected rate (cpd/100 t)
No oscillation	75 ± 4
BPS07(GS98) HighZ	49 ± 4
BPS07(AGS05) LowZ	44 ± 4

BPS07 : High Z vs Low Z

	GS98	AGS05	δ_{TH} % (δ_Z)	EXP
pp	5.97	6.04	0.8 (0.3)	
pep	1.41	1.46	1.3 (0.6)	*
hep	7.90	8.22	15.4 (0.9)	
Be	5.08	4.55	5.0 (2.4)	***
B	5.94	4.72	10.1 (5.3)	4.94 (0.43)
N	2.93	1.93	+20-15 (11)	*
O	2.20	1.37	+23-16 (11)	*
F	5.82	3.24	25 (15)	

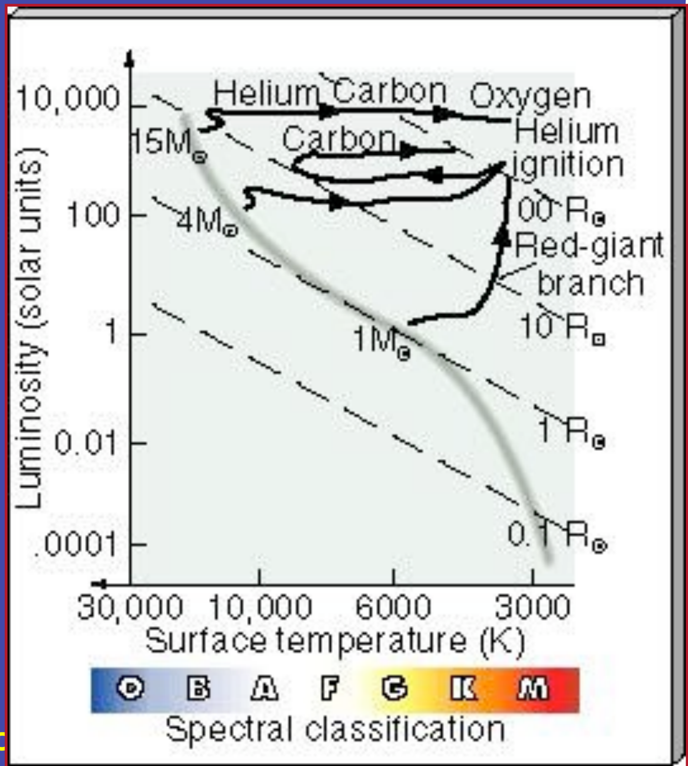
Neutrino fluxes can point out high/low Z model

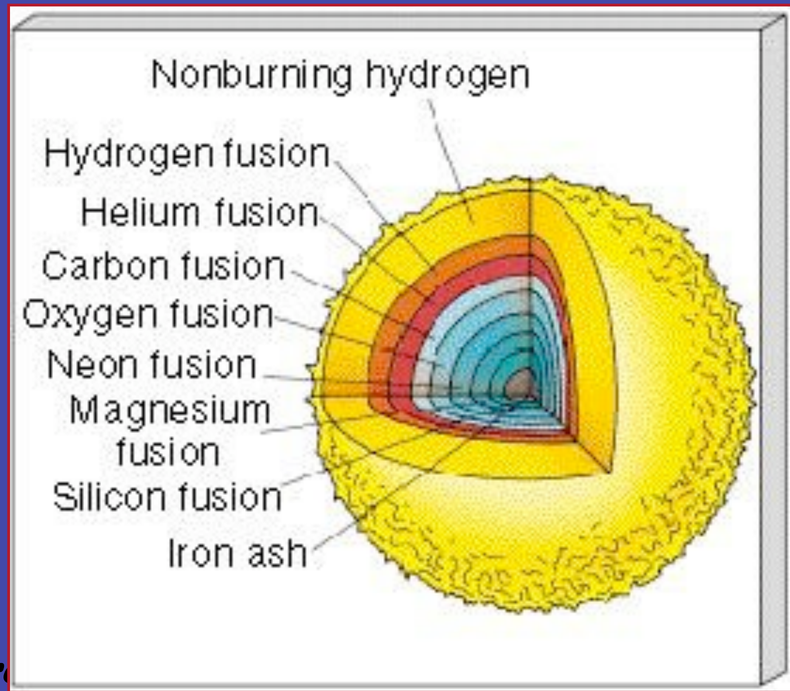
Type II Supernovae



Evoluzione di stelle di grande massa

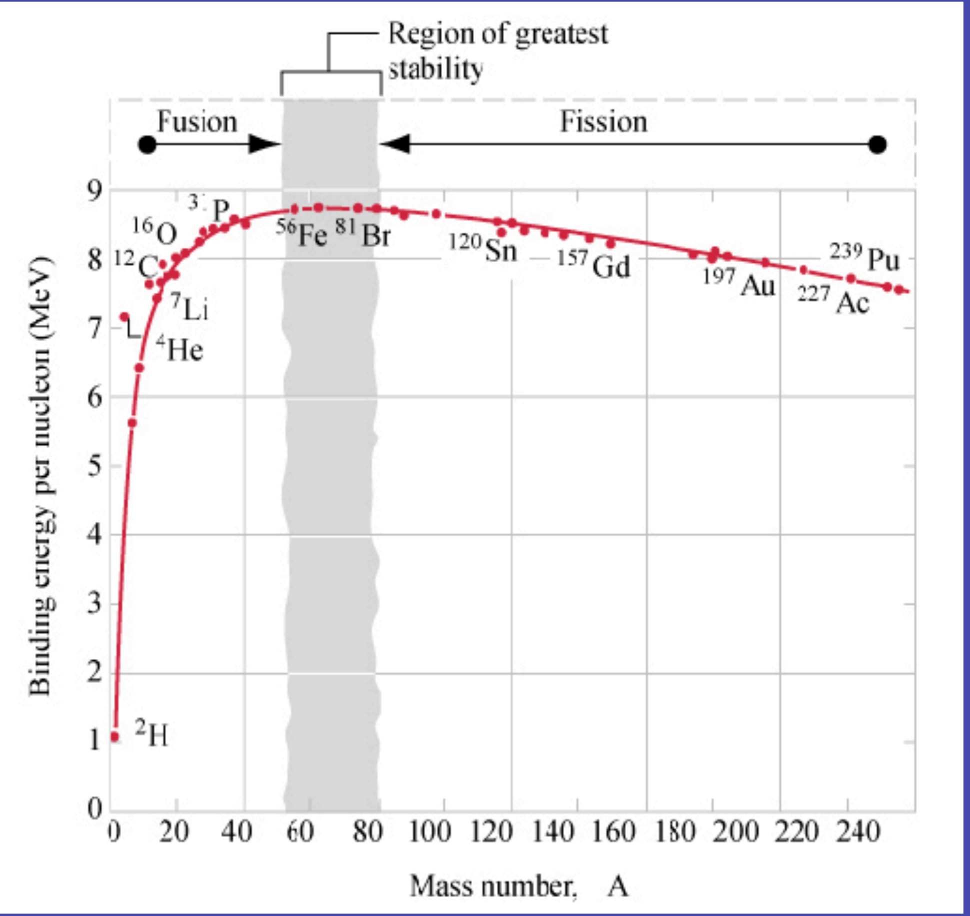
- Evolvono più rapidamente ($t \sim M^{-2.5}$)
- La pressione di radiazione è dominante
- Il nucleo non diventa mai degenere e l'elio si accende in modo non esplosivo
- Formazione di una struttura a shell con sequenza ...li bruciamenti termonucleari





Il nucleo raggiunge la composizione di ferro e nichel

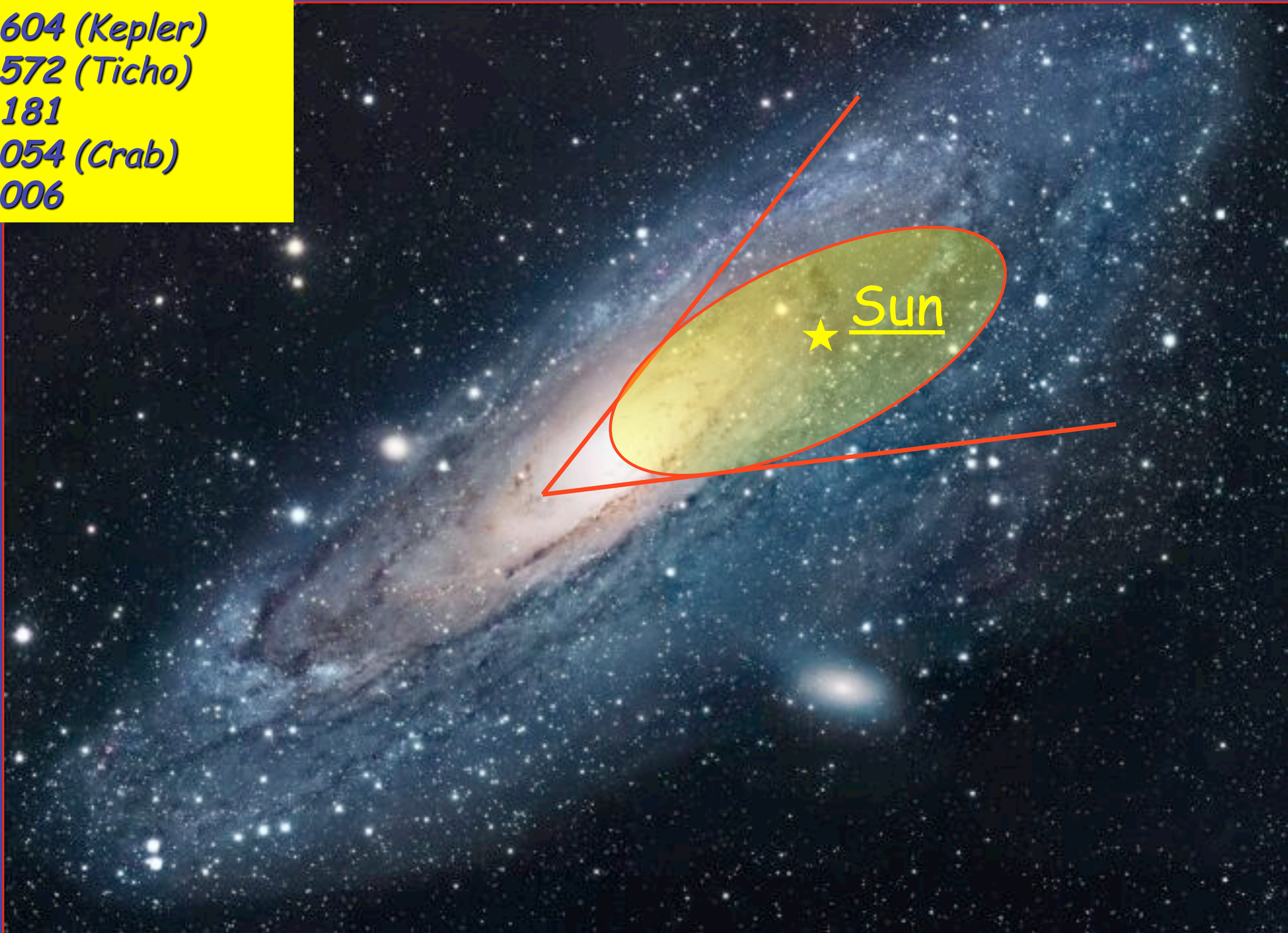
- temperatura di 10^{10} gradi, fotoni di alta energia
- Curva dell'energia di legame dei nucleoni nei nuclei
- Non possono aver luogo ulteriori trasformazioni nucleari esotermiche
- Fotodisintegrazione endotermica del Fe



$$\gamma + {}^{56}_{26}Fe \rightarrow 13\ {}^{4}_{2}He + 4n$$

$$\gamma + {}^{4}_{2}He \rightarrow 2p + 2n$$

1604 (Kepler)
1572 (Ticho)
1181
1054 (Crab)
1006



Supernove di tipo II

- Condizioni fisiche della presupernova

$$T_c \approx 8\times 10^9\ \mathrm{K} \quad \rho_c \approx 10^{10}\ \mathrm{g\,cm^{-3}}$$

- Collasso gravitazionale del core di stelle massive (1.3 $M_\odot$ ≈ 2.5 $M_\odot$) in seguito alla fotodissiciazione dei nuclei di Ferro
- Neutronizzazione e emissione di neutrini, intrappolati nell'inviluppo

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

- Energia liberata: ≈ 10^{53} erg

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

Collasso stellare

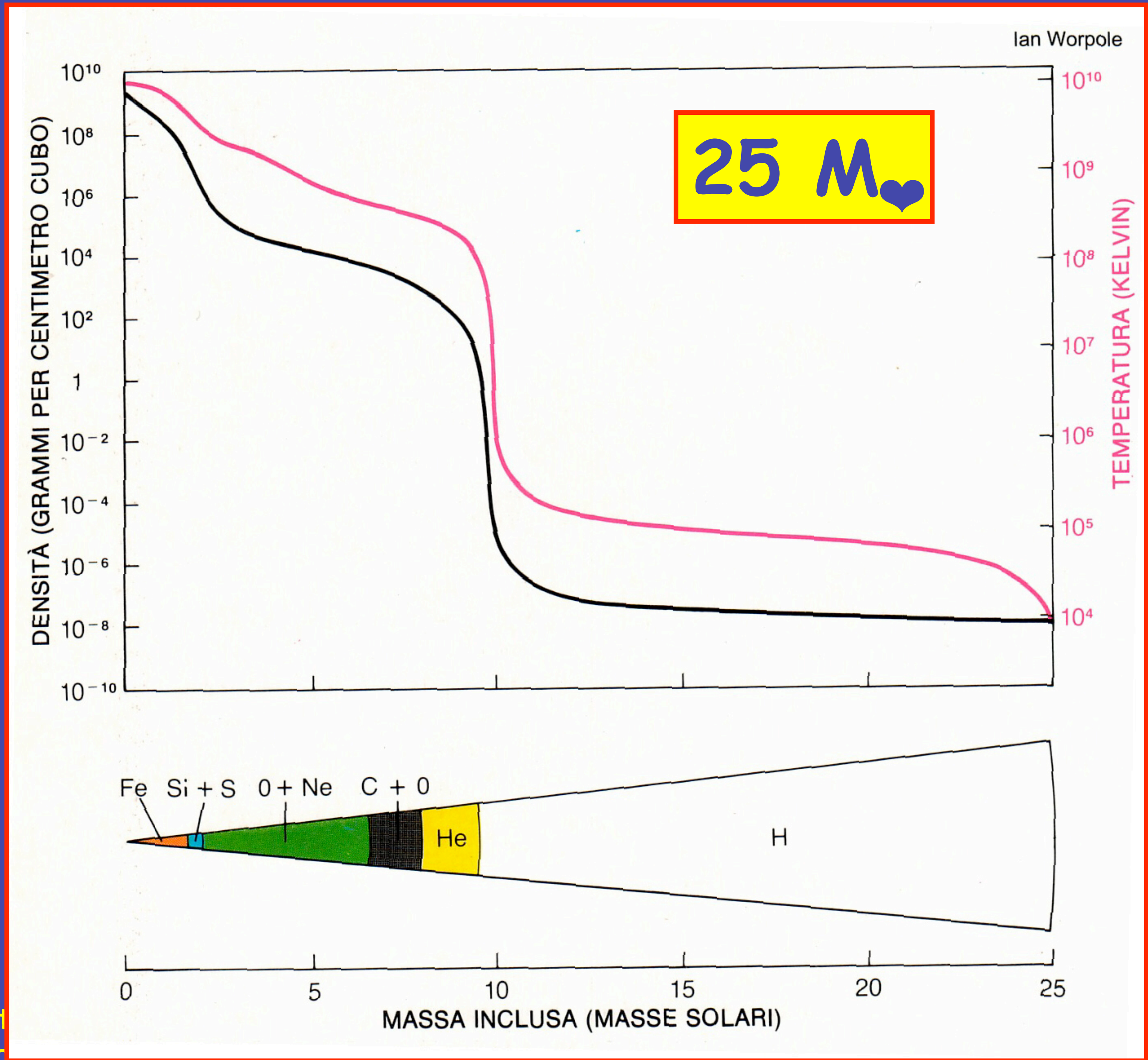
Il collasso stellare è inevitabile quando la massa del core M_C supera la massa di Chandrasekhar

$$M_{Ch} = 5.8 \cdot Y_e^2 M_O \approx 1.44 M_O$$

M_C aumenta per il bruciamento dei gusci intorno al core, M_{Ch} diminuisce perchè diminuisce Y_e in seguito a processi di neutronizzazione, creazione e annichilazione di coppie e fotodissociazione:

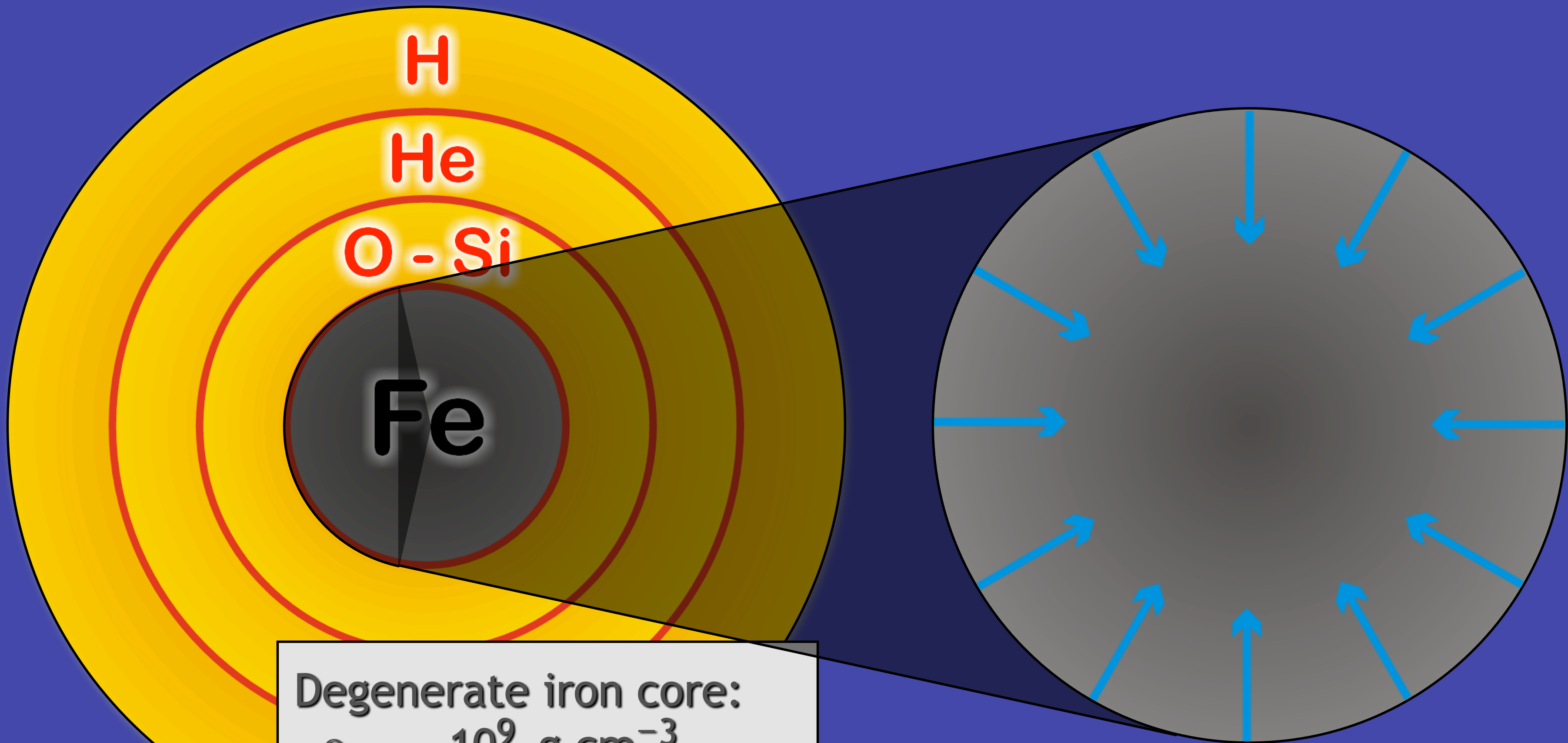
$$e^- + p \rightarrow n + \nu_e, \quad \gamma + \gamma \rightarrow e^+ e^- \rightarrow \nu_e + \overline{\nu}_e,$$

$$\gamma + {}^{56}Fe \rightarrow 13\,{}^4He + 4n, \quad \gamma + {}^4He \rightarrow 2p + 2n$$


Ian Worpole
25 M☉
DENSITÀ (GRAMMI PER CENTIMETRO CUBO)
10¹⁰
10⁸
10⁶
10⁴
10²
1
10⁻²
10⁻⁴
10⁻⁶
10⁻⁸
10⁻¹⁰
TEMPERATURA (KELVIN)
10¹⁰
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
Fe
Si + S
0 + Ne
C + 0
He
H
0
5
10
15
20
25
MASSA INCLUSA (MASSE SOLARI)

Onion structure

Collapse (implosion)



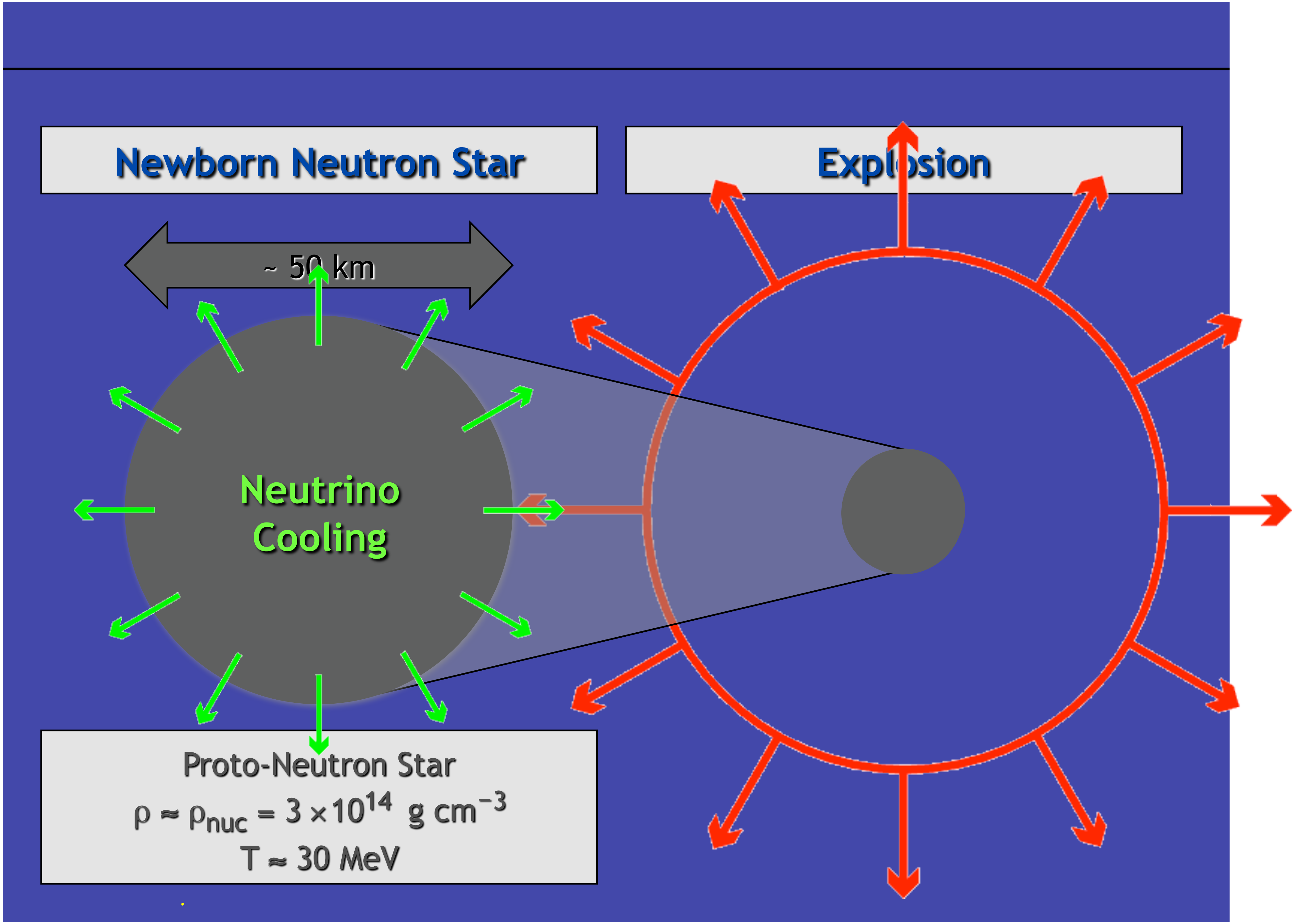
Degenerate iron core:

$\rho \approx 10^9$ g cm^{-3}

$T \approx 10^{10}$ K

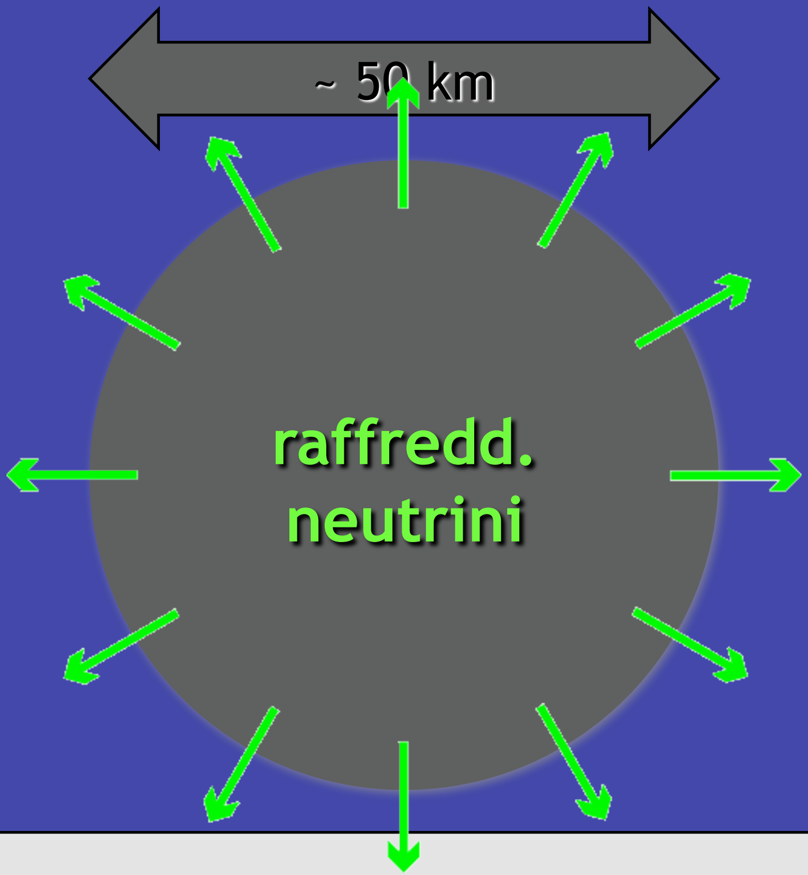
$M_{Fe} \approx 1.5\ M_{sun}$

$R_{Fe} \approx 8000$ km



Newborn Neutron Star
Explosion
~ 50 km
Neutrino
Cooling
Proto-Neutron Star
$\rho \approx \rho_{nuc} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$
$T \approx 30$ MeV

Stella di neutroni neonata



$$\rho \approx \rho_{nuc} = 3 \times 10^{14} \text{ g cm}^{-3}$$
$$T \approx 30 \text{ MeV}$$

Gravitational binding energy

$E_b \approx 3 \times 10^{53}$ erg $\approx$ 17% $M_{SUN} c^2$

emissione

99% Neutrini

1% Energy dell'eplosione
(di cui 1% in raggi cosmici)

0.01% luce, più della Galassia stessa

Luminosità in neutrini

$L_\nu \approx 3 \times 10^{53}$ erg / 3 sec
$\approx 3 \times 10^{19} L_{SUN}$

durante l'esplosione, la luminosità è superiore a quella dell'intero universo

Binding energy emitted as

99% Neutrinos of all flavors

1% Kinetic energy

0.01% Optical luminosity

$$M_C \geq M_{Ch} = 5.76 Y_e^2 M_0$$

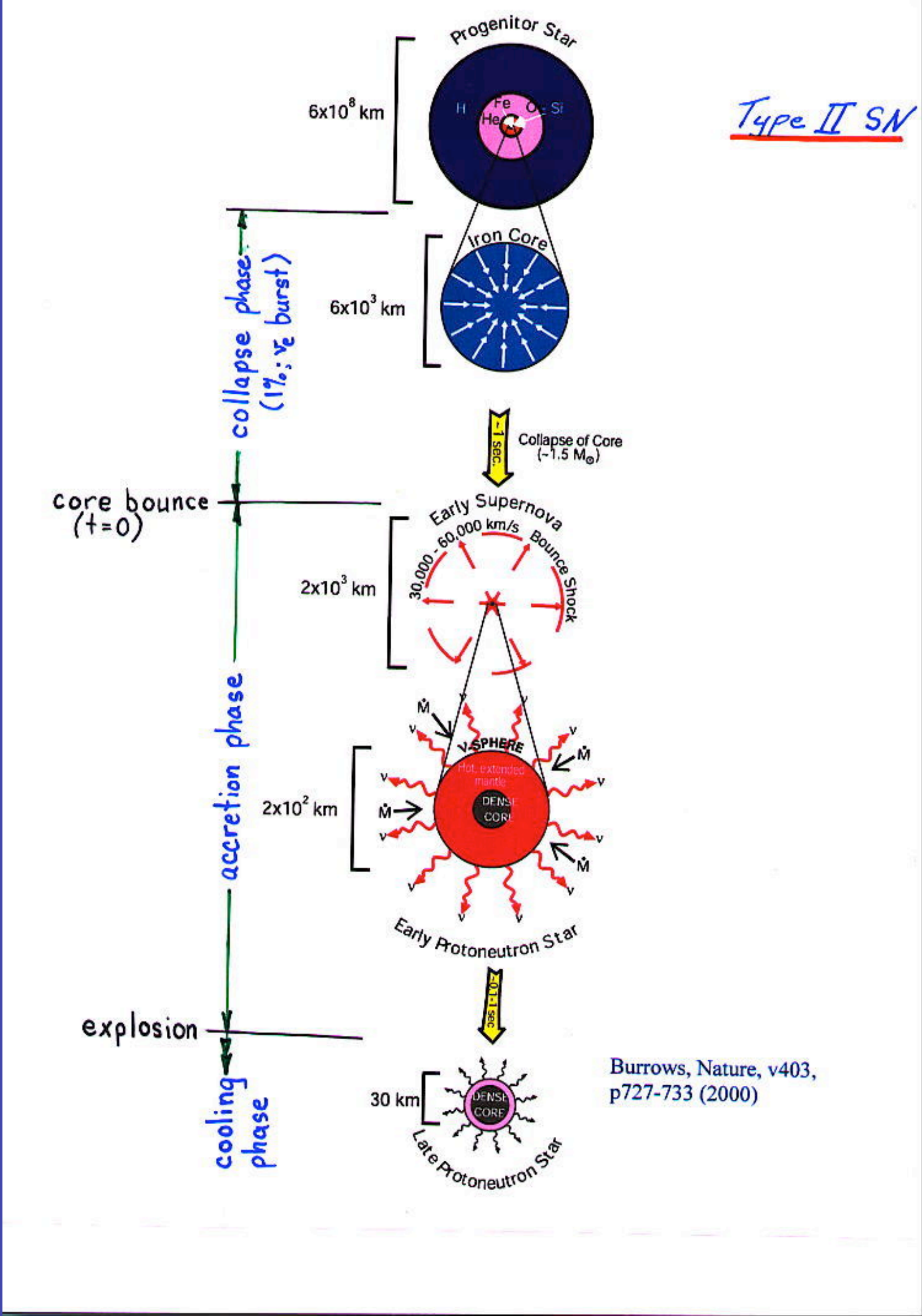
$$e^- + p \rightarrow n + \nu_e$$

$$\gamma + \gamma \rightarrow e^+ + e^- \rightarrow \nu_x + \overline{\nu_x}$$

$$\gamma + {}^{56}Fe \rightarrow 13\,{}^4He + 4n$$

$$\lambda_\nu = \frac{1}{n\sigma}$$

$$\Delta E_B = \frac{GM^2}{R_{ns}} - \frac{GM^2}{R_c}$$



Neutrini da collassi stellari

In un core stellare con $M_C \sim M_{Ch}$ ci sono ~ 10^{57} elettroni; quindi il numero massimo di neutrini da neutronizzazione emessi è 10^{57}. Poichè la loro energia media è ~ 10 MeV = 10^{-12} J, in totale l'energia emessa in questa fase è circa 10^{45} J, ossia ~ 10^{-2} $M_C \cdot c^2$.

L'energia emessa in neutrini durante i processi di annichilazione e^+e^- è ~ 20-30 volte maggiore, ossia ~$3 \cdot 10^{46}$ J. Per un collasso al centro della Galassia (d~8.5 kpc) il flusso di ν_e e $\bar{\nu}_e$ a Terra è:

$$\Phi(\nu_e, \bar{\nu}_e) = \frac{\Phi_0(\nu_e, \bar{\nu}_e)}{6 \cdot 4\pi d^2} \approx 10^{16} (\nu_e, \bar{\nu}_e) \text{ m}^{-2}$$

Spettro di Fermi-Dirac

$$\frac{dN}{dE_\nu} = \frac{E_\nu^2}{\left(1 + e^{E_\nu/kT}\right)} e^{-\alpha(E_\nu/kT)^2}$$

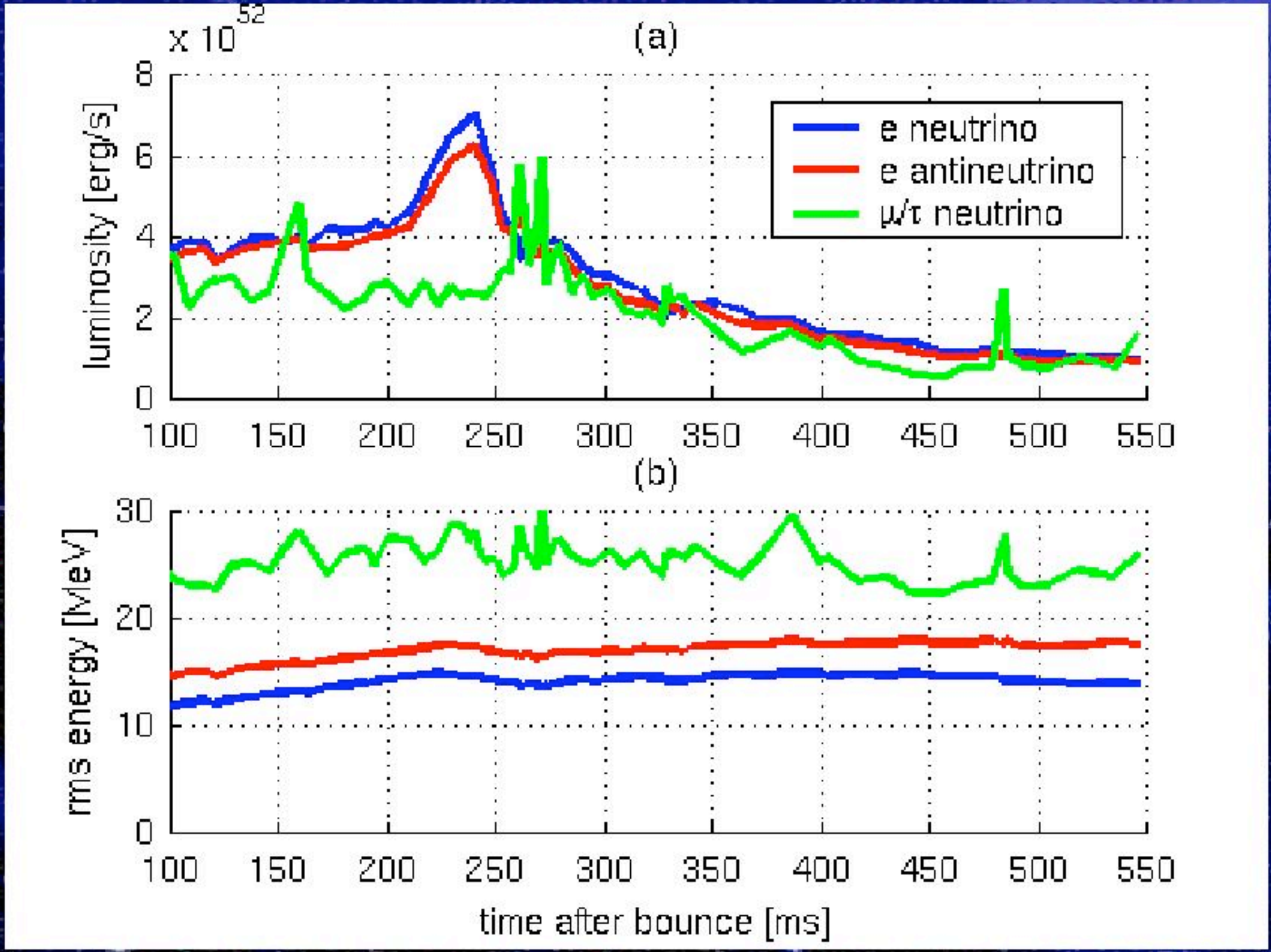
$$< E > = \frac{\int_0^\infty E \frac{dN}{dE} dE}{\int_0^\infty \frac{dN}{dE} dE} = \frac{kT \int_0^\infty x \frac{x^2}{1+e^x} dx}{\int_0^\infty \frac{x^2}{1+e^x} dx} = kT \frac{F_3(x)}{F_2(x)} = 3,15 kT$$

Numero di eventi attesi in un rivelatore

$$N(\tau, E_{th}, d) = q \cdot E_{Tot} \frac{N_p}{4\pi d^2} \int_0^\tau dt \int_{E_{th}}^\infty \frac{d\sigma}{E_\nu dE_\nu} dE_\nu$$

Luminosities
RMS Energies

$$\chi_\nu = \frac{1}{n\sigma}$$



The possibility to observe the neutrino burst depends on background conditions

Sources of background

Cosmic rays $0 < E < \infty$

a) muons

b) secondary particles generated by muons (e, γ, n and long-life isotopes)

c) the products of nuclear reactions and electromagnetic interactions

Natural radioactivity $E < 30$ MeV, mainly $E < 2.65$ MeV

Background reduction

Deep underground location

Low radioactivity materials

Anti-coincidence system

Coincidence of signals in several detectors

Fase del collasso	1	2	3
Energia totale in neutrini (10^{53} erg)	0,1	1,7	3
Energia media dei neutrini (MeV)	12	14	15
Durata temporale (s)	0,04	3,1	15

1. Formazione del core opaco ai neutrini (**neutrinosfera**).
2. Accrescimento dell'inviluppo sul core.
3. Raffreddamento Kelvin della neonata stella di neutroni calda.

kT (MeV)	E_{th} (MeV)	t (s) 0,01	0,1	1	10	≥ 25
3	5	0,15	2,55	9,3	24,4	35,3
	10	0,08	1,33	4,8	12,7	18,3
	15	0,02	0,39	1,4	3,7	5,4
	20	0,00	0,07	0,3	0,7	1,0
4	5	0,23	4,0	14,5	38	55
	10	0,17	3,0	10,9	29	41
	15	0,09	1,6	5,7	15	22
	20	0,04	0,6	2,2	5,9	8,5
5	5	0,31	5,3	19	51	73
	10	0,27	4,6	16,7	44	64
	15	0,19	3,2	11,7	31	45
	20	0,11	1,8	6,6	17	25

Main interactions in scintillator

- Inverse β decay:

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

- Neutrino-elettron scattering:

  $\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^-$

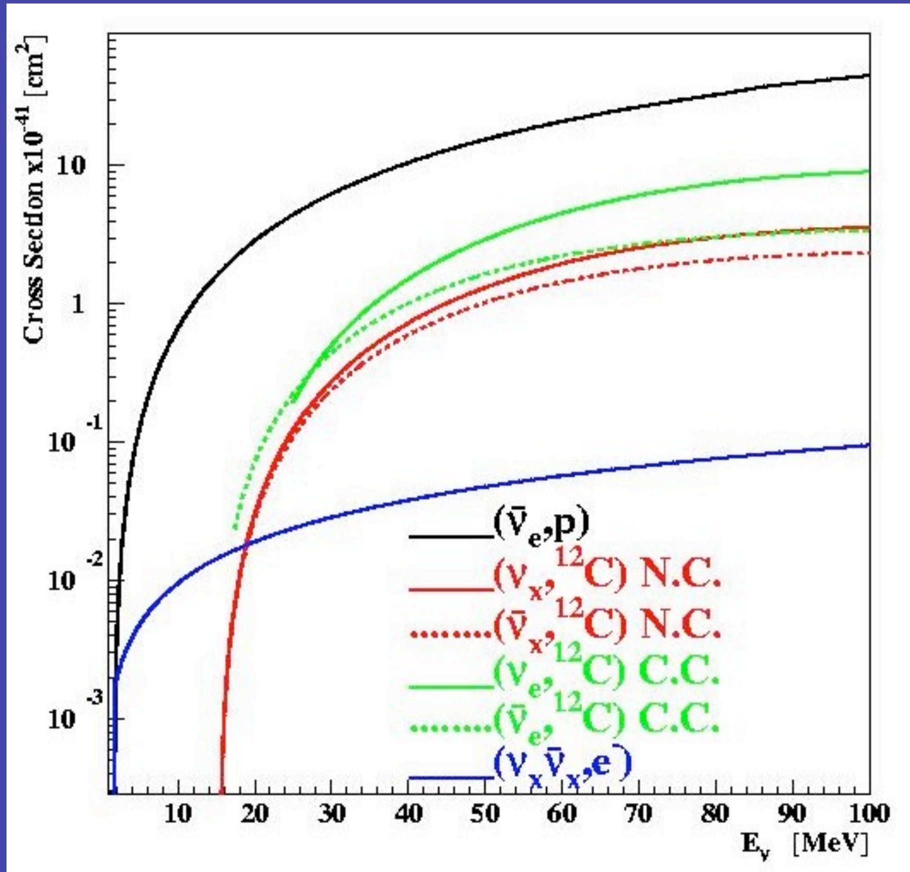
- Neutral currents interactions:

  $\nu_{e,\mu,\tau}(\bar{\nu}_{e,\mu,\tau}) + {}^{12}C \rightarrow \nu_{e,\mu,\tau}(\bar{\nu}_{e,\mu,\tau}) + {}^{12}C^*$

- Charged currents interactions:

  $\bar{\nu}_e + {}^{12}C \rightarrow {}^{12}B + e^+$

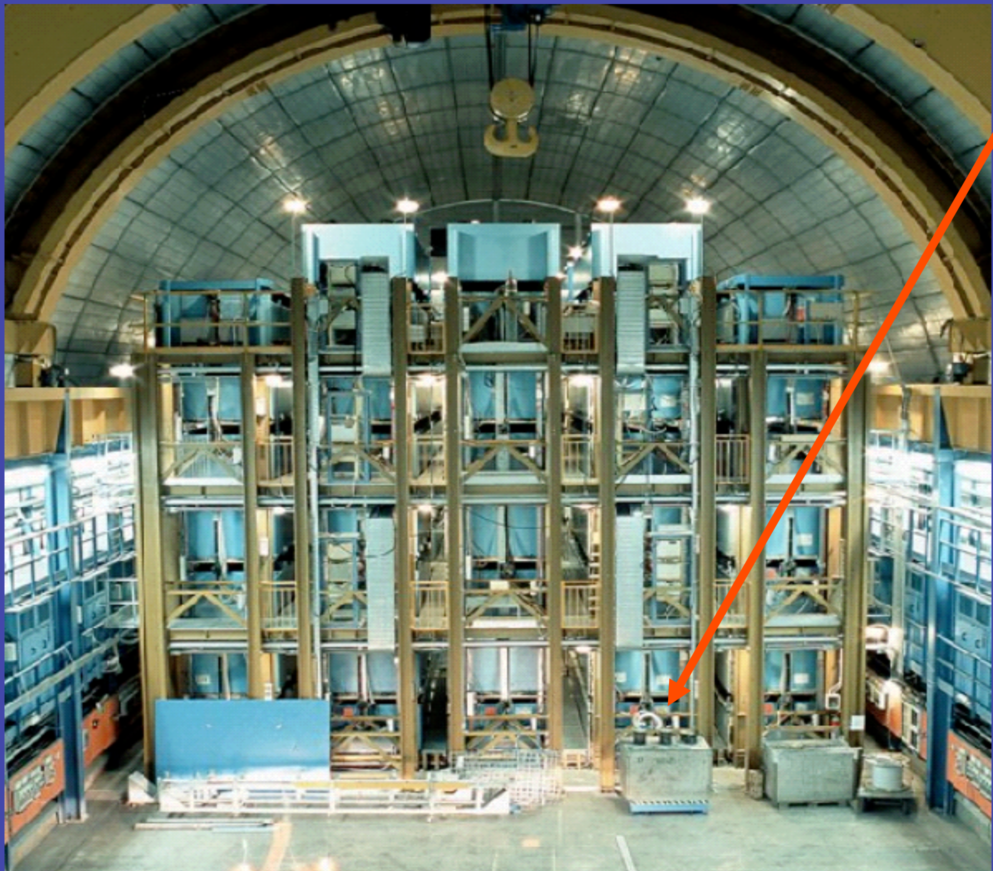
  $\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$



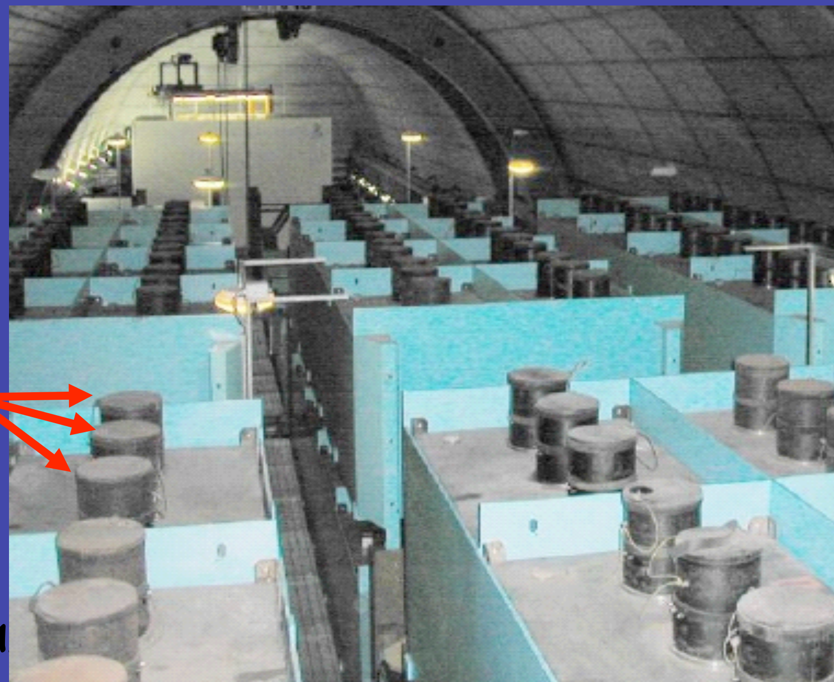
$$\sigma(\nu_e + e) = 10^{-44}\left(\frac{E_\nu}{\mathrm{MeV}}\right)\ \mathrm{cm}^2$$

$$\sigma(\nu_e + n) = \sigma(\bar{\nu}_e + p) = 9 \cdot 10^{-44}\left(\frac{E_\nu}{\mathrm{MeV}}\right)^2\ \mathrm{cm}^2$$

The LVD detector



840 scintillator counters, 1.5 m^3 each, are inserted in modules holding 8 counters each.
The modules are grouped and stacked together to form three towers of 35 modules each.

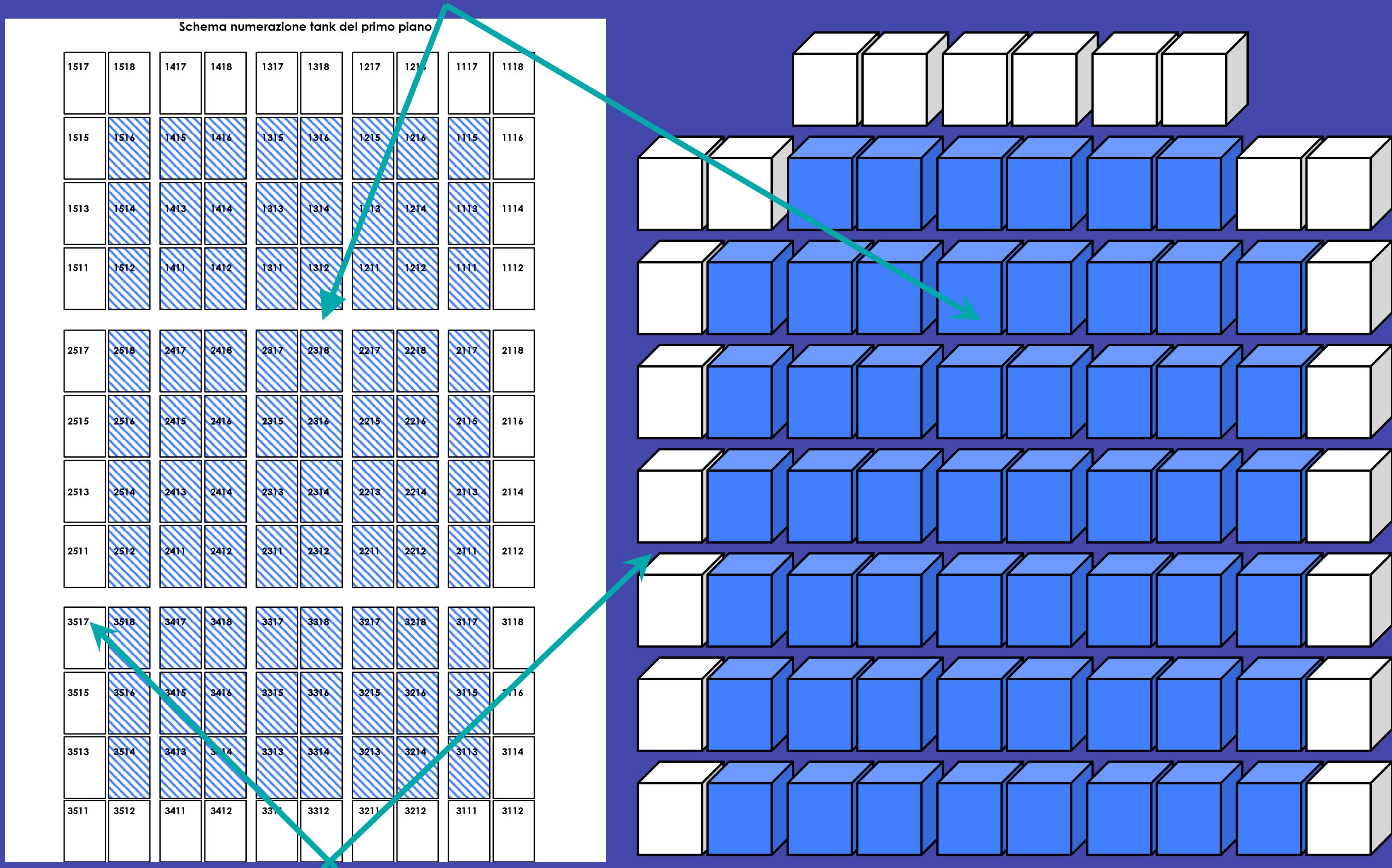


The scintillator of ach counter (1.2 tons) is watched from the top by 3 PMTs (15 cm diameter).

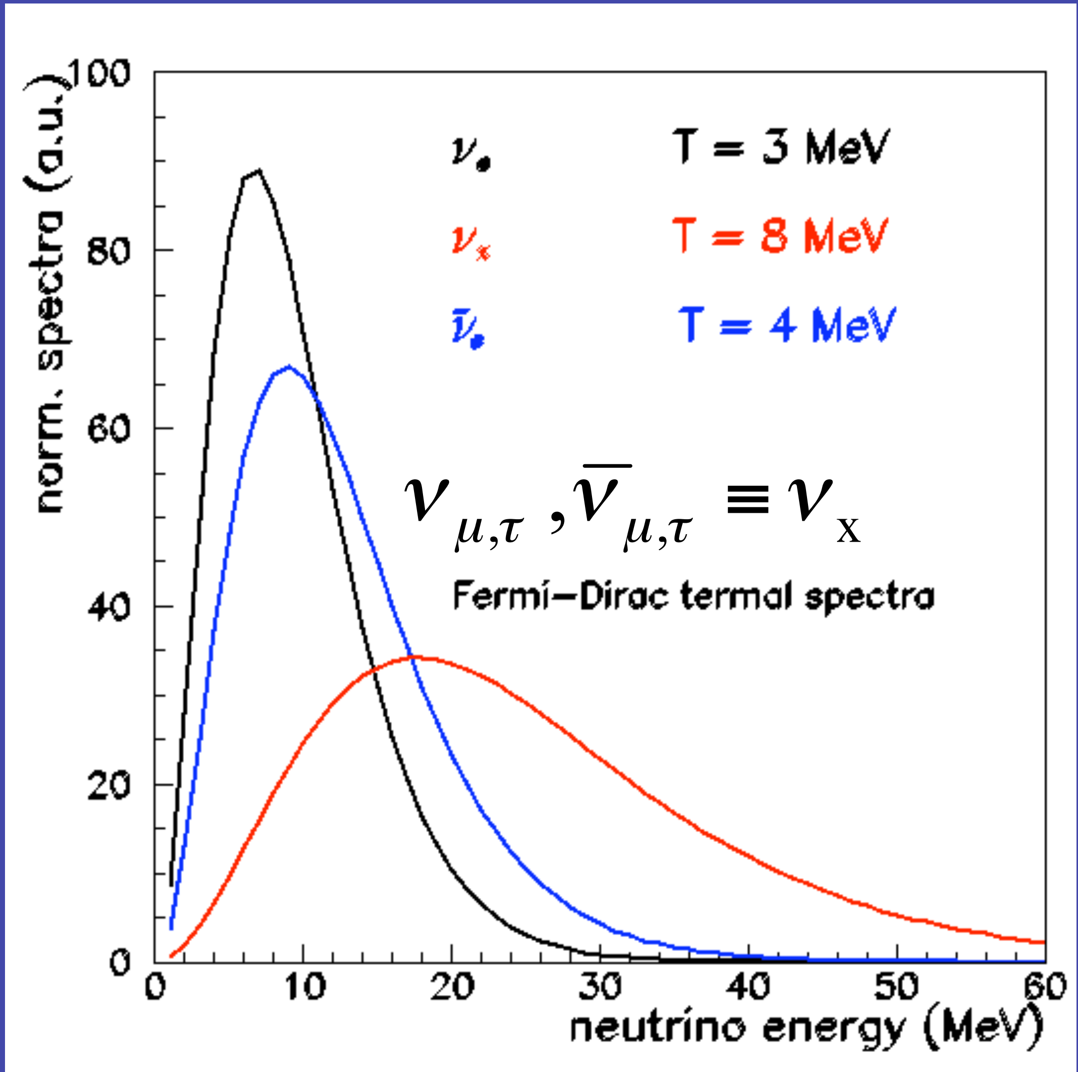
Topology

INTERNAL Counters (M=570 tons)
EXTERNAL Counters (M=430 tons)

TOP VIEW



FRONT VIEW

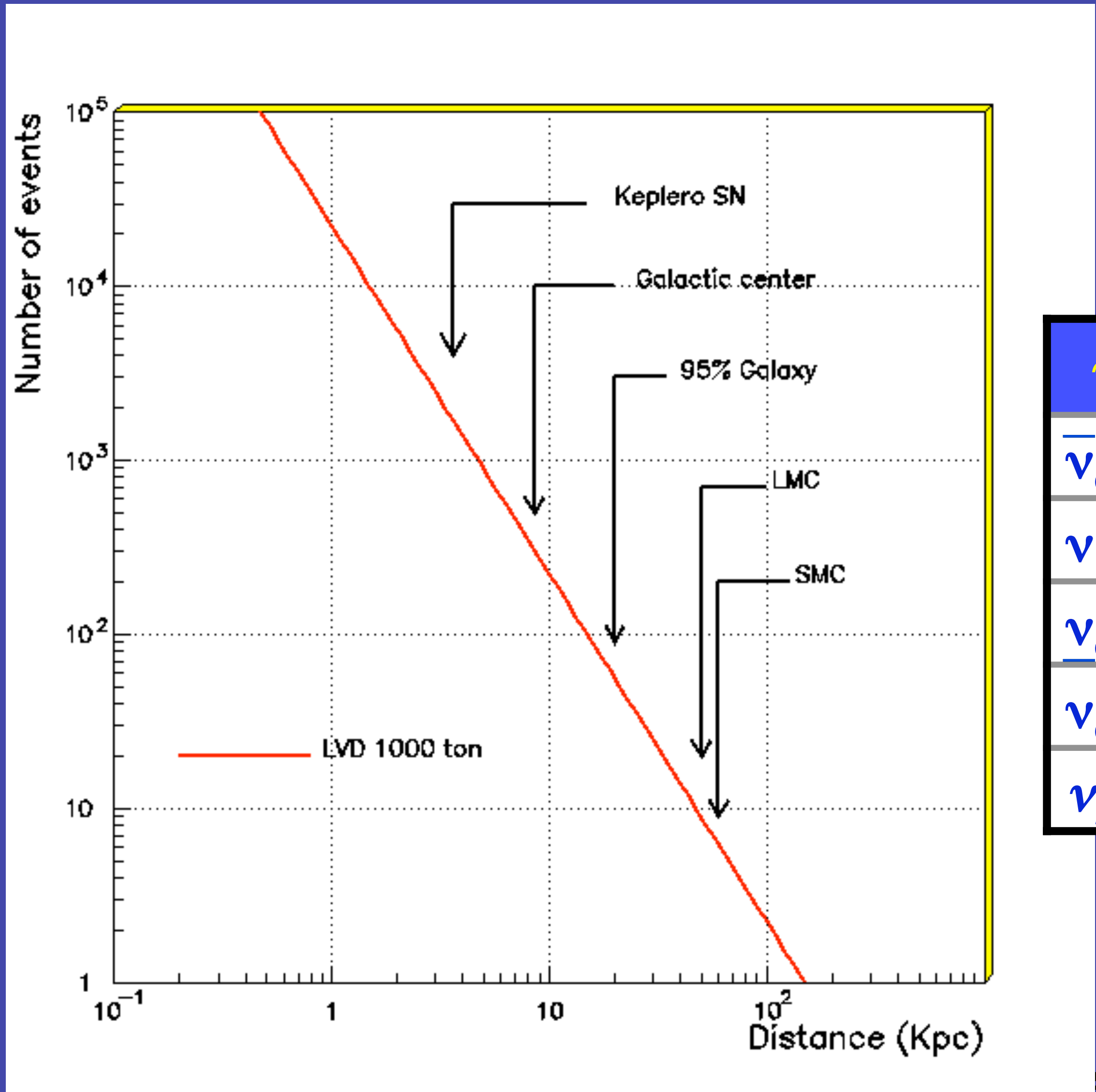


- Quasi-thermal (Fermi -Dirac) neutrino energy spectra from inner layers of collapsing star (neutrinospheres).
- Uncertainties on values of temperatures.
- Typically

$$T_{\nu_e} \leq T_{\bar{\nu}_e} < T_{\nu_x}$$

Typical energy scale ≈ 0-50 MeV

ν Burst Detection in LVD



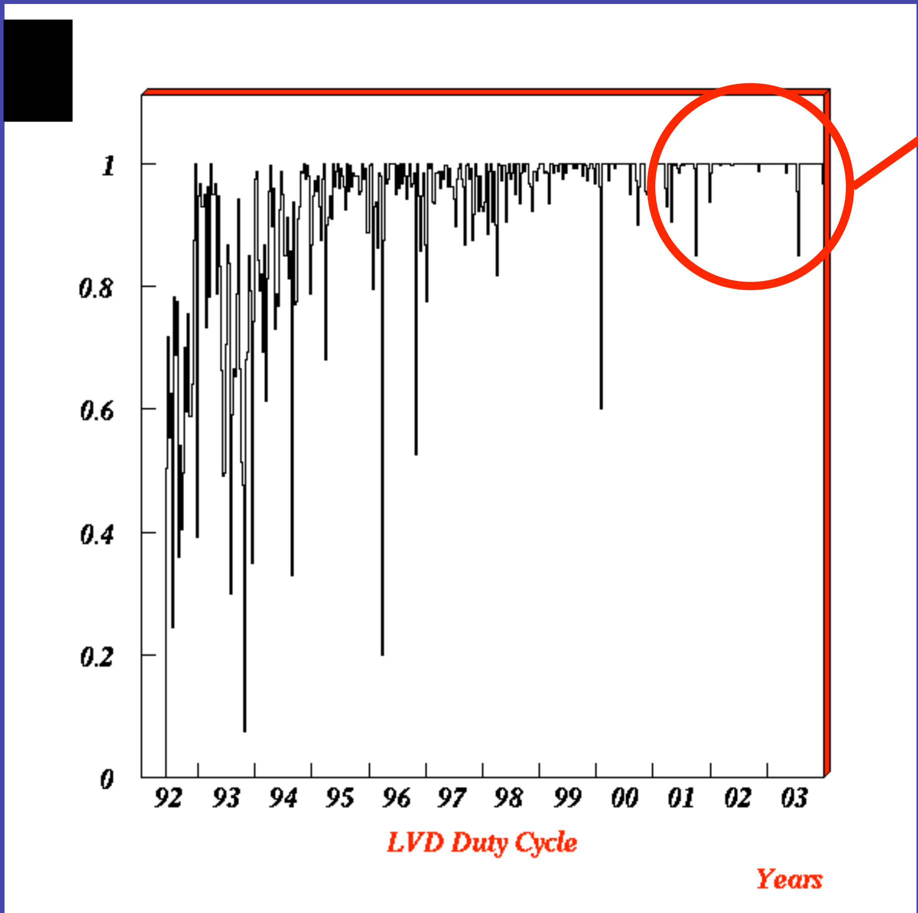
$\bar{\nu}_e$ tagging through detection of delayed γ from n capture at low energy threshold, efficiency 60%.

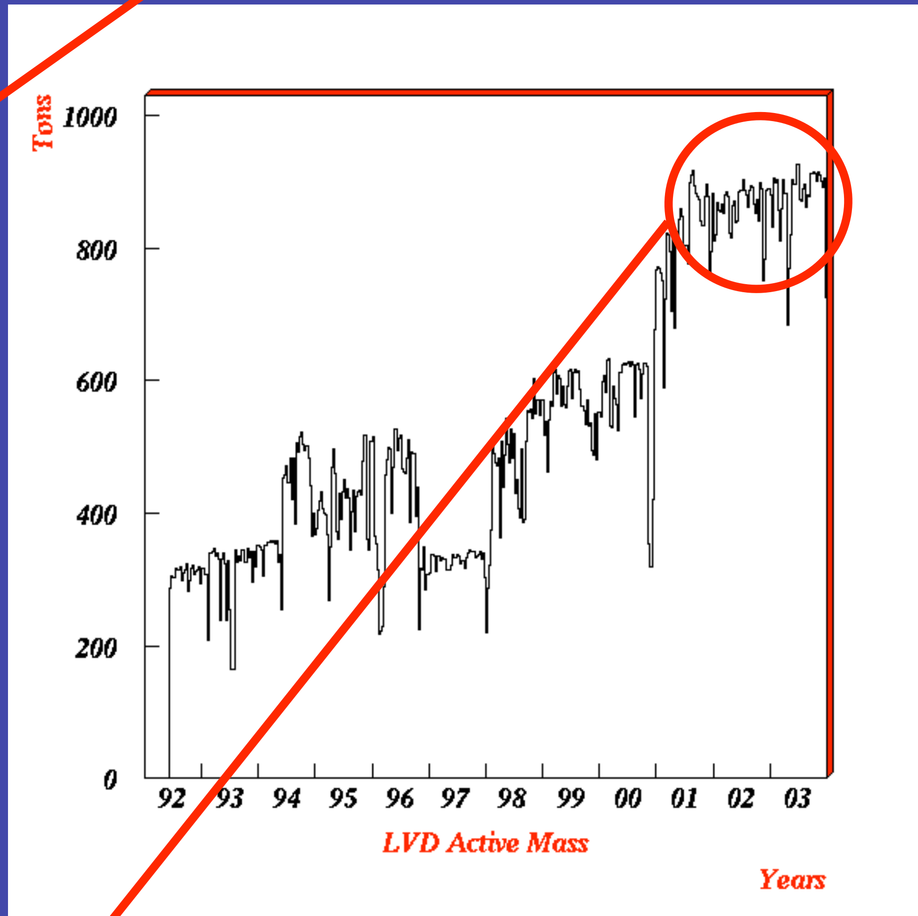
ν interactions in LVD
$\bar{\nu}_e + p \to n + e^+$
$\nu_i\,(\nu_x) + e^- \to \nu_i\,(\nu_x) + e^-$
$\nu_e + {}^{12}C \to {}^{12}N + e^-$
$\bar{\nu}_e + {}^{12}C \to {}^{12}B + e^+$
$\nu_i\,(\nu_x) + {}^{12}C \to \nu_i(\nu_x) + \gamma + {}^{12}C$

NC and CC interactions on carbon nuclei: potentially useful for ν oscillation studies.

LVD 10 years

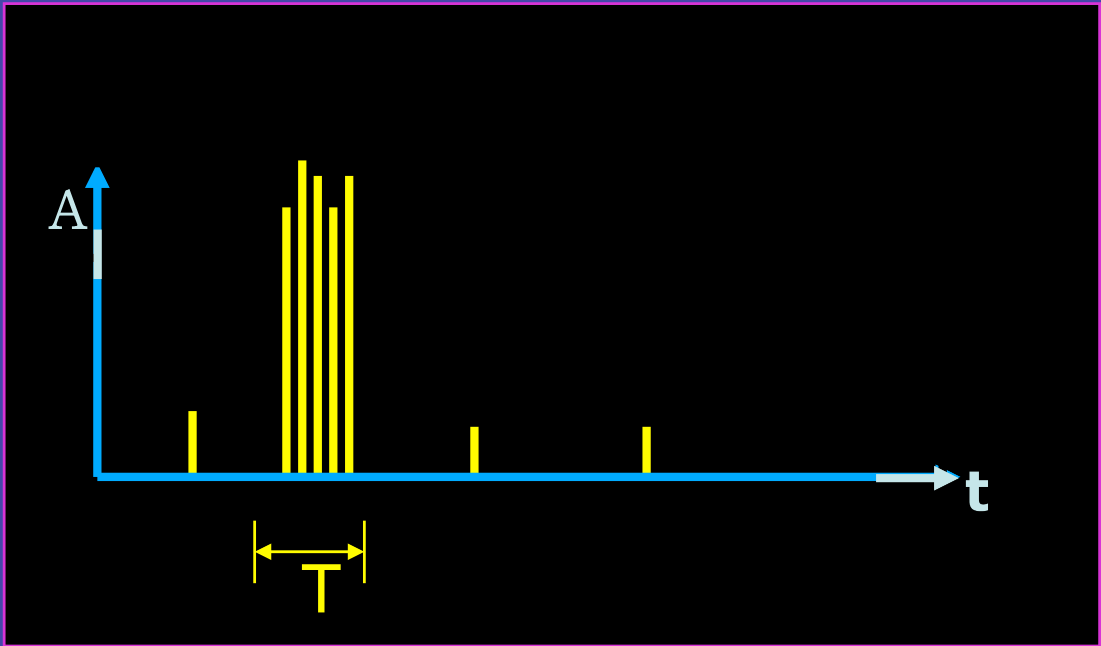
High duty cycle (>99.5% since 2002)





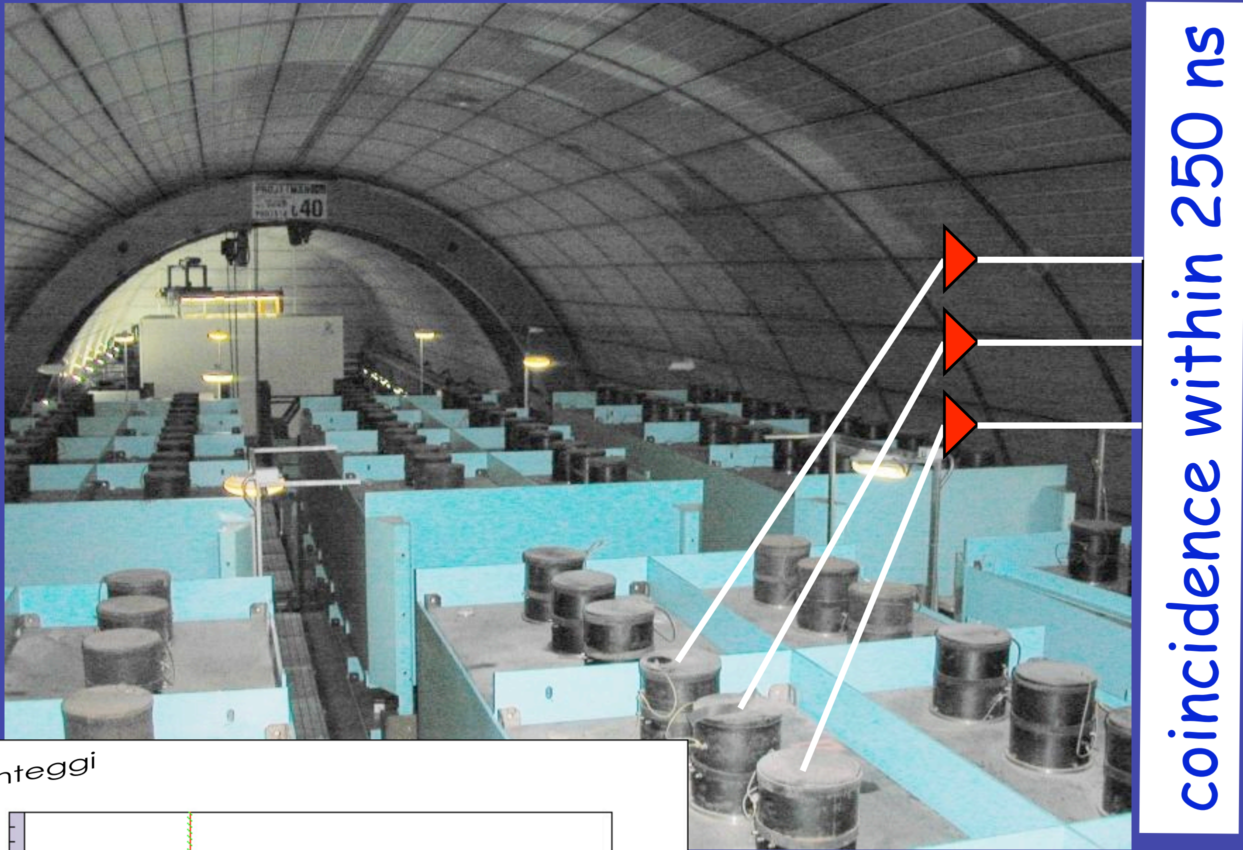
Fiducial Active Mass (M~ 900 tons since Jun/2001)

How can the neutrino burst be identified ?



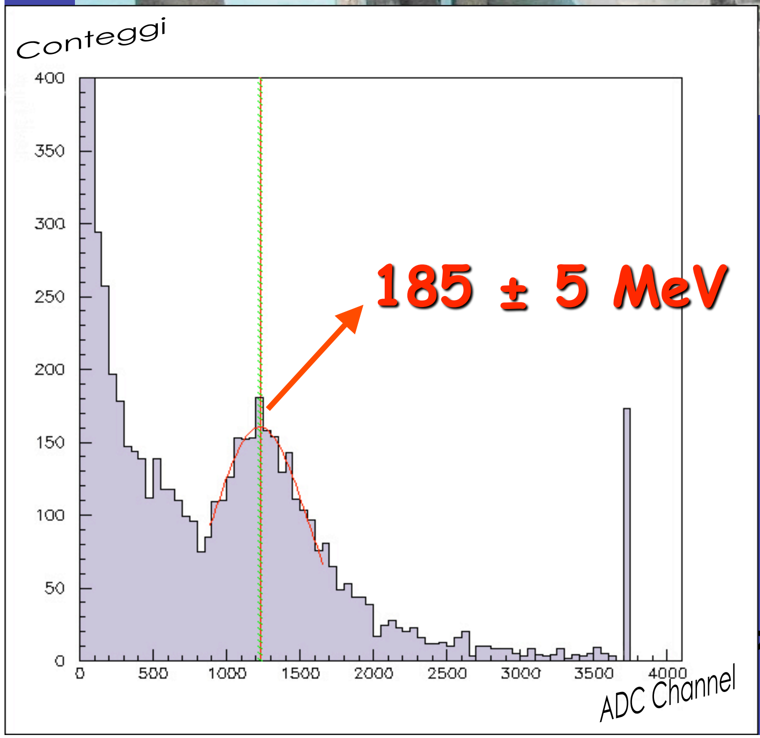
Detection of a burst of N pulses in a short time interval T

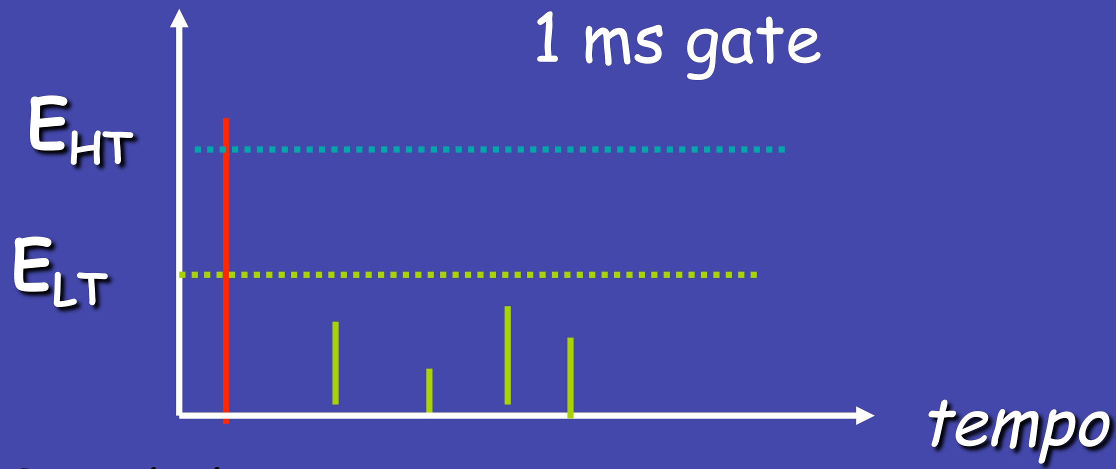
$$N \sim \frac{1}{4\pi R^2} \cdot \sum_i \int_{E_{thr}}^{\infty} I_{\nu_i}(E_{\nu_i}) \cdot \sigma(E_{\nu_i}) dE \cdot M$$

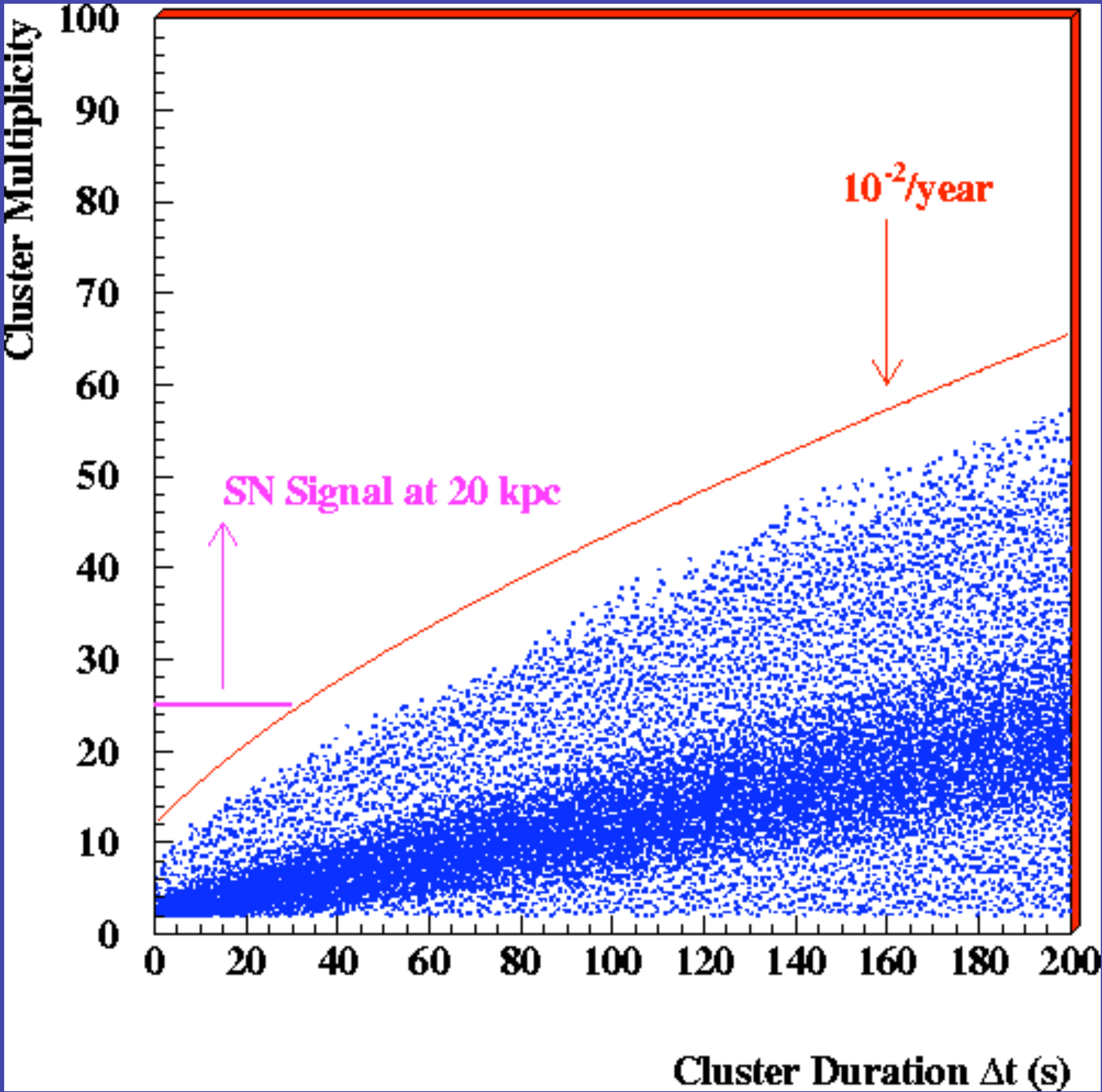


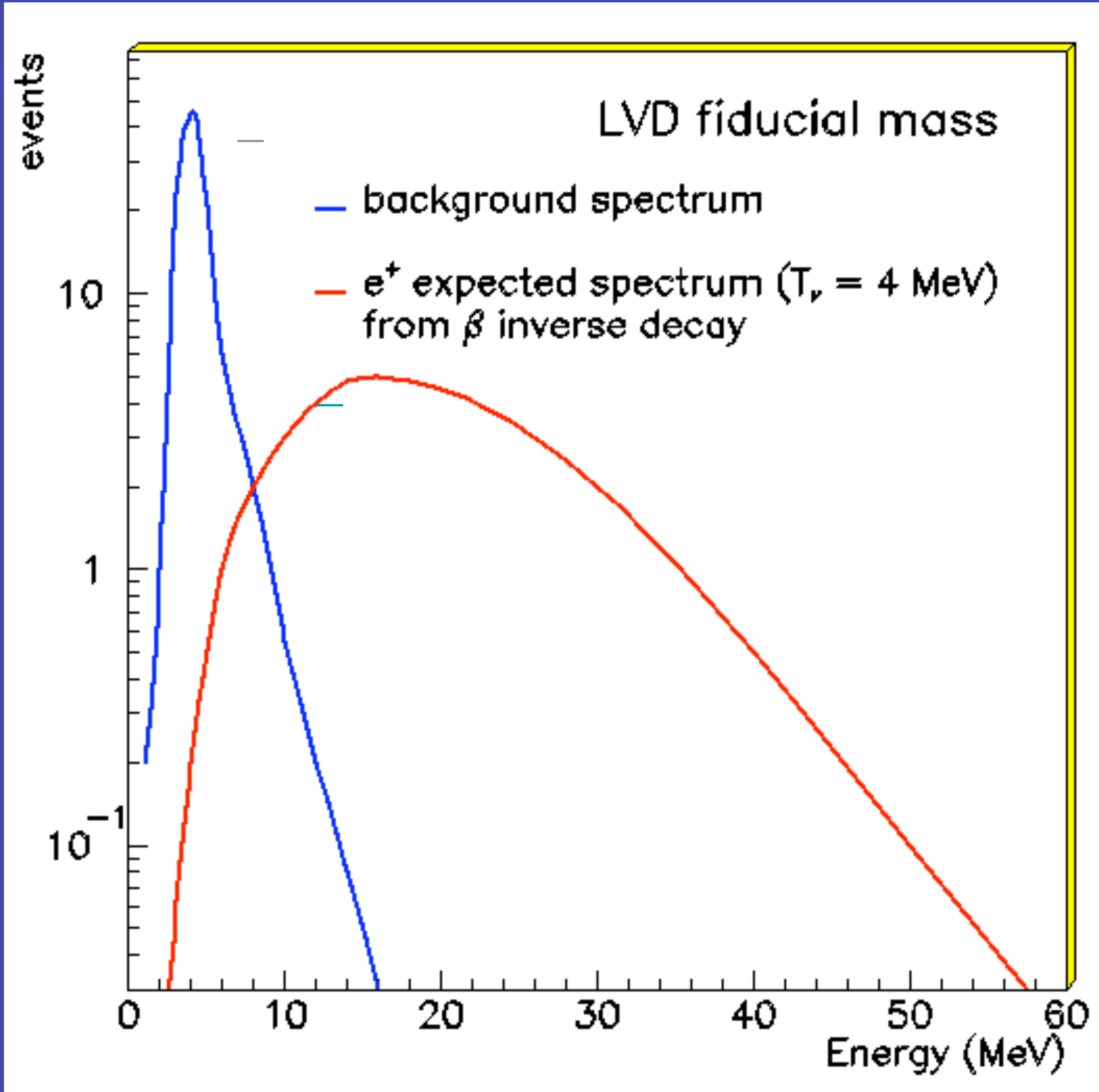
After a HT pulse a 1 ms gate is opened lowering thresholds (E > 0.6 MeV) to allow detection of γ from n-capture.

Trigger






Cluster Multiplicity
100
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
120
140
160
180
200
10^{-2}/year
SN Signal at 20 kpc
Cluster Duration Δt (s)



Normalized to same number of events! In a 10 s burst, 10 events expected from background.

Galaxy survey

RUN	Since:	To:	Uptime [days]	Duty Cycle	Mass [tonn]	PUBLISHED
RUN 1	Jun 6th '92	May 31st '93	285	60%	310	23rd ICRC 1993
RUN 2	Aug 4th '93	Mar 11th '95	397	74%	390	24th ICRC 1995
RUN 3	Mar 11th '95	Apr 30th '97	627	90%	400	25th ICRC 1997
RUN 4	Apr 30th '97	Mar 15th '99	685	94%	415	26th ICRC 1999
RUN 5	Mar 16th '99	Dec 11th '00	592	95%	580	27th ICRC 2001
RUN 6	Dec 12th '00	Mar 24th '03	821	98%	842	28th ICRC 2003
RUN 7	Mar 25th '03	Feb 4th '05	666	>99%	881	29th ICRC 2005
RUN 8	Feb 5th '05	May 31st '07	846	>99%	936	30th ICRC 2007

LVD ==> *4919 days*

==> *rate of Galactic Gravitational Stellar Collapses*

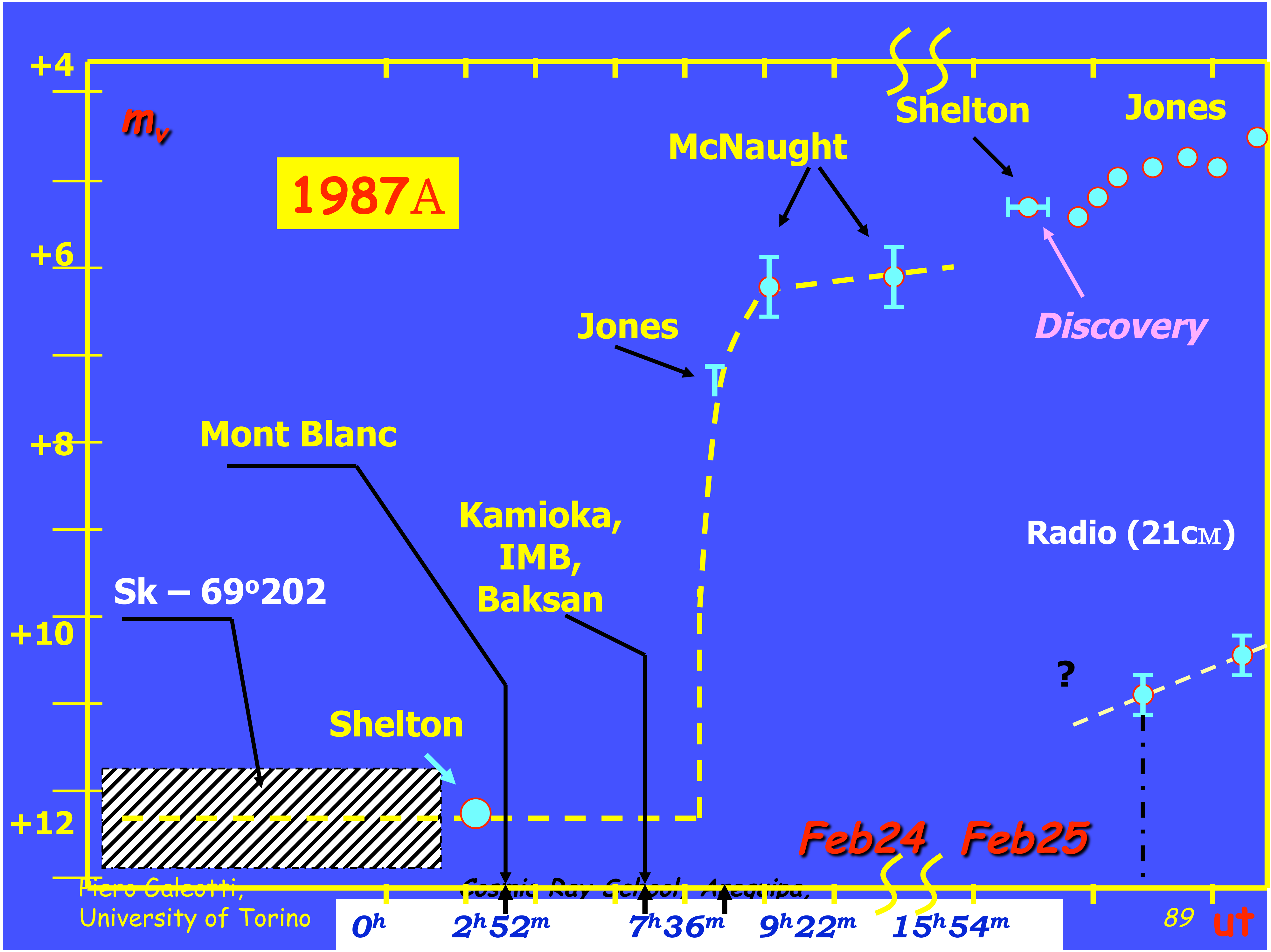
[D≤20kpc] < 0.18 event/year 90% c.l.

SUPER KAMIOKANDE

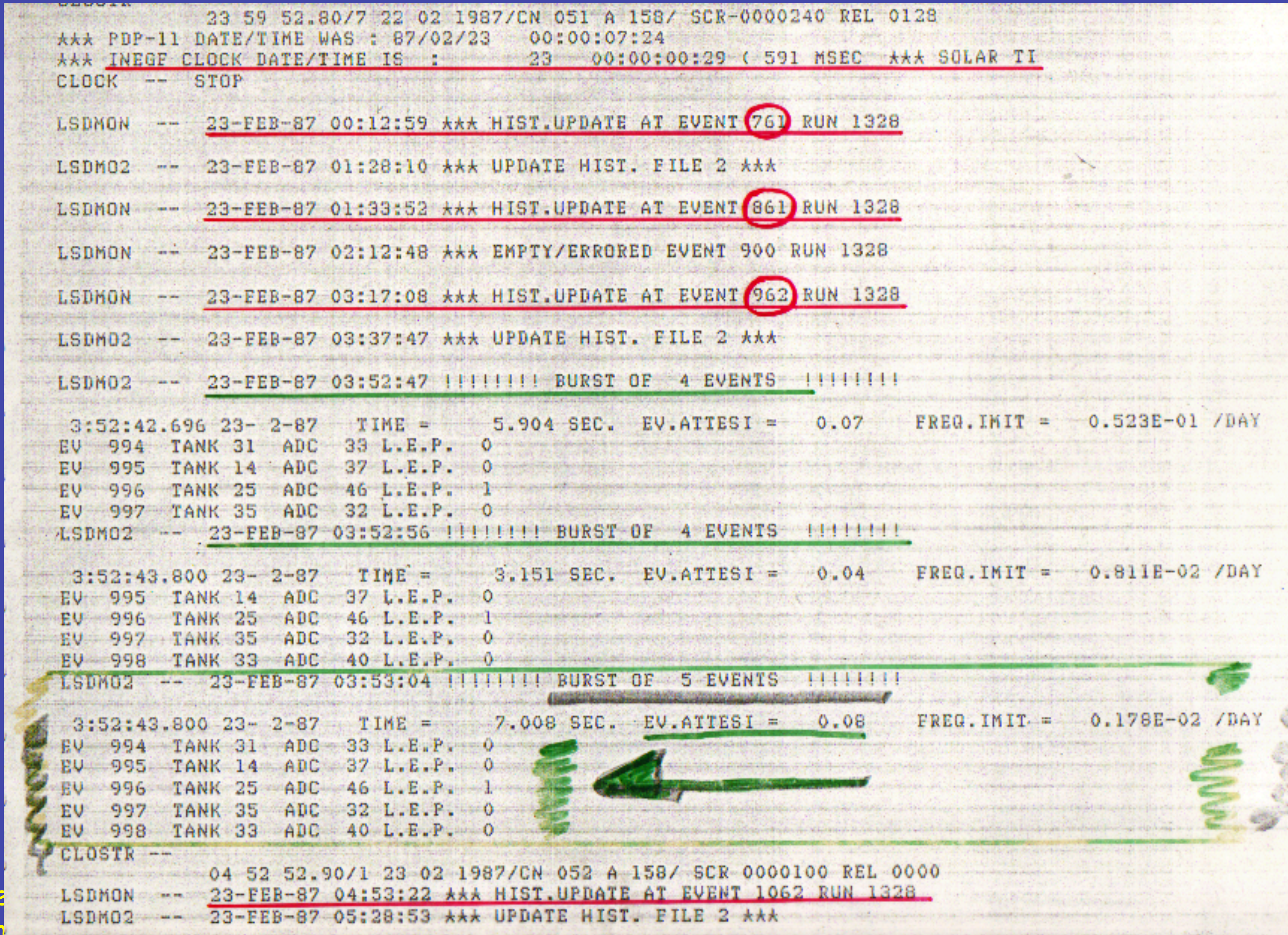
==> *rate of Galactic Gravitational Stellar Collapses*

[D≤100kpc] < 0.32 event/year 90% c.l.


Ian Shelton (U.To)
10" astrograph


1987A
m_v
+4
+6
+8
+10
+12
McNaught
Shelton
Jones
Jones
Discovery
Mont Blanc
Kamioka,
IMB,
Baksan
Radio (21cm)
Sk – 69°202
Shelton
?
Feb24
Feb25
0h
2h52m
7h36m
9h22m
15h54m
ut

On line print of five pulses on 23 febbrury 1987 at 3 hr, 52 min i.t., detected at Mt. Blanc LSD experiment



```
CLOSTR
              23 59 52.80/7 22 02 1987/CN 051 A 158/ SCR-0000240 REL 0128
*** PDP-11 DATE/TIME WAS : 87/02/23    00:00:07:24
*** INEGF CLOCK DATE/TIME IS  :        23   00:00:00:29 ( 591 MSEC  *** SOLAR TI
CLOCK  --  STOP

LSDMON  --  23-FEB-87 00:12:59 *** HIST.UPDATE AT EVENT 761 RUN 1328

LSDM02  --  23-FEB-87 01:28:10 *** UPDATE HIST. FILE 2 ***

LSDMON  --  23-FEB-87 01:33:52 *** HIST.UPDATE AT EVENT 861 RUN 1328

LSDMON  --  23-FEB-87 02:12:48 *** EMPTY/ERRORED EVENT 900 RUN 1328

LSDMON  --  23-FEB-87 03:17:08 *** HIST.UPDATE AT EVENT 962 RUN 1328

LSDM02  --  23-FEB-87 03:37:47 *** UPDATE HIST. FILE 2 ***

LSDM02  --  23-FEB-87 03:52:47 !!!!!!!! BURST OF   4 EVENTS  !!!!!!!!

 3:52:42.696 23- 2-87    TIME =      5.904 SEC.  EV.ATTESI =   0.07     FREQ.IMIT =   0.523E-01 /DAY
EV   994  TANK 31  ADC  33 L.E.P.  0
EV   995  TANK 14  ADC  37 L.E.P.  0
EV   996  TANK 25  ADC  46 L.E.P.  1
EV   997  TANK 35  ADC  32 L.E.P.  0
LSDM02  --  23-FEB-87 03:52:56 !!!!!!!! BURST OF   4 EVENTS  !!!!!!!!

 3:52:43.800 23- 2-87    TIME =      3.151 SEC.  EV.ATTESI =   0.04     FREQ.IMIT =   0.811E-02 /DAY
EV   995  TANK 14  ADC  37 L.E.P.  0
EV   996  TANK 25  ADC  46 L.E.P.  1
EV   997  TANK 35  ADC  32 L.E.P.  0
EV   998  TANK 33  ADC  40 L.E.P.  0
LSDM02  --  23-FEB-87 03:53:04 !!!!!!!! BURST OF   5 EVENTS  !!!!!!!!

 3:52:43.800 23- 2-87    TIME =      7.008 SEC.  EV.ATTESI =   0.08     FREQ.IMIT =   0.178E-02 /DAY
EV   994  TANK 31  ADC  33 L.E.P.  0
EV   995  TANK 14  ADC  37 L.E.P.  0
EV   996  TANK 25  ADC  46 L.E.P.  1
EV   997  TANK 35  ADC  32 L.E.P.  0
EV   998  TANK 33  ADC  40 L.E.P.  0
CLOSTR --
              04 52 52.90/1 23 02 1987/CN 052 A 158/ SCR 0000100 REL 0000
LSDMON  --  23-FEB-87 04:53:22 *** HIST.UPDATE AT EVENT 1062 RUN 1328
LSDM02  --  23-FEB-87 05:28:53 *** UPDATE HIST. FILE 2 ***
```

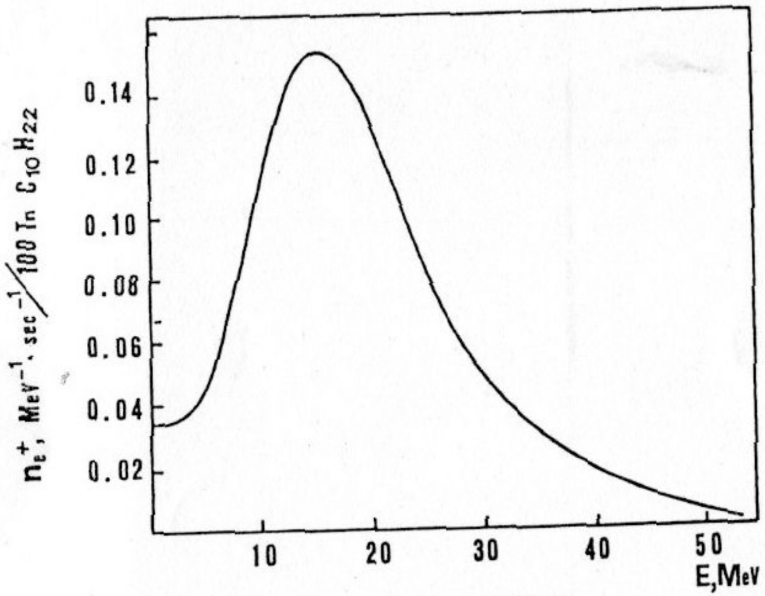


Fig.3

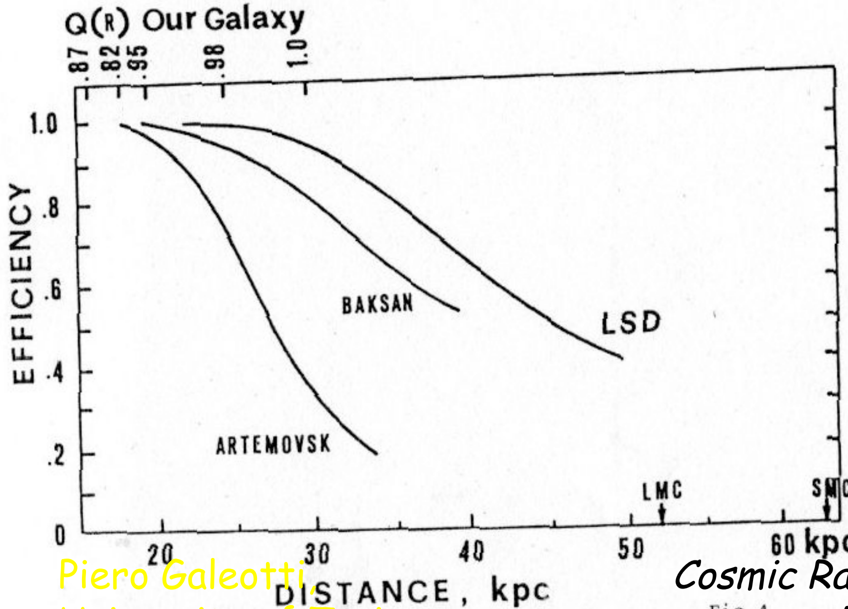


Fig.4

Finally, if the collapse occurs within our Galaxy, a large ammount of information on the dynamics of the collapse and on the physical conditions inside the pre-supernova core can be obtained by observing not only the $\bar{\nu}_e$ through reaction (1), but also the ν_e through the elastic scattering reaction $\nu_e + e^- \rightarrow \nu_e + e^-$, which however produces a lower number of interactions in the detector. The signature of the electron neutrinos is given in LSD by pulses above the high energy threshold of 7 MeV, without any low energy delayed pulse. In this way, since ν_e are emitted as early as the neutronization stage of the collapse, the initial phases of the development of a collapsing star can be study.

4. Solar neutrinos

Since in our apparatus the local radioactivity background from the surrounding rock has been reduced to very low counting rates, we are checking the possibility to detect high energy solar neutrinos from the ^{10}B decay in the Sun, through the elastic scattering reaction with the electrons of our detector.

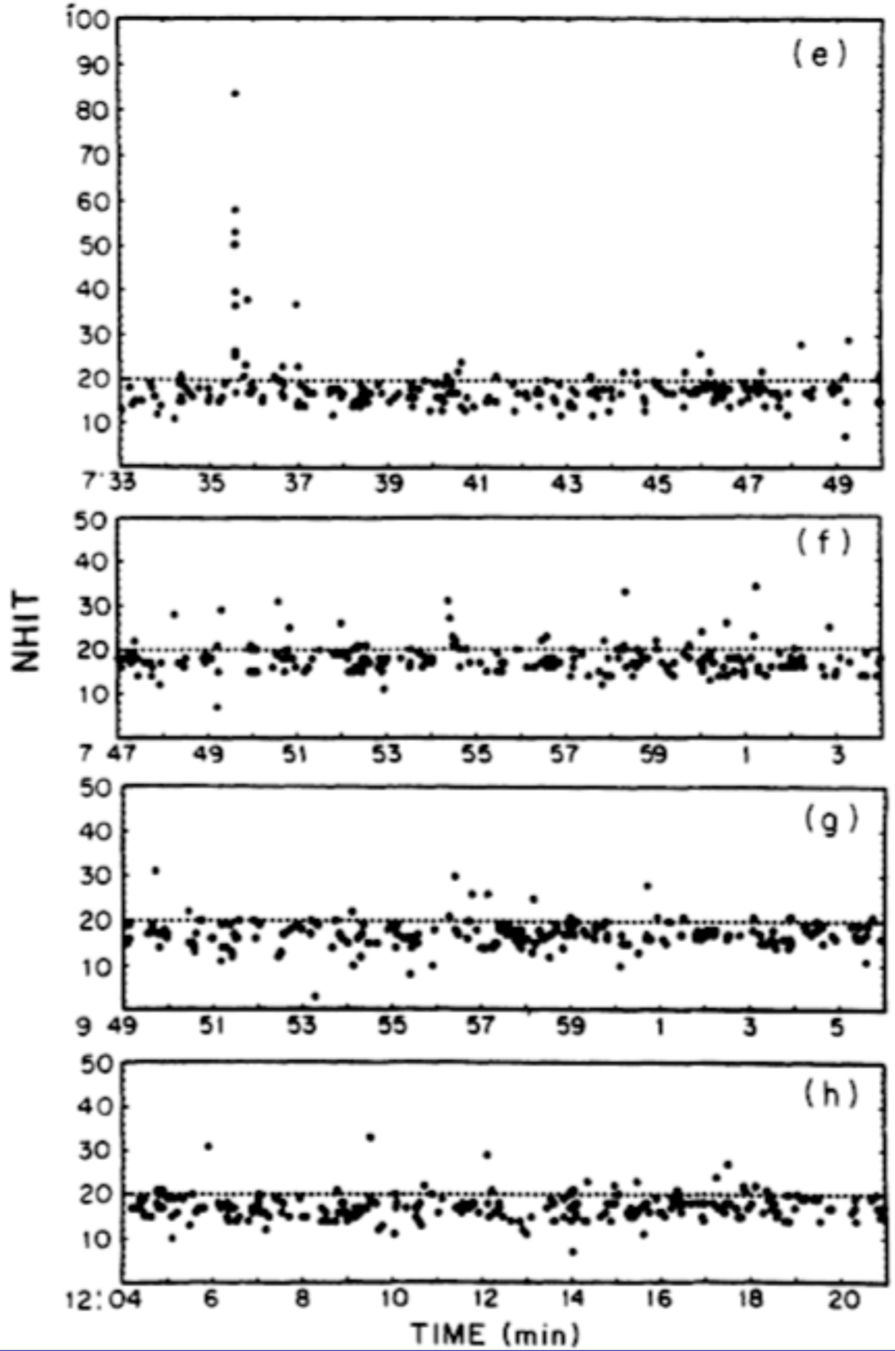
By using the present limit flux of solar neutrinos observed in the Brookhaven detector, and taking into account that the energy threshold in our apparatus can be set at 5 MeV, the number of detectable electrons from solar neutrinos is ~ 0.3/day.

5. Atmospheric neutrinos

At low energy range, $10 \leq E_\nu \leq 700$ MeV, no experimental information is at present available for the atmospheric neutrino spectrum; also the theoretical predictions are not well defined in this region, even if some calculations have been recently made for energies $\gg$ 200 MeV to stimate the neutrino background in proton decay experiments in underground laboratories. However, new efforts are in progress, Gaisser[7], to predict the neutrino spectrum at low energies.

With our LSD experiment we intend to directly measure the $\bar{\nu}_e$ atmospheric neutrinos above an energy threshold of $\geq$10 MeV through reaction (1). By measuring inside the fiducial volume of LSD both the energy of the contained e^+ and the associate γ-pulse from neutron capture, we'll obtain a direct experimental measure of the $\bar{\nu}_e$ atmospheric spectrum, with a very clear signature that makes such events easily distinguishable from any other type of neutrino interactions. At a threshold of 10 MeV, the total number of atmospheric neutrino interactions has been estimated to be of the order of a few tens per year.

Hirata et al.
PR D 448 (1988)



relative Kamiokande time

IMB

hour	min	sec	nhit	number	duration [s]	prob [years]
7	35	33.67	58	11	12.4	1.21 10^7
7	35	33.78	36			
7	35	33.98	25			
7	35	34.00	26			
7	35	34.18	39			
7	35	35.21	83			
7	35	35.40	55			
7	35	35.59	51			
7	35	42.89	21			
7	35	44.11	37			
7	35	46.11	24			

DETECTED NEUTRINO SIGNALS

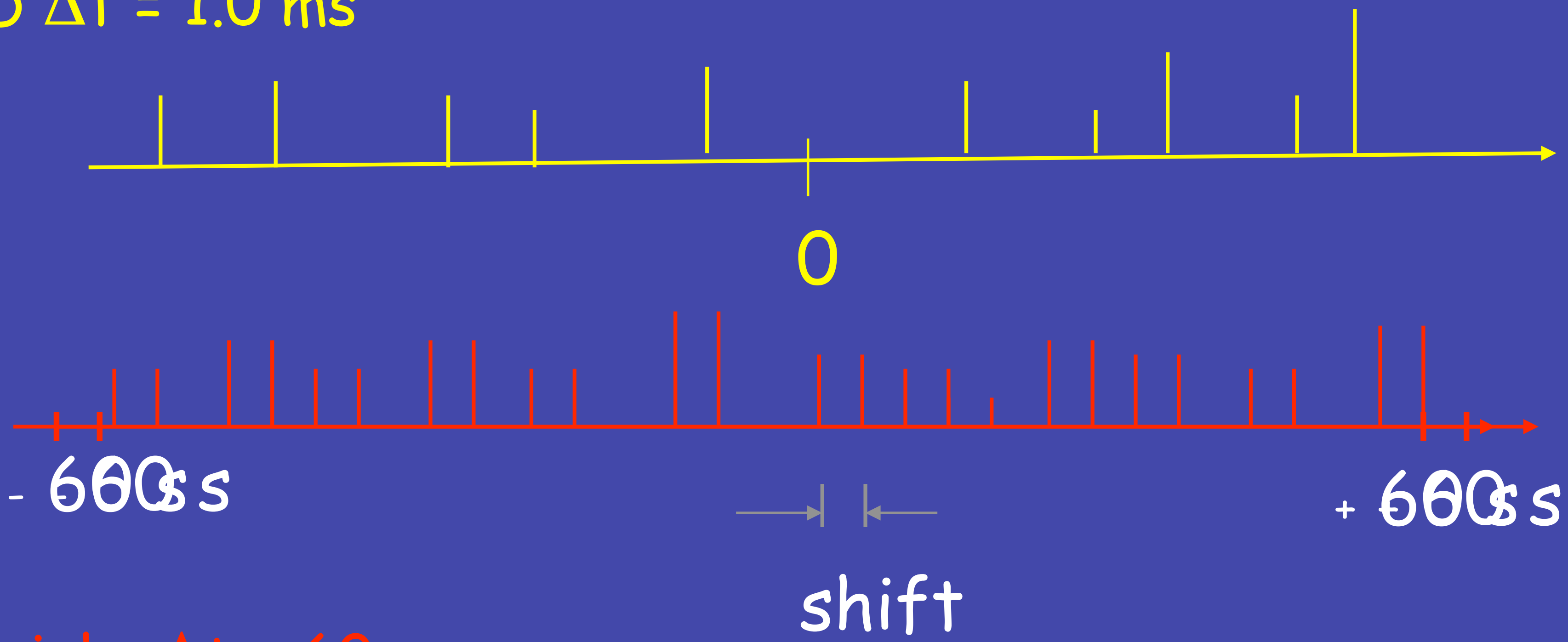
Mont Blanc	5 pulses	$E \geq 5$ MeV	UT 2:52:36.8 $\pm$ 2 ms
Kamioka	11 "	8	7:35:35 $\pm$ 1 min
IMB	8 "	25	7:35:41 $\pm$ 5 ms
BST	(2+5) "	10	2:52:34 and 7:36:06 (+ 2s-54s)

The main signal comes from electron antineutrinos: $\bar{\nu}_e p \rightarrow n e^+$ followed by e^+e^- annihilation producing 2 γ's, detectable in scintillator but not in water. The Mont Blanc signal ($5.8 \leq E_{vis} \leq 7.8$ MeV) corresponds to $4.6 \leq E_{vis} \leq 6.6$ MeV in water, at the limit to be detected in Kamioka.

Kamioka - Mont Blanc correlations

$$N_c = 2\frac{N_1 \cdot N_2}{T}\Delta\tau$$

LSD Δt = 1.0 ms

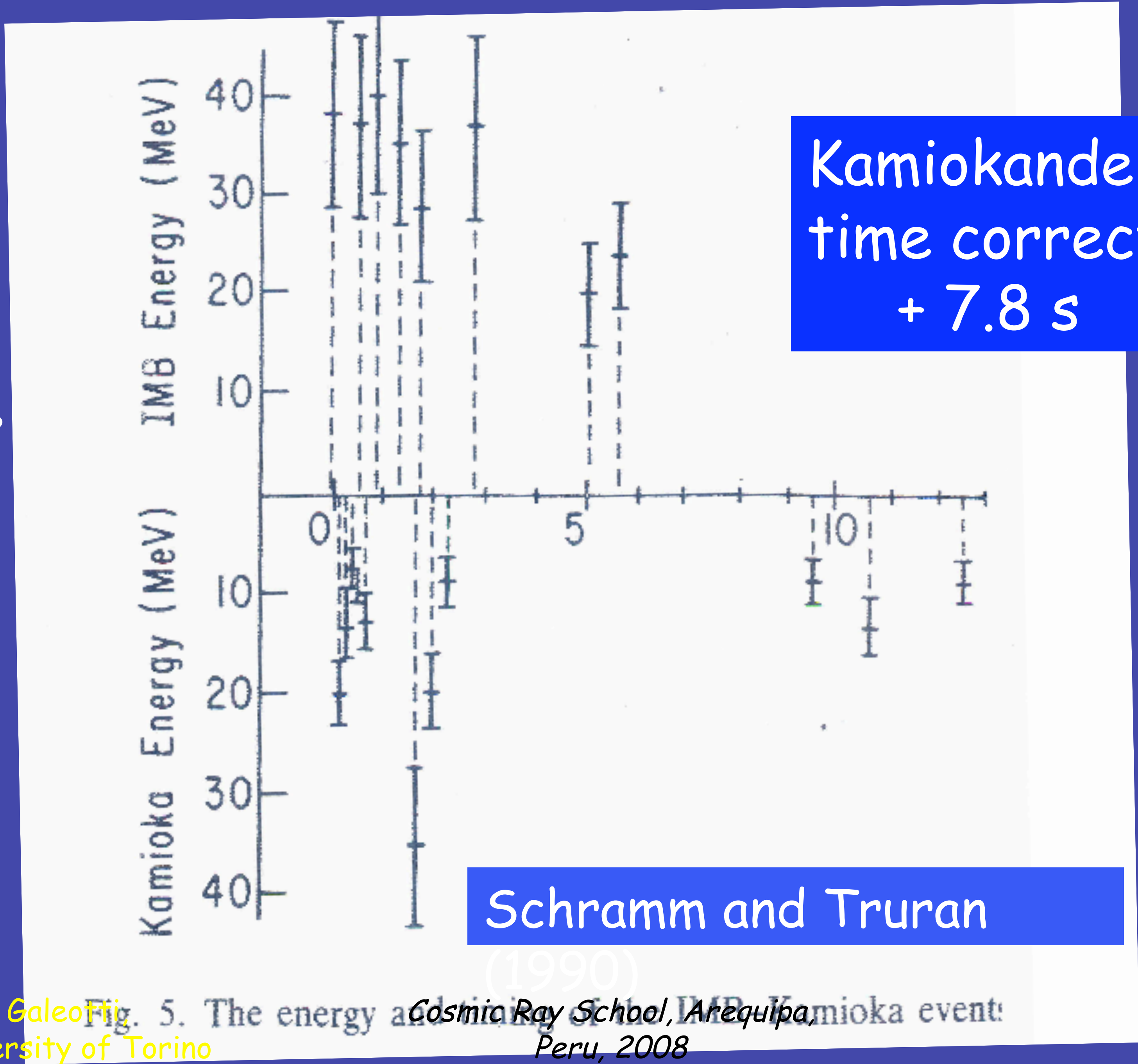


Kamioka Δt= 60 sec

Kamiokande has a time error ± 1 minute

IMB

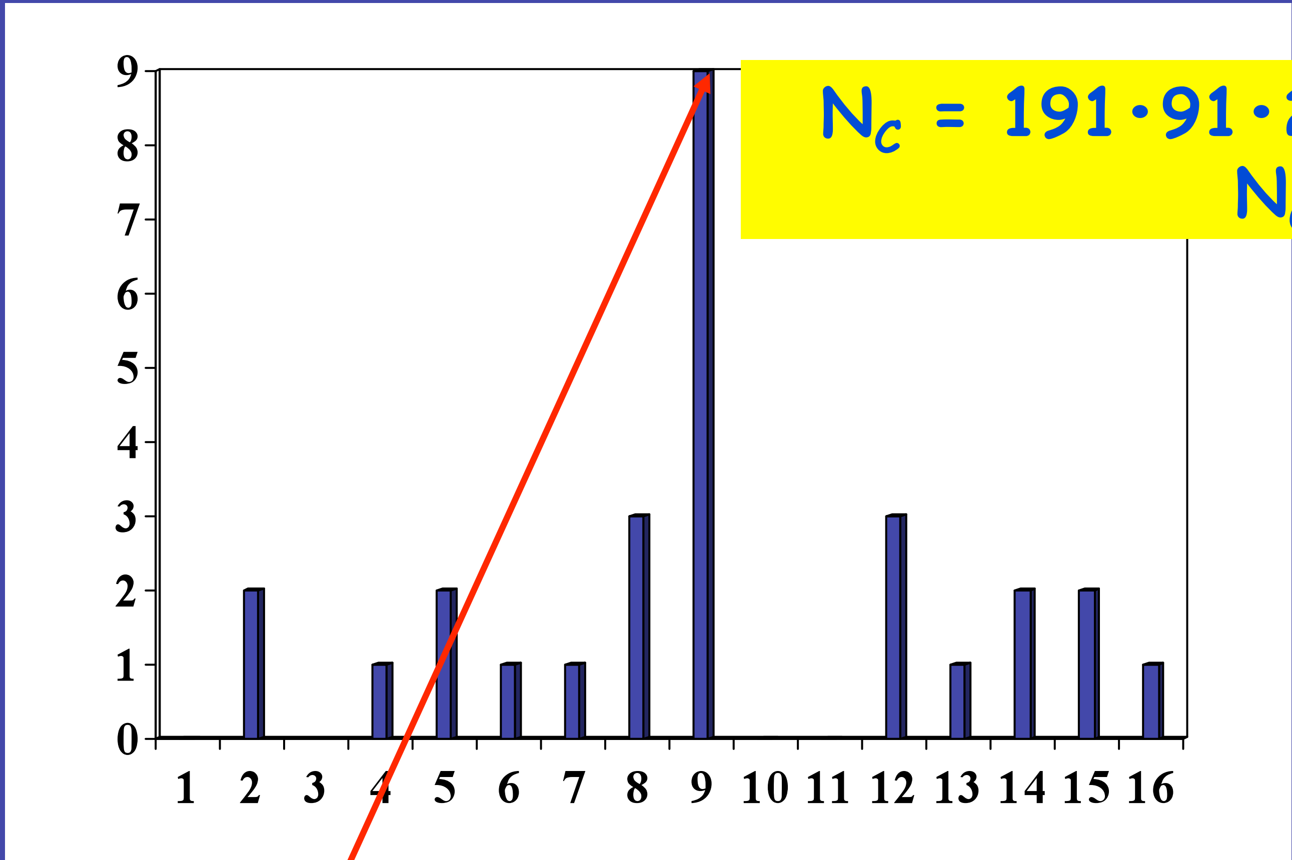
K



Kamiokande time correction + 7.8 s

Schramm and Truran (1990)

Coincidences Mt.Blanc-Kamioka

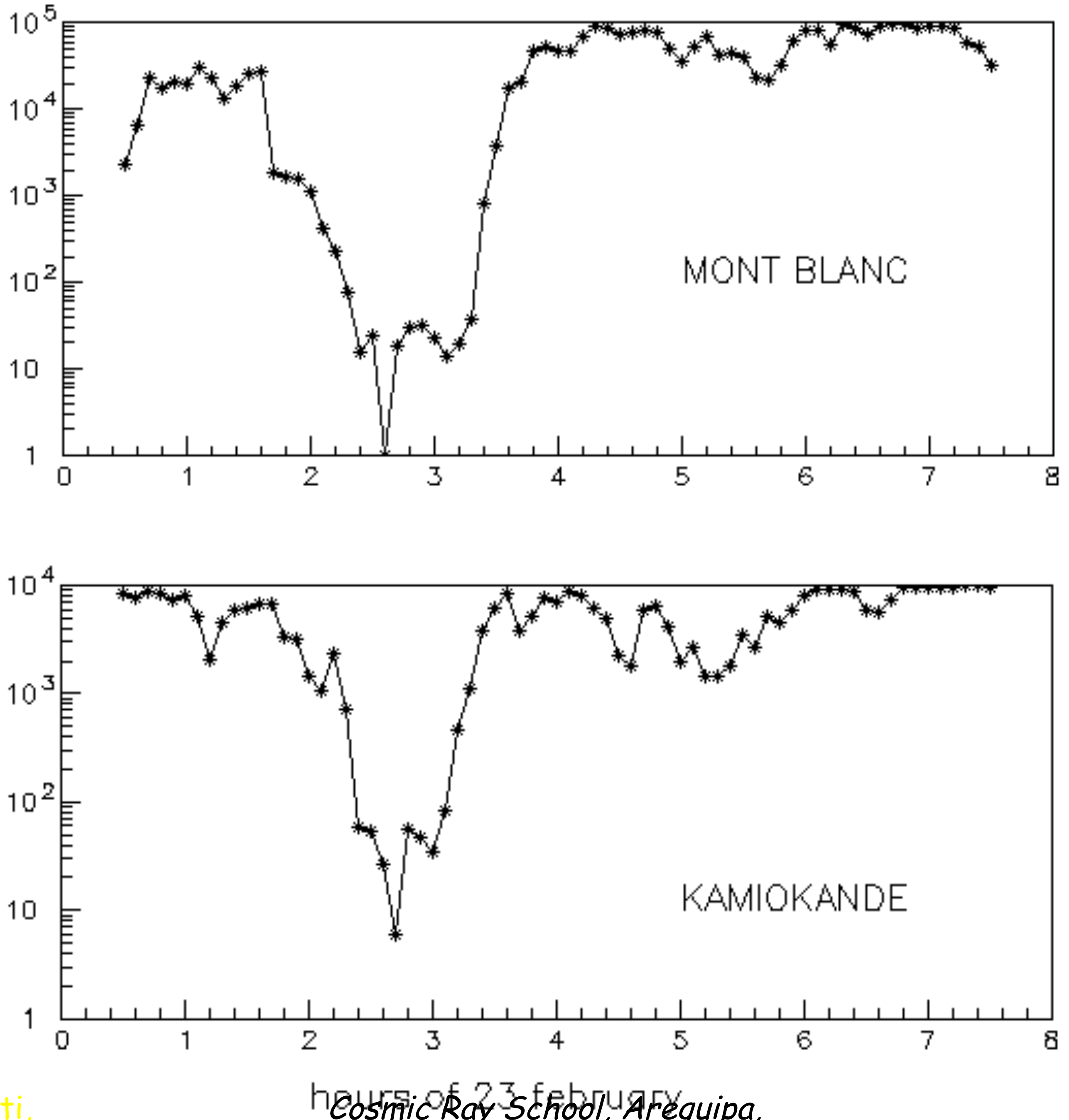


$N_C = 191 \cdot 91 \cdot 2 \cdot 0.5/7200 = 2.4$

$N_O = 9$

Mt. Blanc event time
1:45 - 3.45 U.T.

Coincidence window $\Delta t = \underline{+}\, 0.5$ s
Bin width: 2 hours
Coincidence time: 34 hours
Kamioka time + 7 seconds



10^5
10^4
10^3
10^2
10
1
0 1 2 3 4 5 6 7 8
MONT BLANC
10^4
10^3
10^2
10
1
0 1 2 3 4 5 6 7 8
KAMIOKANDE
hours of 23 february

IL NUOVO CIMENTO   VOL. 12 C, N. 1   Gennaio-Febbraio 1989

Analysis of the Data Recorded by the Mont Blanc Neutrino Detector and by the Maryland and Rome Gravitational-Wave Detectors during SN1987A.

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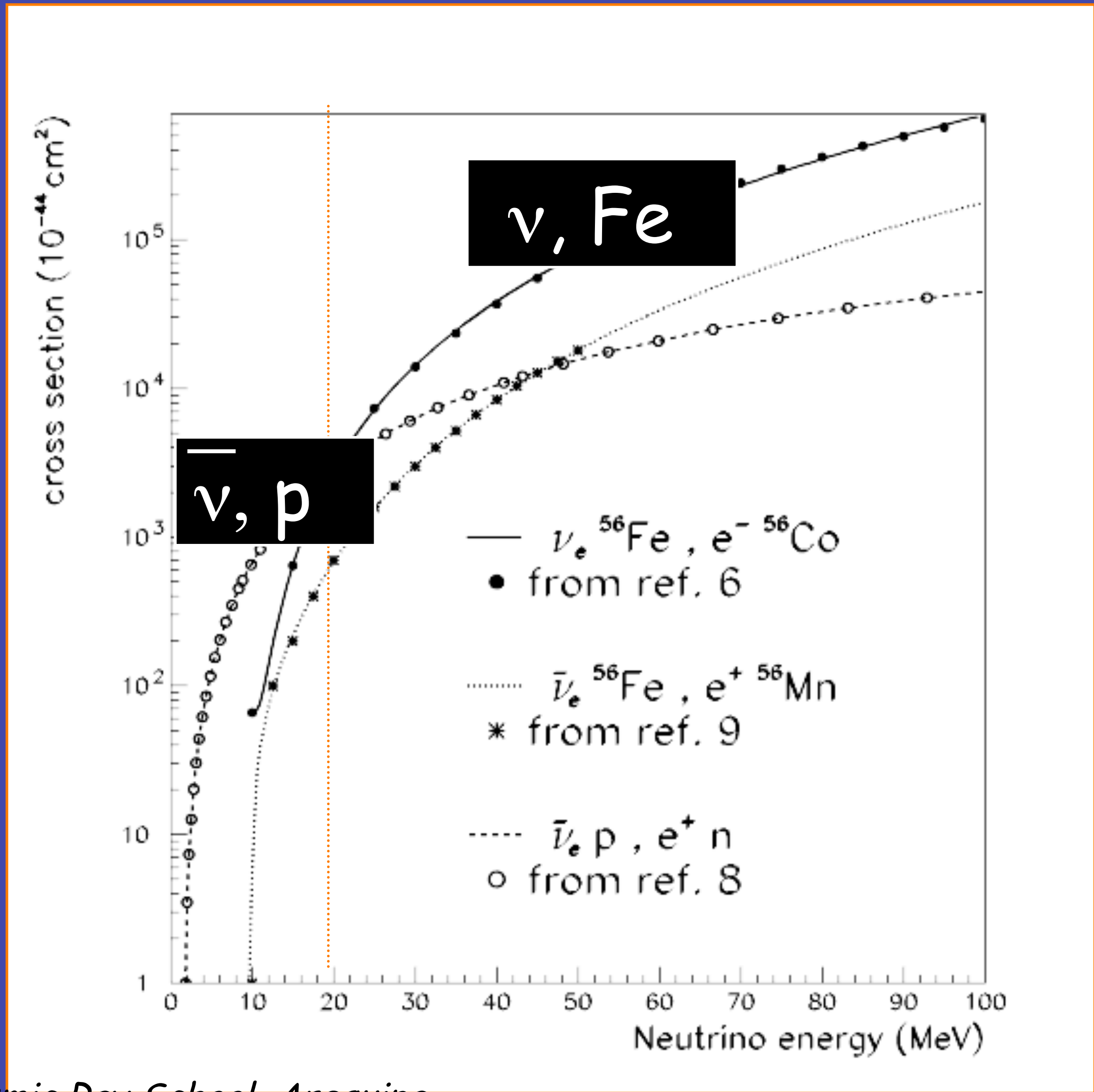
Department of Physics and Astronomy, University of Maryland, USA

(ricevuto il 6 Settembre 1988)

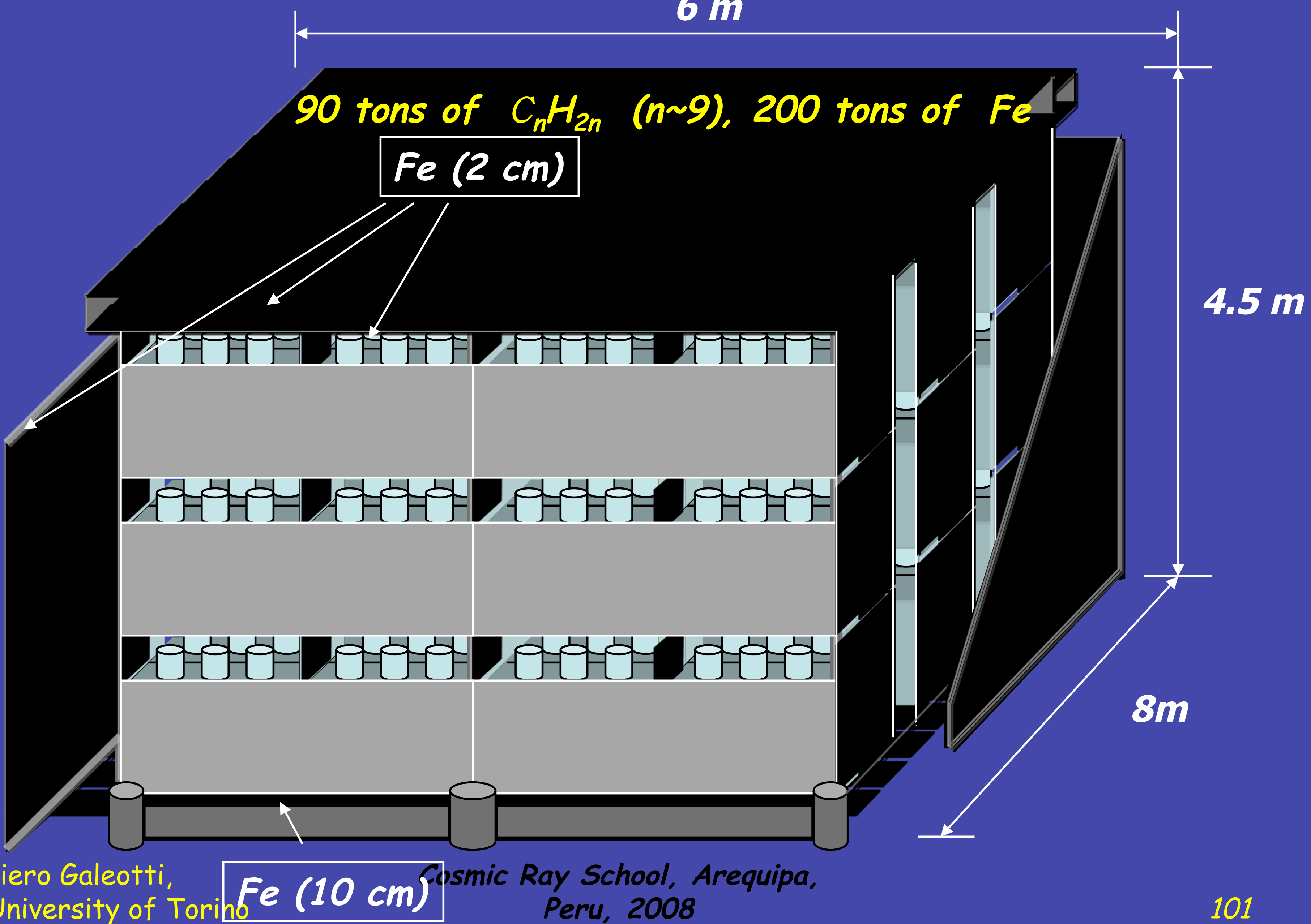
Neutrino interactions in iron

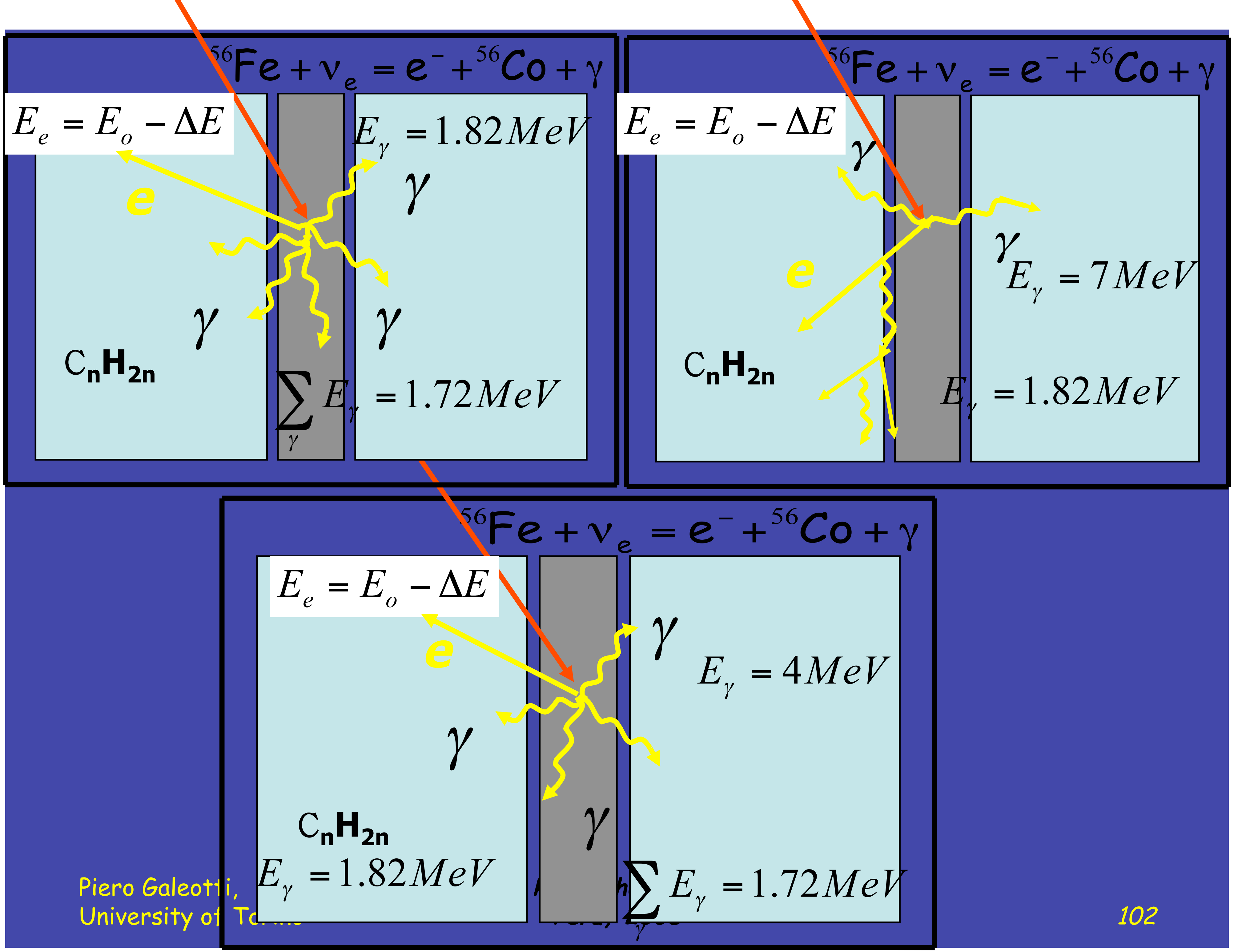
$\nu_e + {}^{56}Fe \Rightarrow {}^{56}Co + e^-$

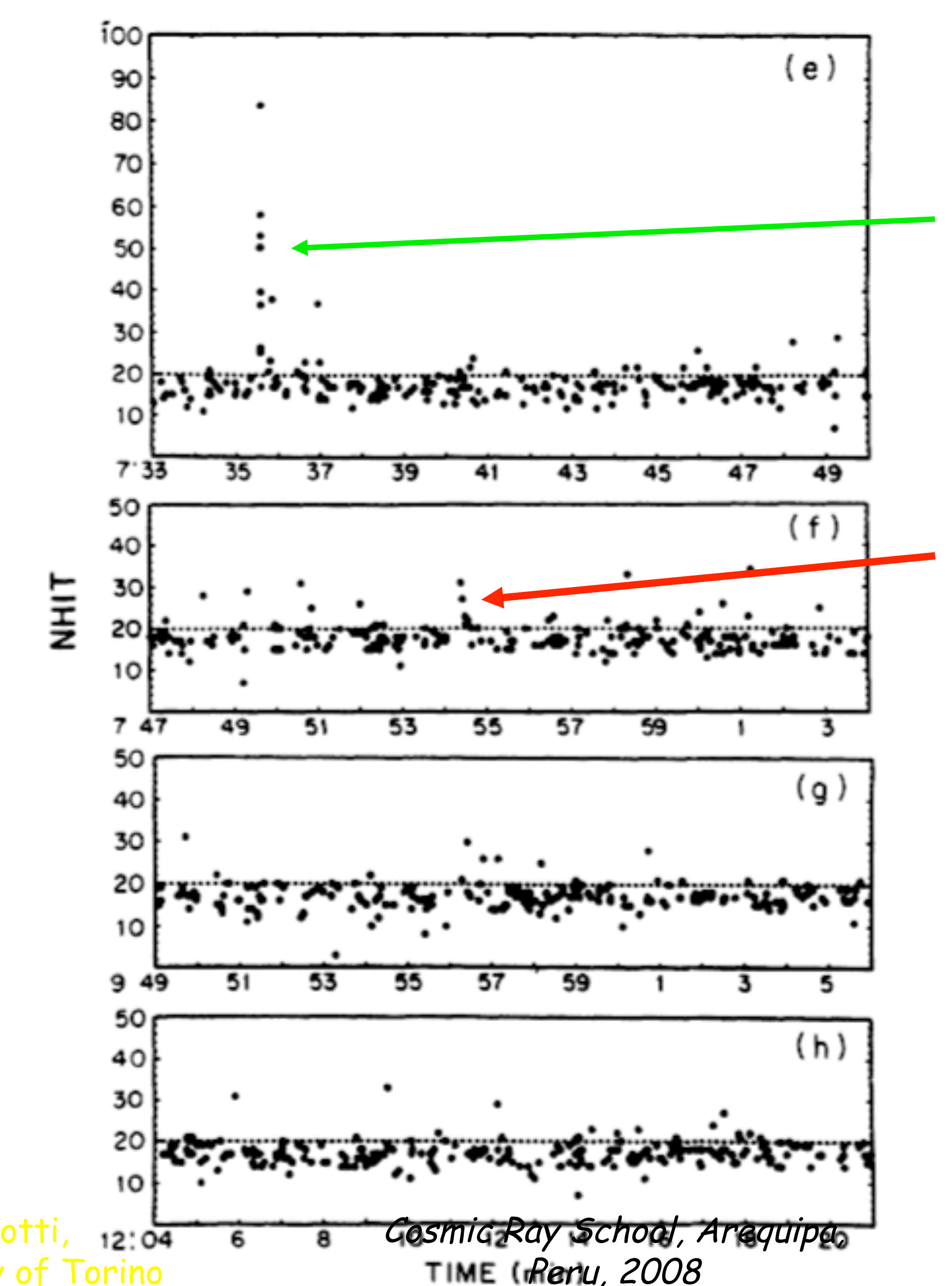


Liquid Scintillator Detector (LSD)

H=5200 m.w.e.
72 counters




$^{56}Fe + \nu_e = e^- + ^{56}Co + \gamma$
$E_e = E_o - \Delta E$
$E_\gamma = 1.82 MeV$
e
γ
γ
γ
C_nH_{2n}
$\sum_\gamma E_\gamma = 1.72 MeV$
$^{56}Fe + \nu_e = e^- + ^{56}Co + \gamma$
$E_e = E_o - \Delta E$
γ
e
γ
$E_\gamma = 7 MeV$
C_nH_{2n}
$E_\gamma = 1.82 MeV$
$^{56}Fe + \nu_e = e^- + ^{56}Co + \gamma$
$E_e = E_o - \Delta E$
e
γ
$E_\gamma = 4 MeV$
γ
γ
C_nH_{2n}
$E_\gamma = 1.82 MeV$
$\sum_\gamma E_\gamma = 1.72 MeV$



11 ν in 12 s
Nh > 20

7 ν in 6 s
Nh > 21

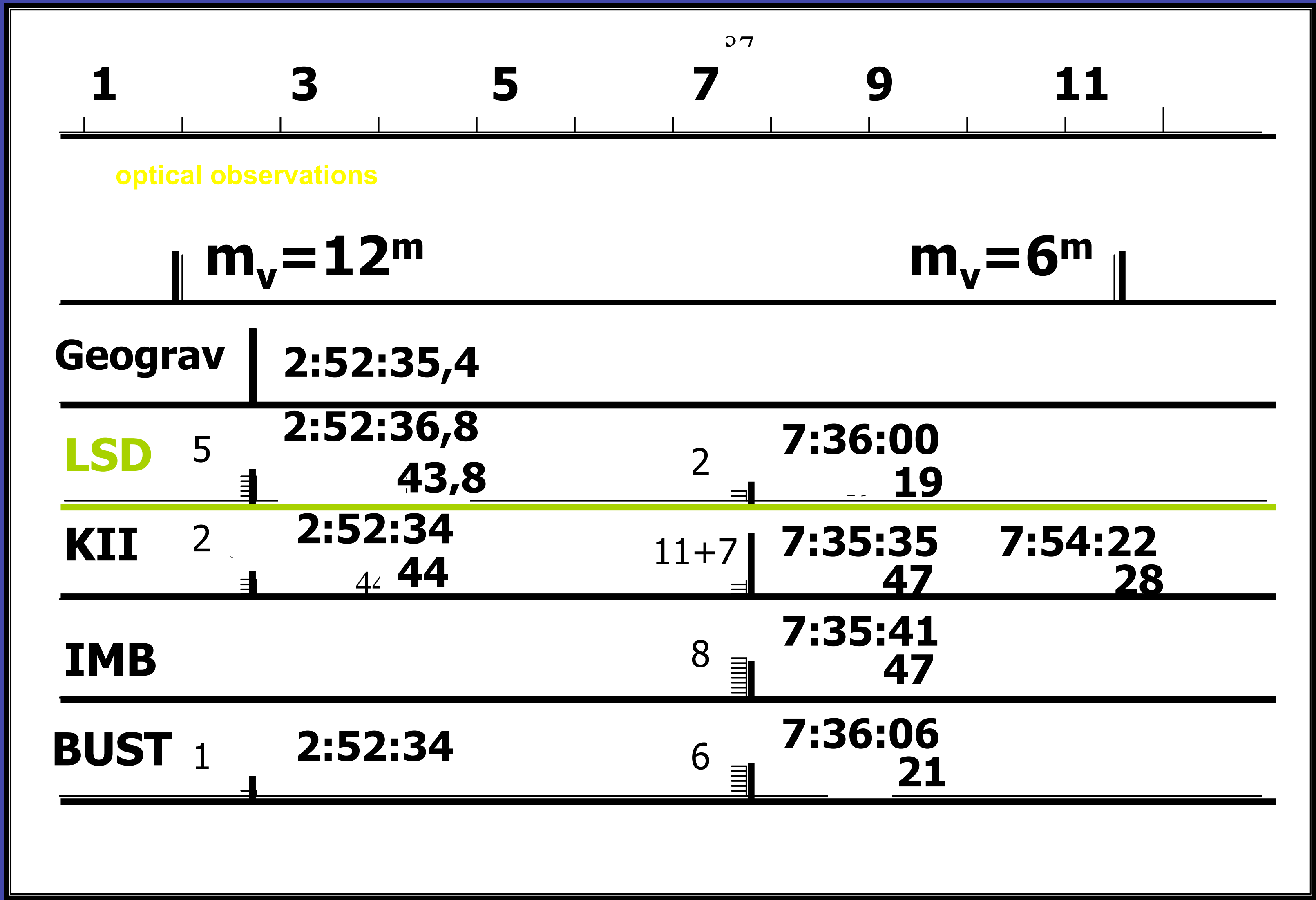
IMB
E > 15 MeV

hour	min	sec	nhit	number	duration [s]	prob [years]
7	35	33.67	58	11	12.4	$1.21\ 10^7$
7	35	33.78	36			
7	35	33.98	25			
7	35	34.00	26			
7	35	34.18	39			
7	35	35.21	83			
7	35	35.40	55			
7	35	35.59	51			
7	35	42.89	21			
7	35	44.11	37			
7	35	46.11	24			

No IMB
E < 15 MeV

7	54	22.26	33	7	6.2	669
7	54	24.11	29			
7	54	25.33	28			
7	54	25.34	27			
7	54	27.13	22			
7	54	28.37	22			
7	54	28.46	22			

February 23, 1987



A rotating collapsar

The Two-Stage Gravitational Collapse Model

[Imshennik V.S., Space Sci Rev, **74**, 325-334 (1995)]