Rivelatori a scintillazione e fotomoltiplicatori

Walter Fulgione

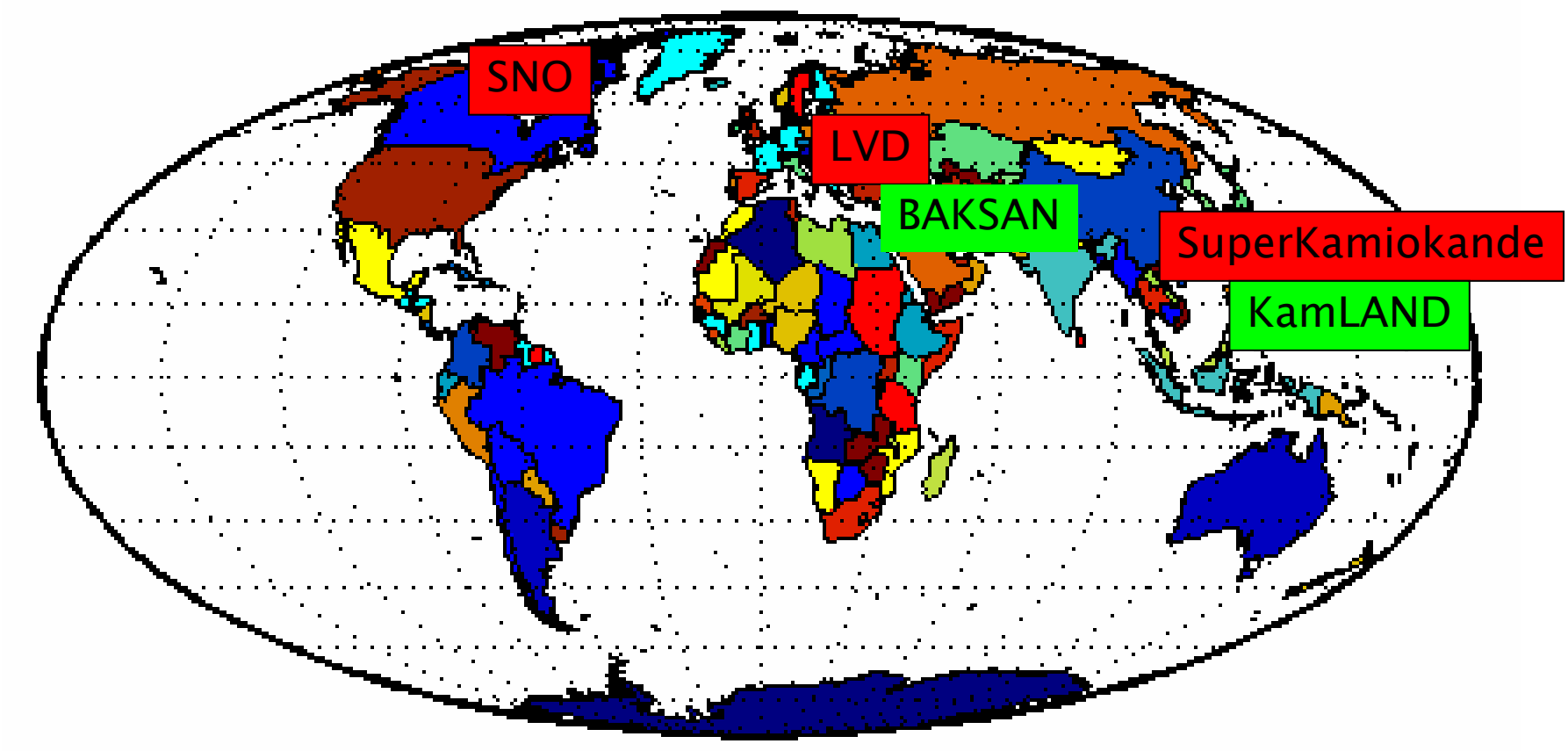
Rivelatori massivi

- Obiettivi:
  - studio della vita media del protone;
  - studio di deboli flussi di particelle di origine cosmica o da acceleratore (ν)

- Grandi masse bersaglio: 100 – 50.000 – 1.000.000 tonnellate
  - H_2O Super Kamiokande
  - D_2O Sudbury Neutrino Observatory
  - C_nH_n LVD, KamLAND, Borexino
  - Ar ICARUS

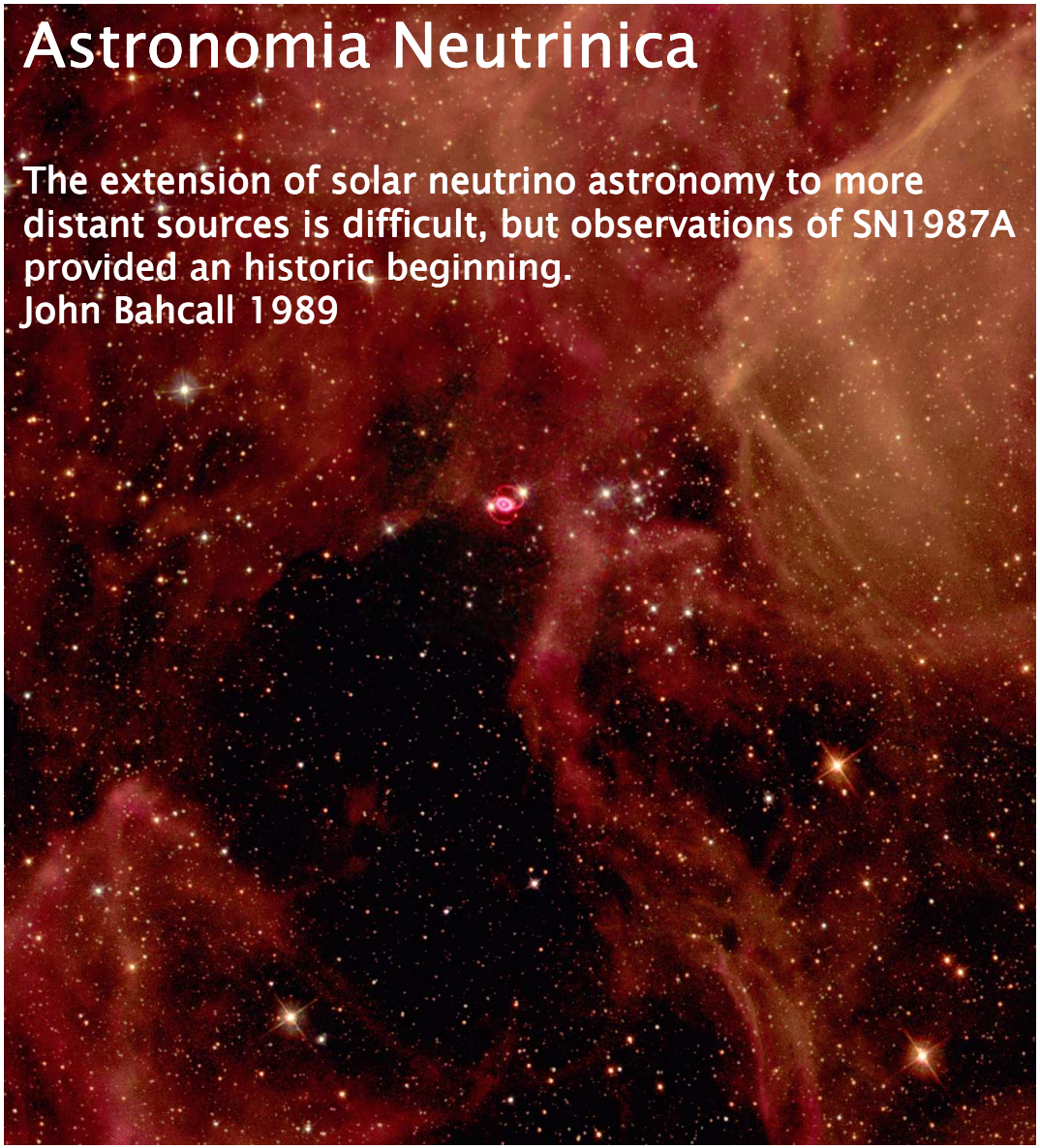
- Tecnica
  - Luce Cherenkov
  - Scintillazione
  - Drift

SNEWS (Supernova Early Warning System): rete di allarme on-line tra i più grandi osservatori neutrinici (SuperKamiokande, Sudbury, LVD)



Astronomia Neutrinica

The extension of solar neutrino astronomy to more distant sources is difficult, but observations of SN1987A provided an historic beginning.
John Bahcall 1989



Per la prima volta furono rivelati neutrini di origine cosmica extrasolare.

Furono rivelati segnali di neutrini da 4 rivelatori:

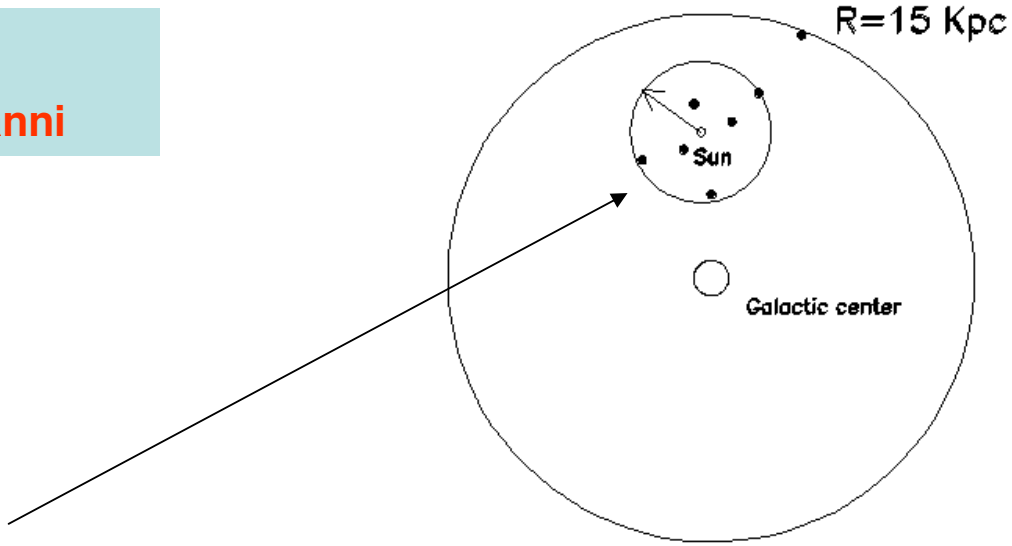
- due esperimenti per la determinazione della vita media del protone: **Kamiokande** ed **IMB**;
- un rivelatore di raggi cosmici: **BAKSAN**;
- il rivelatore di neutrini da SN **LSD**.

凡十一日沒三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次將歷屏星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九斿星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁
宋史志卷九
Georg Raffelt, Max-Planck-Institut für Physik (München)

Supernove storiche e rate attesi nella galassia

- **supernove "storiche"**

viste nell'ottico negli ultimi 1000 anni

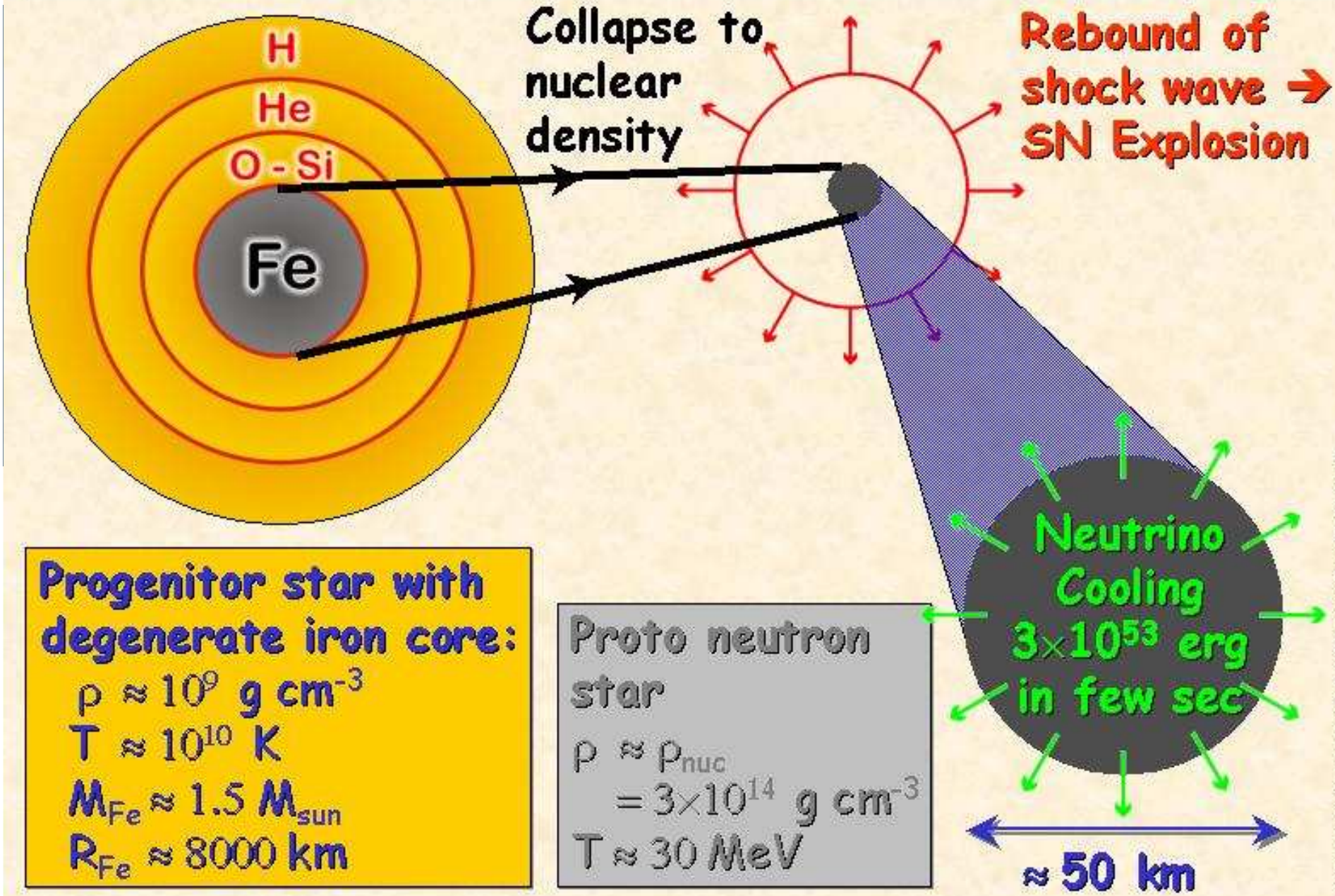


R=4 Kpc

5% galassia

1 SN ogni 20-30 anni attesa nella nostra galassia

Stellar Collapse and Supernova Explosion



Progenitor star with 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

Proto neutron star

$\rho \approx \rho_{nuc}$
$= 3\times10^{14}$ g cm^{-3}

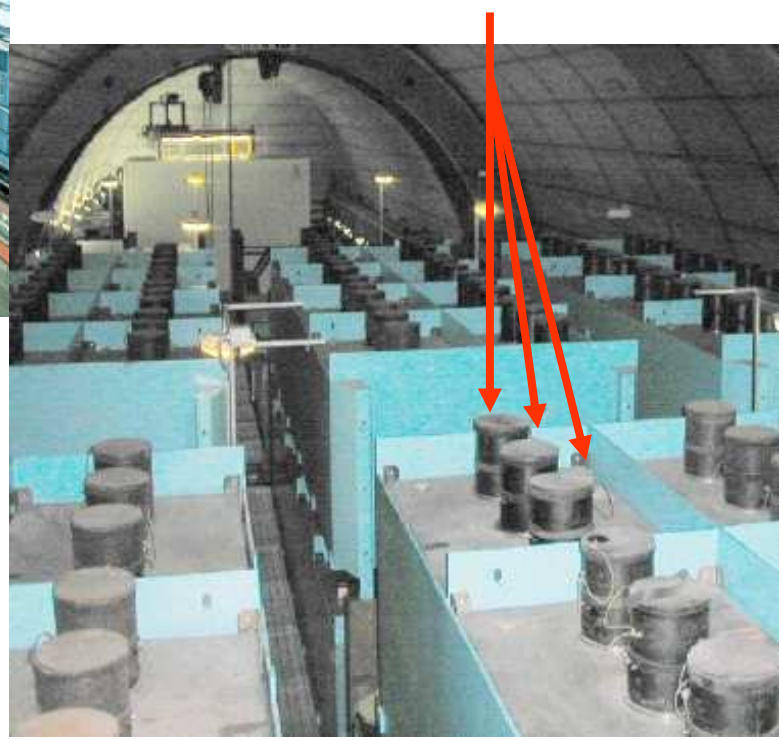
$T \approx 30$ MeV

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

LVD:
Laboratori del Gran Sasso dell'INFN.

840 contatori di 1 x 1 x 1.5 m^3 raggruppati in tre torri formate ciascuna da 35 portatank (gruppo di 8 tank).

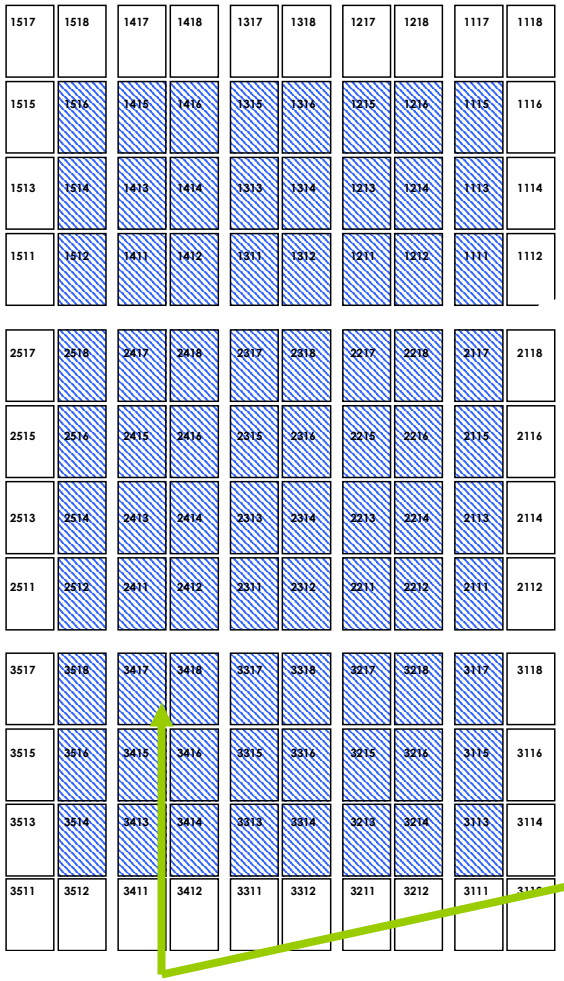
Ciascuna tank contiene 1.2 ton di scintillatore liquido ed e' vista da 3 PM

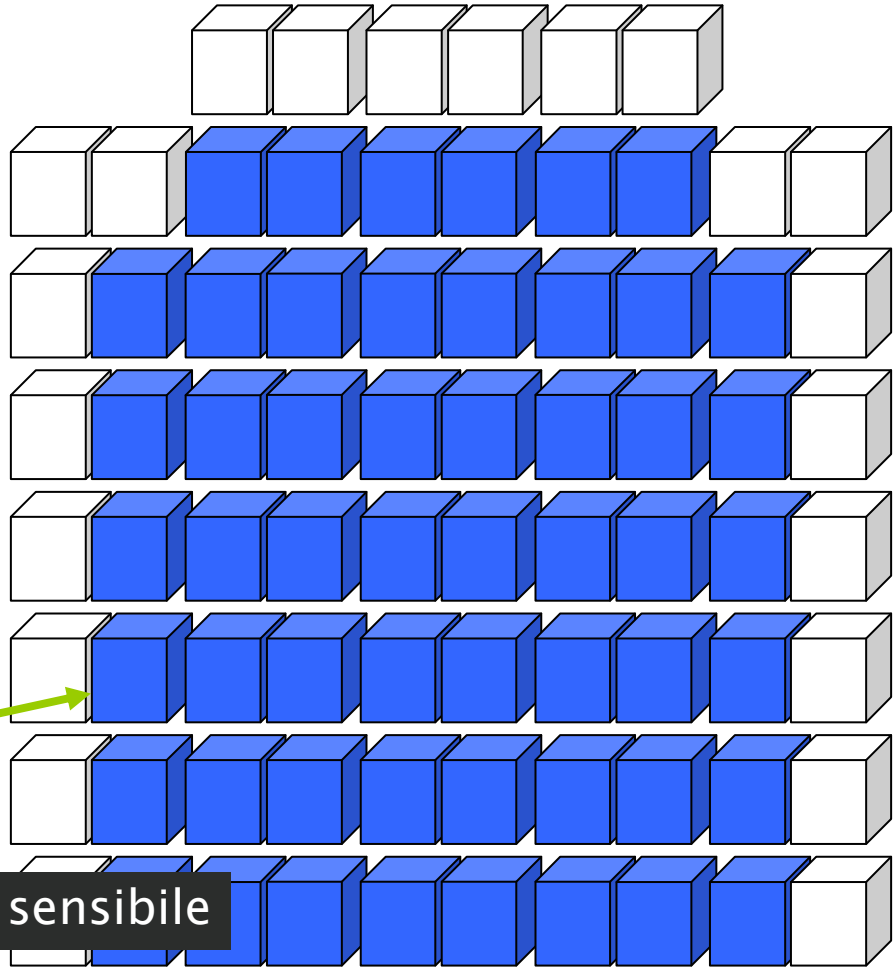


Il sistema di tracking:
- contatori ad L contenenti 2 strati di tubi streamer lunghi 6.3 m.
- lettura bidimensionale: strip di 4 cm poste parallele e perpendicolari ai tubi
- risoluzione superiore a 4 mrad.

LVD Coll., Nuovo Cimento A105 (1992) 1793

Schema numerazione tank del primo piano





il core comprende il 57% della massa sensibile

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

$$n + p \rightarrow d + \gamma \qquad E_\gamma = 2.2\ \text{MeV} \qquad \tau = 185\ \text{ms}$$

J.B. Birks, *The Theory and Practice of Scintillation Counting*, New York, 1964
G.F. Knoll, *Radiation Detection and Measurement*, New York, 1989
S.E. Derenzo, *Scintillation Counters, Photodetectors and Radiation Spectroscopy*, IEEE Short Course *Radiation Detection and Measurement*, 1997 Nuclear Science Symp.

- Incident particles or photons excite atoms or molecules in the scintillating medium.
- Excited states decay under emission of photons, which are detected and converted into electric signals.

1. Scintillation materials

Both organic and inorganic materials,

can be solid, liquid or gaseous

a) organic scintillators (e.g. plastics)

states of interest are energy levels of individual molecules, i.e. no interactions with neighbors

⇒ excitation and emission spectra practically the same whether in solid, liquid or gaseous state.

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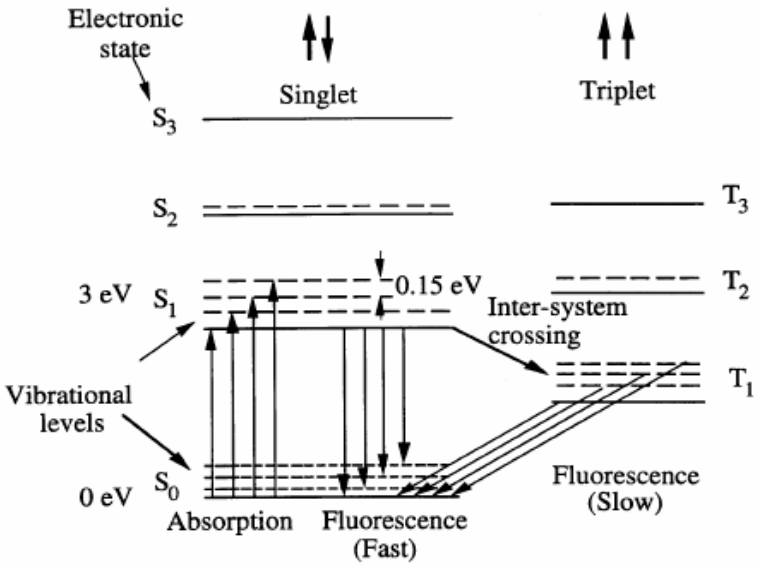
Typical energy levels

(from Birks, as redrawn by Derenzo)



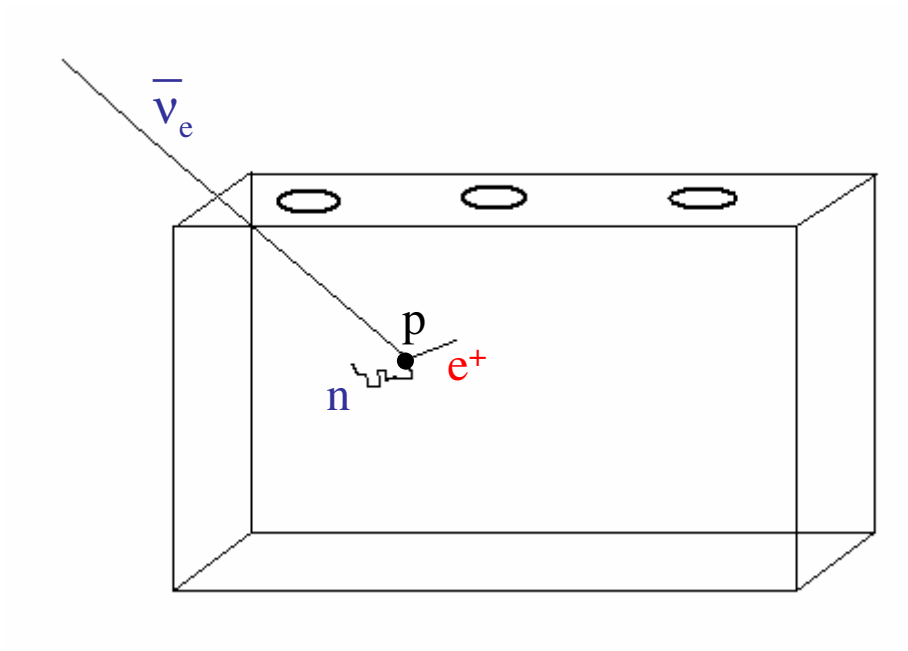
a) At room temperature practically all electrons in ground state. (since energy of S1 states >> 0.025 eV)

b) Incident radiation populates S_1 states

vibrational levels within S1 band decay radiation-less to S_1 base state, which in turn decays under emission of light to the S_0 band.

c) S1 can also decay to adjacent triplet levels. Since their energy is significantly lower, the decay time is much longer.

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

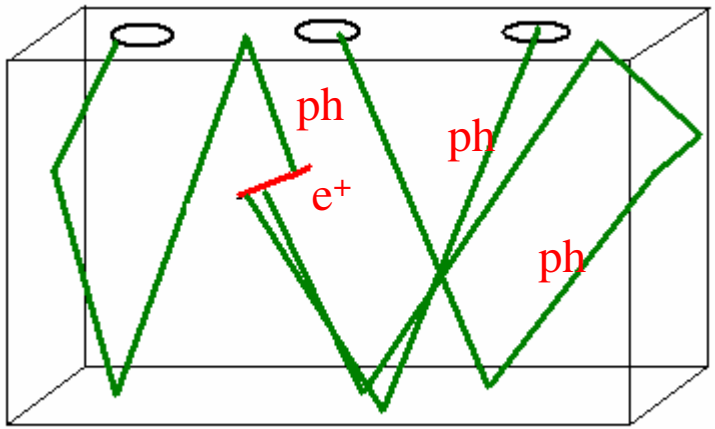


In una tank ci sono: ~ $1 \cdot 10^{29}$ protoni liberi

La sezione d'uro di interazione per E_ν = 10 MeV e': ~ $1 \cdot 10^{-41}$ cm^2

Occorre una fluenza di $1/(1 \cdot 10^{29} \cdot 1 \cdot 10^{-41}) = 1 \cdot 10^{12}$ neutrini / cm^2 per avere un segnale.

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



Time dependence of emitted light

a) non-radiative transfer of energy from vibrational states to fluorescent state

typical time: 0.2 – 0.4 ns

b) decay of fluorescent state

typical time: 1 – 3 ns

⇒ rise with time constant τ_r

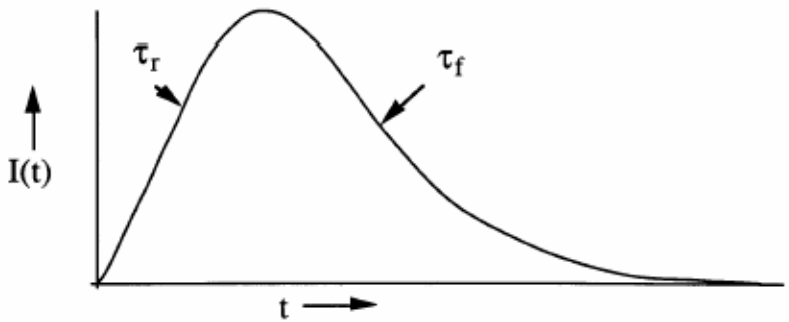
$$I(t) \propto 1 - e^{-t/\tau_r}$$

fall with time constant τ_f

$$I(t) \propto e^{-t/\tau_f}$$

total pulse shape

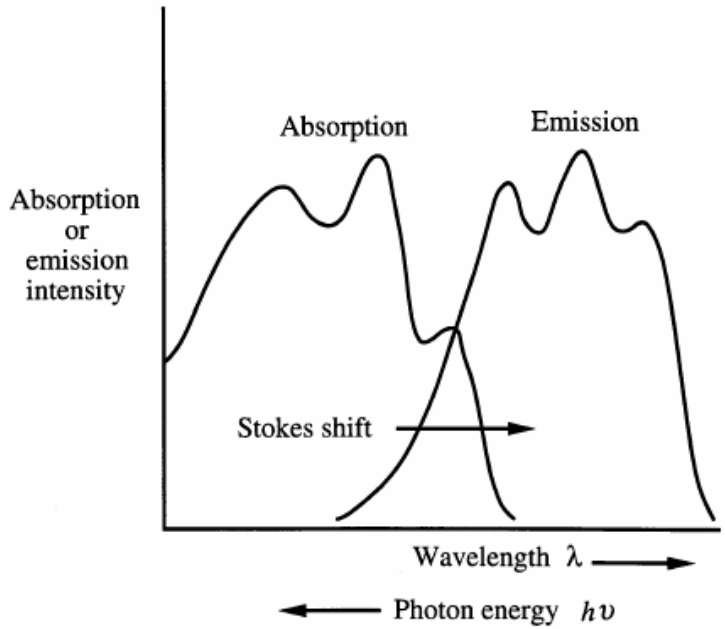
$$I(t) = I_0 (e^{-t/\tau_f} - e^{-t/\tau_r})$$



Why isn't emitted light re-absorbed?

Since excitation goes to higher vibrational states in the S_1 band, whereas decay goes from the base S_1 state, the emission spectrum is shifted to lower energies (longer wavelengths).

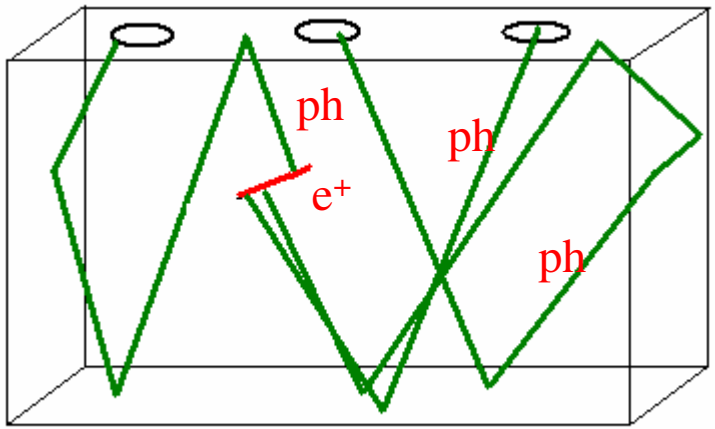
$\Rightarrow$ only small overlap of emission and absorption spectra



Properties of some typical organic scintillators

Material	State	λ_{max} [nm]	τ_f [ns]	ρ [g/cm^3]	photons/MeV
Anthracene	crystal	447	30	1.25	$1.6 \cdot 10^4$
Pilot U	plastic	391	1.4	1.03	$1.0 \cdot 10^4$
NE104	plastic	406	1.8	1.03	$1.0 \cdot 10^4$
NE102	liquid	425	2.6	1.51	$1.2 \cdot 10^4$
C_nH_{2n+2}	**liquid**	**420**	**~ 2**	**0.78**	**$7.8\ 10^3$**

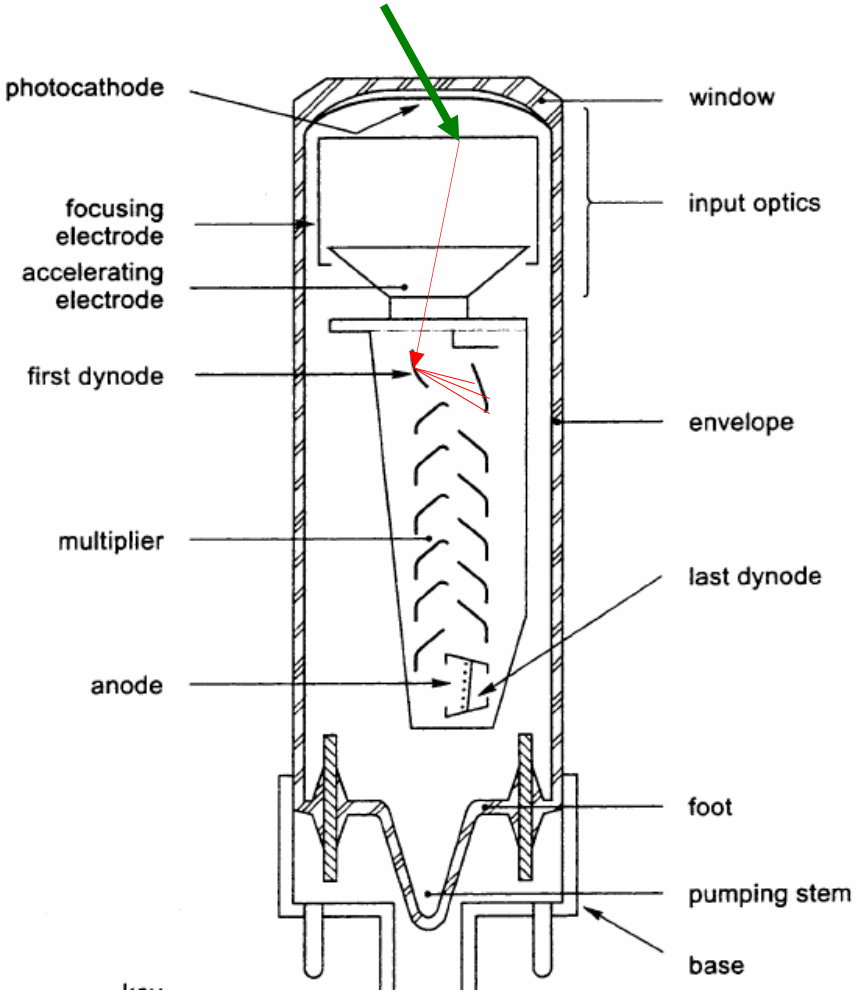
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



Conversion of Scintillation Light to Electrical Signal

Most Common Device:

Photomultiplier Tube



Summary of Photocathode Materials
(from Derenzo)

Cathode type	Composition	Peak Q.E.	Peak λ
S1	AgOCs	0.4%	800 nm
S10	BiAgOCs	7%	420 nm
S11	CS_3SbO	21%	390 nm
S20 (multi-alkali)	Na_2KSbCs	22%	380 nm
Bialkali	K_2CsSb	27%	380 nm
Bialkali (high temp)	Na_2KSb	21%	360nm
	KCsRbSb	24%	440 nm
Bialkali	RbCsSb	25%	450 nm
Solar blind*	CeTe	18%	200 nm
Solar blind**	CsI	15%	135nm

* Q.E. > 0.1% above 320 nm
** Q.E. > 0.1% above 210 nm

Maximum quantum efficiency n above table is 27%.
Is this reasonable?

- no electric field within photocathode to direct electrons to emitting surface
- photoelectrons initially emitted isotropically
  - ⇒ ½ directed toward faceplate
  - ⇒ ½ directed toward dynode structure
- transmission losses (bialkali photocathodes 40% transmissive

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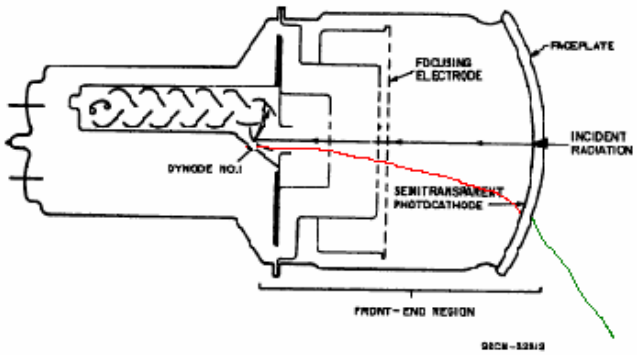


Fig. 26 - Photomultiplier design with curved faceplate and in-line dynode structure to provide a minimum transit time and transit-time spread.

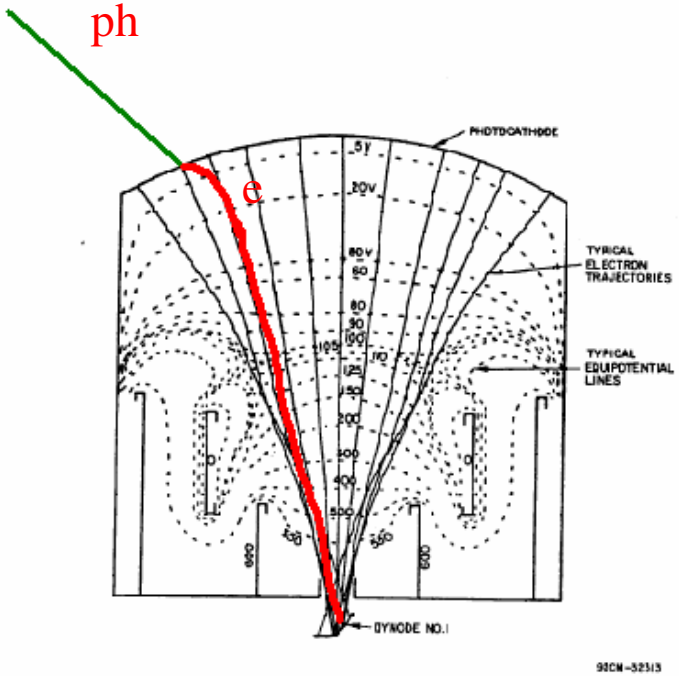


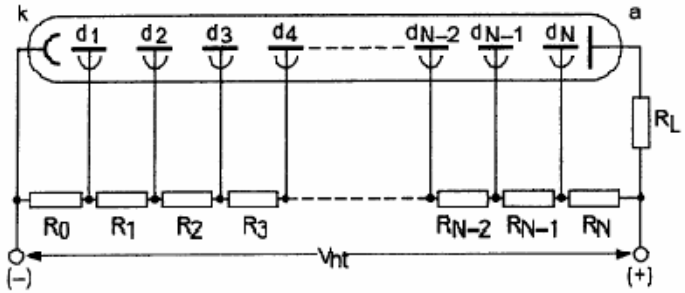
Fig. 27 - Cross section of a photomultiplier showing equipotential lines and electron trajectories that were plotted by computer.

(from *Photomultiplier Handbook*, Burle Industries)

Operational aspects of using PMTs

Electron multiplication at dynodes depends on potential between successive dynodes.

Potential distribution commonly set by resistive divider.



(from *Photomultiplier Tubes*, Philips Photonics)

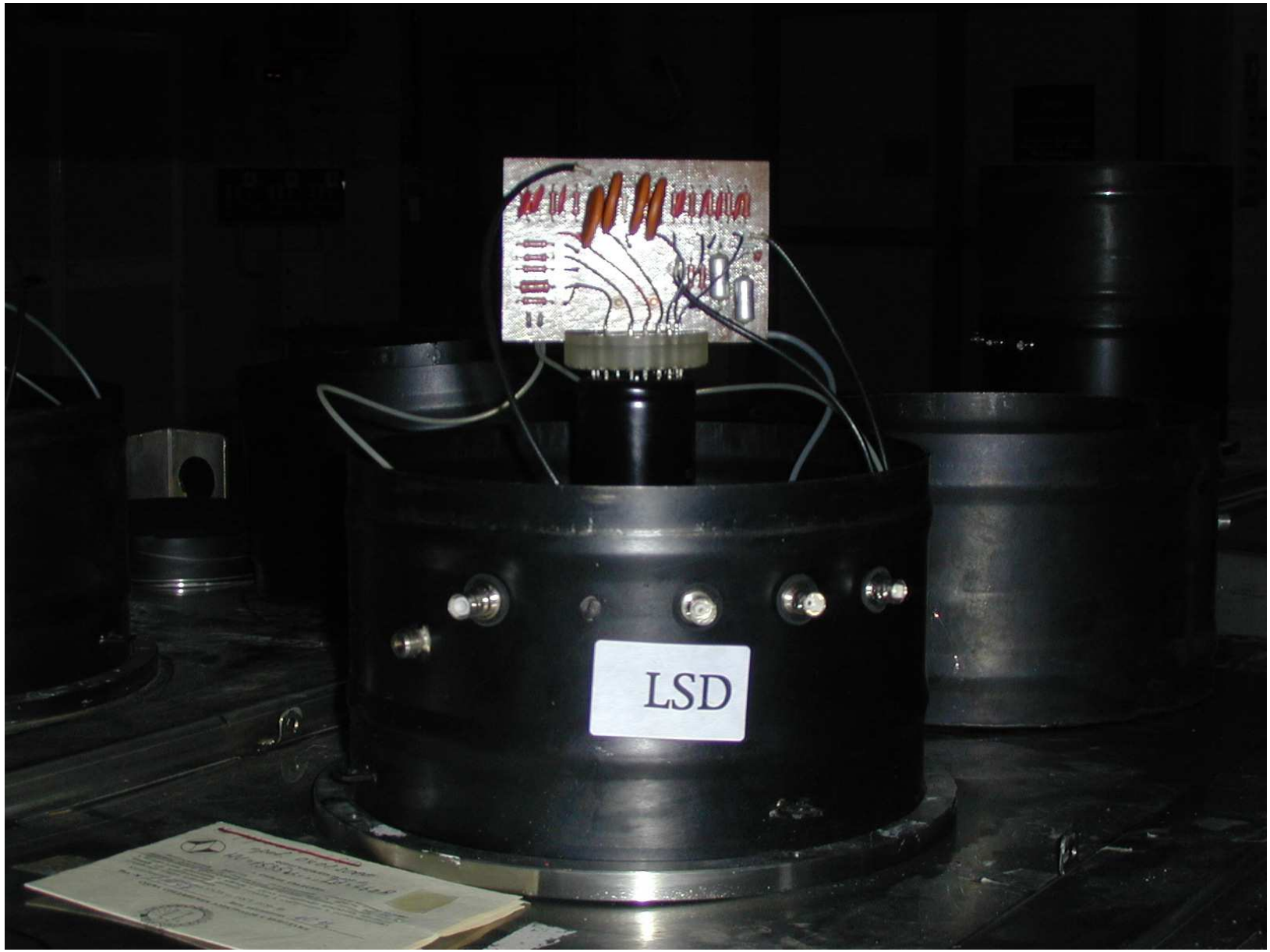
Secondary electrons are emitted with low energy and accelerated by potential difference between dynodes.

Advantageous especially at first dynode to improve gain distribution of multiplication chain.

Typically, PMTs are operated with total supply voltages of 2 kV.

8 to 14 stages (number of dynodes) are common, with 100 to 150 V between dynodes.

The potential between the photocathode and the first dynode is typically 4 times as large to improve the collection efficiency and the gain in the first stage.


LSD

Signal Evolution

1. energy is absorbed in scintillator
2. population of states that emit photons

   number of radiative states

   $$N_0 = E_{abs}/\varepsilon_i$$

   E_{abs} energy absorbed in scintillator

   ε_i energy required to produce 1 photon

3. population of radiative states decays

   $\Rightarrow$ rate of photon emission

   $$\frac{dN_{ph}}{dt} \equiv n_{ph}(t) = \frac{N_0}{\tau} e^{-t/\tau}$$

   Total number of photons emitted after time T

   $$N_{ph}(T) = \int_0^T n_{ph}(t)dt = N_0(1 - e^{-T/\tau})$$

4. photons absorbed in photocathode, producing photoelectrons

   $$n_{pe}(t) = QE \cdot n_{ph}(t) = QE \cdot \frac{N_0}{\tau} e^{-t/\tau}$$

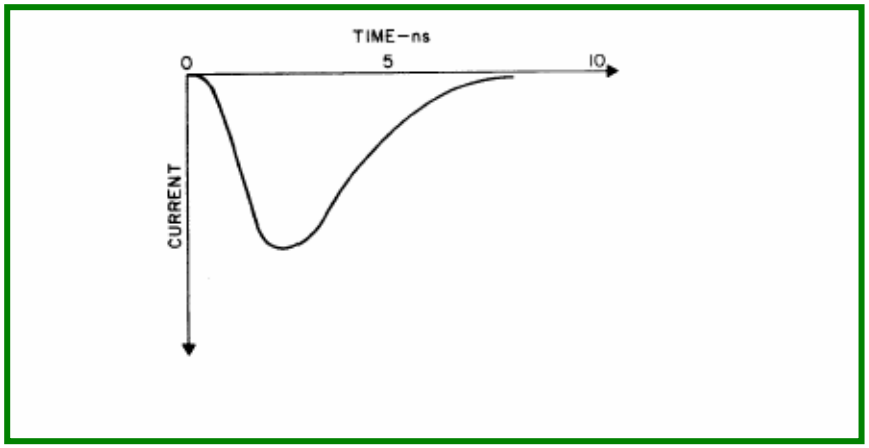
5. photoelectrons transported through gain structure (dynodes in PMT) multiplied by G

   $\Rightarrow$ electric current at anode

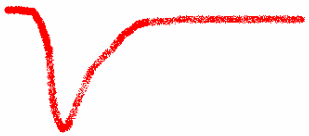
   $$I_{anode}(t) = G \cdot QE \cdot \frac{N_0}{\tau} e^{-t/\tau}$$

$$\int I_{anodo}(t)\, dt = G \cdot QE \cdot N_0/\tau \cdot \int e^{-t/\tau}\, dt$$

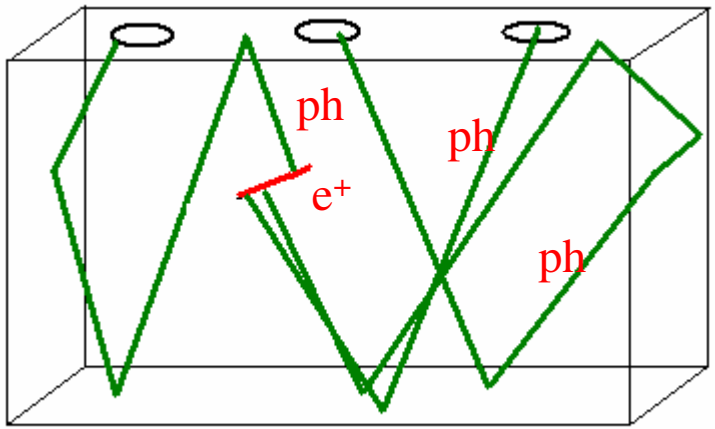
$$\text{Carica} = G \cdot QE \cdot N_0 = G \cdot QE \cdot E_{abs}/\varepsilon_i$$



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

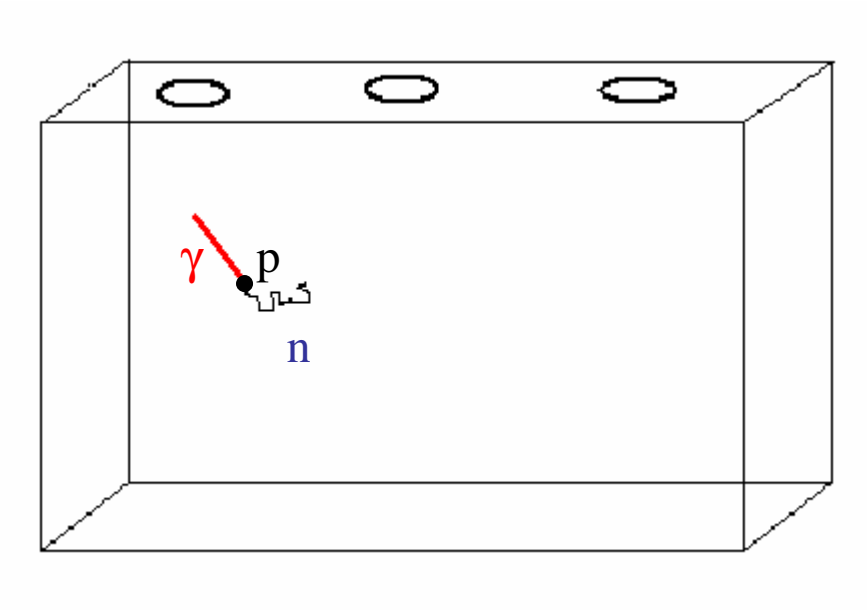


$$\text{Carica} = \text{cost} \cdot E_{e+}$$



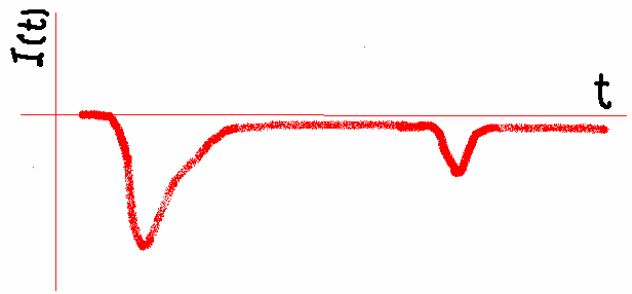
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

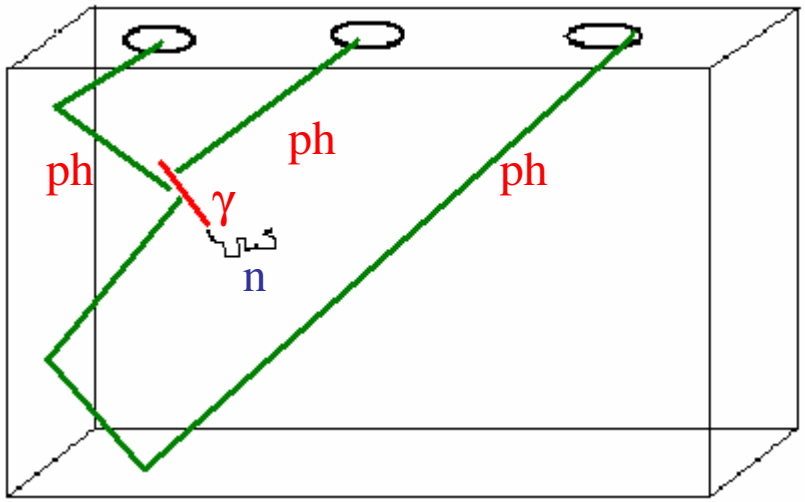
$$n + p \rightarrow D^* \rightarrow D + \gamma$$



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

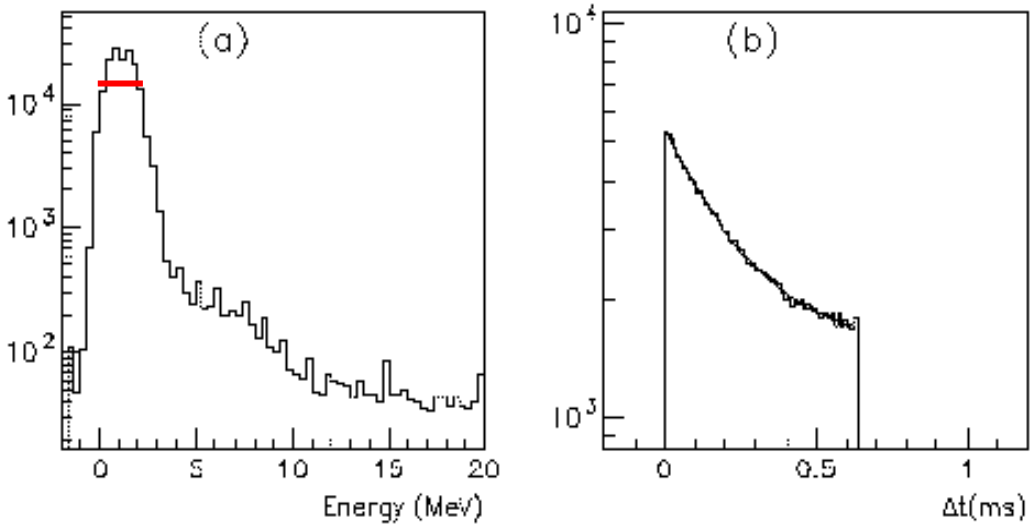
$n + p \rightarrow D^* \rightarrow D + \gamma$





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

$n + p \rightarrow d + \gamma$ $E_\gamma = 2.2$ MeV $\tau = 185$ ms



Apertura di un gate di 1 ms a soglia bassa (0.8-1.6 MeV) successivamente a un trigger di soglia alta (4-7 MeV) per permettere tagging della cattura del neutrone

efficienza cattura neutroni: 60%

FWHM (2.2 MeV) = 75%

spettro "puro" di $\bar{\nu}_e$

Typical NaI(Tl) system (from Derenzo)

511 keV gamma ray

⇓

25000 photons in scintillator

⇓

15000 photons at photocathode

⇓

3000 photoelectrons at first dynode

⇓

$3 \cdot 10^9$ electrons at anode

2 mA peak current

Resolution of energy measurement determined by statistical variance of produced signal quanta.

$$\frac{\Delta E}{E} = \frac{\Delta N}{N} = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$$

Resolution determined by smallest number of quanta in chain, i.e. number of photoelectrons arriving at first dynode.

In this example

$$\frac{\Delta E}{E} = \frac{1}{\sqrt{3000}} = 2\% \text{ r.m.s.} = 5\% \text{ FWHM}$$

Typically 7 – 8% obtained, due to non-uniformity of light

LVD

2.2 MeV gamma ray

17000

↓ 50

300

30

$1.5\ 10^7$

10 μA

@ 2 MeV

DE/E = 1/√30 = 18% r.m.s. = 42% FWHM

@ 10 MeV

DE/E = 1/√150 = 8% r.m.s. = 20% FWHM

$$\varepsilon = S_{sensibile} / S_{totale} = 3 \cdot 7^2 \cdot \pi / 8 \cdot 10^4 \text{ cm}^2 = 5 \cdot 10^{-3}$$

$$\varepsilon = S_{sensibile} / S_{totale} = 840 \cdot 3 \cdot 7^2 \cdot \pi / 6 \cdot 10^6 \text{ cm}^2 \sim 5 \cdot 10^{-2}$$