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# Oltre il Modello Standard in Astroparticle Physics

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“Il bosone di Higgs compie un anno”  
Bologna, 4 luglio 2013

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# Outline

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Ci sono già evidenze sperimentali di fisica oltre il Modello Standard  $SU(2)_L \times U(1)$

- **Neutrini:**
  - Oscillazione e massa:
    - violazione del numero leptonico di flavour,
    - esistenza anche di  $n_R$
  - (Decadimento doppio beta senza neutrini):
    - violazione del numero leptonico globale,
    - Dirac o Majorana ?
- **Dark Matter:**
  - Particelle massive, neutre, stabili e non barioniche:
    - Nessun candidato nello SM
- **Altro ?**
  - Onde gravitazionali
  - Asimmetria materia-antimateria nell'Universo

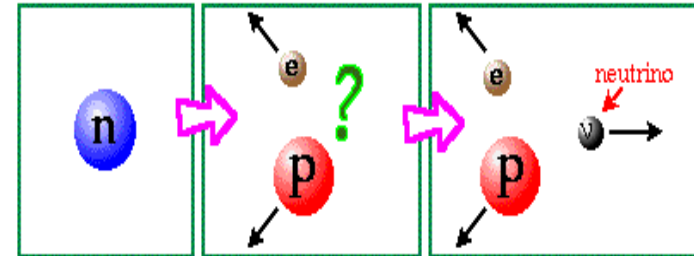
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**Neutrino: da sempre sorprese !**

# Neutrini: l'origine (1930)

1930, W. Pauli propone l'esistenza di una particella neutra senza massa come ultima risorsa per spiegare lo spettro continuo degli elettroni emessi nello spettro beta. E' la prima proposta di una particella che non fa parte della materia ordinaria

Il neutrino ( $\nu$ ) "nasce" come "rimedio disperato" per spiegare lo spettro continuo dei raggi  $\beta$



*Original: Photostigma of 24. 12. 1933*  
Abschrift/15.12.33 PW

Öffener Brief an die Gruppe der Radioaktiven bei der  
Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut  
der Eidg. Technischen Hochschule  
Zürich

Zürich, 4. Des. 1930  
Gloriastrasse

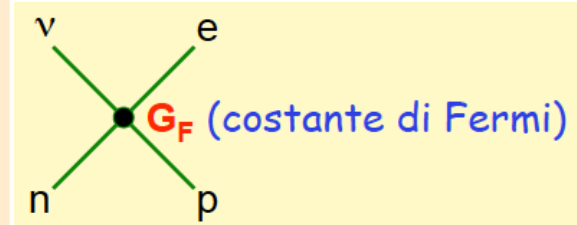
Liebe Radioaktive Damen und Herren,

Wie der Überbringer dieser Zeilen, den ich baldmöglichst anhören bitte, Ihnen das näherem auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der  $\alpha$ - und  $\beta$ -Kerne, sowie des kontinuierlichen  $\beta$ -Spektrums auf einen verweifelten Ausweg verfallen um den "Wechselzatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin  $1/2$  haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als  $0,01$  Protonenmasse. Das kontinuierliche  $\beta$ -Spektrum wäre dann verständlich unter der Annahme, dass beim  $\beta$ -Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Prime proprietà cinematiche: spin  $1/2$ , massa piccola, carica nulla

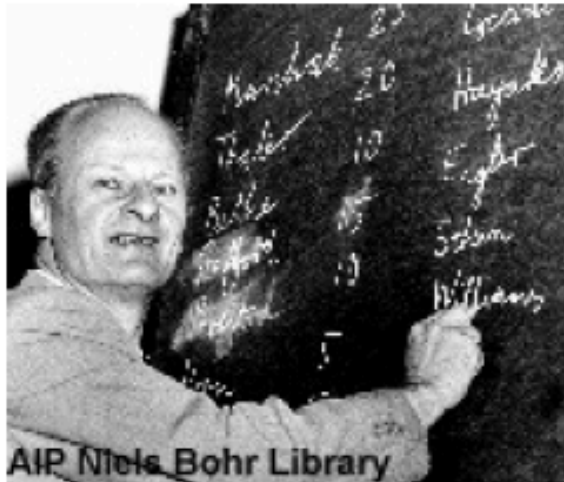
# Neutrini: trattazione teorica (1933-34)

1933, E. Fermi chiama questa particella neutrino e formula la teoria dei decadimenti deboli. Fermi afferma che dopo aver capito l'elettrodinamica quantistica, la teoria delle interazioni deboli conseguiva in modo naturale. E' la prima proposta di una interazione senza analogo classico



# Neutrini: trattazione teorica (1933-34)

1934, **Bethe e Peiers** calcolano la sezione d'urto per i processi  $\nu + n \rightarrow e^- + p$  e  $\bar{\nu} + p \rightarrow e^+ + n$ . L'articolo conclude: "... This meant that one obviously would never be able to see a neutrino." In effetti  $\sigma = 4\frac{G_F^2}{\pi} p_e E_e \simeq 2.3 \cdot 10^{-44} \text{cm}^2 \left(\frac{p_e E_e}{m_e^2}\right)$ , ciò vuol dire che in acqua la lunghezza di assorbimento per un neutrino da 2.5 MeV ( $\lambda = 1/n\sigma$ ) risulta  $2.5 \cdot 10^{20} \text{cm} \simeq$  lo spessore del disco della galassia, o un anno luce di piombo.



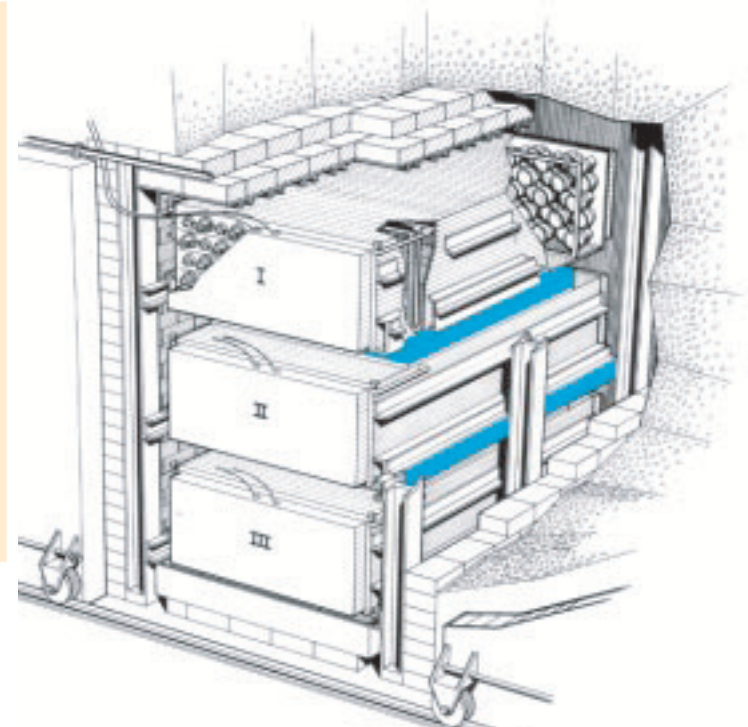
# Neutrini: la scoperta (1956)

Reines e Cowan a Los Alamos, dopo la fine della II guerra mondiale, cominciano comunque a studiare la possibilità di rivelare i neutrini emessi dai reattori nucleari. Un reattore nucleare emette un flusso di neutrini, fra 1 e 10 MeV:

$$\frac{d\Phi}{d\Omega} \simeq \frac{2 \cdot 10^{20}}{4\pi} \left( \frac{\text{Potenza}}{\text{GWatt}} \right) \frac{\bar{\nu}_\mu}{\text{srad}}$$

Installando un rivelatore di qualche centinaio di chili d'acqua a circa 10 m dal nocciolo di un reattore é così possibile rivelare qualche decina di eventi all'anno. (L'idea originale é di Pontecorvo, 1946.)

Evidenza di rivelazione di neutrini nell'esperimento decisivo al reattore di Savannah River nel South Carolina, 1956. Il premio Nobel verrà attribuito 40 anni dopo (!)



PHYSICAL REVIEW

VOLUME 117, NUMBER 1

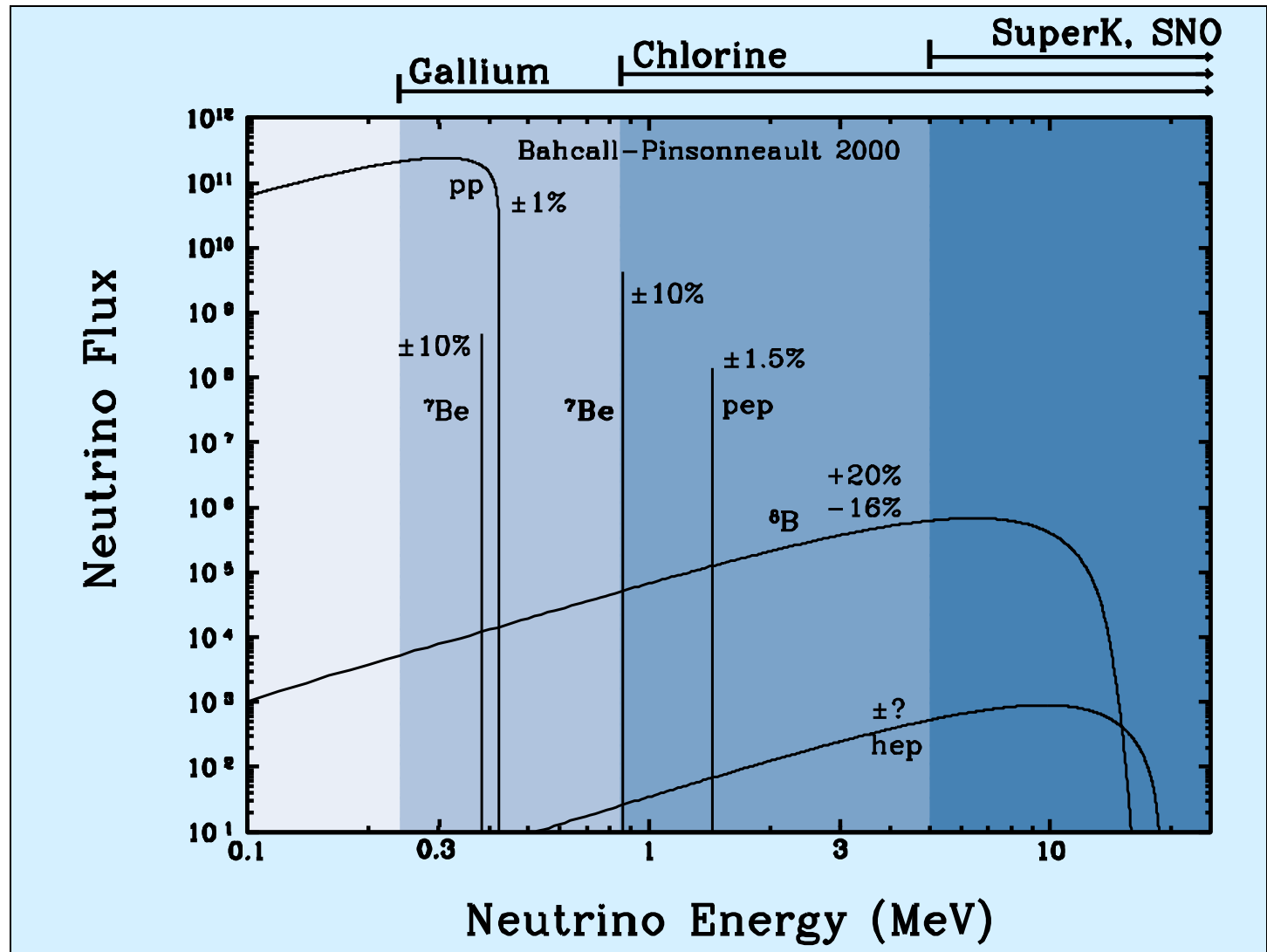
JANUARY 1, 1960

## Detection of the Free Antineutrino\*

F. REINES,† C. L. COWAN, JR.,‡ F. B. HARRISON, A. D. MCGUIRE, AND H. W. KRUSE  
*Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico*  
(Received July 27, 1959)

The antineutrino absorption reaction  $\bar{\nu}(\beta^+)_n$  was observed in two 200-liter water targets each placed between large liquid scintillation detectors and located near a powerful production fission reactor in an antineutrino flux of  $1.2 \times 10^{13} \text{ cm}^{-2} \text{ sec}^{-1}$ . The signal, a delayed-coincidence event consisting of the annihilation of the positron followed by the capture of the neutron in cadmium which was dissolved in the water target, was subjected to a variety of tests. These tests demonstrated that reactor-associated events occurred at the rate of  $3.0 \text{ hr}^{-1}$  for both targets taken together, consistent with expectations; the first pulse of the pair was due to a positron; the second to a neutron; the signal depended on the presence of protons in the target; and the signal was not due to neutrons or gamma rays from the reactor.

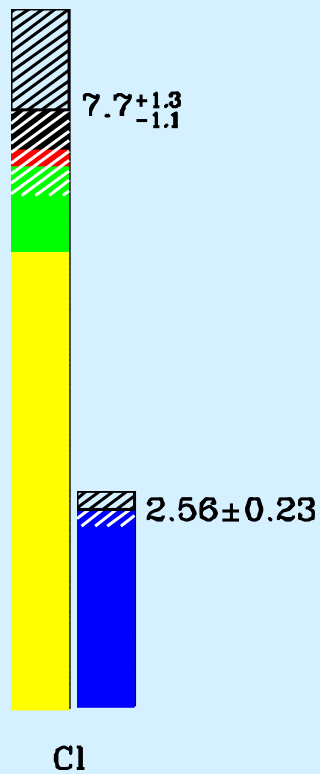
# Neutrini: anomalia nei neutrini solari ('60)





# Neutrini: anomalia nei neutrini solari ('60)

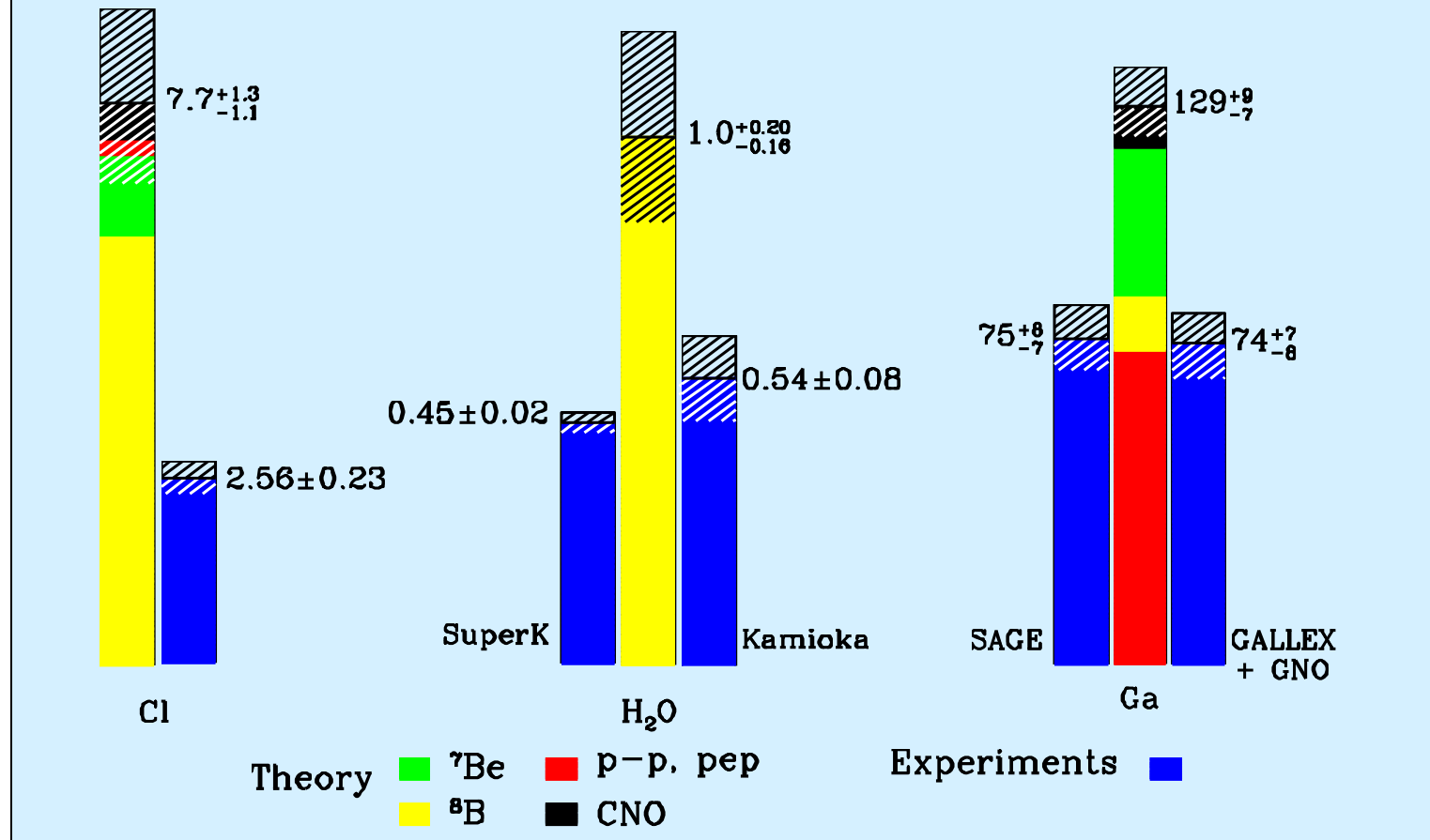
Total Rates: Standard Model vs. Experiment  
Bahcall-Pinsonneault 2000



Theory  $^7\text{Be}$   $^8\text{B}$  p-p, pep CNO Experiments

# Neutrini: anomalia nei neutrini solari ('90)

Total Rates: Standard Model vs. Experiment  
Bahcall-Pinsonneault 2000



# Neutrini: anomalia nei neutrini solari

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## Possibili cause:

- Modello teorico dell'emissione dei neutrini solari errato
- Errori sperimentali
- Nuova fisica nel cammino dei neutrini dal Sole alla Terra

## La soluzione (B. Pontecorvo, Maki, Nakagawa, Sakata):

- I neutrini hanno massa
  - Gli autostati di sapore non coincidono con gli autostati di massa
  - Neutrini emessi con un certo sapore, dopo aver percorso un cammino  $L$ , possono essere rivelati sotto forma di un altro sapore
-

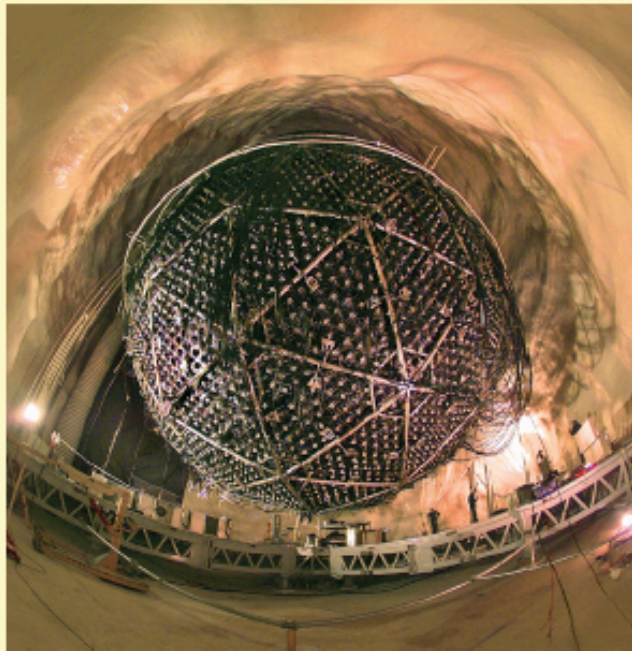
# Oscillazione di Neutrini

Analogia con esperimento di interferenza con due fenditure



$$P(\nu_\alpha \rightarrow \nu_\beta) = 4 \sin^2 \theta \cos^2 \theta \sin^2 \left( \frac{\Delta m_{ij}^2 L}{4E} \right) \quad (\text{Oscillazione periodica di sapore})$$

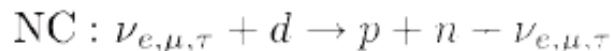
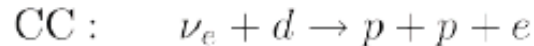
# Neutrini solari, la soluzione SNO (2002)



## Sudbury Neutrino Observatory:

1000 tonnellate di acqua pesante

(disponibili solo in Canada, per una serie di eventi e circostanze fortunate che hanno origine nelle ricerche nucleari francesi durante la II guerra mondiale)



$$\frac{\text{CC}}{\text{NC}} \sim \frac{\phi(\nu_e)}{\phi(\nu_e) + \phi(\nu_{\mu,\tau})}$$

quindi:

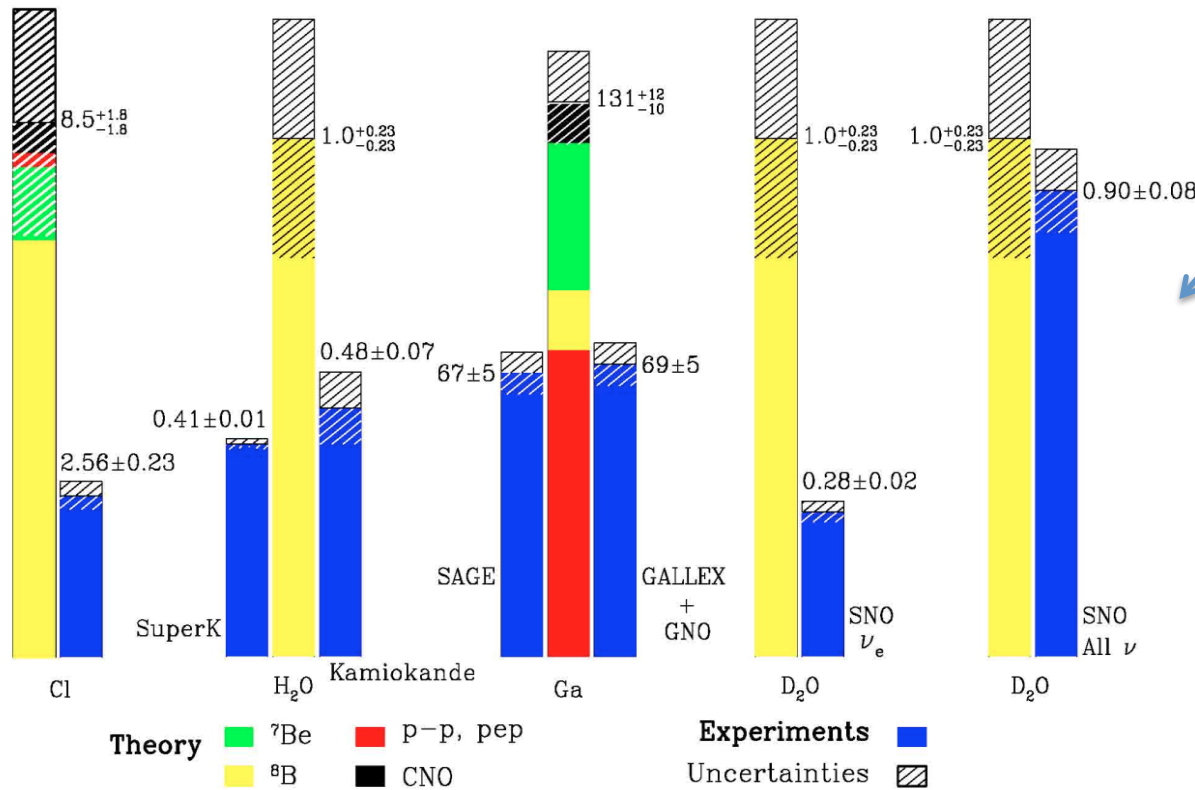
$$\frac{\text{CC}}{\text{NC}} < 1 \Rightarrow \phi(\nu_{\mu,\tau}) > 0 \Rightarrow \nu_e \rightarrow \nu_{\mu,\tau}$$

**SNO, 2002: CC/NC ~ 1/3**

Evidenza di cambiamento di sapore indipendente da modelli


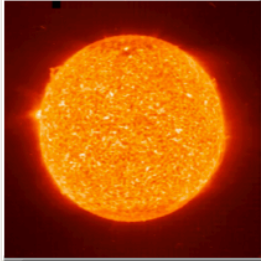

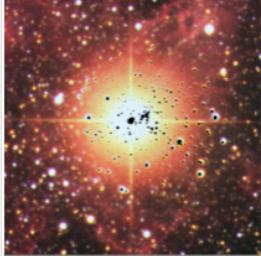
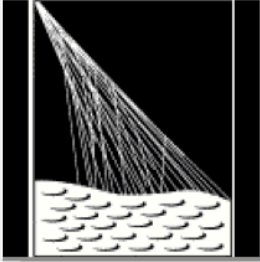
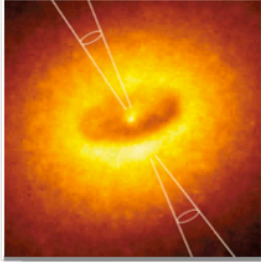

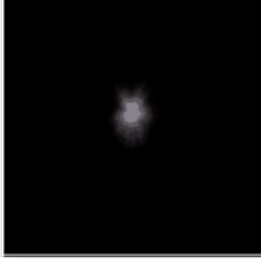
# Neutrini solari, la soluzione SNO (2002)

Total Rates: Standard Model vs. Experiment  
Bahcall-Pinsonneault 2004



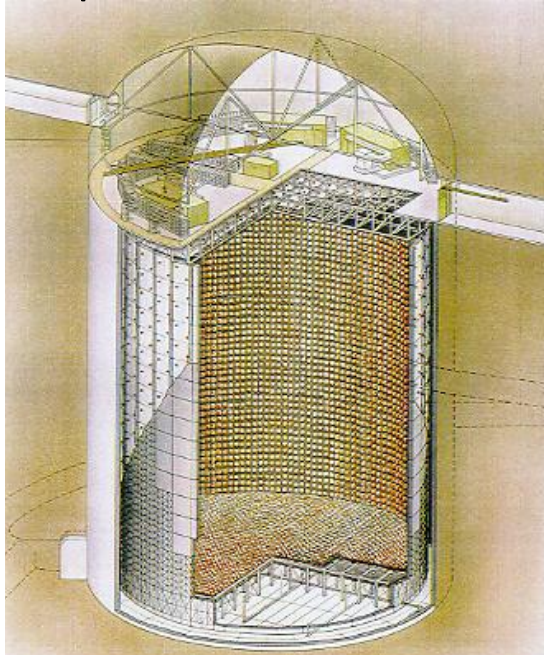
Le interazioni a corrente neutra (sensibili a tutti i sapori di neutrini) sono in accordo con quanto previsto dalla teoria.

# Sorgenti di neutrini naturali e artificiali

✓ Nuclear Reactors			Sun ✓
✓ Particle-Accelerators			Supernovae (Stellar Collapse) SN 1987A ✓
✓ Earth Atmosphere (Cosmic Rays)			Astrophysical Accelerators Soon ?
2003 ? Earth Crust (Natural Radioactivity)			Cosmic Big Bang (Today $330 \text{ v/cm}^3$ ) Indirect Evidence

# Un altro canale: $n_m \rightarrow n_t$

## Super-Kamiokande

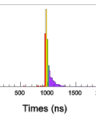
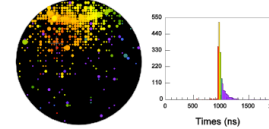
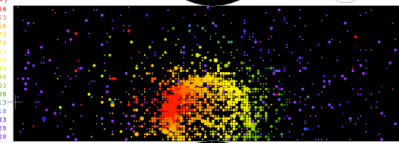


electron-like event

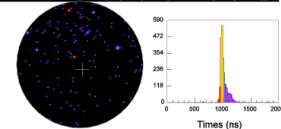
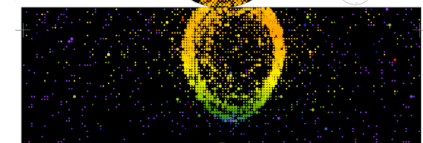
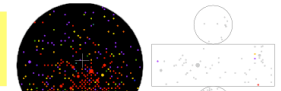
D Wall: 897.4 cm  
PC e-like: p = 443.8 Metric

Time (ns)

- 0-258
- 259-517
- 518-775
- 776-1033
- 1034-1291
- 1292-1550
- 1551-1809
- 1810-2067
- 2068-2326
- 2327-2585
- 2586-2843
- 2844-3102
- 3103-3360
- 3361-3619
- 3620-3877
- 3878-4136
- 4137-4394
- 4395-4652
- 4653-4910
- 4911-5168
- 5169-5426
- 5427-5684
- 5685-5942
- 5943-6200
- 6201-6458
- 6459-6716
- 6717-6974
- 6975-7232
- 7233-7490
- 7491-7748
- 7749-8006
- 8007-8264
- 8265-8522
- 8523-8780
- 8781-9038
- 9039-9295
- 9296-9553
- 9554-9811
- 9812-10070
- 10071-10328
- 10329-10586
- 10587-10844
- 10845-11103
- 11104-11361
- 11362-11620
- 11621-11878
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- 12395-12652
- 12653-12910
- 12911-13168
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- 13943-14200
- 14201-14458
- 14459-14716
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- 18587-18844
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- 19619-19876
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- 27359-27616
- 27617-27874
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- 28649-28906
- 28907-29164
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- 29423-29680
- 29681-29938
- 29939-30196
- 30197-30454
- 30455-30712
- 30713-30970
- 30971-31228
- 31229-31486
- 31487-31744
- 31745-32002
- 32003-32260
- 32261-32518
- 32519-32776
- 32777-33034
- 33035-33292
- 33293-33550
- 33551-33808
- 33809-34066
- 34067-34324
- 34325-34582
- 34583-34840
- 34841-35098
- 35099-35356
- 35357-35614
- 35615-35872
- 35873-36130
- 36131-36388
- 36389-36646
- 36647-36904
- 36905-37162
- 37163-37420
- 37421-37678
- 37679-37936
- 37937-38194
- 38195-38452
- 38453-38710
- 38711-38968
- 38969-39226
- 39227-39484
- 39485-39742
- 39743-40000



muon-like event



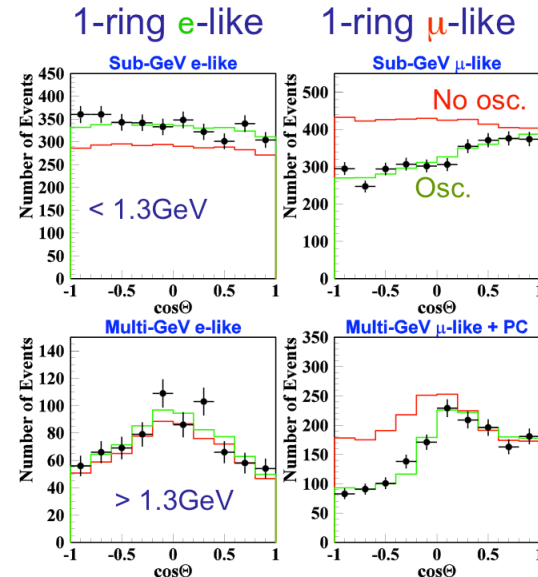
e: electromagnetic shower, multiple Coulomb scattering

$\mu$ : propagate almost straightly, loose energy by ionization loss

Difference in the event pattern

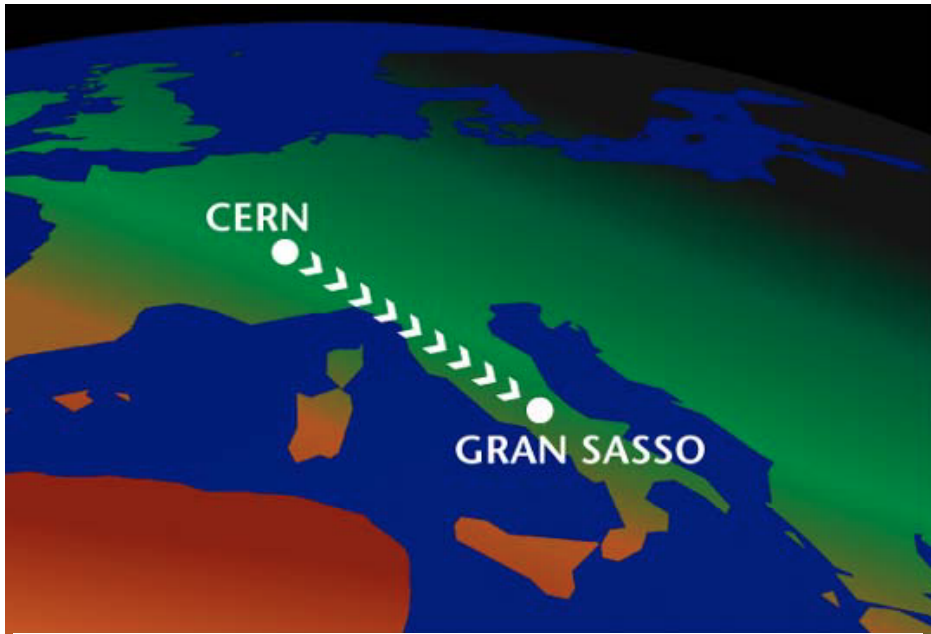
Eventi indotti da  $\nu_e$ :  $\sim$  come previsto  
Eventi indotti da  $\nu_\mu$ : deficit dal basso

Oscillazioni  $\nu_\mu \rightarrow \nu_e$ ? **No** (o secondarie)  
Oscillazioni  $\nu_\mu \rightarrow \nu_\tau$ ? **Si** (dominanti)





# Un altro canale: $n_m \rightarrow n_t$

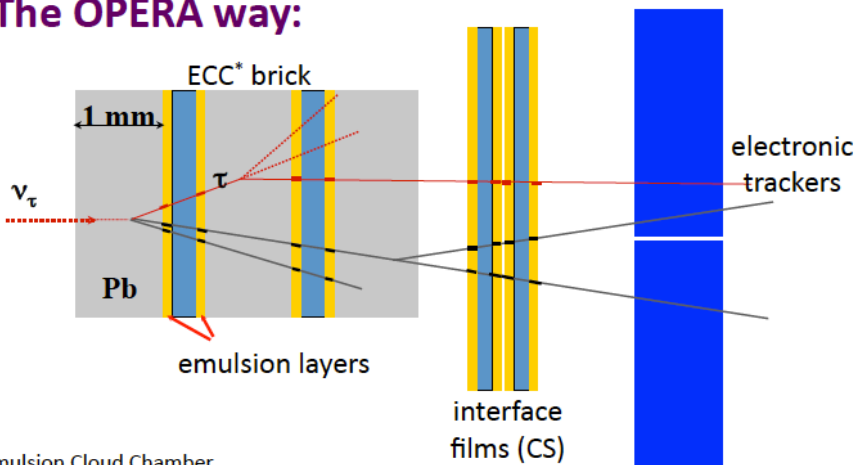


26 marzo 2013

COMUNICATO STAMPA: OPERA VEDE IL TERZO NEUTRINO TAU

La collaborazione internazionale OPERA ai Laboratori Nazionali del Gran Sasso ha osservato per la terza volta un neutrino "tau". Si tratta di un neutrino partito dal CERN come neutrino di sapore muonico che, nel percorrere i 730 chilometri che separano Ginevra dai LNGS, ha cambiato "sapore" trasformandosi in neutrino di tipo tau. Un evento rarissimo che conferma le precedenti osservazioni del 2012 e 2010 e che comporta la prova del fenomeno dell'oscillazione del neutrino per cui è stato concepito, nel 2001, il gigantesco rivelatore OPERA orientato in direzione del CERN dove un fascio di neutrini muonici viene prodotto in direzione dei LNGS. OPERA cerca i neutrini tau sapendo che in partenza dal CERN i neutrini sono tutti muonici. Trovare neutrini di un altro sapore comporta la prova dell'esistenza dell'oscillazione durante i 730 chilometri di viaggio. Questi nuovi dati vengono presentati oggi ai LNGS nell'ambito del seminario "New results of the OPERA experiment".

## The OPERA way:



\*Emulsion Cloud Chamber

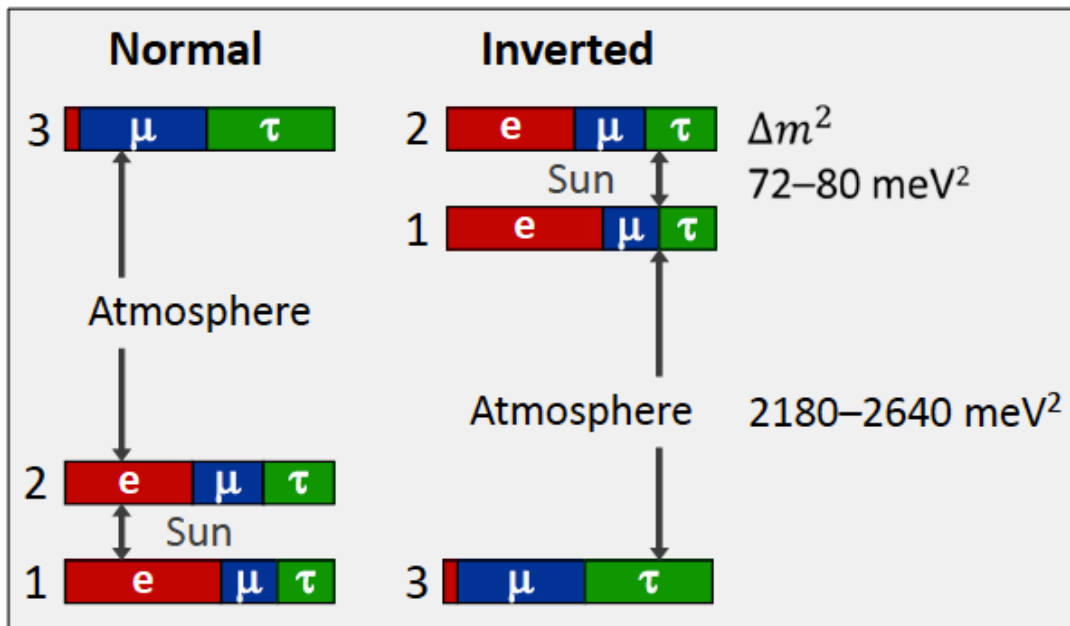


# Neutrino oscillation summary

Three mixing angles  $\theta_{12}, \theta_{13}, \theta_{23}$  (Euler angles for 3D rotation),  $c_{ij} = \cos \theta_{ij}$ , a CP-violating “Dirac phase”  $\delta$ , and two “Majorana phases”  $\alpha_2$  and  $\alpha_3$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{39^\circ < \theta_{23} < 53^\circ} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix}}_{7^\circ < \theta_{13} < 11^\circ} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{33^\circ < \theta_{12} < 37^\circ} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_2}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_3}{2}} \end{pmatrix}}_{\text{Relevant for } 0\nu 2\beta \text{ decay}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric/LBL-Beams
Reactor
Solar/KamLAND
Relevant for  $0\nu 2\beta$  decay



## Tasks and Open Questions

- Precision for all angles
- CP-violating phase  $\delta$ ?
- Mass ordering?  
(normal vs inverted)
- Absolute masses?  
(hierarchical vs degenerate)
- Dirac or Majorana?

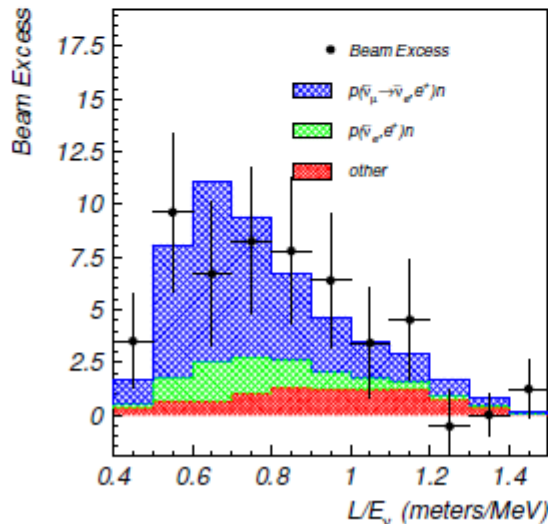
# Neutrino: + di 3 sapori, neutrino sterile ?

## ● LSND:

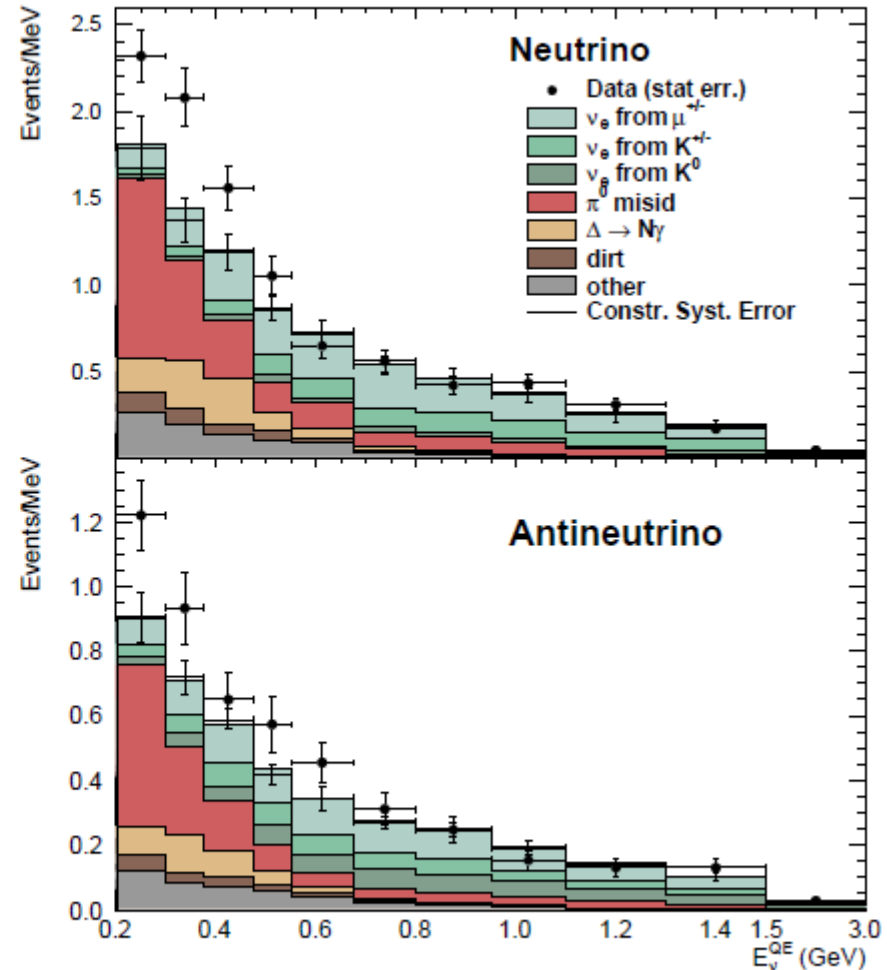
- ▶  $\bar{\nu}_e$  appearance in  $\bar{\nu}_\mu$  beam from stopped pion source ( $> 3\sigma$ )

## ● MiniBooNE:

- ▶ No significant  $\nu_e$  or  $\bar{\nu}_e$  excess in the LSND-preferred region
- ▶ but  $\bar{\nu}_e$  consistent with LSND
- ▶ Low- $E$  excess not understood



LSND hep-ex/0104049



MiniBooNE arXiv:1207.4809

# Neutrino: + di 3 sapori, neutrino sterile ?

irfu

cea

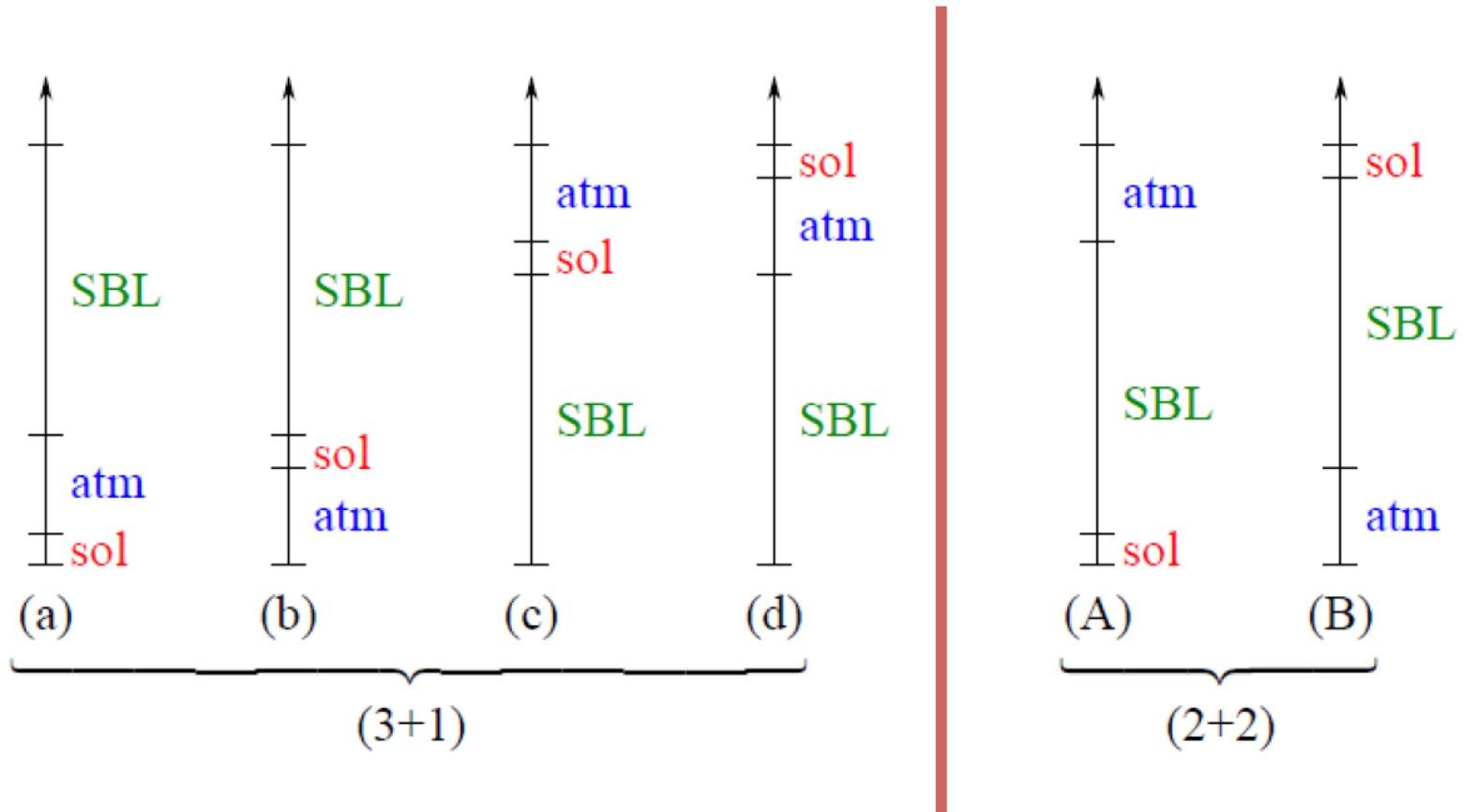
saclay

## Many experimental projects



Sources	Reactors	Beams
<b>CeLAND</b> $^{144}\text{Ce}$ 75 kCi @ KamLAND funded	<b>Nucifer</b> 7 m from Osiris reactor Data taking	<b>IsoDAR</b> Cyclotron to produce $^8\text{Li}$ arXiv:1205.4419
<b>SoX in Borexino</b> $^{51}\text{Cr}$ > 5 MCi & $^{144}\text{Ce}$ funded	<b>Stereo</b> 8m @ ILL	<b>OscSNS</b> New « Karmen type » exp. arXiv:0810.3175
<b>Baksan</b> $^{51}\text{Cr}$ 3 MCi unlikely funded	<b>Solid</b> 8m @ ILL	<b>MicroBoone</b> Clarification of LSND/MiniBoone anomalies ?
<b>SNO+ / LENS</b> $^{51}\text{Cr}$ 10 MCi R & D	<b>Scream, Neutrino-4, DANNS, Poseidon</b>	<b>Icarus/Nessie</b> 2 liq. Ar detec @ CERN
<b>Katrin</b> $^3\text{He}$ in construction	...	...

$$3+1 \neq 2+2$$



**4 neutrinos = 6 mixing angles and 3 CP phases**



# Come “dare” massa al neutrino ?

- See-saw mechanism ?

M. Gell-Mann, P. Ramond and R. Slansky, in *Supergravity*, ed. by P. van Nieuwenhuizen and D. Z. Freedman (North Holland, Amsterdam, 1979), p. 315; T. Yanagida, in *Proc. of the Workshop on the Unified Theory and Baryon Number in the Universe*, ed. By O. Sawada and A. Sugamoto (KEK report 79-18, 1979), p.95, Tsukuba, Japan; R.N. Mohapatra and G. Senjanović, *Phys. Rev. Lett.* 44 (1980) 912

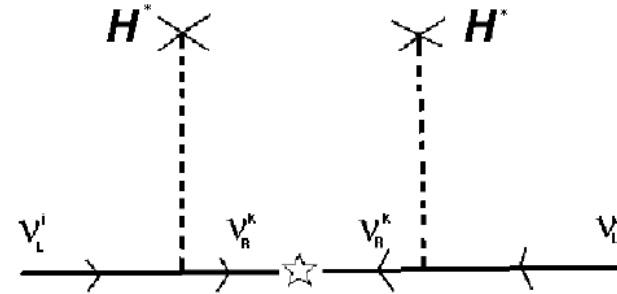
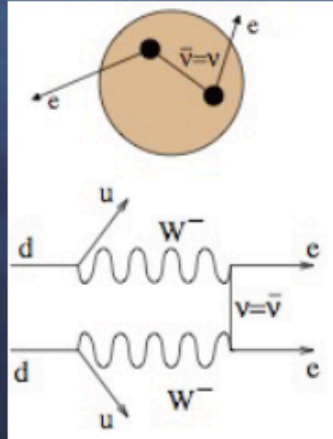


Figure 6: Diagram for the see-saw neutrino masses. The right-handed neutrinos are supposed to be heavy, and act only as quantum fluctuations. However, they introduce a new ingredient, the violation of the lepton number (testified by the clashing arrows). Instead, the  $U(1)_Y$  charge flows in the vacuum through the HIGGS boson lines.

- Iso-Tripletto di Higgs ?
- Cambiamo gruppo di gauge ?  $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- Operatori non rinormalizzabili ?

F. Vissani, arXiv: hep-ph/0007040  
E. Ahkmedov, arXiv: hep-ph/0001264

# Neutrino-less double-beta decay



Nuclear process:  $(A, Z) \rightarrow (A, Z+2) + 2 e^-$

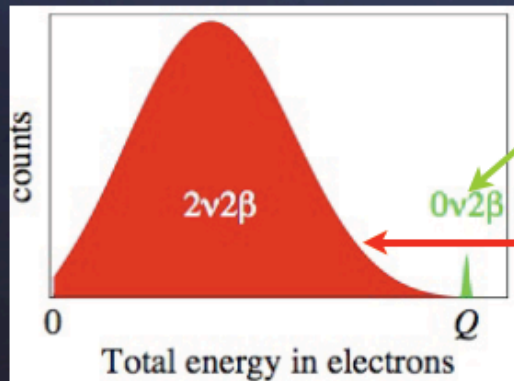
The measurable quantity is the half-life ( $T_{1/2}^{0\nu}$ ):

$$\frac{1}{T_{1/2}^{0\nu}} = G(Q, Z) |M_{nucl}|^2 |m_{\beta\beta}|^2$$

Phase space factor:  $\sim Q^5$

Nuclear Matrix Element

Effective neutrino mass



Signature: monochromatic line at the Q-Value

Backgrounds:

- Double Beta Decay
- Primordial U,Th ( $\tau \sim 10^9$  y)
- Neutron and cosmic induced

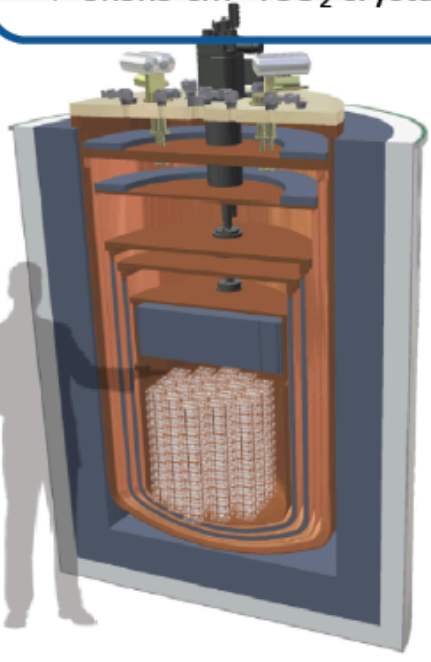
If observed  $\longrightarrow$  MAJORANA NEUTRINO



# 0n2b-decay experiments: CUORE

Searching for neutrinoless double beta decay of  $^{130}\text{Te}$

- ▶  $^{130}\text{Te}$  good DBD candidate: high natural abundance (34.2 %), reasonably high Q-value (2528 keV)
- ▶  $\text{TeO}_2$  is a compound with good mechanical and thermal properties containing  $^{130}\text{Te}$
- ▶  $5 \times 5 \times 5 \text{ cm}^3$   $\text{TeO}_2$  crystals have a high detection efficiency for  $0\nu\beta\beta$  events:  $\sim 87.4\%$

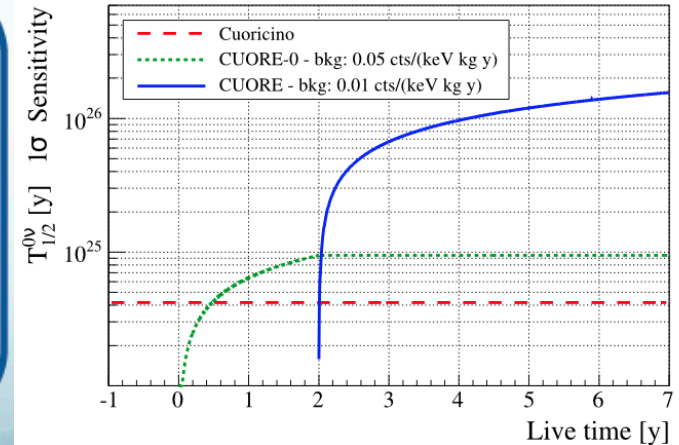


In Hall A of LNGS

CUORE Hut

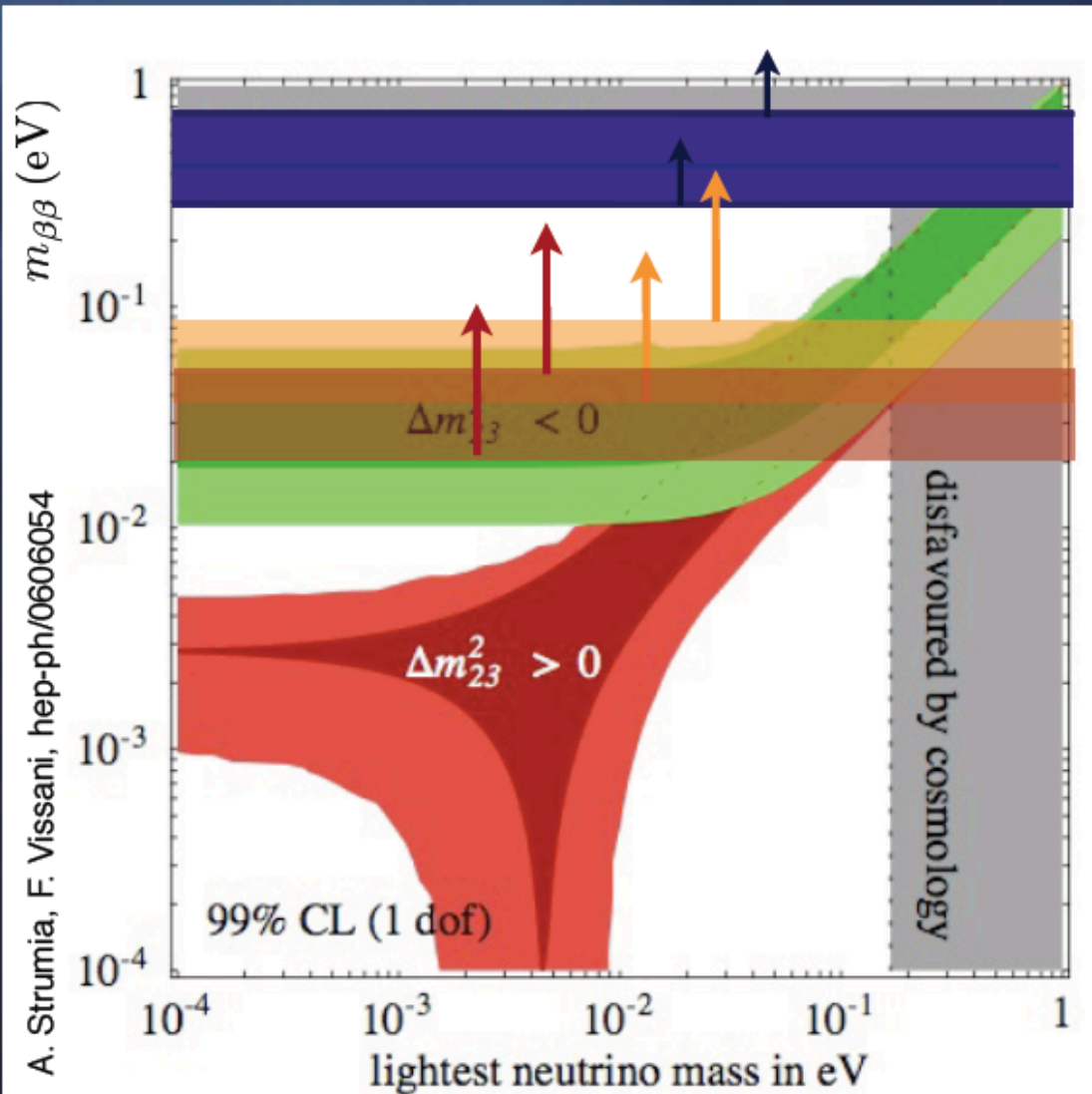


**CUORE setup**  
**988  $\text{TeO}_2$   $5 \times 5 \times 5 \text{ cm}^3$  crystals**  
(750 g each)  
**Detector Mass: 741 kg  $\text{TeO}_2$**   
 **$^{130}\text{Te}$  mass (natural i.a.) :**  
206 kg of  $^{130}\text{Te}$   
**Array: 19 towers**



**CUORE background goal: 0.01 counts/kg keV y**

# 0n2b-decay experiments: CUORE



## CUORICINO

$$m_{\beta\beta} < 0.3 \div 0.7 \text{ eV}$$

## CUORE "BASELINE"

background @0vDBD  
0.01 counts/keV/kg/y

$$m_{\beta\beta} < 35 \div 82 \text{ meV}$$

## CUORE "OPTIMISTIC"

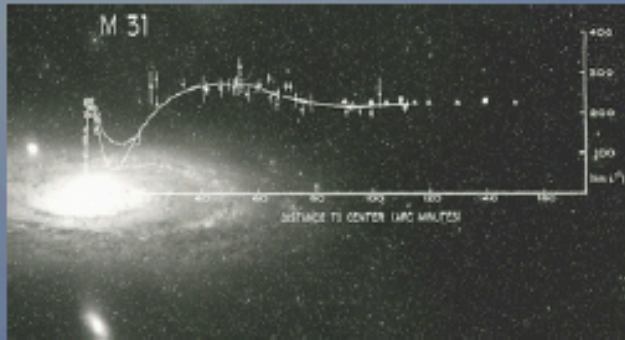
background @0vDBD  
0.001 counts/keV/kg/y

$$m_{\beta\beta} < 20 \div 47 \text{ meV}$$

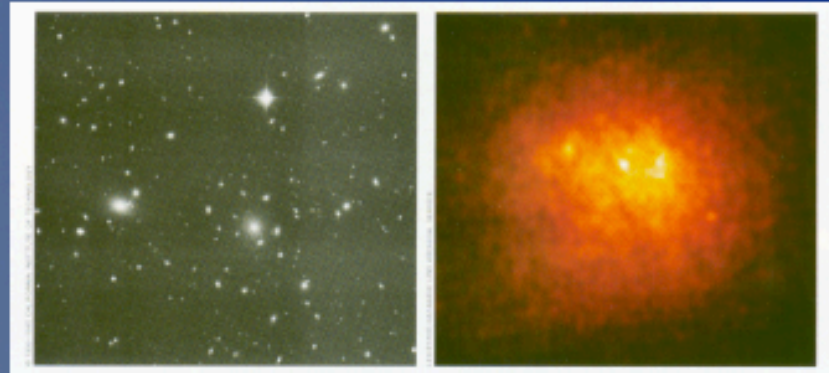
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# Dark Matter

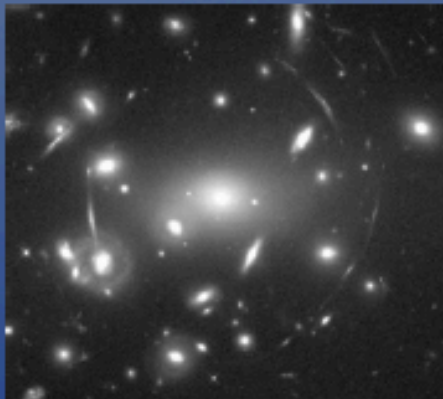
# Velocità di rotazione delle galassie



Galactic rotation curves:  
Newton says  $v_c \sim 1/\sqrt{r}$   
Observed  $v_c = \text{constant}$

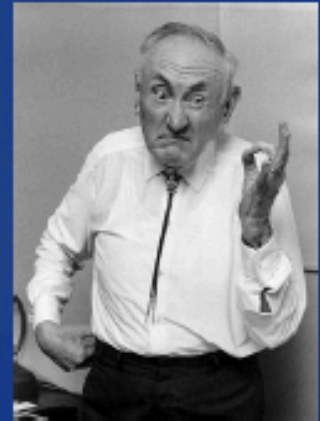


Coma cluster:  
Virial theorem states  $\langle V \rangle + 2 \langle K \rangle = 0$   
Measurements of  $\langle V \rangle$  (mass via x-ray)  
disagree with measurements of  $\langle K \rangle$  (velocities)  
by factor 100



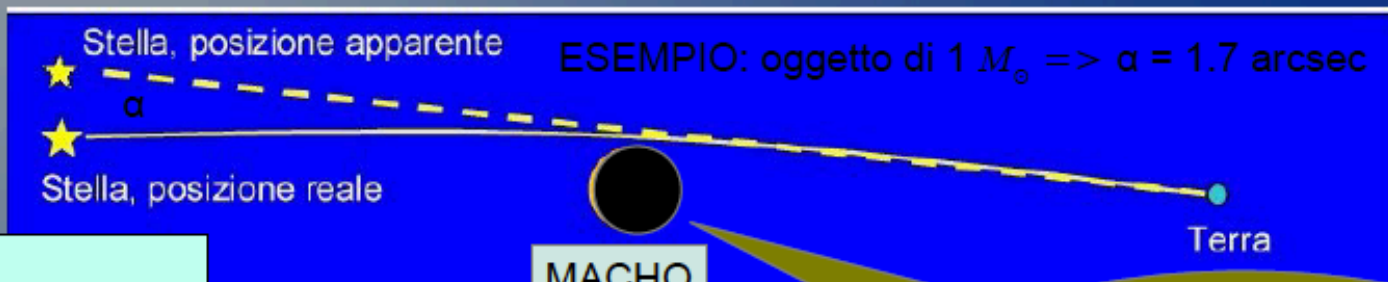
Gravitational lensing

Much more gravitational than luminous mass  
Implies existence of "dark matter" coined by  
Fritz Zwicky in 1933



# Lensing gravitazionale

La gravità può influenzare la traiettoria dei fotoni agendo come una *lente*.



$$\alpha = \frac{4GM}{c^2 b}$$

Misurando  $\alpha$  si può calcolare M

Nane brune, nane bianche,  
stelle di neutroni e buchi neri:  
MACHO (Massive Compact  
Halo Objects)

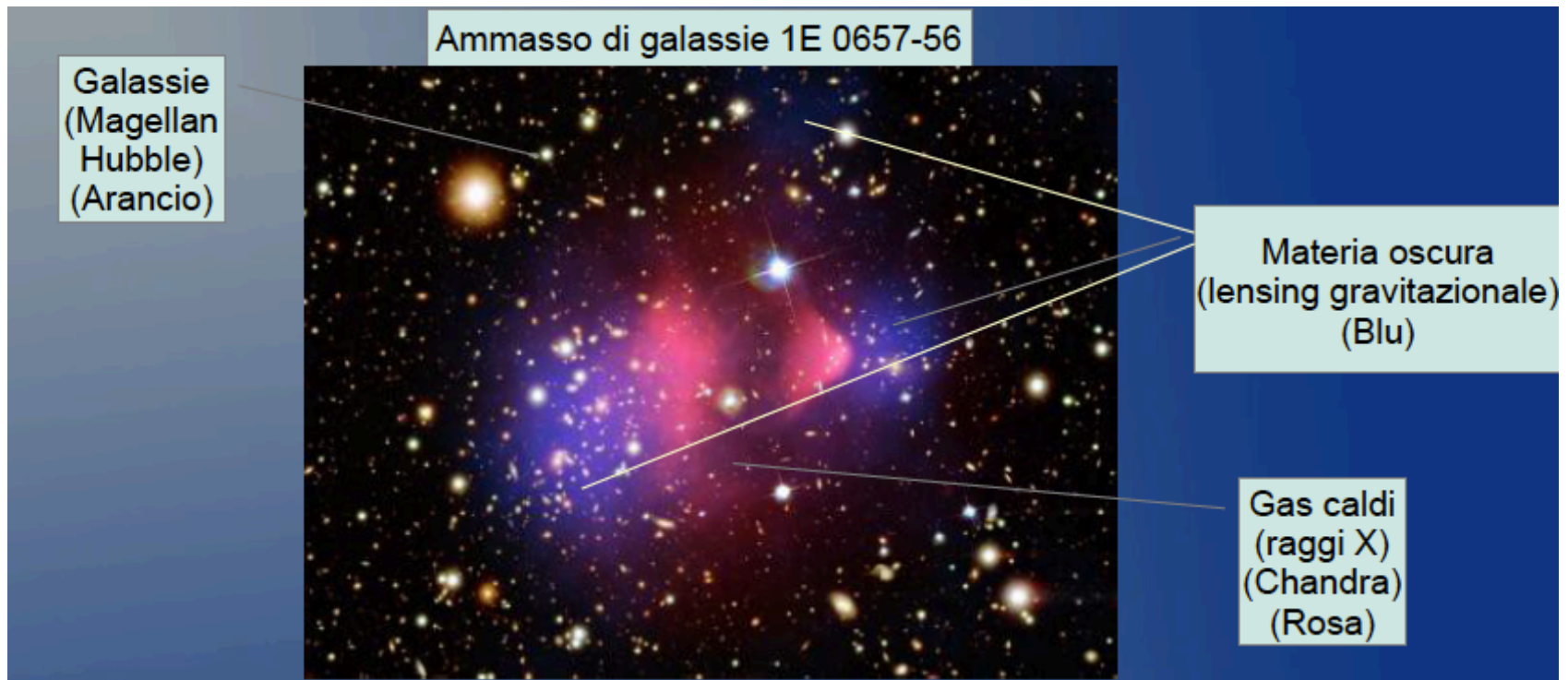


Le lenti gravitazionale sono presenti a qualsiasi scala di masse.

Esempio: Lensing gravitazionale nell'ammasso *Abel 2218*.

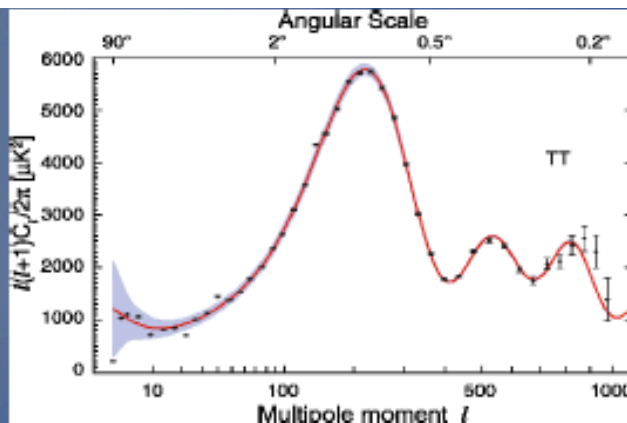
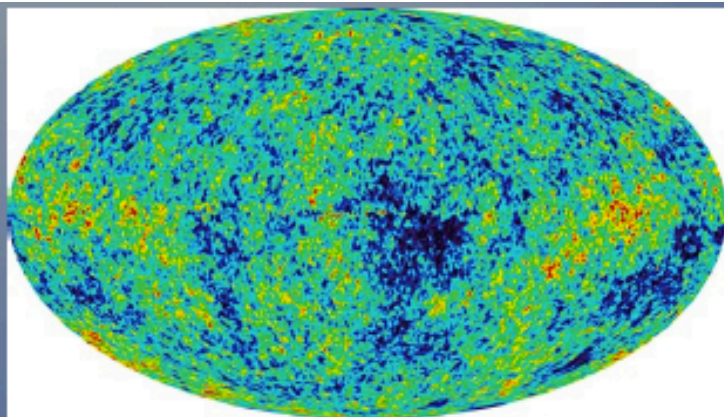
( $z = 0.18$  ;  $d = 770 \text{ Mpc}$ )

# Bullet Cluster



- ➔ Formato circa 150 milioni di anni fa a causa della collisione di due ammassi più piccoli.
- ➔ Evidenza diretta di come materia oscura e materia barionica abbiano proprietà differenti: I gas si urtano e si riscaldano ( $T_{\text{gas}} \approx 10^8 \text{ K}$ ) => forte onda d'urto (proiettile); galassie e materia oscura si compenetrano senza urtarsi.
- ➔ Fenomeno temporaneo: la gravità fra qualche milione d'anni riporterà l'ammasso alla configurazione di materia barionica immersa in un alone di D.M.

# Fluttuazioni di temperatura nella CMB



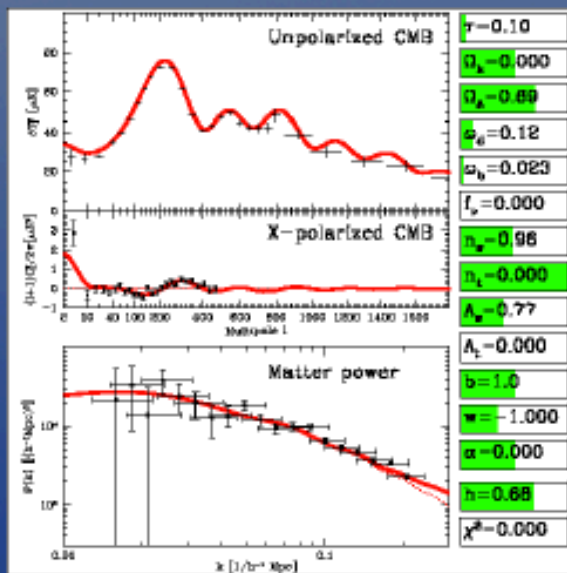
Measurements by  
WMAP, Planck

$$\Omega_{\text{tot}} = 1$$

$$\Omega_{\text{m}} = 0.27$$

$$\Omega_{\text{b}} = .045$$

Non-baryonic dark  
matter



Hot (relativistic) Dark Matter

Suppresses small scale structure formation

Baryons drive structure formation, dark matter follows

Cold Dark Matter

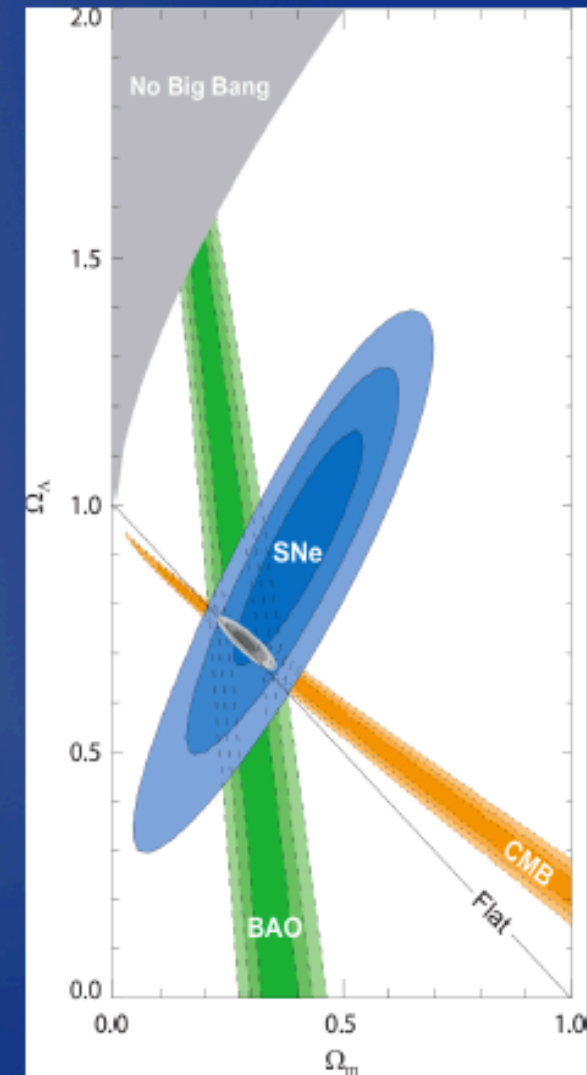
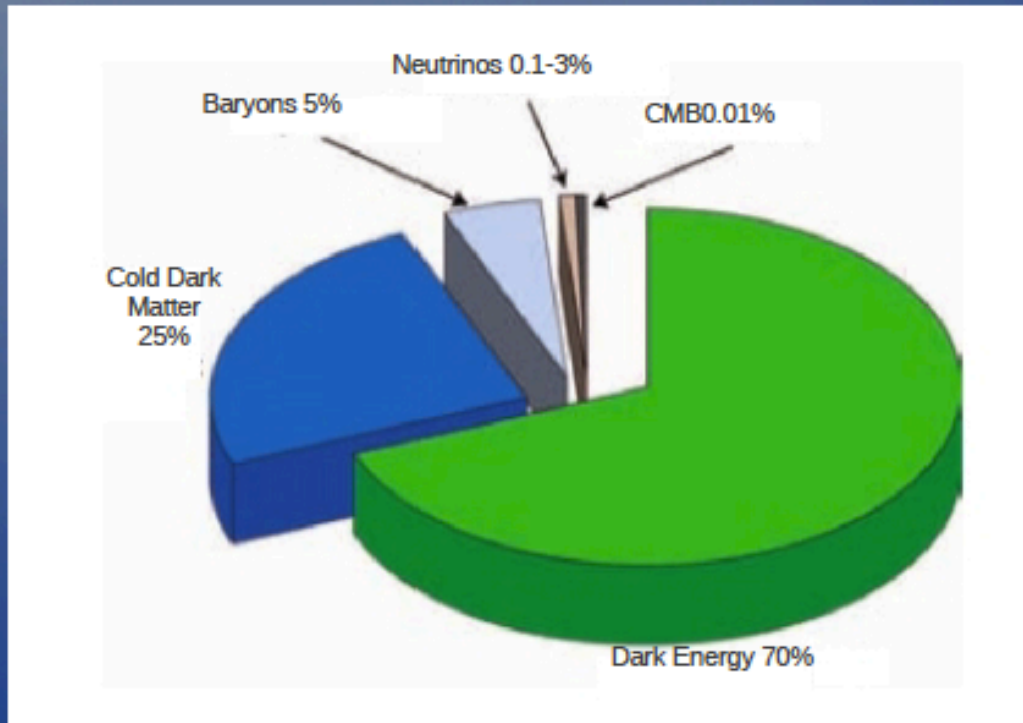
Necessary to produce observed structure

Dark matter drives structure formation, baryons follow

# Modello $\Lambda$ CDM

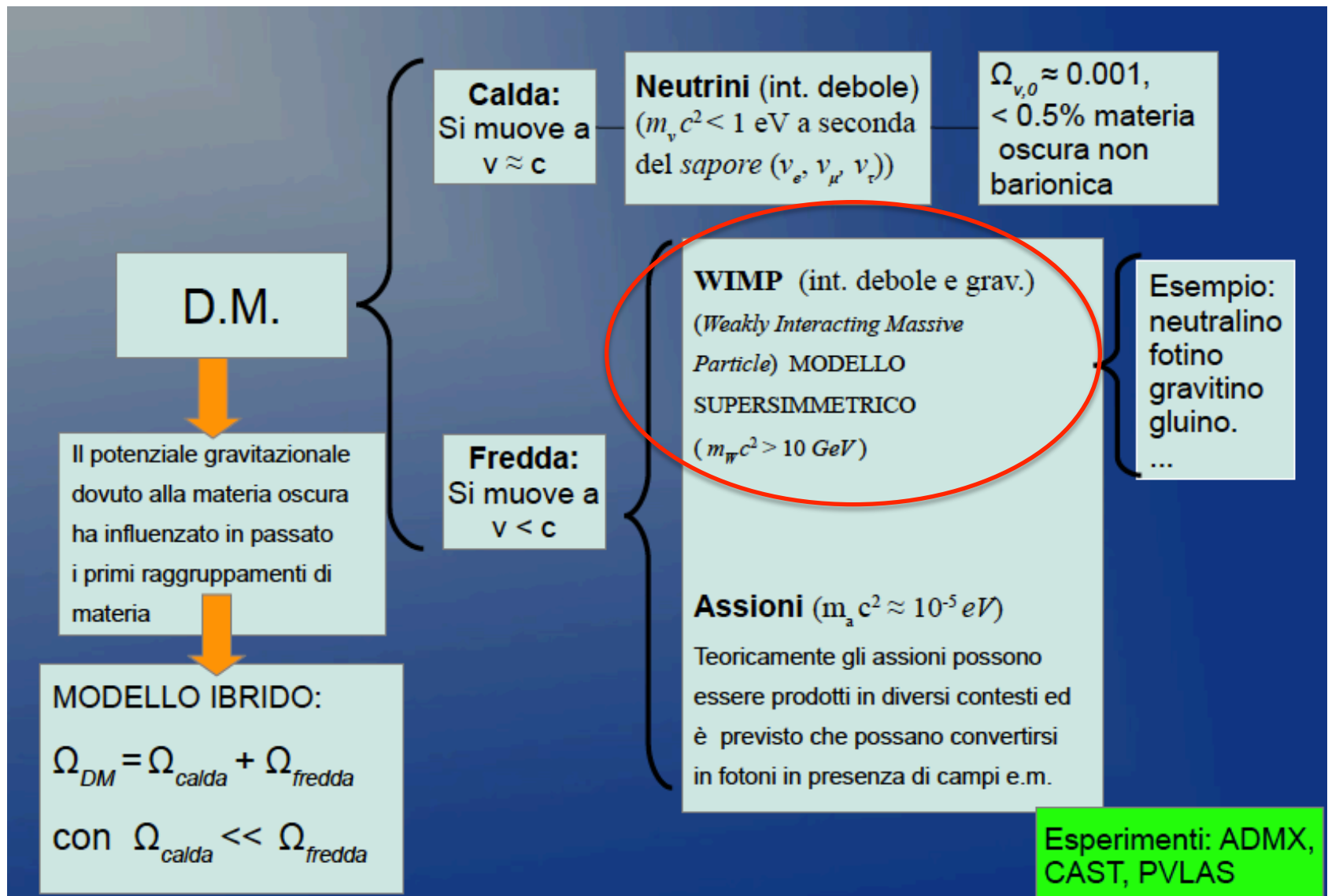
Evidence from many experiments point to same model

Our universe contains dark energy and non-baryonic cold dark matter





# Candidati per la Dark Matter



# “The WIMP miracle”

Dark matter in thermal equilibrium in early universe

Decouples as universe expands

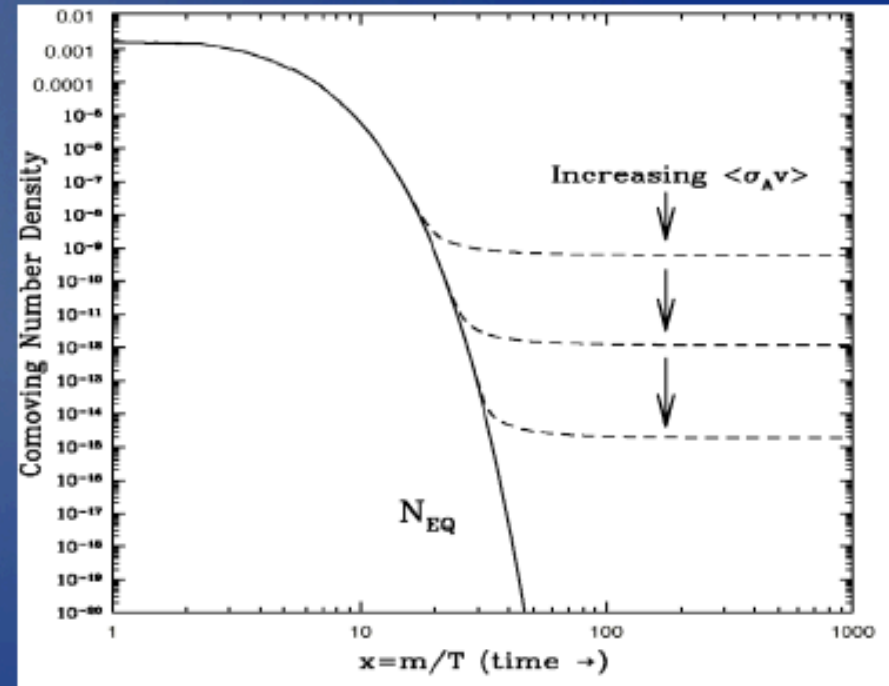
Thermal relic → present today

The WIMP coincidence

$$\Omega h^2 = \frac{3 \cdot 10^{-27} \text{ cm}^3 \text{ s}^{-1}}{\sigma_{AV}}$$

Weak scale cross section yields correct abundance

Weakly Interacting Massive Particle (WIMP)



# SUSY e Dark Matter

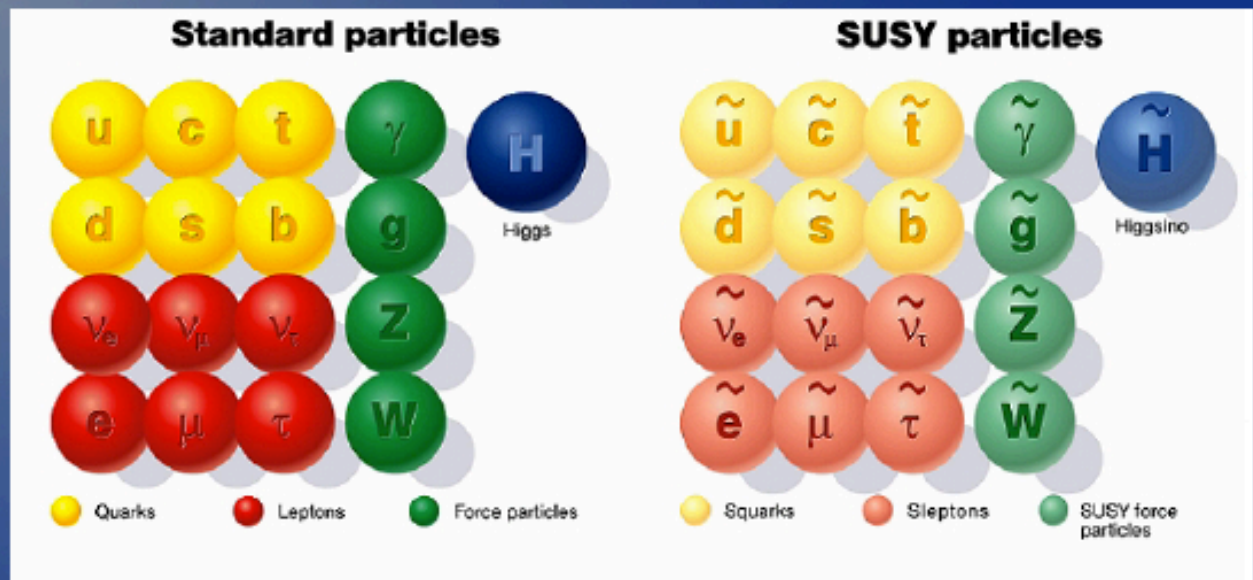
## Supersymmetry (SUSY)

Natural extension for physics beyond the SM

Solves many theoretical problems

Natural dark matter candidate

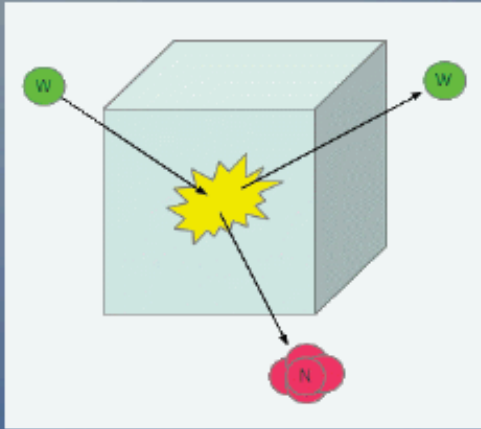
Neutralino:  
Superposition of neutral gauge and Higgs bosons



# La ricerca di WIMP

## Rivelazione diretta:

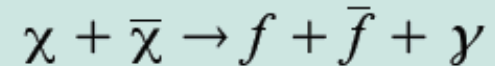
Scattering di WIMP su nuclei bersaglio



## Metodi

## Rivelazione indiretta:

Rivelazione dei prodotti delle reazioni di annichilazione delle WIMP nell'alone galattico, nel Sole e nella Terra



Dove:  $\chi$  = WIMP,  $f$  = fermione (neutrino, leptone o quark),  $\gamma$  = fotone.

Si pensa che un flusso di WIMP sia presente nella galassia e che attraversi la Terra. Stime ragionevoli indicano che:

$$\begin{cases} \rho_0 \approx 0.3 \text{ GeV/cm}^3 \\ \langle v \rangle \approx 270 \text{ Km/s} \end{cases}$$

Il rate di eventi attesi per scattering su nuclei bersaglio è:

$$R \propto N_t \frac{\rho_0}{m_\chi} \sigma_{\chi n} \langle v \rangle$$

Abbiamo:

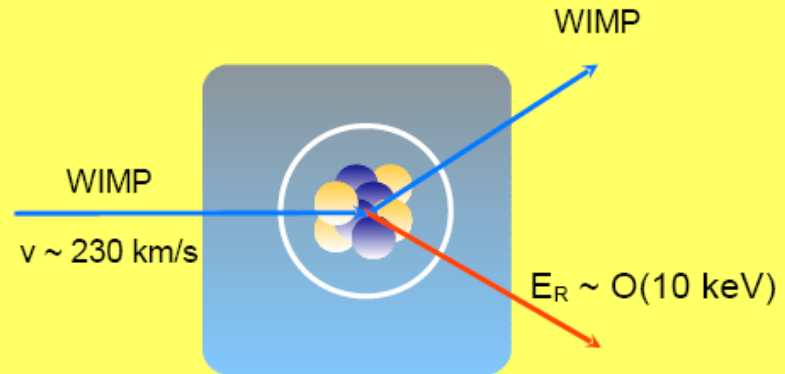
$$\sigma_{\chi\chi} \approx \sigma_{v,nucleo}$$

Inoltre: flusso dei prodotti  $\propto (\rho_{DM})^2$

=> conviene indirizzare la ricerca nelle regioni a più alta densità

# Ricerca diretta di WIMP

Elastic Scattering of  
WIMPs off target nuclei  
→ nuclear recoil



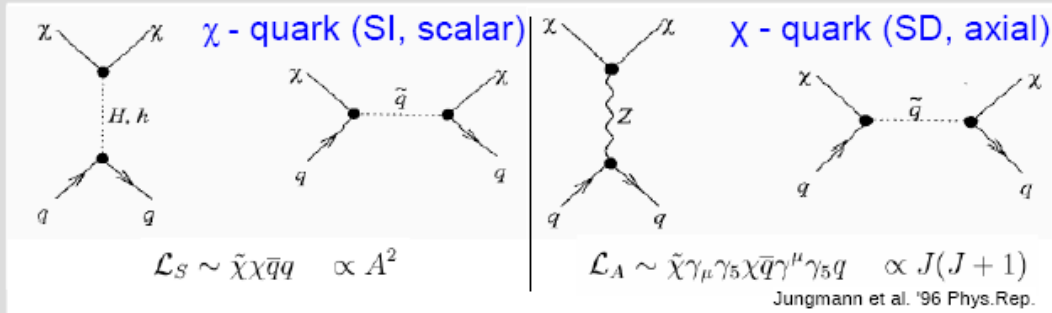
Recoil Energy: 
$$E_r = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N} (1 - \cos \theta) \sim \mathcal{O}(10 \text{ keV})$$

Event Rate: 
$$R \propto N \frac{\rho_X}{m_X} \langle \sigma_{X-N} \rangle$$

$N$  number of target nuclei  
 $\rho_X/m_X$  local WIMP density  
 $\langle \sigma \rangle$  velocity-averaged scatt. X-section

→ need information on halo and interaction to get rate

# Ricerca diretta di WIMP



Result: Tiny Rates

$$R < 0.01 \text{ evt/kg/day}$$

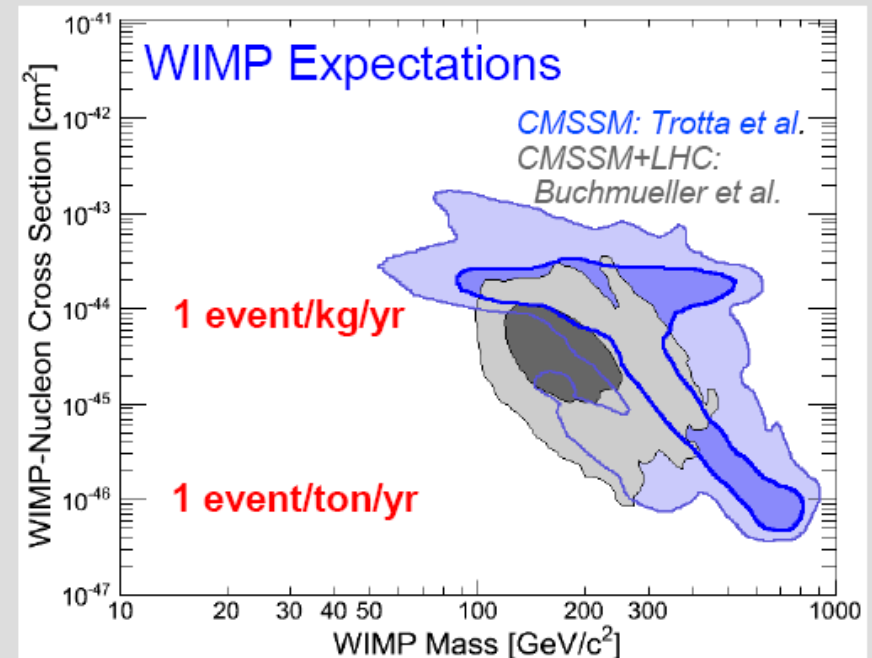
$$E_r < 100 \text{ keV}$$

## What do we look for?

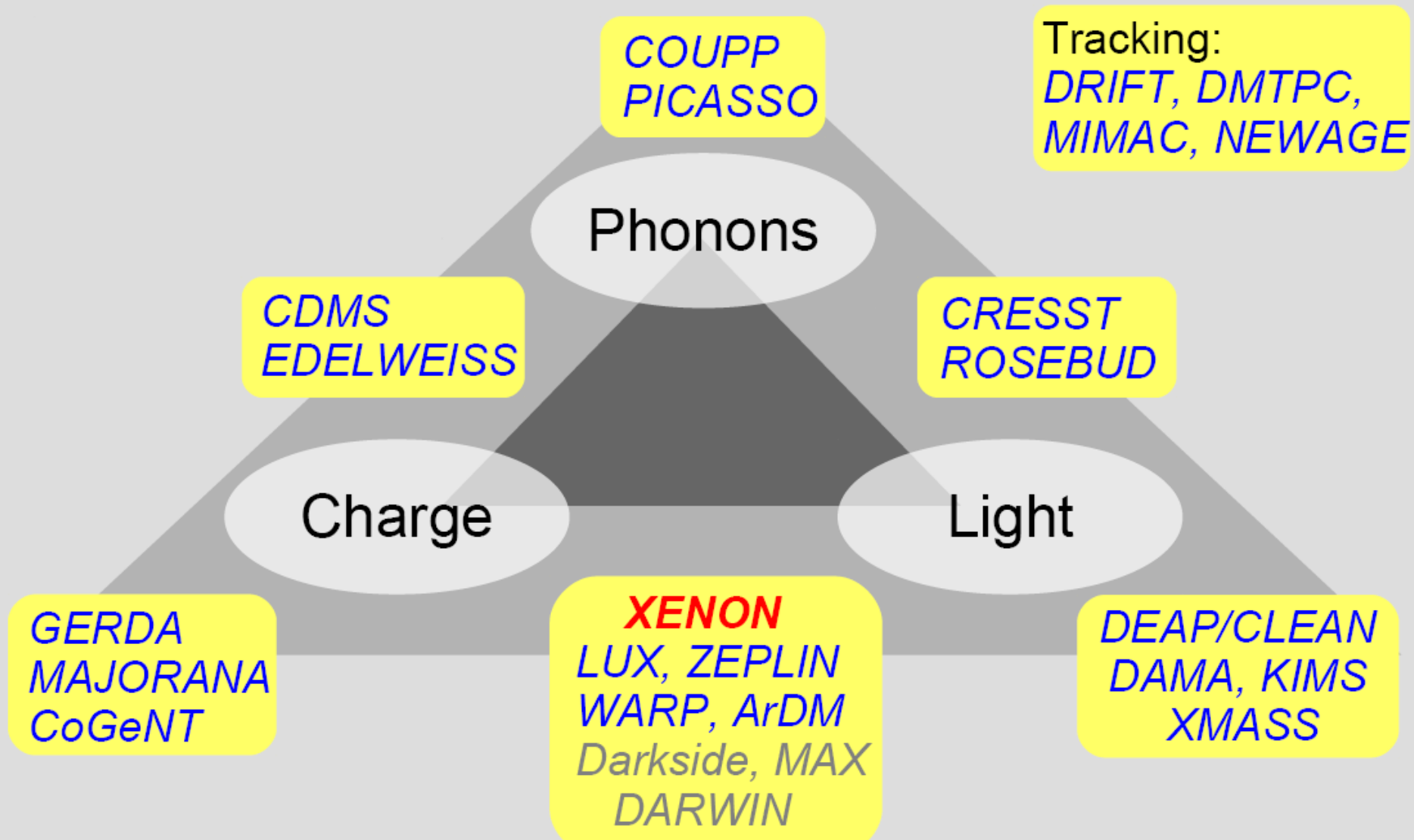
- nuclear recoils, single scatters
- recoil spectrum falls with  $E$
- dependence on  $A$ , spin?
- annual flux modulation?

## How to build a WIMP detector?

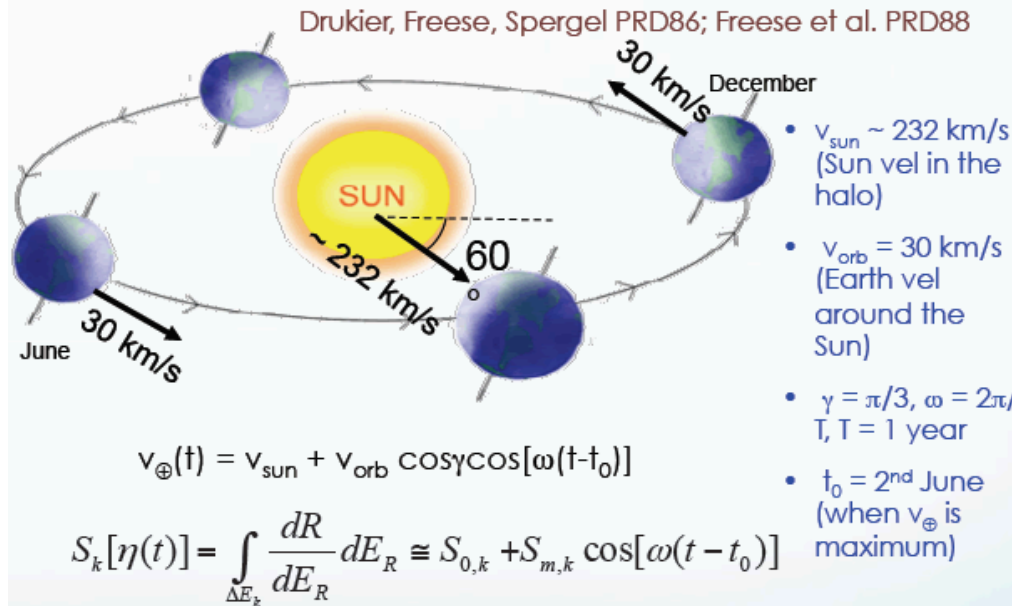
- large total mass, high  $A$
- low energy threshold
- ultra low background
- good background discrimination



# Tecniche di Rivelazione di WIMP

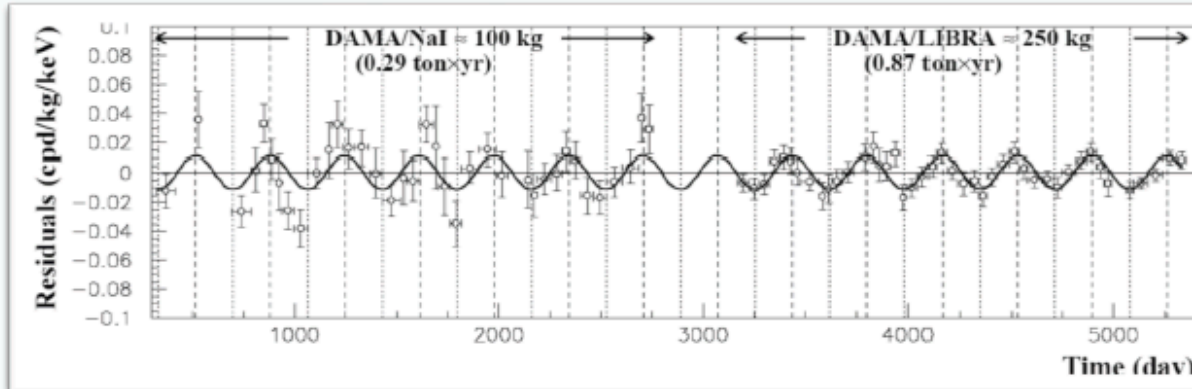


# Modulazione annuale : DAMA/LIBRA



**DAMA/NaI (7 years) + DAMA/LIBRA (6 years)** Total exposure: 425428 kg×day = **1.17 ton×yr**

**Single-hit residuals rate vs time in 2-6 keV**



**EPJC 56(2008)333, EPJC 67(2010)39**

continuous line:  $t_0 = 152.5 \text{ d}, T = 1.0 \text{ y}$

$A = (0.0114 \pm 0.0013) \text{ cpd/kg/keV}$

$\chi^2/\text{dof} = 64.7/79 \quad 8.8 \sigma \text{ C.L.}$

**Absence of modulation? No**

$\chi^2/\text{dof} = 140/80 \quad P(A=0) = 4.3 \times 10^{-5}$

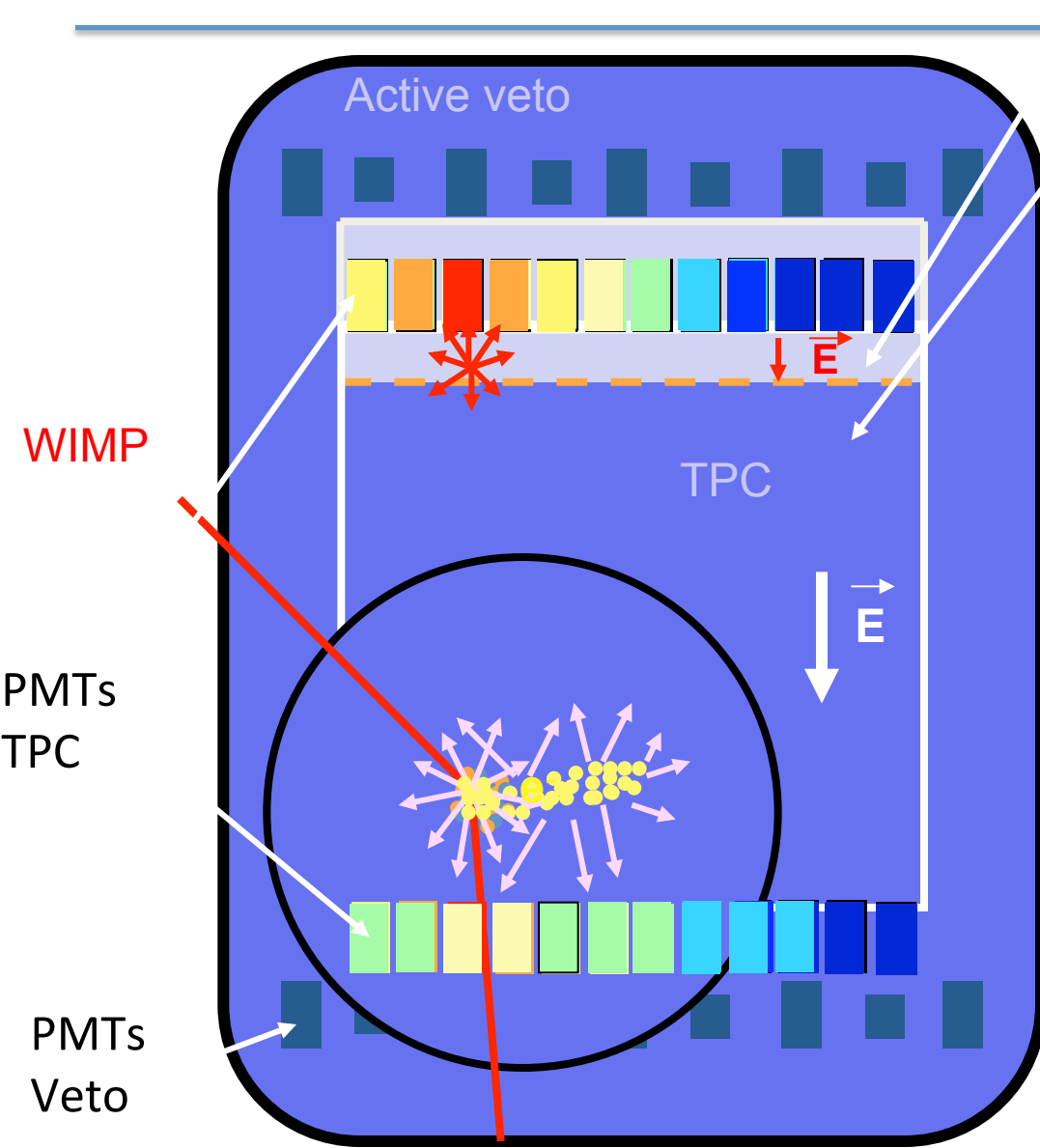
**fit with all the parameters free:**

$A = (0.0116 \pm 0.0013) \text{ cpd/kg/keV}$

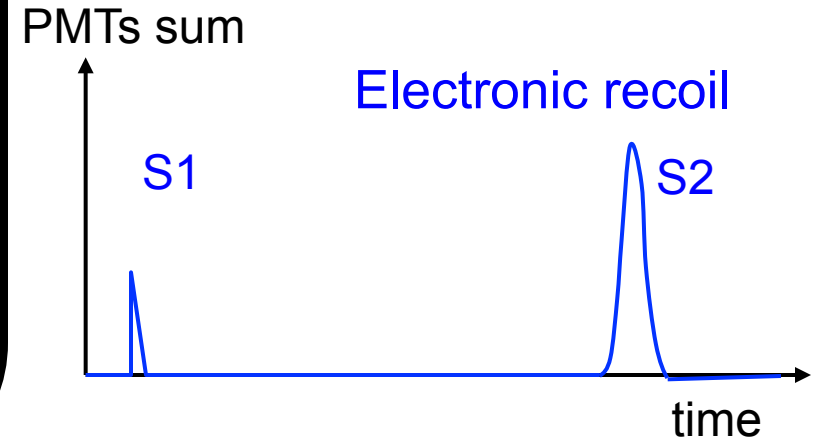
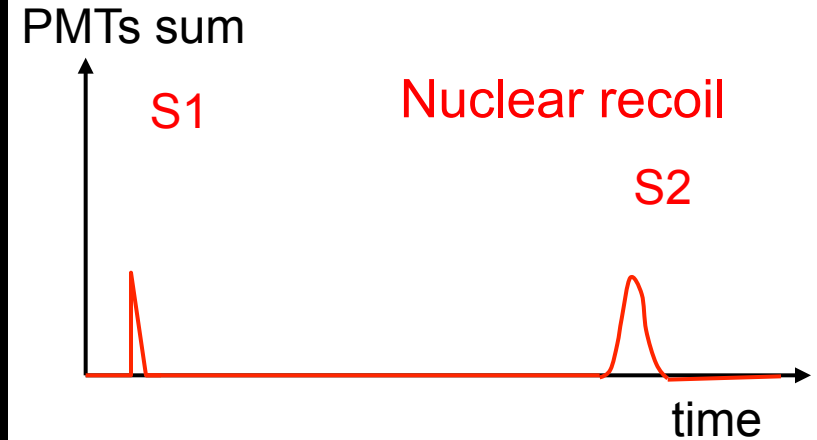
$t_0 = (146 \pm 7) \text{ d} - T = (0.999 \pm 0.002) \text{ y}$



# Liquid-gas Xe TPC: XENON100

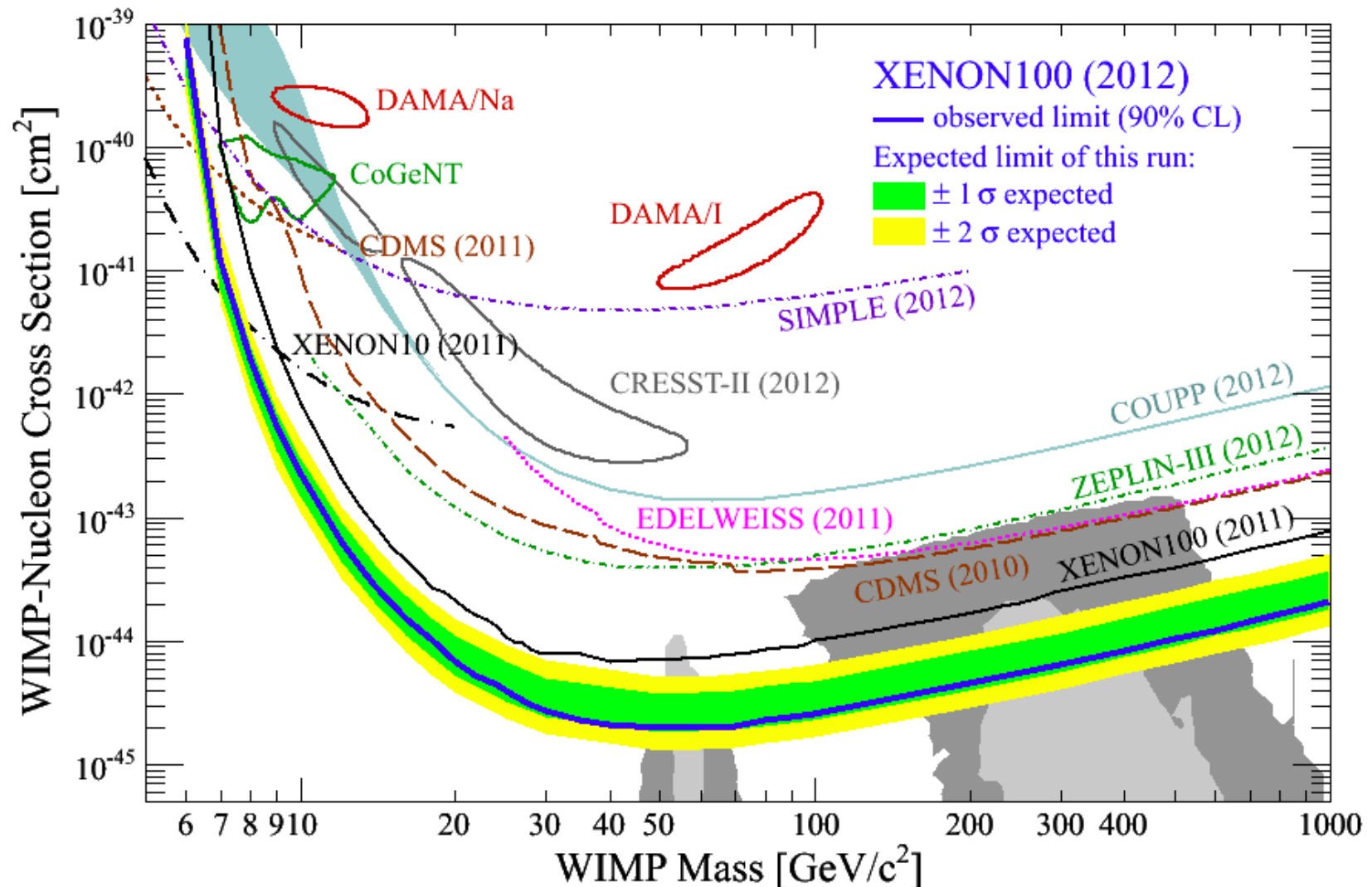


3D localization  
(millimeter precision)  
=> fiducial volume  
and single scatters



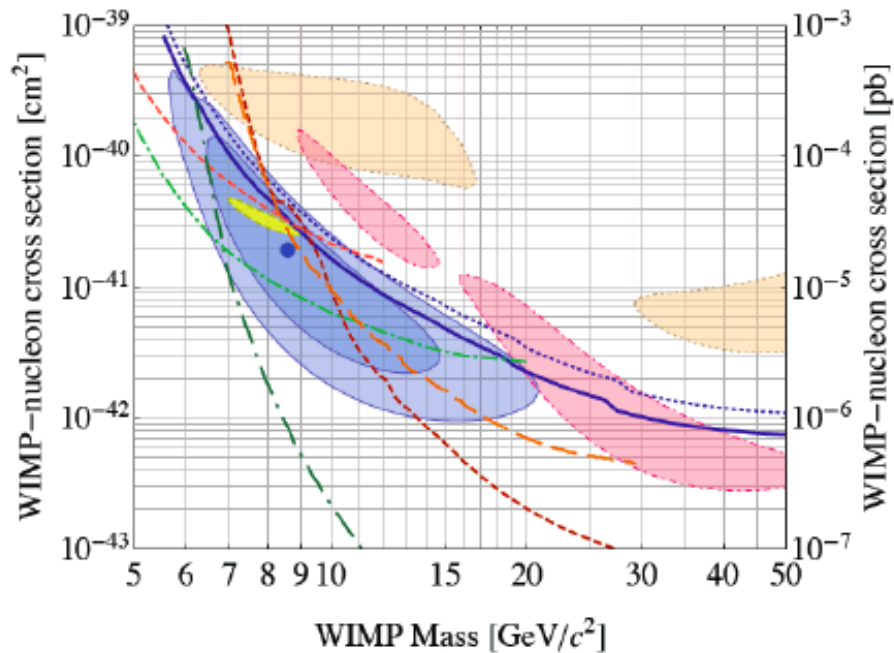
$$(S2/S1)_{WIMP} \ll (S2/S1)_g$$

# Sommario dei risultati sperimentali

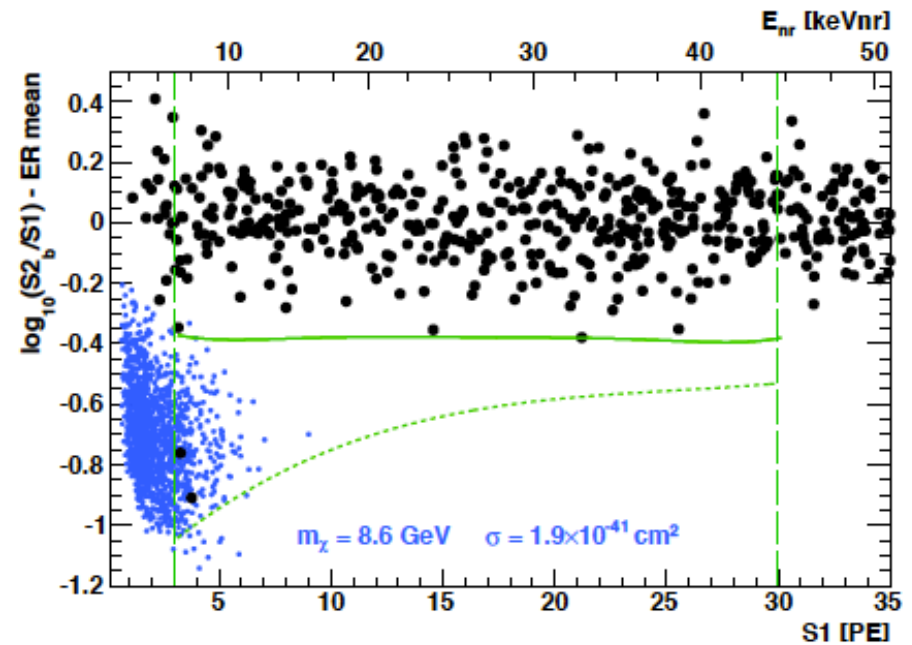


E. Aprile et al. (XENON100), Phys. Rev. Lett. 109, 181301 (2012)

# Recente "Claim" di CDMS vs XENON100

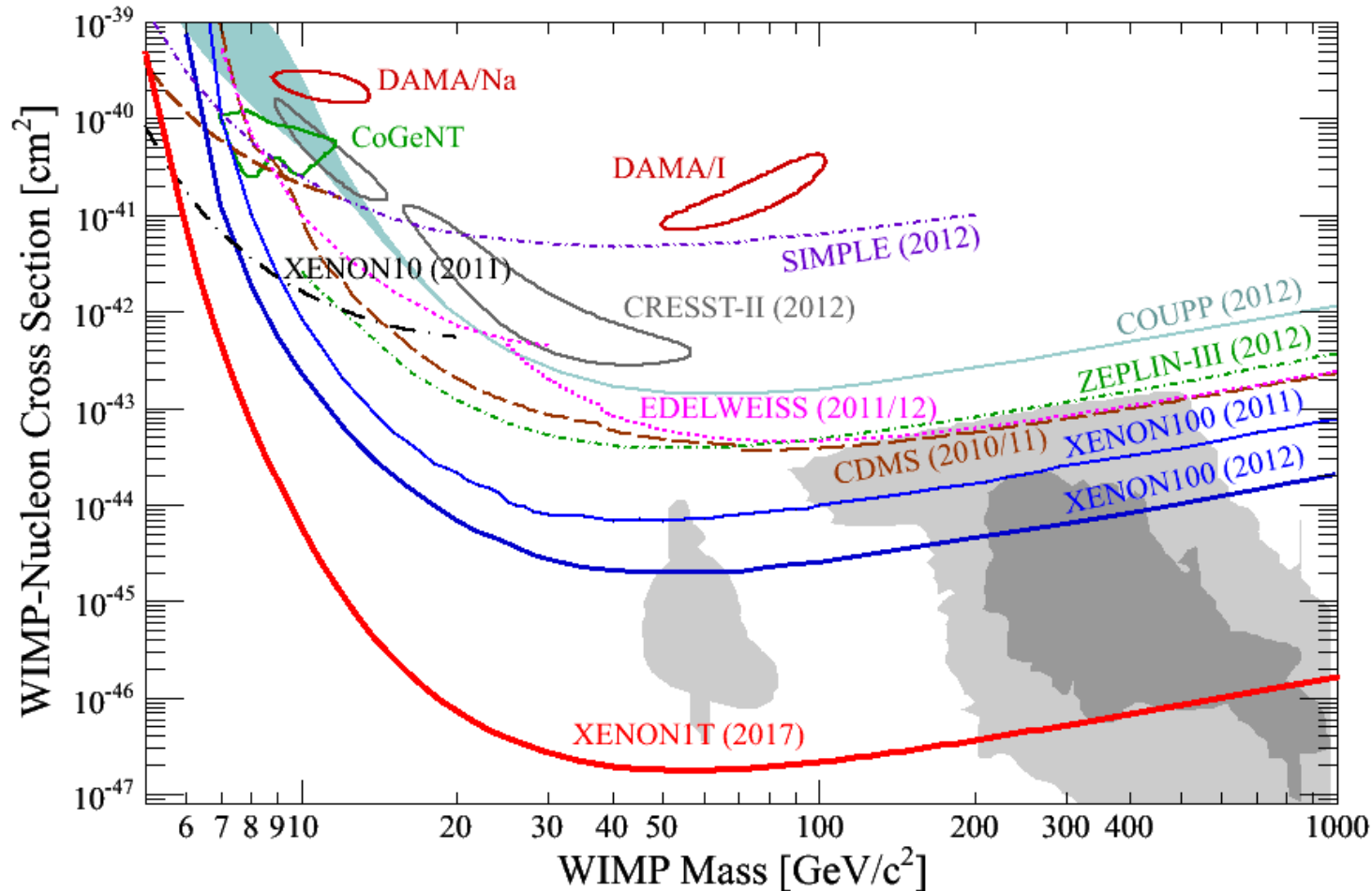


Best fit at  $1.9 \cdot 10^{-41} \text{ cm}^2$  at  
 $8.6 \text{ GeV}/c^2$  WIMP mass



Event distribution that XENON100  
would observe for the best fit  
point of CDMS

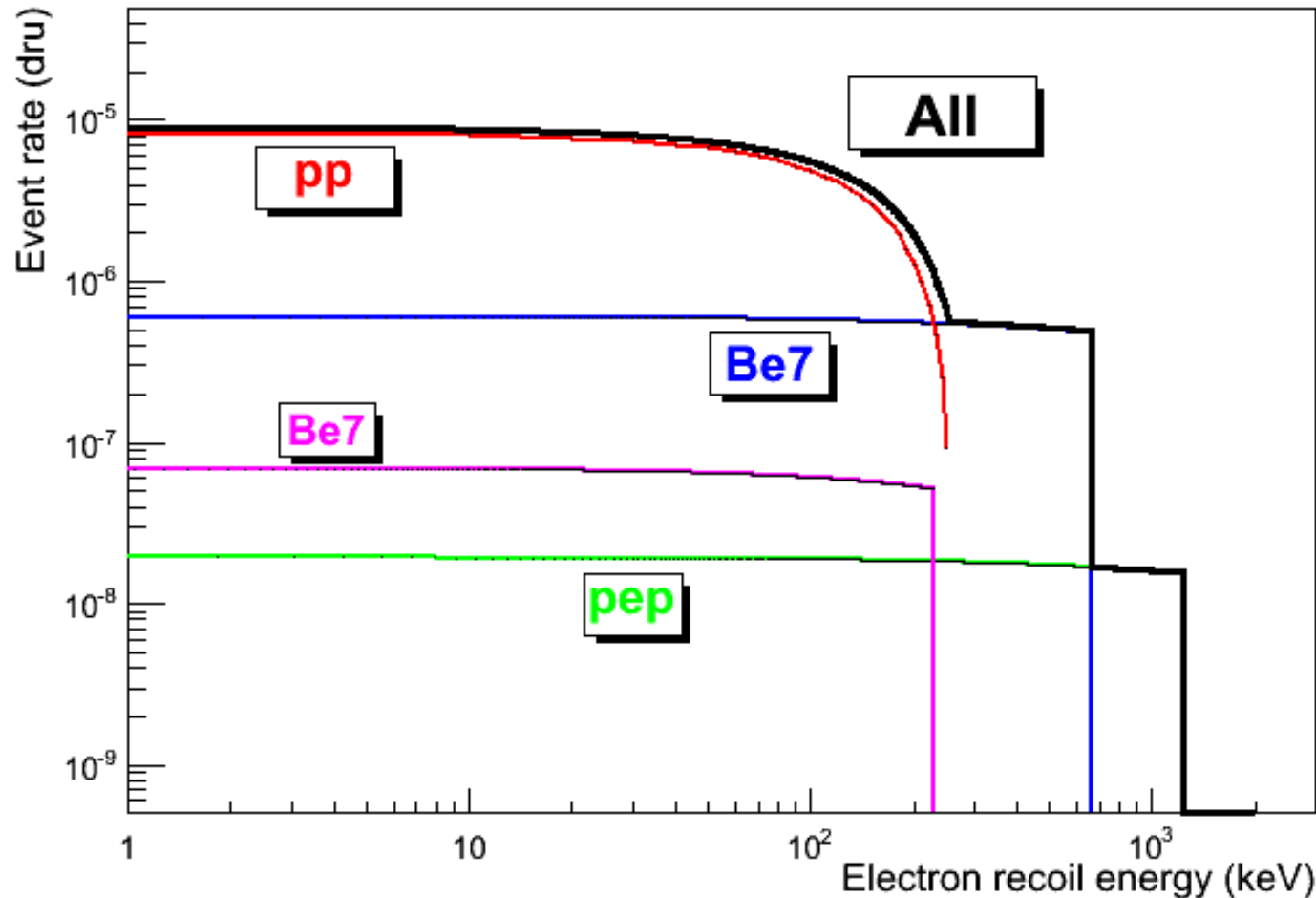
# Il futuro: XENON1T



Volendo estendere la sensibilità oltre  $10^{-48}$  cm<sup>2</sup> il background più importante è rappresentato dai neutrini solari ... in pochi decenni da “prezioso segnale” a “sporco fondo” !!

# Background principale: n solari !!

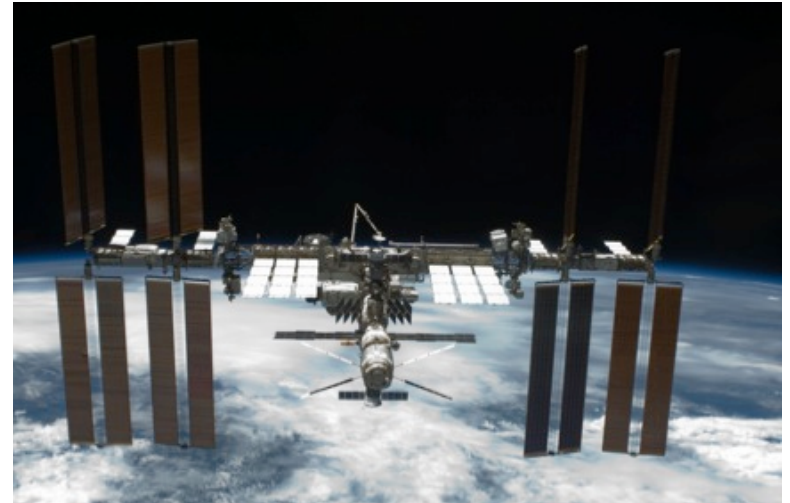
Rate di interazione dei neutrini solari in XENON1T, via elastic scattering sugli elettroni



Volendo estendere la sensibilità oltre  $10^{-48}$  cm<sup>2</sup> il background più importante è rappresentato dai neutrini solari ... in pochi decenni da “prezioso segnale” a “sporco fondo” !!

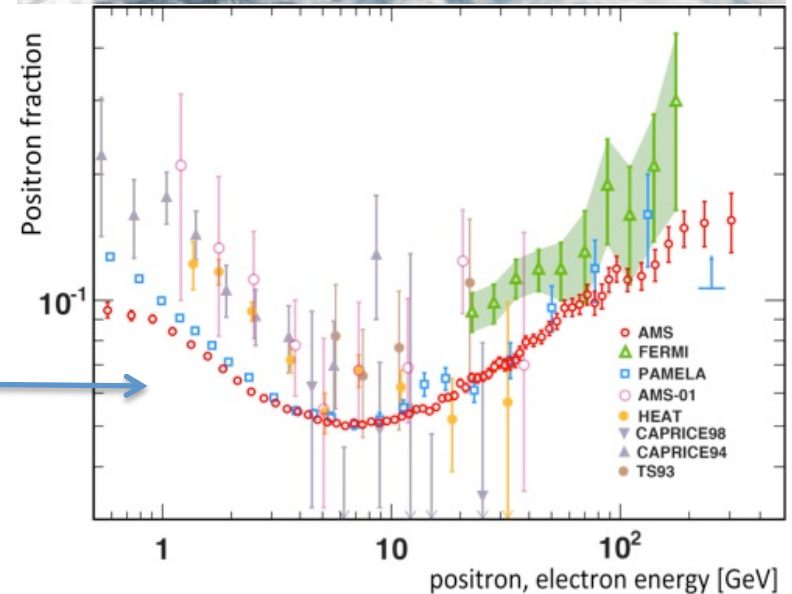
# Ricerca indiretta di WIMP: AMS

AMS sulla Stazione Spaziale Internazionale



Aumento della frazione di positroni ad alta energia:

- Annichilazione di WIMPs ?
- Pulsar ?



# Conclusioni

Ci sono già evidenze sperimentali di fisica oltre il Modello Standard

$SU(2) \times U(1)$

- **Neutrini:**

- Oscillazione e massa:

- violazione del numero leptonico di flavour,
- esistenza anche di  $n_R$

- (Decadimento doppio beta senza neutrini):

- violazione del numero leptonico globale,
- Dirac o Majorana ?

- **Dark Matter:**

- Particelle massive, neutre, stabili e non barioniche:

- Nessun candidato nello SM

- Ampio contributo dei gruppi di Bologna in tutti i topics più importanti e negli esperimenti con maggiore sensibilità nel proprio ambito.

- Misure sperimentali di precisione su tutta la matrice di mixing.
- Ancora da misurare/scoprire: gerarchia di massa, dCP, neutrini sterili

- Nel prossimo futuro primi risultati che esploreranno il claim KK e le masse dei neutrini nel caso di gerarchia inversa.

- Claim di DAMA non confermato da altri esperimenti (XENON100)
- Entro 5 anni sarà esplorata la regione di (massa, sezione d'urto) prevista dal CMSSM

---

Grazie !



# Neutrino-less double-beta decay

①

$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$$

$$(A, Z) \rightarrow (A, Z-2) + 2e^+ + 2\nu_e$$

$$(A, Z) + e_a \rightarrow (A, Z-2) + e^+ + 2\nu_e$$

$$(A, Z) + 2e_a \rightarrow (A, Z-2) + 2\nu_e$$

**2ν Double Beta Decay (2νββ)**  
 allowed by the Standard Model  
 already observed -  $\tau \sim 10^{18} - 10^{21}$  yr

②

$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$

$$(A, Z) \rightarrow (A, Z-2) + 2e^+$$

$$(A, Z) + e_a \rightarrow (A, Z-2) + e^+$$

$$(A, Z) + 2e_a \rightarrow (A, Z-2) + \gamma$$

**neutrinoless Double Beta Decay (0νββ)**  
 never observed except  
 Klapdor's meas. -  $\tau \Rightarrow 10^{25}$  yr

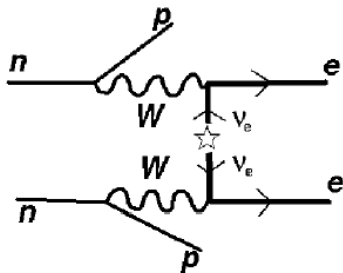
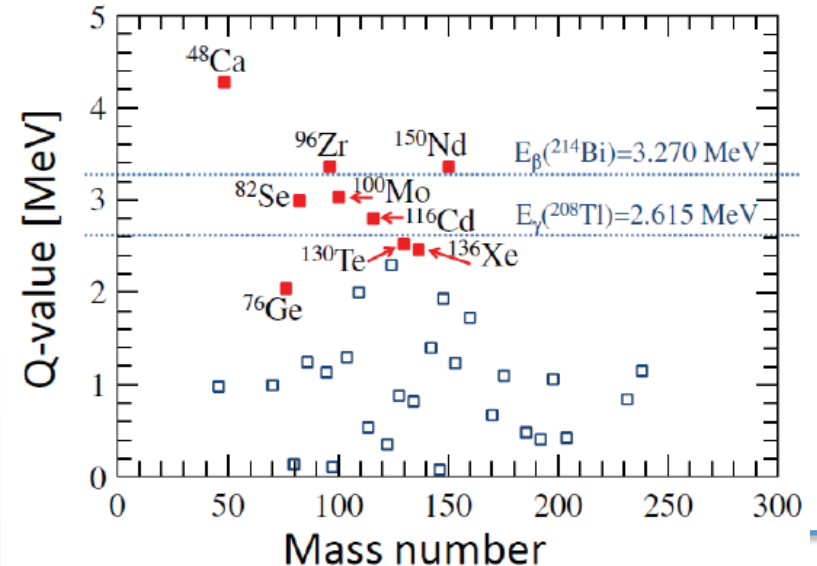


Figure 5: Diagram for neutrinoless-2β decay at level of nucleons (n, p are neutrons and protons). Note the clashing arrows in the the neutrino lines, that are characteristic of the MAJORANA mass of neutrinos, and signal the violation of the lepton number.



# Neutrino-less double-beta decay

## DBD and Majorana neutrinos

Schechter Valle theorem:  $\left\{ \text{Observation of } \mathbf{0\nu\text{-DBD}} \rightarrow \left. \begin{array}{l} m_\nu \neq 0 \\ \nu \equiv \bar{\nu} \end{array} \right\} \right.$  Majorana particle

Neutrinoless  $\beta\beta$  decay rate  $\rightarrow$  Phase space  $\rightarrow$  Axial vector coupling constant  $\rightarrow$  Nuclear matrix elements  $\rightarrow$  Effective Majorana mass

$$1/\tau = G(Q,Z) g_A^4 |M_{\text{nucl}}|^2 \langle m_{\beta\beta} \rangle^2$$

$$\langle m_{\beta\beta} \rangle = \left| |U_{e1}|^2 m_1 + e^{i\alpha1} |U_{e2}|^2 m_2 + e^{i\alpha2} |U_{e3}|^2 m_3 \right|$$

- This generation of experiments will start to explore the IH region
- Possibly, the next generation will be necessary to complete the IH region exploration
- DH still far from now

Nuclear matrix elements uncertainties



Needed different nuclei

### Neutrino mass hierarchy

