Low Energy Neutrino Astronomy and Results from BOREXINO

DESY Hamburg / DESY Zeuthen

March 25th and 26th

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Neutrinos as probes ?

Charge 0 -1 +2/3 -1/3

Interactions w w,e w,e,s

$$\begin{pmatrix}\nu_{e}\\ e\end{pmatrix} \quad \begin{pmatrix}\nu_{\mu}\\ \mu\end{pmatrix} \quad \begin{pmatrix}\nu_{\tau}\\ \tau\end{pmatrix}$$

$$\begin{pmatrix}u\\ d\end{pmatrix} \quad \begin{pmatrix}c\\ s\end{pmatrix} \quad \begin{pmatrix}t\\ b\end{pmatrix}$$

Neutrinos undergo only weak interactions:

No deflection in electric or magnetic fields, extremely penetrating => *ν's are perfect carriers* of information from the centers of astrophysical objects

Neutrino Mixing

Flavor eigenstates = **Mixing matrix** x **Mass eigenstates**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

2 mixing angles are measured: $\Theta_{12} \sim 34^0$ $\Theta_{23} \sim 45^0$

$|m^2_3 - m^2_2| \sim 2.6 \times 10^{-3}\ eV^2$ *atmospheric* ν *and accelerator* ν *exp.*

$m^2_2 - m^2_1 \sim 8 \times 10^{-5}\ eV^2$ *solar and reactor* ν *experiments*

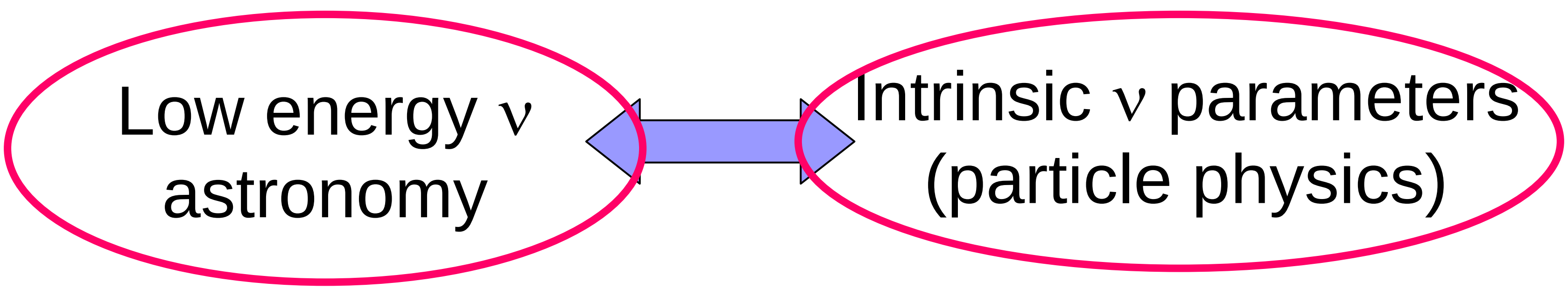
Open: Θ_{13} ? **CP violating phase** δ ?

Absolute mass scale (m_ν < 2.2 eV) ? Mass hierarchy ?

Neutrino oscillations (i.e. flavor transitions) proven

⇒ May complicate interpretation of astrophysical processes

⇒ However, it allows access to **ν intrinsic properties**, which are not available in laboratory experiments !

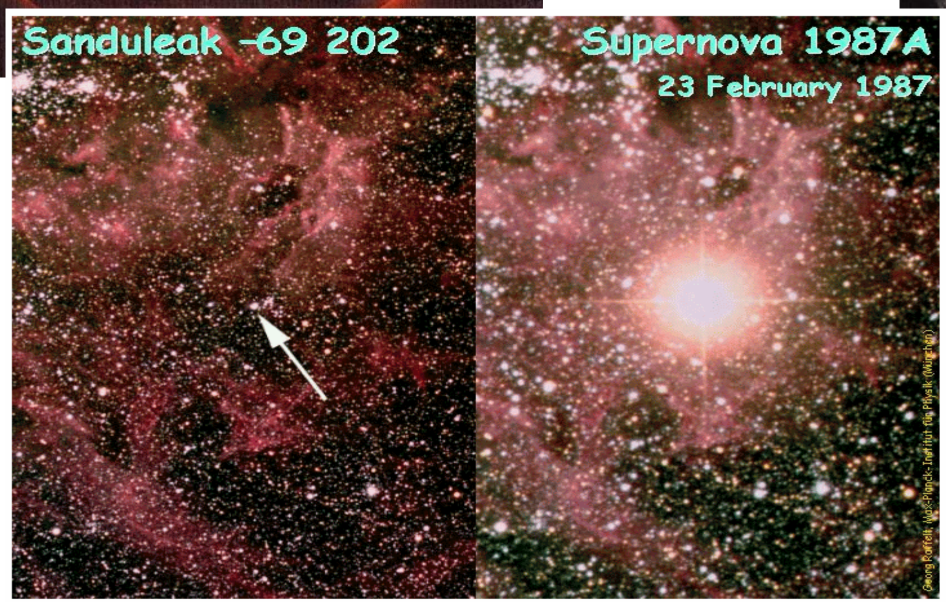


Natural Neutrino Sources

(experimentally verified)

Sun

(since 1970)



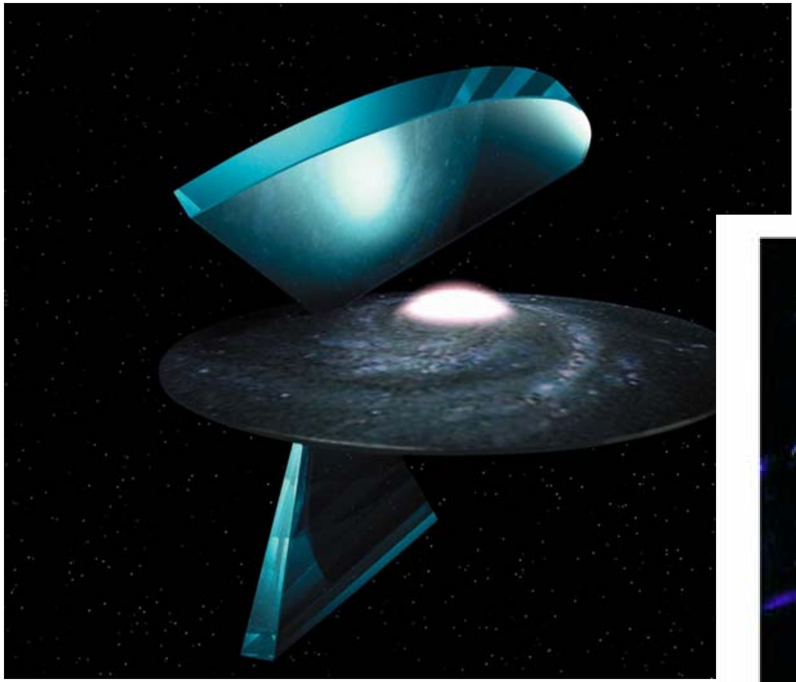
Earth
(since 2005)

Atmosphere
(since ~1990)

Supernova (1987)

Natural Neutrino Sources

(not yet verified)



Big Bang

An artists concept of an active galactic nuclei

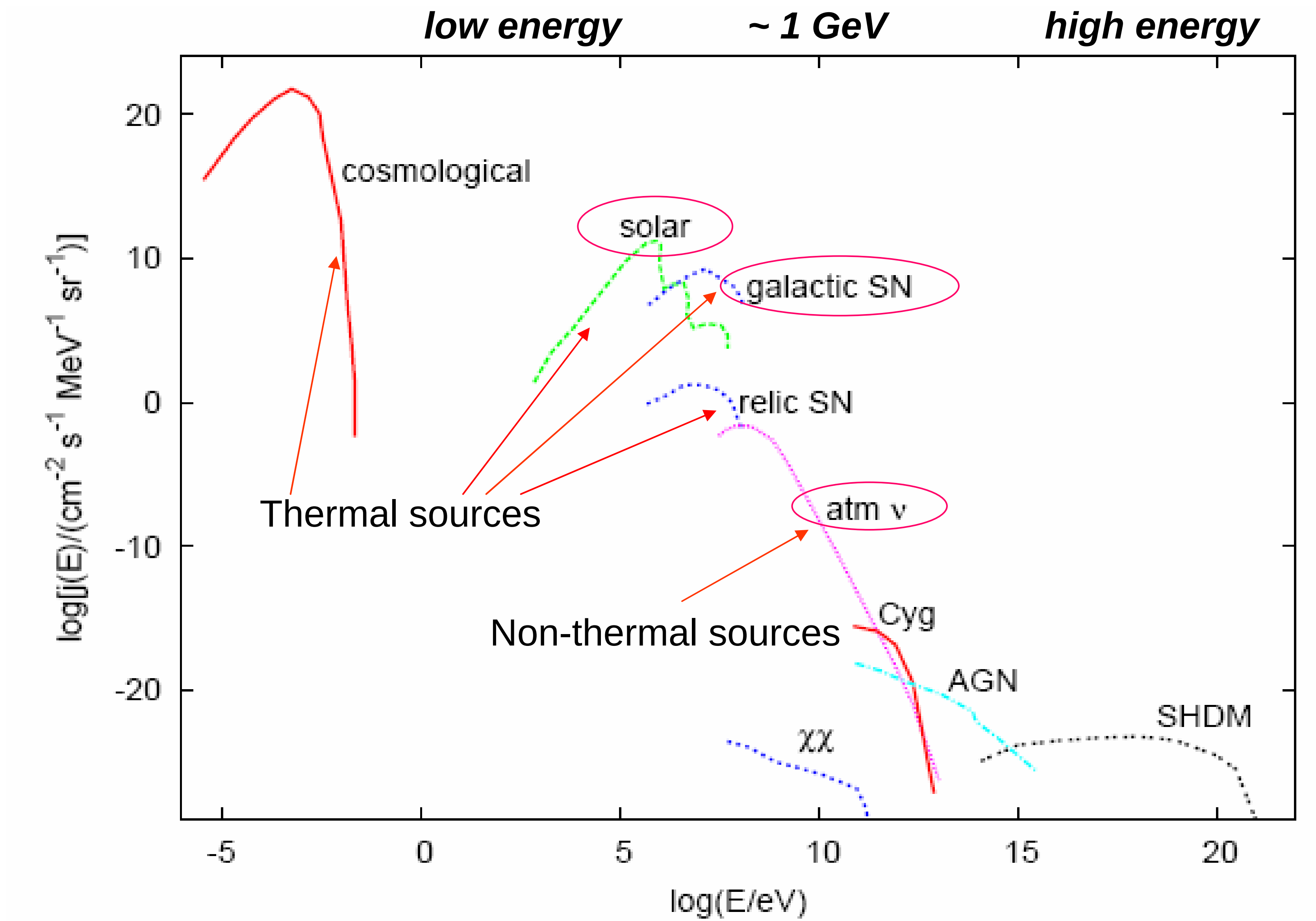
Active galactic nuclei ?

Supernovae remnants ?,

Gamma ray bursts ?,

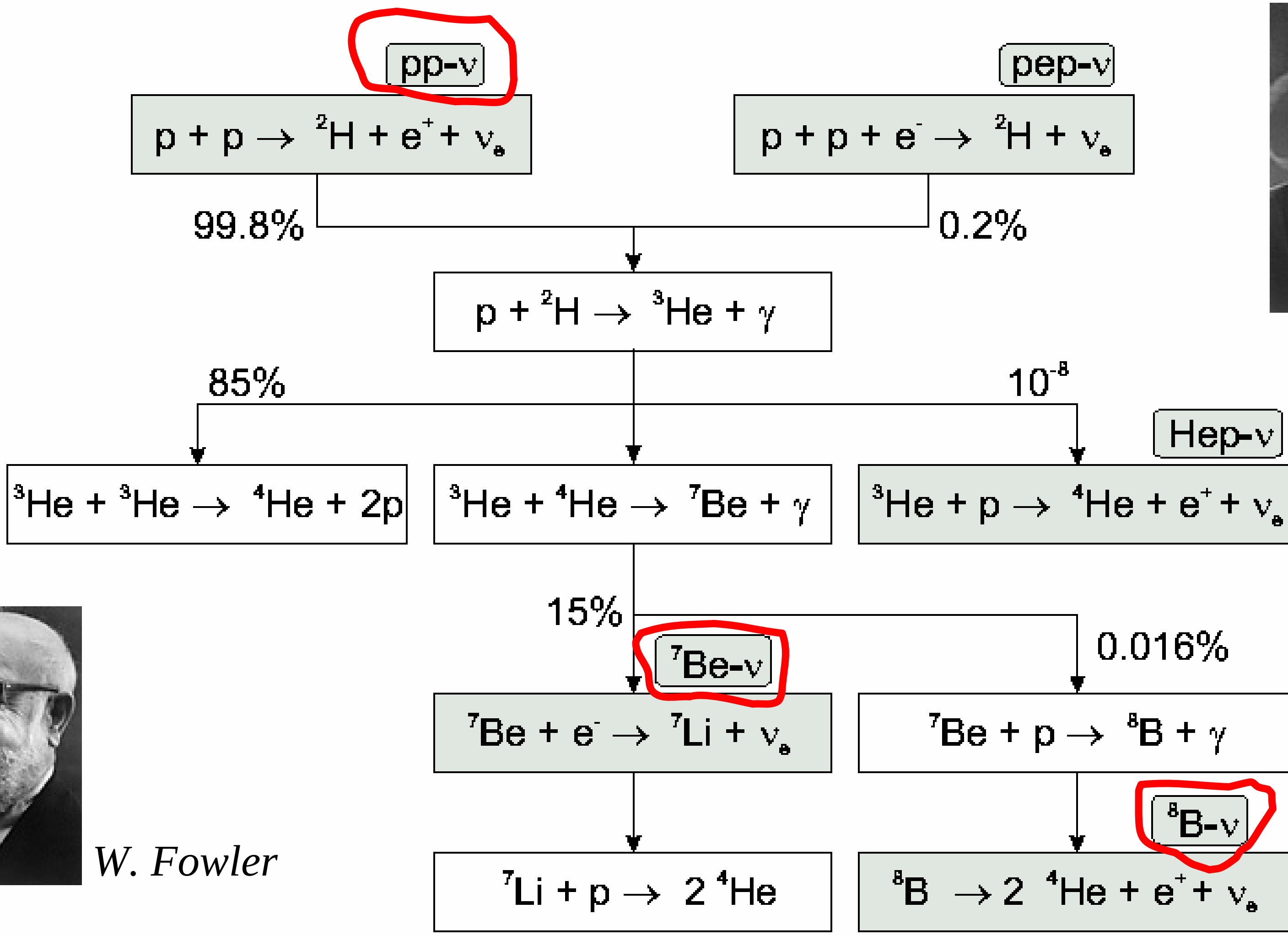
Supernovae relic neutrinos ?...

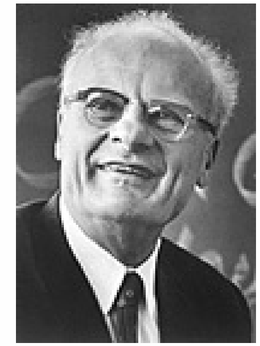
Energy Spectra of Astrophysical Neutrinos



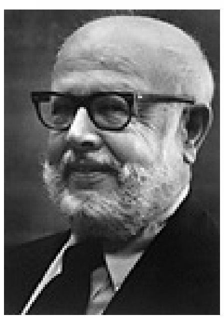
Solar Neutrinos

The dominating solar pp - cycle





H. Bethe



W. Fowler

pp - 1

pp -2

pp -3

The sub-dominant solar CNO - cycle

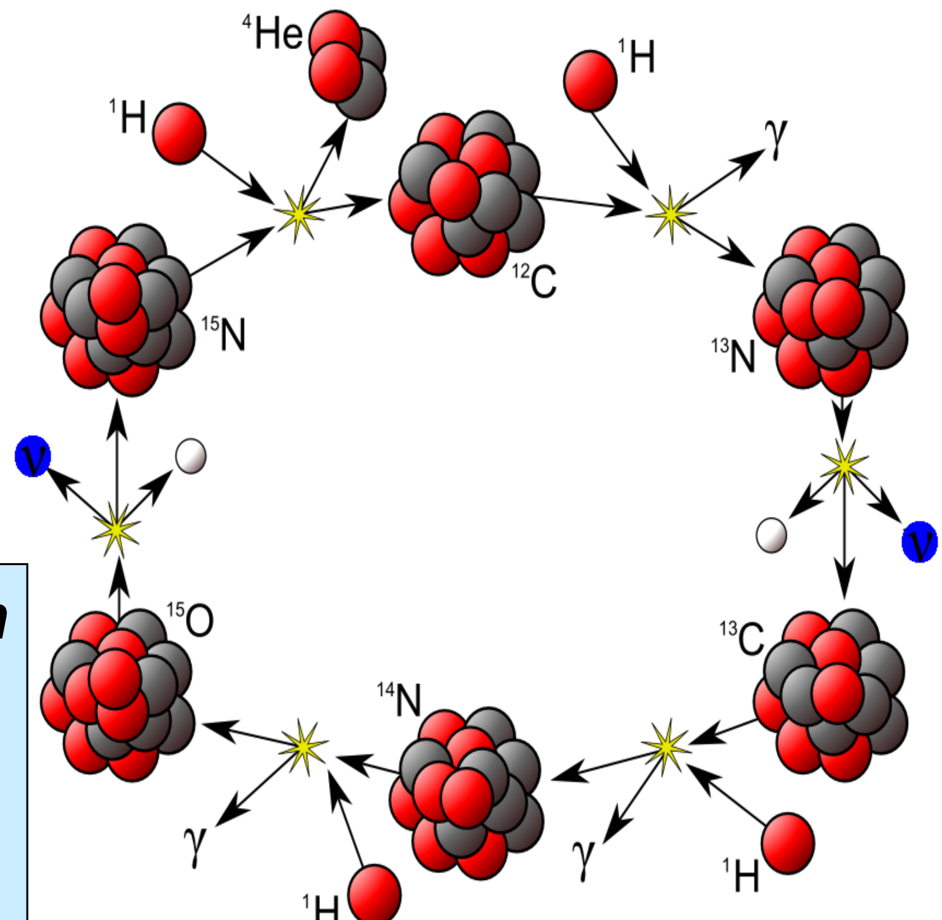
…dominates in stars more massive as the Sun…

=>Large astrophysical relevance

"bottle-neck" reaction slower than expected (LUNA result)

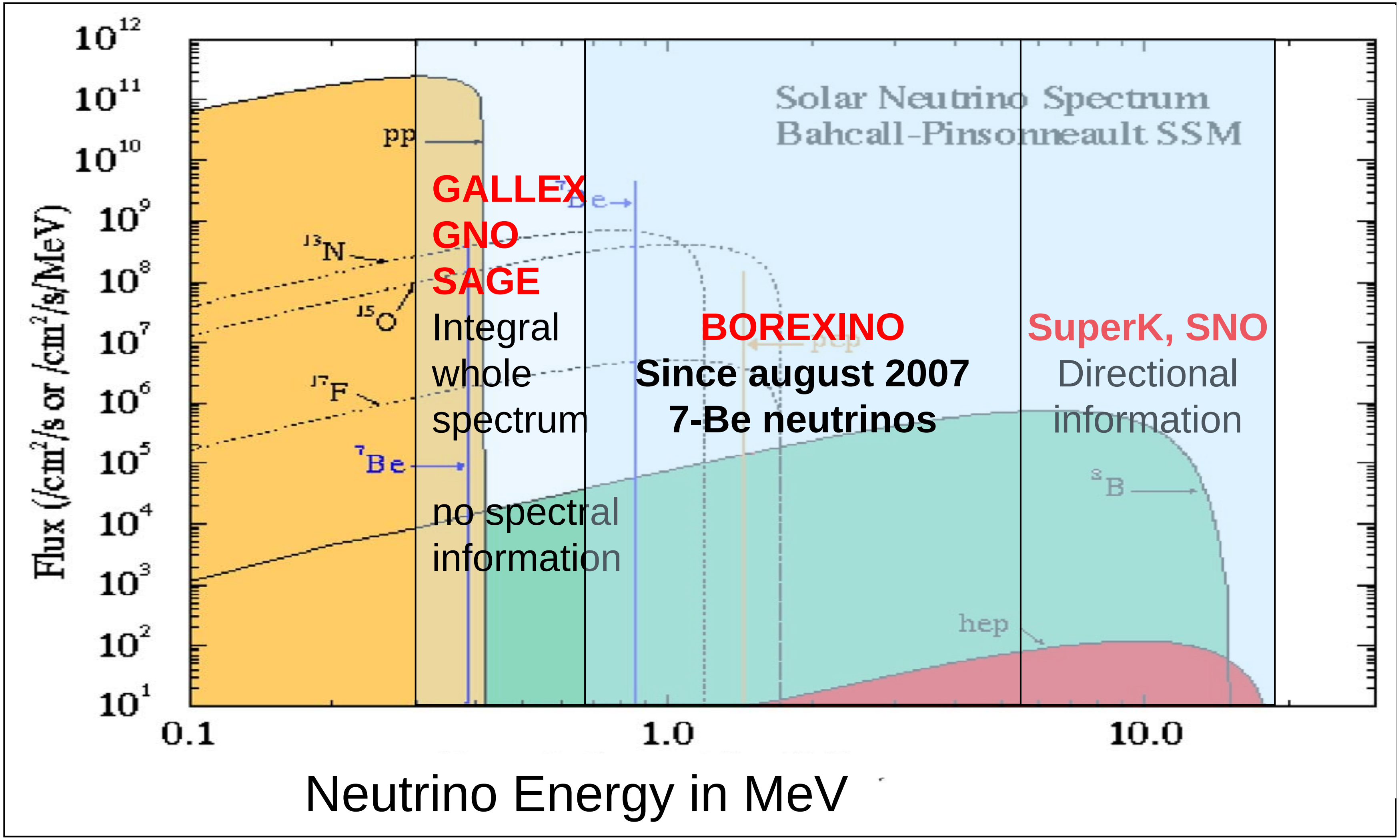
⇒Solar CNO-ν prediction lowered by factor ~ 2 !

⇒ Impact on age of globular clusters



Solar Neutrinos

$$4p \rightarrow \mathrm{He}^4 + 2e^+ + 2\nu_e + 26.7\,\mathrm{MeV}$$



Oscillations and matter effects

Oscillation length ~ 10^2 km

=> oscillation *smeared out*

and non-coherent

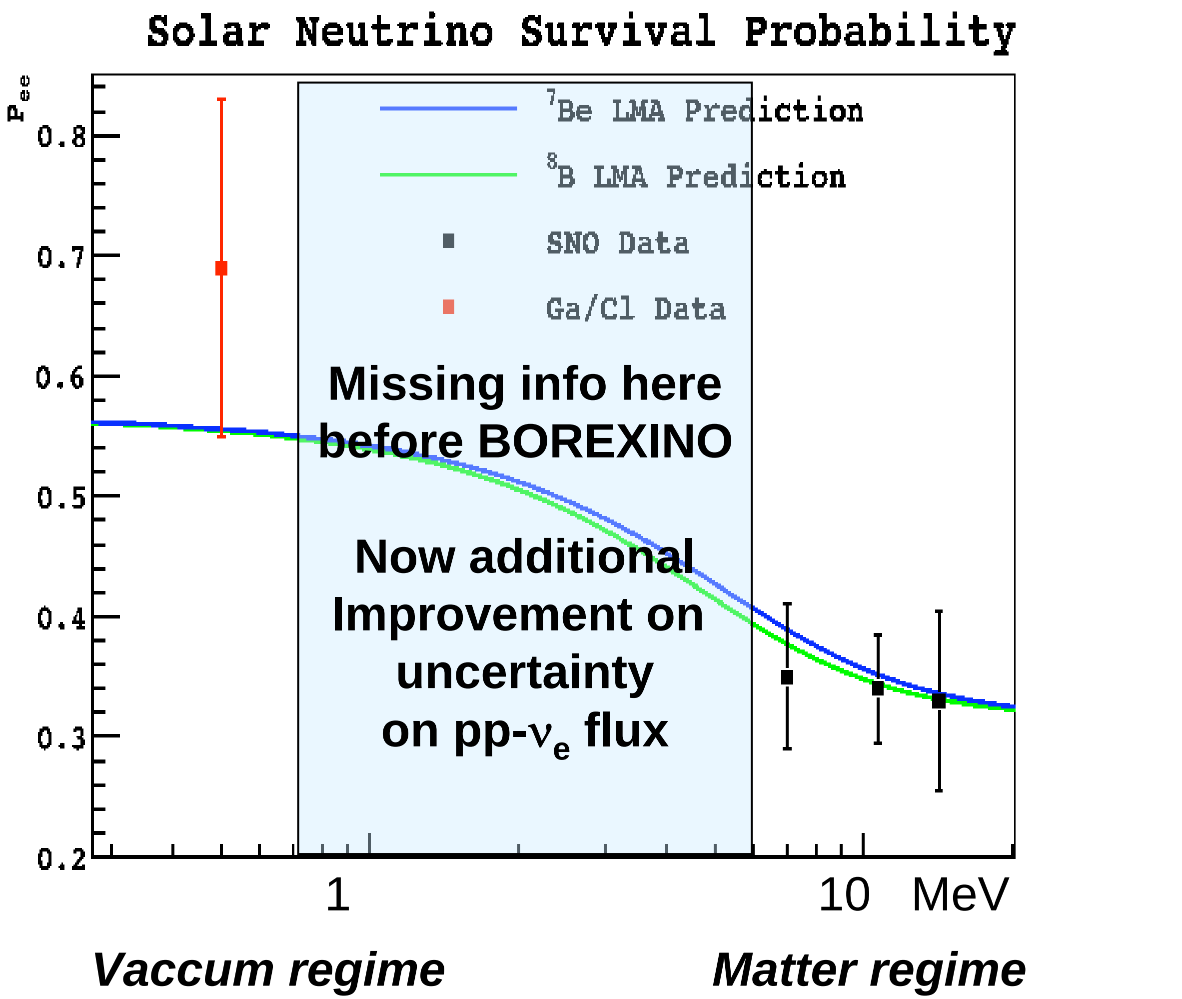
Effective ν_e mass (due to forward scattering on electrons) **is enhanced by potential A**

$A \sim G_F N_e E^2$

=> for E > 1 MeV

matter effect dominates

and leads to an enhanced ν_e suppression for those energies…

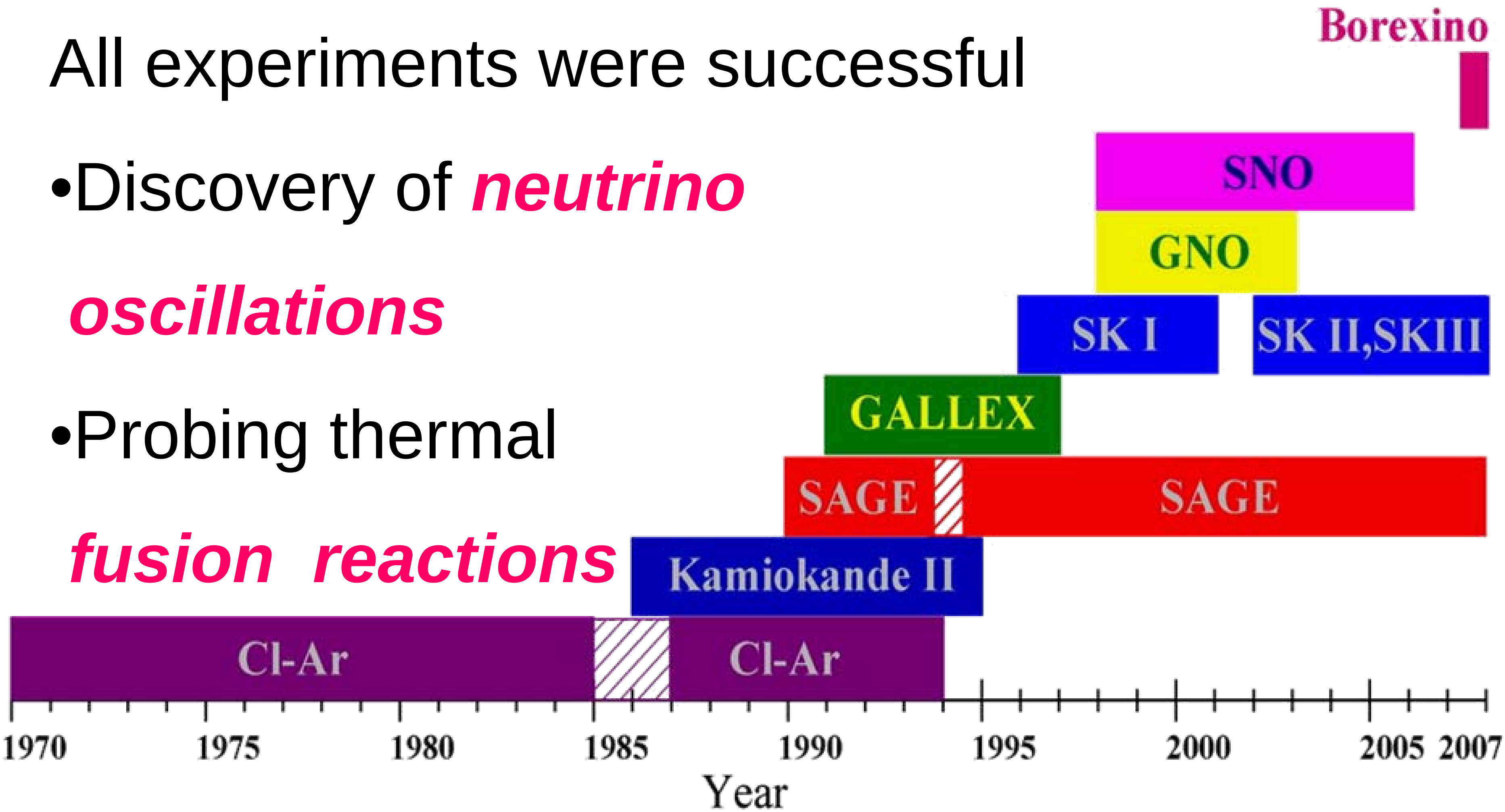


History of solar neutrino experiments at 2007

All experiments were successful

•Discovery of ***neutrino oscillations***

•Probing thermal ***fusion reactions***



BOREXINO

Neutrino electron scattering $\nu e \rightarrow \nu e$

Liquid scintillator technology (~300t):

→ Low energy threshold (~60 keV)

Good energy resolution (~4.5% @ 1 MeV)

Sensitivity on sub-MeV neutrinos

Online since May 16th, 2007

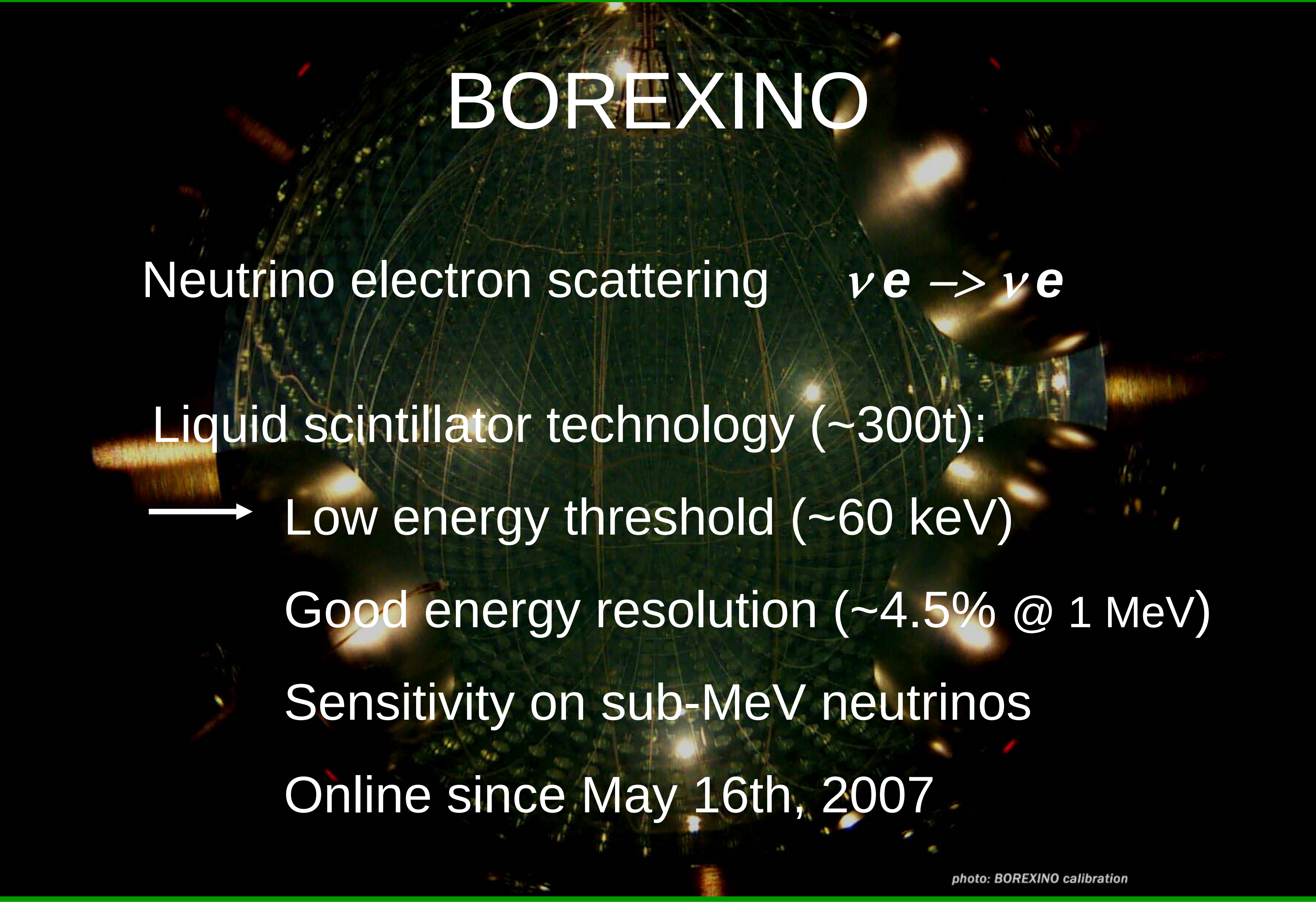


photo: BOREXINO calibration

Borexino Collaboration

Genova

Milano

Perugia

APC Paris

Princeton University

Virginia Tech. University

Dubna JINR
(Russia)

Kurchatov
Institute
(Russia)

Jagiellonian U.
Cracow
(Poland)

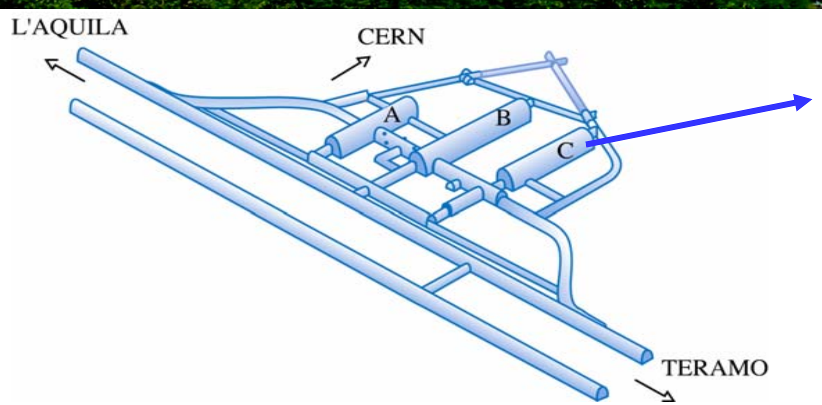
Heidelberg
(Germany)

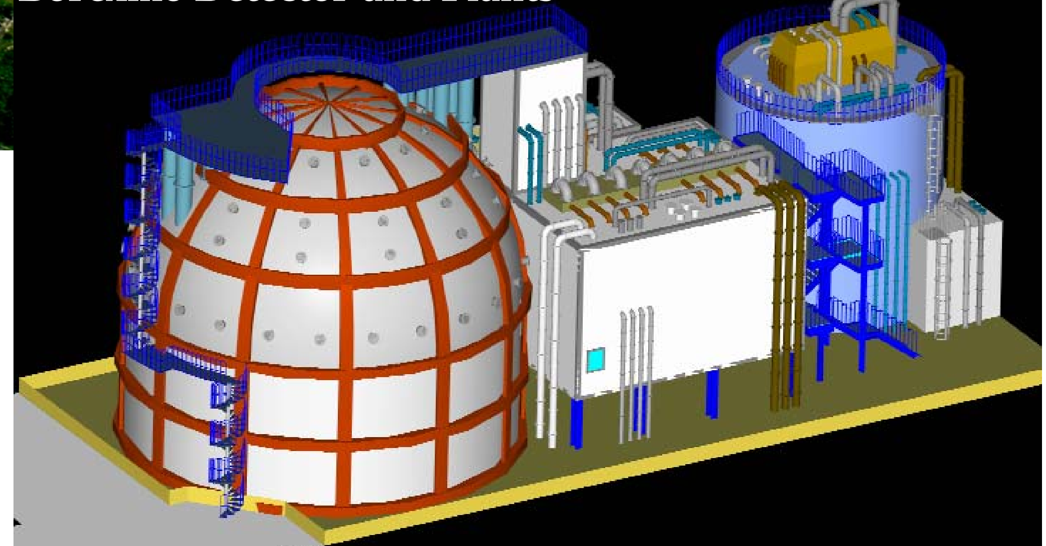
Munich
(Germany)

BOREXINO in the Italian Gran Sasso Underground Laboratory in the mountains of Abruzzo, Italy, ~120 km from Rome

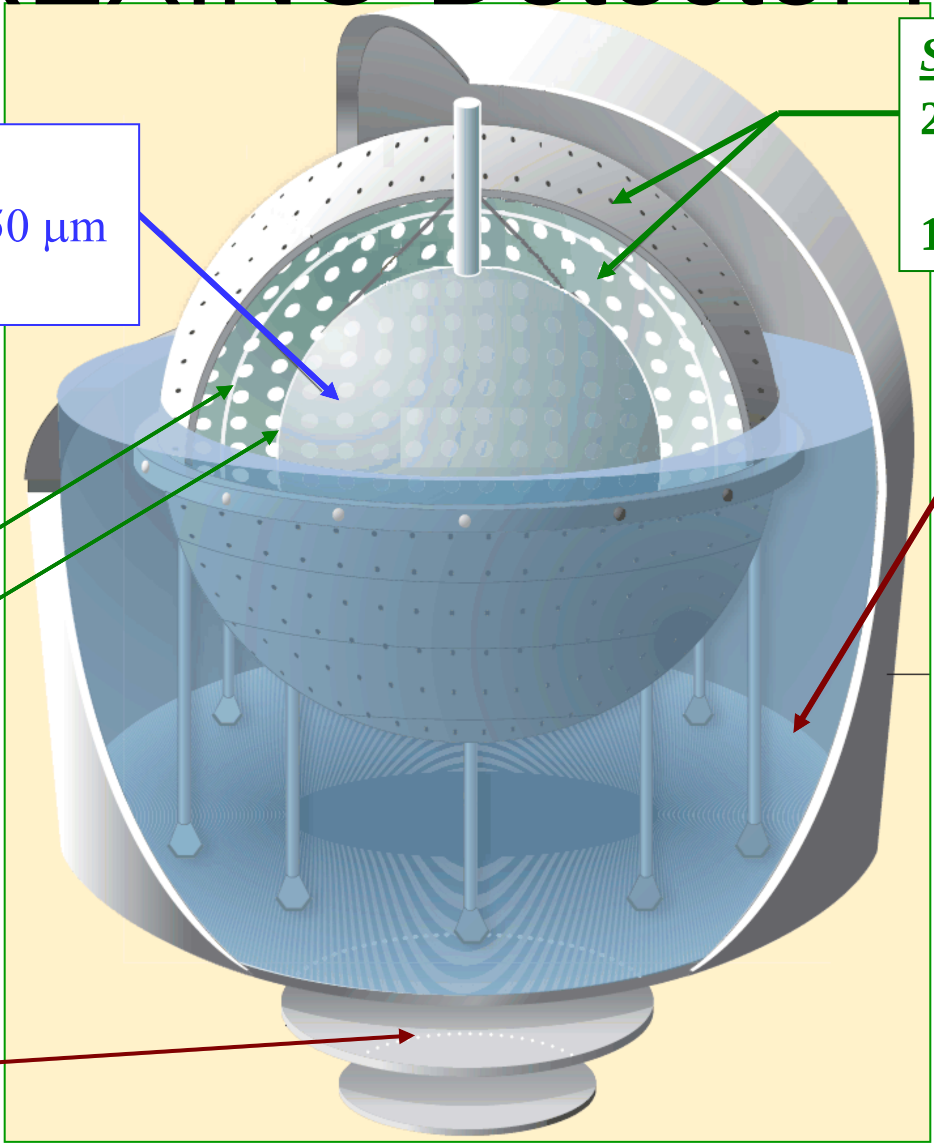
Laboratori Nazionali del Gran Sasso LNGS

Shielding ~3500 m.w.e




Borexino Detector and Plants

BOREXINO Detector layout



Scintillator:
270 t PC+PPO in a 150 μm thick nylon vessel

Stainless Steel Sphere:
2212 PMTs + concentrators
1350 m³

Nylon vessels:
Inner: 4.25 m
Outer: 5.50 m

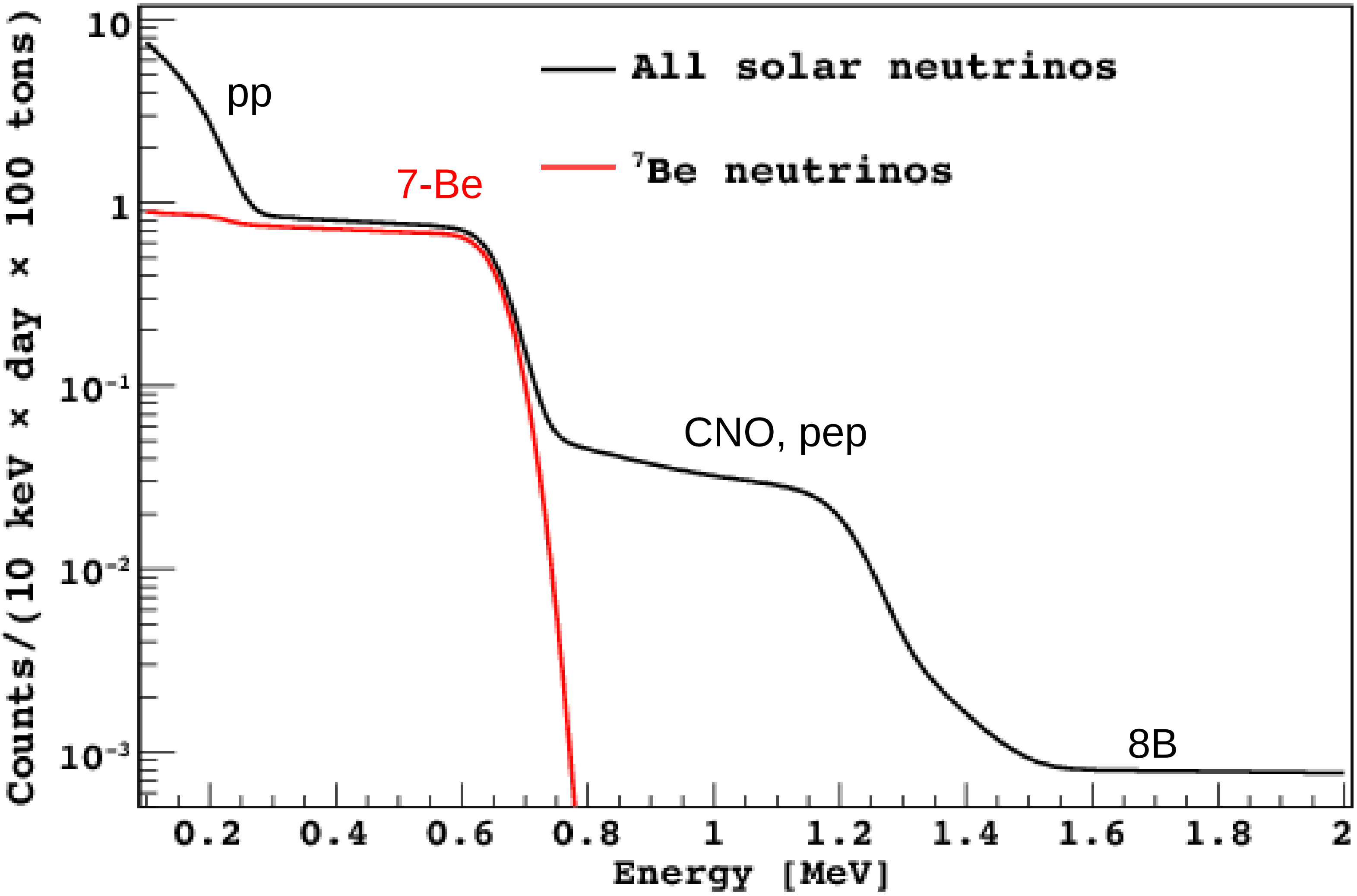
Water Tank:
γ and n shield
μ water Č detector
208 PMTs in water
2100 m³

Carbon steel plates

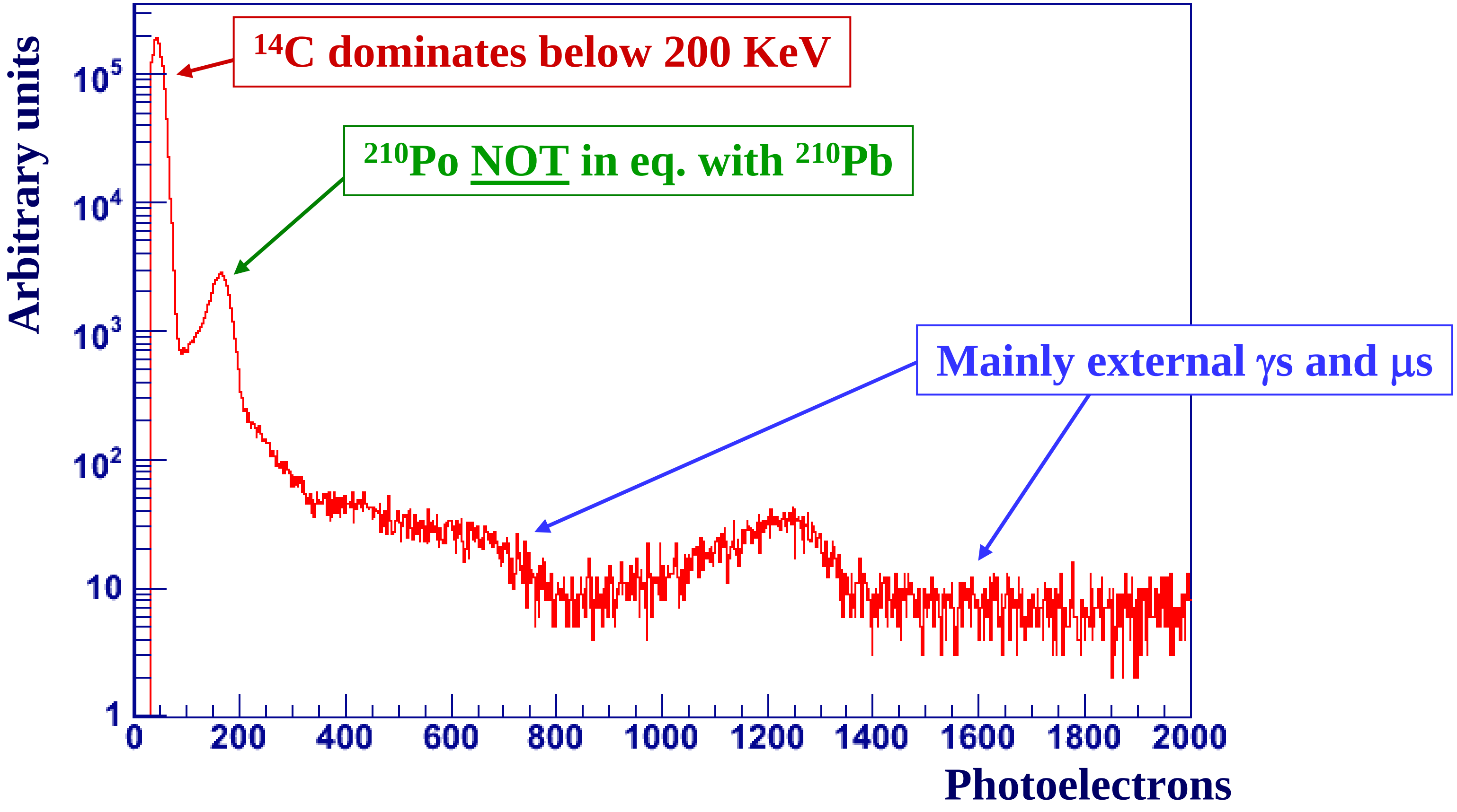
Excellent ***shielding*** of external background

Increasing ***purity*** from outside to the central region

The ideal electron recoil spectrum due to solar neutrino scattering



Energy Spectrum (no cuts)



Statistics of this plot: ~ 1 day

Determination of pulse-height to energy conversion

Fit to the shape of the intrinsic ^{14}C betas

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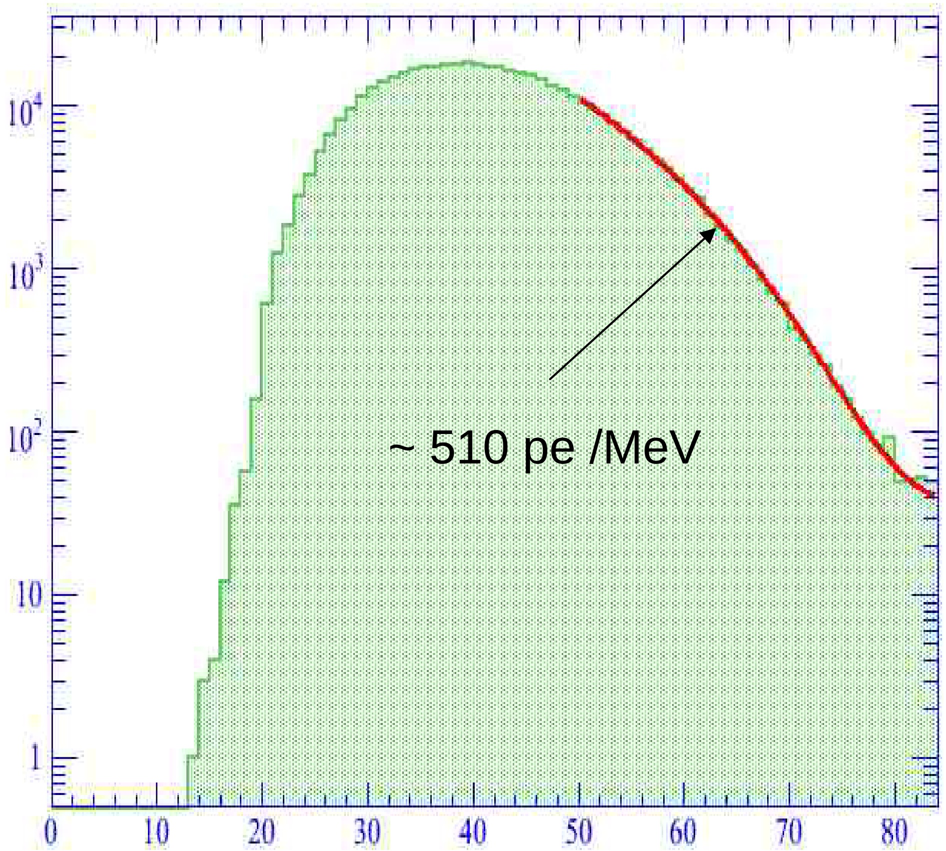
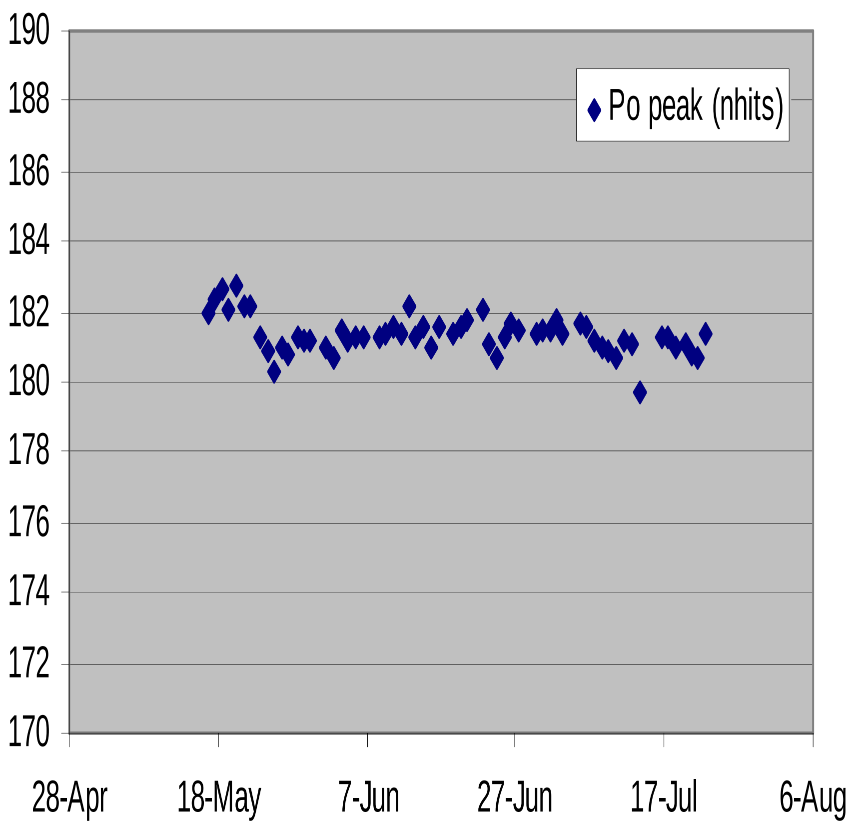


Number of PM-hits

Monitor of the detector stability

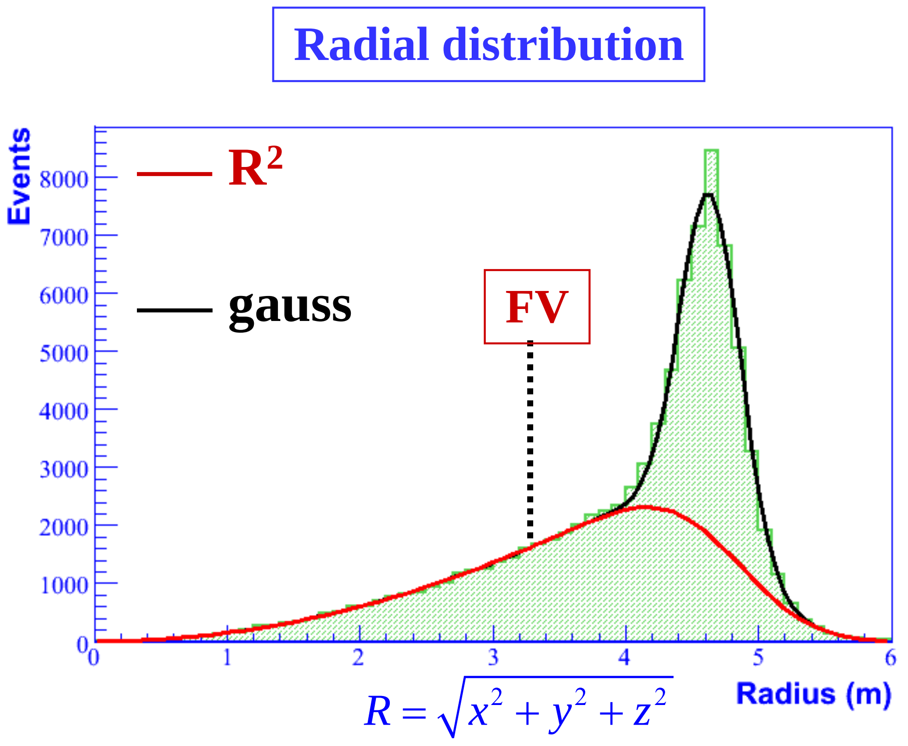


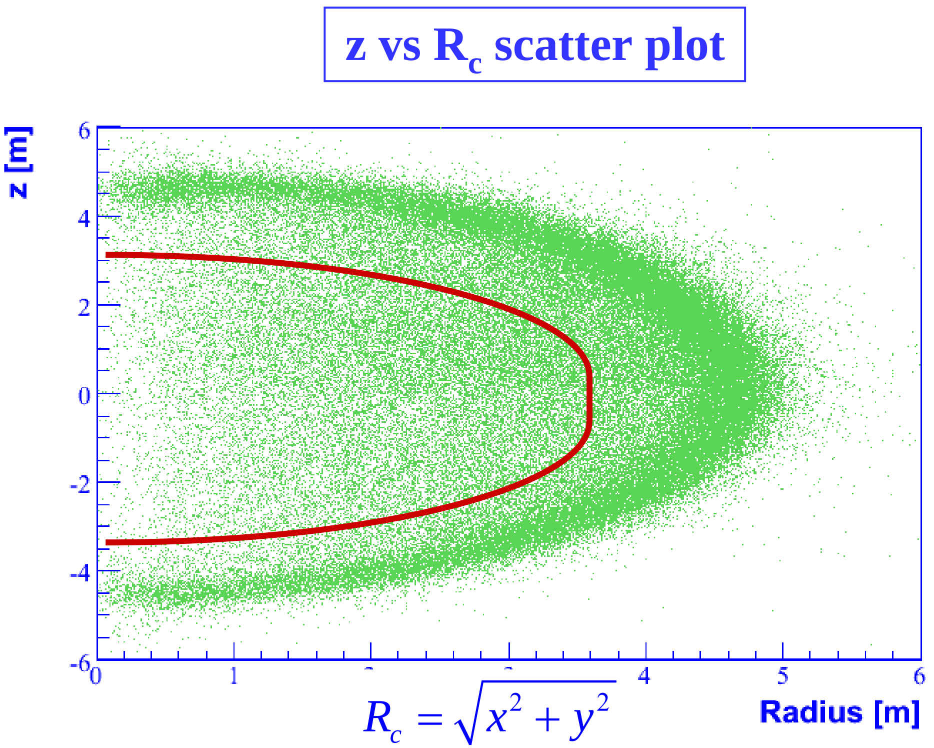
Date

Fiducial volume cut

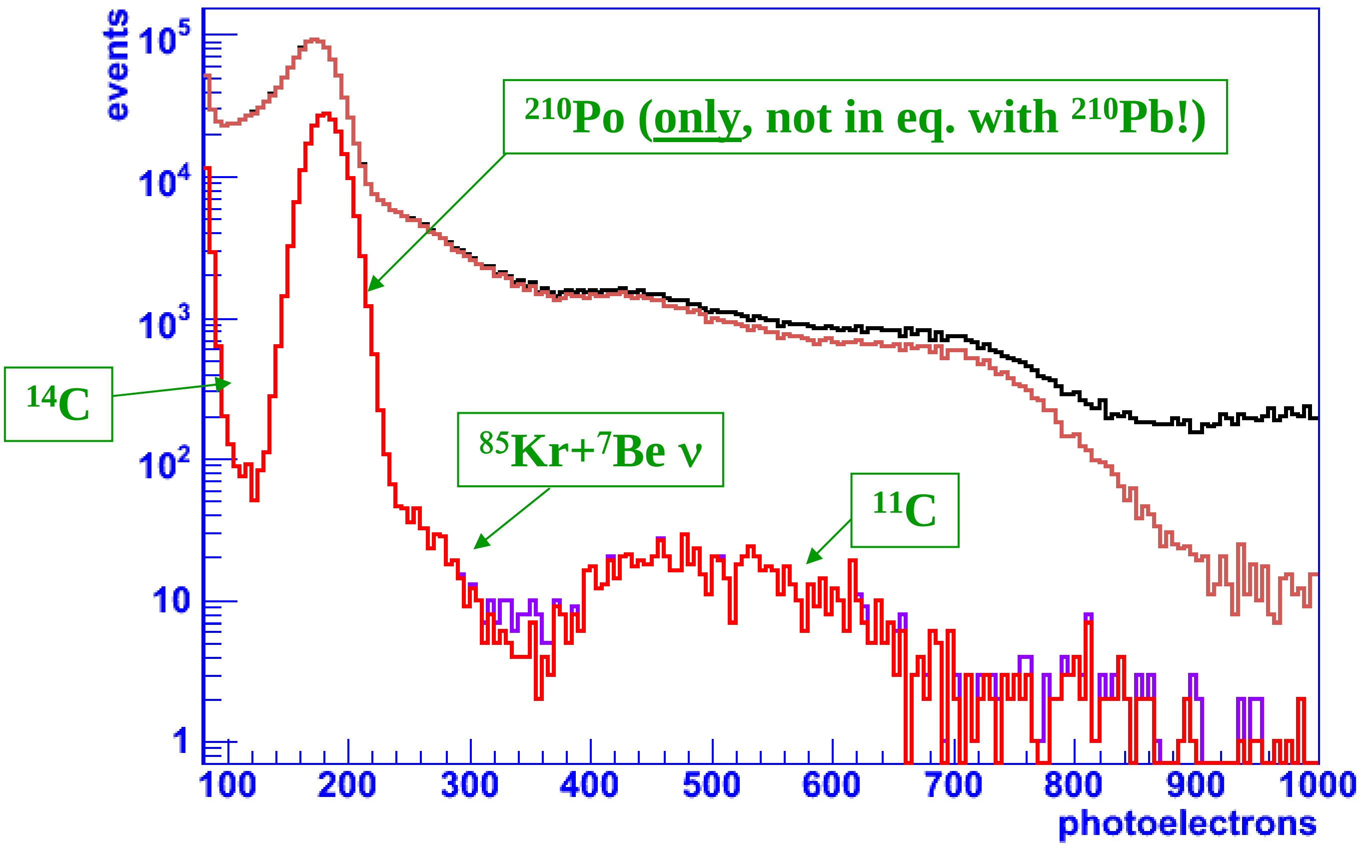
Rejection of external background (mostly gammas)

R < 3.3 m (100 t nominal mass)





Spectrum after muon and fiducial volume cuts



Next cut: ^{214}Bi-^{214}Po and Rn daughters removal

^{238}U and ^{232}Th

$\tau = 432.8$ ns

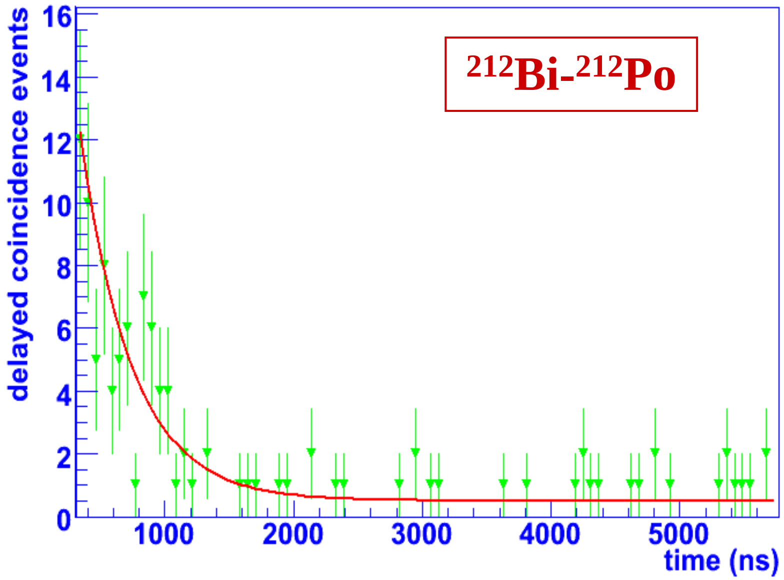
^{212}Bi $\xrightarrow{\beta}$ ^{212}Po $\xrightarrow{\alpha}$ ^{208}Pb

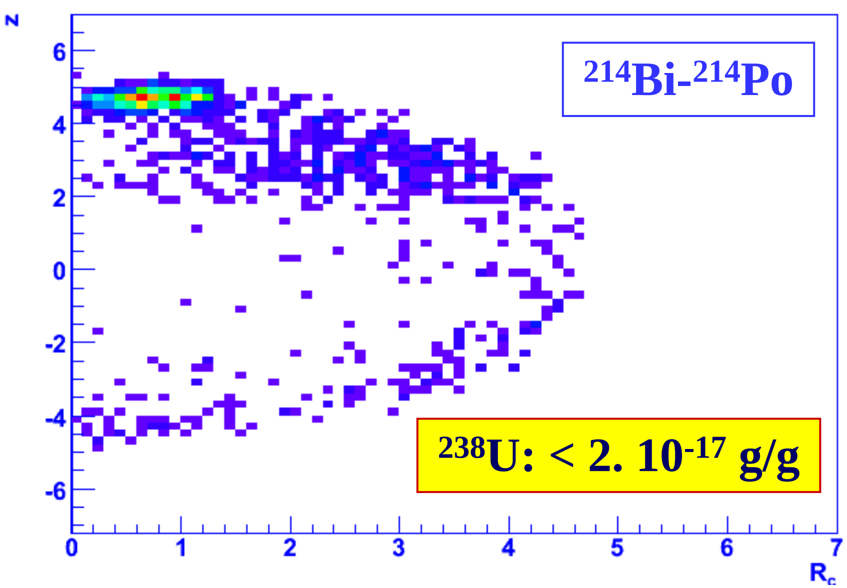
2.25 MeV ~800 KeV eq.

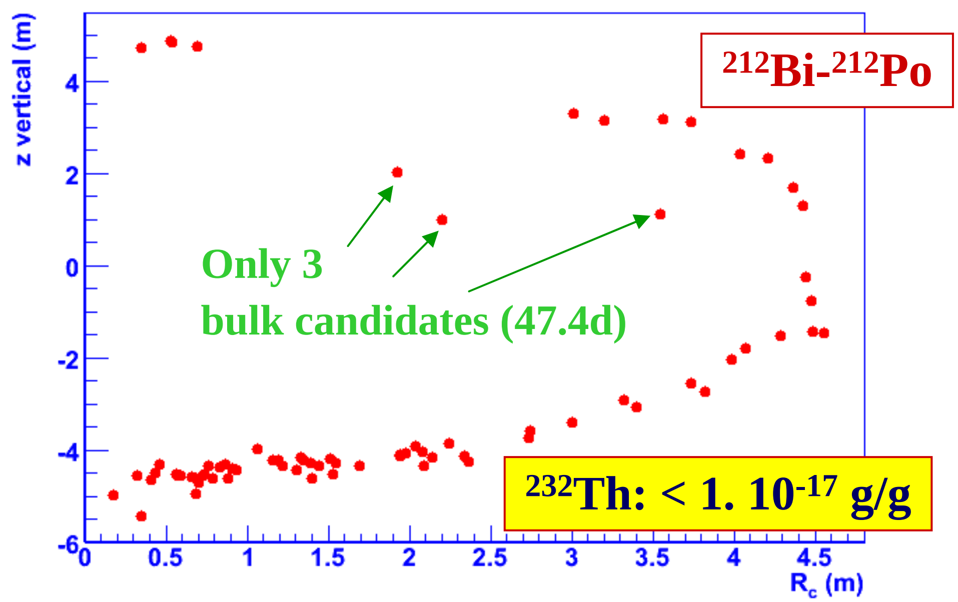
$\tau = 236$ μs

^{214}Bi $\xrightarrow{\beta}$ ^{214}Po $\xrightarrow{\alpha}$ ^{210}Pb

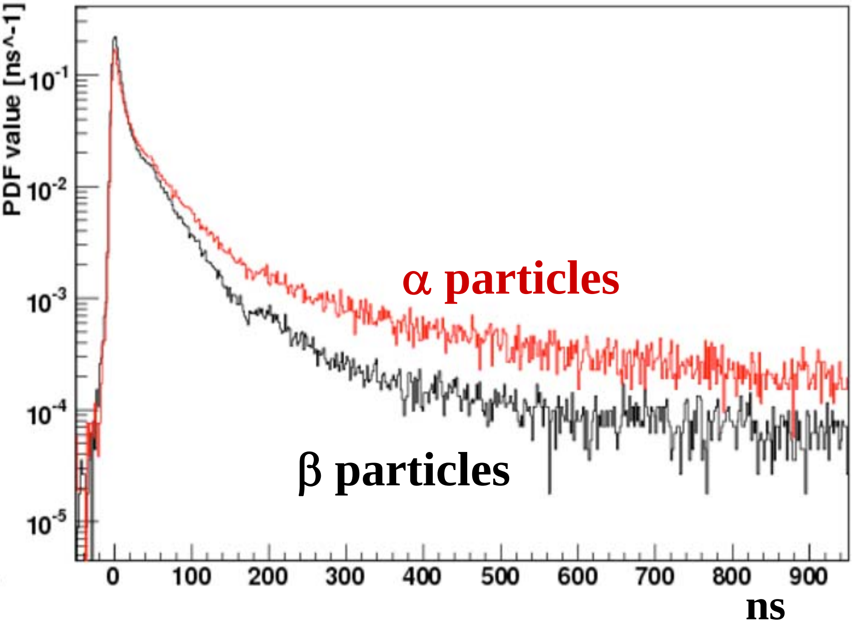
3.2 MeV ~700 KeV eq.



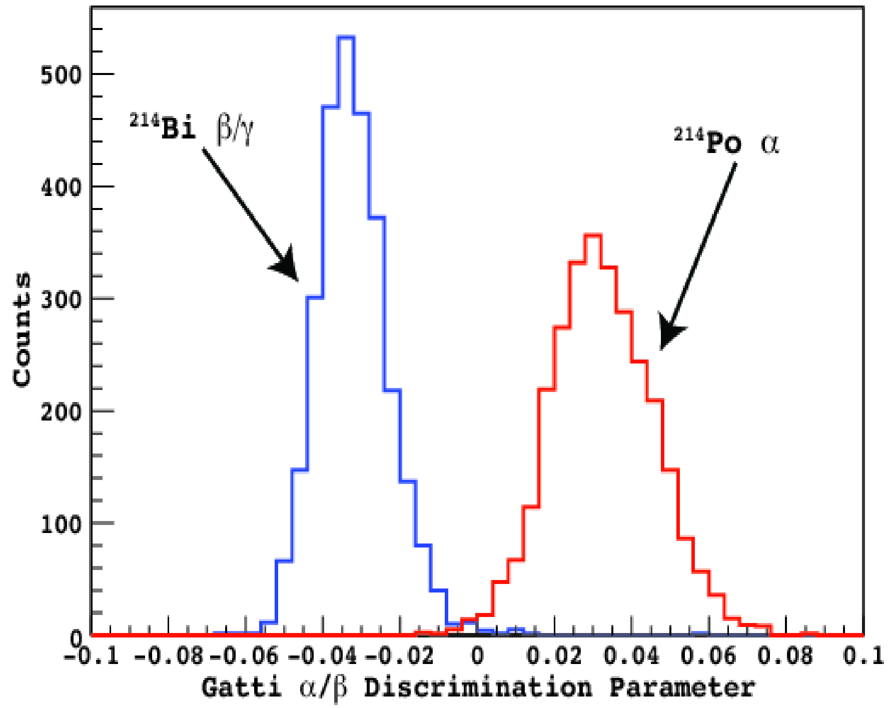




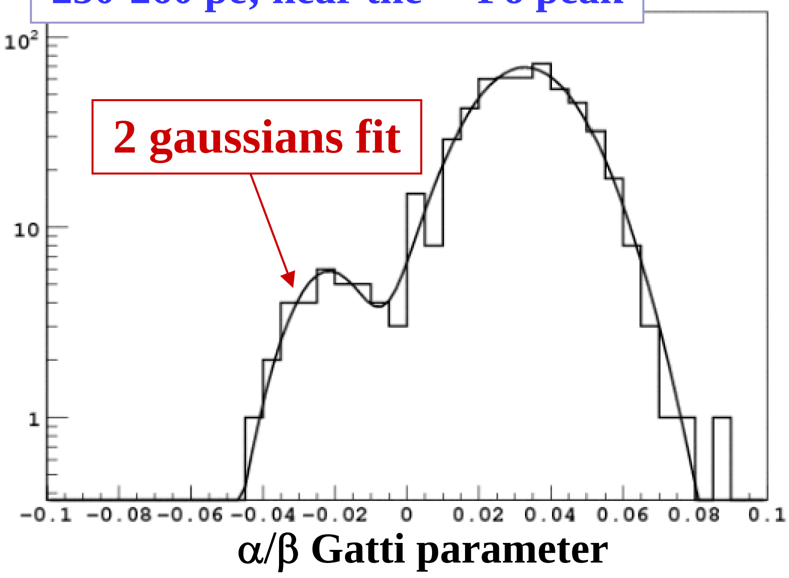
α/β Separation in BOREXINO



Full separation at high energy

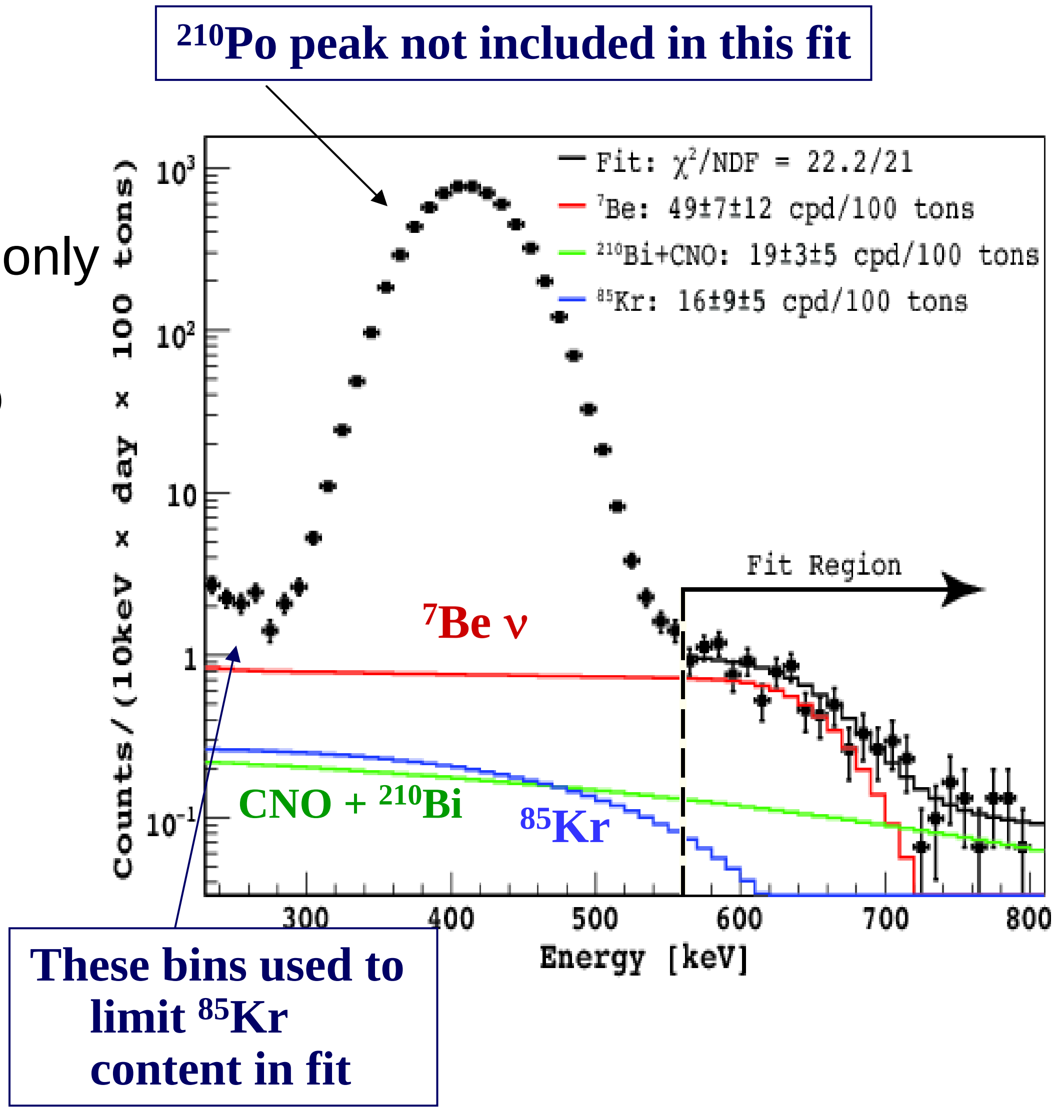


250-260 pe; near the ^{210}Po peak



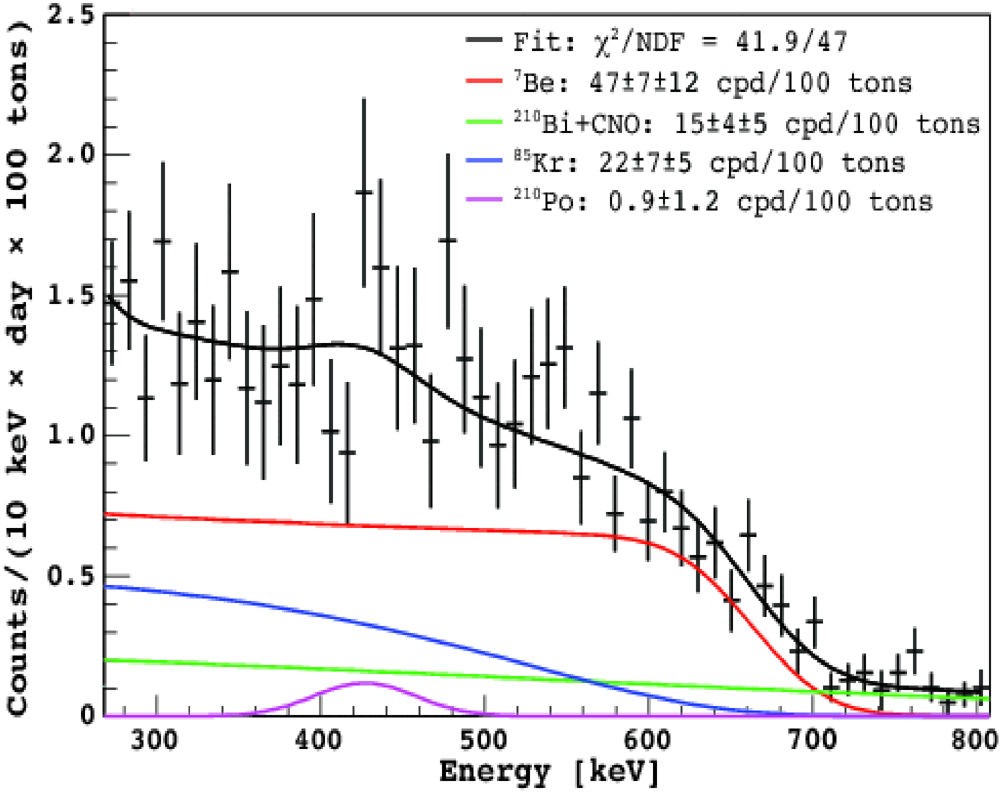
^{7}Be signal: fit without α/β subtraction

- Strategy:
  - Fit the shoulder region only
  - Area between ^{14}C end point and ^{210}Po peak to limit ^{85}Kr content
  - pep neutrinos fixed at SSM-LMA value
- Fit components:
  - ^{7}Be ν
  - ^{85}Kr
  - CNO+^{210}Bi combined
  - Light yield left free



^{7}Be signal: fit α/β subtraction of ^{210}Po peak

- ^{210}Po background is ***subtracted:***
  - For **each energy bin**, a **fit to the α/β Gatti** variable is done with two gaussians
  - From the fit result, the **number of α particles in that bin is determined**
  - This number is subtracted
  - The resulting spectrum is fitted in the energy range between 270 and 800keV



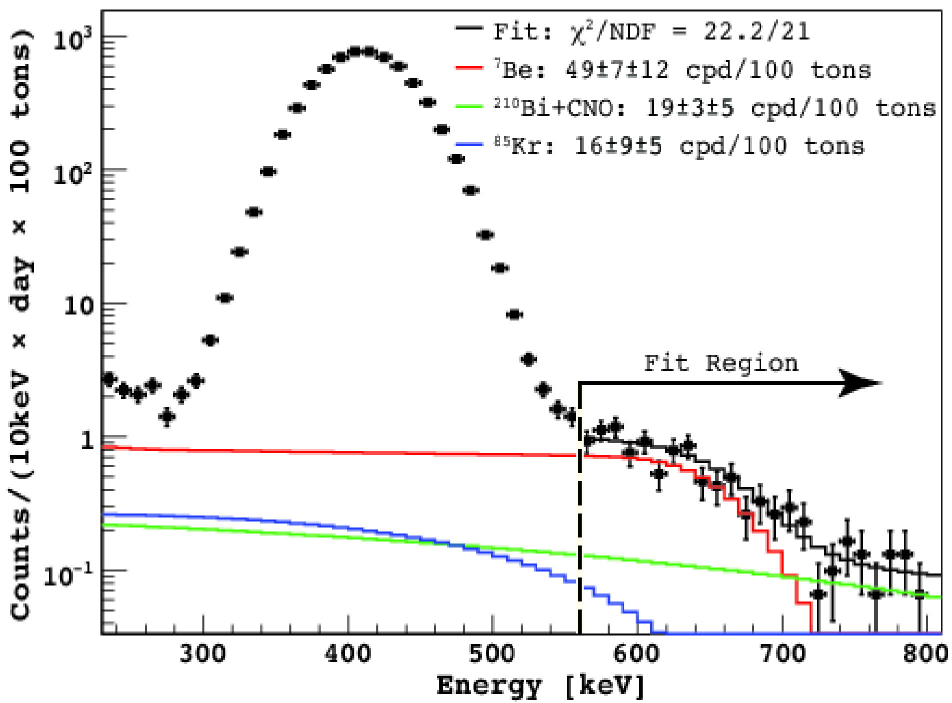
The two analysis yield fully compatible results

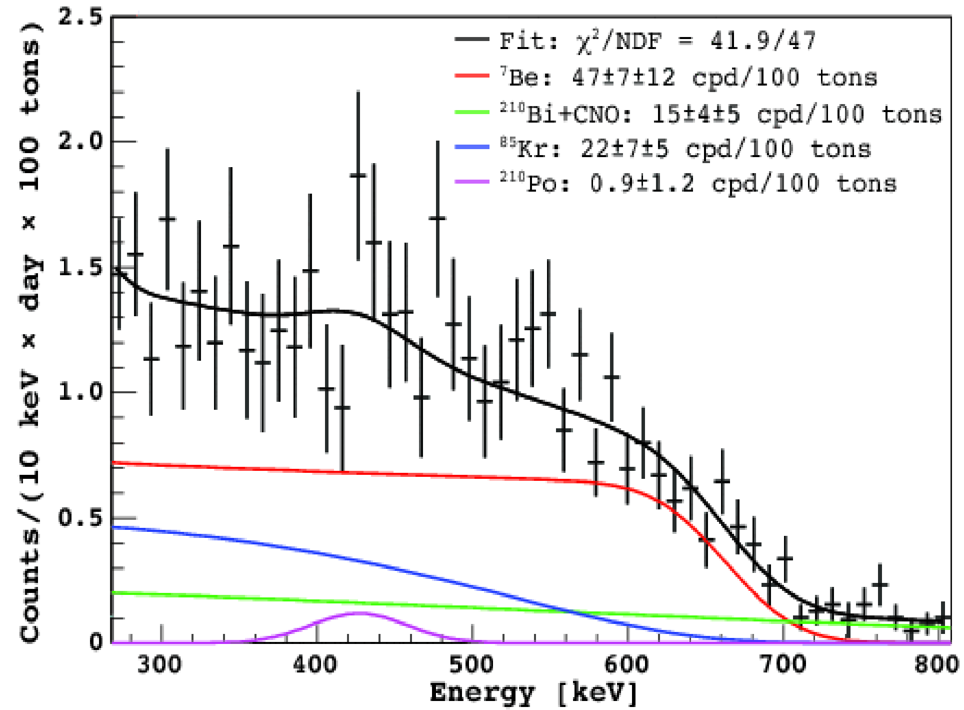
BOREXINO 1st result

(astro-ph 0708.2251v2)

- Scattering rate of **^{7}Be solar ν** on electrons

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





BOREXINO and ν-Oscillations

- **No oscillation hypothesis**

  75 ± 4 c/100t/d

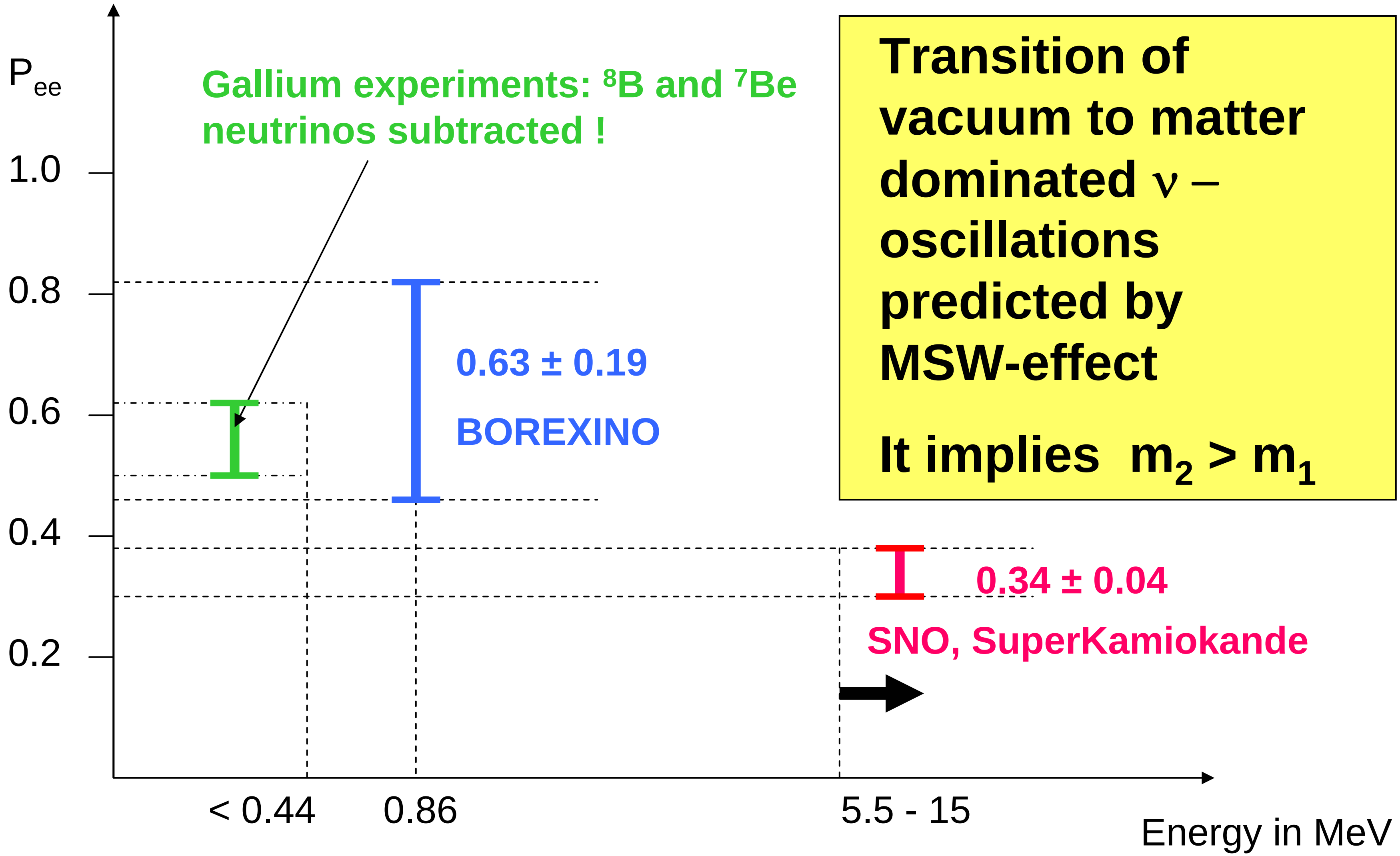
- **Oscillation** (so-called Large Mixing Solution)

  49 ± 4 c/100t/d

- **BOREXINO experimental result**

  $47 \pm 7_{stat} \pm 12_{sys}$ c/100t/d

Survival probability P_{ee} for solar ν_e



Transition of vacuum to matter dominated ν – oscillations predicted by MSW-effect

It implies $m_2 > m_1$

Prospects of BOREXINO

- Improvement of systematical uncertainty
  up to now it is dominated by uncertainty on fiducial volume
  => calibrations
- ^{7}Be flux measurement with 10% uncertainty => 1% accuracy for pp-neutrinos ! (BOREXINO + LMA parameters + solar luminosity)
- Theoretical uncertainty on pp-neutrino flux ~ 1%
  => **high precision test of thermal fusion processes**
- Aim to measure **CNO** and **pep**-neutrinos, perhaps pp-neutrinos and ^{8}B-neutrinos below 5.5 MeV
- Additional features: Geo neutrinos & reactor neutrinos & Supernova neutrinos (~100 events) for a galactic SN type II

CNO and pep Neutrinos

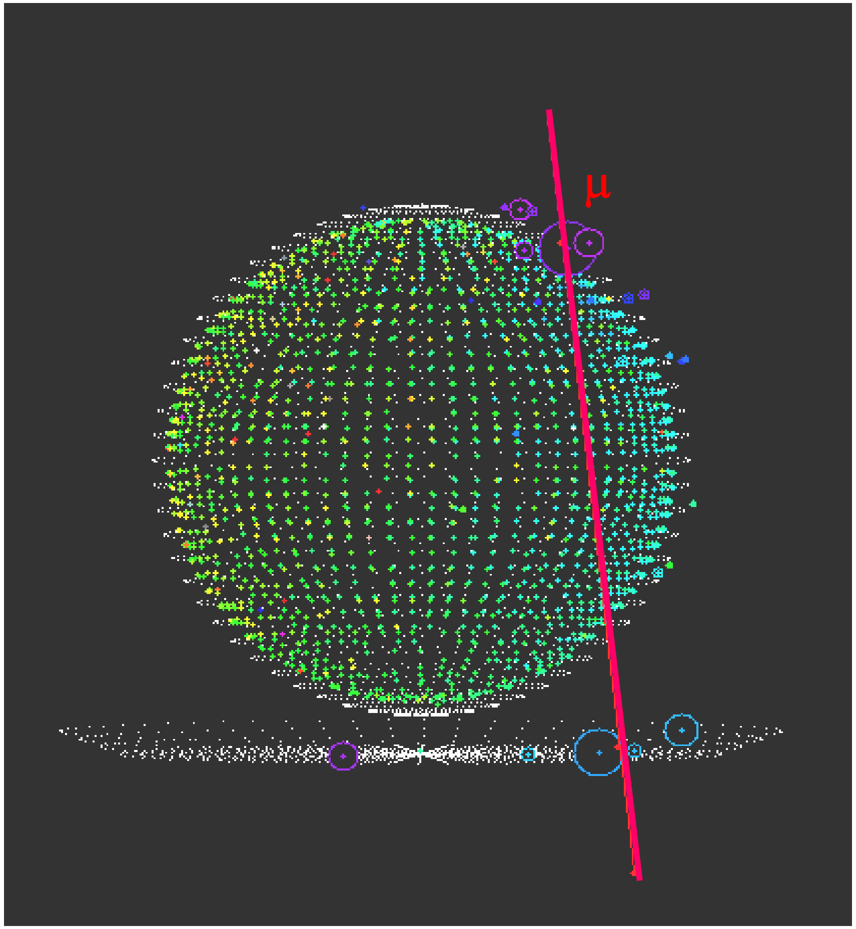
- **Problem: muon induced ^{11}C nuclei**

  $^{11}C \rightarrow {}^{11}B\ e^{+}\ \nu_e$ (Q = 1.0 MeV, $T_{1/2}$=20.4min)

- **Aim: tag via 3-fold delayed coincidence**

  μ, n (~ms) reconstruct position of n-capture veto region around this position for ~ 1 hour. Required rejection factor ~ 10

μ track reconstruction



Low Energy Neutrino Astronomy in the Future

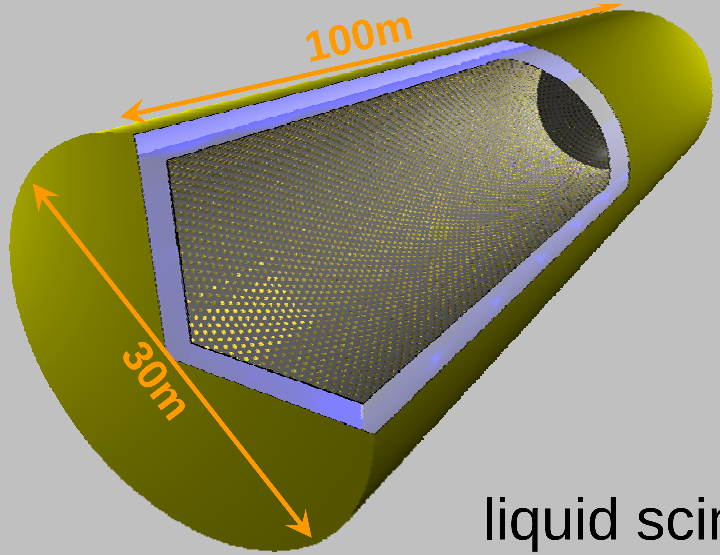
- Details of a **gravitational collapse** (Supernova Neutrinos)
- Studies of **star formation** in former epochs of the universe („Diffuse Supernovae Neutrinos Background" DSNB)
- High precision studies of **thermo-nuclear fusion processes** (Solar Neutrinos)
- Test of **geophysical models** ("Geo-neutrinos")

LAGUNA

- **L**arge **A**pparatus for **G**rand **U**nification and **N**eutrino **A**stronomy
- Future Observatory for **ν-Astronomy** at low energies
- Search for **proton decay** (GUT)
- Detector for "**long-baseline**" experiments
- Institutes from Europe
- ~ 1.7 M€ for site feasibility studies (FP7 program)

LAGUNA

Large Apparatus for Grand Unification
and Neutrino Astrophysics



LENA

liquid scintillator

~50 kt target, *13,500 PMs*

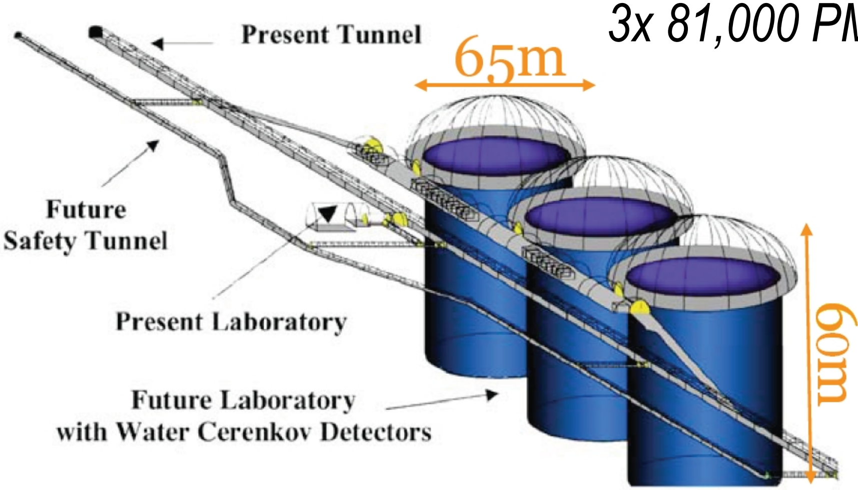
Čerenkov muon veto

coordinated F&E “Design Study”
European Collaboration,
FP7 Proposal
APPEC Roadmap

MEMPHYS

Water Čerenkov

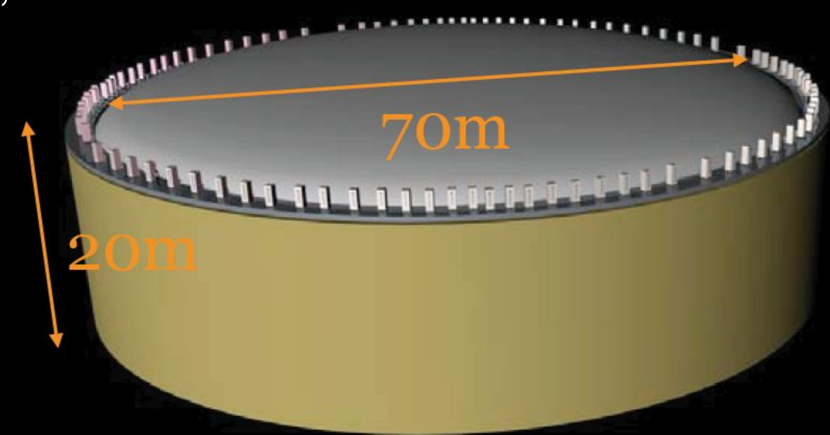
500 kt target in 3 tanks,
3x 81,000 PMs



GLACIER

liquid-Argon

~100 kt target, 20m drift length,
28,000 PMs for Čerenkov- und scintillation



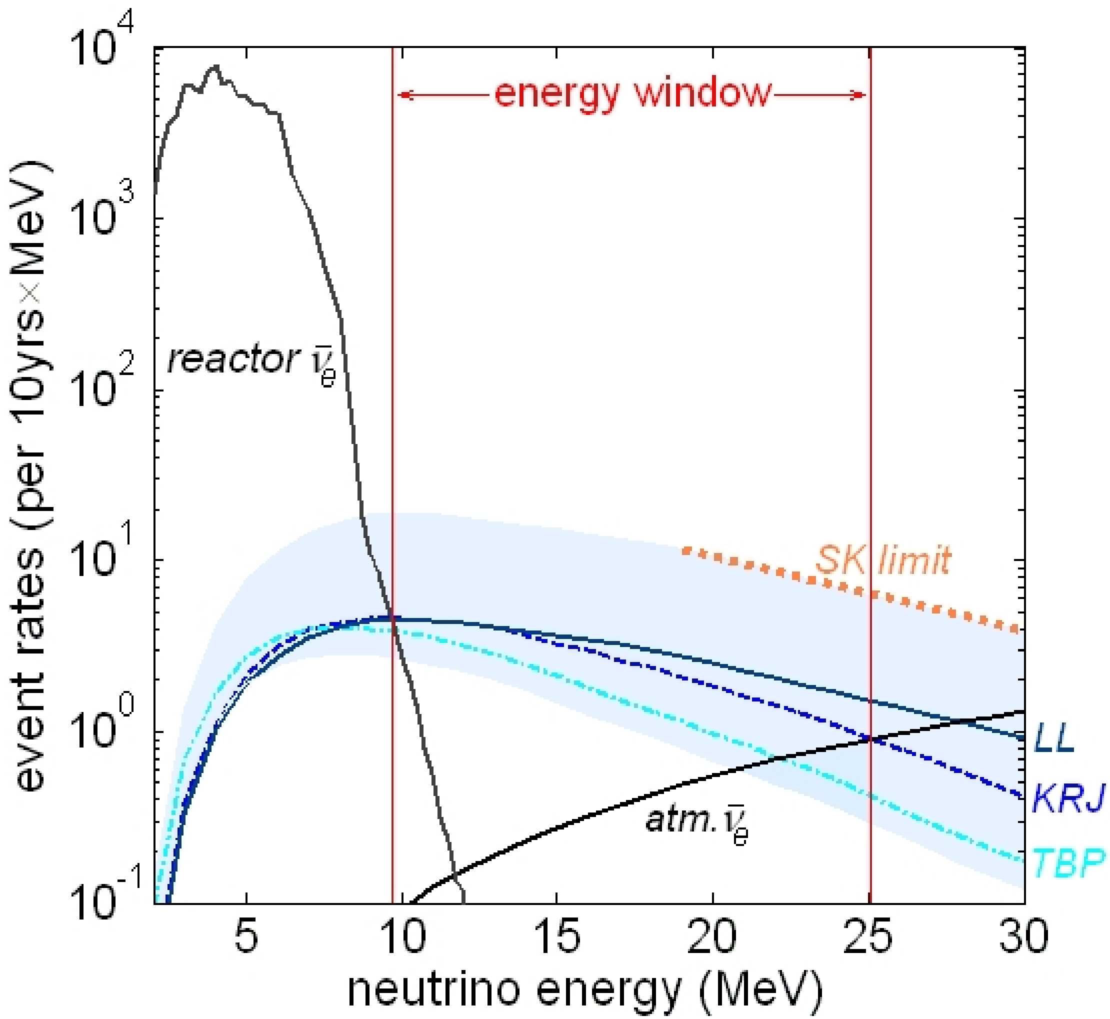
LAGUNA

DETECTOR LOCATIONS

COLLABORATING INSTITUTES

APC, Paris, France
CEA, Saclay, France
CPPM, IN2P3-CBRS, Marseille, France
CUPP, Pyhäsalmi, Finland
ETHZ, Zürich, Switzerland
Institute for Nuclear Research, Moscow, Russia
IPNO, Orsay, France
LAL, IN2P3-CNRS, Orsay, France
LPNHE, IN2P3-CNRS, Paris, France
MPI-K Heidelberg, Germany
Max Planck für Physik, München, Germany
Technische Universität München, Germany
Universidad de Granada, Spain
Universität Hamburg, Germany
University of Bern, Switzerland
University of Helsinki, Finland
University of Jyväskylä, Finland
University of Oulu, Finland
University of Silesia, Katowice, Poland
University of Sheffield, UK

LENA: Diffuse SN Background



M. Wurm et al., Phys. Rev D 75 (2007) 023007

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

Delayed coincidence

Spectral information

Event rate depends on

-Supernova type II rates

-Supernova model

Range: 20 to 220 / 10 y

Background: ~ 1 per year

Conclusions

- **L**ow **E**nergy **N**eutrino **A**stronomy is very successful (Borexino ➔ direct observation of sub-MeV neutrinos)
- Strong impact on questions in **particle**- and **astrophysics**
- New technologies (photo-sensors, extremely low level background…)
- Strong European groups