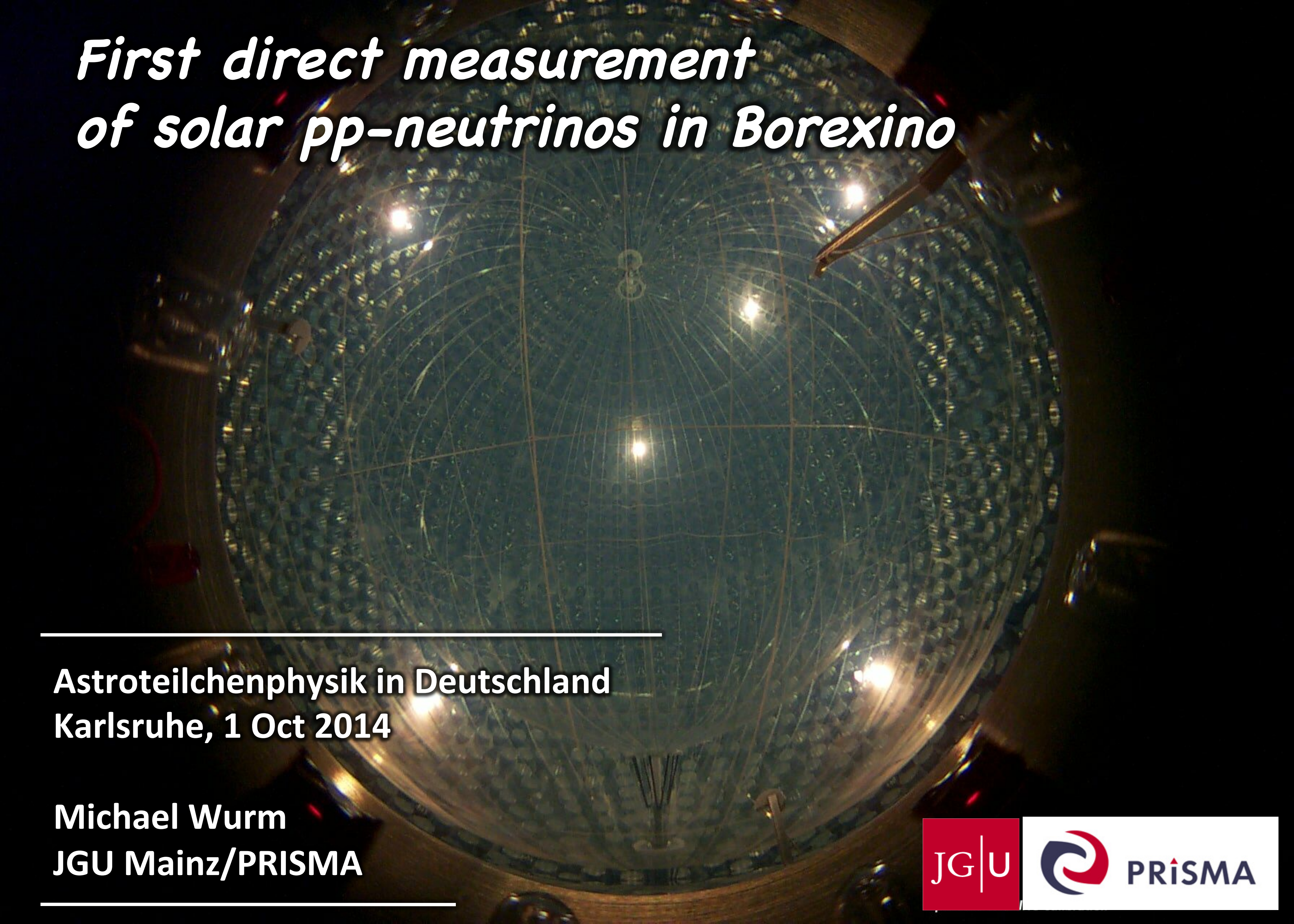


First direct measurement of solar pp-neutrinos in Borexino

Astroteilchenphysik in Deutschland
Karlsruhe, 1 Oct 2014

Michael Wurm
JGU Mainz/PRISMA

Outline

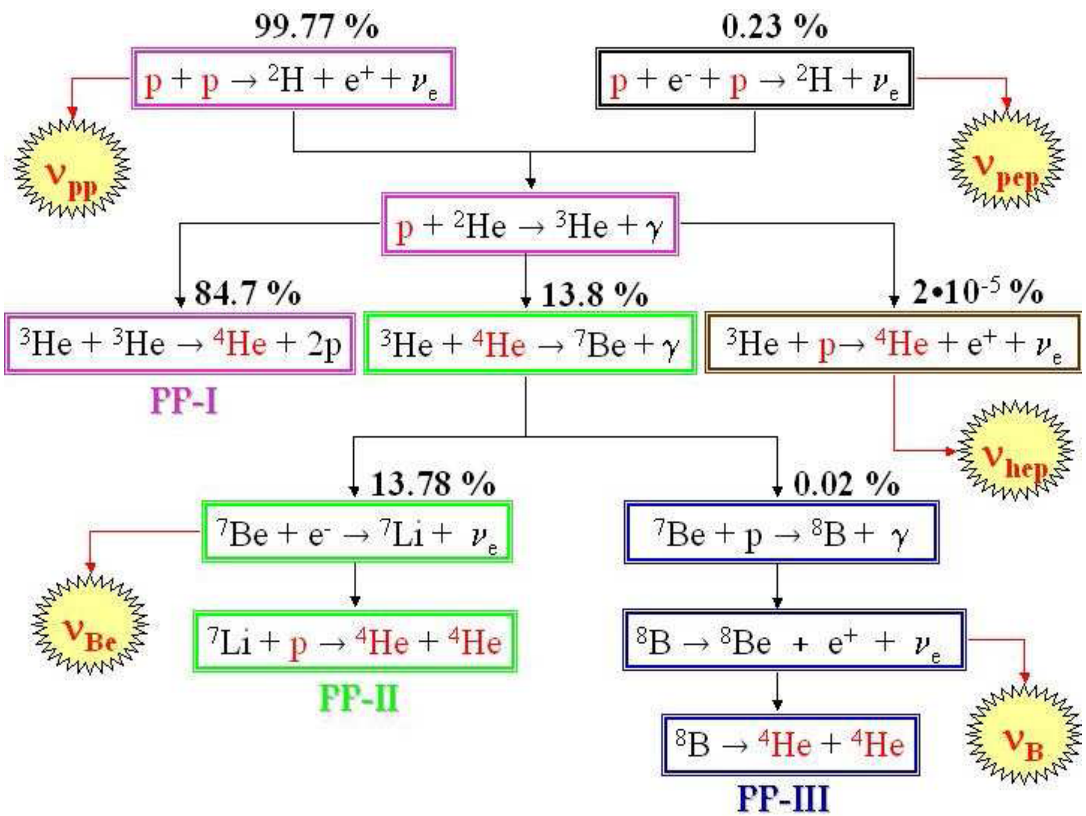
- Solar fusion
  and pp neutrinos
- Expected signal
  in BOREXINO
- Main challenges:
  – Radiopurity
  – ^{14}C background
- Results obtained
  by BOREXINO
  [Nature 512 (2014) 7515]
- Relevance for
  neutrino oscillations
  and solar physics

Solar fusion processes

Basic fusion reaction: $4p \rightarrow {}^4He + 2e^+ + 2\nu_e$ [+26.7 MeV]

proton-proton-chain

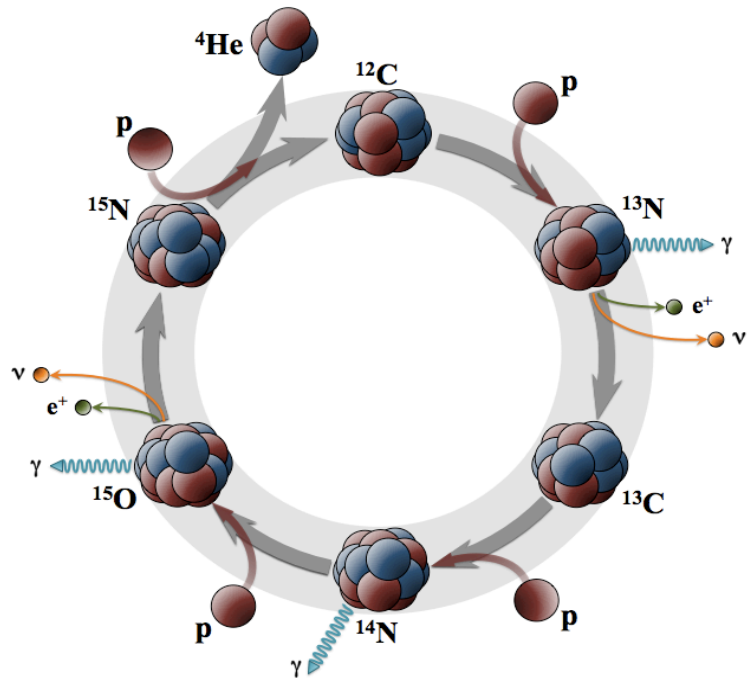
~99% of energy release



CNO cycle

<1% of energy

theory: poorly known
experiment: undetermined



Real-time measurements of solar neutrinos

Basic fusion reaction: $4p \rightarrow {}^4He + 2e^+ + 2\nu_e$ [+26.7 MeV]

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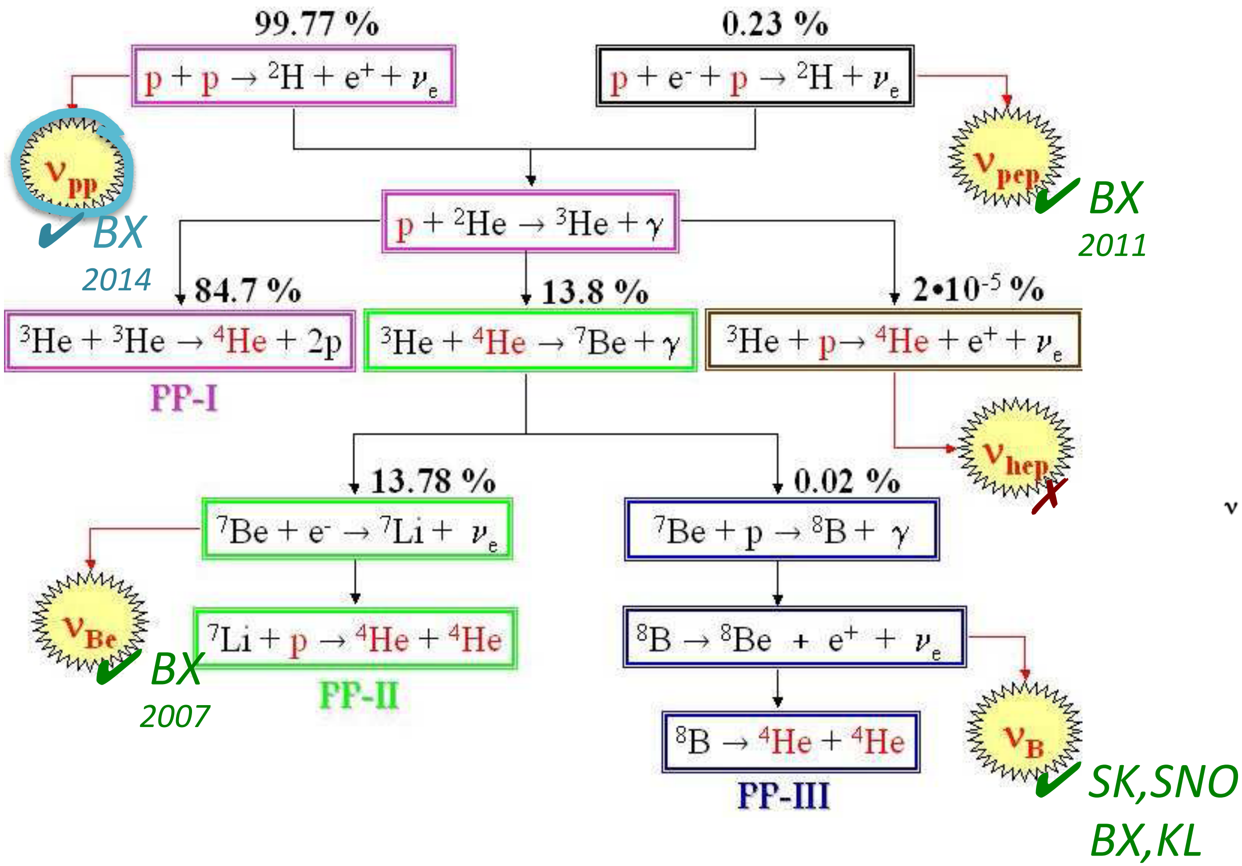

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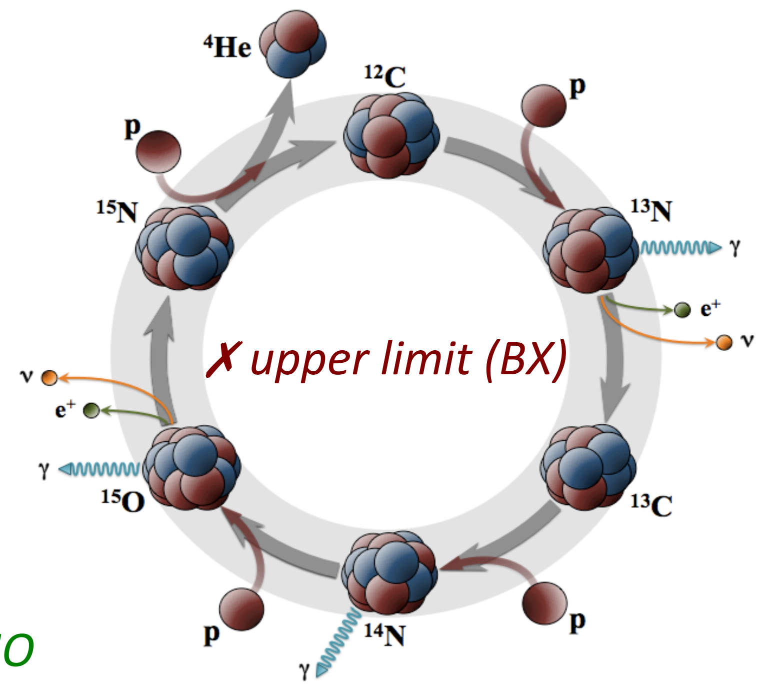
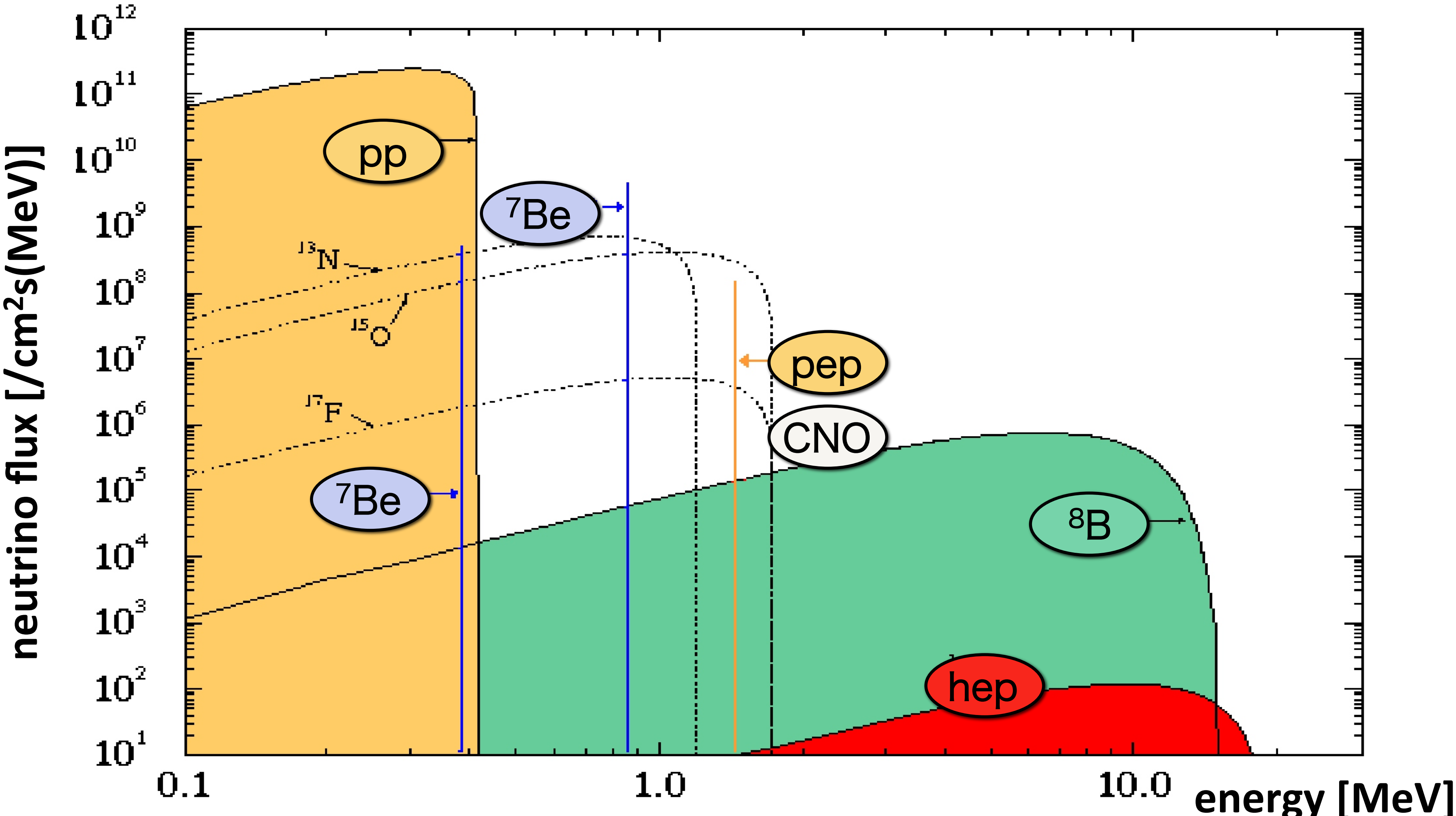


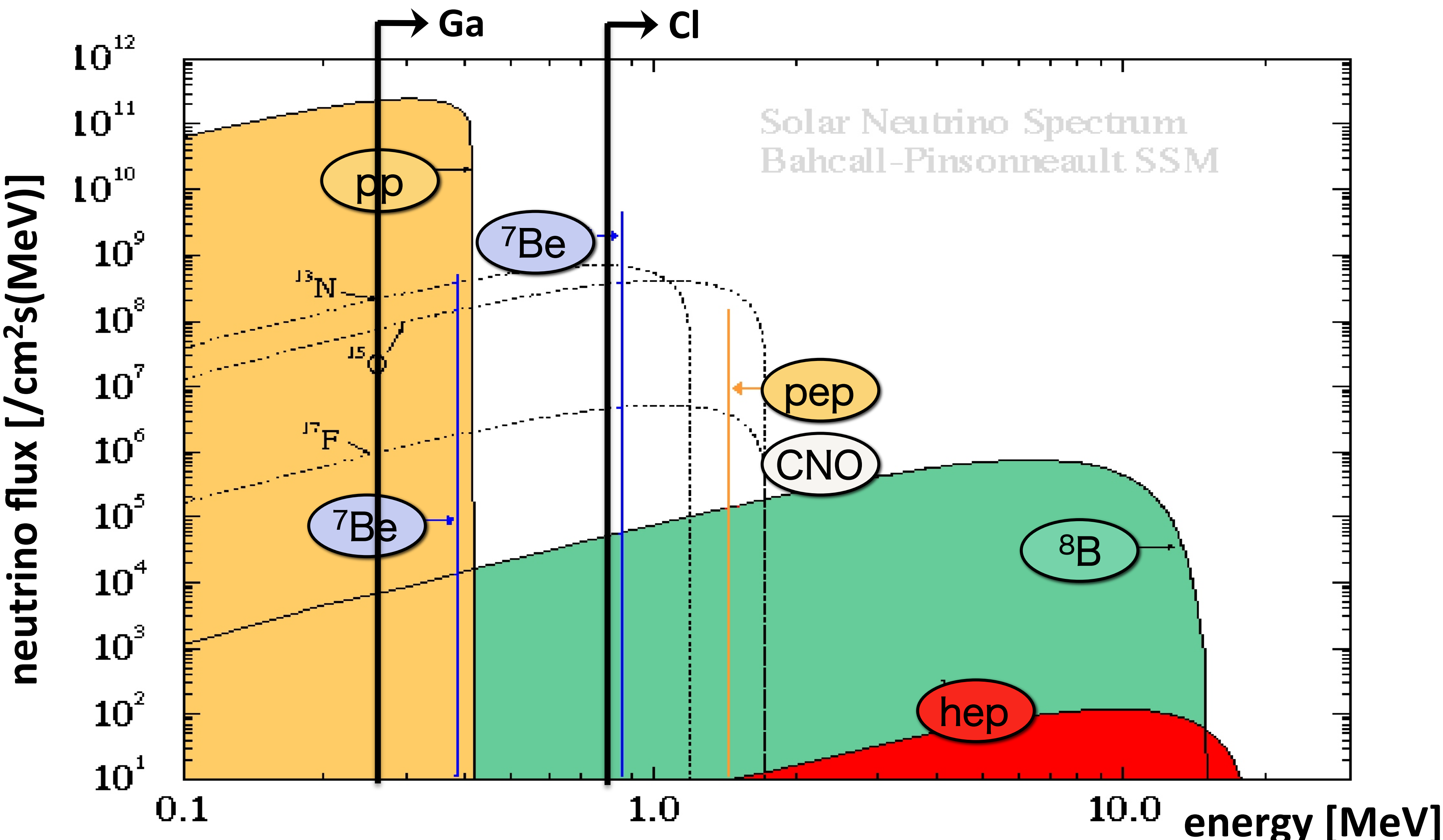
Solar neutrino spectrum

Standard Solar Model (SSM) by Bahcall, Pinsonneault



Solar neutrino spectrum

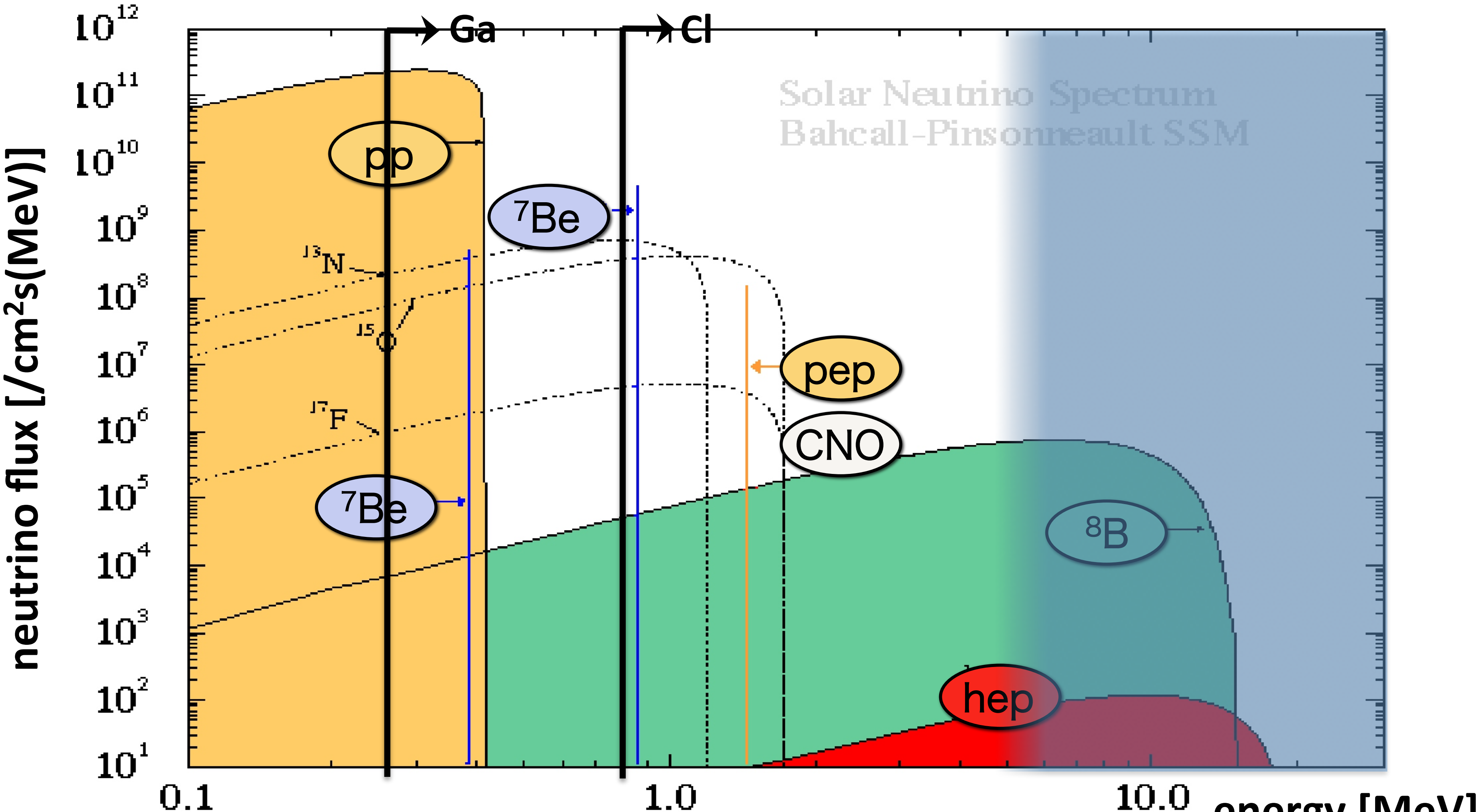
Radiochemical experiments: integrated measurement only



Solar neutrino spectrum

Radiochemical experiments: integrated measurement only

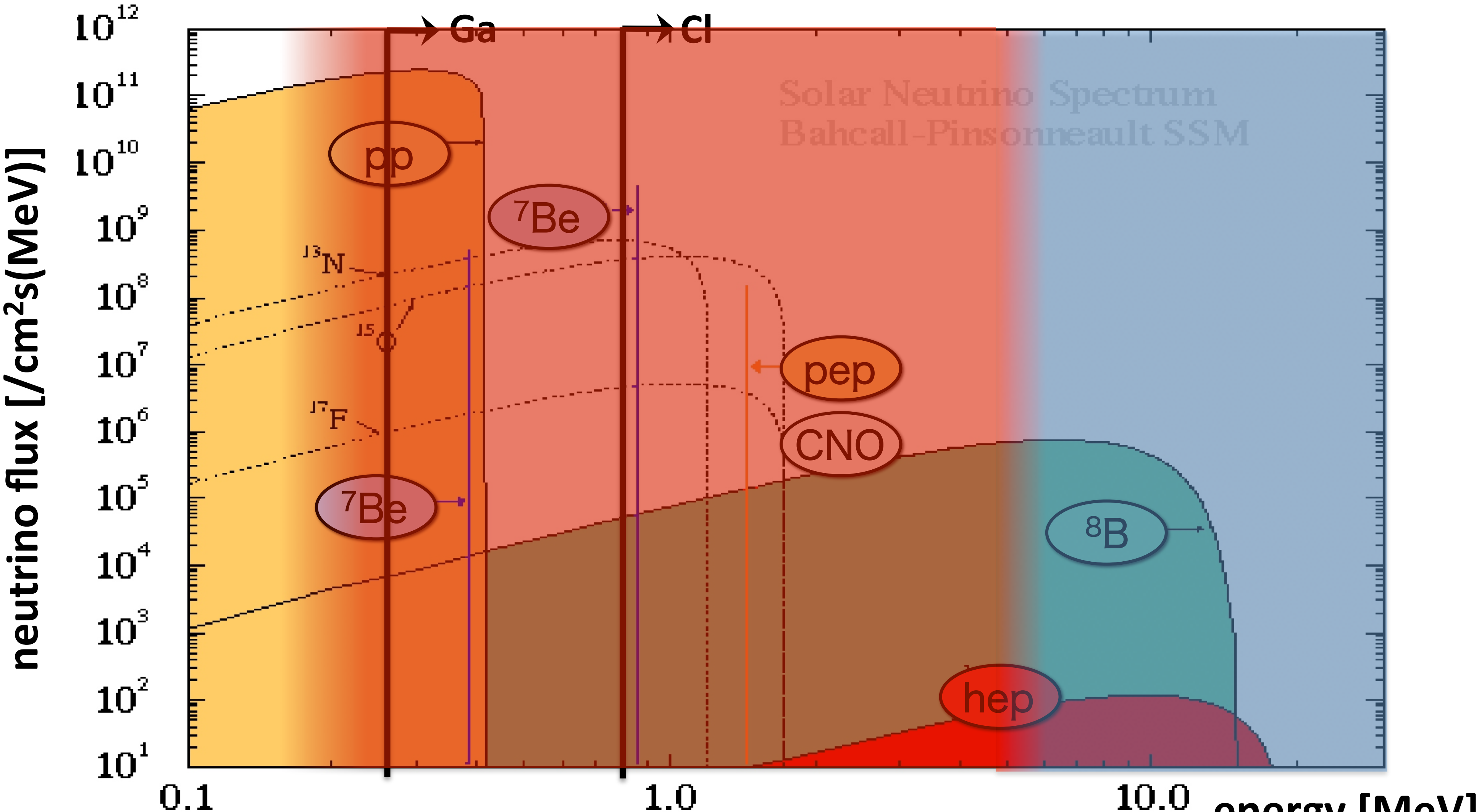
Water Cherenkov Detectors: E > 3.5 MeV



Solar neutrino spectrum

Radiochemical experiments: integrated measurement only

Water Cherenkov: E > 3.5 MeV -- Liquid Scintillator: E > 200 keV



the Borexino Collaboration

INFN

Milano

München

Max-Planck-Institut für Kernphysik Heidelberg

Hamburg

Mainz

LNGS Gran Sasso

Perugia

Genova

Napoli

TU Dresden

Jagiellonian Kraków

Borexino Gran Sasso

JINR Dubna

Virginia Tech

Houston

Paris

Moscow

Los Angeles

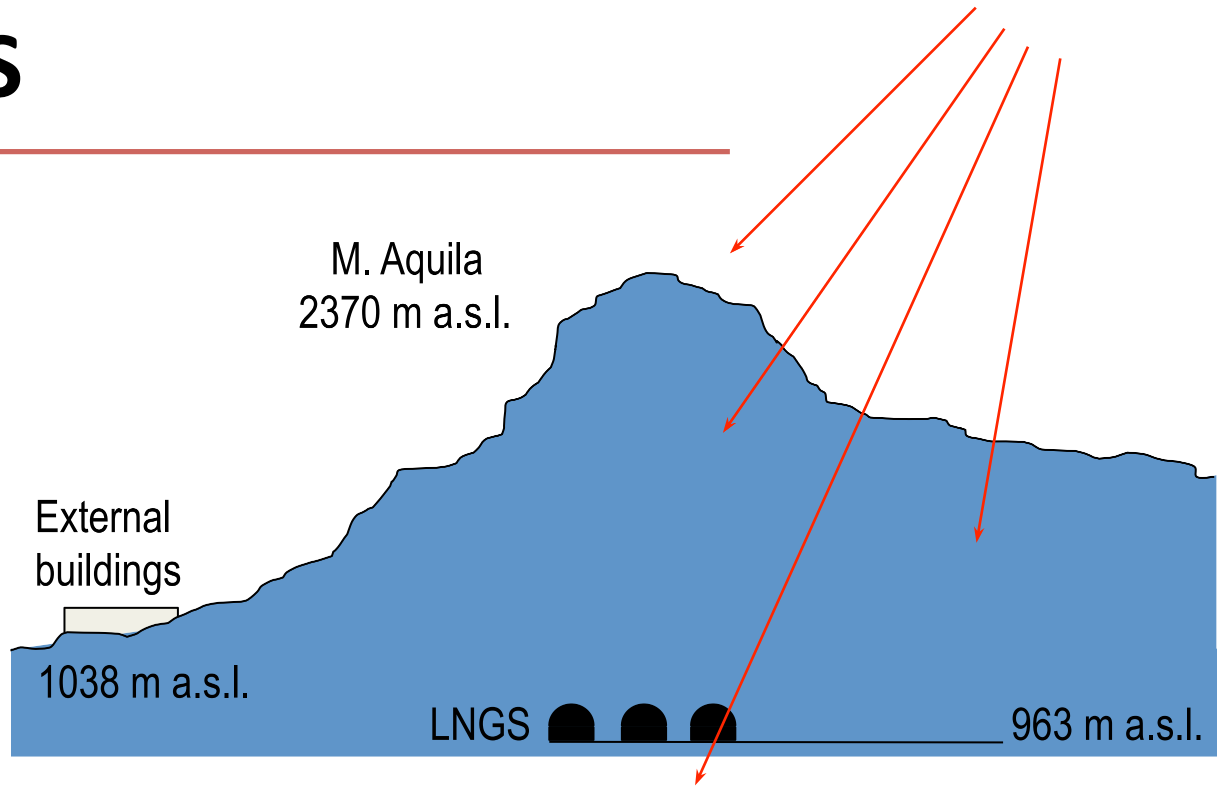
Princeton

UMass Amherst

St. Petersburg

Kurchatov Moscow

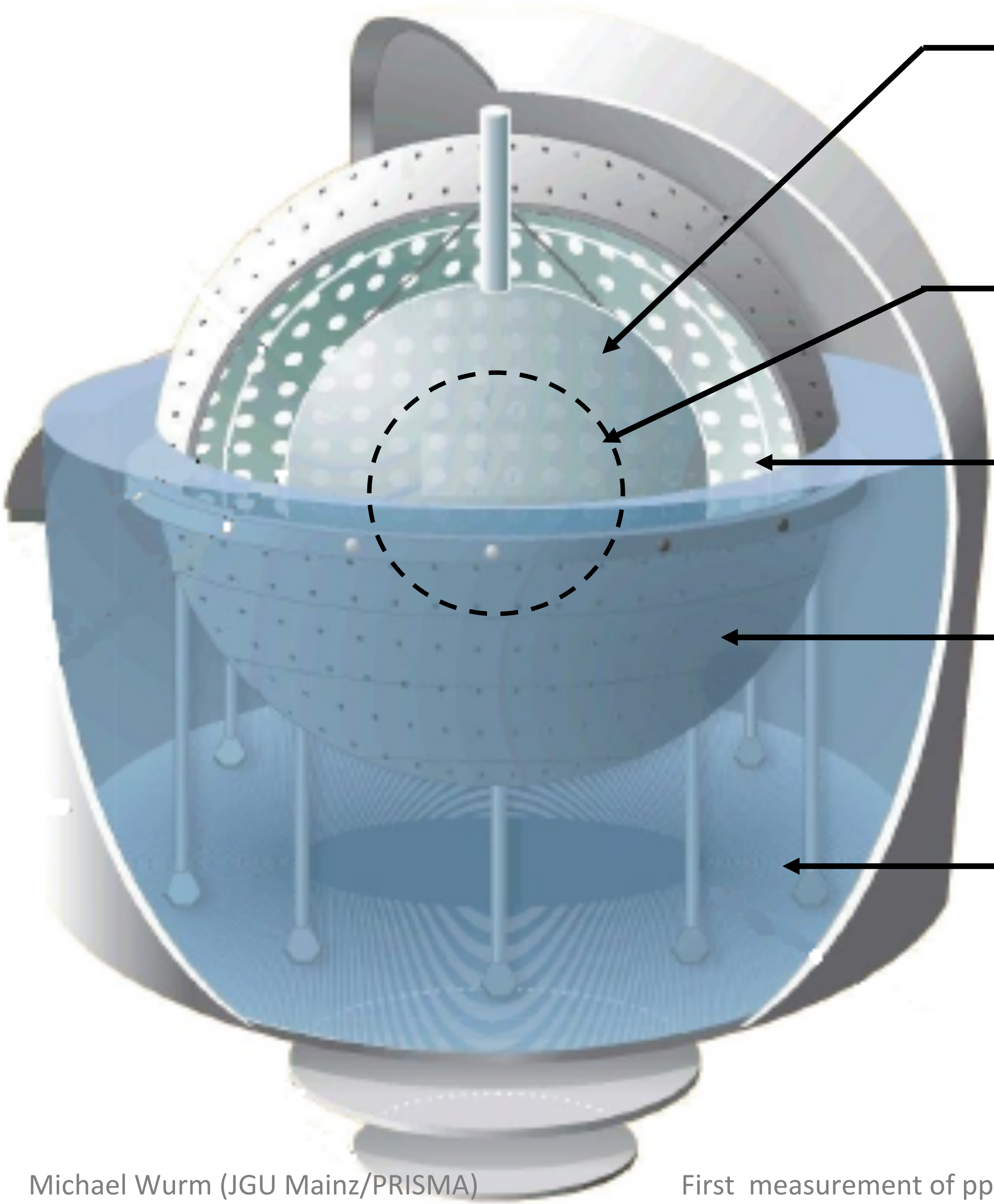
Borexino @ LNGS



Borexino is located in Hall C of the **LNGS**
(Laboratori Nazionali del Gran Sasso)

corresponding rock shielding:
1400 m (3500 mwe)
residual cosmic muon flux:
~1.2/m^{2}h or 4300/d in Bx ID

Layout of the Borexino detector



Active volume
270t of liquid scintillator (PC)
in nylon vessel of R=4.25 m

Fiducial volume: 100t
radiopurity: ~10^{-18} g/g U/Th

Inactive buffer volume
shielding of external γ-rays

Stainless steel sphere
radius: 6.85 m
2212 inward-facing PMTs

Inner Detector

Outer muon veto
2.1 kt of water, R=9m
208 PMTs
muon-Cherenkov veto

Outer Detector

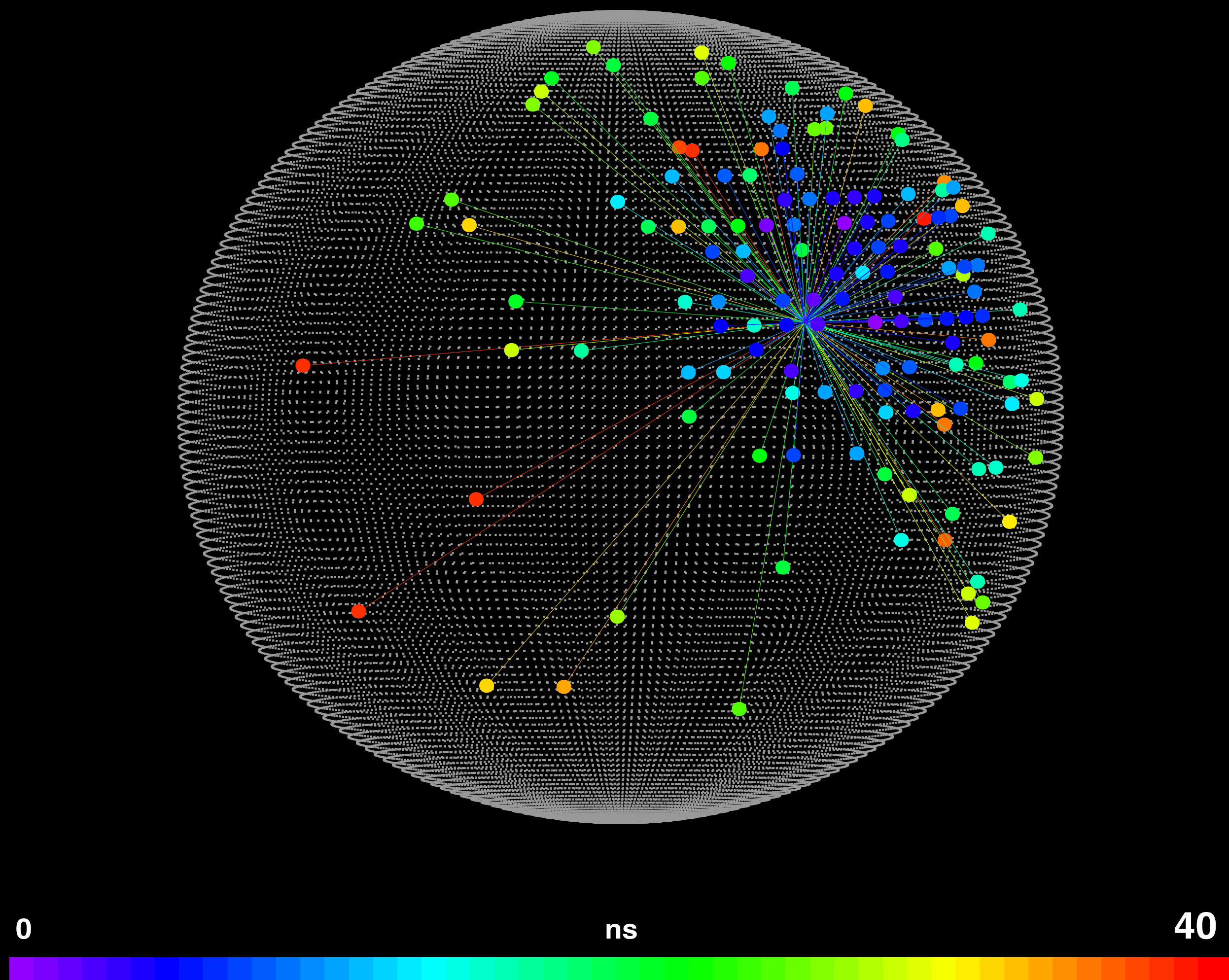
Event reconstruction in Borexino

- **Scintillation light yield**
  ~500 photoelectrons per MeV

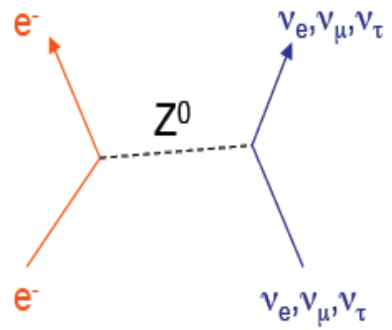
- **Instrumental threshold**
  ~25 pe – 50 keV

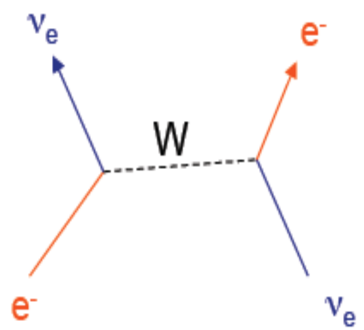
- **Energy reconstruction**
  number of detected photoelectrons
  → $\Delta E/E \sim 5\%$ @ 1 MeV

- **Spatial reconstruction**
  photon arrival time pattern (tof)
  → $\Delta x \sim 10$ cm @ 1 MeV



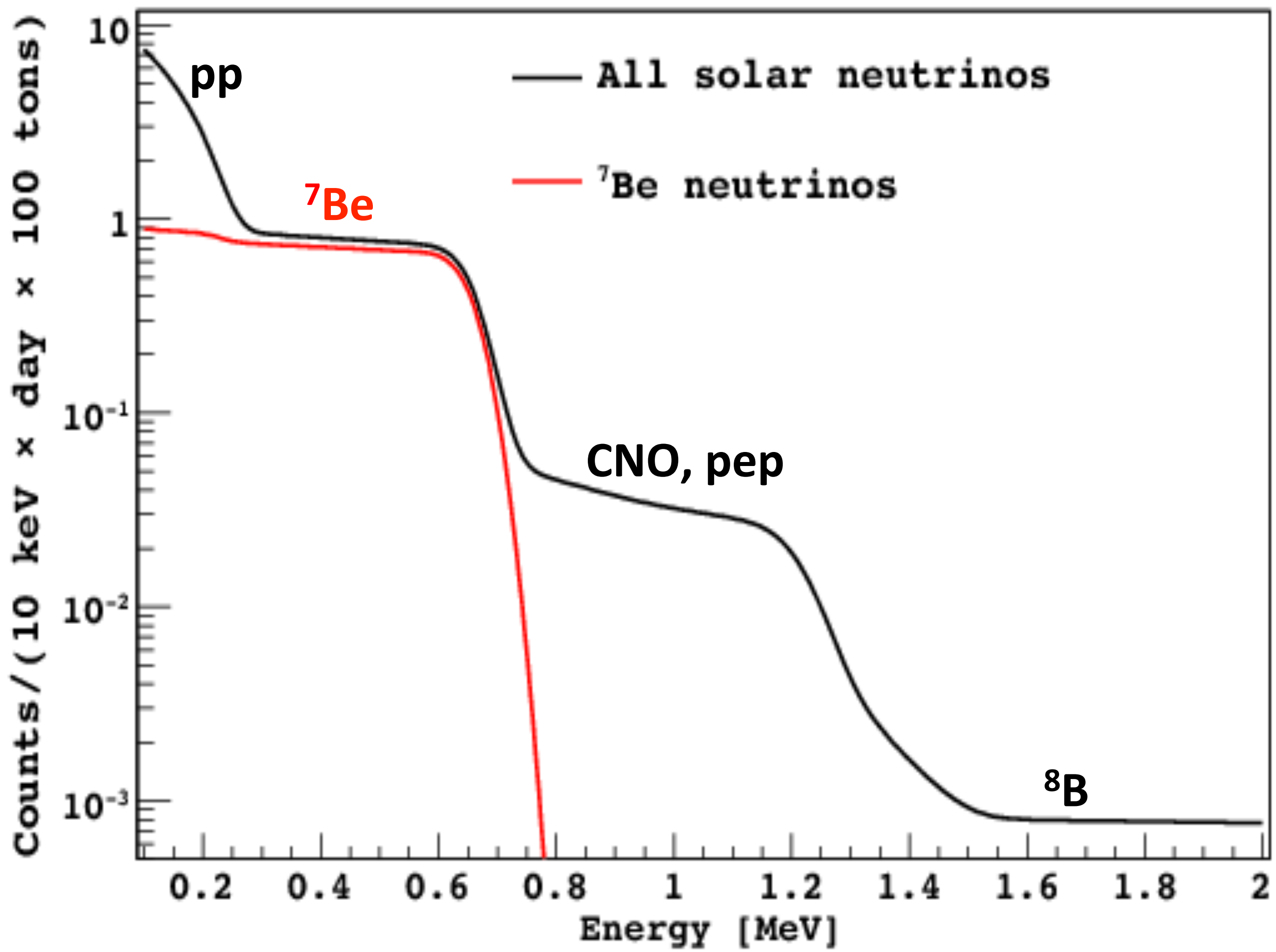
Detection by neutrino-electron scattering



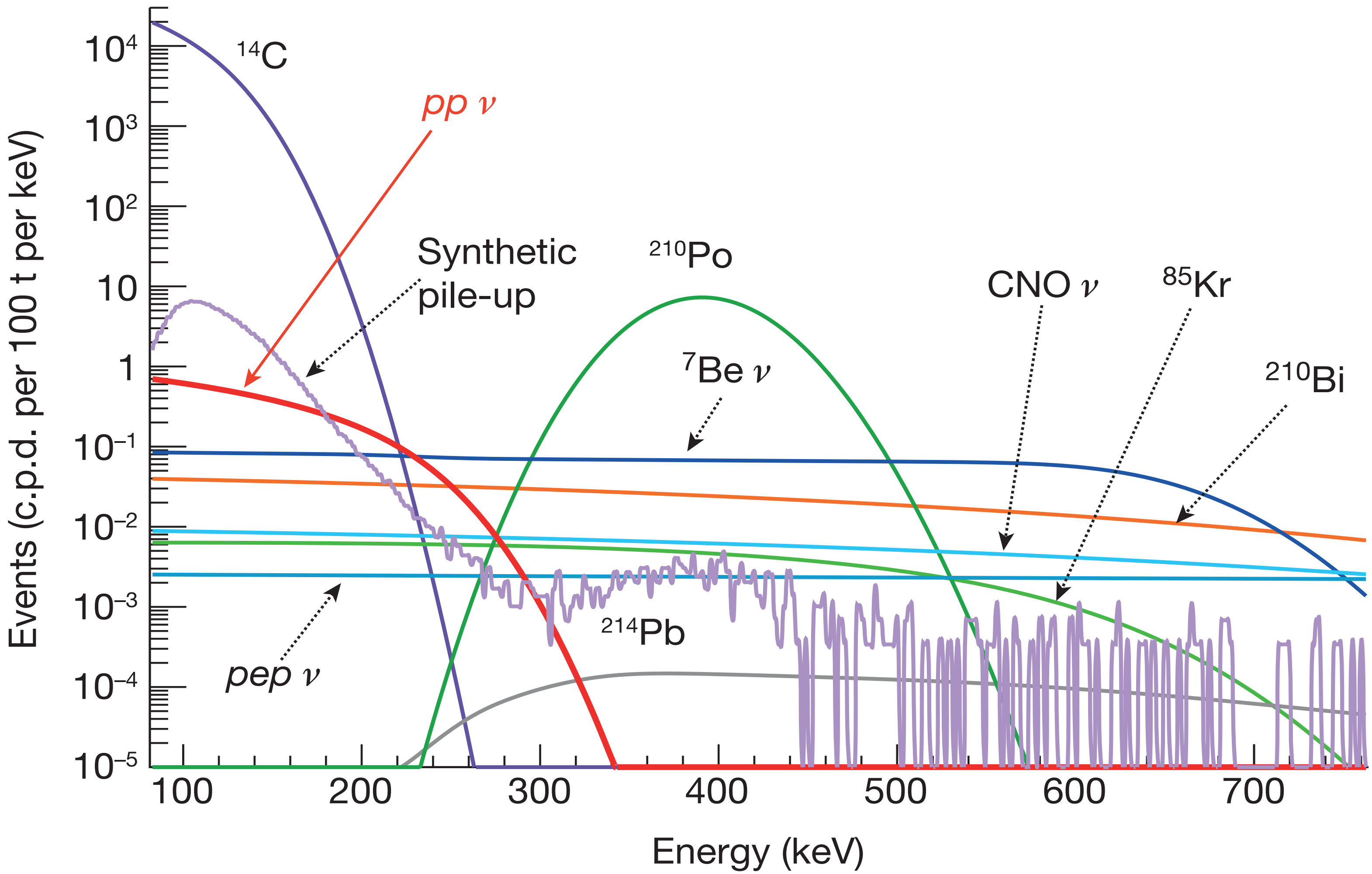


→ Larger cross-section for electron neutrinos

Expected electron recoil spectrum



Backgrounds in the region of interest

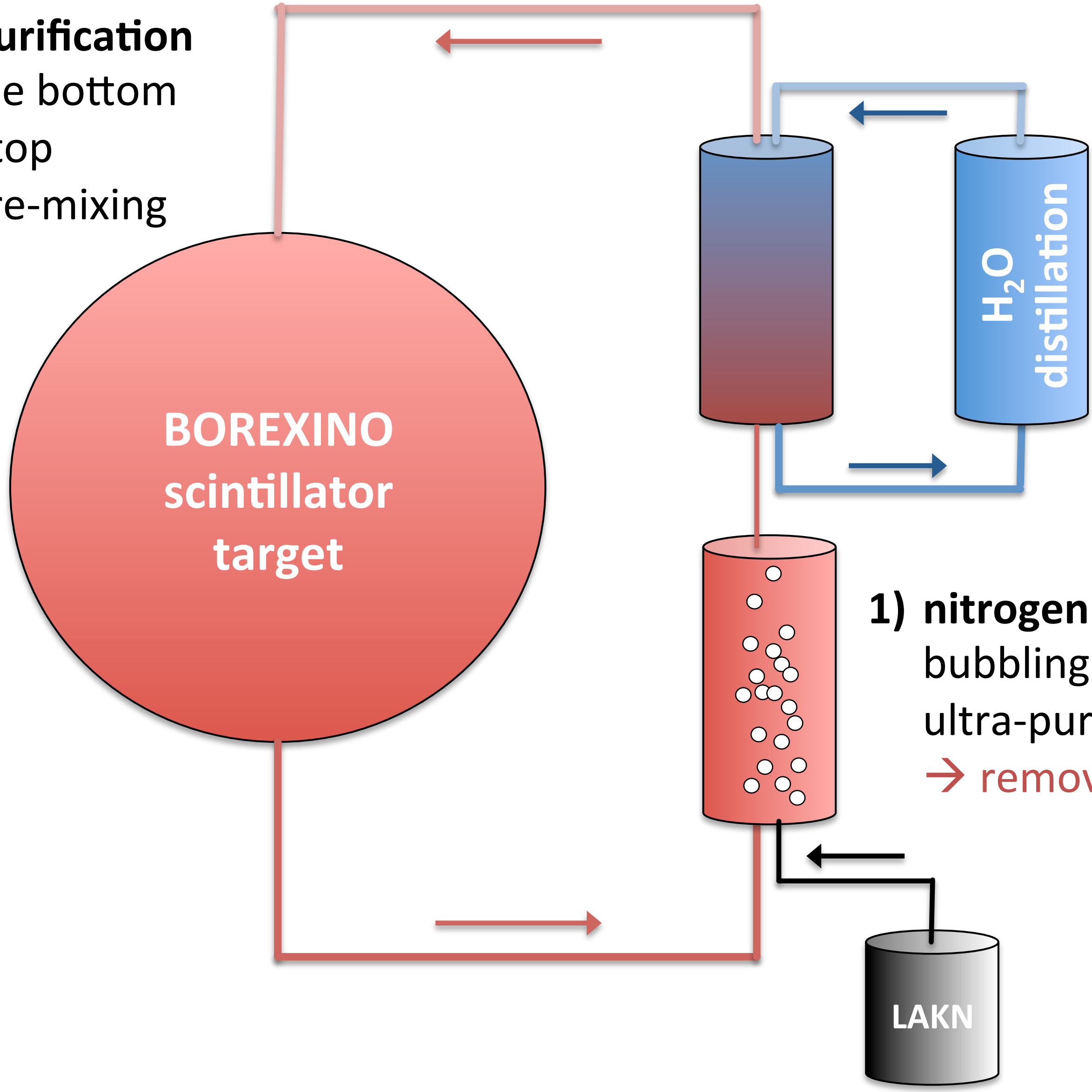


Above 240 keV: solar ^{7}Be neutrinos, decays of ^{210}Bi, ^{85}Kr

Below: decay of ^{14}C and ^{14}C pile-up

Borexino purification campaign

loop-mode purification
- extract at the bottom
- refill at the top
- try to keep re-mixing inside low

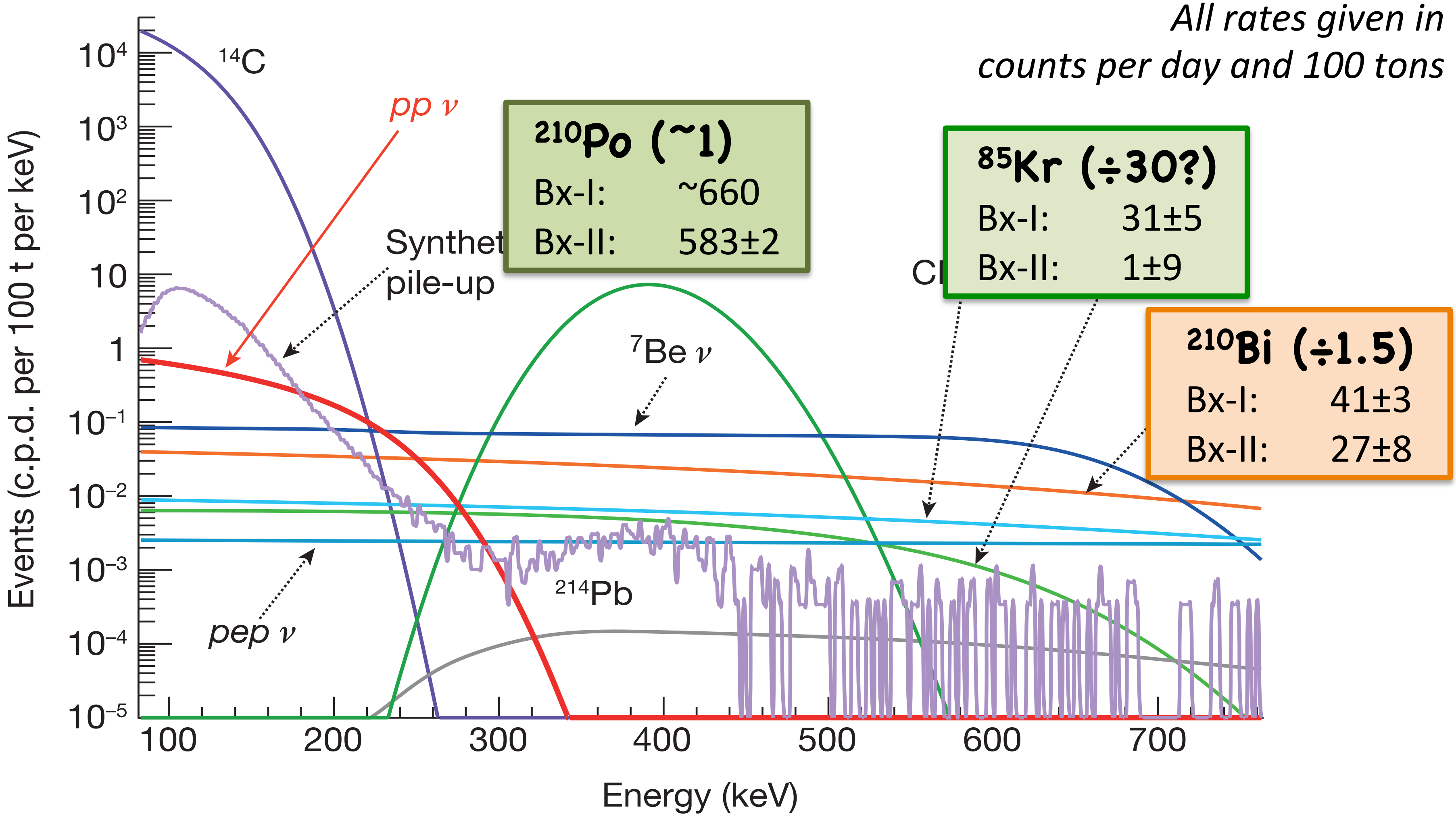


2) water extraction
washing LS with ultrapure water
→ removes ^{210}Pb
→ adds ^{210}Po?

1) nitrogen purging
bubbling LS with ultra-pure nitrogen
→ removes ^{85}Kr

Effect of purifications

All rates given in counts per day and 100 tons

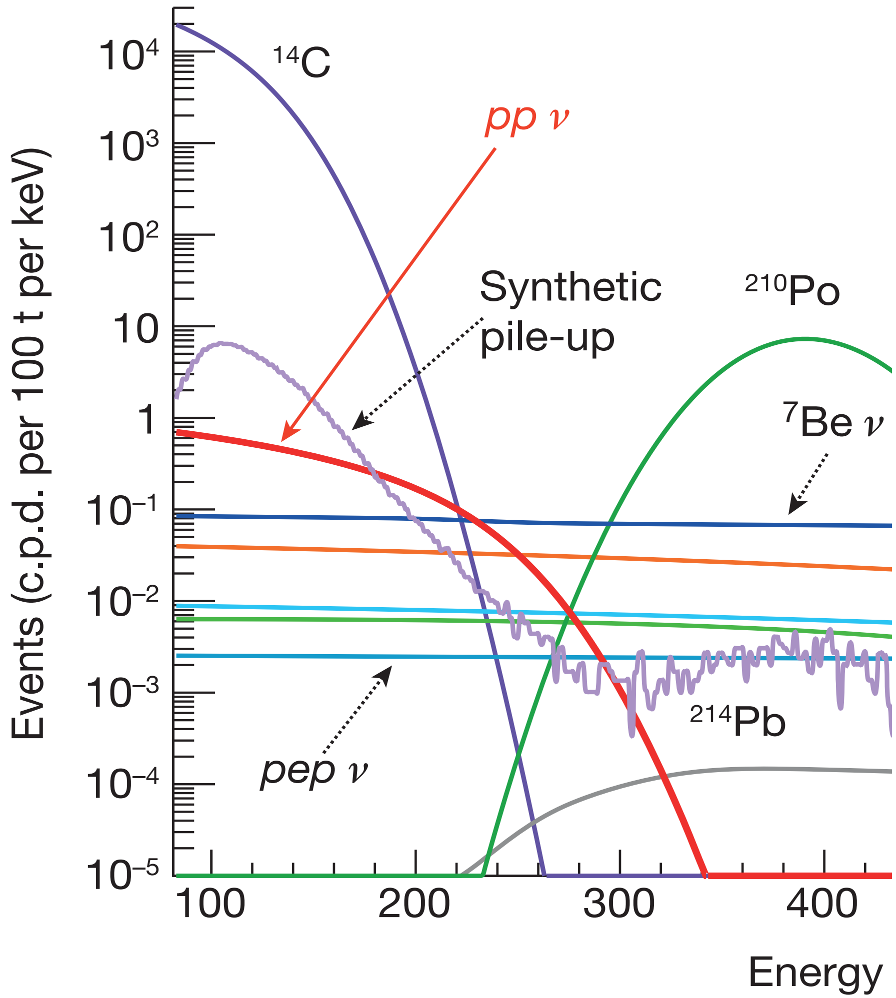


Decay chains: (broken)

^{238}U Bx-I: $(5.3\pm0.5)\times10^{-18}$ g/g → Bx-II: $< 9.7\times10^{-19}$ g/g

^{232}Th $(3.8\pm0.8)\times10^{-18}$ g/g $< 2.9\times10^{-18}$ g/g

Carbon-14



- intrinsic to the scintillator: pseudocumene -- C_9H_{12}
- very low concentration $n(^{14}C)/n(^{12}C) \sim 2.7\text{x}10^{-18}$
  → still ~10^2 Bq in 100 tons
- mostly below threshold
  → hard to fit spectral shape
  → actual decay rate?
- forms pile-up due to high rate
  → additional signals in pp-region?

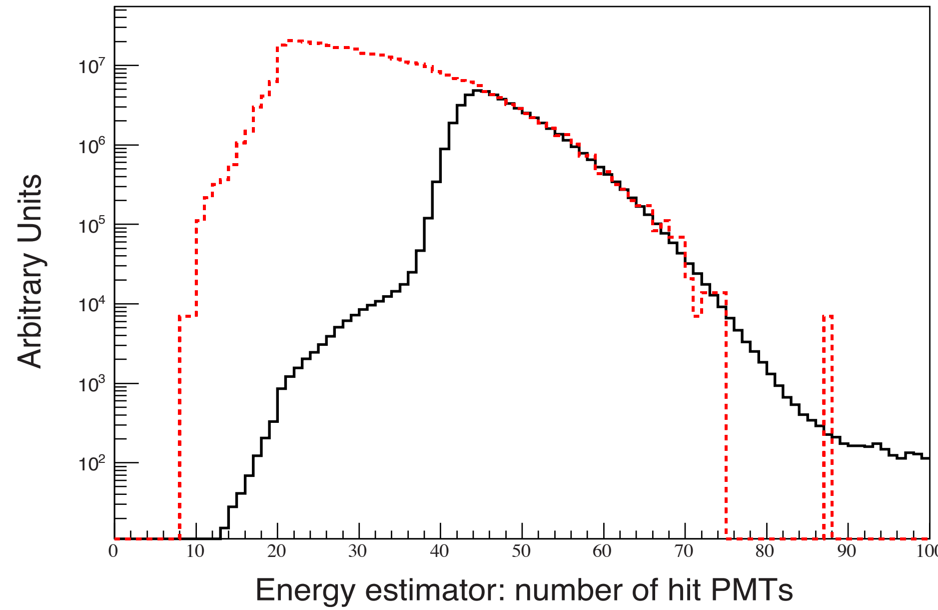
→ ***main obstacle to pp detection***

True spectrum based on random ^{14}C events

- length of Bx trigger gate is 16μs

- at low probability, a second event is included → mostly ^{14}C

- trigger threshold does not apply to second event
  → undistorted spectrum!



- *spectrum of 1st triggers*
- *spectrum of random in-gate events*

True spectrum based on random ^{14}C events

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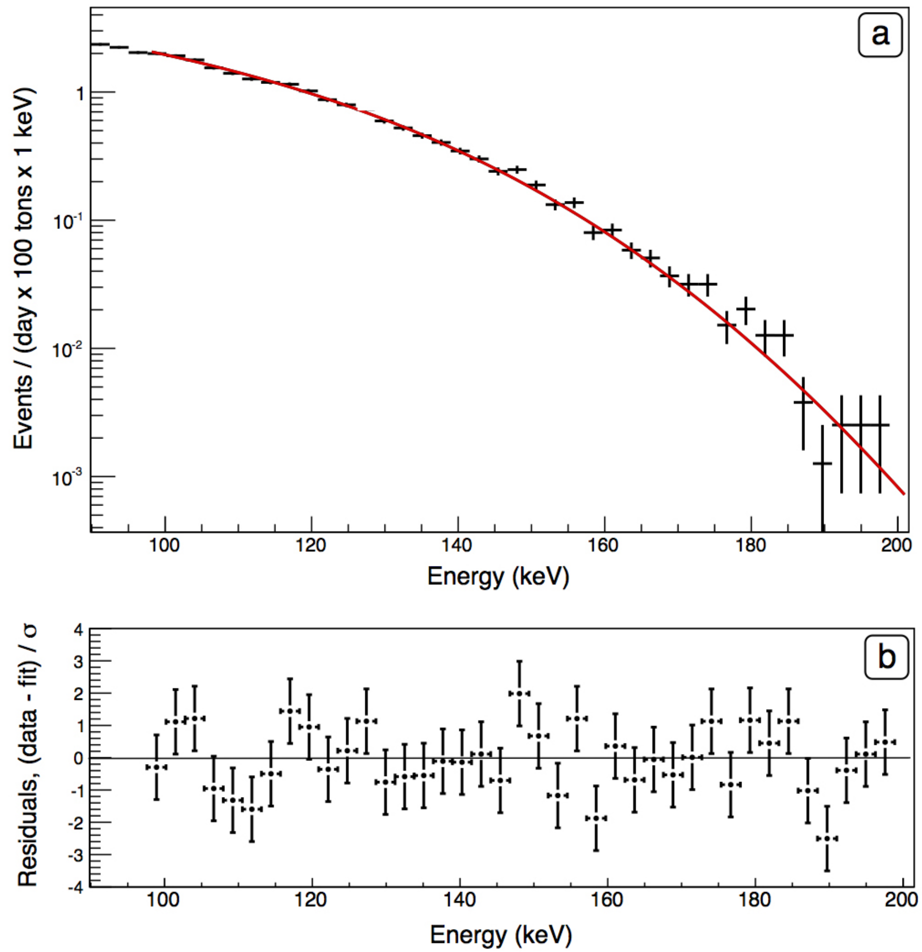


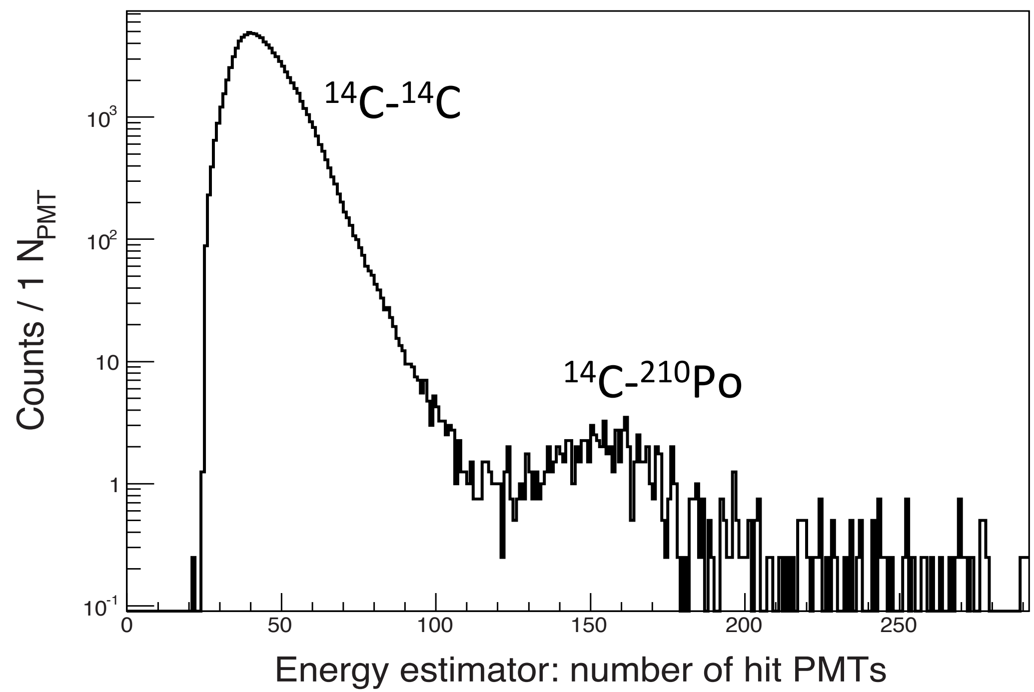
→ ^{14}C decay rate determined by fit:
40±1 Bq per 100 ton

Pile-up spectrum from synthetic pile-up

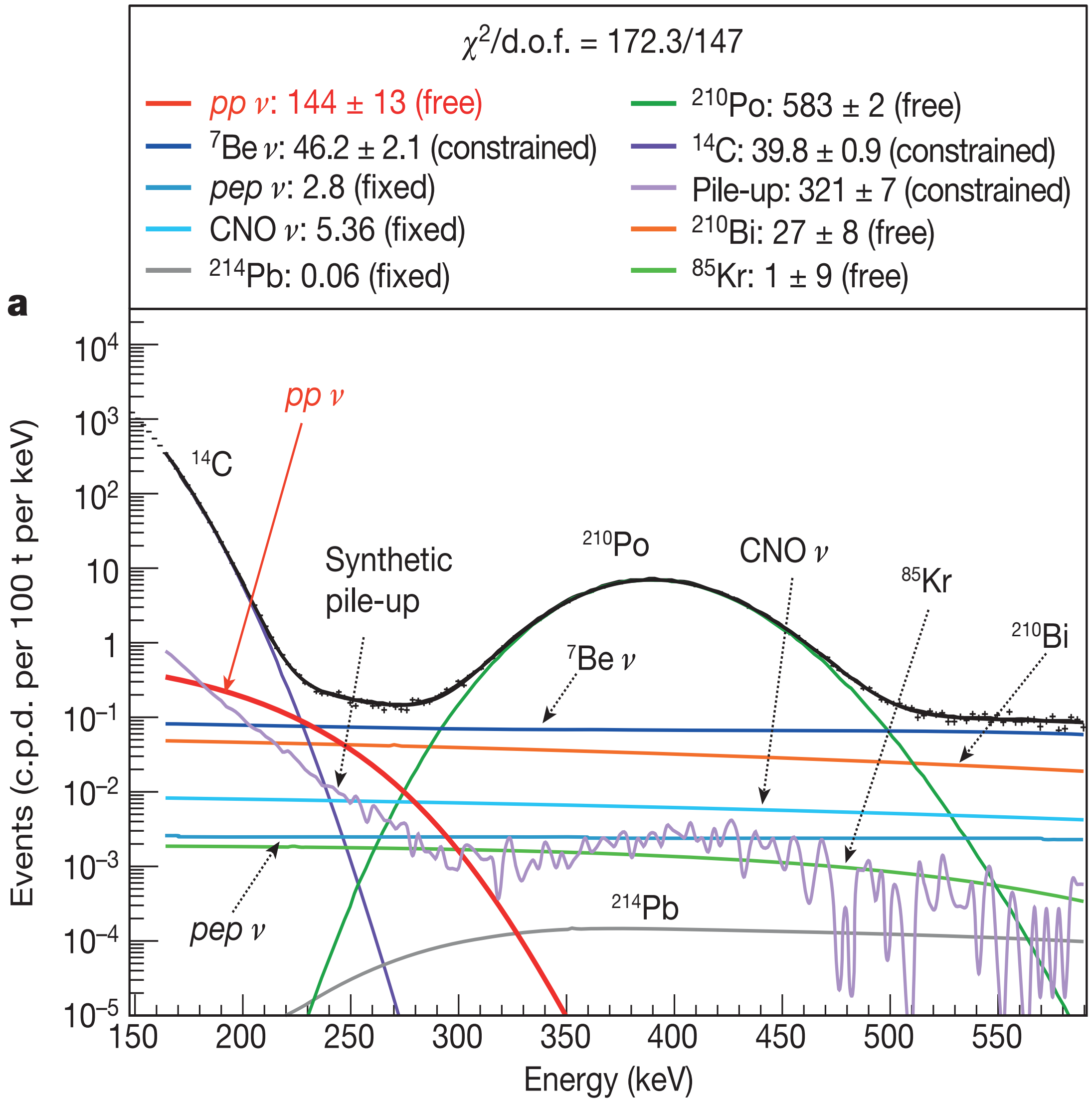
- Synthetic method uses:
  Random real event samples
  delayed ^{14}C events (no LE cut-off)

- Real PMT hit patterns of both events are overlayed
  → reconstructed by regular analysis code

→ ***pile-up energy spectrum***



pp-rate from spectral fit



Systematic uncertainties

- energy estimator
- fit energy range
- data selection
- pile-up evaluation

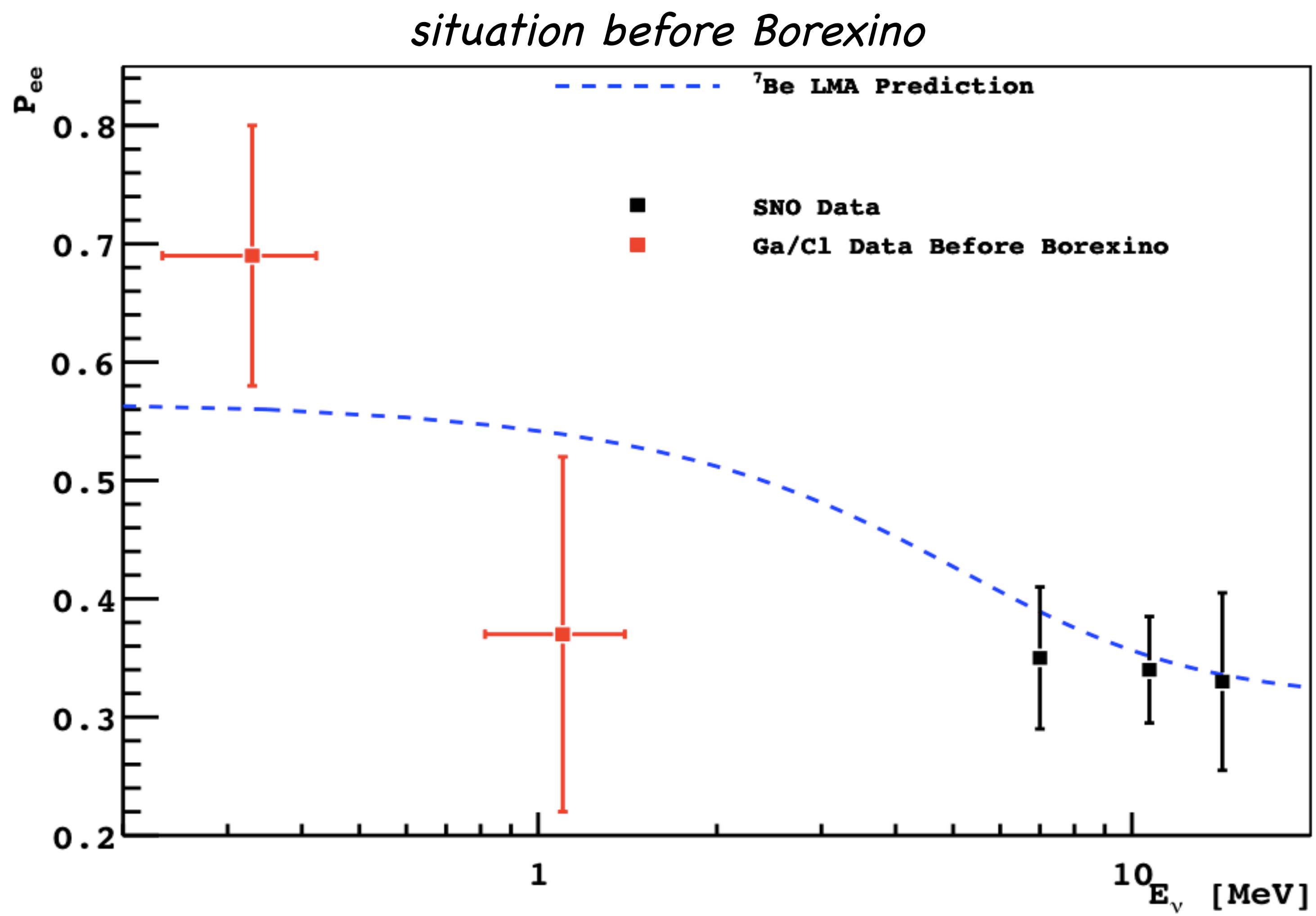
7%

- fiducial mass 2%

Resulting pp rate

$144 \pm 13_{(stat)} \pm 10_{(syst)}$ /d·100t

Electron-neutrino survival probability P_{ee}



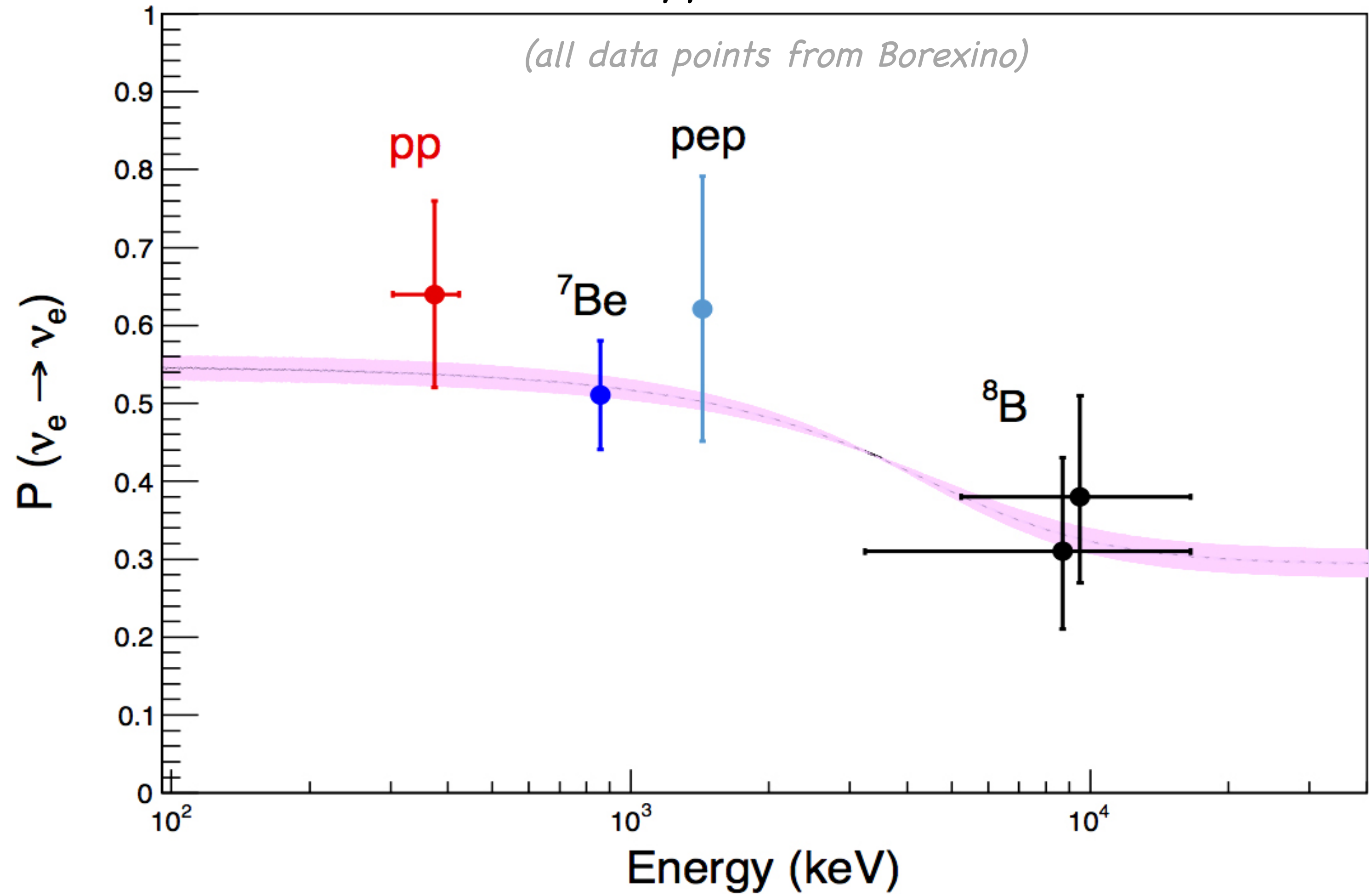
Oscillations in vacuum
probability averages
over long distances, **P_{ee}≈0.55**

⇔

Matter-enhanced oscillations
interaction with solar matter
increases osc. probability, **P_{ee}≈0.3**

Electron-neutrino survival probability P_{ee}

situation after pp-neutrino measurement

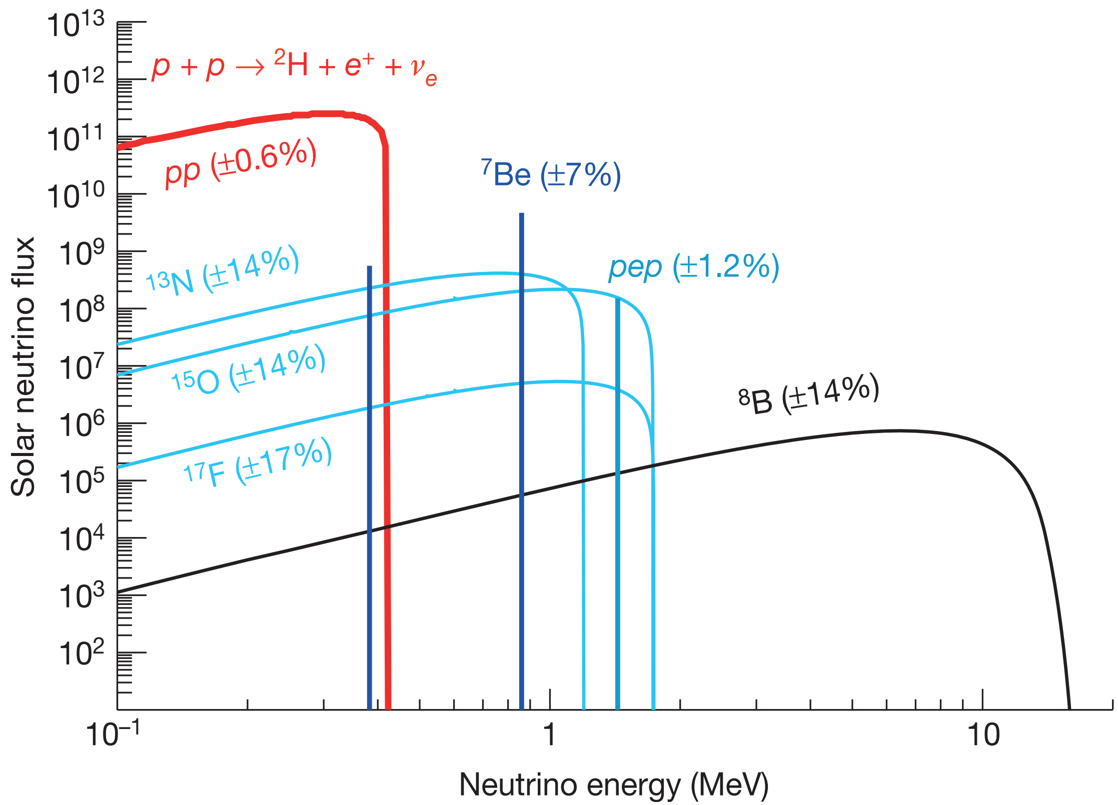


→ confirmation of basic LMA-MSW oscillation scheme at low energy

→ intermediate transition regime still to be explored

pp-neutrinos and solar luminosity

Solar neutrino spectrum with SSM uncertainties



Including oscillation effects,
Bx pp-ν rate translates to

$\Phi_{exp} = (6.6 \pm 0.7) \times 10^{10}$ /cm²s

Prediction from
Standard Solar Model (SSM)

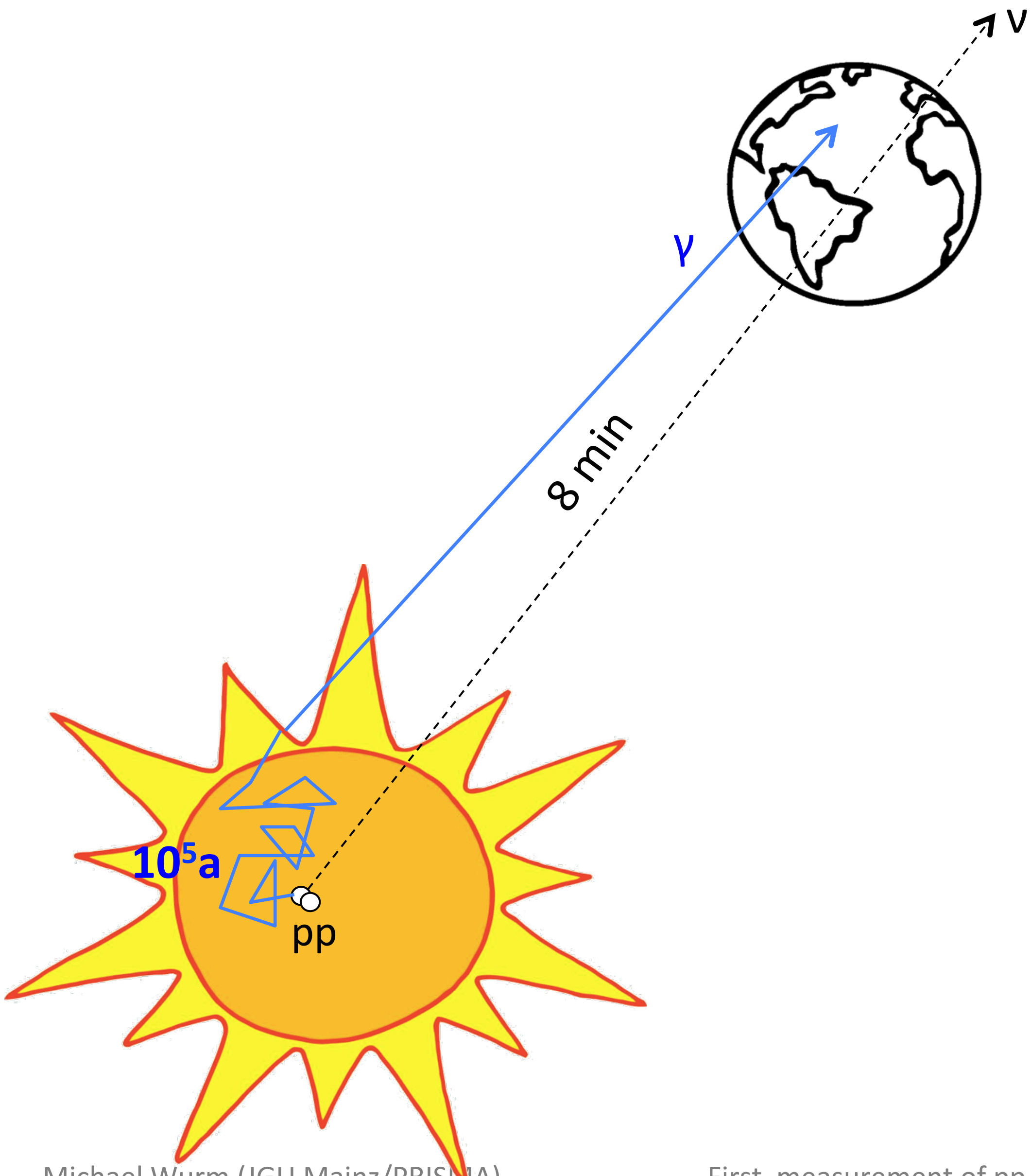
$\Phi_{pp} = (5.98 \pm 0.04) \times 10^{10}$ /cm²s

*pp fusion rate **tightly linked** to overall solar power in SSM*

→ direct cross-check of solar photon luminosity

$L_{\odot} = 3.85 \times 10^{26}$ W

Stability of solar hydrogen burning



Time of flight of neutrinos from production to Earth:

tof ≈ 8 min

Duration of energy transport from solar core to surface:

t_{diff} ≈ several 10^4 yrs

pp-neutrinos monitor directly solar energy output

→ *check of solar fusion long-term stability* (on the level of ±11%)

Conclusions & Outlook

- Borexino performed first real-time measurement of solar pp-neutrino flux
- Result confirms vacuum oscillation probabilities
- Full agreement with Standard Solar Model

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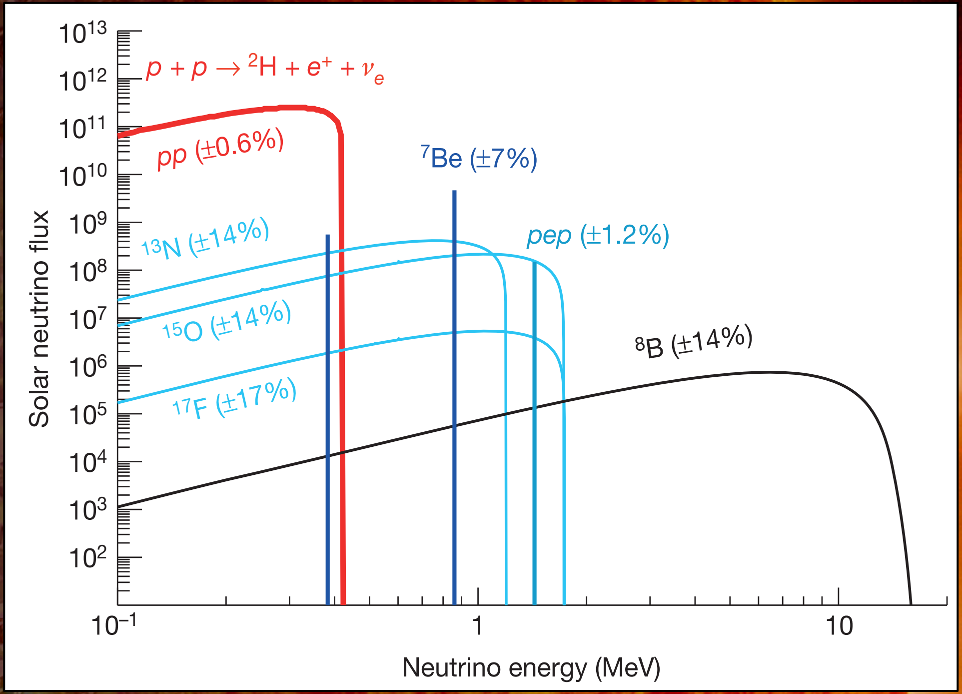

Future aims:

- Increase precision on ^{7}Be, pep, ^{8}B and geo-neutrinos
- Better limit/first detection of **CNO neutrinos**
- **Sterile neutrino** search in SOX → see next talk by Matteo Agostini


Thank you!
photo: BOREXINO calibration