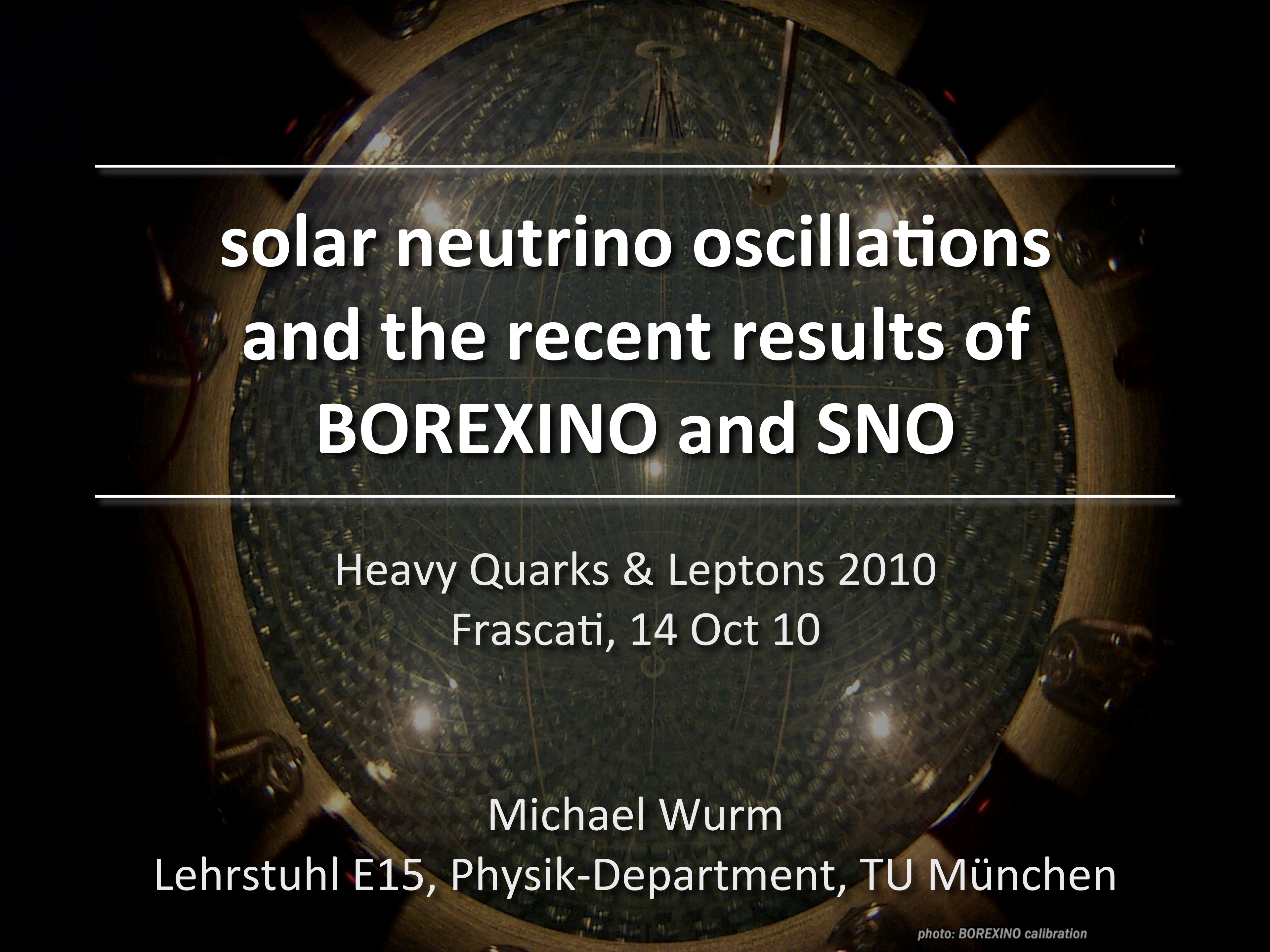


solar neutrino oscillations and the recent results of BOREXINO and SNO

Heavy Quarks & Leptons 2010
Frascati, 14 Oct 10

Michael Wurm
Lehrstuhl E15, Physik-Department, TU München

photo: BOREXINO calibration

Outline

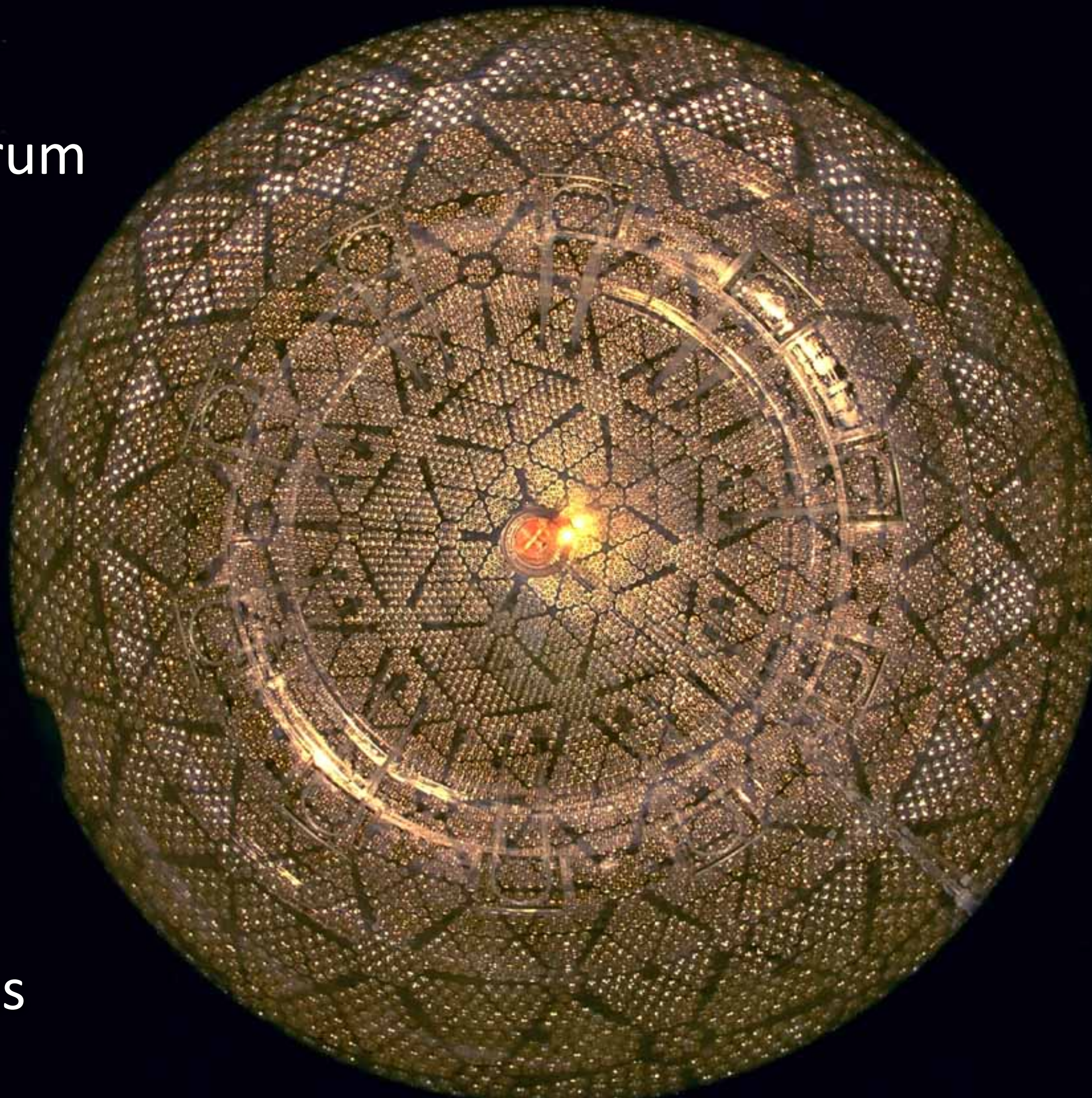
solar neutrino spectrum

recent results from BOREXINO and SNO

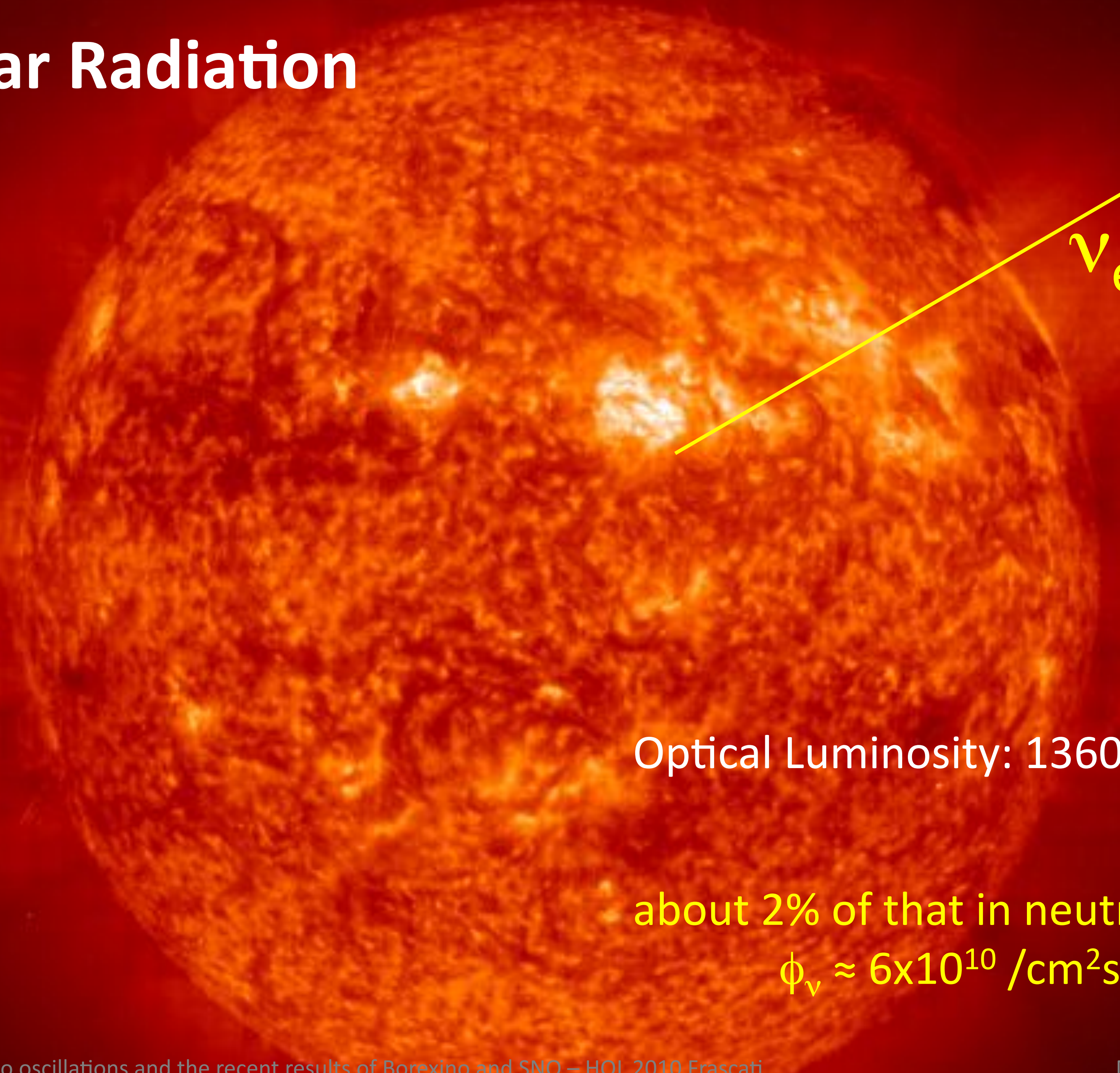
measuring solar ν_e survival probabilities

searches for non-standard effects

prospects of future measurements



Solar Radiation

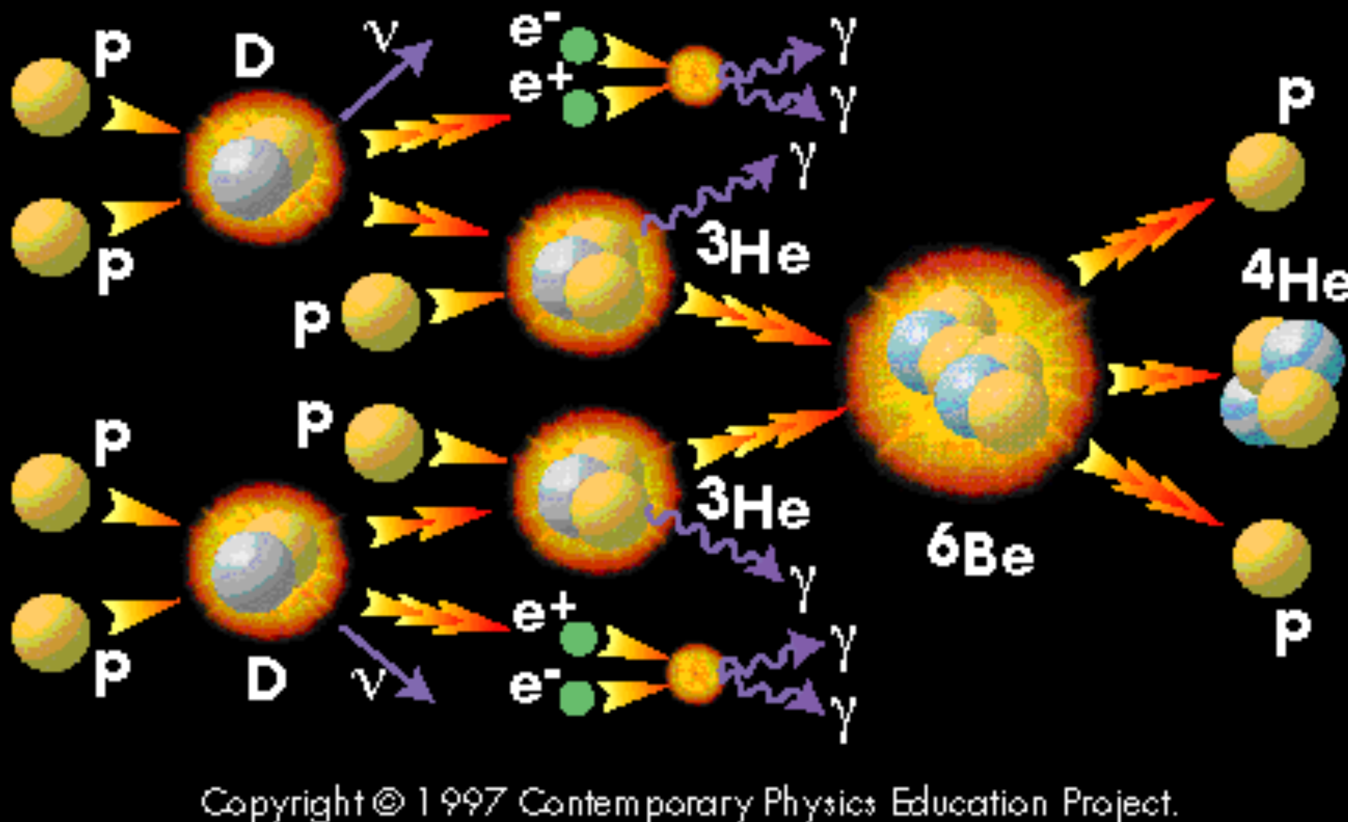


Optical Luminosity: 1360 W/m^2

about 2% of that in neutrinos:

$\phi_\nu \approx 6 \times 10^{10}$ /cm^{2}s

Solar Energy Production



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

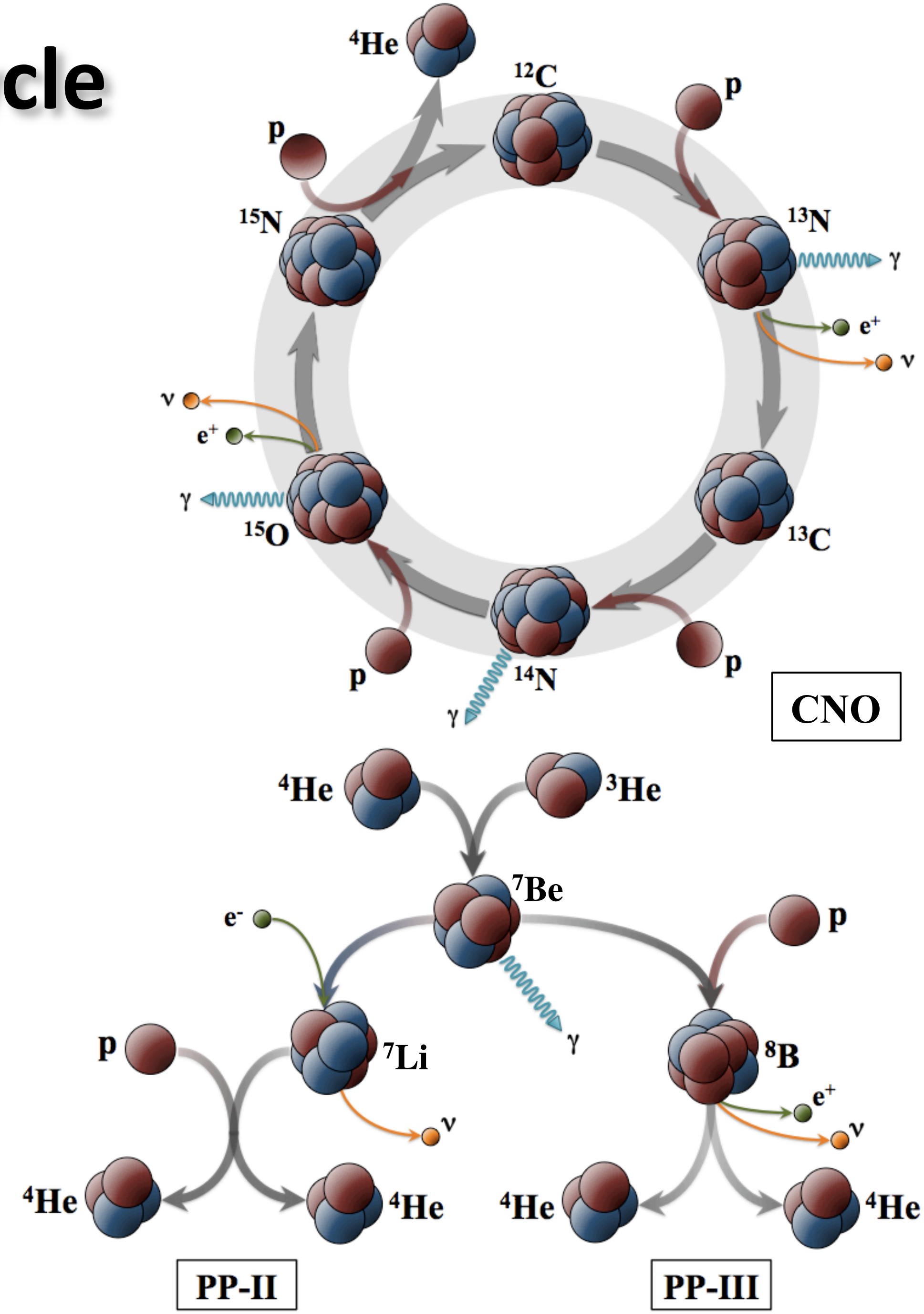
maximum energy of pp-I neutrinos: 420 keV

pp-Chain and CNO-Cycle

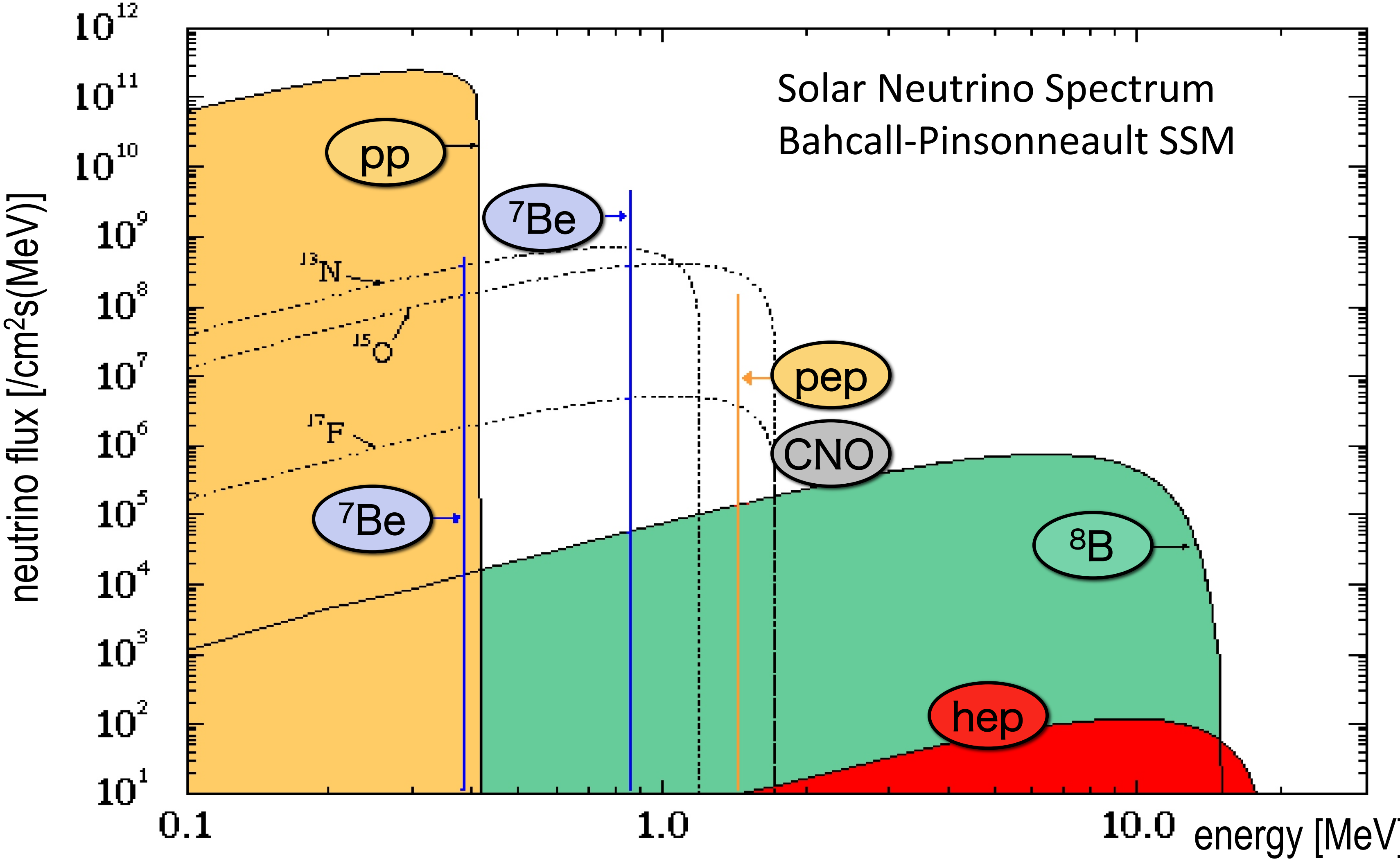
- Subbranches of the pp-chain and ν's from the CNO cycle contribute at larger energies.
- Standard Solar Model (SSM) predicts neutrino fluxes:

ν's	Energy (MeV)	Flux on Earth (/cm²s)
pp	<0.42	6.0×10^{10}
^{7}Be	0.86	5.1×10^{9}
pep	1.44	1.4×10^{8}
^{8}B	<14.6	5.9×10^{6}
hep	<18.8	7.9×10^{3}
CNO	<1.74	5.0×10^{8}

BPS08(GS)

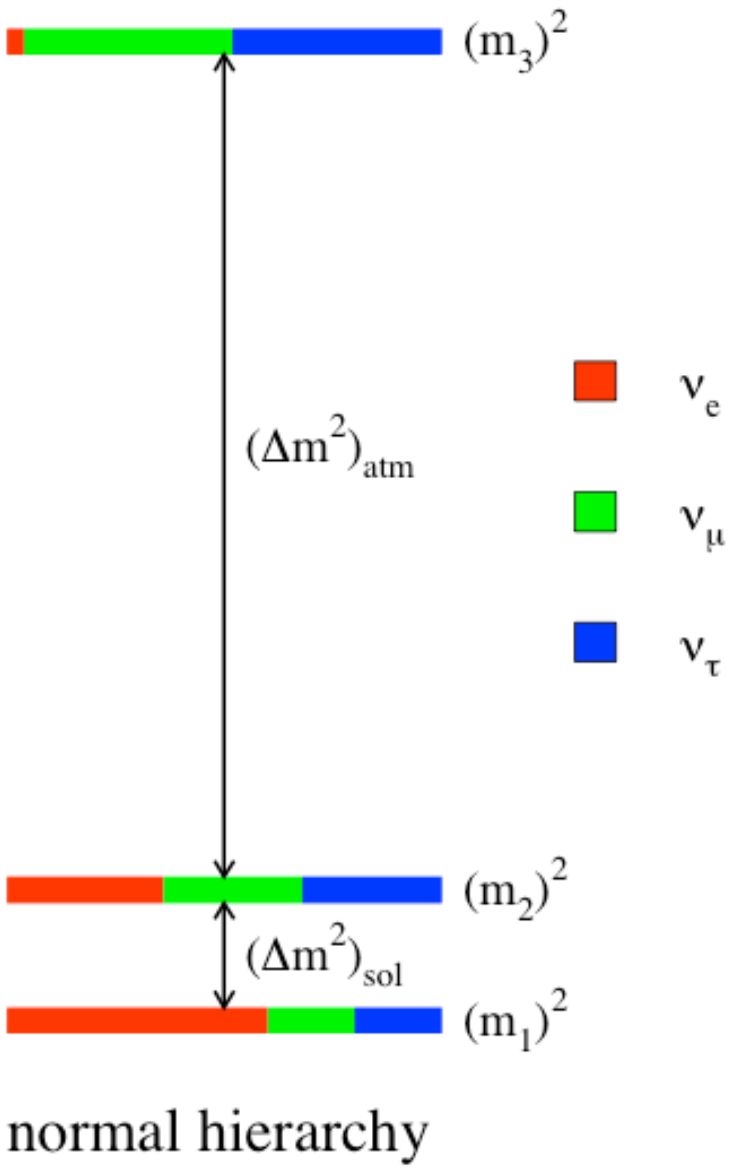


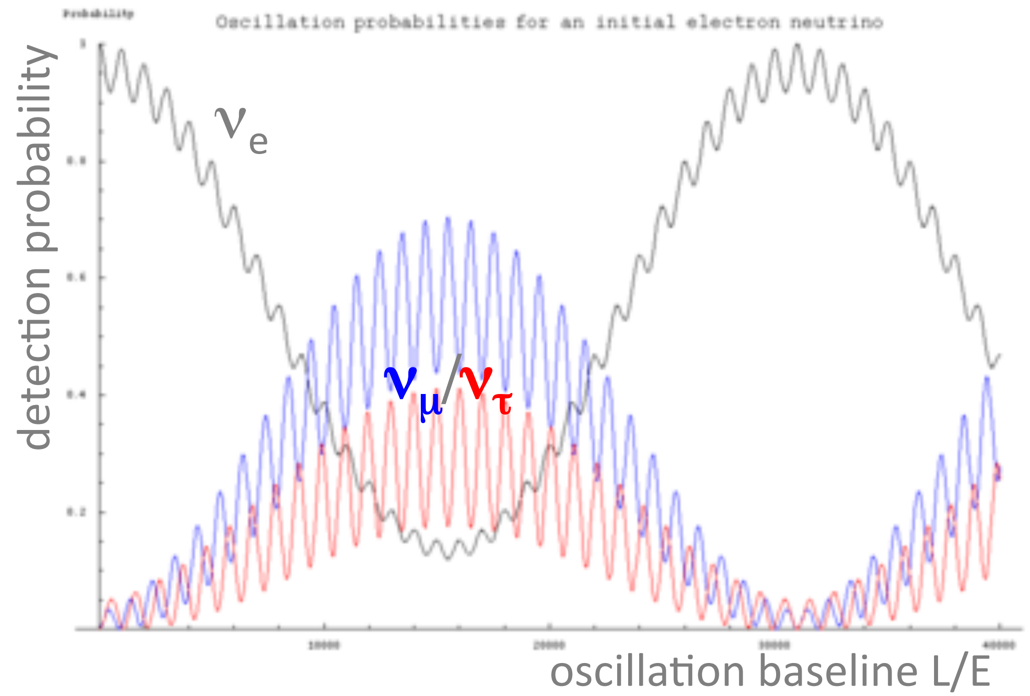
Solar Neutrino Spectrum



But this spectrum gets distorted by neutrino oscillations ....

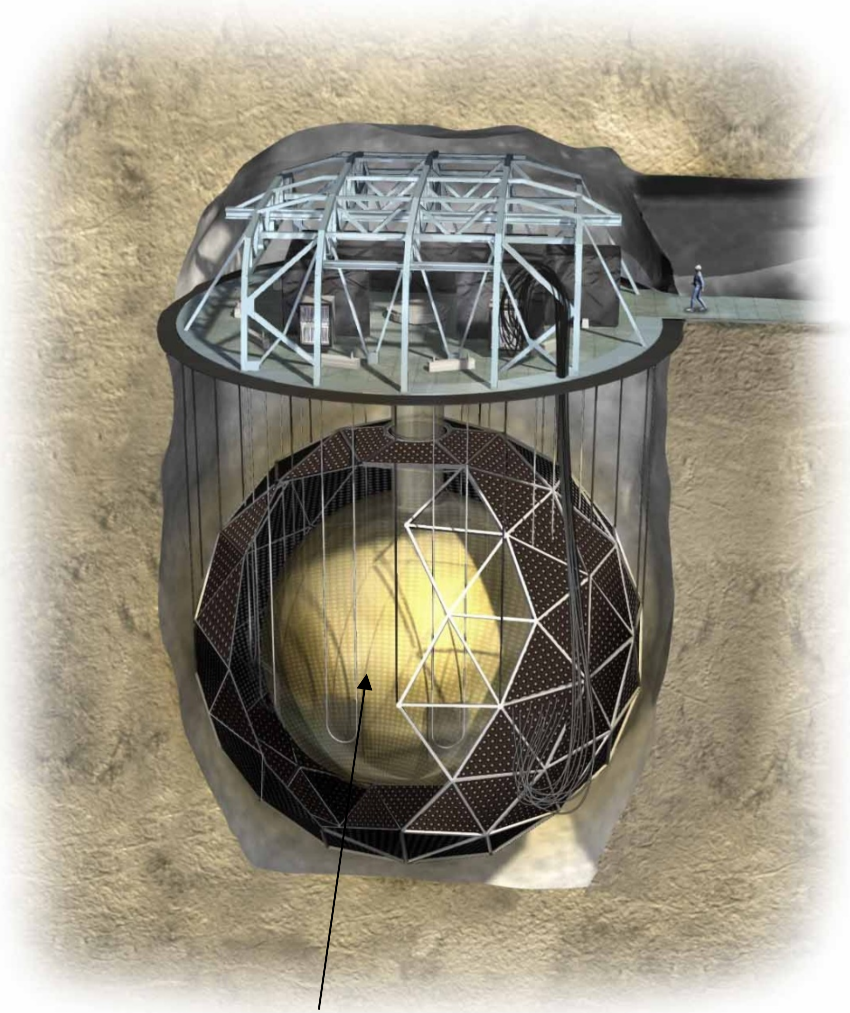
Flavor Oscillations





- ν production (and detection) is in flavor eigenstates (ν_e, ν_μ, ν_τ)
- ν propagation is in mass eigenstates (m_1, m_2, m_3)
- mass eigenstates pick up different phase factors in propagation, causing a partial conversion of $\nu_e \rightarrow \nu_{\mu,\tau}$

Sudbury Neutrino Observatory SNO



1kt Heavy Water
Cherenkov detector

Three detection channels

- charged current interaction (CC)

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

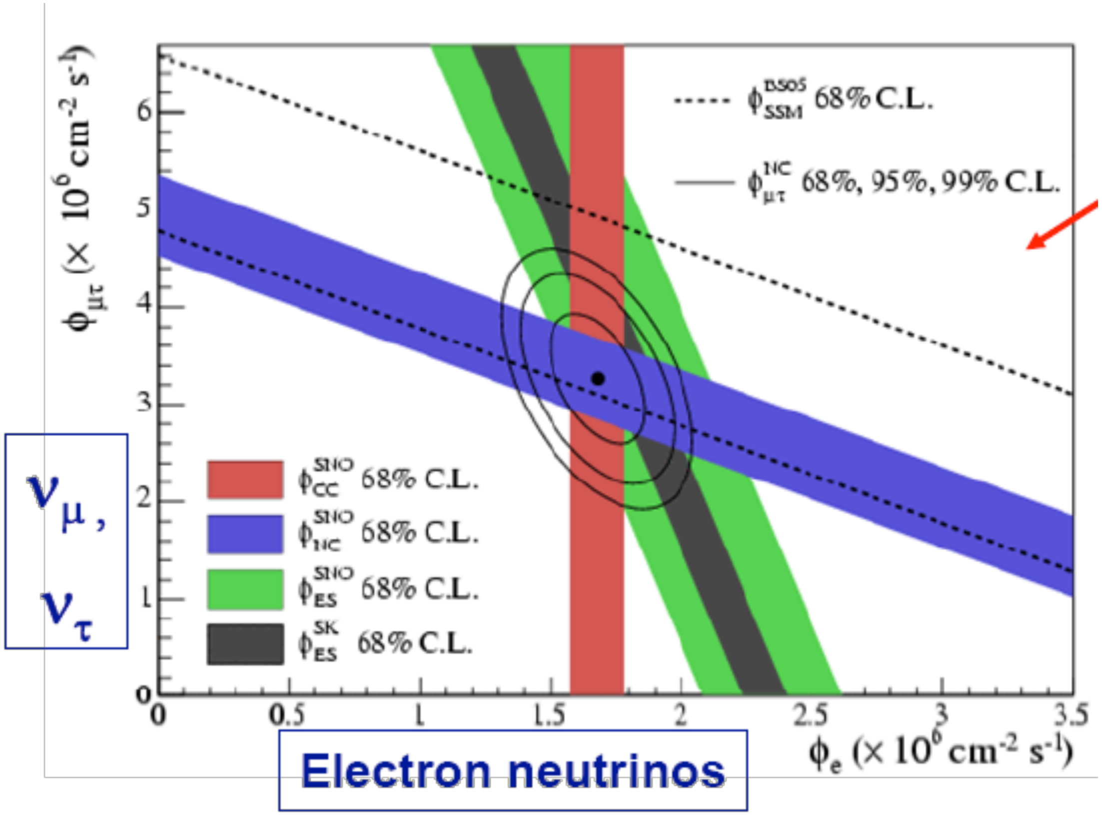
- neutral current interaction (NC)

$$\nu_x + D \rightarrow \nu_x + p + n$$

- neutrino-electron scattering (CC+NC)

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

SNO result: Proof of neutrino oscillations



$$\phi_{CC} = 1.68 \ ^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.})$$

$$\phi_{NC} = 4.94 \ ^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.})$$

$$\phi_{ES} = 2.35 \ ^{+0.22}_{-0.22}(\text{stat.})^{+0.15}_{-0.15}(\text{syst.})$$

(In units of $10^6\,\text{cm}^{-2}\text{s}^{-1}$)

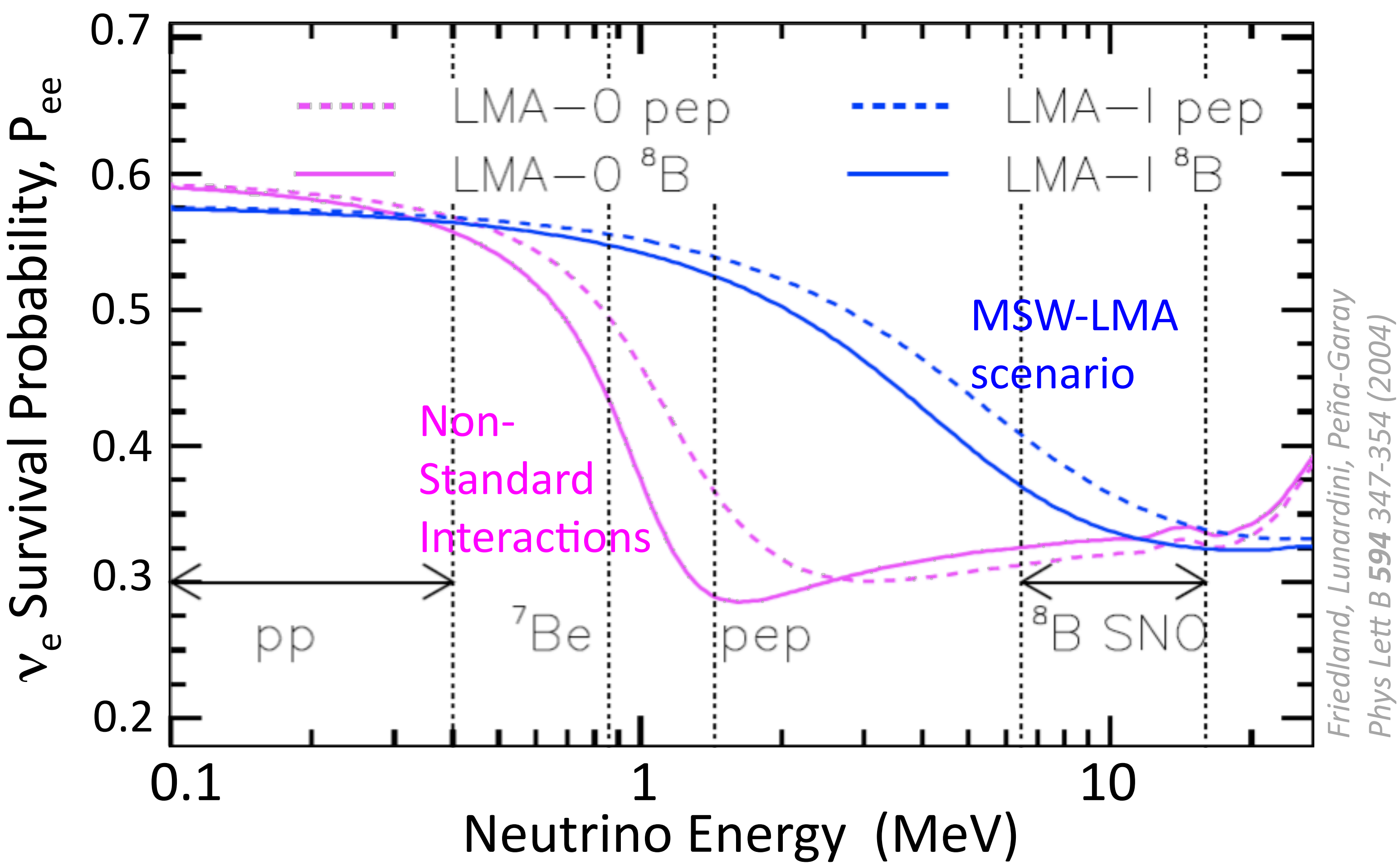
- flavor transition: confirmed at 7σ!
- agreement with SSM, if ν NC reaction is considered!

measurement of ^{8}B-ν spectrum above 5 MeV:

Effect of oscillations
~ 1/3 remain as ν_e
~ 2/3 change to $\nu_{\mu,\tau}$

[Phys.Rev.Lett.92:181301,2004]
new: [Phys.Rev.C81:055504,2010]

The MSW-LMA Oscillation Scenario

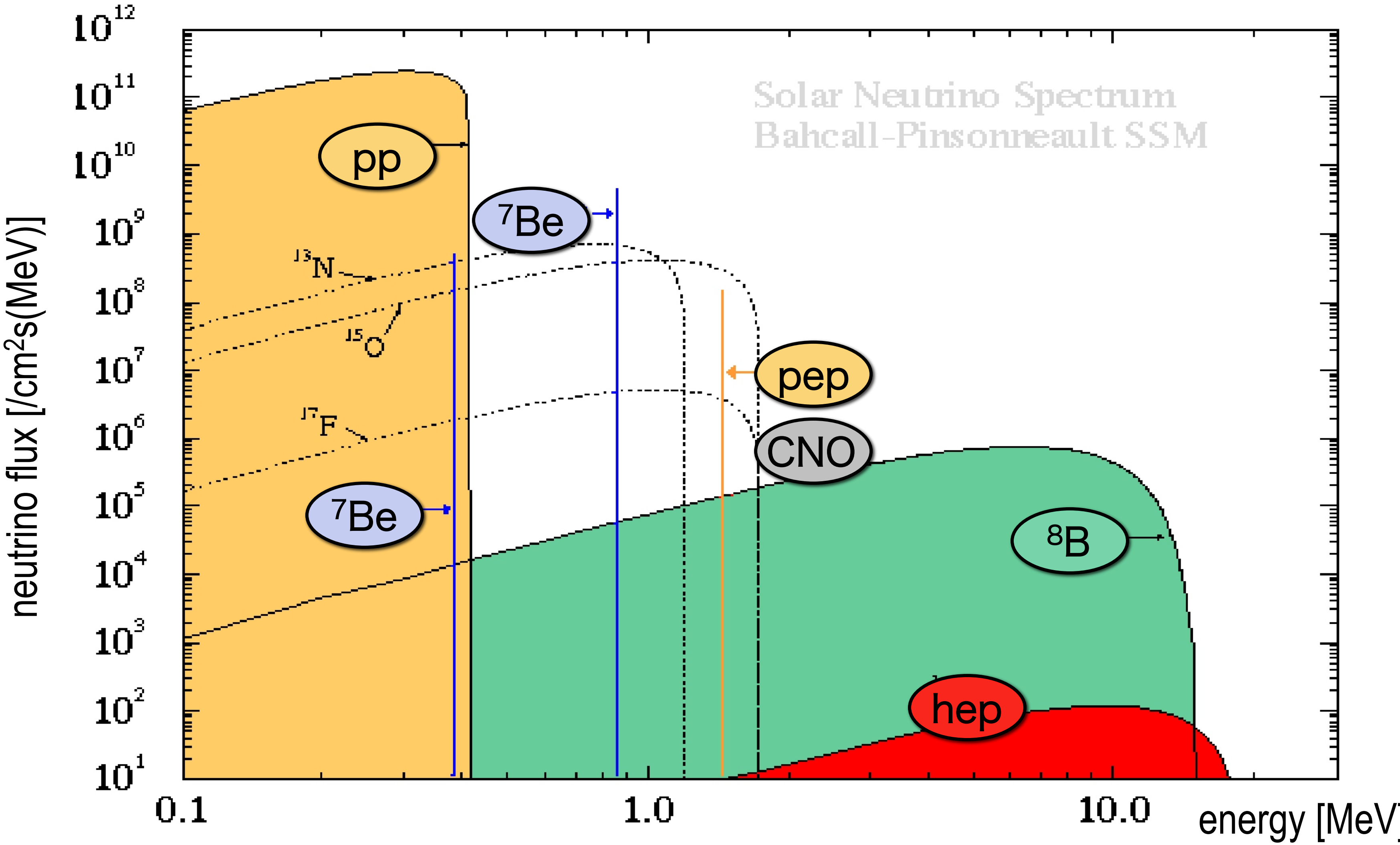


Oscillations in vacuum
probability averages
over long distances, **P_{ee}≈2/3**

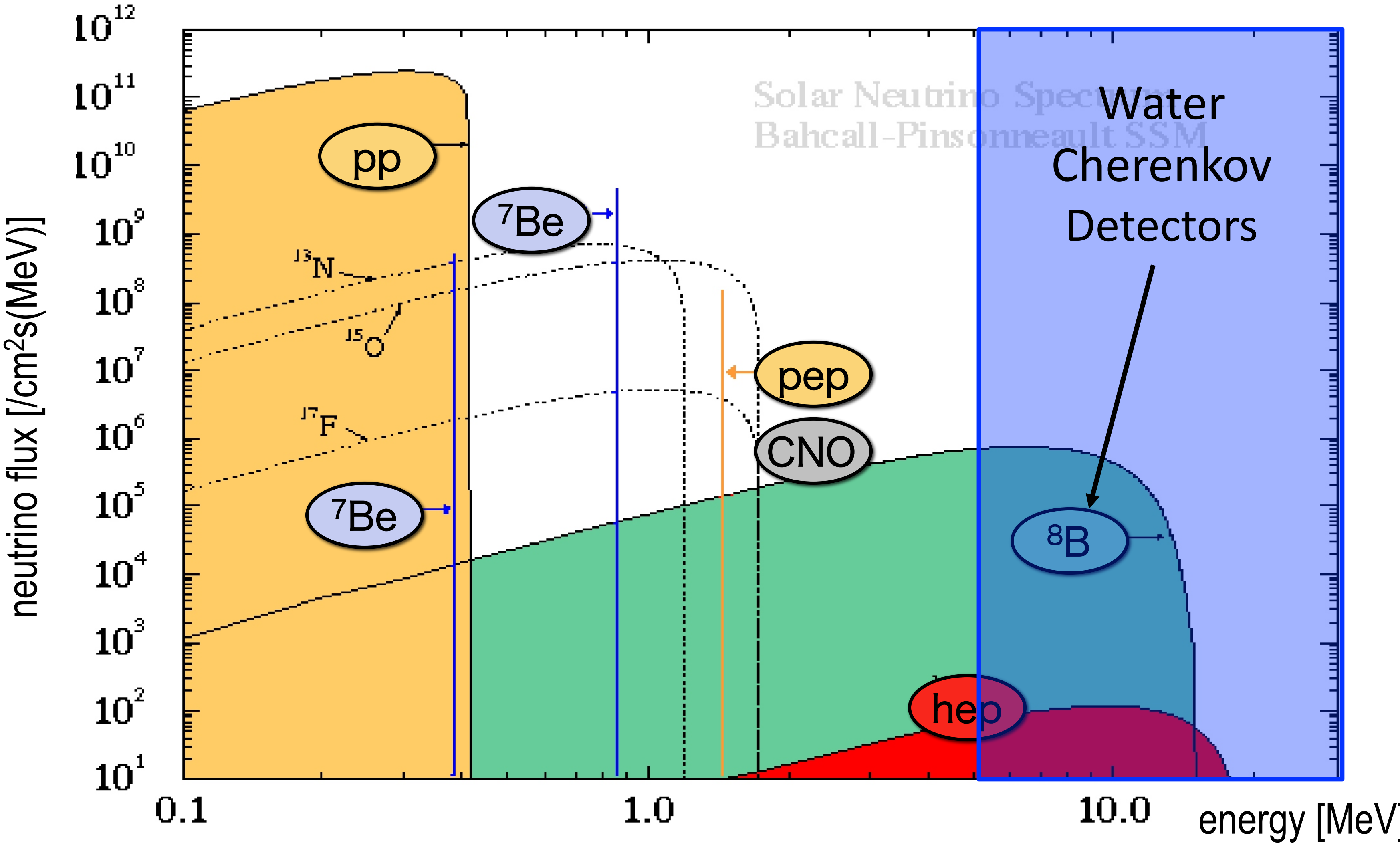
⟺

Matter-enhanced oscillations
interaction with solar matter
increases osc. probability, **P_{ee}≈1/3**

Real-Time Spectroscopy of Solar Neutrinos

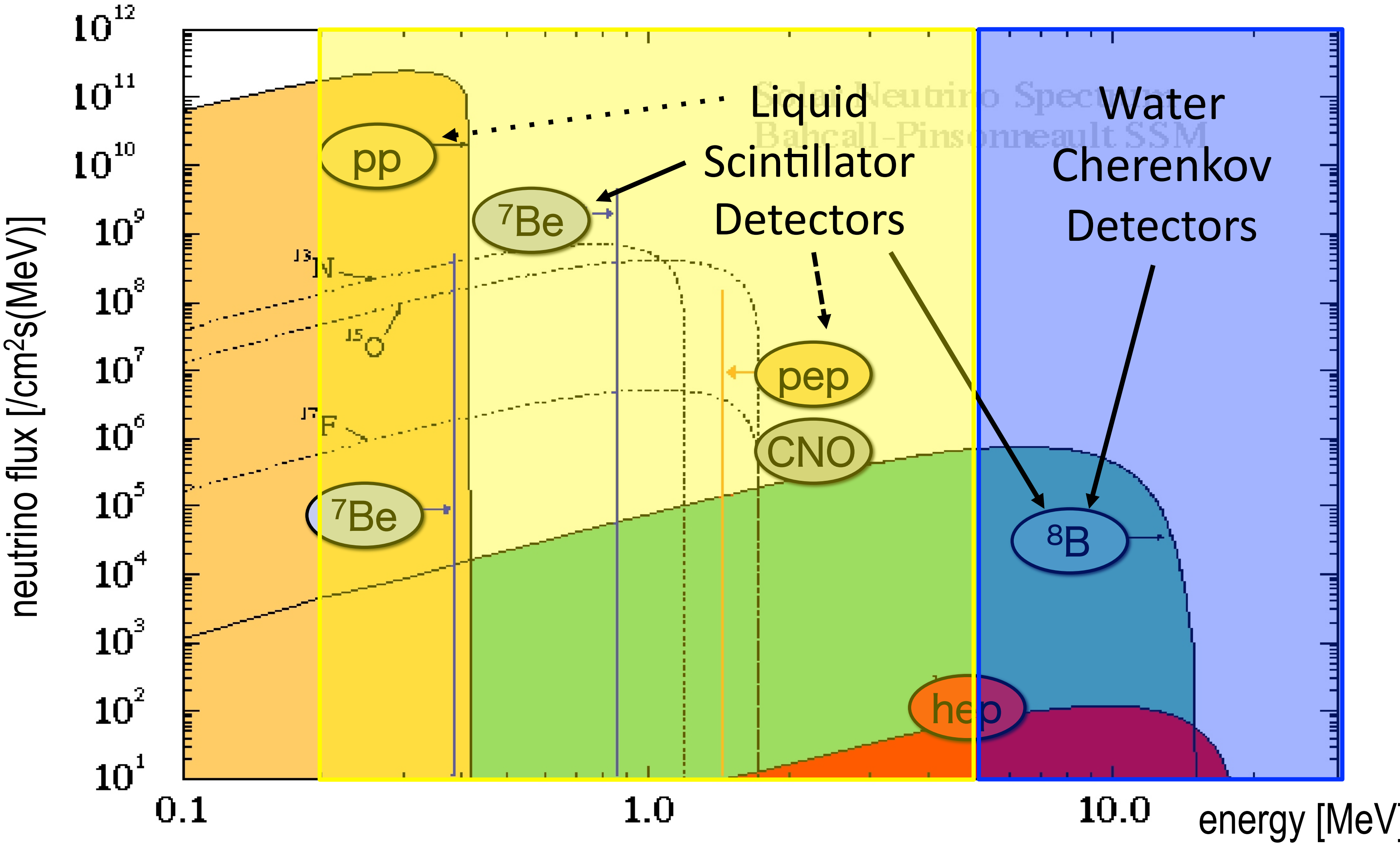


Real-Time Spectroscopy of Solar Neutrinos



Water Cherenkov Detectors (SNO, Super-K) threshold: 4-5 MeV.

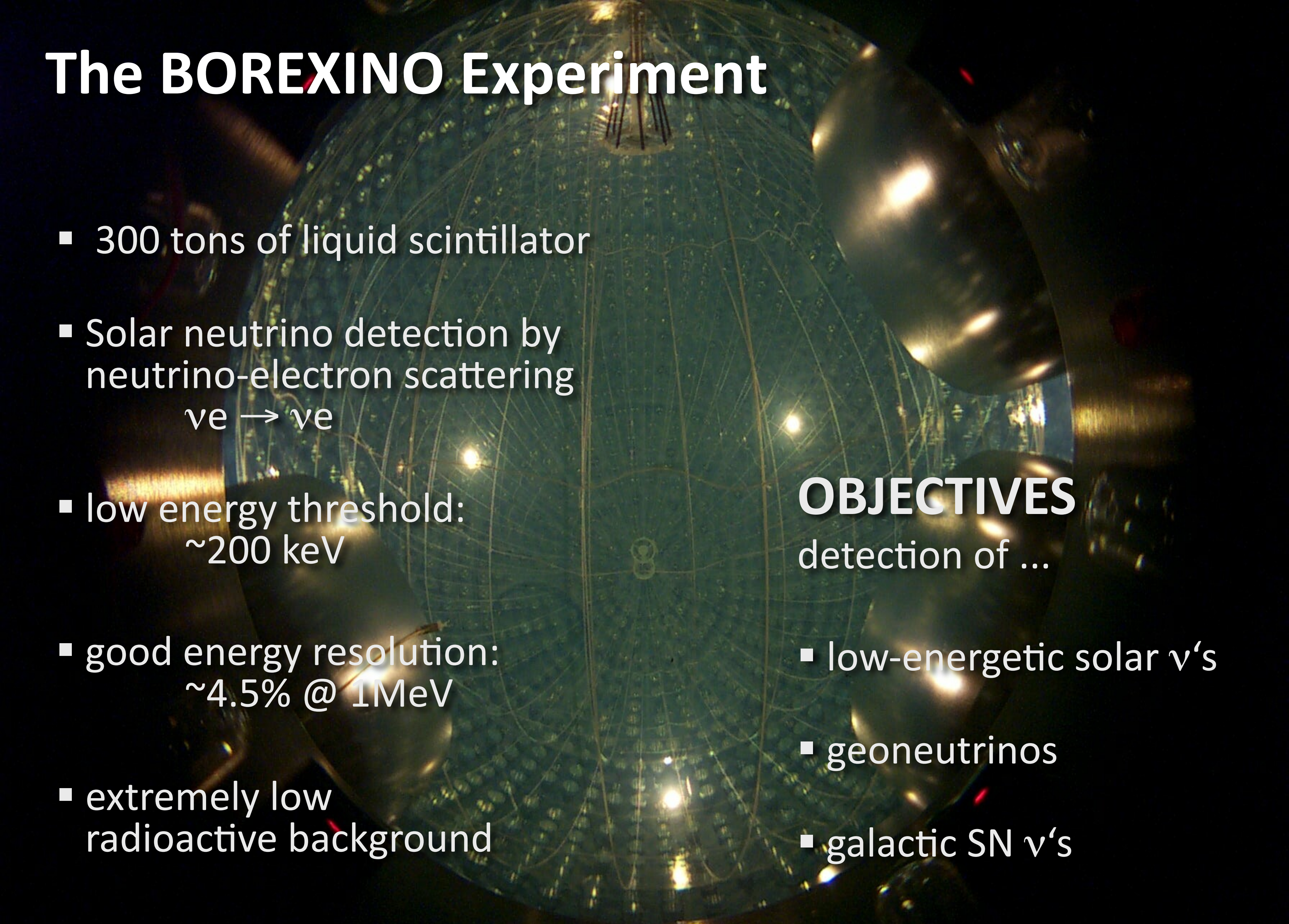
Real-Time Spectroscopy of Solar Neutrinos



Water Cherenkov Detectors (SNO, Super-K) threshold: 4-5 MeV.

Since 2007: Measurement of low-energy regime by BOREXINO.

The BOREXINO Experiment



- 300 tons of liquid scintillator
- Solar neutrino detection by neutrino-electron scattering

  $\nu e \rightarrow \nu e$
- low energy threshold:

  ~200 keV
- good energy resolution:

  ~4.5% @ 1MeV
- extremely low radioactive background

OBJECTIVES

detection of ...

- low-energetic solar ν's
- geoneutrinos
- galactic SN ν's

photo: BOREXINO calibration

Borexino Collaboration

Milano

Genova

Virginia Tech. University

Kurchatov Institute (Russia)

Jagiellonian U. Cracow (Poland)

Heidelberg (Germany)

Dubna JINR (Russia)

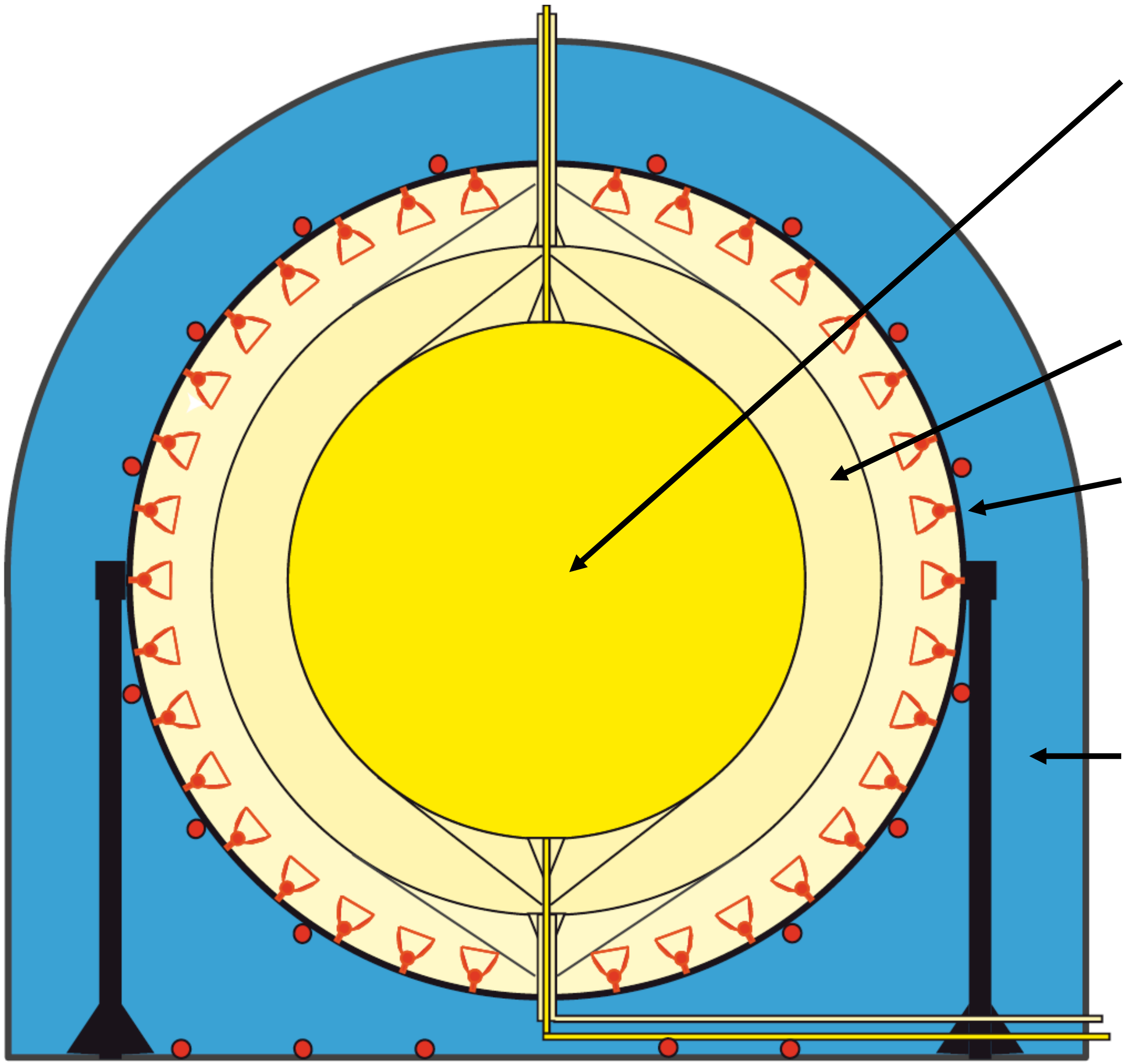
APC Paris

Munich (Germany)

Perugia

Princeton University

Borexino Detector Layout



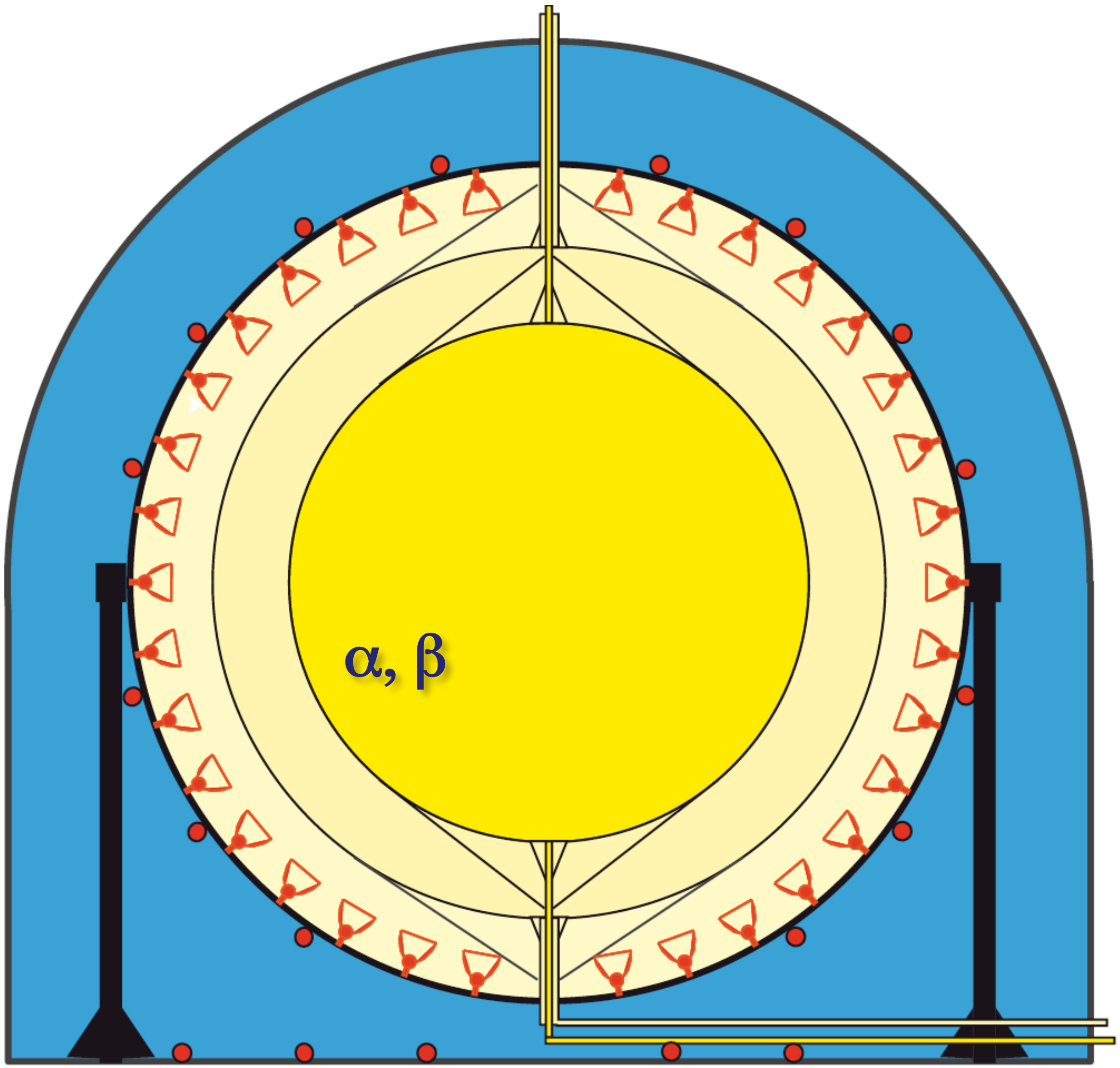
Target: 300 tons of liquid scintillator confined by nylon vessel of R=4.25 m

non-scintillating buffer

stainless steel sphere
6.85 m in radius
2212 inward-facing PMTs

outer water tank
2.8 kt of water, 9 m radius
equipped with 208 PMTs
for Muon Cherenkov Veto

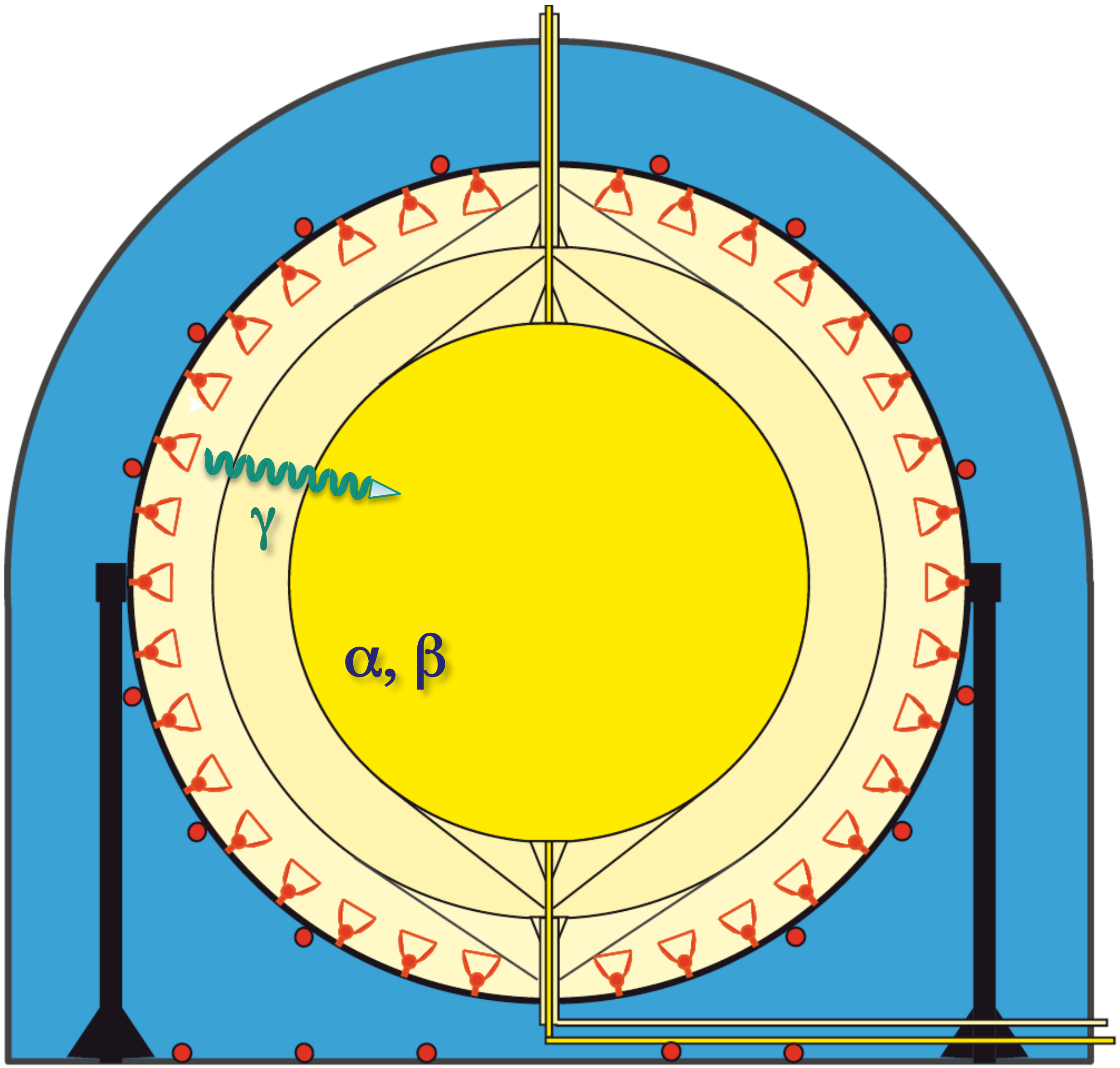
Central Challenge: Background Reduction



Internal Radioactivity

traces of radioisotopes in the scintillator (U/Th,^{40}K)

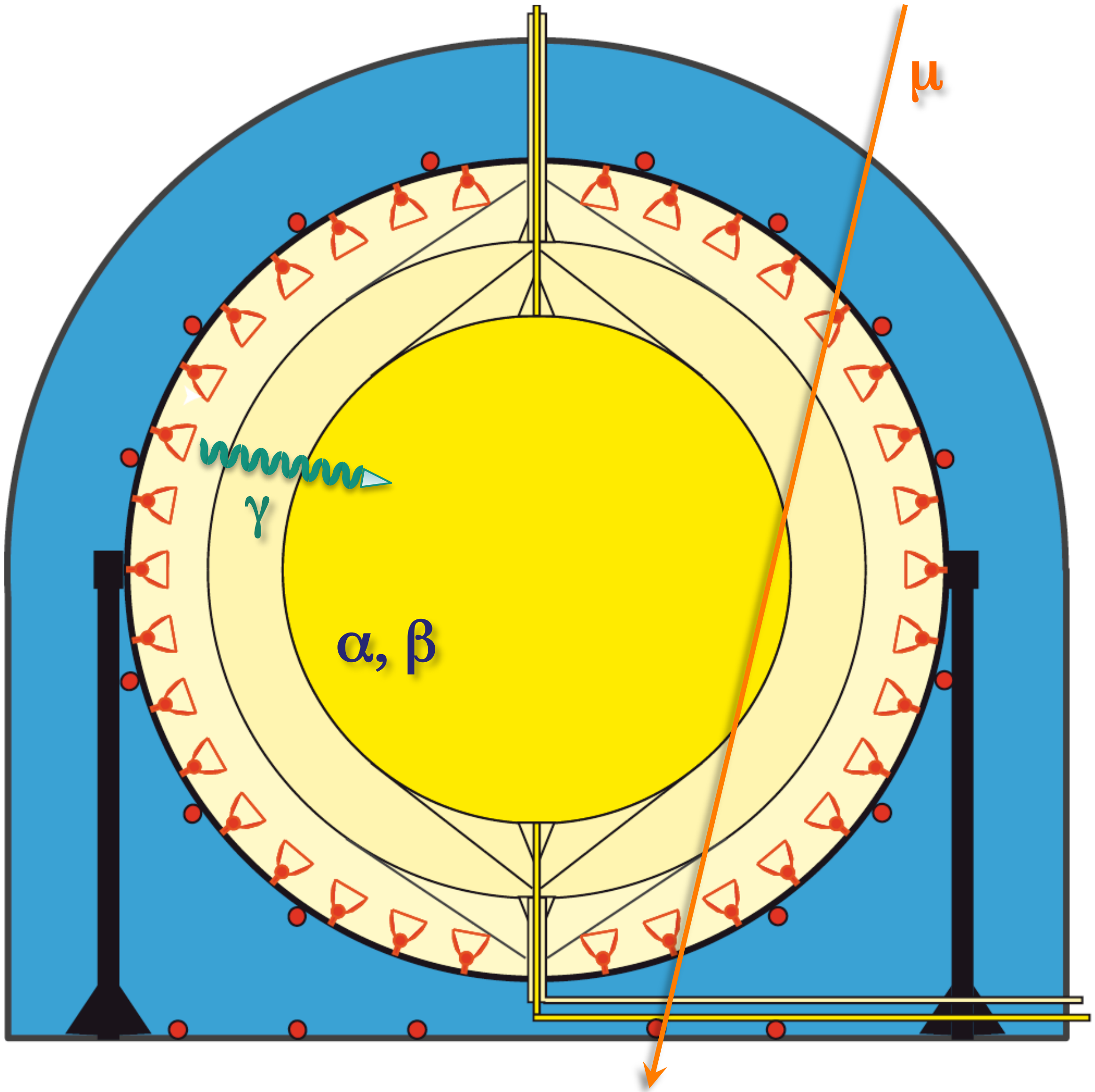
Central Challenge: Background Reduction



Internal Radioactivity
traces of radioisotopes in the scintillator (U/Th, ^{40}K)

External Gamma-Rays
from buffer, steel sphere, PMT glass (^{40}K, ^{208}Tl …)

Central Challenge: Background Reduction



Internal Radioactivity
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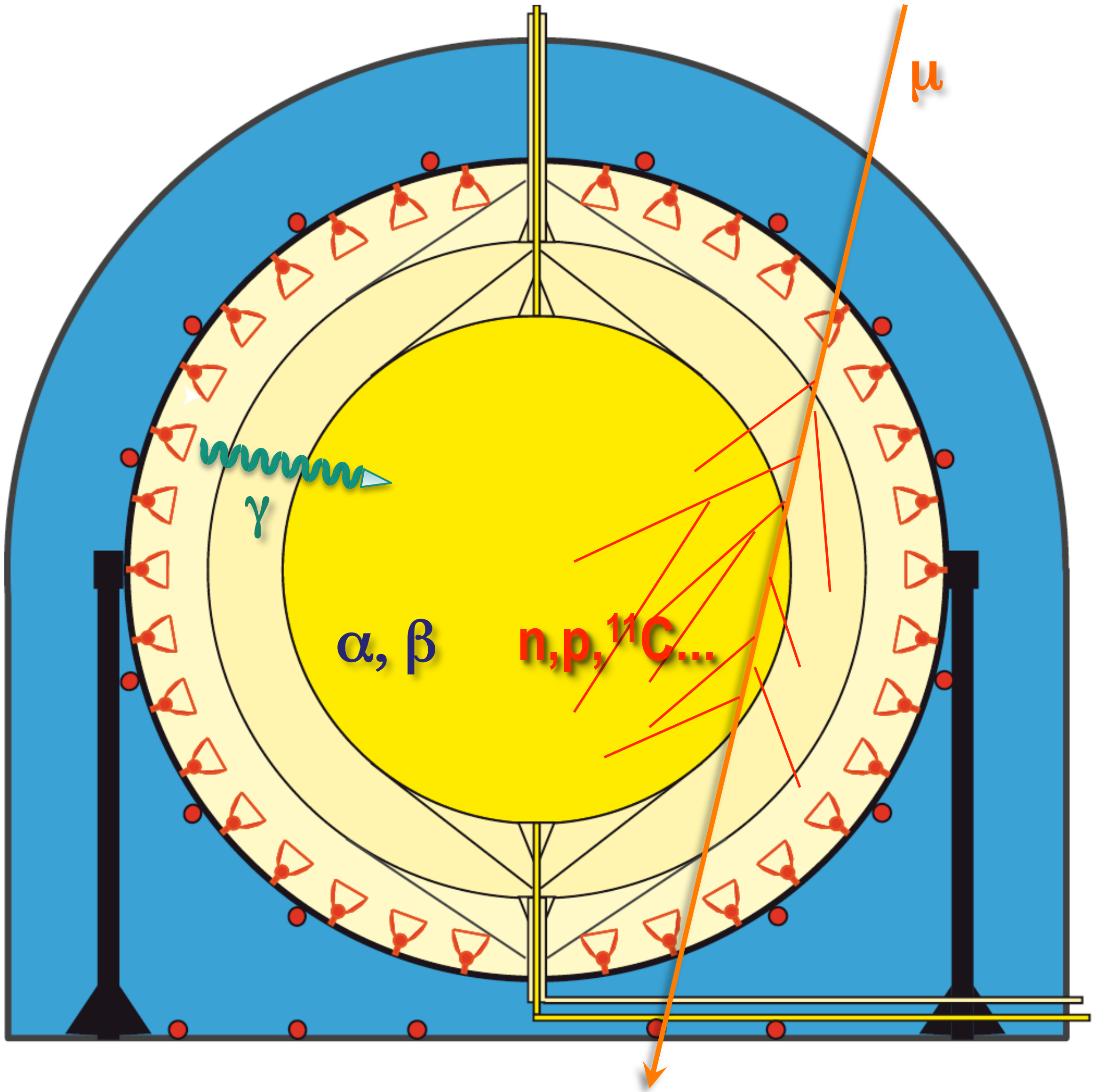
Cosmic Muons

Central Challenge: Background Reduction



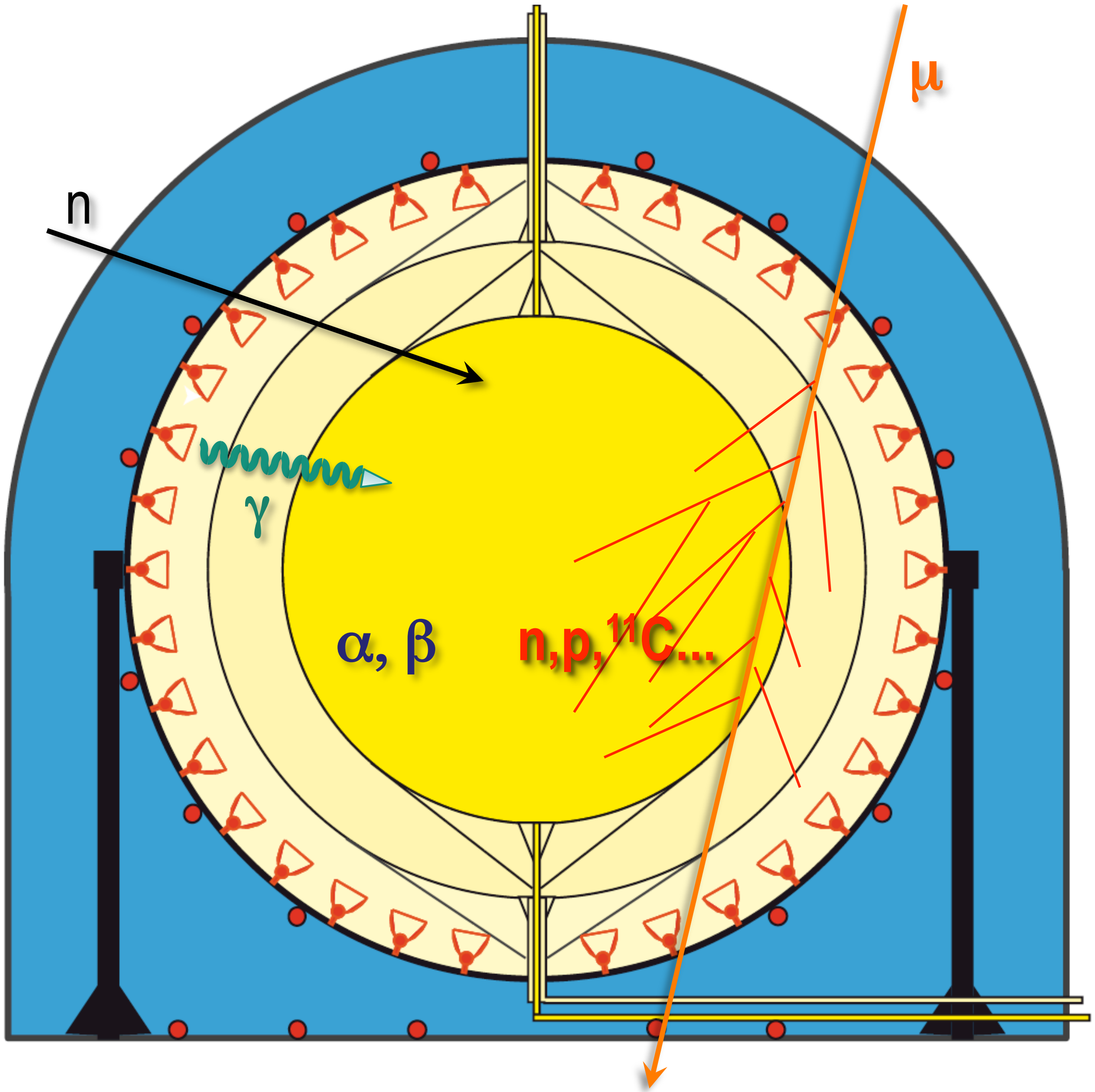
Internal Radioactivity
traces of radioisotopes in the scintillator (U/Th,^{40}K)

External Gamma-Rays
from buffer, steel sphere, PMT glass (^{40}K, ^{208}Tl …)

Cosmic Muons

Cosmogenics
neutrons and radionuclides from muon-spallation and hadronic showers

Central Challenge: Background Reduction



Internal Radioactivity
traces of radioisotopes in the scintillator (U/Th,^{40}K)

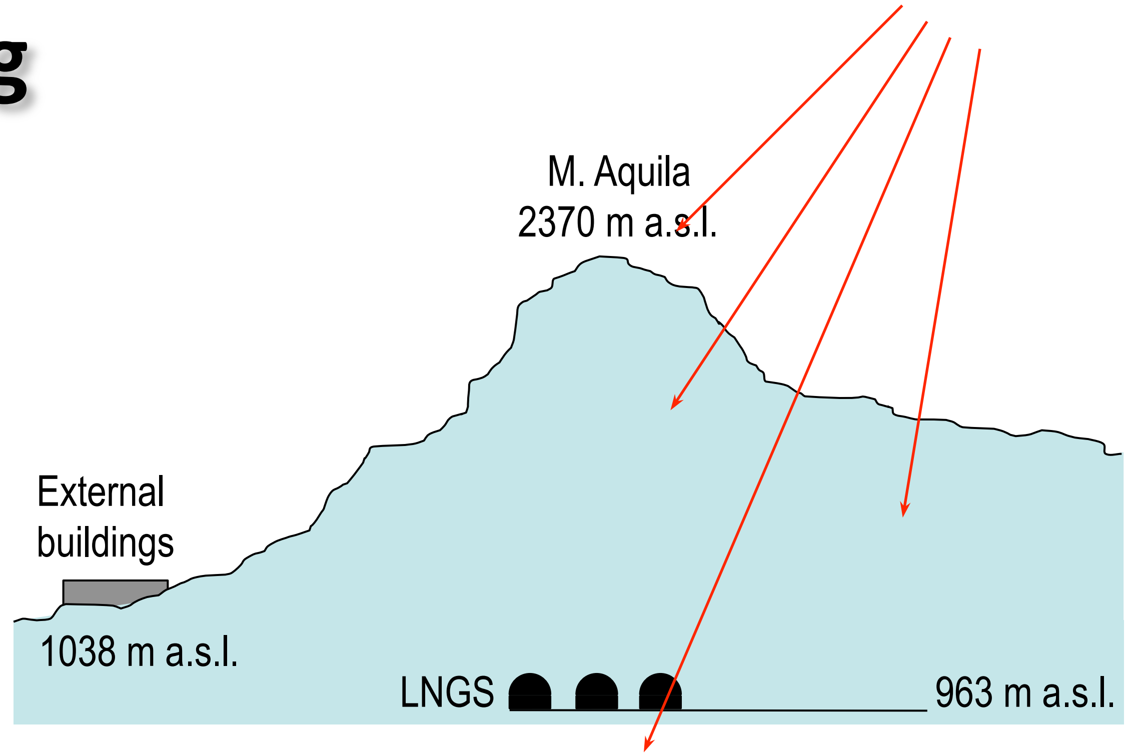
External Gamma-Rays
from buffer, steel sphere, PMT glass (^{40}K, ^{208}Tl ...)

Cosmic Muons

Cosmogenics
neutrons and radionuclides from muon-spallation and hadronic showers

Fast Neutrons
from external muons

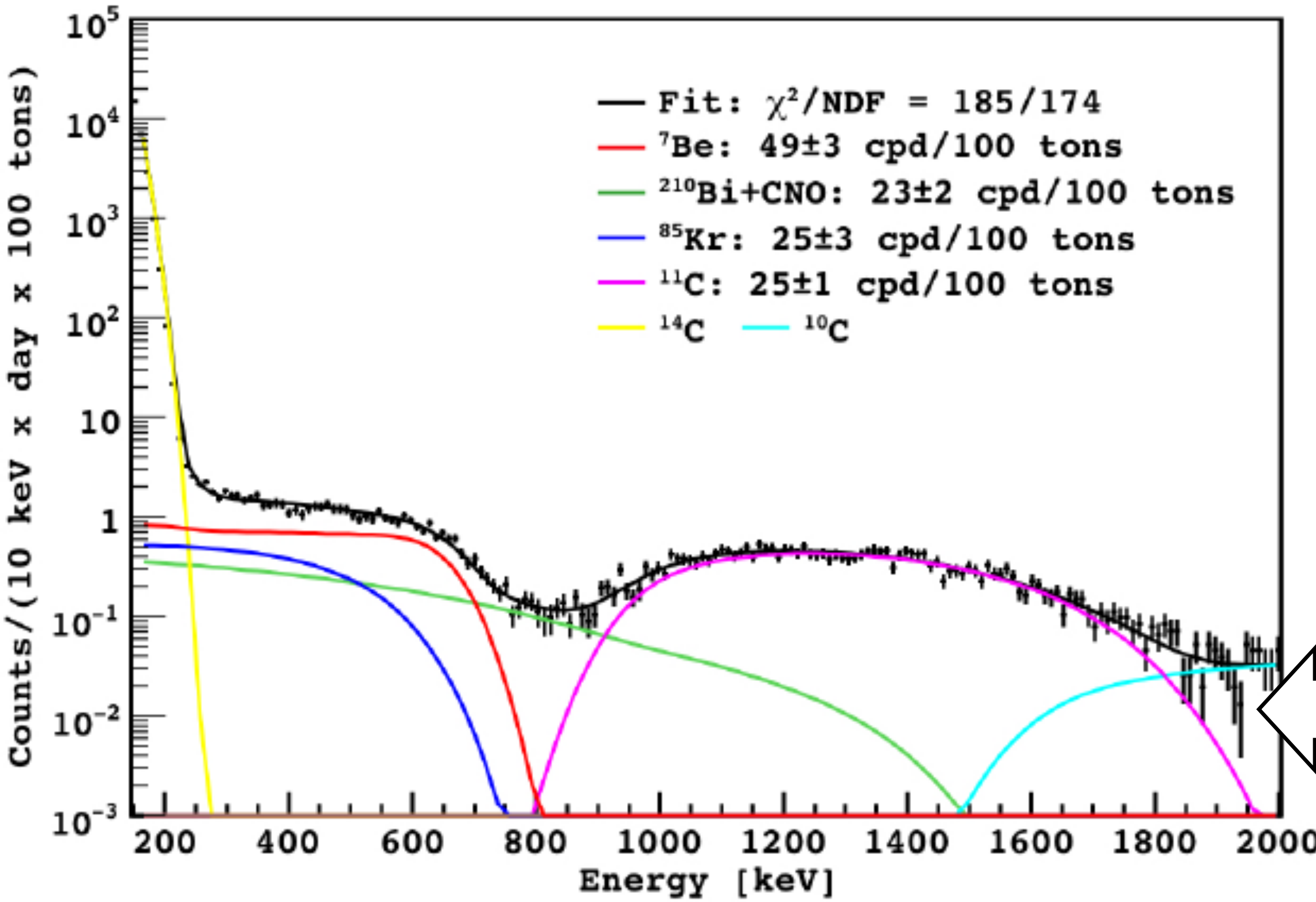
Passive Shielding

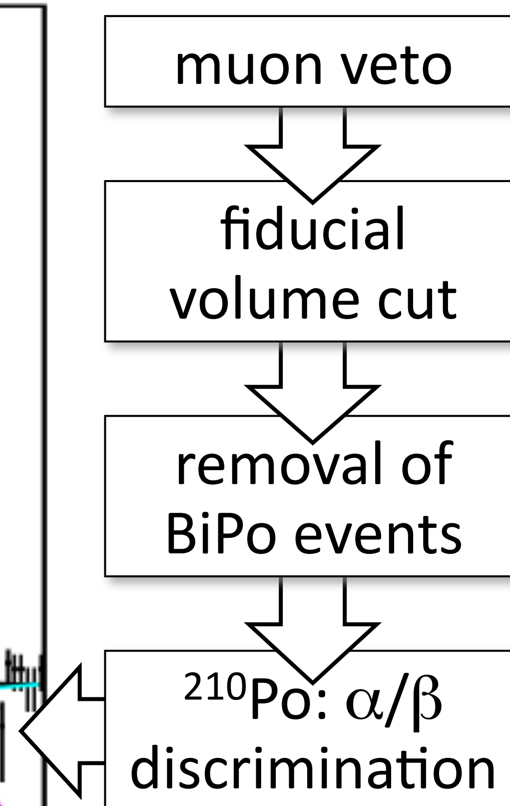


Borexino is located at the **LNGS**
(Laboratori Nazionali del Gran Sasso)

corresponding rock shielding:
1400 m (3500 m.w.e.)
residual cosmic muon flux:
~1/m^{2}h or 4300/d in Bx ID

Borexino measuement of ^{7}Be neutrinos





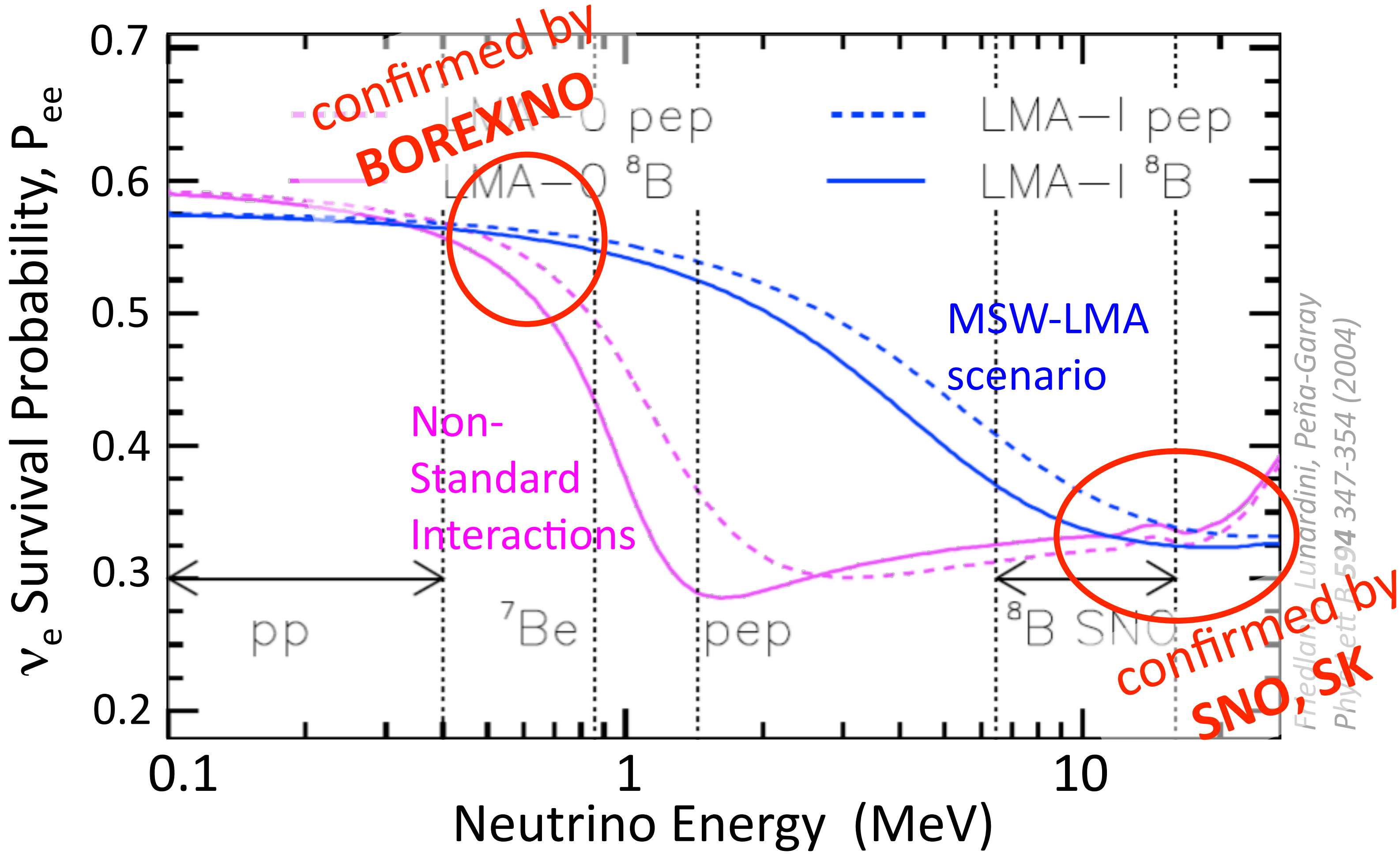
Live time of 200 days:

[Phys.Rev.Lett.101:091302,2008]

Result on ^{7}Be rate

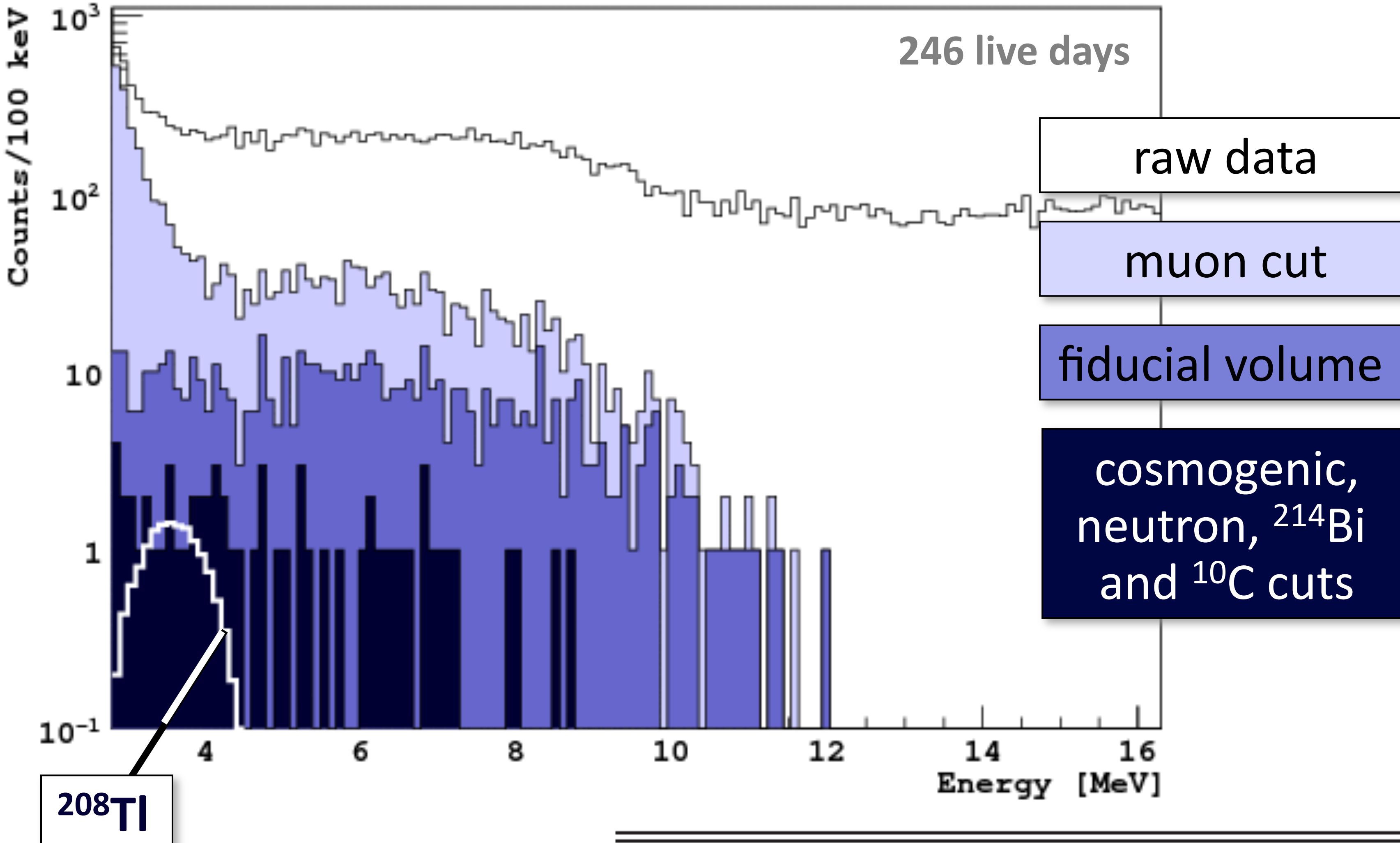
$49 \pm 3_{stat} \pm 4_{sys}$ cpd/100t

The MSW-LMA Oscillation Scenario



But what about the transition region?

BOREXINO: Measuring ^{8}B-νs to 3 MeV



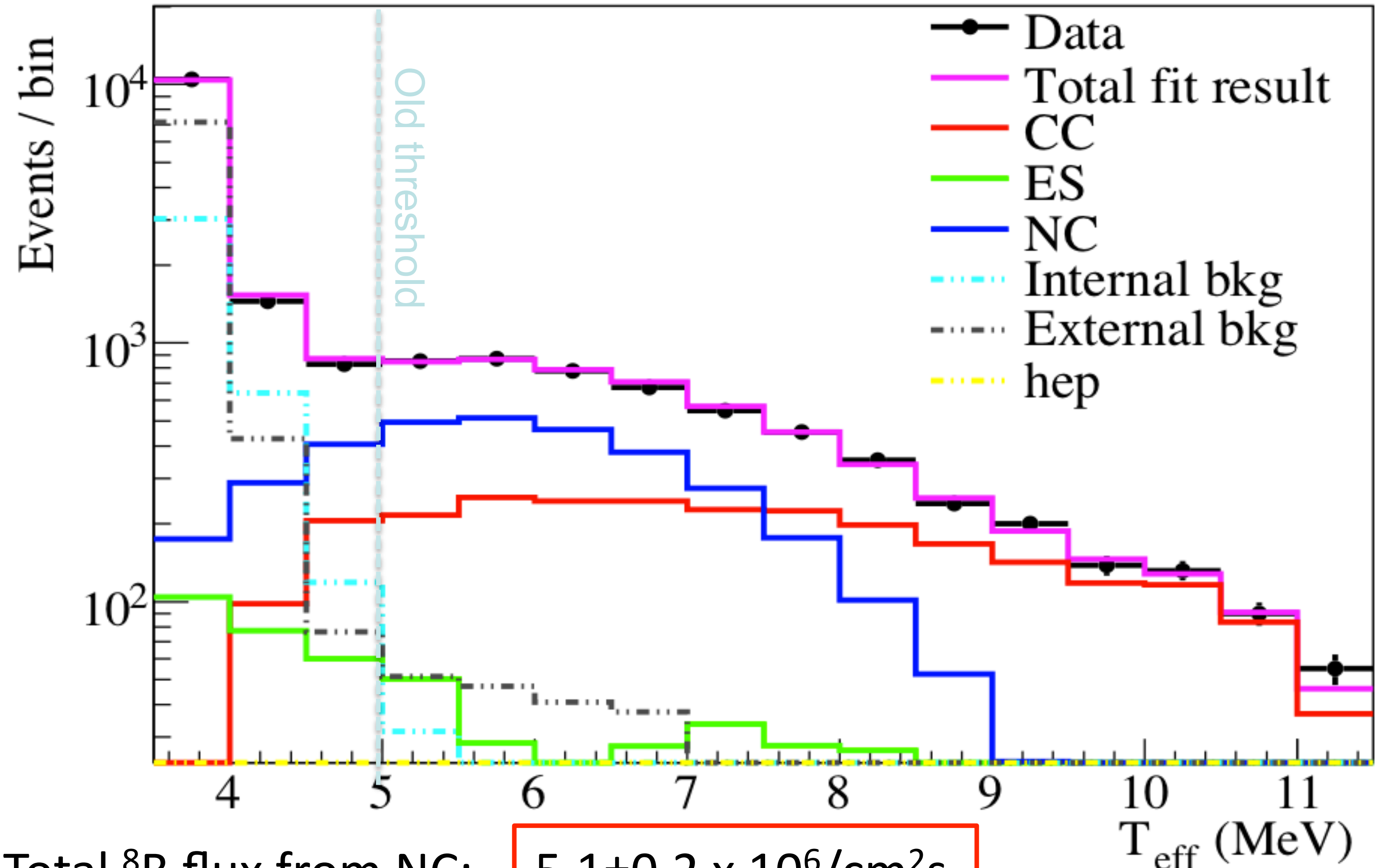
based on 345 days life time:

[Phys Rev D 82 (2010) 033006]

	3.0–16.3 MeV	5.0–16.3 MeV
Rate [cpd/100 t]	0.22±0.04±0.01	0.13±0.02±0.01
Φ^{ES}_{exp} [10^6 cm^{-2}s^{-1}]	2.4±0.4±0.1	2.7±0.4±0.2
$\Phi^{ES}_{exp}/\Phi^{ES}_{th}$	0.88±0.19	1.08±0.23

SNO: Lowering threshold to 3.5 MeV

Kinetic Energy Spectrum

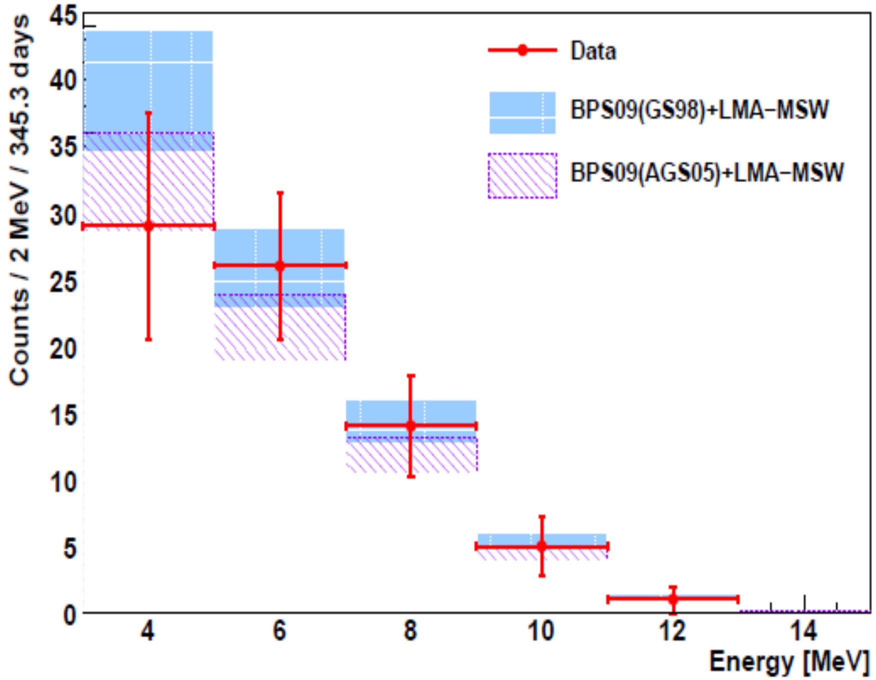


Total ^8B flux from NC: $5.1 \pm 0.2 \times 10^6/cm^2s$

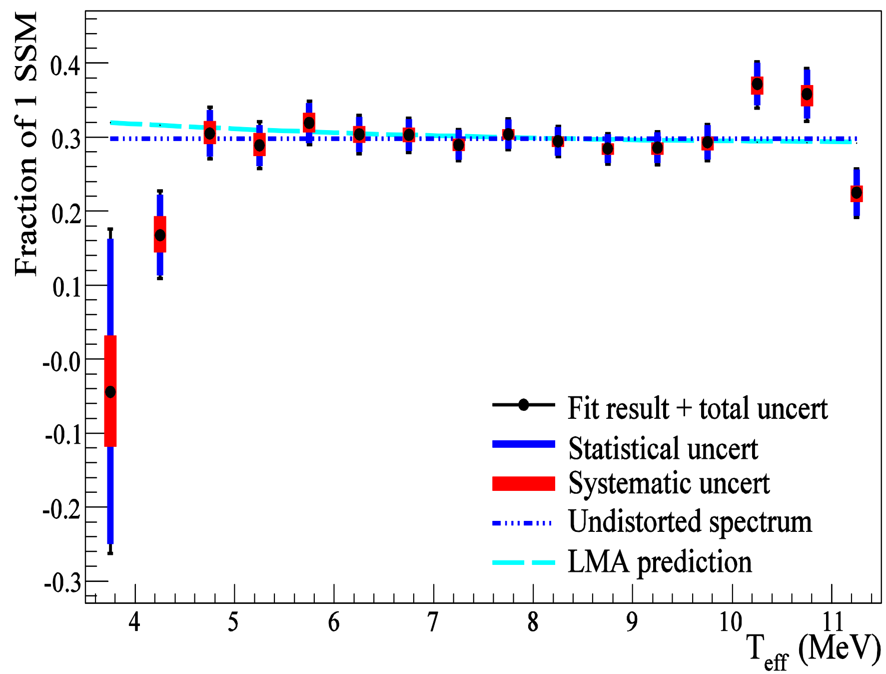
[Phys.Rev.C81:055504,2010]

New results vs. LMA-MSW predictions

BOREXINO (ES)



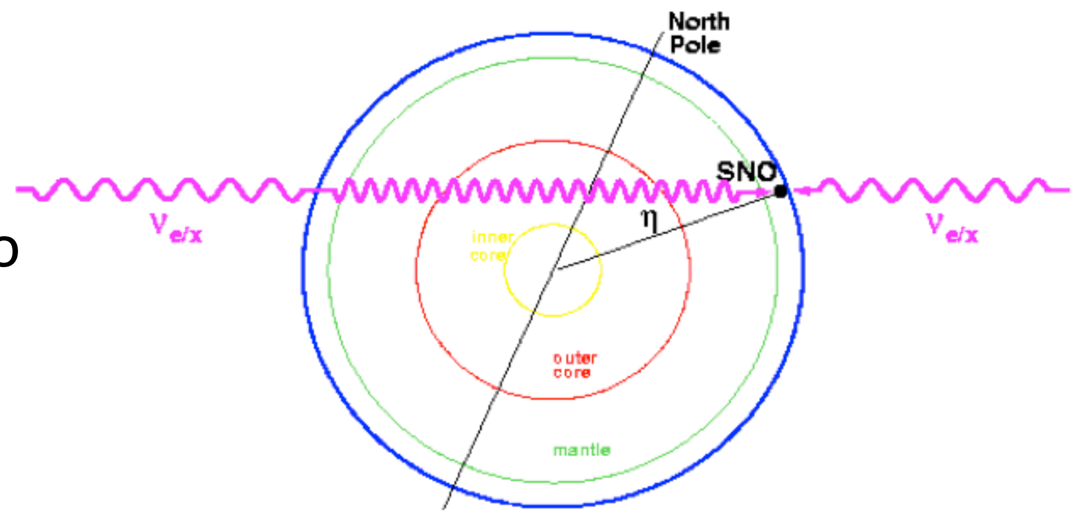
SNO (CC)



- Borexino and SNO results are in good agreement
- Up to now no conflict with LMA-MSW scenario

Search for modulations in ^{7}Be signal

- passage through Earth matter might influence ν_e survival probability, predicted for LOW scenario
- similar effect predicted for mass varying neutrinos
  P.C. de Holanda, JCAP07 (2009) 024



search for day/night asymmetry in ^{7}Be rate:

$$A_{DN} = \frac{2(N-D)}{N+D}$$

N: rate at night
D: rate at day

Model	P_{ee}	A_{DN}
LMA	0.64±0.07	≈0
LOW	0.58±0.05	0.23±0.11
MaVaN		-0.23

Borexino search for day/night effect

Available statistics

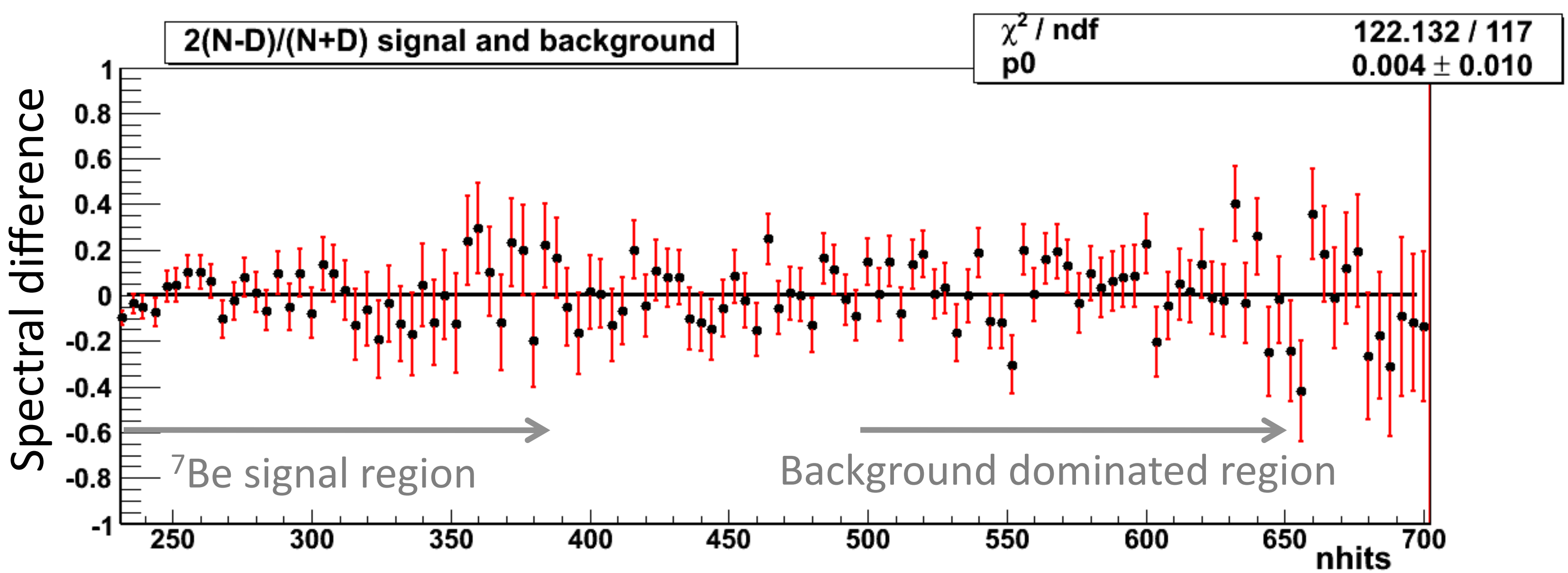
^{7}Be Day spectrum	387.46 days
^{7}Be Night spectrum	401.57 days
Statistical error	2.3 c/d100t

Preliminary result:

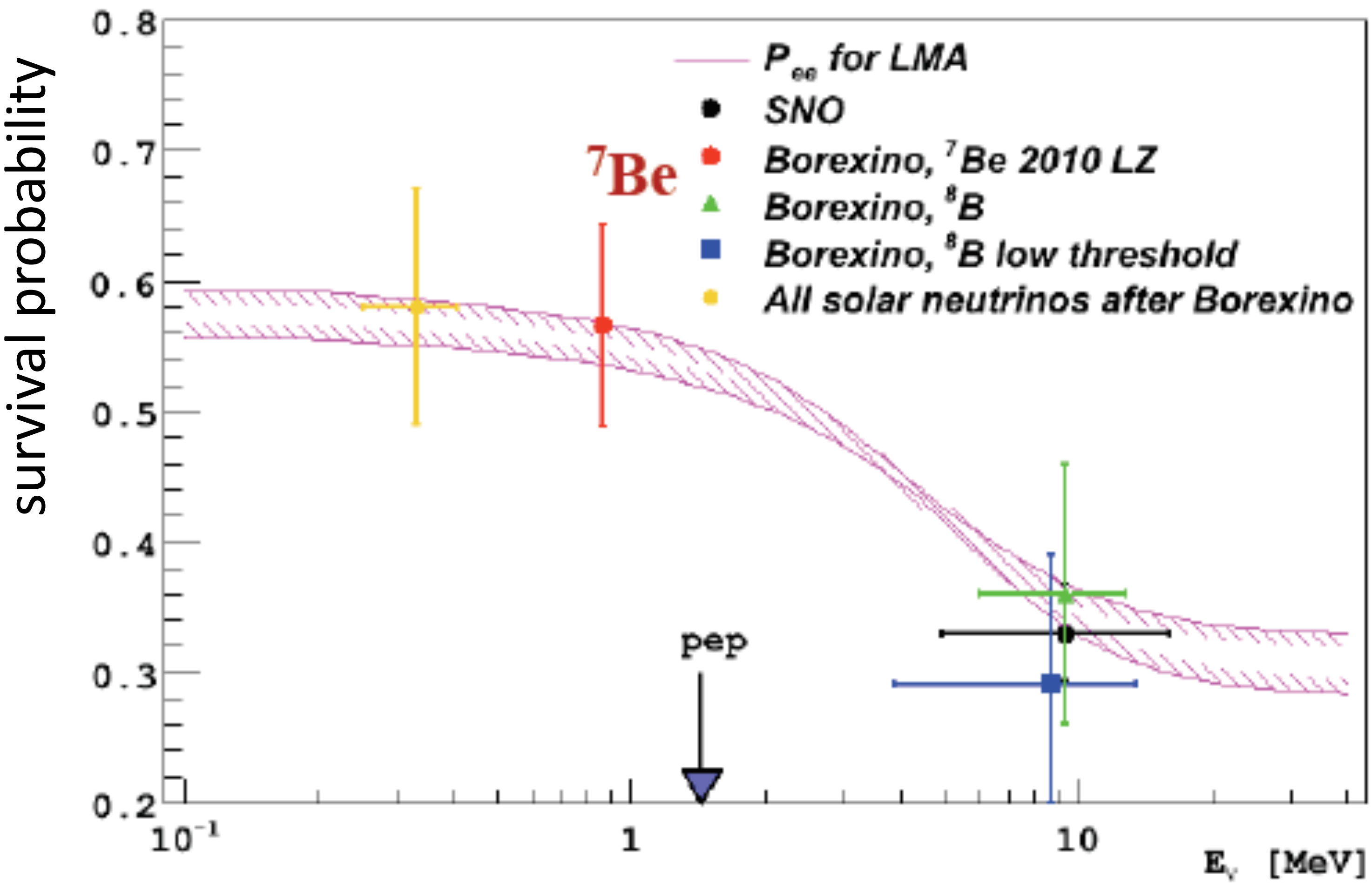
A_{DN}=-0.007±0.073

excludes LOW and MaVaN at 3σ!

^{7}Be rate from fit to separate day and night spectra:



How to proceed from here?



- reduce uncertainties of ^{7}Be flux measurement
- lower ^{8}B detection threshold (2 MeV?)
- measure pep neutrino survival probability

Improve accuracy of ^{7}Be result

Current Borexino Result:
$49 \pm 3_{stat} \pm 4_{sys}$ cpd/100 tons

Contribution	error (1σ)
statistics	± 6%
total scintillator mass	± 0.2%
live time	± 0.1%
efficiency of cuts	± 0.3%
detector response functn	± 6%
fiducial mass	± 6%
total systematics	± 8.5%

photo: BOREXINO calibration

Improve accuracy of ^{7}Be result

Current Borexino Result:
$49 \pm 3_{stat} \pm 4_{sys}$ cpd/100 tons

Aim of new analysis:
reduce uncertainties to <5%!

Contribution	error (1σ)
statistics	± 6%
total scintillator mass	± 0.2%
live time	± 0.1%
efficiency of cuts	± 0.3%
detector response functn	± 6%
fiducial mass	± 6%
total systematics	± 8.5%

Calibration campaign to reduce systematical uncertainties

work in progress ....

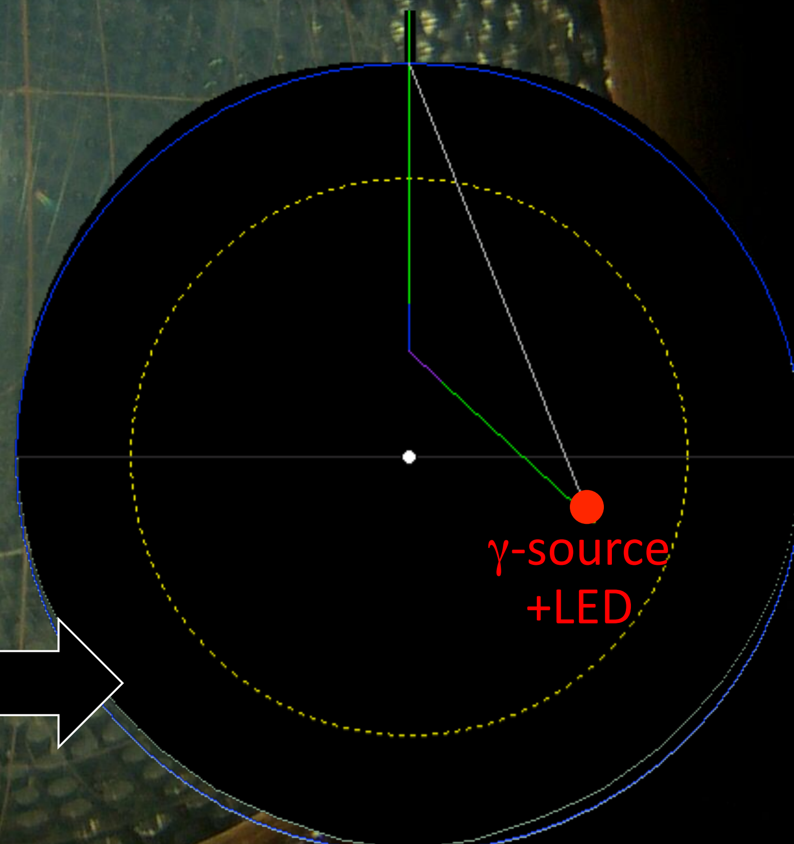
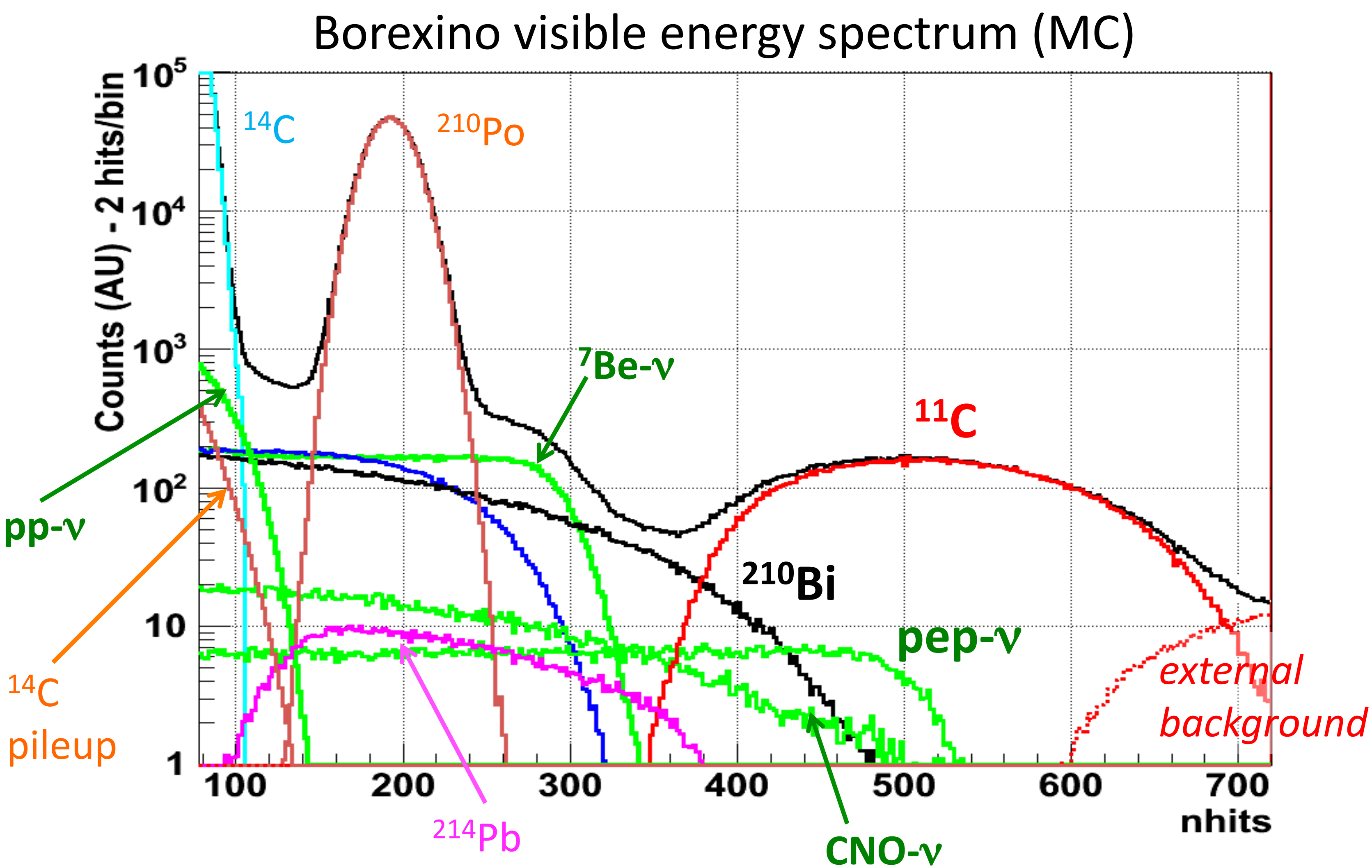


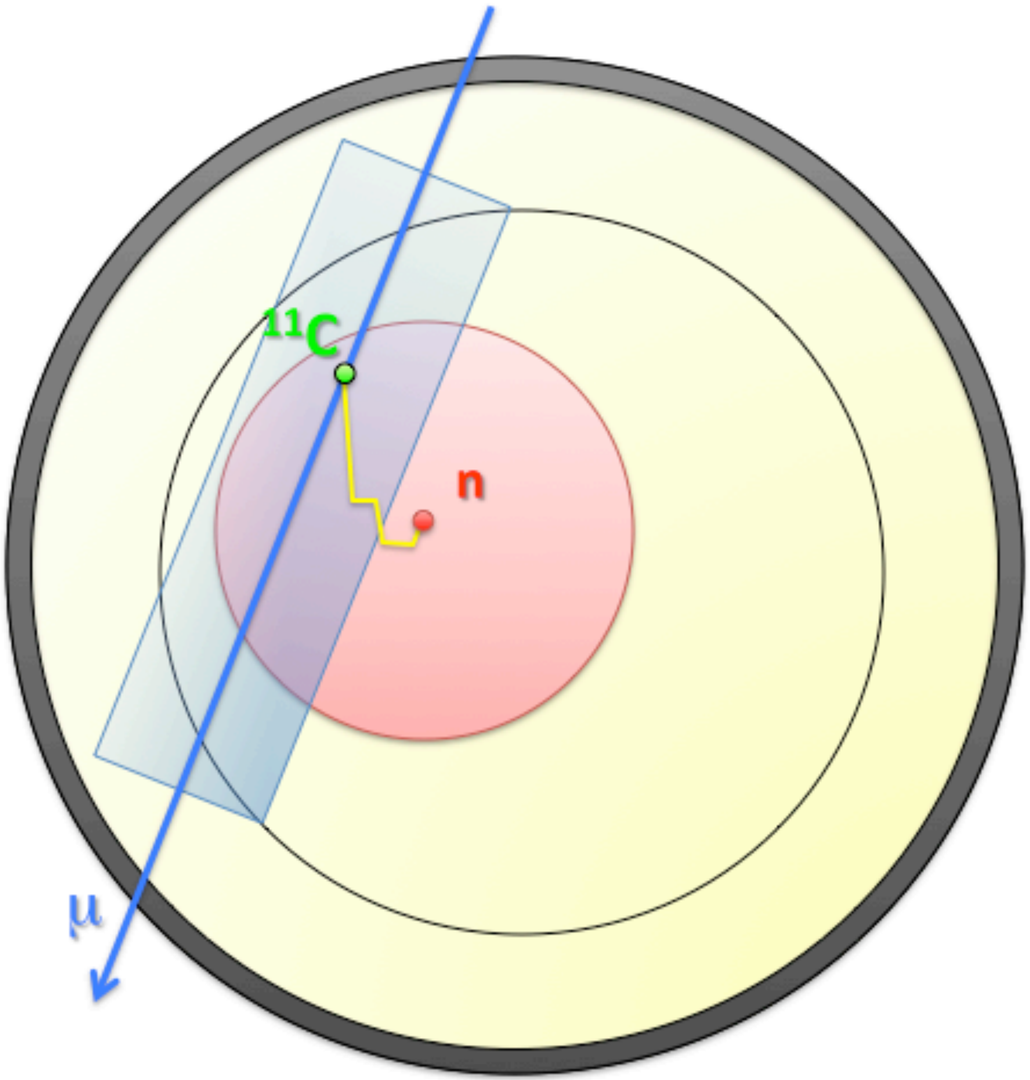
photo: BOREXINO calibration

Measuring pep neutrinos in Borexino



Cosmogenic ^{11}C surpasses pep/CNO signals by about a factor 10!

^{11}C subtraction by threefold coincidence



- ^{11}C is produced by cosmic muons in the scintillator:
  $^{12}C \rightarrow {}^{11}C + n$
- neutron capture on H
  $n + p \rightarrow d + \gamma$ [2.2MeV]
- rates in Borexino (3.5kmwe)

muons	4300	/day
neutrons	>250	
^{11}C	25	

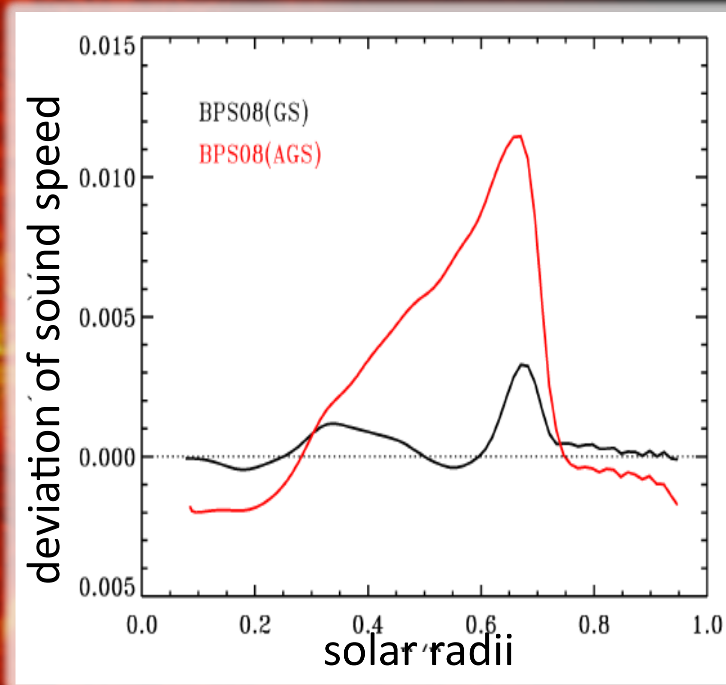
- ^{11}C half-life is 20 minutes

→ event-by-event tagging must rely on both time and spacial information!

work in progress …

CNO neutrinos and solar metallicity

- new analysis of solar metallicity in conflict with helioseismology



- solar neutrino production depends on metallicity Z
- based on SSM and different Z: *[arXiv:0811.2424]*:

Branch	**Error**	**ΔZ**		
pp	0.6%	1.2%		
pep	1.1%	2.8%		
^{7}Be	6%	10%	←	Liquid Scintillator
^{8}B	11%	21%	←	Water Cherenkov
CNO	16%	31-44%	←	Liquid Scintillator?

- Up to now, neutrino data is not sufficient to decide ...

Conclusions

- Solar neutrinos have led to surprising insights in astrophysics and particle physics (ν oscillations!).

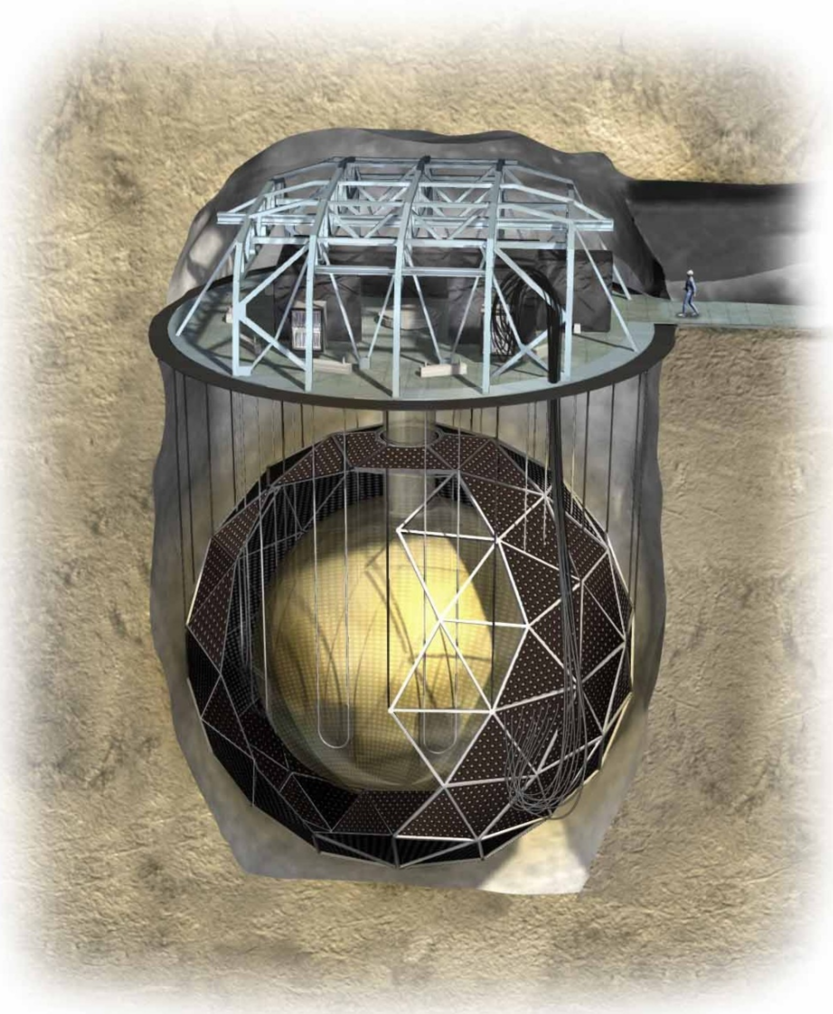
- Measurement of solar ^{7}Be and ^{8}B neutrinos have solidified the basic MSW-LMA oscillation scenario.

- The MSW transition region remains mostly unexplored: A lower ^{8}B detection threshold, an increase in ^{7}Be accuracy and the detection of pep ν's may reveal new physics!

- Stay tuned for new results!

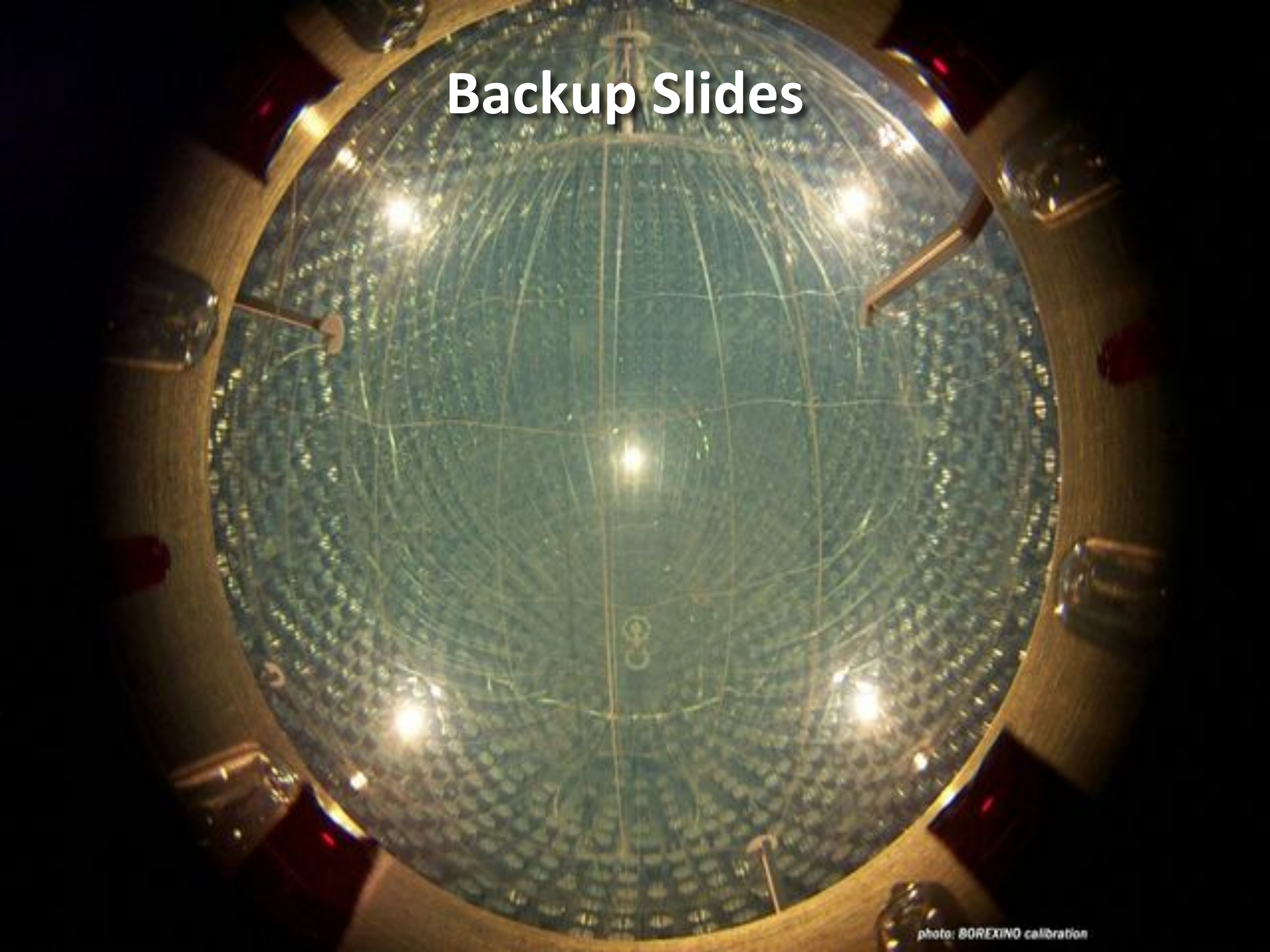
photo: BOREXINO calibration

Outlook: SNO+

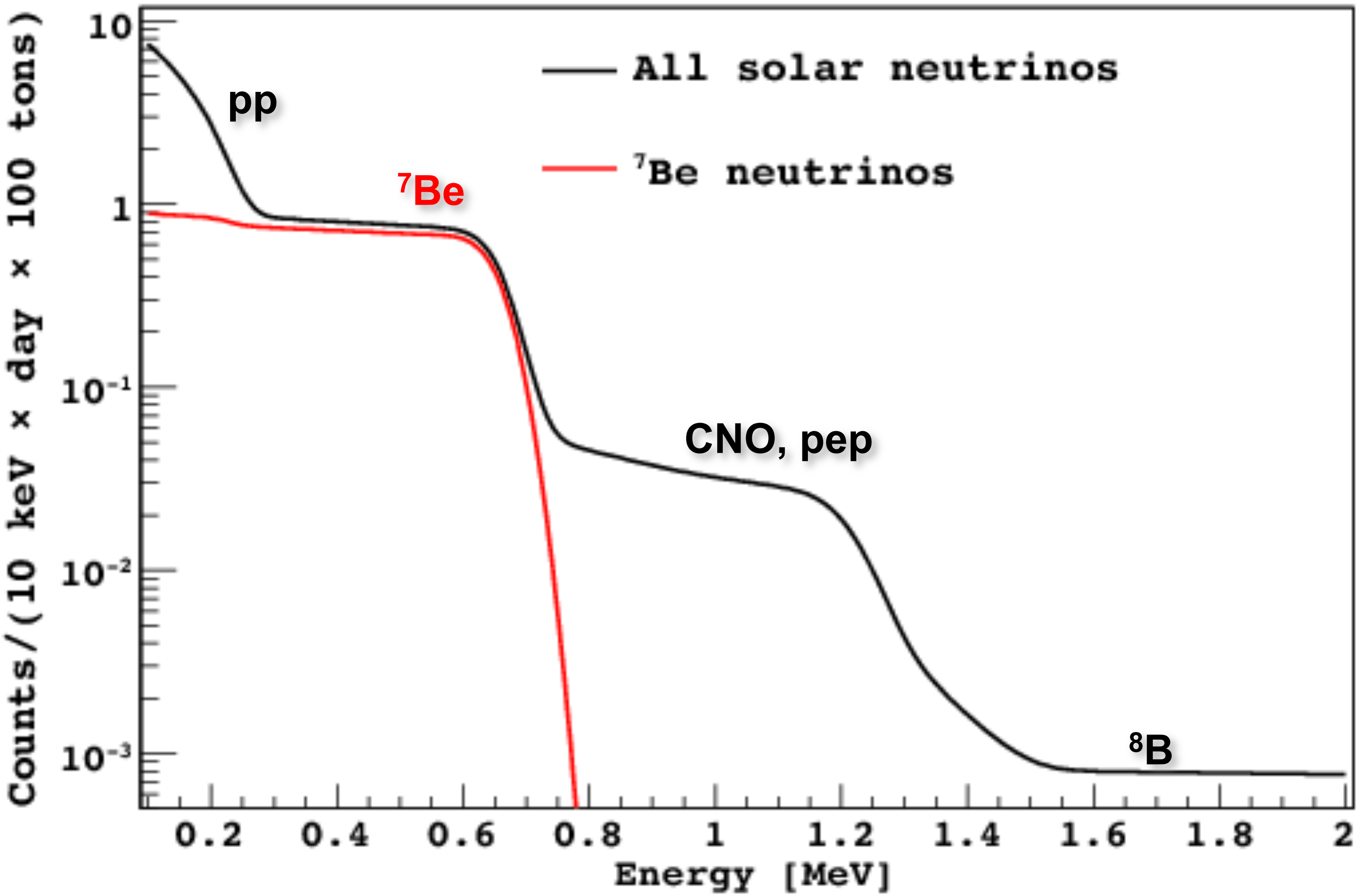


- refill the old SNO experiment with (doped) liquid scintillator
- 1kt target: 3x Borexino statistics
- 6000 mwe overburden: CNO/pep signal essentially free of cosmogenic ^{11}C background
- measurement of geo-ν's/SN ν's
- search for neutrinoless double beta decay in Nd-doped scintillator

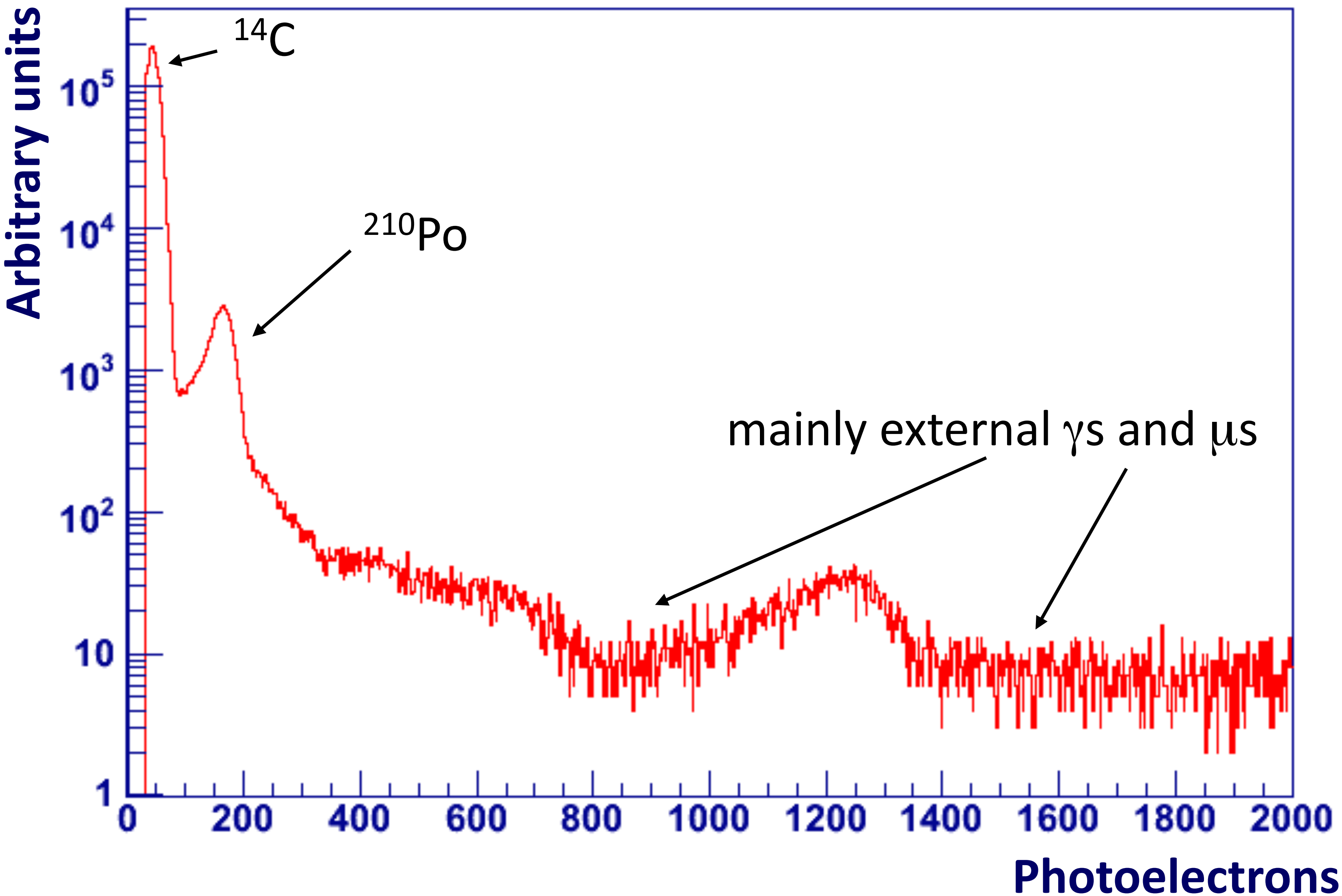
Backup Slides



Expected Electron Recoil Spectrum



Initial Data Spectrum



Background Rejection