Latest results from Borexino

DBD11 Workshop
Osaka, Japan
14-17 November, 2011

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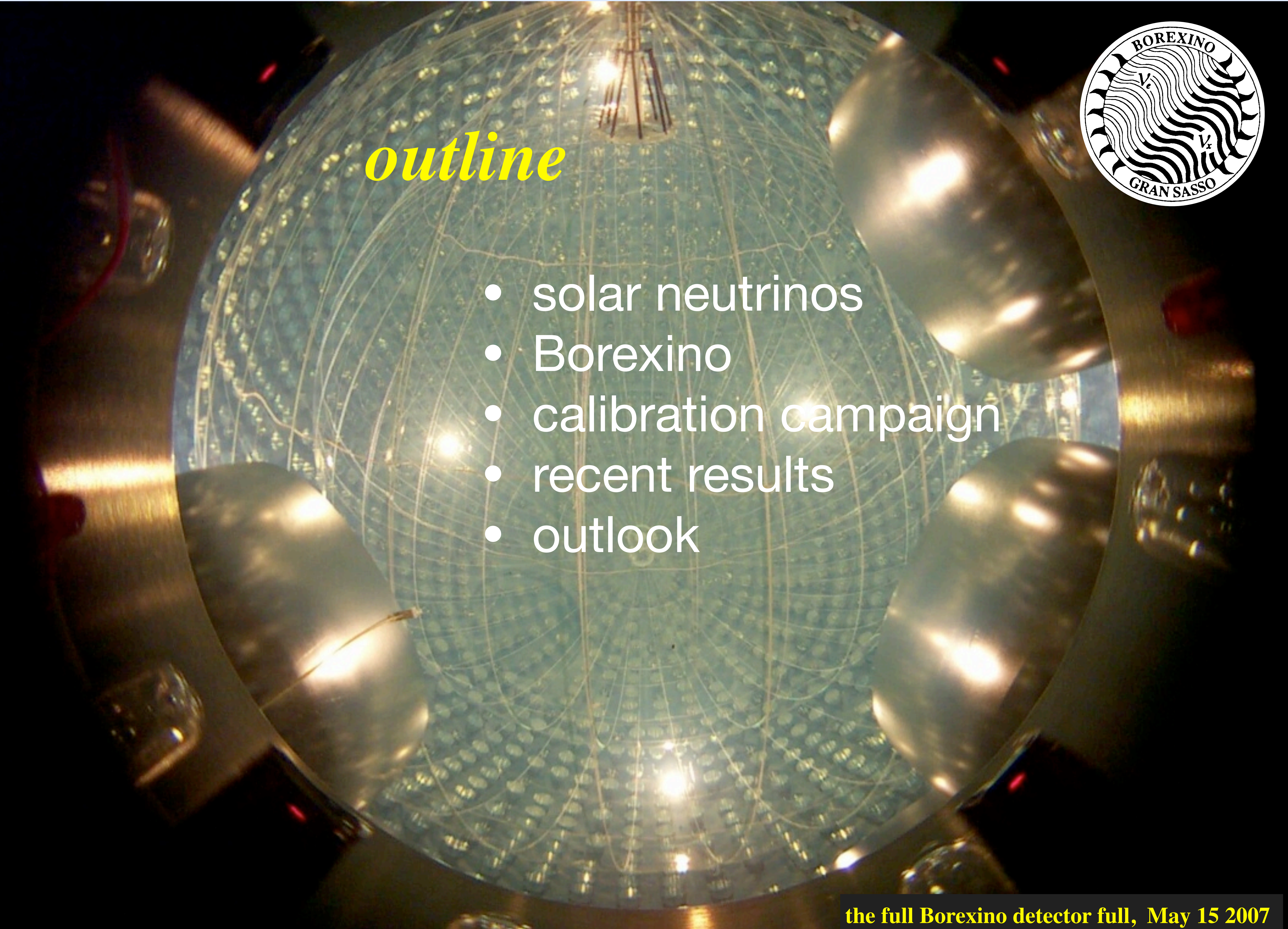
(on behalf of the Borexino Collaboration)

outline

- solar neutrinos
- Borexino
- calibration campaign
- recent results
- outlook



the full Borexino detector full, May 15 2007

Solar Fusion Reactions

p-p Solar Fusion Chain

$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$ $\quad$ $p + e^{-} + p \rightarrow {}^{2}H + \nu_e$

$\downarrow$

${}^{2}H + p \rightarrow {}^{3}He + \gamma$

${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2\,p$ $\quad$ ${}^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$

${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \gamma + \nu_e$ $\quad$ ${}^{7}Be + p \rightarrow {}^{8}B + \gamma$

$\downarrow$ $\quad$ $\downarrow$

${}^{7}Li + p \rightarrow \alpha + \alpha$ $\quad$ ${}^{8}B \rightarrow 2\,\alpha + e^{+} + \nu_e$

CNO Solar Fusion Cycle

${}^{12}C + p \rightarrow {}^{13}N + \gamma$

${}^{13}N \rightarrow {}^{13}C + e^{+} + \nu_e$

${}^{13}C + p \rightarrow {}^{14}N + \gamma$

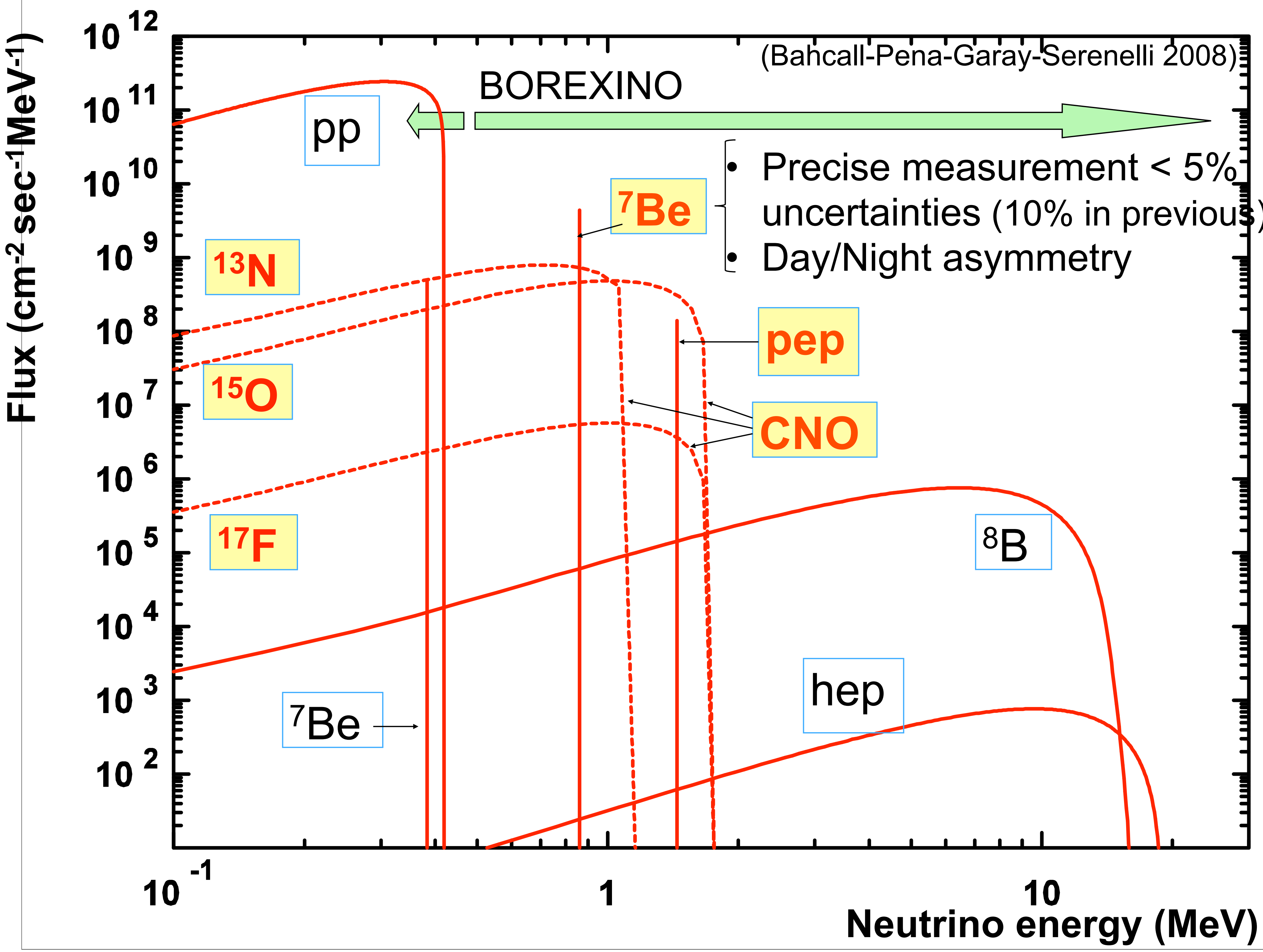
${}^{14}N + p \rightarrow {}^{15}O + \gamma$

${}^{15}O \rightarrow {}^{15}N + e^{+} + \nu_e$

${}^{15}N + p \rightarrow {}^{12}C + {}^{4}He$

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

solar neutrino spectrum



BPS08: (Bahcall) Pena-Garay, C., & Serenelli, A. 2008, arXiv:0811.2424

Lower preferred heavy metal content (metallicity) decreased ^{7}Be by ~10%.

See also A. Serenelli, S. Basu, J. Ferguson, M. Asplund, arXiv:0909.26668v2

neutrino oscillations

solar, atmospheric, reactor, beam neutrinos give a nice picture of the oscillation of three active flavors

$$\delta m^2_{12} \sim 7.6 \times 10^{-5}\mathrm{eV}^2$$

$$\sin^2\theta_{12} \sim 0.3$$

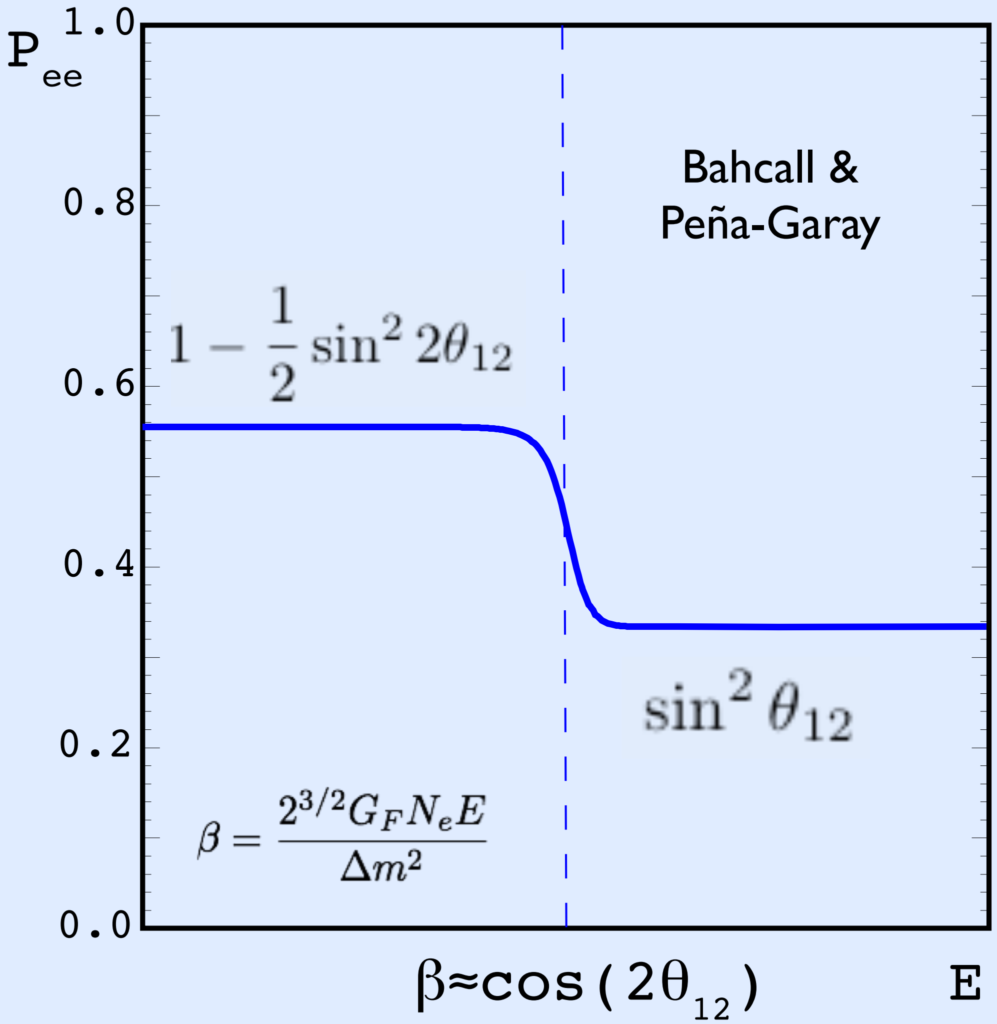
$$\delta m^2_{23} \sim 2.4 \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2\theta_{23} \sim 0.4$$

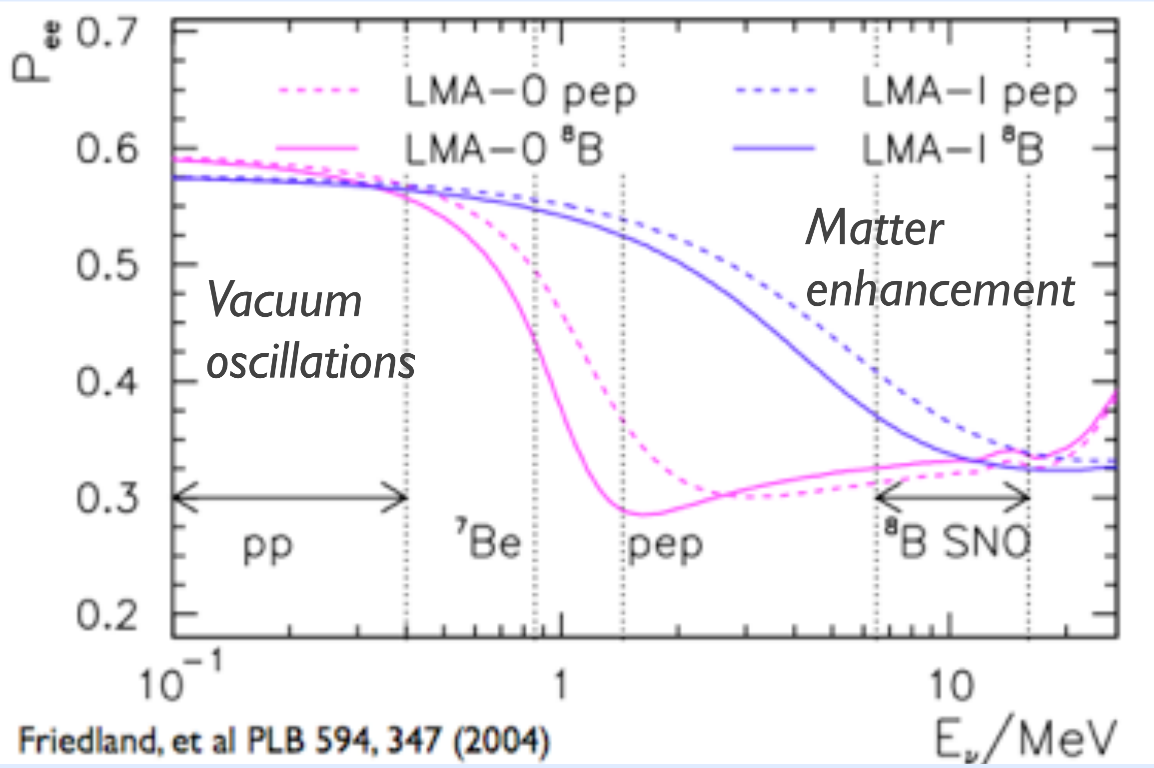
$$\sin^2\theta_{13} \sim \mathrm{small}$$

neutrino oscillations are now a firmly established experimental fact

the MSW-LMA solution for solar neutrinos predicts an energy-dependent survival probability for electron neutrinos



Borexino science

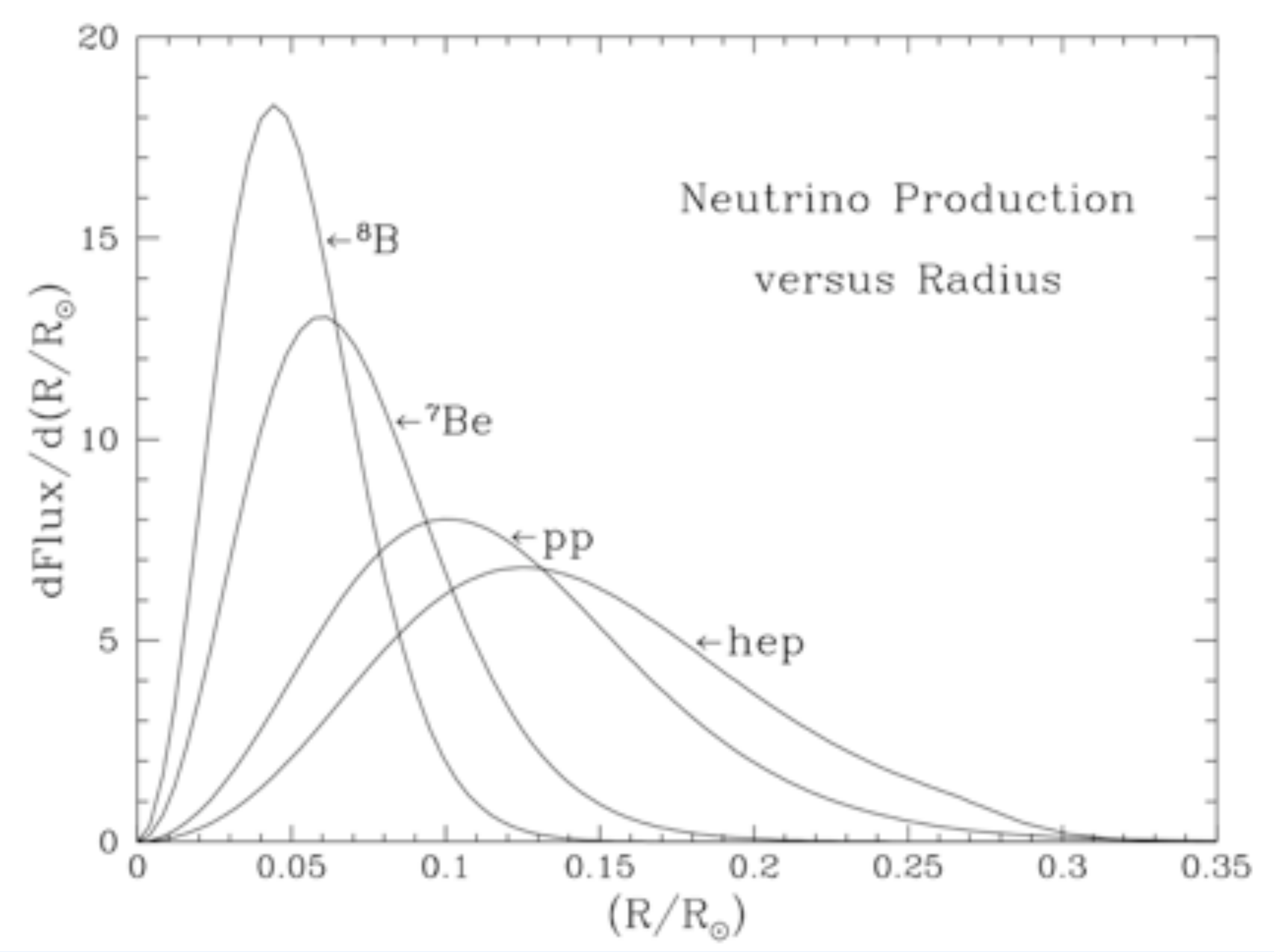


Physics of neutrino oscillation

Precision measurements of solar neutrino fluxes can help map out the *transition region,* sensitive to new physics.

Solar physics

A spectroscopic measurement of the different solar neutrino rates can verify the Standard Solar Model predictions, rule out accretion scenarios and help determine the core C+N abundance.



the Borexino Collaboration

Gran Sasso

Perugia

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Heidelberg

Hamburg

Budapest

Milano

Genova

München

Kraków

Kurchatov Moscow

JINR Dubna

Princeton

Virginia Tech

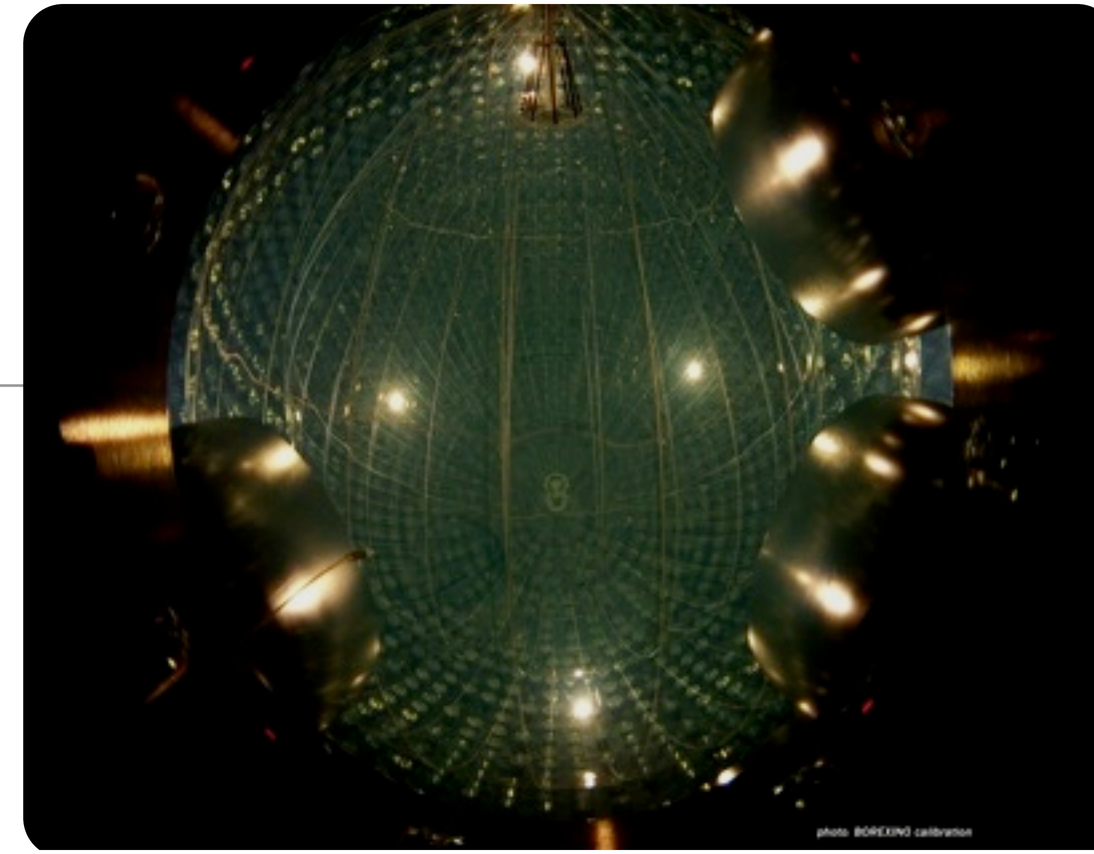
UMass Amherst

Paris

St. Petersburg

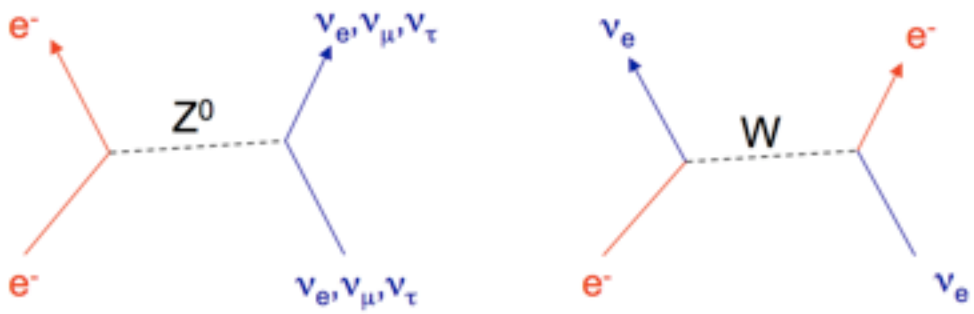
Borexino

(online since May 16, 2007)



Real time measurement of ^{7}Be ν flux

- Detection reaction: elastic scattering
  $\nu + e^- \rightarrow \nu + e^-$ in liquid scintillator



Cross section for ν_e is ~5 times larger than $\nu_{\mu,\tau}$

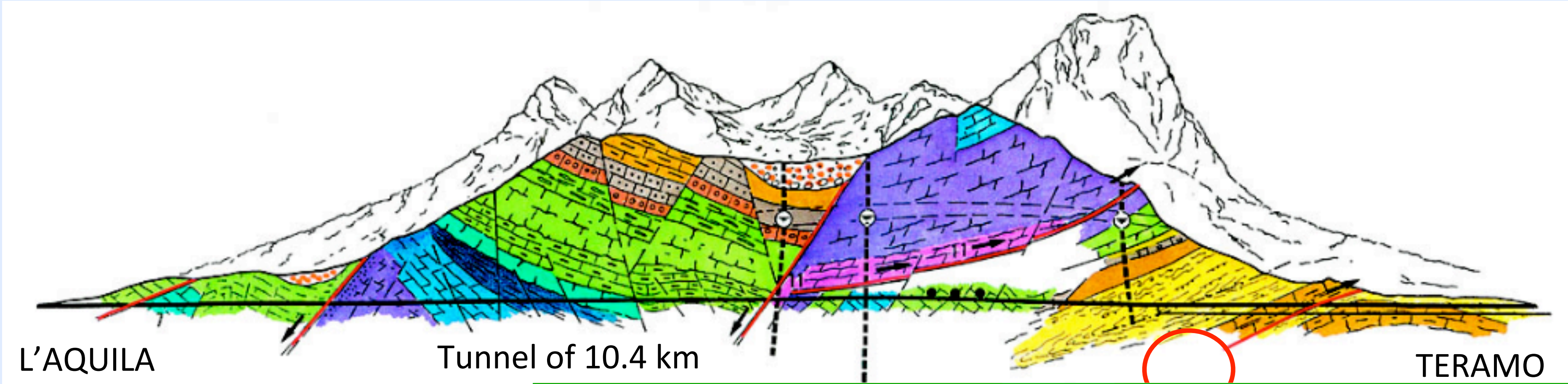
- ^{7}Be ν rate in 100t fiducial mass: 74/d (SSM), 48/d MSW-LMA conversion $\nu_e \rightarrow \nu_{\mu,\tau}$
- No directionality, but vertex reconstruction from photon arrival time
- Real time enables observation of possible periodic variations (seasonal, day-night)

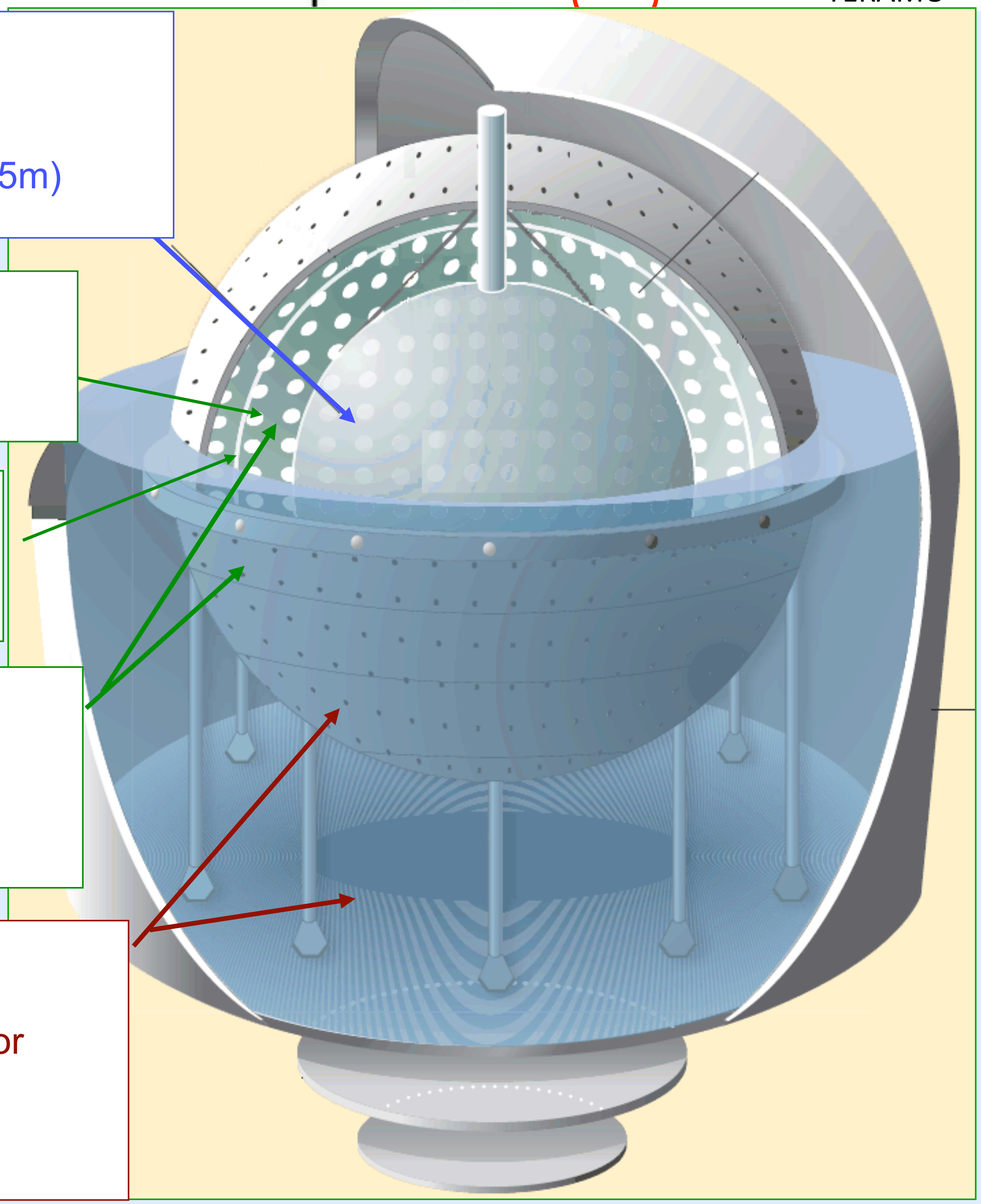
Energy spectroscopy (resolution: ~ 5% @ 1 MeV)

- Software threshold set by ^{14}C at 200 keV (hardware threshold: ~60 keV)
- Neutrino signature: shape of the energy spectrum

Key point: suppression of background sources

Borexino





Scintillator:
270 t PC+PPO (1.5g/l)
in a 150μm thick
Inner nylon vessel (R=4.25m)

Buffer region:
PC+DMP quencher (5g/l)
4.25m<R<6.75m

Outer nylon vessel:
R=5.50m
(^{222}Rn Barrier)

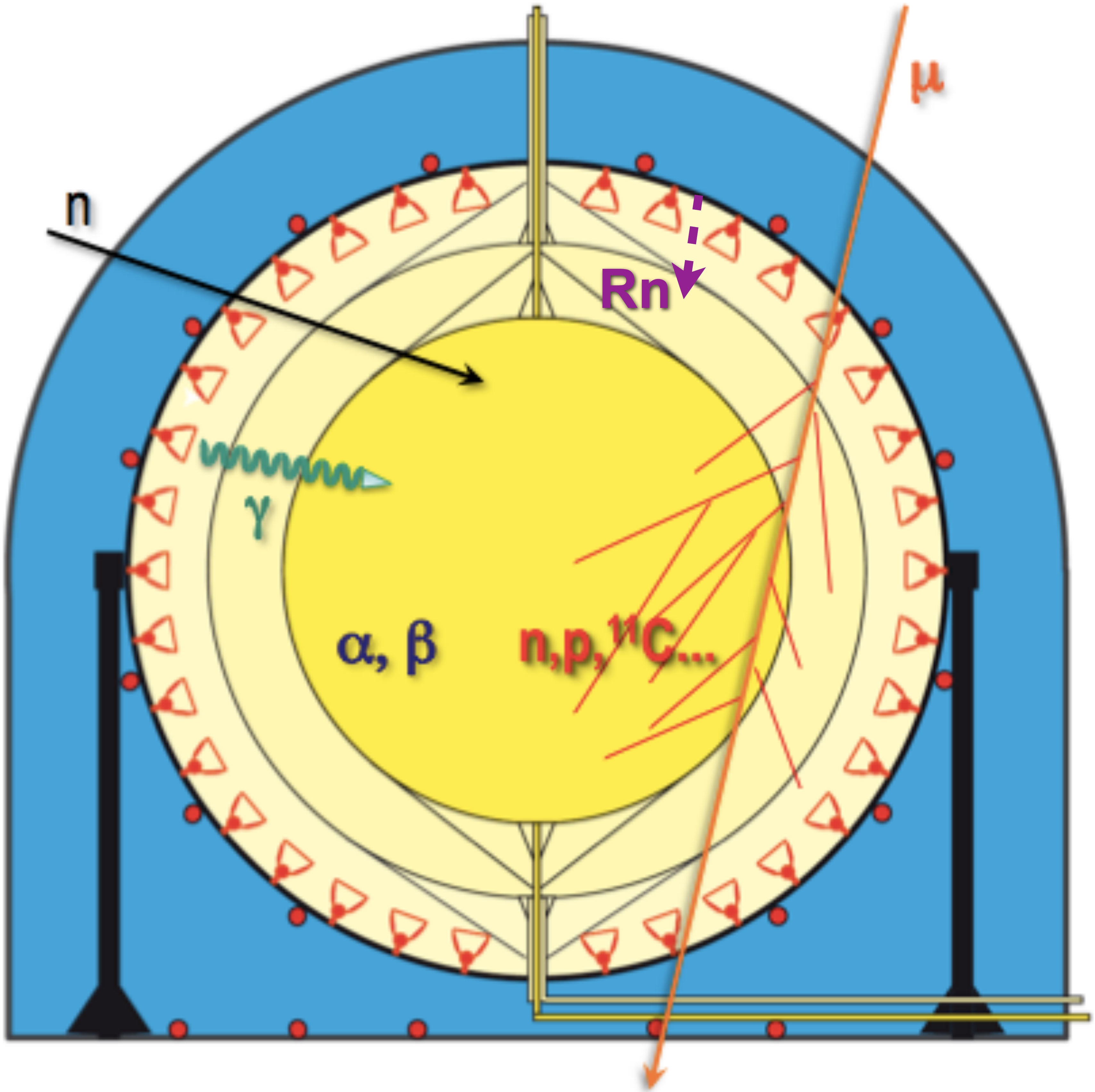
Stainless Steel Sphere:
R=6.75m
2212 8" PMTs with
light guide cone. 1350m^3

Water tank:
γ and n shield
μ water cherenkov detector
208 PMTs in water
2100m^3

Designed according to the idea of **graded shielding**:

excellent ***shielding*** of external background
Increasing ***purity*** from outside to the central region

background reduction: graded shielding design



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

external γ rays
from fluid buffer, steel sphere, PMT glass and light concentrators (^{40}K,^{208}Tl,^{214}Bi)

radon emanation
from the PMTs and steel sphere

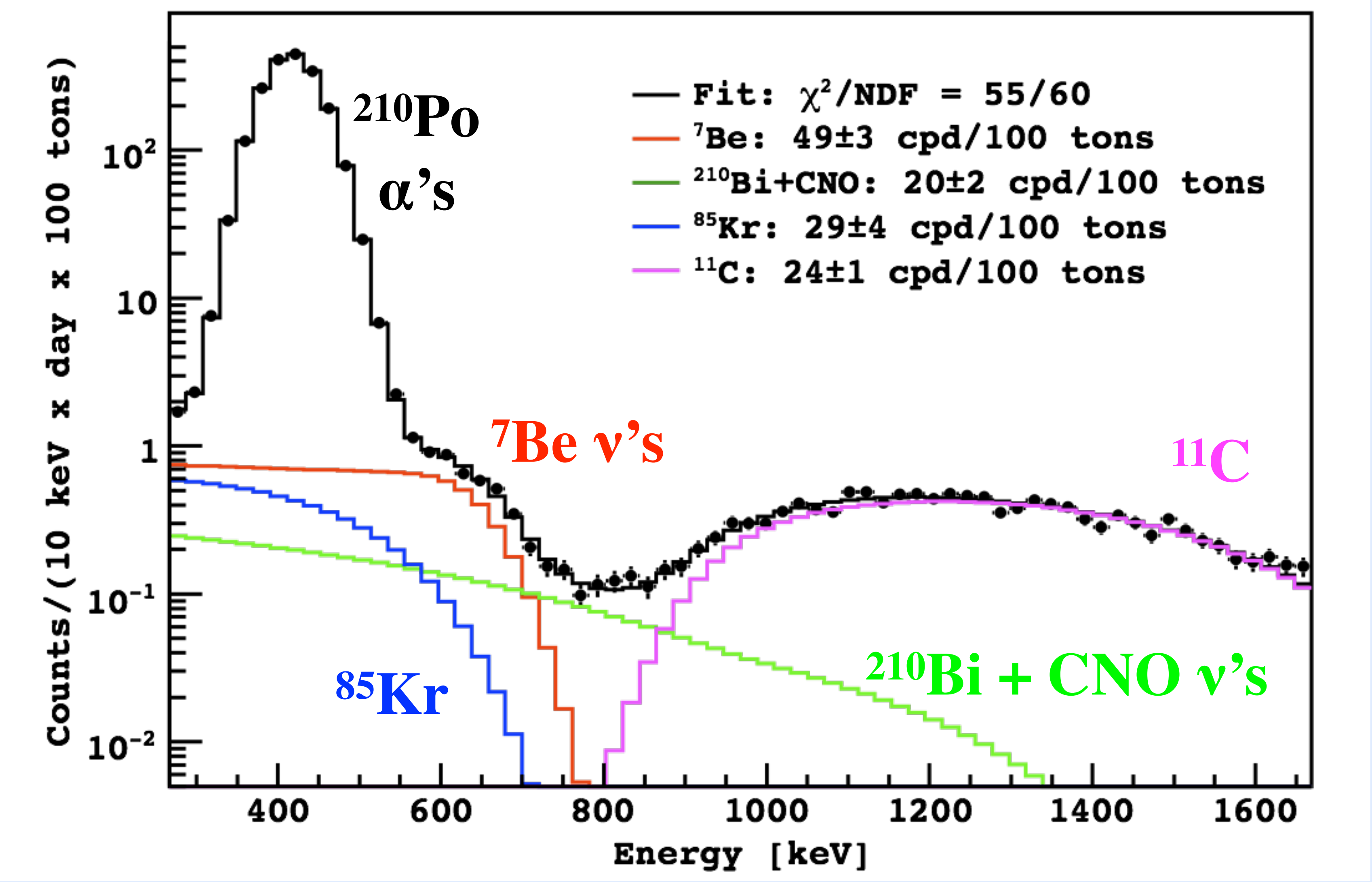
cosmic muons
and their secondaries

cosmogenics
neutrons and radionuclides from μ spallation and hadronic showers

fast neutrons
from external muons

measurement of the ^{7}Be solar neutrino flux

192 live days of data - Phys. Rev. Lett. 101, 091302 (2008)



Free parameters in fit:
LY, ^{7}Be, ^{11}C, ^{85}Kr, CNO+^{210}Bi, ^{210}Po
Statistical error: ± 3 cpd/100t (6.2%)

Systematic Errors	(%)
1. Scintillator mass.	0.2
2. Live time	0.1
3. Efficiency of cuts	0.3
4. Fiducial mass ratio	6.0
5. Detector response	6.0
TOTAL SYSTEMATIC ERROR	8.5

$$\mathrm{Rate}(^7\mathrm{Be}) = 47 \pm 3(\mathrm{stat}) \pm 4(\mathrm{sys}) \ \ \mathrm{cpd}/100\,\mathrm{tons}$$

$$\Phi(^7\mathrm{Be}) = (5.18 \pm 0.51) \times 10^9 \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

$$\mathrm{Rate}(\mathrm{o}\not{\mathrm{s}}\mathrm{c}) = 74 \pm 4 \ \ \mathrm{cpd}/100\,\mathrm{tons}\,(\mathrm{high\ Z})$$

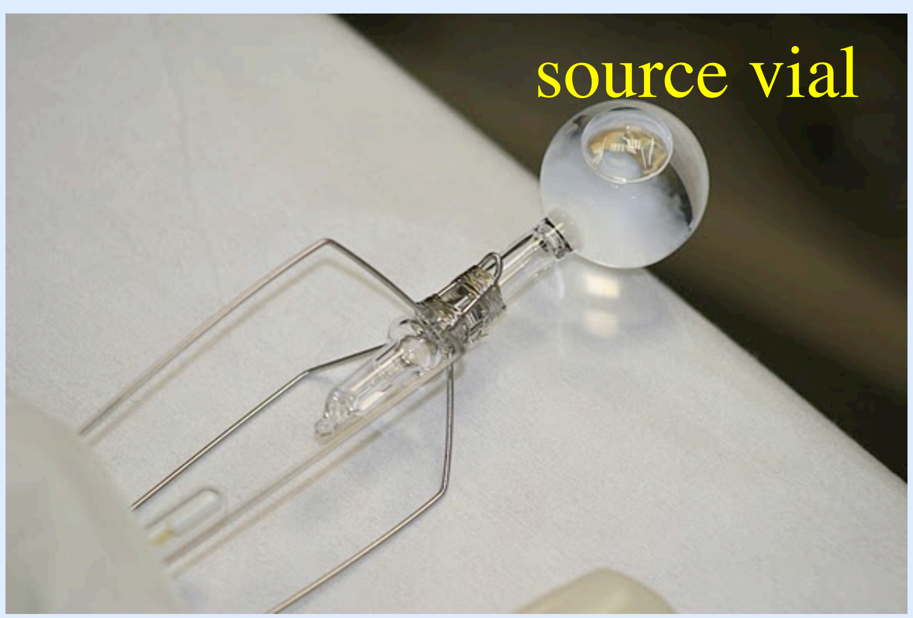
calibration sources

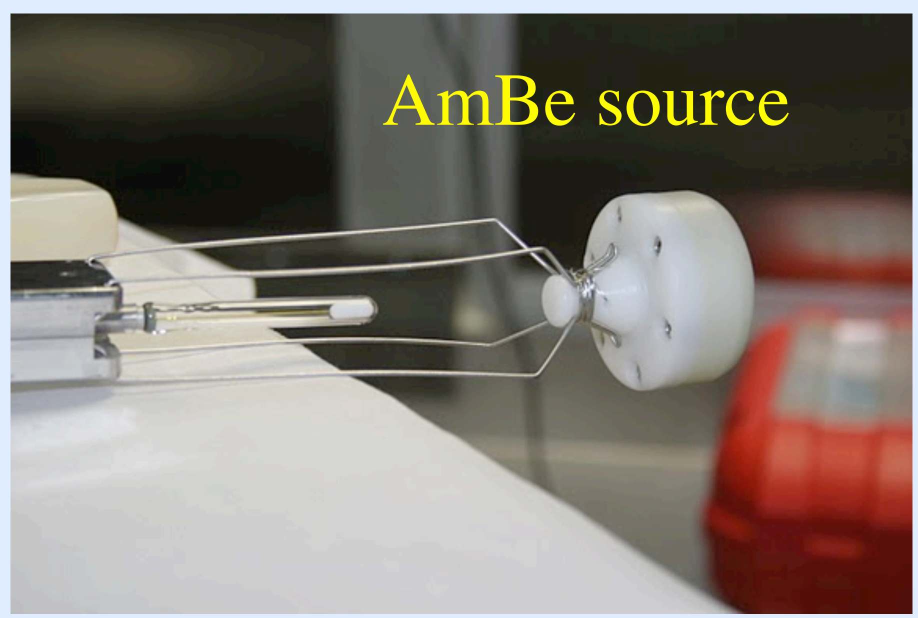
	γ								β		α	n		
	^{57}Co	^{139}Ce	^{203}Hg	^{85}Sr	^{54}Mn	^{65}Zn	^{60}Co	^{40}K	^{14}C	^{214}Bi	^{214}Po	n-p	n +^{12}C	n+Fe
energy (MeV)	0.122	0.165	0.279	0.514	0.834	1.1	1.1, 1.3	1.4	0.15	3.2		2.226	4.94	~7.5

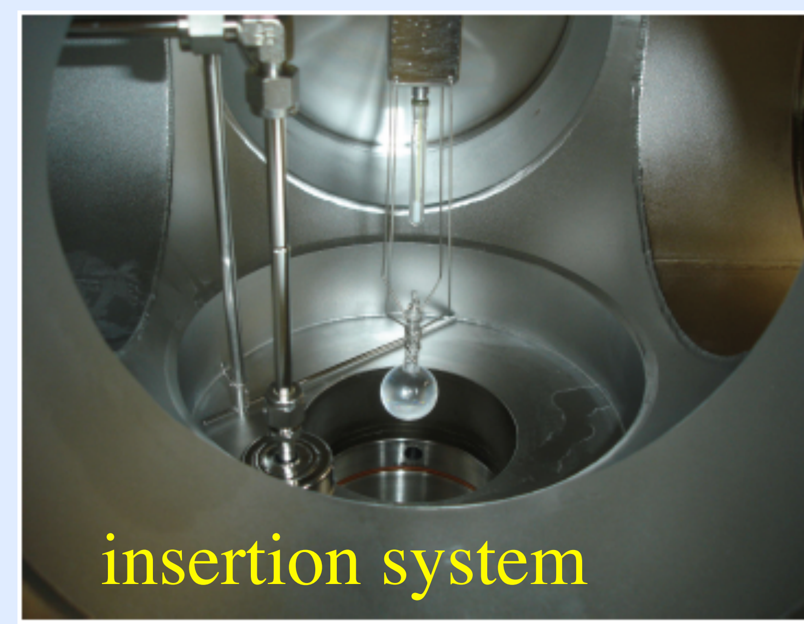
spiked water vial

spiked scintillator vial

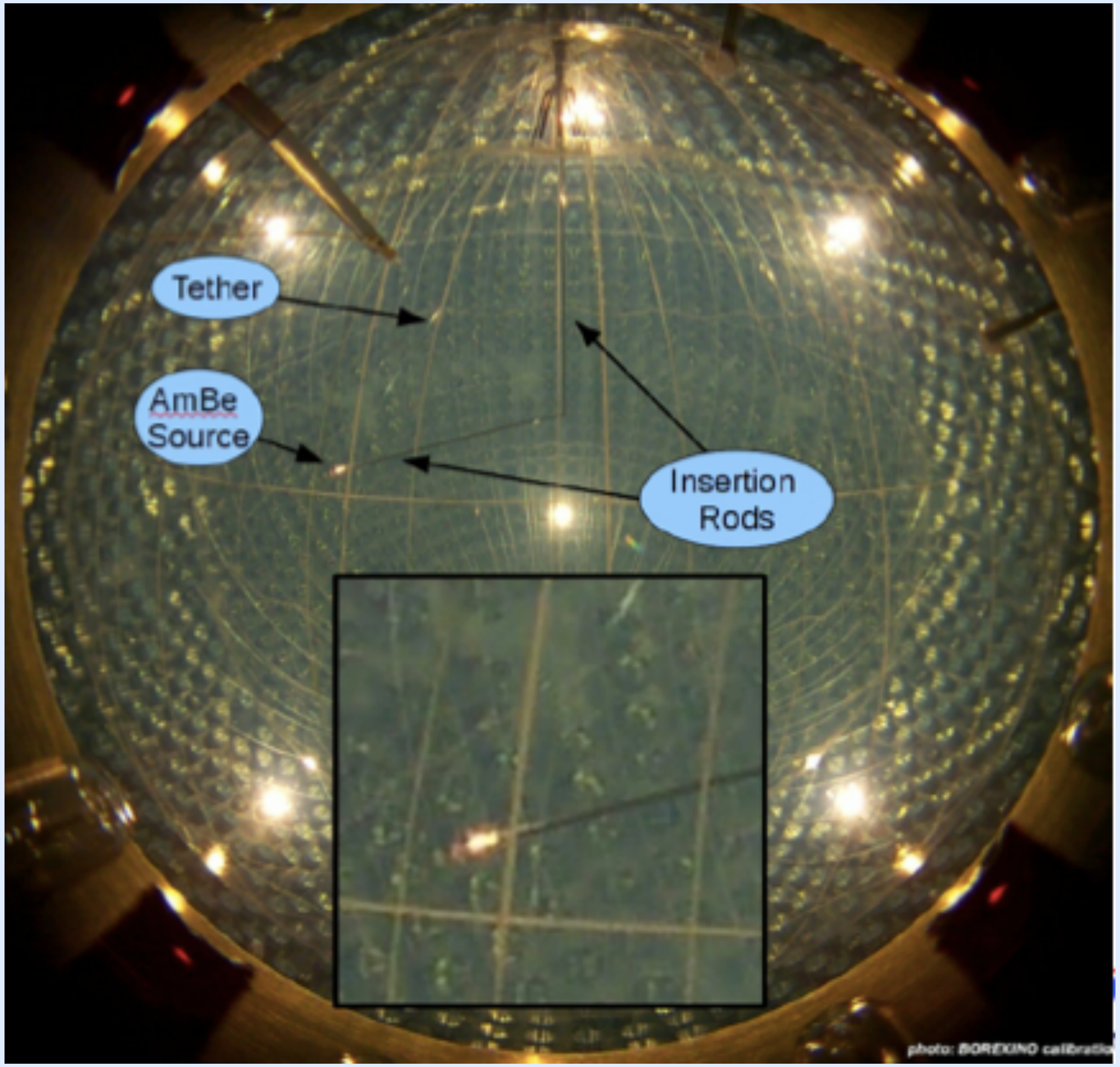
AmBe

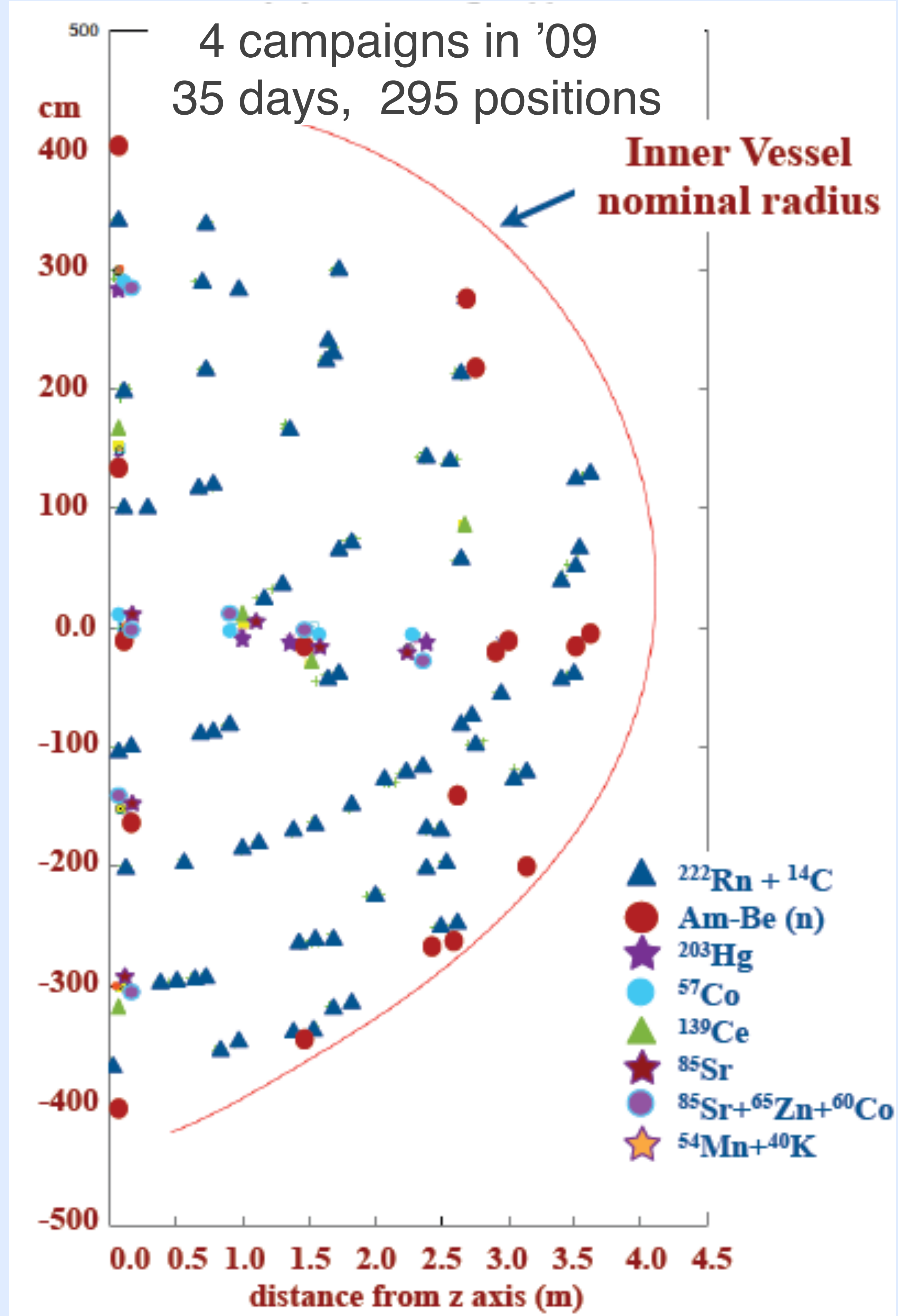






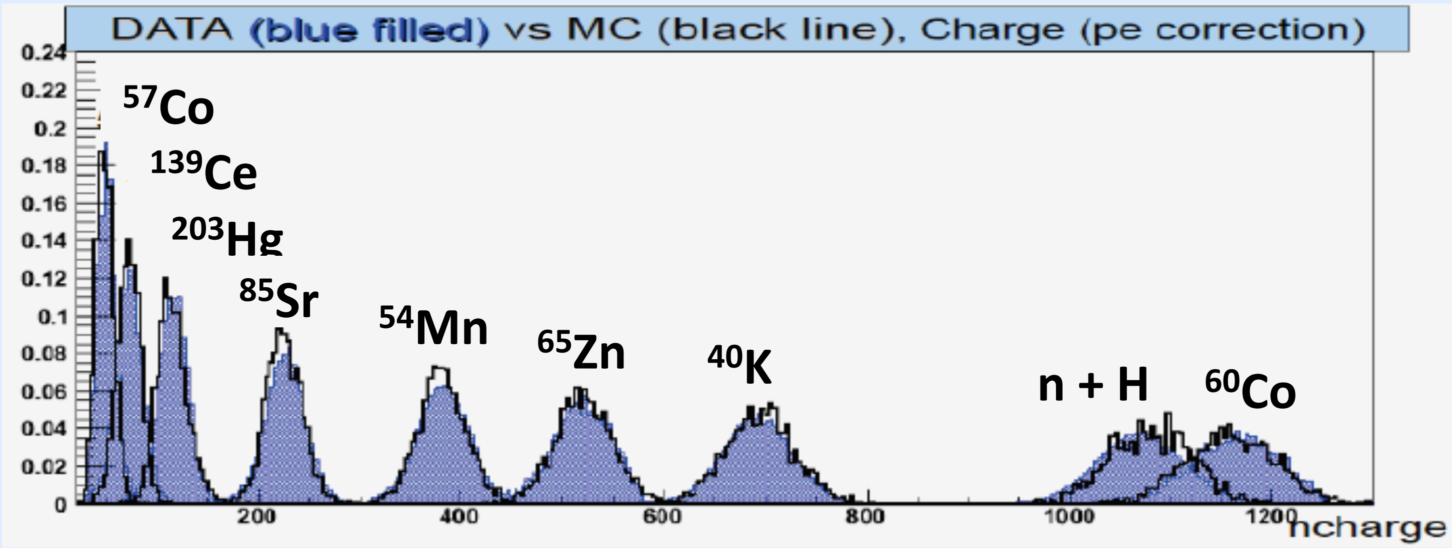
detector calibrations





- position known with ~2 cm accuracy with 7 CCD cameras mounted on the steel sphere
- external γ source deployed in water tank ('10)

position and energy calibration



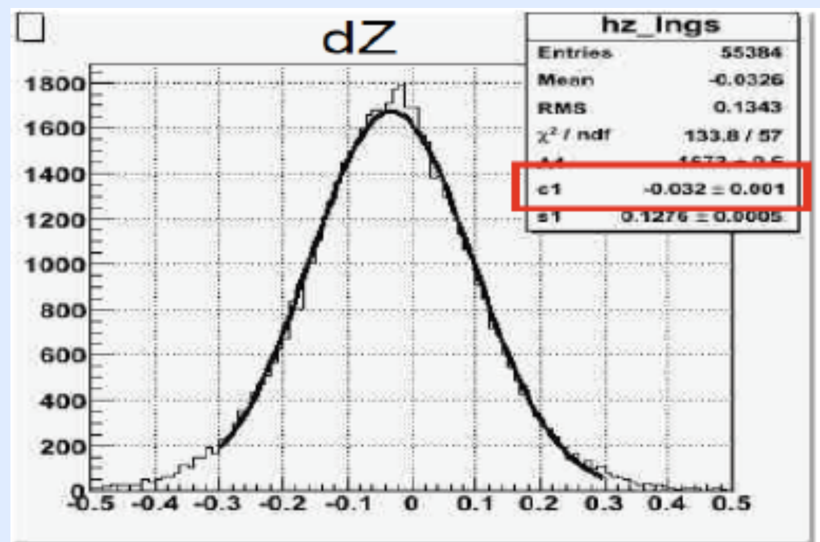
Study light yield, quenching, position variation.

→ *Data-MC mean light yields agree to 1% in F.V.*

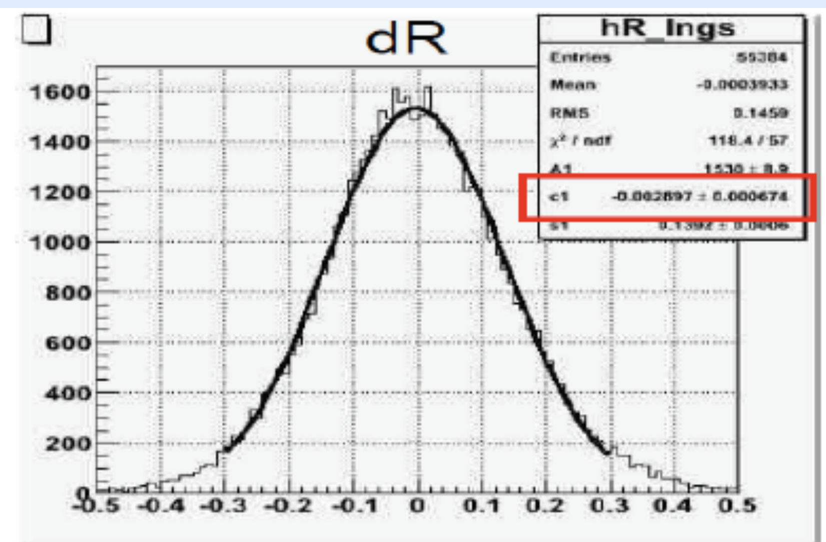
Measure position resolution: 10 – 12 cm

→ *Fiducial Volume:*

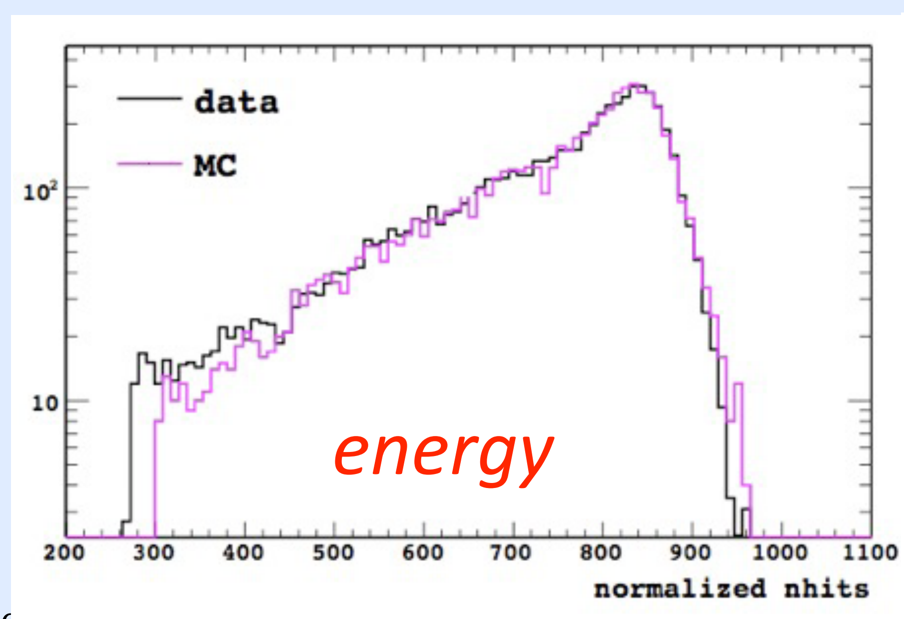
$1.0^{+0.005}_{-0.013}$

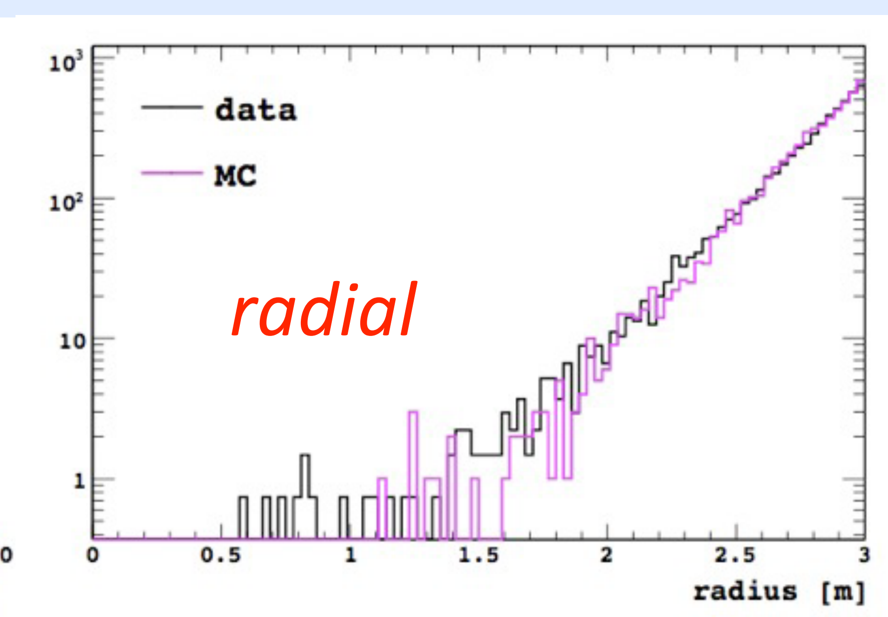


$Z_{rec} - Z_{ccd}$ (m)



$R_{rec} - R_{ccd}$ (m)

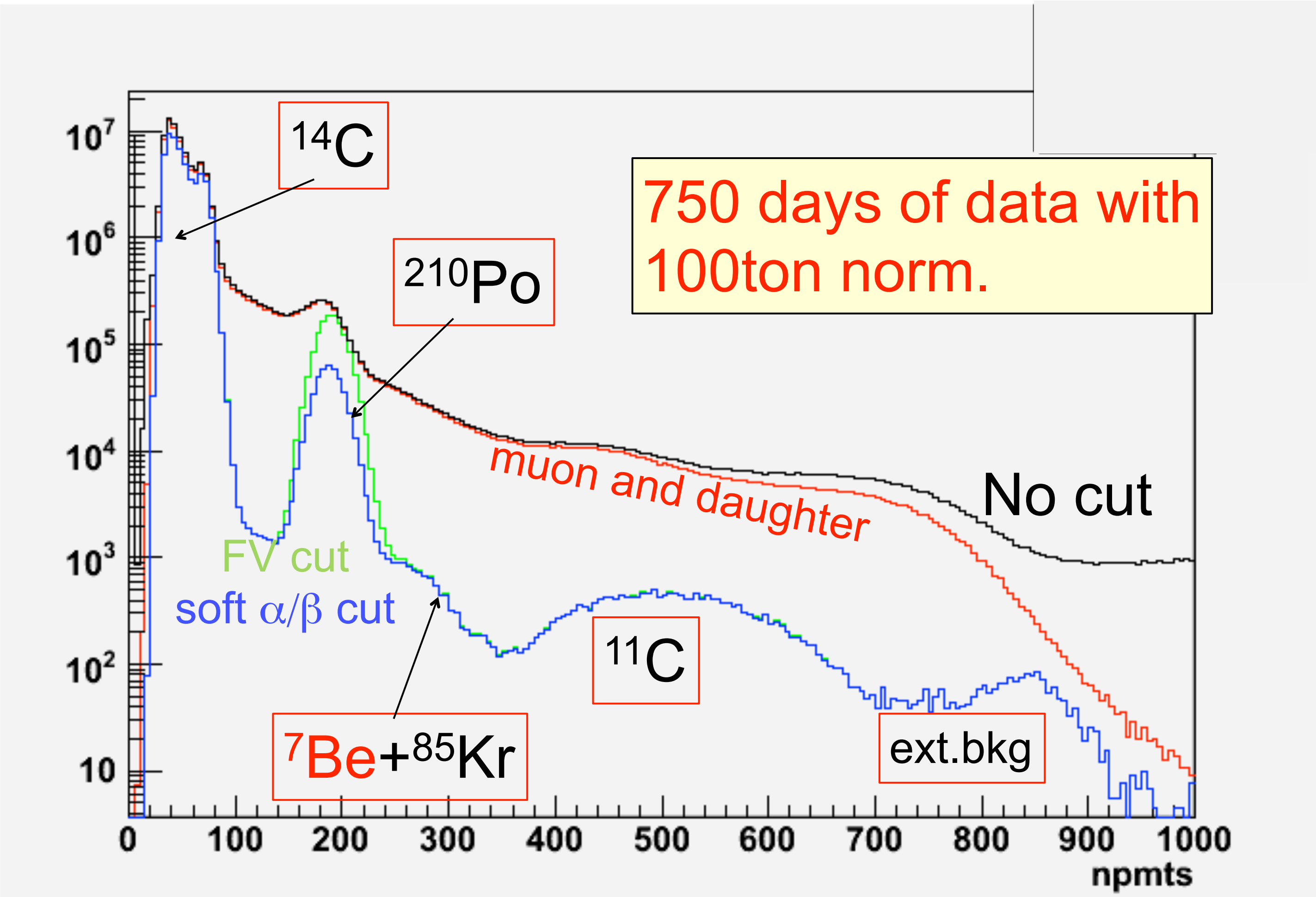


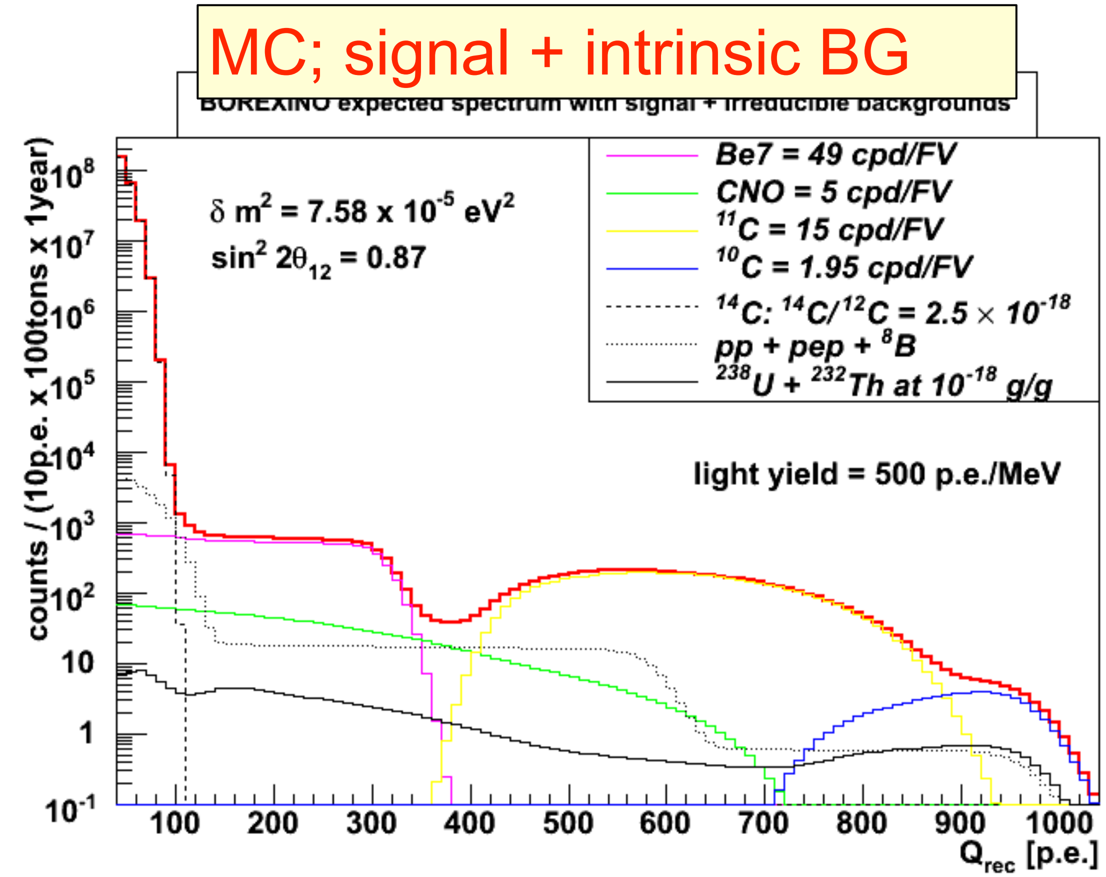


Confirm energy/radial PDF for external bg with high intensity Th-228 source

(arXiv 1110.1217)

data reduction and signal extraction





- A spectral fit is applied including the following signal + all intrinsic background components.
  - ^{7}Be, ^{85}Kr, ^{14}C, ^{11}C
  - ^{210}Bi (very similar to CNO in this limited energy region)
  - pp, pep, ^{8}B, and CNO neutrinos fixed at SSM-LMA value
- Fit with and without statistical subtraction of ^{210}Po events, based on α/β pulse shape discrimination.
- Two independent methods (MC based and analytical) were applied.

^{7}Be solar neutrino flux in Borexino

First measurement: 192 days **[PRL 101 091302 (2008)]**

Rate $_{7Be}$ = 49 ± 3(stat) ± 4 (sys) events/day/100 ton

New results **[PRL 107 141302 (2011)]**

Rate $_{7Be}$ = 46 ± 1.5 (stat) $^{+1.5}_{-1.6}$ (sys) events/ day / 100 ton

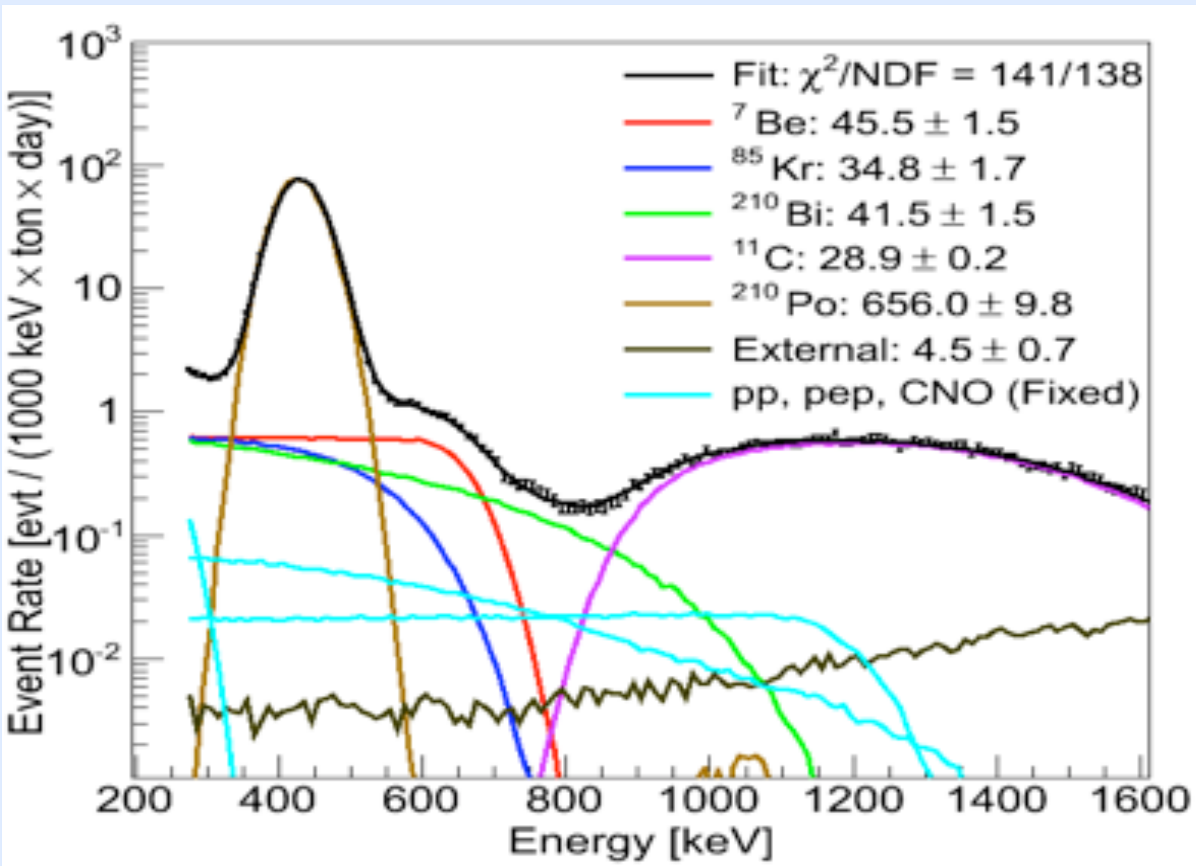
➡ Increased statistics (about x4 times)

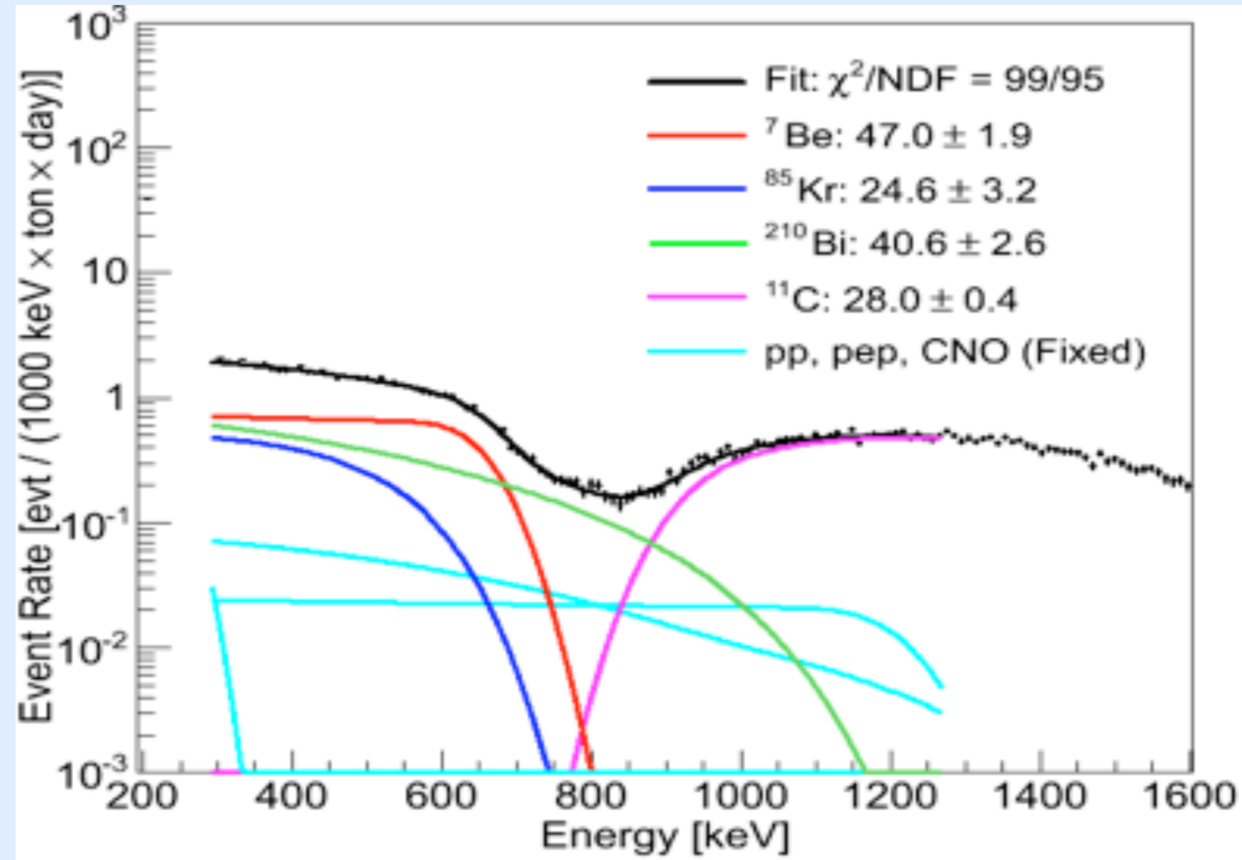
➡ Lower systematic errors (calibration campaign)

➡ <5% total uncertainty

Scenario	Expected rate (events / day / 100 ton)
No oscillations	74 ± 5 rejected at 5 σ
BPS07(GS98) - High metallicity	48 ± 4
BPS07(AGS05) - Low metallicity	44 ± 4

spectral fits





- Different fits:
  - with and without alpha subtraction
  - Monte Carlo vs analytical
  - energy scale and resolution
- removed muons, Radon delayed coincidences
- ^{210}Bi, ^{85}Kr, ^{11}C are free parameters
- *pp*, *pep*, CNO rates fixed

^{7}Be ν	46.0 ± 1.5 (stat) $^{+1.5}_{-1.6}$ (sys)
^{85}Kr	31.2 ± 1.7 (stat) ± 4.7 (sys)
^{210}Bi	41.0 ± 1.5 (stat) ± 2.3 (sys)
^{11}C	28.5 ± 0.2 (stat) ± 0.7 (sys)

Borexino systematics

First measurement: 192 days
[PRL 101 (2008) 091302]

Source	Uncertainty (%)
Total scintillator mass	0.2
Fiducial mass ratio	6.0
Live Time	0.1
Detector response function	6.0
Cuts efficiency	0.3
Total Systematic Error	8.5

New results
[PRL 107 141302 (2011)]

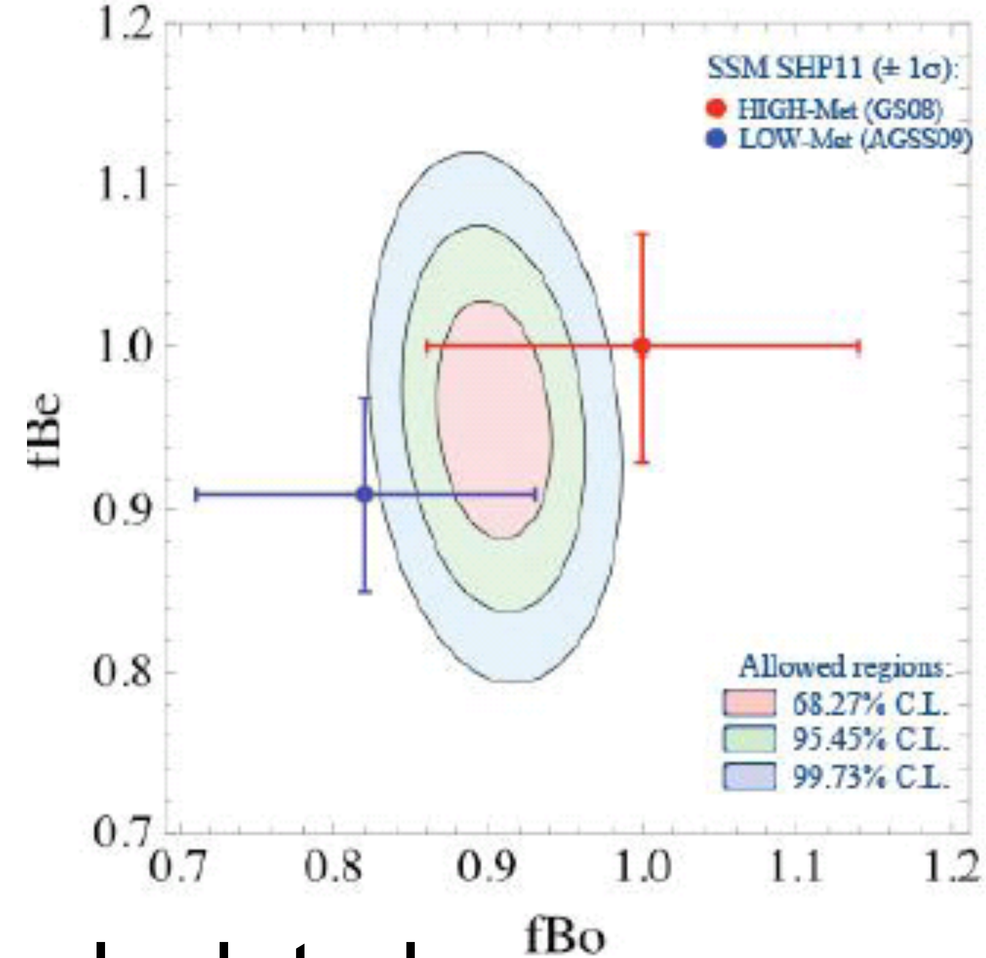
Source	Uncertainty (%)
Scintillator density	0.05
Fiducial volume	+0.5 -1.3
Live Time	0.04
Optical response	2.7
Cuts efficiency	0.1
Fit methods	2.0
Trigger efficiency, stability	<0.1
Total Systematic Error	+3.4 -3.6

Implication on solar physics

- Metallicity controversy

  Fit to the available all solar neutrino data leaving free f_{Be} and f_B ($f = \Phi/\Phi(SSM)$)

  Hard to discriminate



- Other solar neutrino sources

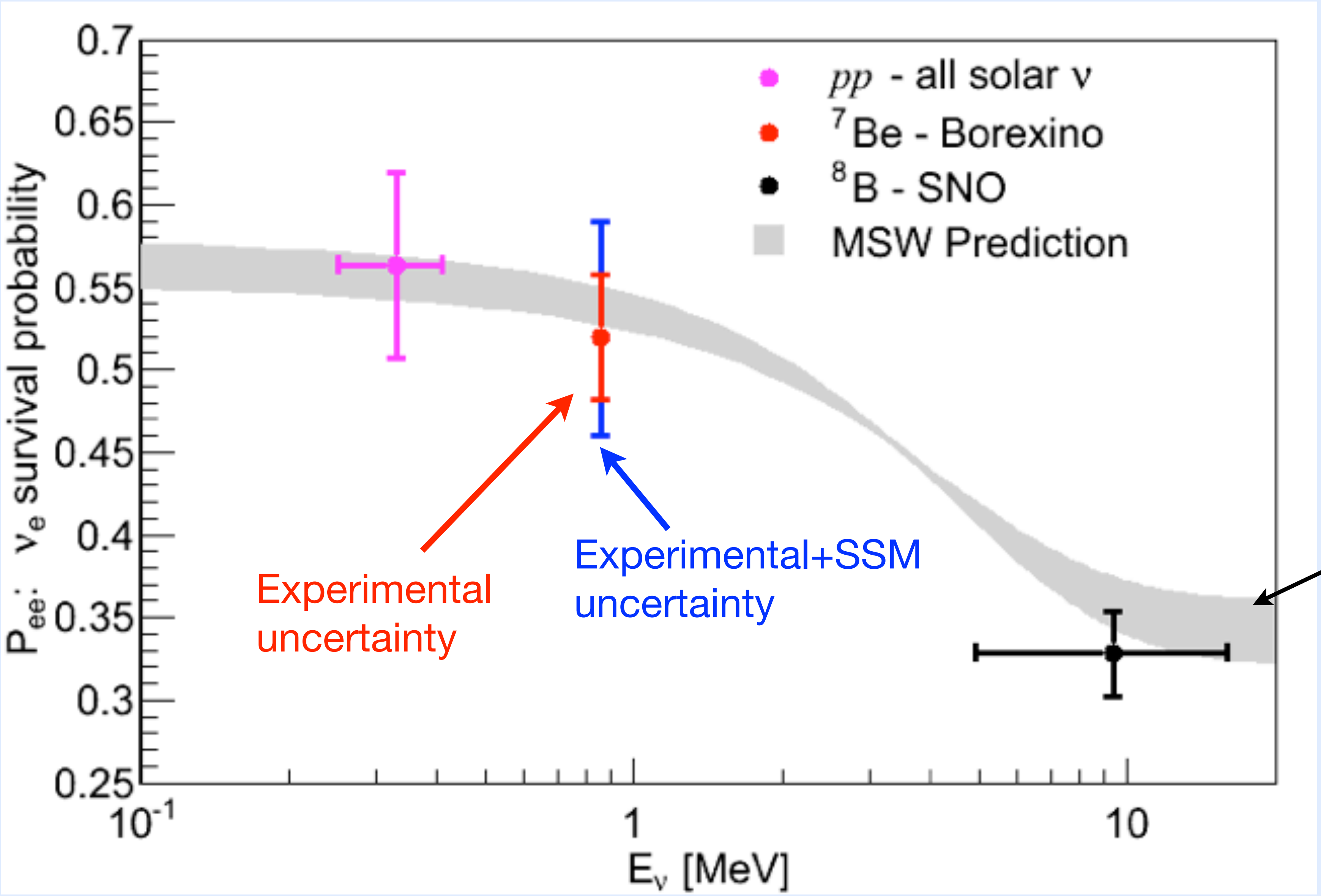
  Each solar neutrino flux can be calculated with solar luminosity constraint.

M.C.Gonzalez-Garcia, M.Martoni, J.Salvado
JHEP 05(2010)072 / 0910.4584

$\Phi_{pp} = (6.06\,^{+0.02}_{-0.06})\times10^{10}cm^{-2}s^{-1}$ ($f_{pp} = 1.013$)

$\Phi_{CNO} < 1.3\times10^{9}cm^{-2}s^{-1}$ ($f_{CNO} < 2.5$) at 95%C.L.

P_{ee} survival probability (862 keV)



$$P_{ee} = 0.51 \pm 0.07$$

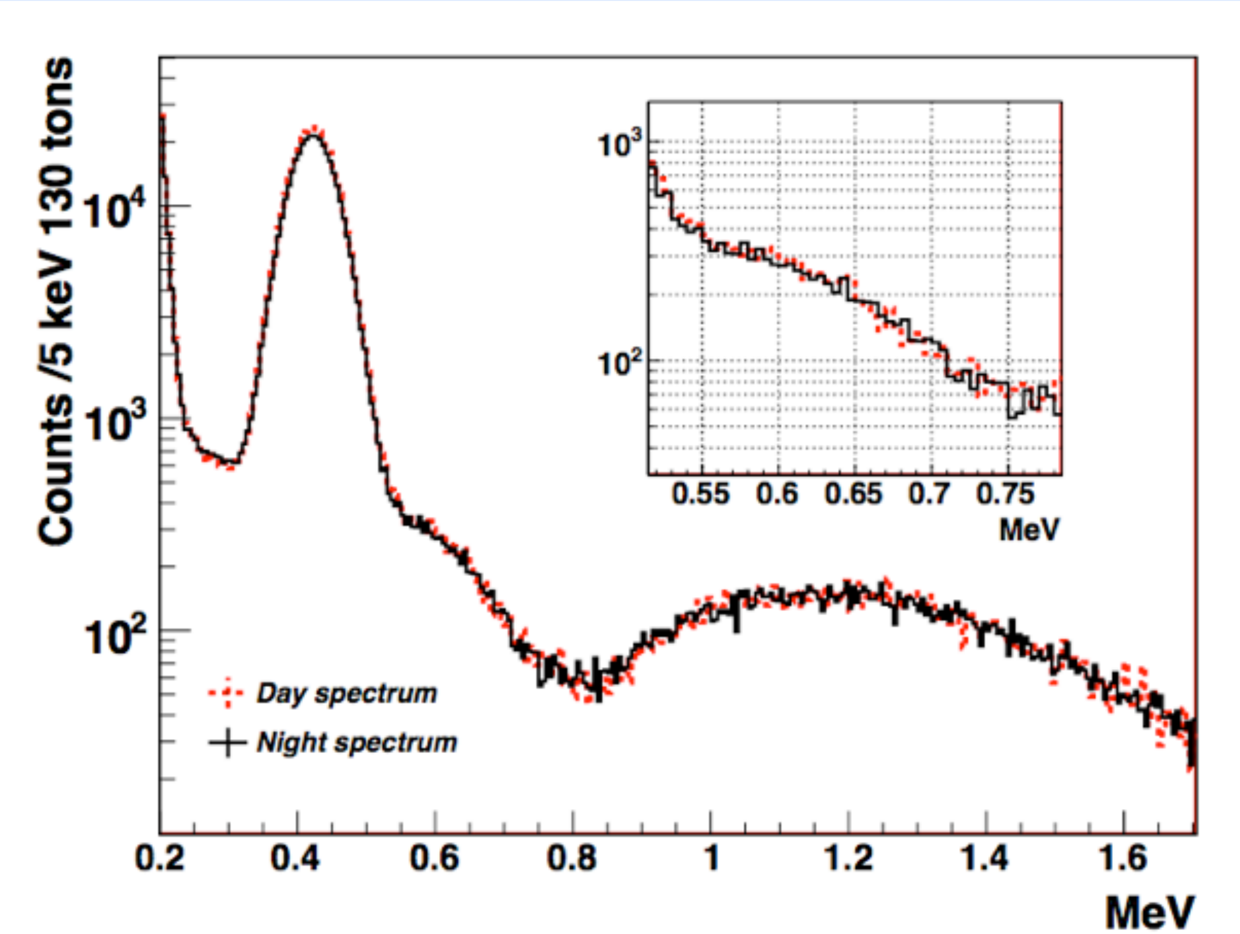
MSW-LMA with 1σ range of mixing parameters

un-oscillated 862 keV ν_e flux: $(2.78 \pm 0.13) \times 10^9\ cm^{-2}s^{-1}$ [$(3.10 \pm 0.15) \times 10^9\ cm^{-2}s^{-1}$ total]

with the MSW-LMA solution, the absolute ^{7}Be ν_e flux is: $(4.84 \pm 0.24) \times 10^9\ cm^{-2}s^{-1}$

Ratio of the Borexino measurement to the SSM prediction is $f_{Be} = 0.97 \pm 0.09$

no day/night effect

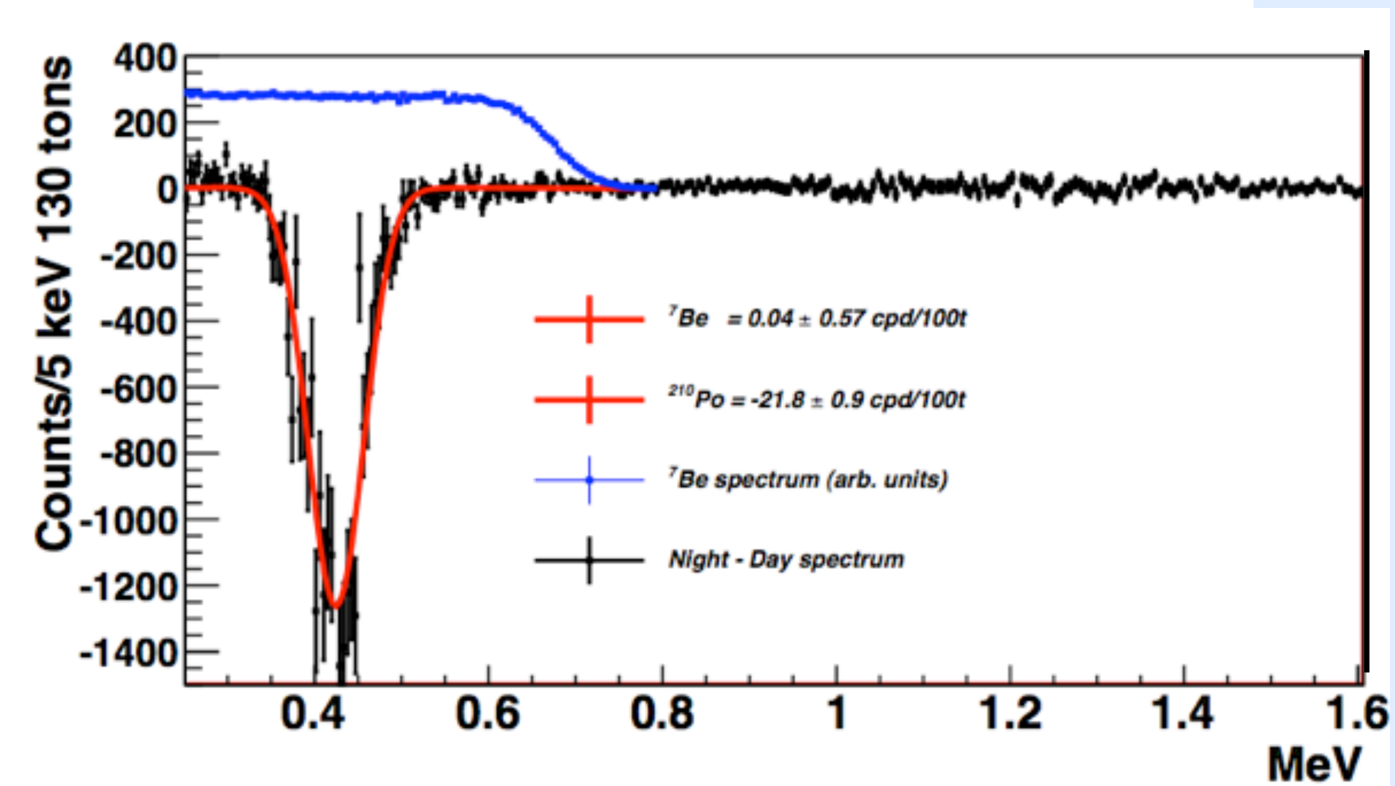


matter effects of neutrinos crossing the earth could enhance the night rate by regeneration of electron neutrinos

$$A_{dn} = 2\,\frac{R_N - R_D}{R_N + R_D}$$

depends on:
oscillation parameters and neutrino energy

Source	A_{dn} error
Live-time	< 5 x 10^{-4}
Cut efficiency	0.001
^{210}Bi time variation	± 0.005
Fit procedure	± 0.005
Sys error	0.007



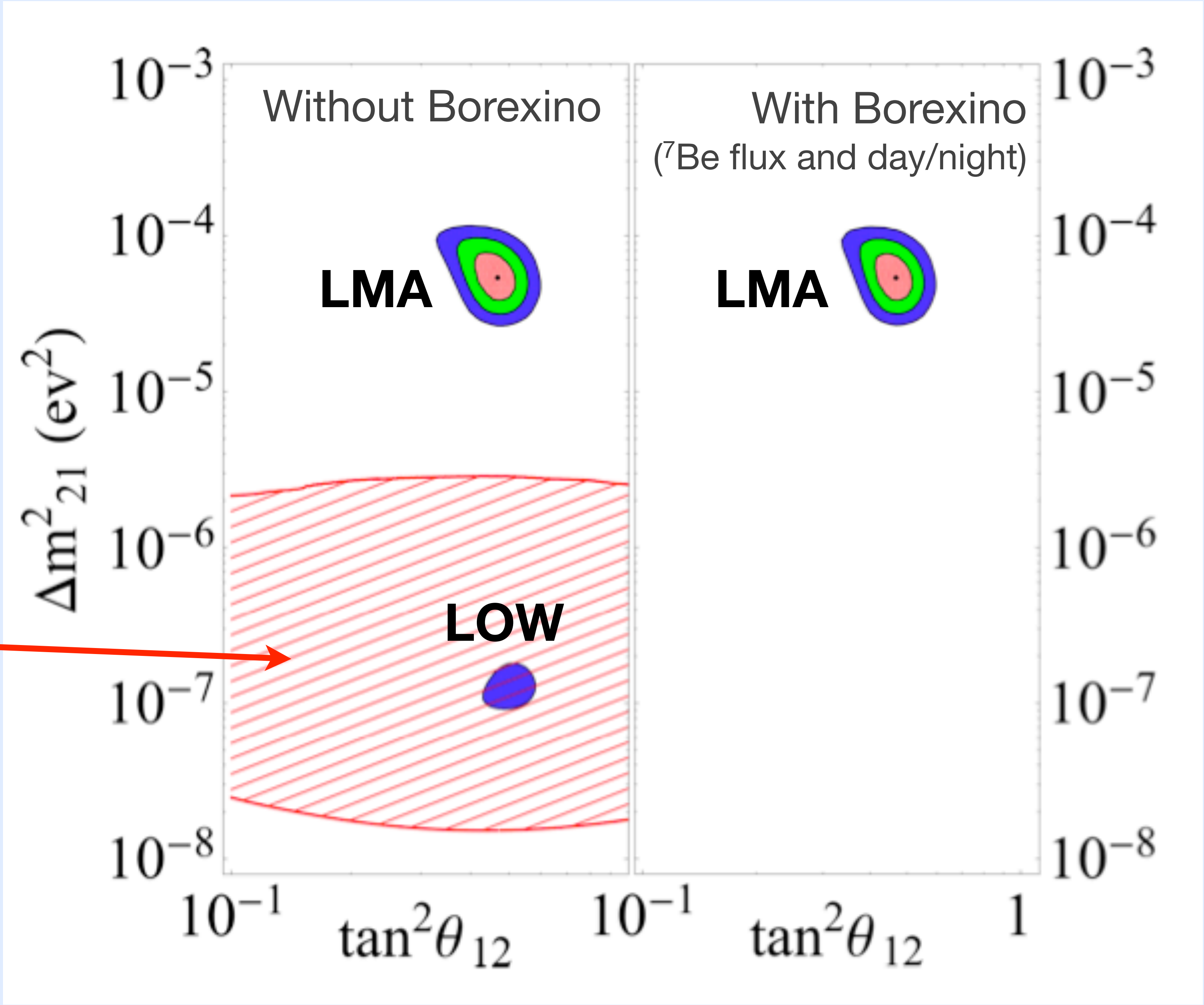
$$A_{dn} = 0.001 \pm 0.012\ (stat) \pm 0.007\ (syst)$$

effect on neutrino oscillations

MSW	A_{dn}
LMA	~ 0%
LOW	23 ± 11%

Best fit:
$\Delta m^2 = 5.3 \times 10^{-5}\ eV^2$
$\tan^2\theta = 0.46$

Excluded by Day/Night 99.73% CL



LOW is excluded at > 8.5 σ

^{8}B solar neutrinos at low threshold

$$R(^{8}B) = 0.22 \pm 0.04\ (stat) \pm 0.01\ (syst)\ \ \text{cpd}/100\ t$$

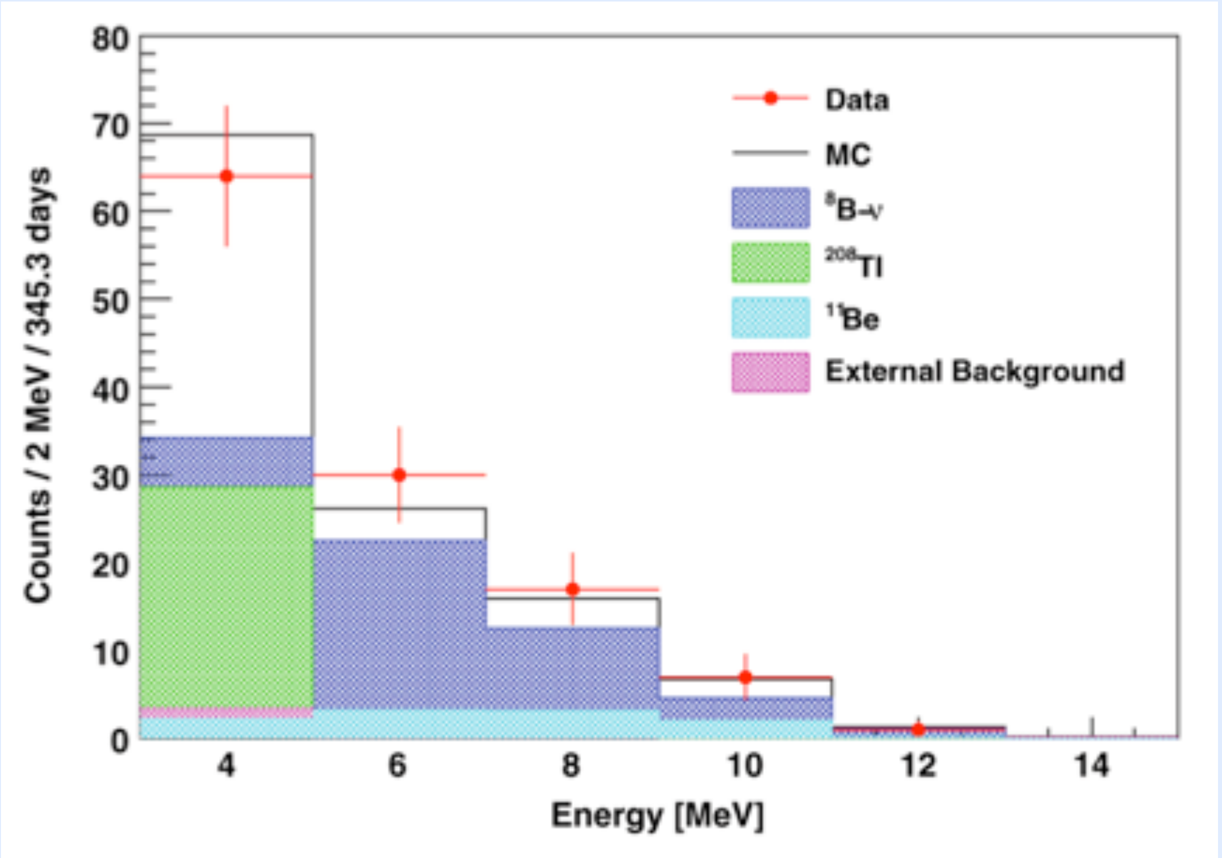
First measurement of P_{ee} in vacuum (^{7}Be ν) and matter-enhanced regime (^{8}B ν) in the same detector

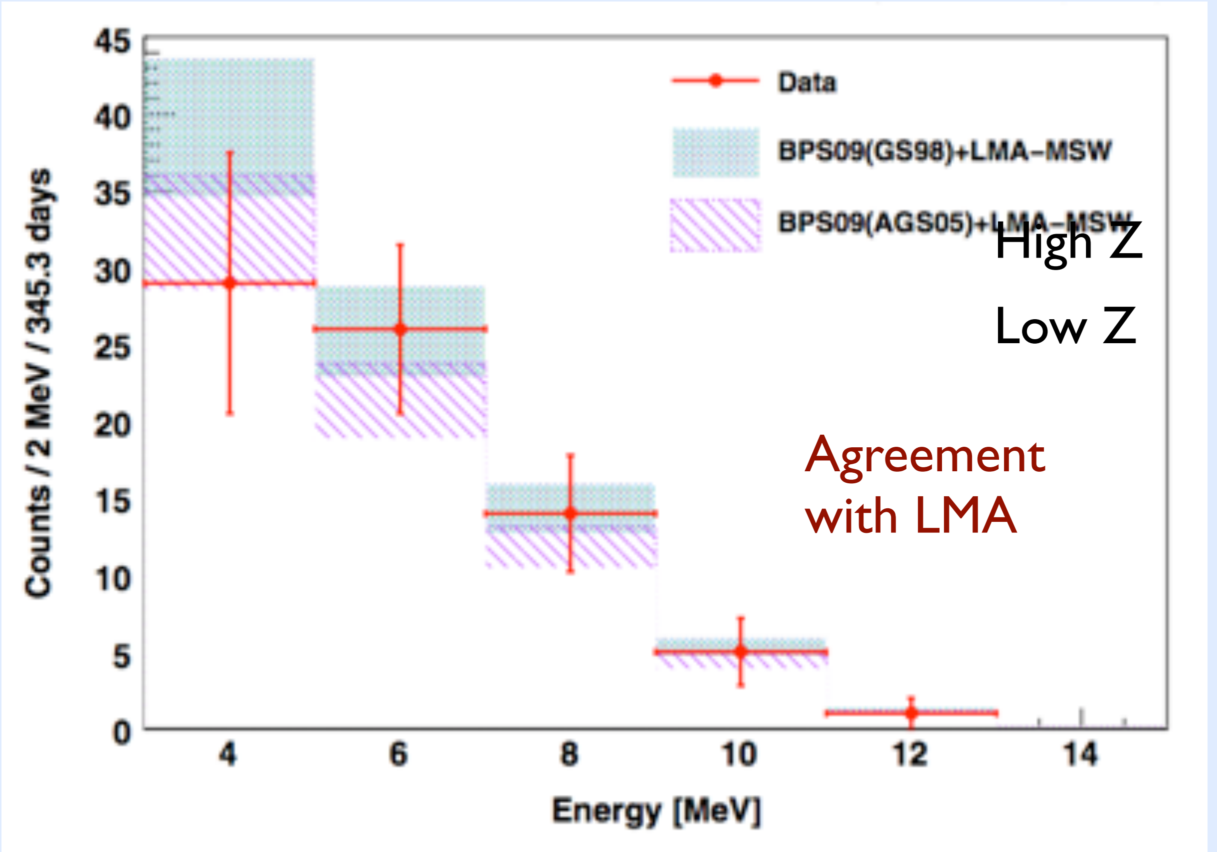
$$P_{ee} = 0.29 \pm 0.10$$

TABLE IV. Systematic errors.

Source	$E > 3$ MeV σ_+	$E > 3$ MeV σ_-	$E > 5$ MeV σ_+	$E > 5$ MeV σ_-
Energy threshold	3.6%	3.2%	6.1%	4.8%
Fiducial mass	3.8%	3.8%	3.8%	3.8%
Energy resolution	0.0%	2.5%	0.0%	3.0%
Total	5.2%	5.6%	7.2%	6.8%

Phys Rev D 82, 0330006 (2010)



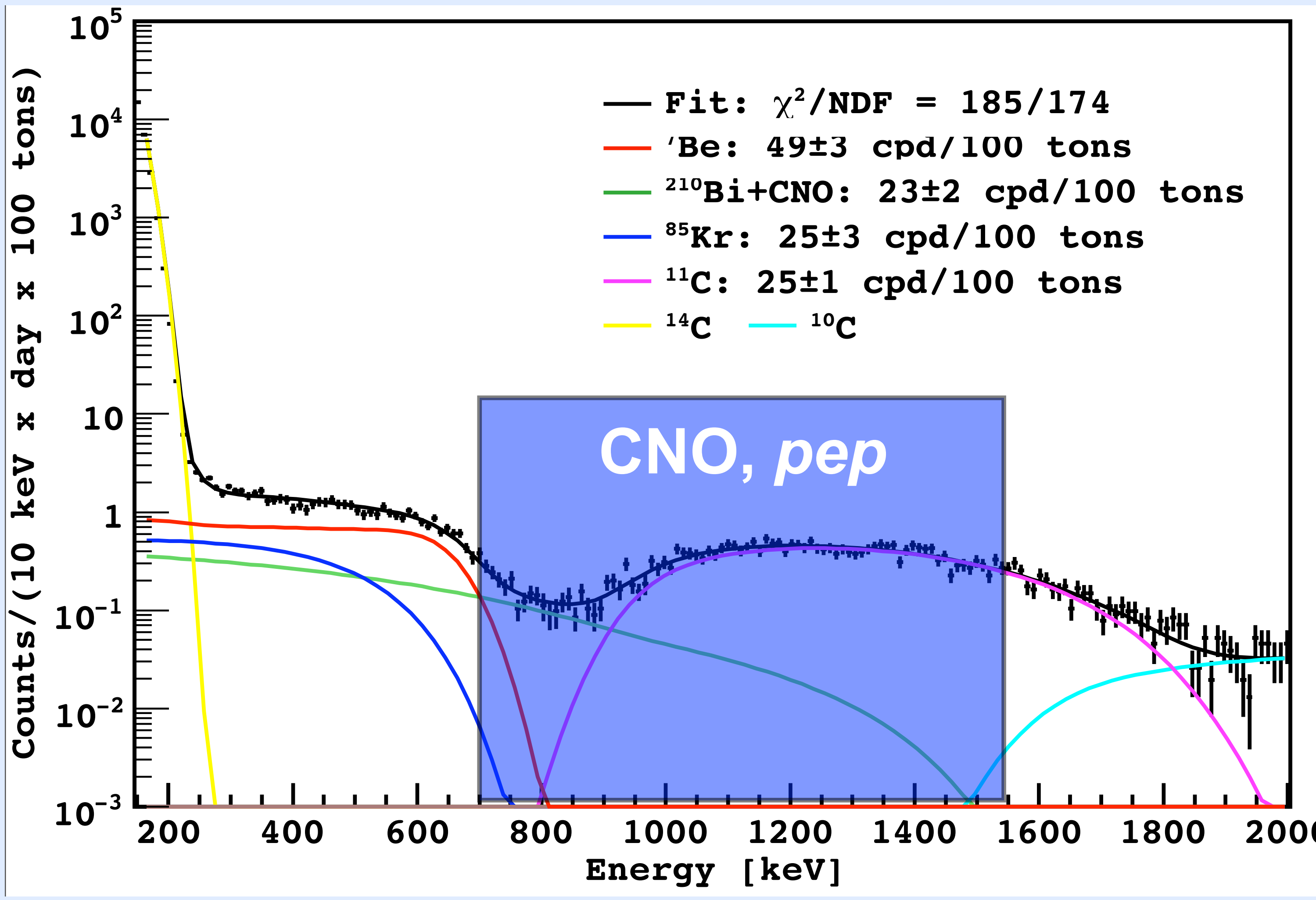


pep and CNO solar neutrinos ?

1. Scientifically desirable

+ *pep* rate is closely connected with *pp* rate (low energy, mostly obscured by ^{14}C), first fusion step in the sun

+ CNO flux has large theoretical uncertainty (30%) depending on unknown factors of the solar chemical composition (metallicity of the mantle)



2. Hard to detect

+ the expected *pep* and CNO solar neutrino rates are 5-10 times smaller than ^7Be, which obscures most of their spectrum

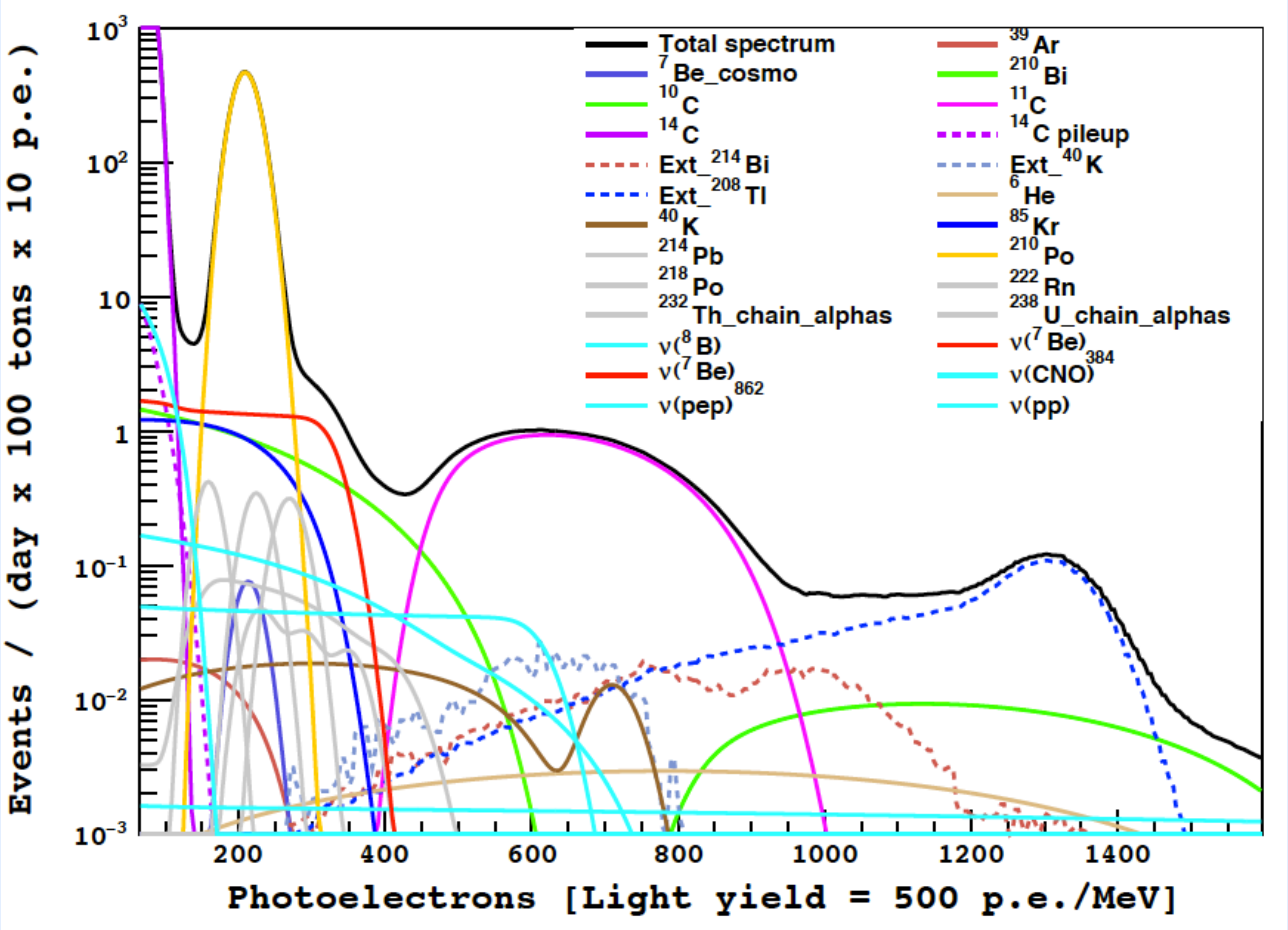
+ ^{210}Bi, ^{40}K and ^{208}Tl (^{232}Th) backgrounds

3. ^{11}C subtraction

+ when a muon produces a ^{11}C, simulations suggest that a free neutron is also emitted ~95% of the times, allowing for event-by-event subtraction

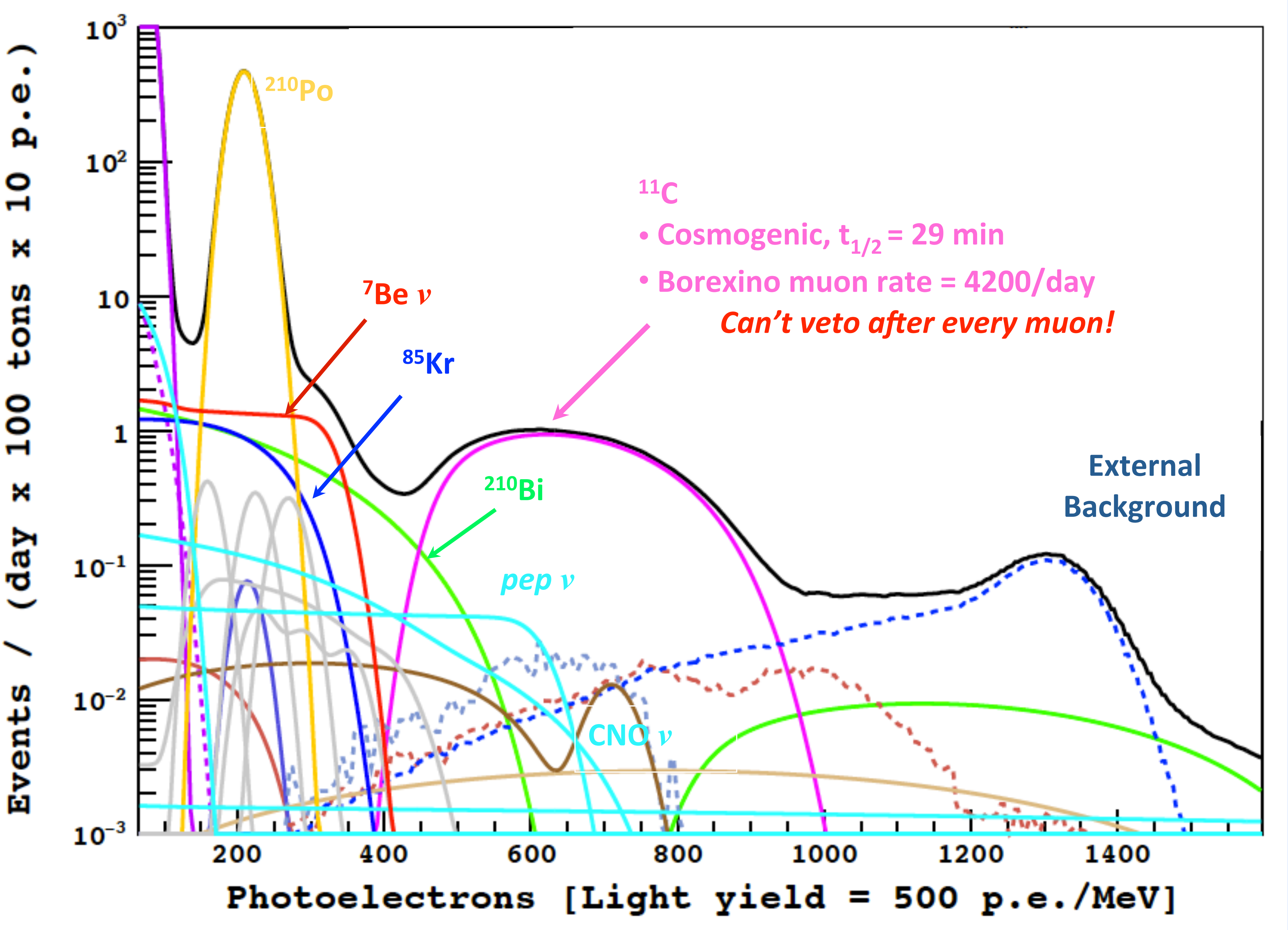
+ investigating statistical subtraction

pep and CNO neutrinos



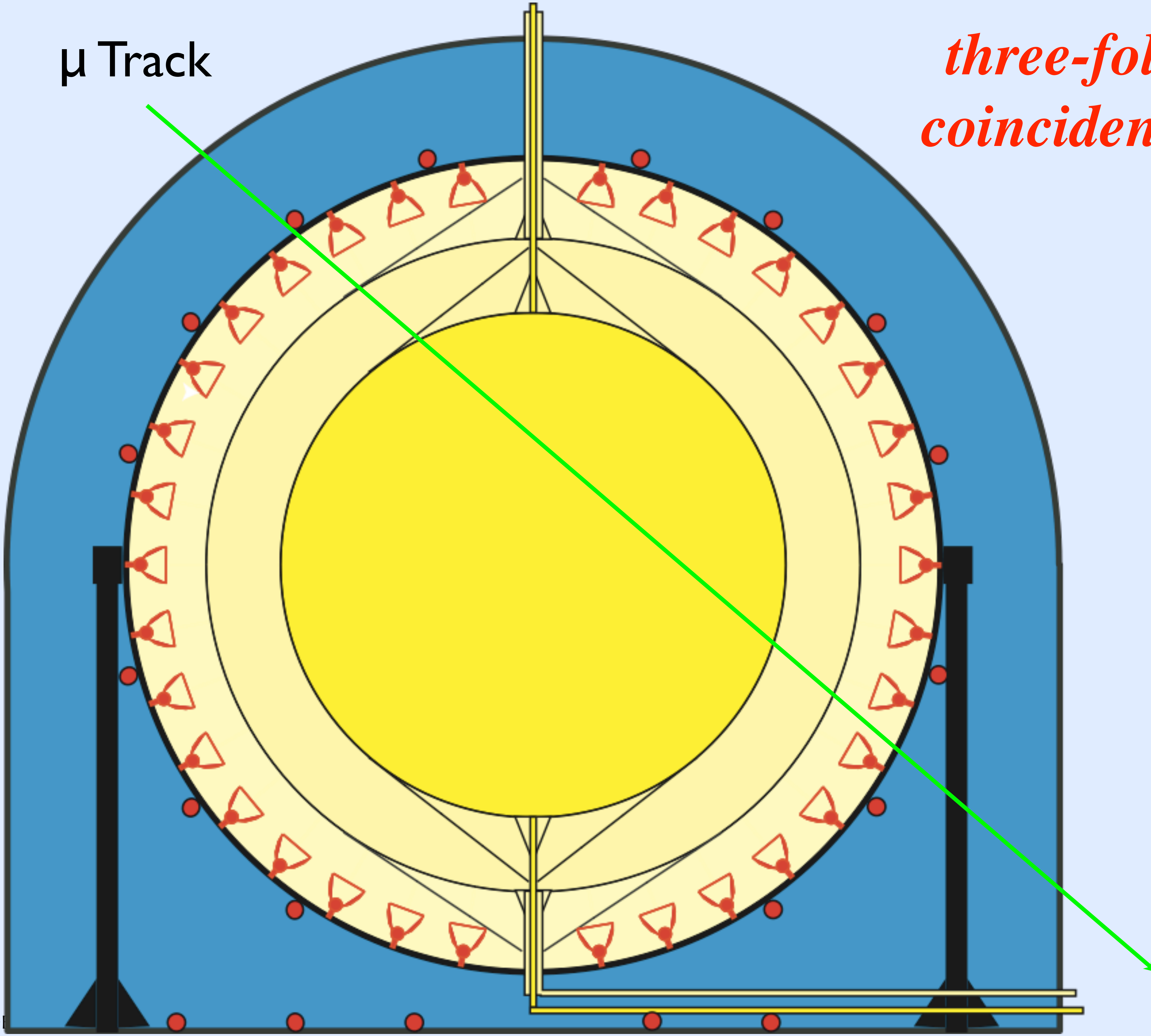
The 125 muon-neutron coincidences/day can be vetoed without excessive loss of live time by a 3-fold coincidence rejection

pep and CNO neutrinos

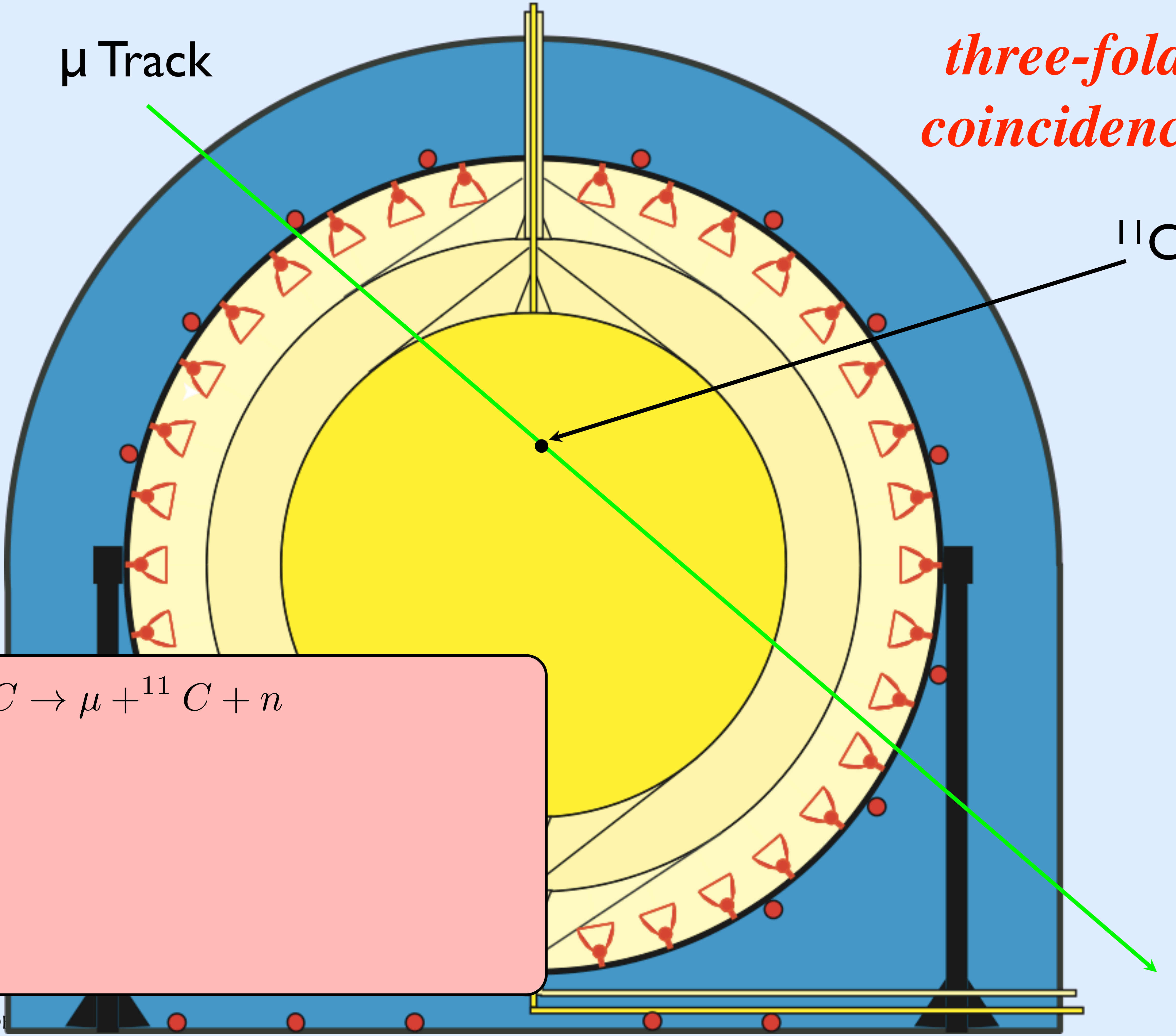


The 125 muon-neutron coincidences/day can be vetoed without excessive loss of live time by a 3-fold coincidence rejection

three-fold coincidence

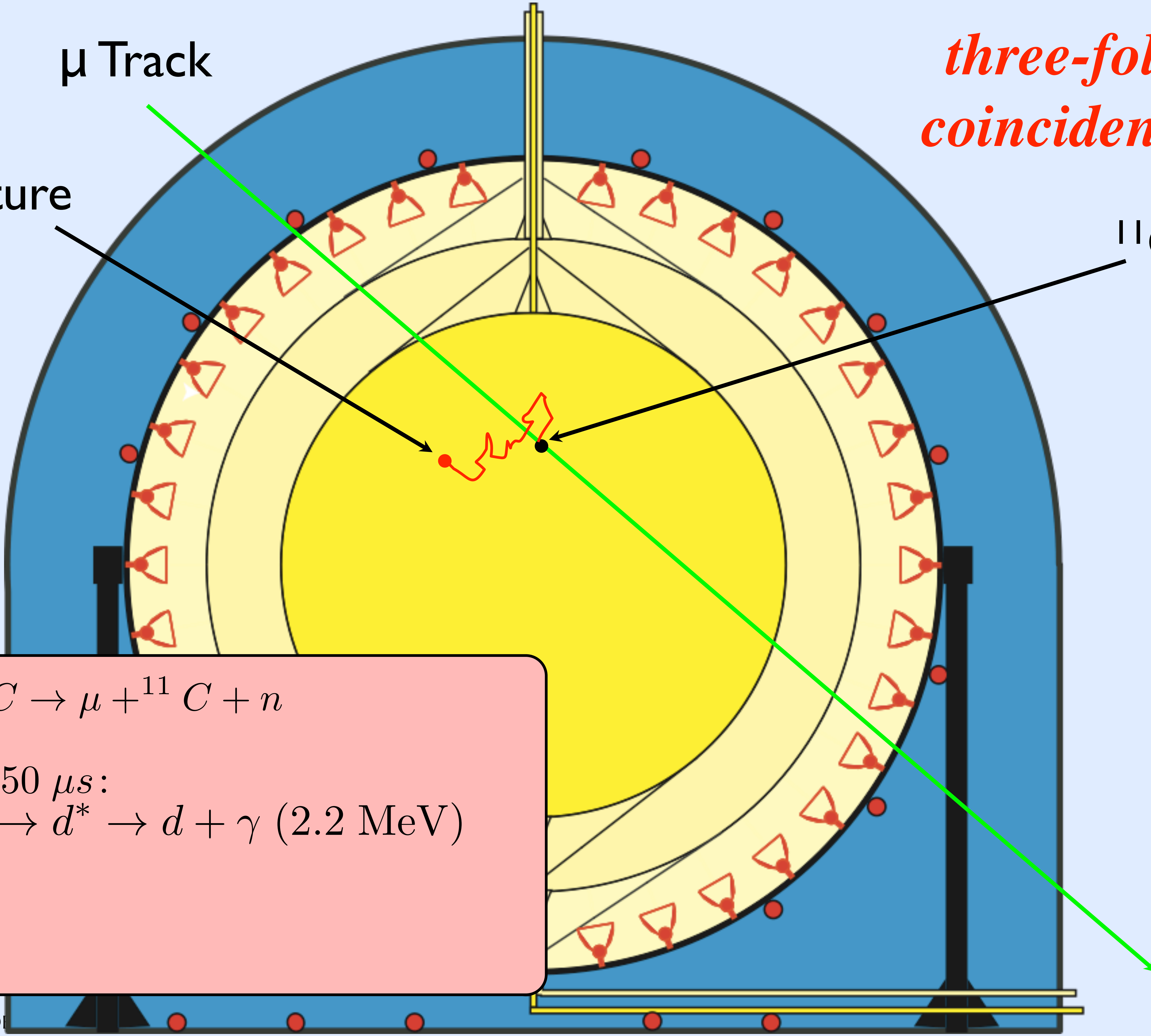


three-fold coincidence



$$\mu +^{12} C \rightarrow \mu +^{11} C + n$$

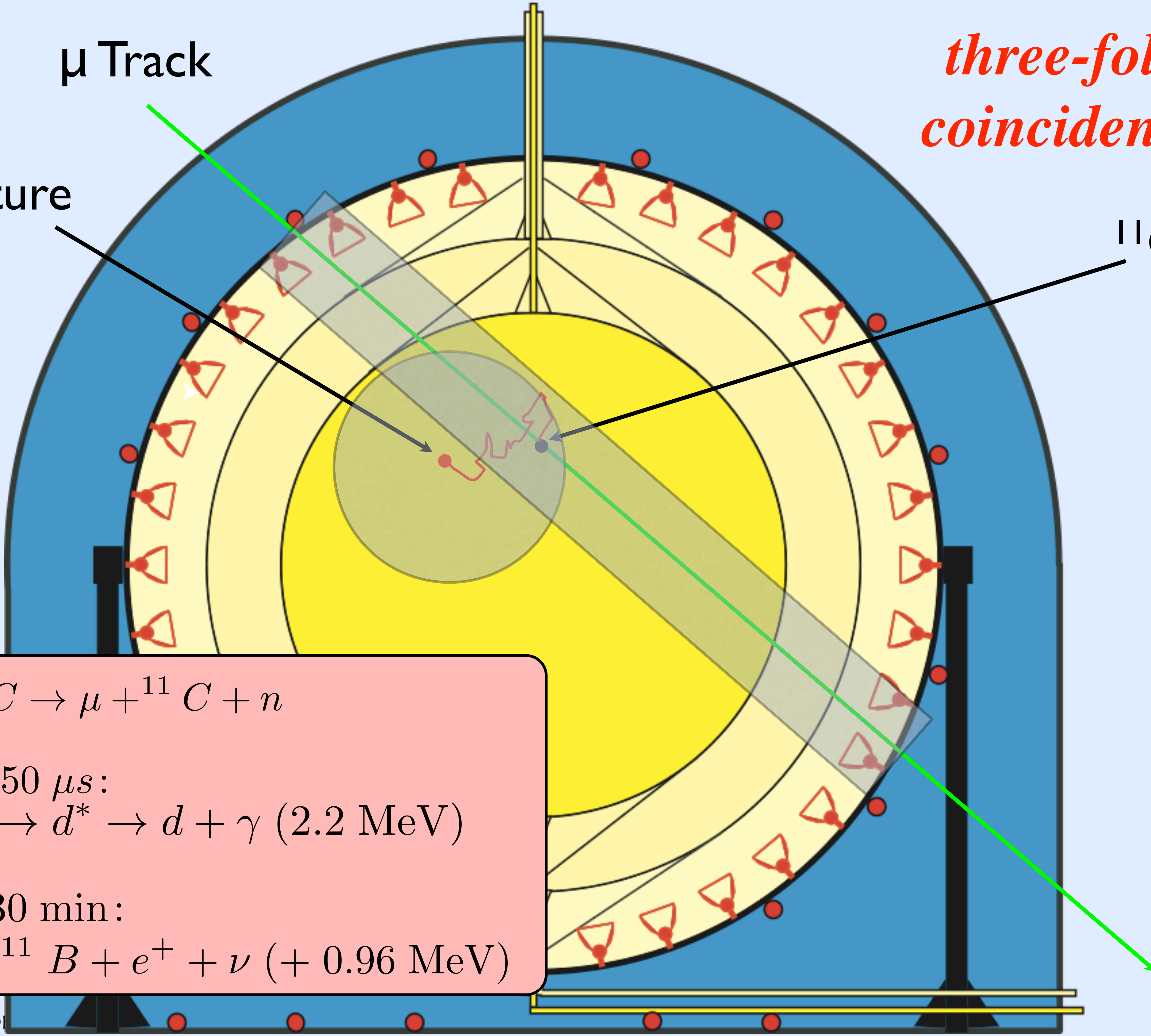
three-fold coincidence



$$\mu + ^{12}C \rightarrow \mu + ^{11}C + n$$

$$\Delta t \sim 250\ \mu s:$$
$$n + p \rightarrow d^* \rightarrow d + \gamma\ (2.2\ \mathrm{MeV})$$

three-fold coincidence

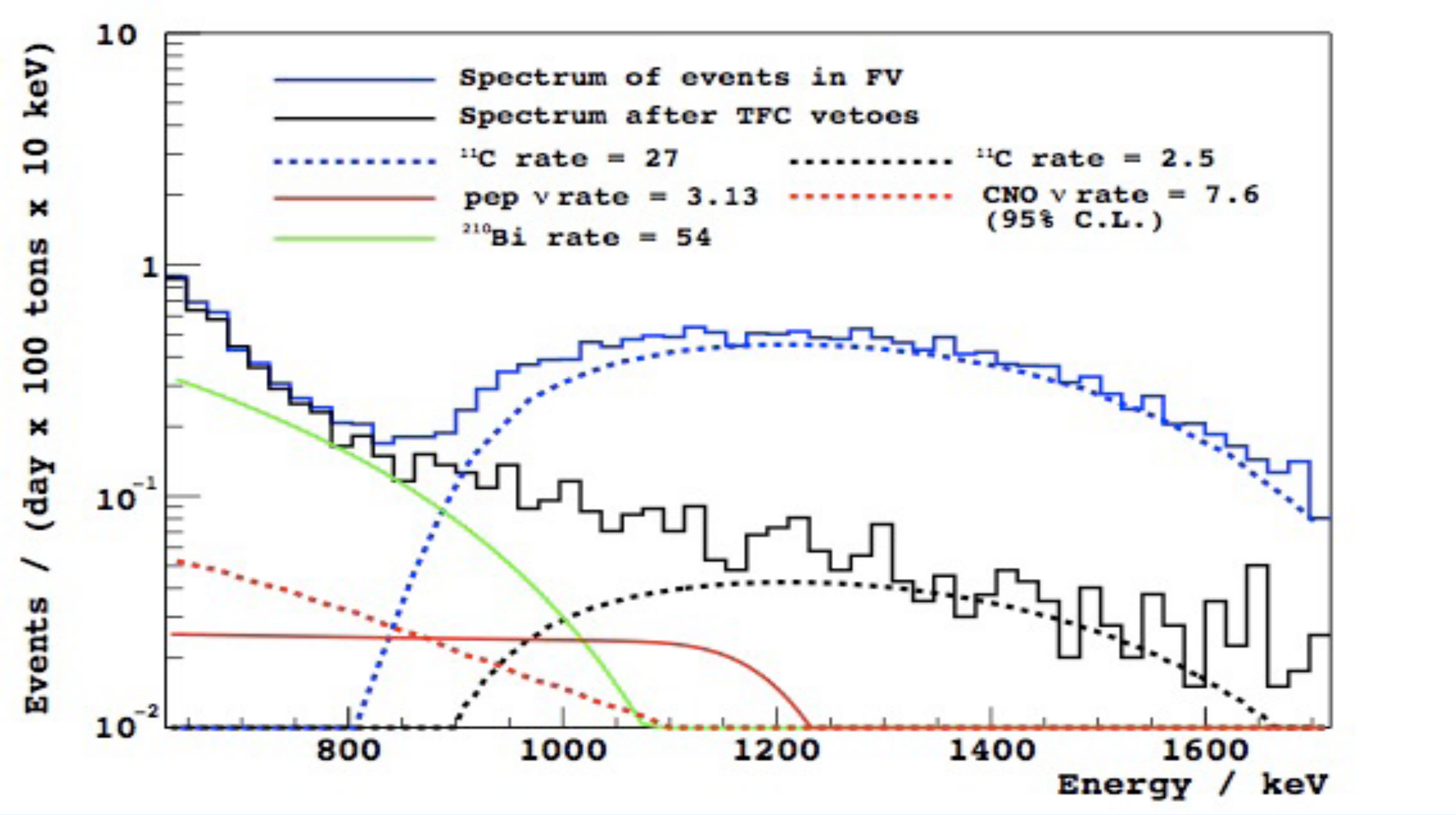


$$\mu +^{12} C \rightarrow \mu +^{11} C + n$$

$\Delta t \sim 250\ \mu s:$
$$n + p \rightarrow d^* \rightarrow d + \gamma\ (2.2\ \mathrm{MeV})$$

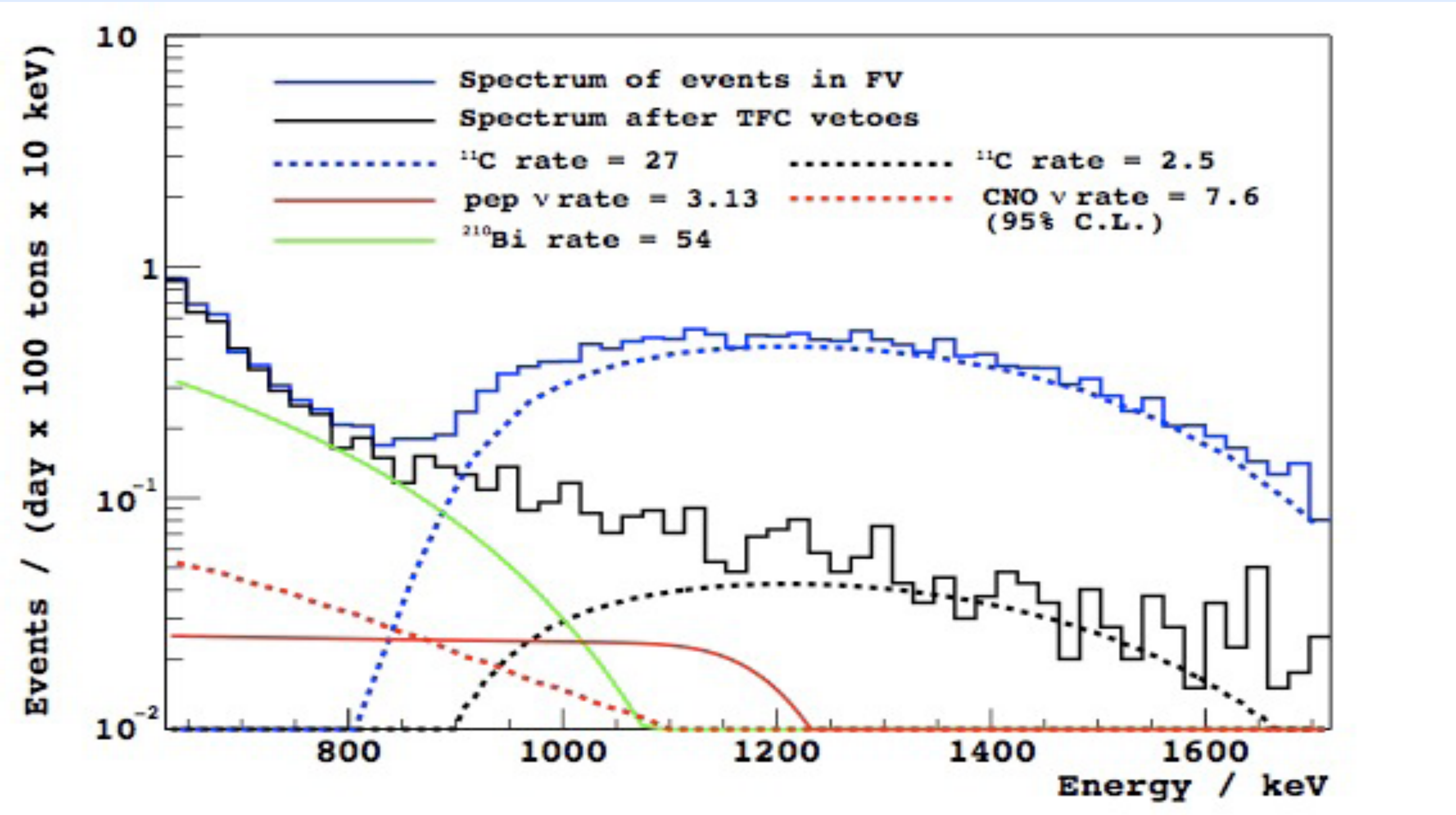
$\Delta t \sim 30\ \mathrm{min}:$
$$^{11}C \rightarrow^{11} B + e^+ + \nu\ (+\ 0.96\ \mathrm{MeV})$$

3-fold coincidence results (not only)

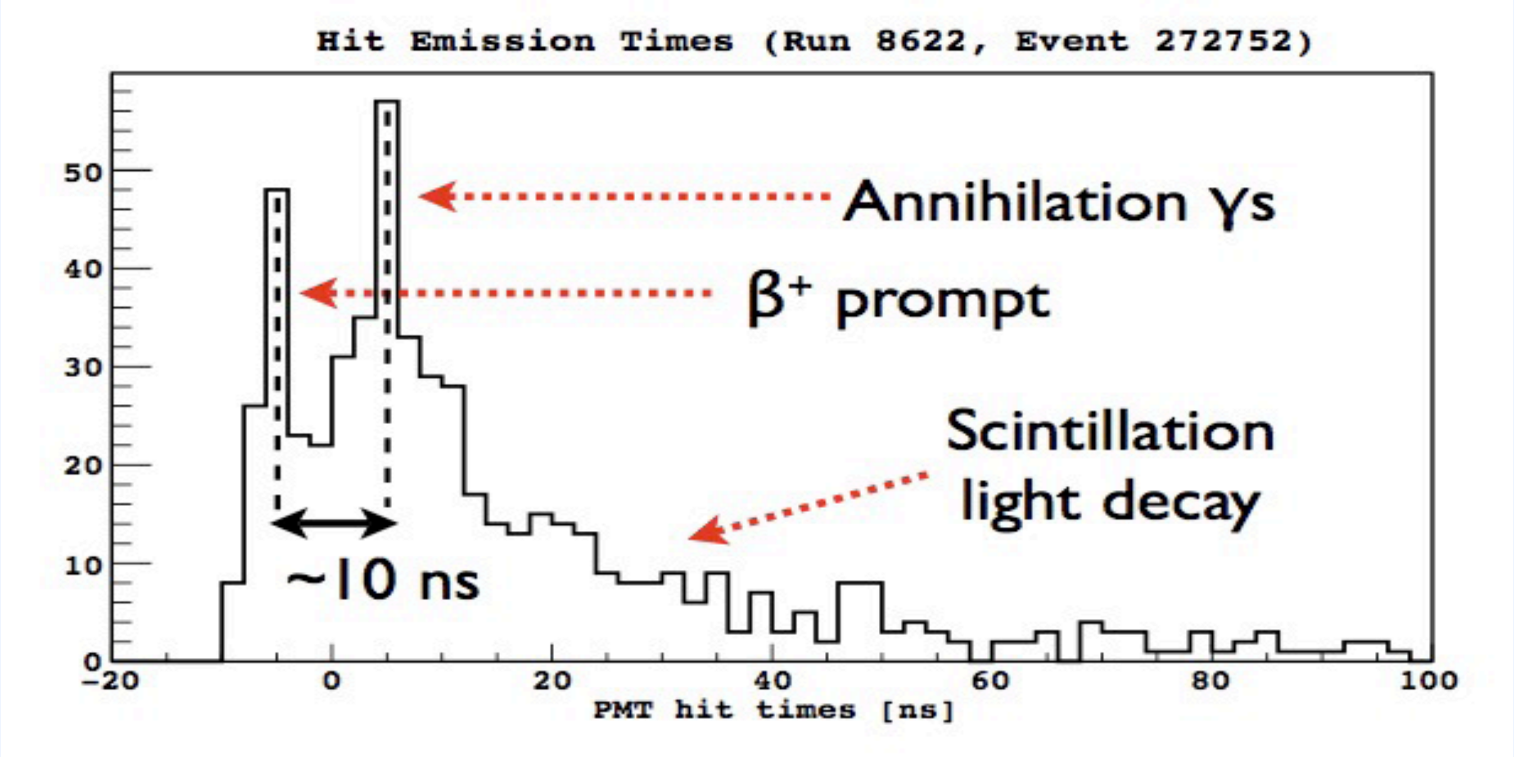


remove 91% of background
sacrificing 51.5% of live time

3-fold coincidence results (not only)



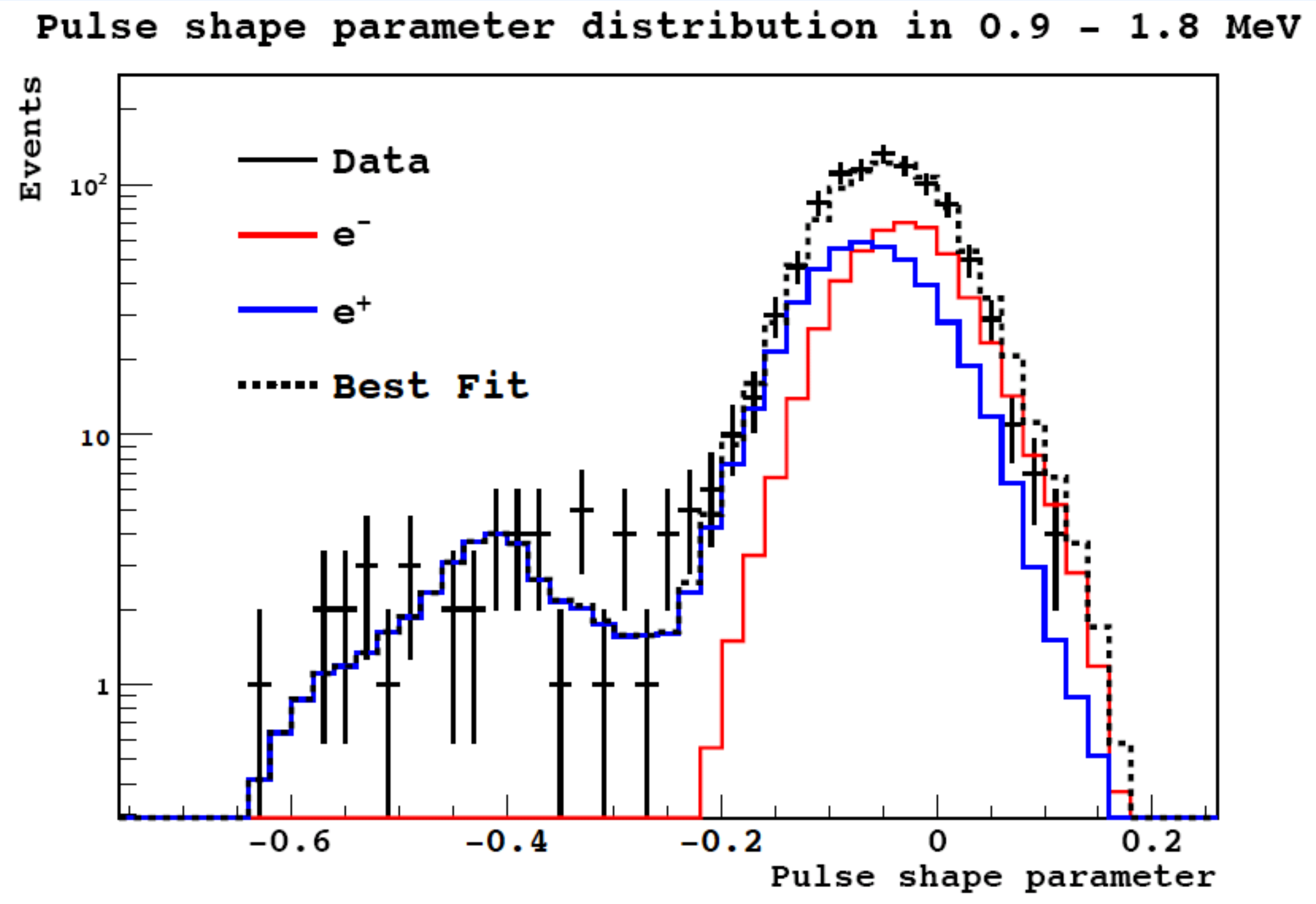
remove 91% of background sacrificing 51.5% of live time



50% of β^+ decays produce ortho-positronium ($t_{1/2}$=3 ns):

- time shift
- multi-site (gammas)
- ionization density profile

electron/positron pulse shape discrimination



use boosted decision tree (BDT) to optimize discrimination

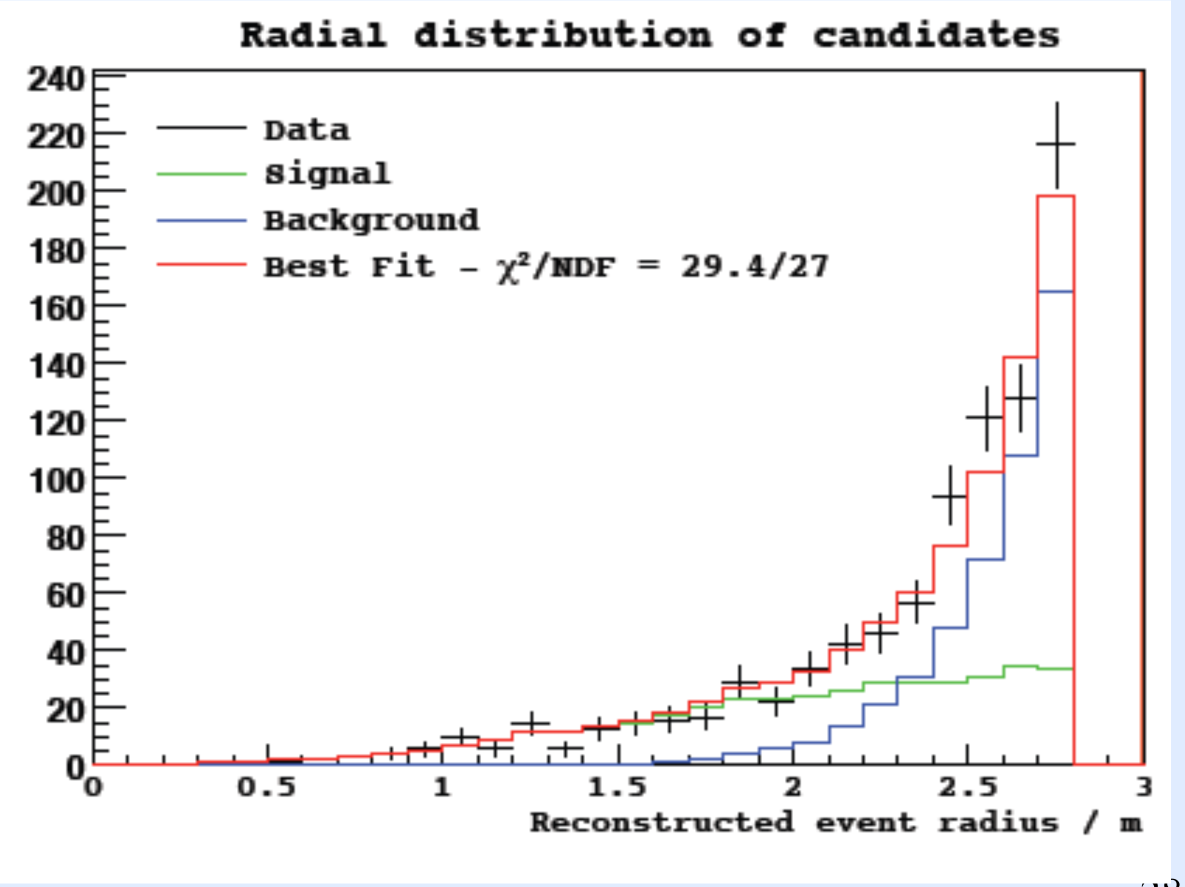
- train, test, build PDF with events selected by TFC

- include BDT variable in signal extraction

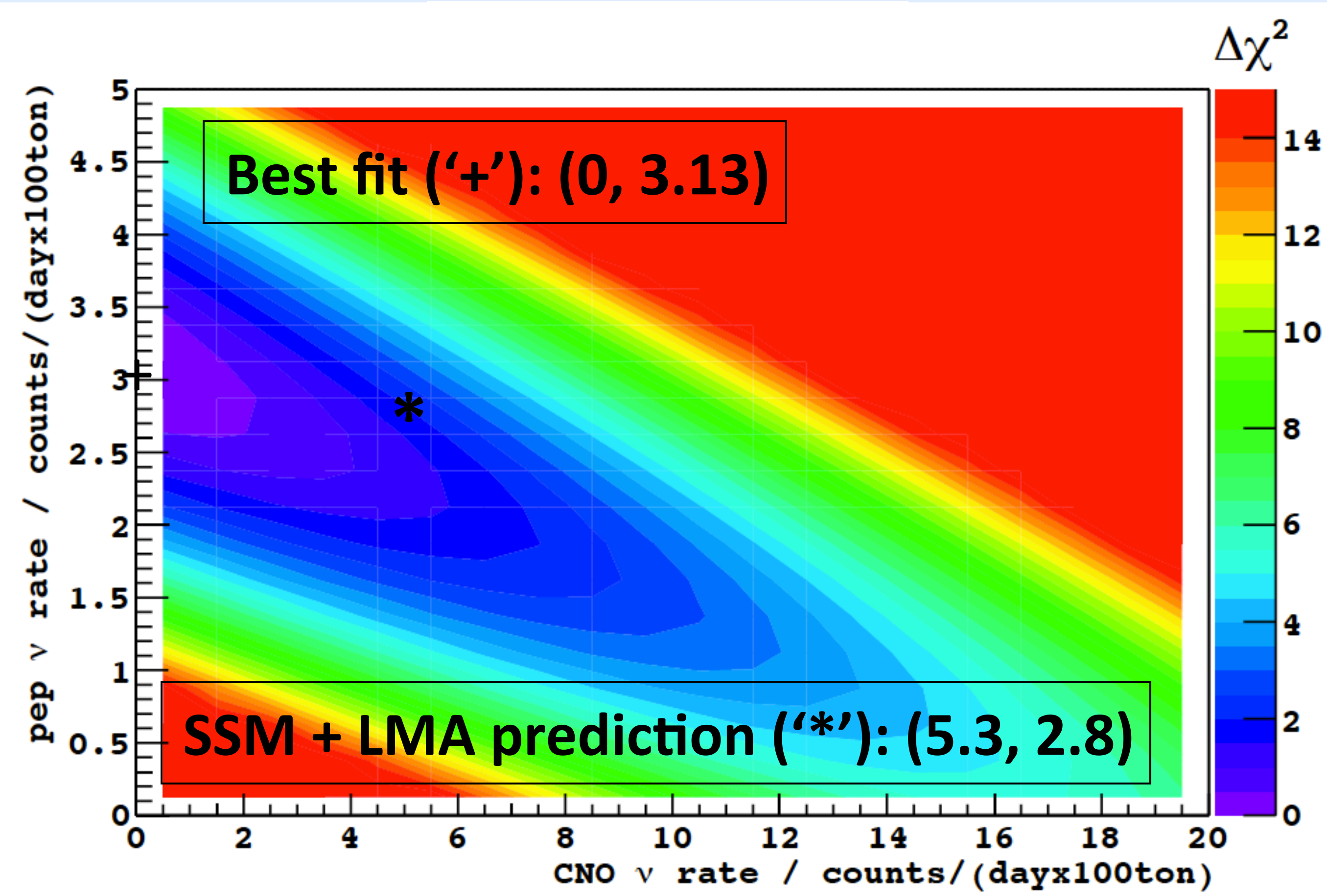
- binned likelihood fits in energy, radius and BDT

- 2D energy/radius and energy/BDT pdf's

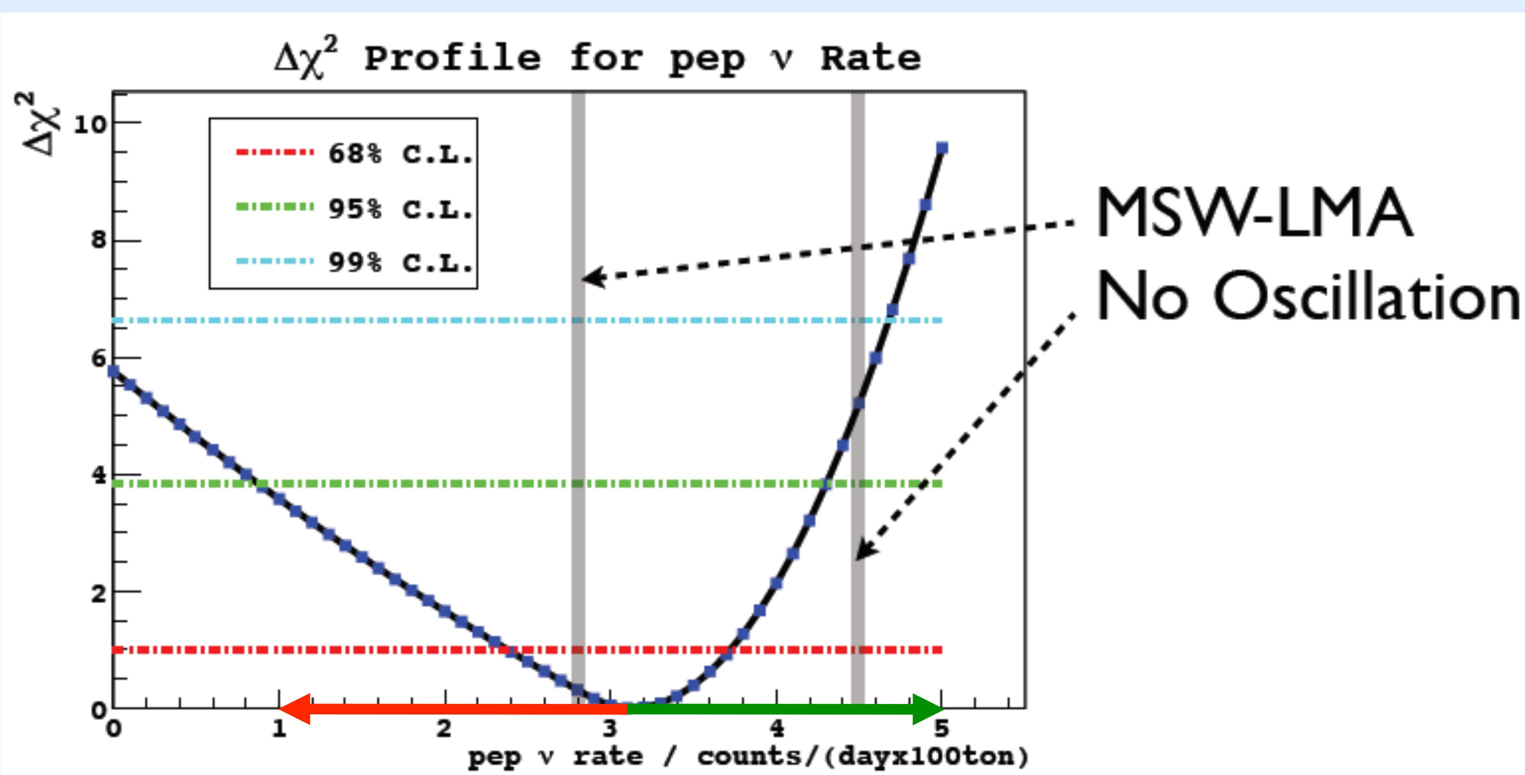
- simultaneous fits to TCF-accepted and rejected events (double bg statistics)

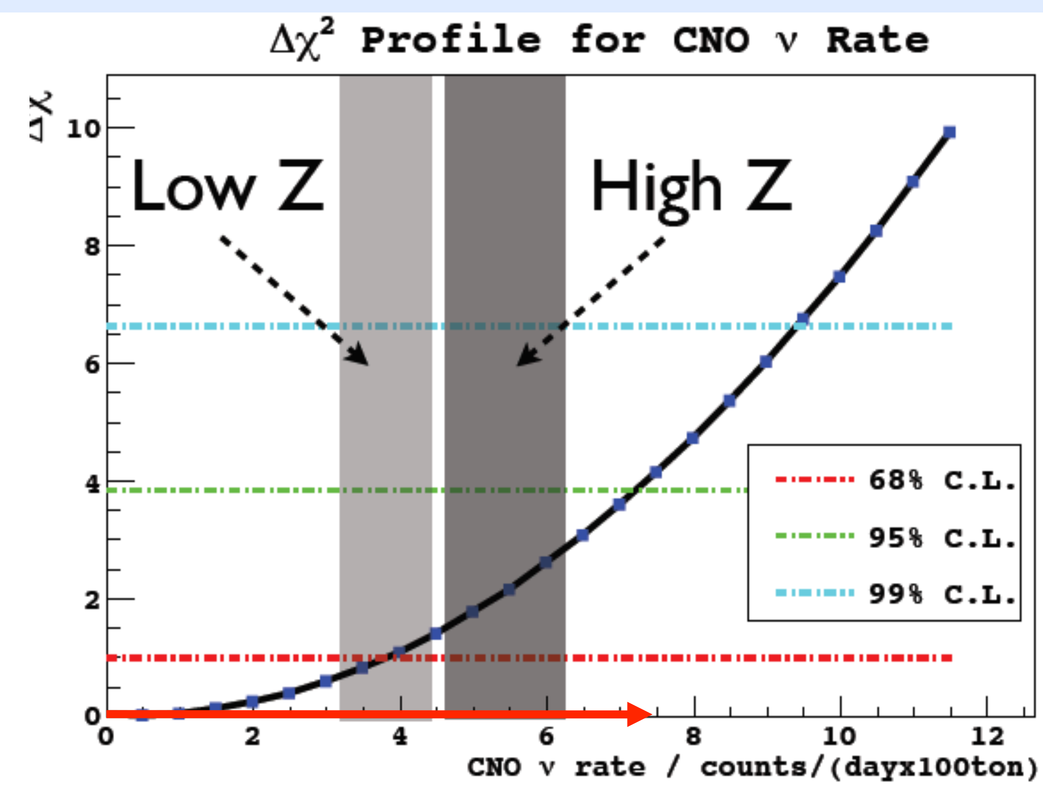


pep and CNO results



Systematics	
Fiducial Exposure	$^{+0.6}_{-1.1}$%
Energy Response	4.1%
^{210}Bi shape	$^{+1.0}_{-5.0}$%
Fit Methods	5.7%
^{85}Kr constraint	$^{+3.9}_{-0.0}$%
γ-rays in BDT	2.7%
BDT PDF statistics	5.0%
Total	**10%**





pep and CNO results

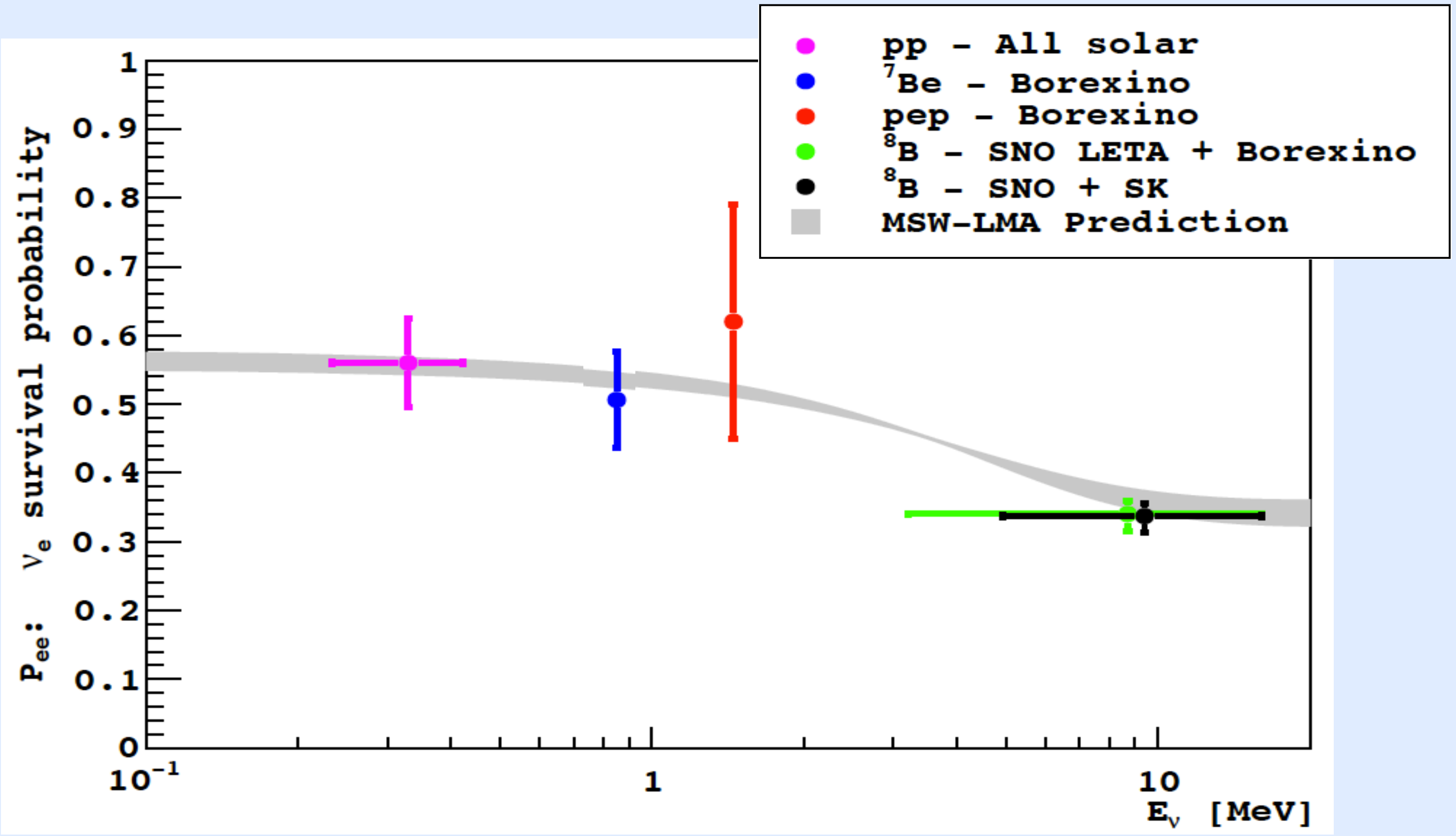
Borexino *pep* counting rate: $3.1 \pm 0.6_{stat} \pm 0.3_{sys}$ /(d 100T)

P_{ee}(1.44 MeV) = 0.62 ± 0.17

Φ_{pep} = 0 disfavoured at 98% C.L.

Borexino CNO counting rate: < 7.9 (<$7.1_{stat\ only}$) /(d 100T) (95% C.L)

(< 1.5 x high Z SSM)



outlook

Scintillator purification

Operations to further purify the scintillator ongoing since July 2010
- no sign of ^{85}Kr since January 2011
- moderate reduction in ^{210}Bi
- operations continue targeting ^{210}Bi (and maybe ^{210}Po)

Physics

Borexino will operate for 3 or more years
- neutrino “snapshot” of entire solar neutrino spectrum
- CNO, pp?
- better statistics for ^{8}B, pep, geo-neutrinos
- supernovae neutrinos
- exotica

summary

- Borexino has achieved its original design goal
- precision 7Be measurements improves experimental constraint at low energy
- day/night improves solar only constraint on mixing parameters
- first evidence of pep flux
- attempt at measuring CNO, pep fluxes
- supernovae, geo-neutrinos, superluminal neutrinos, other exotic physics

summary

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thank you!

Andrea Pocar – SILAFAE 2010 – Dec. 8, 2010