2 MeV detection threshold of ^{8}B solar neutrinos with JUNO

Vito Antonelli(Milano U.), **Xuefeng Ding (GSSI & Milano U.),** Emanuela Meroni(Milano U.), Gioacchino Ranucci(Milano U.), Alessandra Re(Milano U.), Barbara Ricci(Ferrara), Giuseppe Salamanna(Roma TRE)
(Italian Solar Neutrino working group)

JUNO-Italia meeting
@INFN-Ferrara, Italy 8–9 May 2019

Outline

- Why low threshold ^{8}B solar neutrinos?
- High precision measurements with Borexino
- Potential of JUNO
- Future: CNO solar neutrinos
- Conclusions

Neutrino oscillations in Matter

- Presence of **matter** (The Sun for solar neutrinos) adds potential to the evolution operator (Hamiltonian) and **changes** the flavor eigenstate and thus **the mixing angle**.

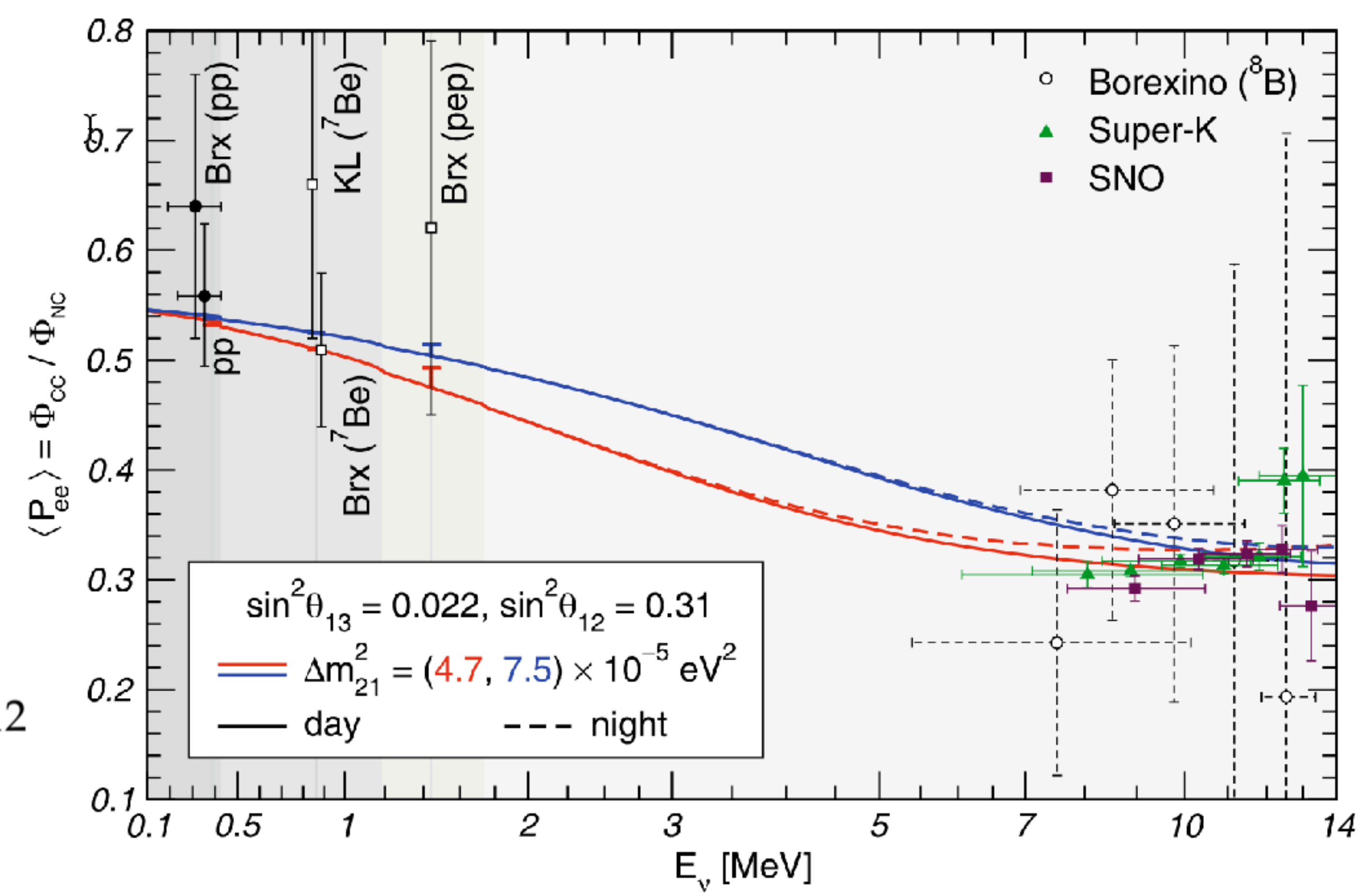
$$P^{\text{adiabatic}}_{\nu_e \to \nu_e}(L) = \frac{1}{2} + \frac{1}{2} \cos 2\theta^m_{\text{p}} \cos 2\theta^m_{\text{d}}$$

$$\cos 2\theta^m = \frac{\cos 2\theta - \epsilon}{\sqrt{(\cos 2\theta - \epsilon)^2 + (\sin 2\theta)^2}}$$

$$\epsilon = \frac{2 \cdot E_\nu \cdot \sqrt{2} G_F n_e^{\text{p}}}{\Delta m^2}$$

Vacuum regime $\epsilon_{12} \to 0: \quad \cos 2\theta^m_{12} \to \cos 2\theta_{12}$

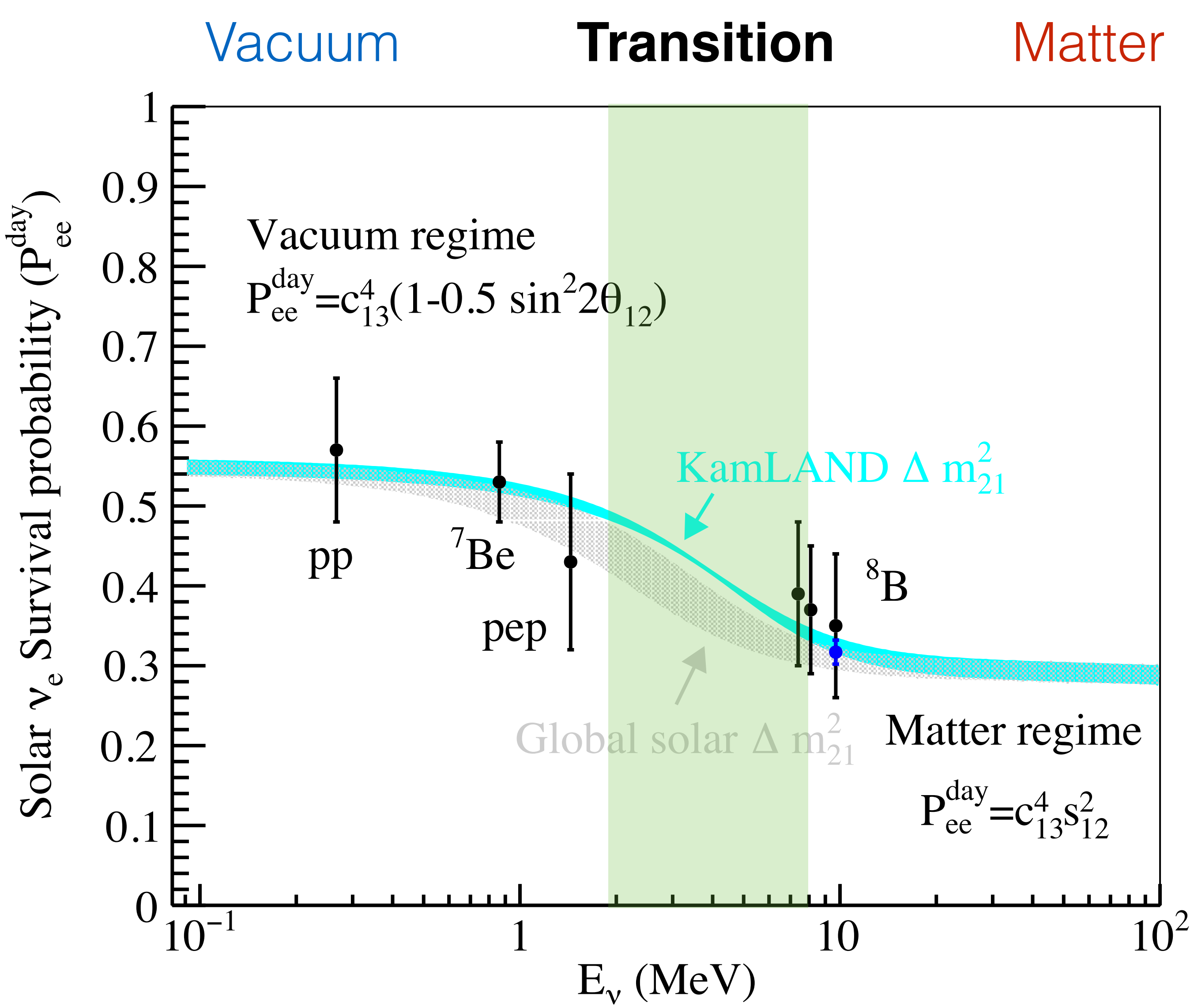
Matter regime $\epsilon_{12} \to +\infty: \quad \cos 2\theta^m_{12} \to -1$

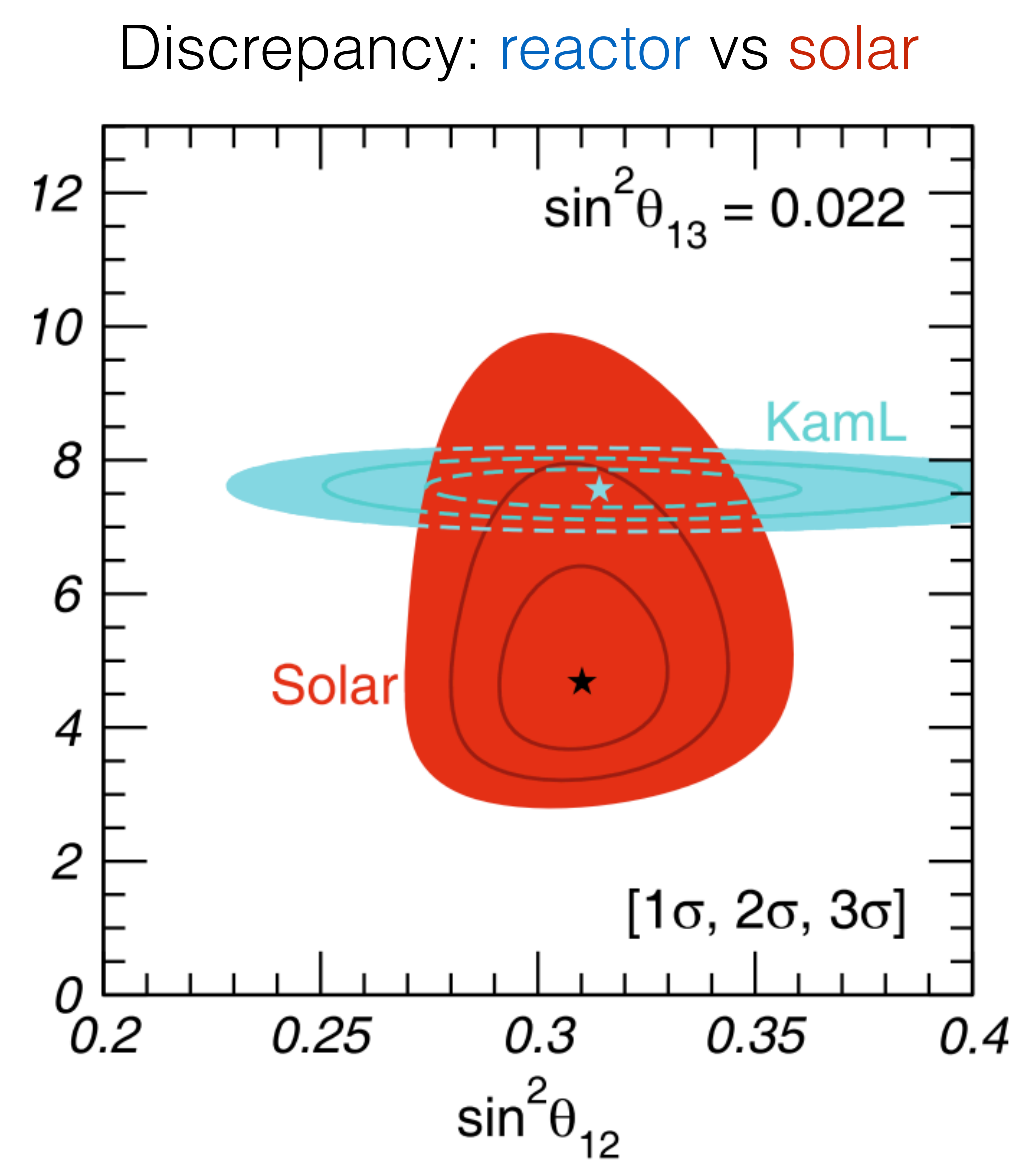


M. Maltoni and A. Yu. Smirnov, "**Solar neutrinos and neutrino physics,**" *Eur. Phys. J. A*, vol. 52, no. 4, p. 87, Apr. 2016.

Why transition region?

- Neutrino oscillation **transition region** not observed yet.
- **2σ Discrepancy** between KamLAND and solar on Δm_{21}^2





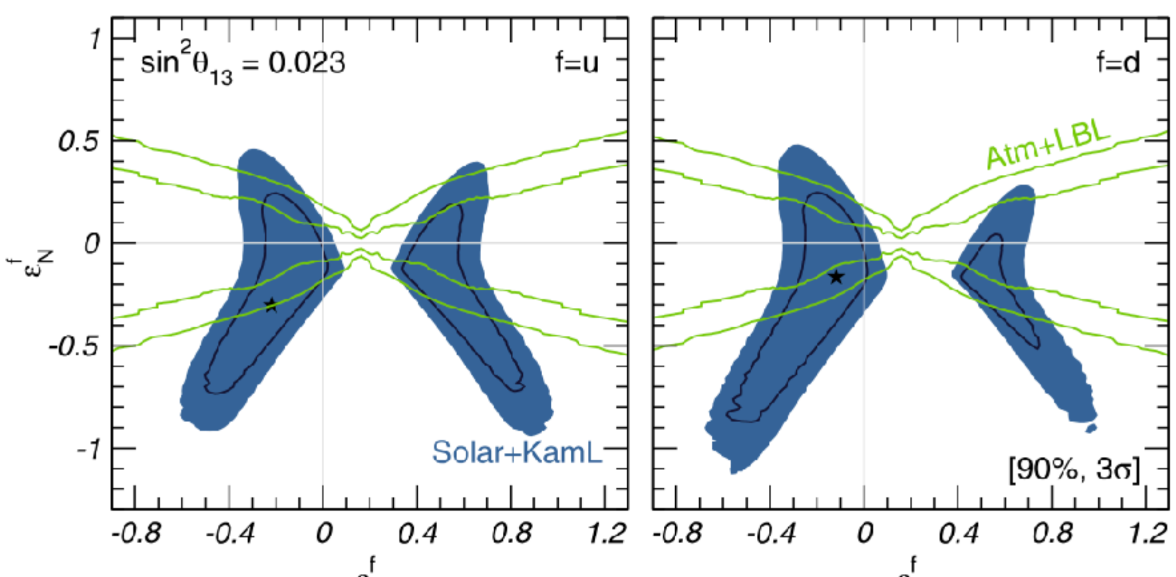
Maltoni et al. Eur. Phys. J. A (2016) 52:87

Why transition region?

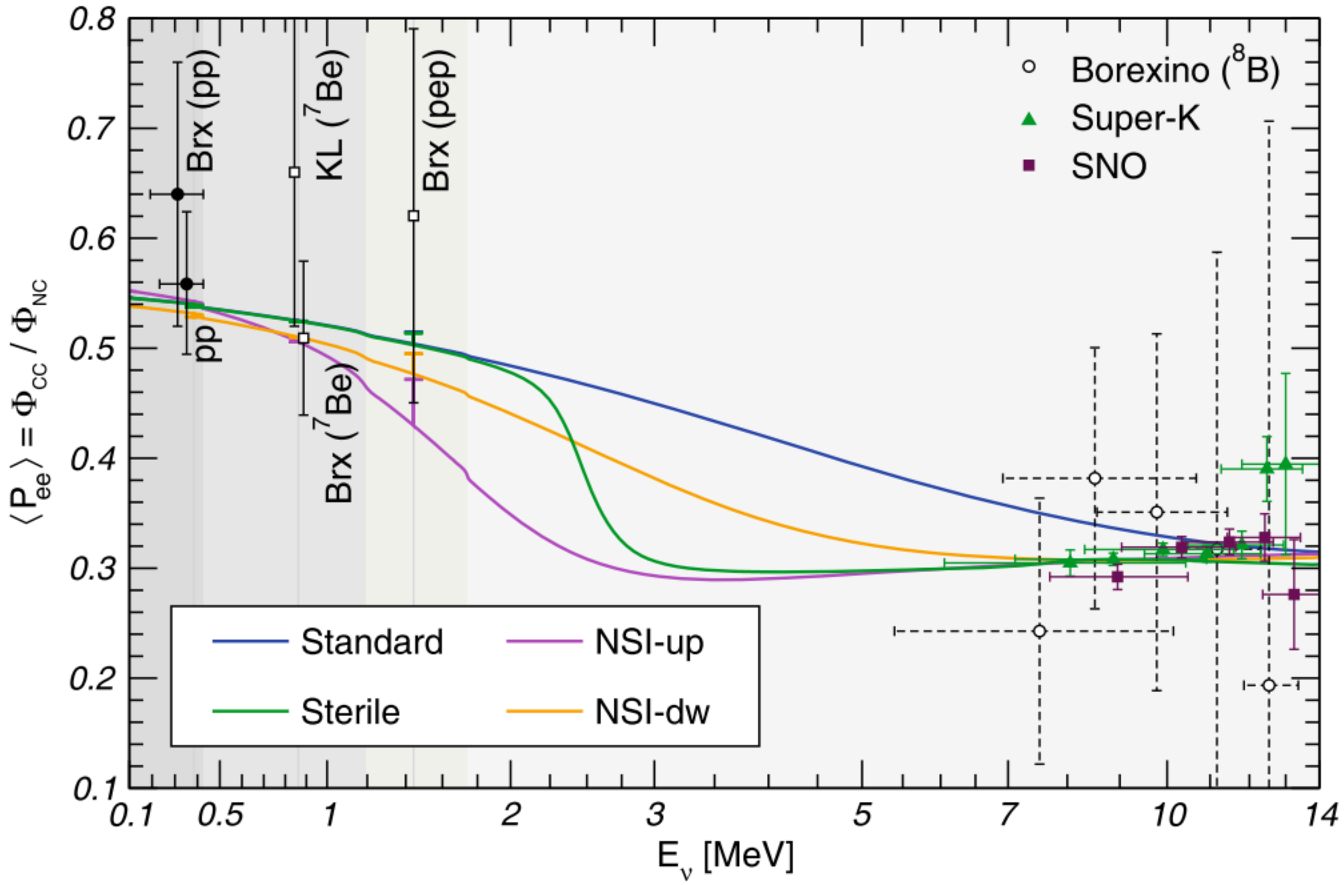
- Transition zone: criteria for new physics (M.M. Guzzo, P.C. de Holanda, O.L.G. Peres 2002)

A. Friedland, C. Lunardini, and C. Peña-Garay, "**Solar neutrinos as probes of neutrino–matter interactions,**" *Phys. Lett. B*, vol. 594, no. 3–4, pp. 347–354, Aug. 2004.
M. . Guzzo, P. . de Holanda, and O. L. . Peres, "**Effects of non-standard neutrino interactions on MSW-LMA solution to the solar neutrino problem**," *Phys. Lett. B*, vol. 591, no. 1–2, pp. 1–6, Jul. 2004.

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F\varepsilon^{fP}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu\nu_\beta)(\bar{f}\gamma_\mu P f)$$



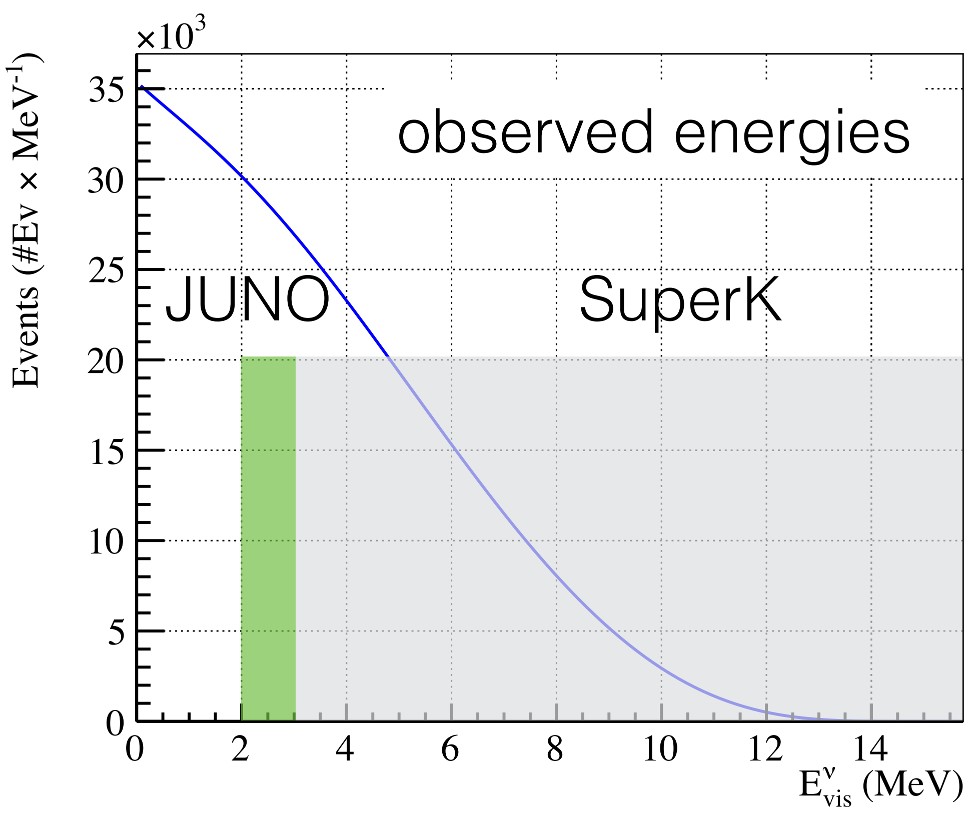
Maltoni et al. Eur. Phys. J. A (2016) 52:87

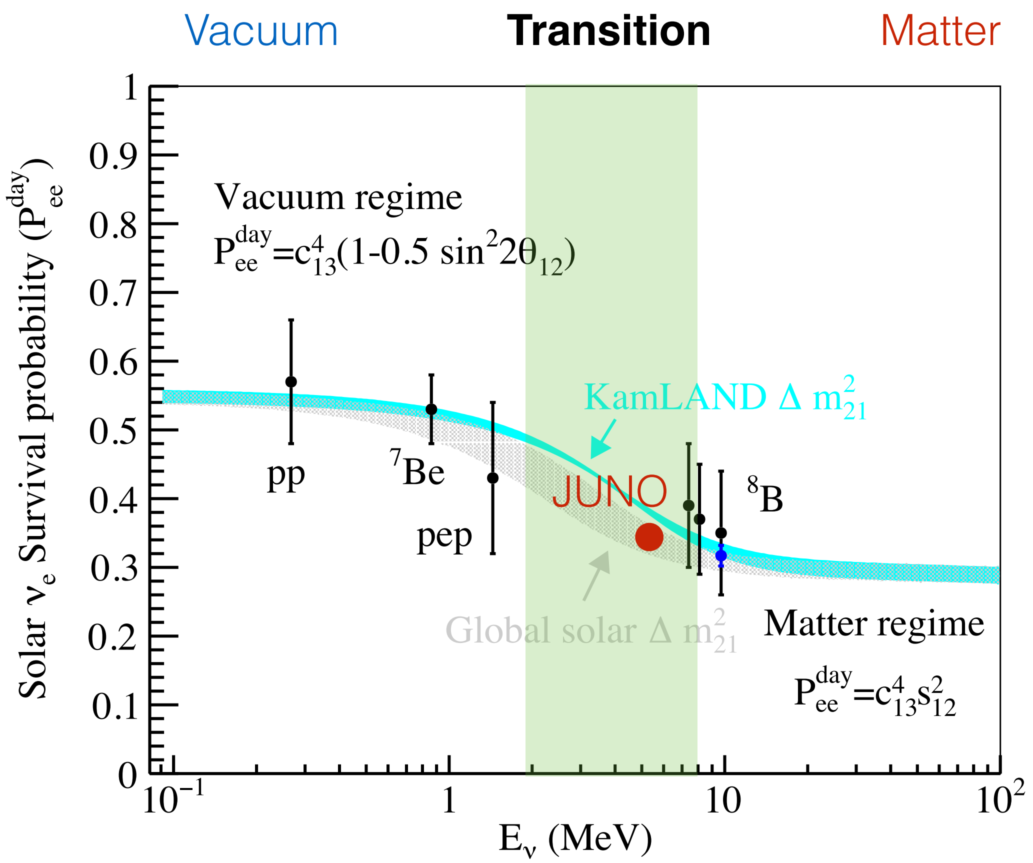


Maltoni et al. Eur. Phys. J. A (2016) 52:87

✤ **Can probe transition region.**

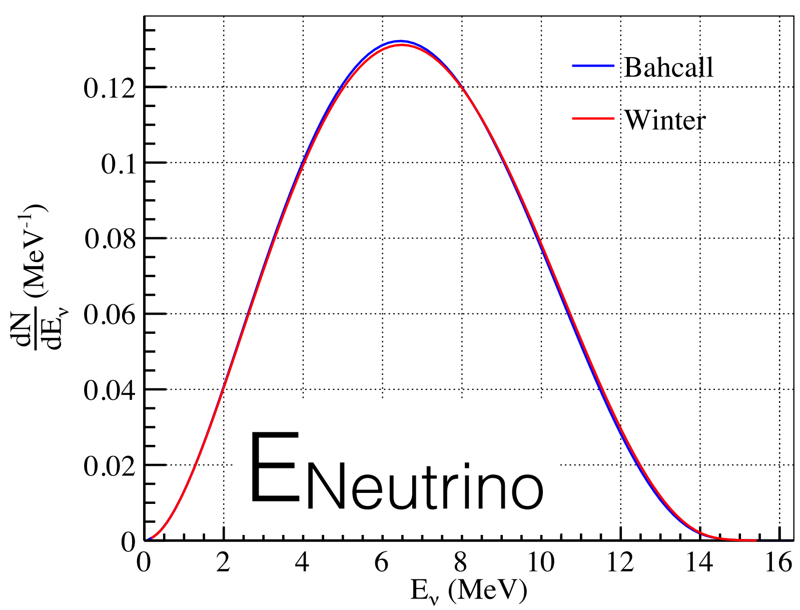
- SuperK/BX: T **3—5** MeV E_ν~7.4 MeV (almost outside the transition region). SuperK: high threshold. Borexino: too small.
- JUNO: T **2—3** MeV E_ν~6.2 MeV (in the transition region) JUNO is big and can cut external backgrounds.



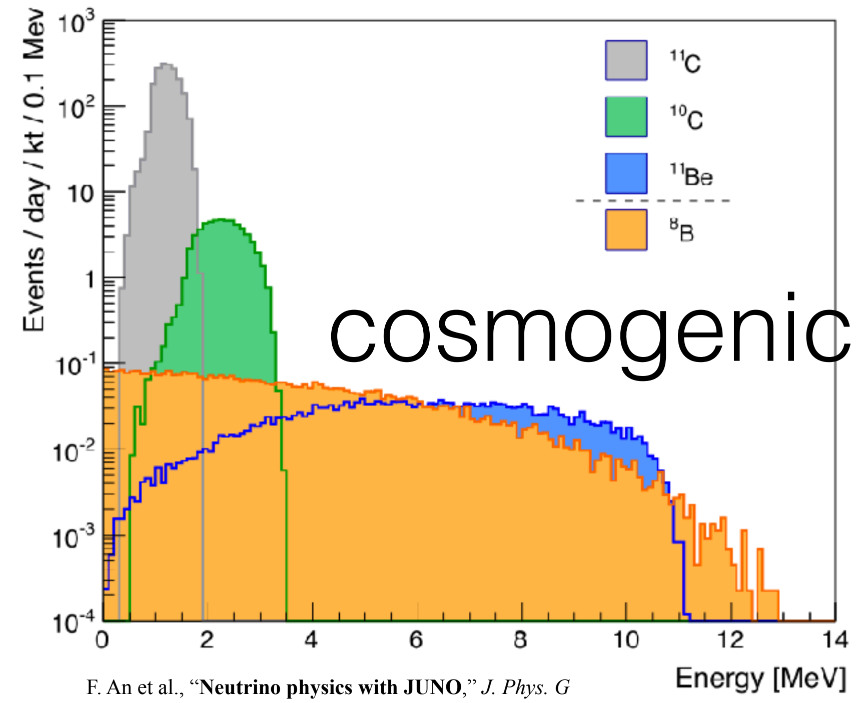


Signal and major backgrounds

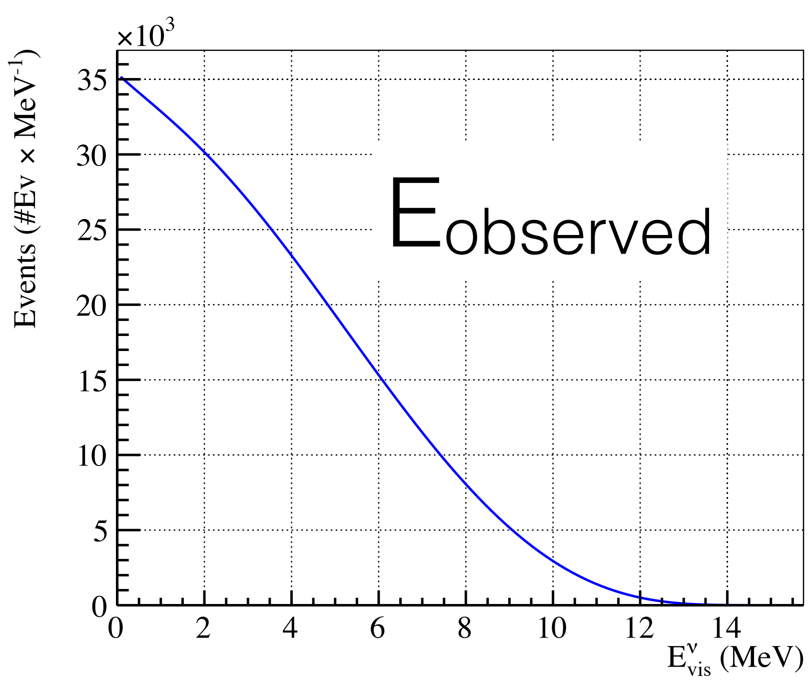
Elastic scattering signals

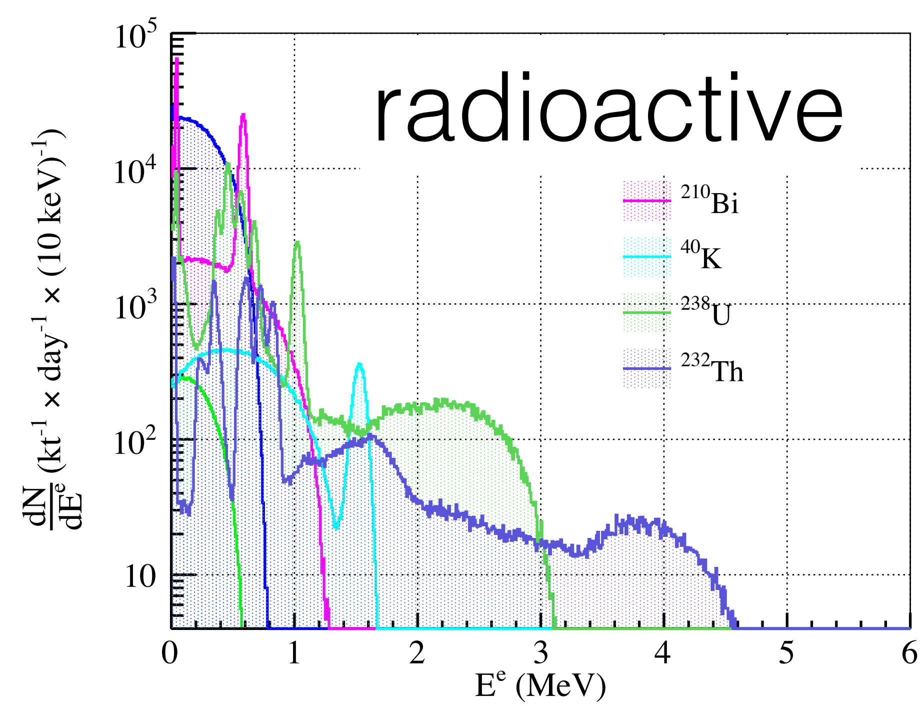


J. N. Bahcall: 10.1103/PhysRevD.51. 6146
W. T. Winter: 10.1103/PhysRevC.73. 025503

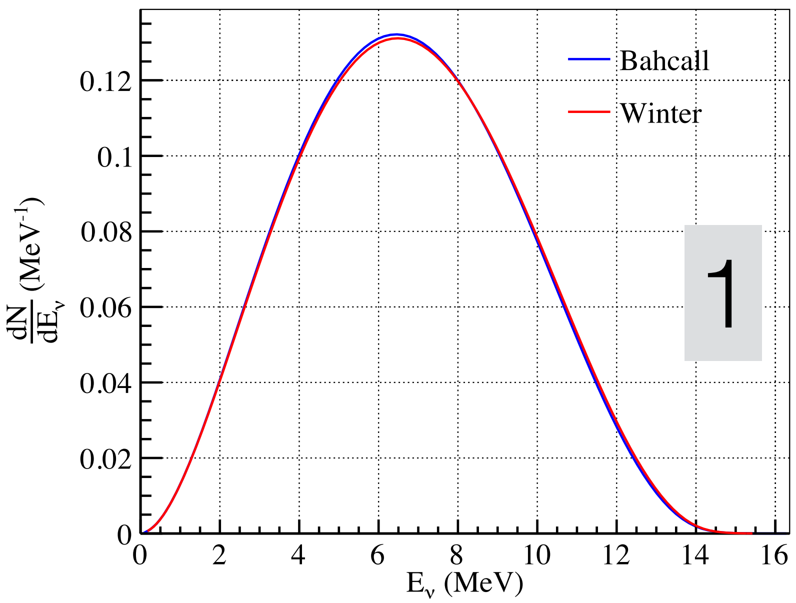


F. An et al., "**Neutrino physics with JUNO**," *J. Phys. G Nucl. Part. Phys.*, vol. 43, no. 3, p. 030401, 2016.

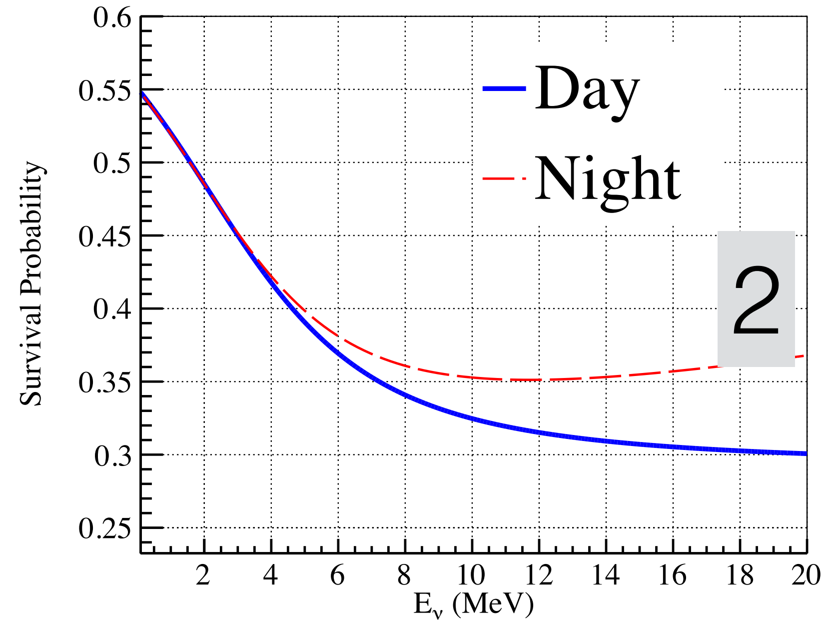




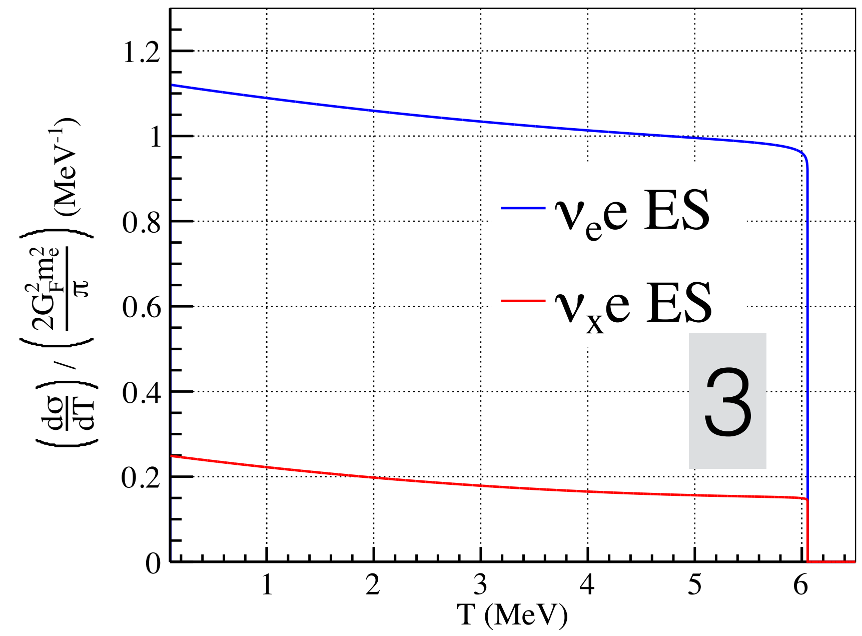
ν(^{8}B) Elastic scattering on e⁻



J. N. Bahcall: 10.1103/PhysRevD.51. 6146
W. T. Winter: 10.1103/PhysRevC.73. 025503



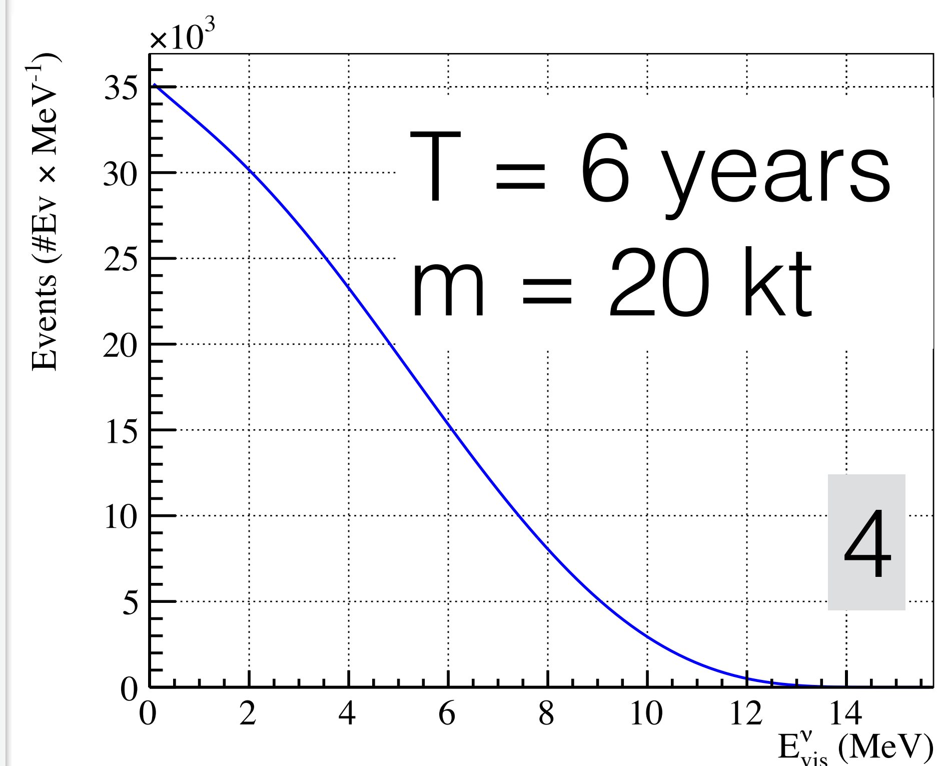
Maltoni et al. 10 . 1140/epja/i2016-16087-0
F. Vissani 10.15407/jnpae2017.01.005.



J. N. Bahcall 10.1103/PhysRevD.51. 6146.

- Estimation of signal rate
- ROI: [2, 3] MeV

X	R_X^{tot} (day^{-1})	R_X^{ROI} (day^{-1})
^{8}B ν ES	90.55	13.23

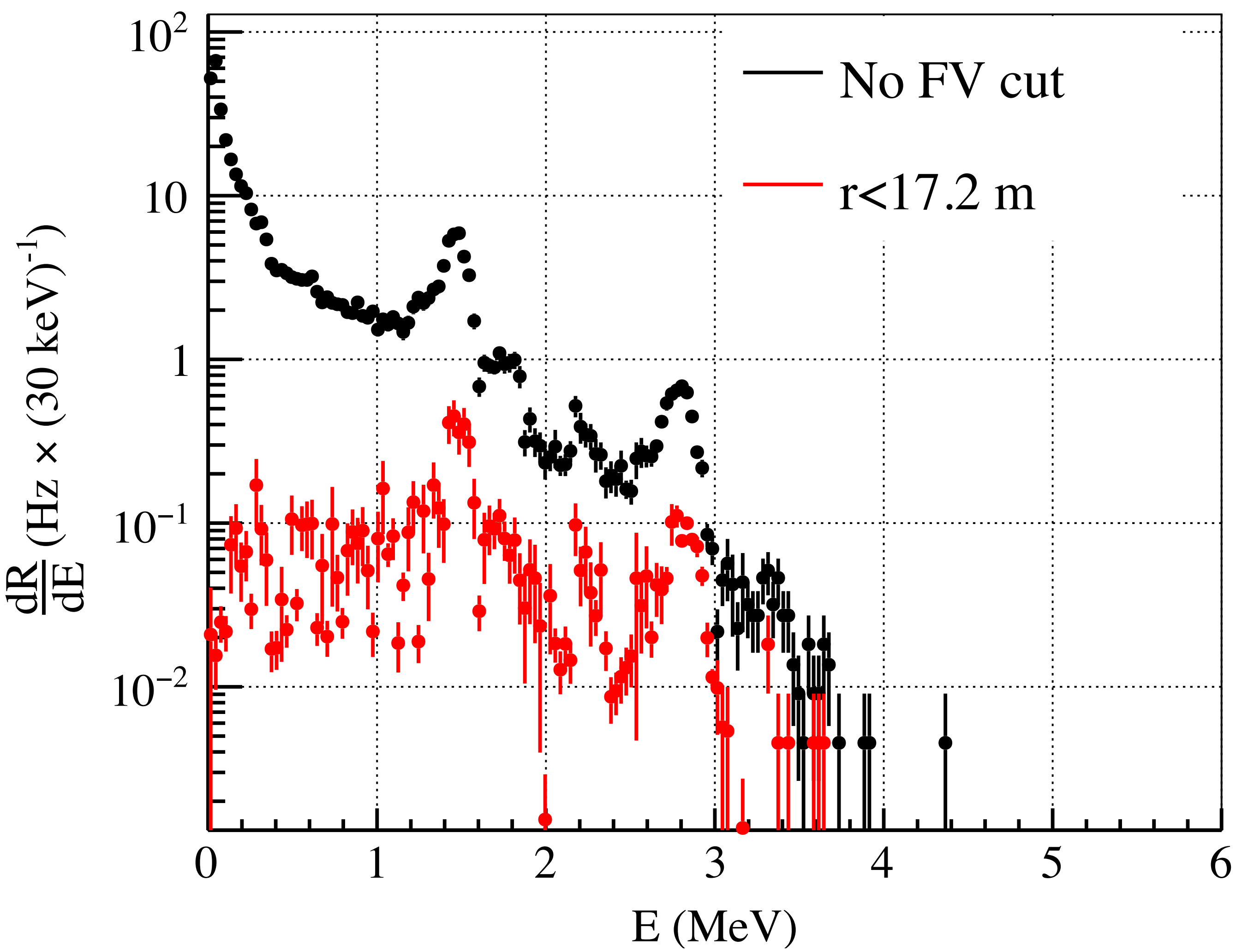


External backgrounds: γ

- Based on X.Y. Li et al, 10.1088/1674-1137/40/2/026001
- Acrylic ball, PMT glass, Steel, Copper, Water, Rock

Contribution to ROI (no cut)

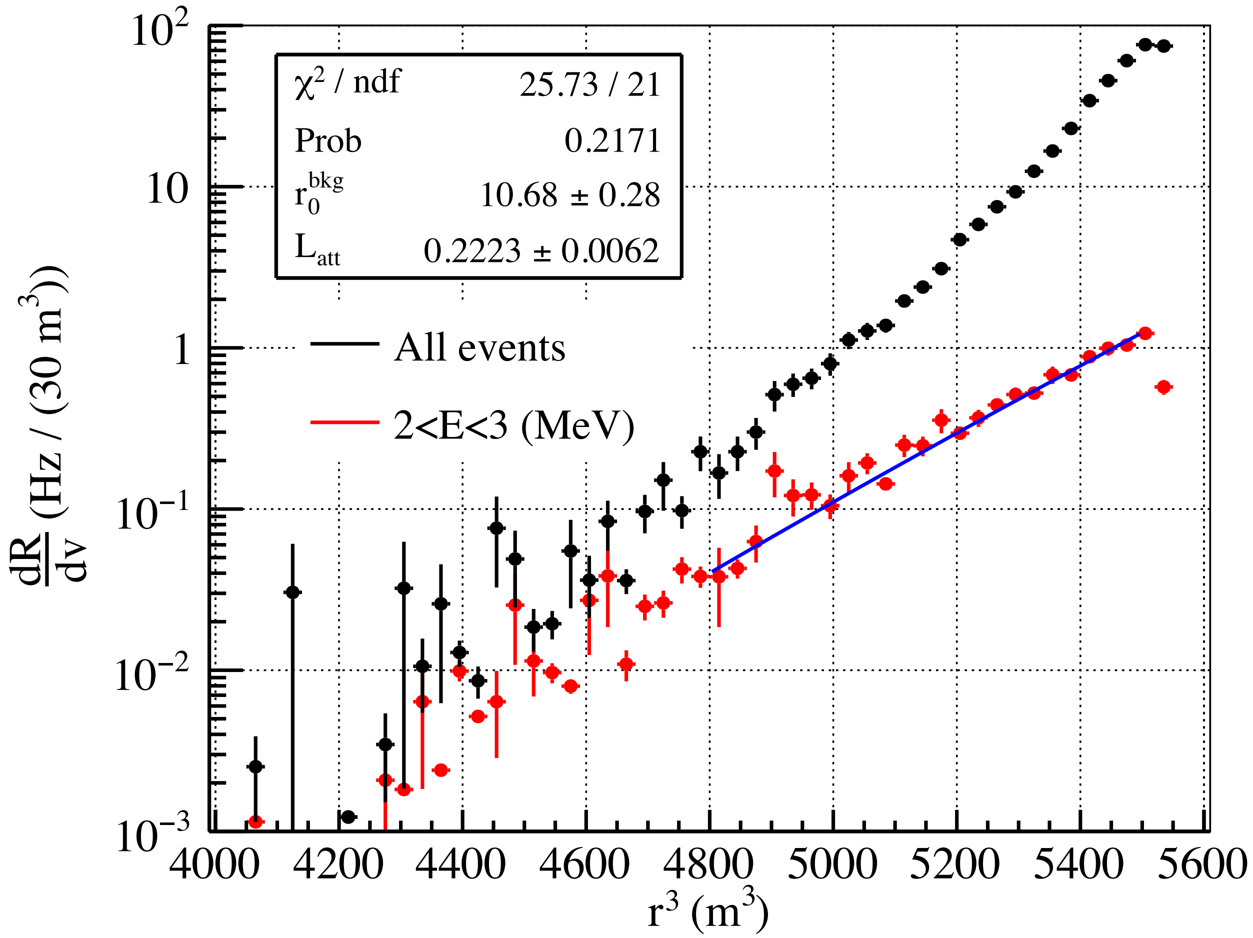
X	R_X^{tot} (day^{-1})	R_X^{ROI} (day^{-1})
^8B ν ES	90.55	13.23
External γs	3.333×10^7	9.105×10^5

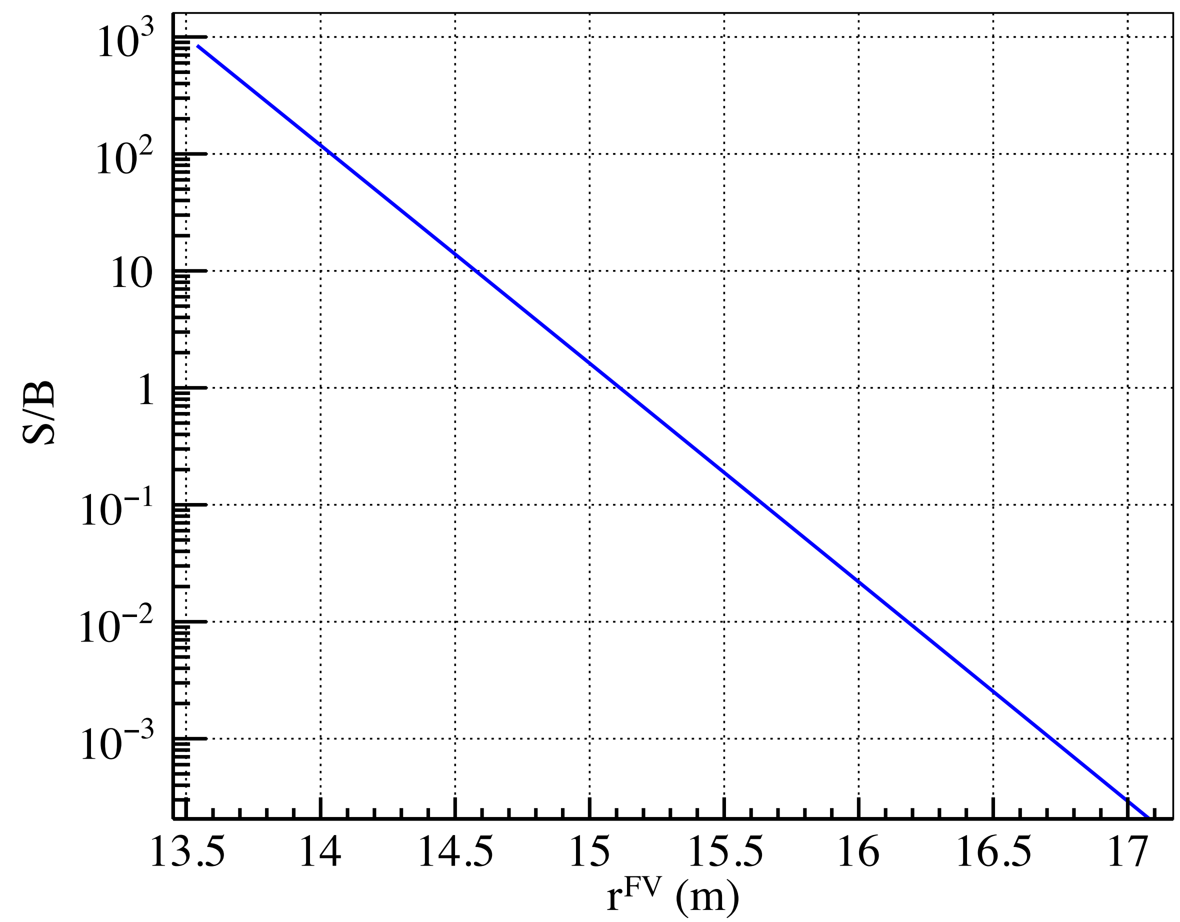


Fiducial volume cut

- Residual ext. γ extrapolated using exponential law
- S/B optimized to 100:1 => FV cut: **r<14 m** (ε_{FV}=49.48%)

$$\frac{dR^{ROI}_{bkg}}{dv} = \frac{1}{3 \cdot v^{2/3}} \cdot \frac{r_0^{bkg}}{\lambda} \cdot \exp\left(-\frac{r_0 - v^{1/3}}{\lambda}\right)$$





Cosmogenic: Scaling data

- scale from data: power law

$$\frac{R_X^{\text{JUNO}}}{R_X^{\text{ref}}} = \frac{\left(E_\mu^{\text{JUNO}}\right)^{\alpha(X)}}{\left(E_\mu^{\text{ref}}\right)^{\alpha(X)}} \cdot \frac{\epsilon_C^{\text{JUNO}}}{\epsilon_C^{\text{ref}}} \cdot \frac{\rho^{\text{JUNO}}}{\rho^{\text{ref}}} \cdot \frac{R_\mu^{\text{JUNO}}}{R_\mu^{\text{ref}}} \cdot \frac{L_\mu^{\text{JUNO}}}{L_\mu^{\text{ref}}}$$

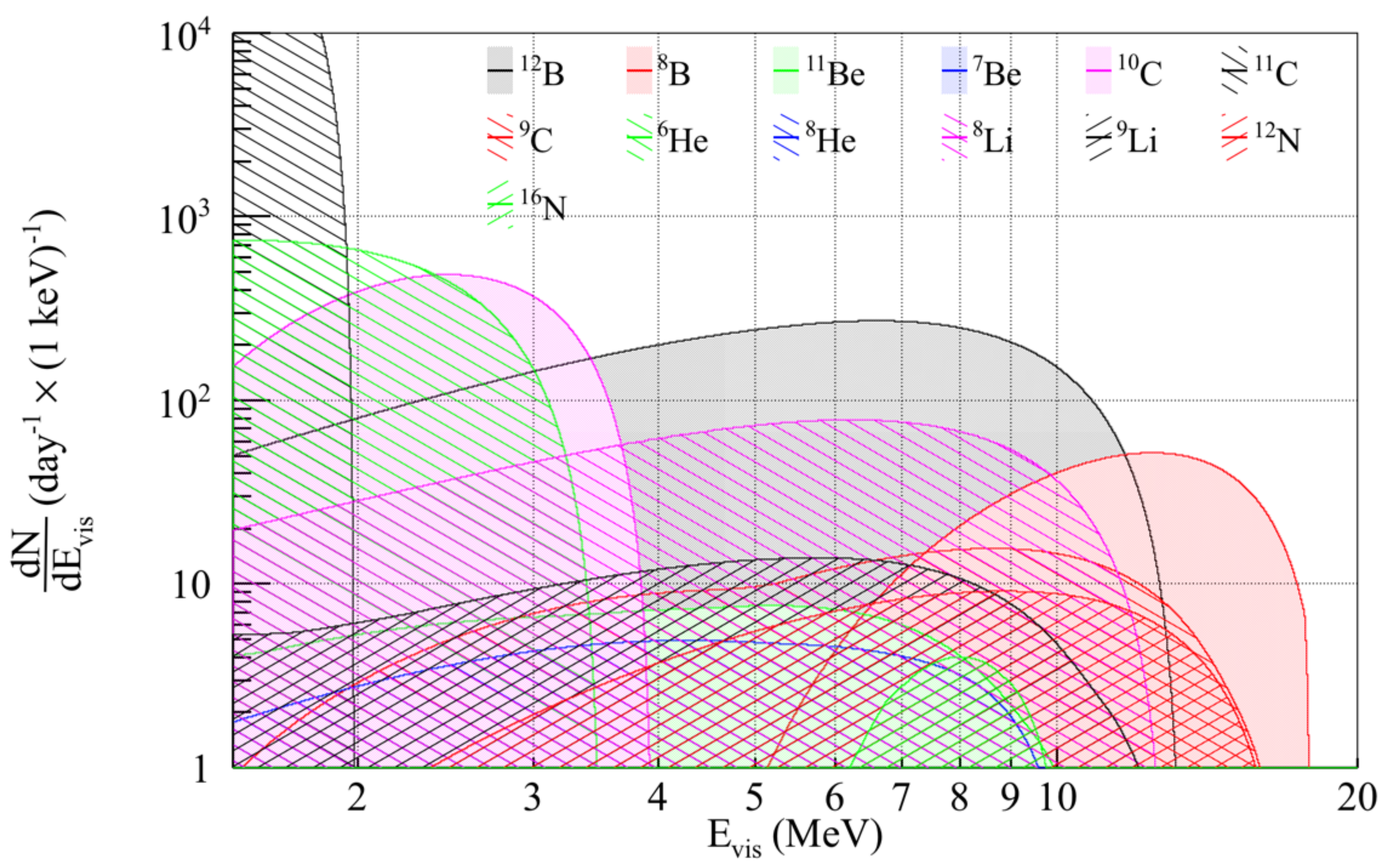
KamLAND 10.1103 / PhysRevC.81.025807.
F. An et al. 10.1088/0954- 3899/43/3/030401
Borexino 10. 1088/1475-7516/2013/08/049

Experiment	E_μ	ϵ_C	ρ	R_μ	L_μ	m
Unit	GeV		g/cm^3	Hz	m	kton
JUNO	215	0.8792	0.856	3.0	23.6	20
KamLAND	260	0.8568	0.780	0.198	8.78	0.913
Borexino	283	0.9007	0.88	0.00965	4.0	0.0995

Contribution to ROI (no cut)

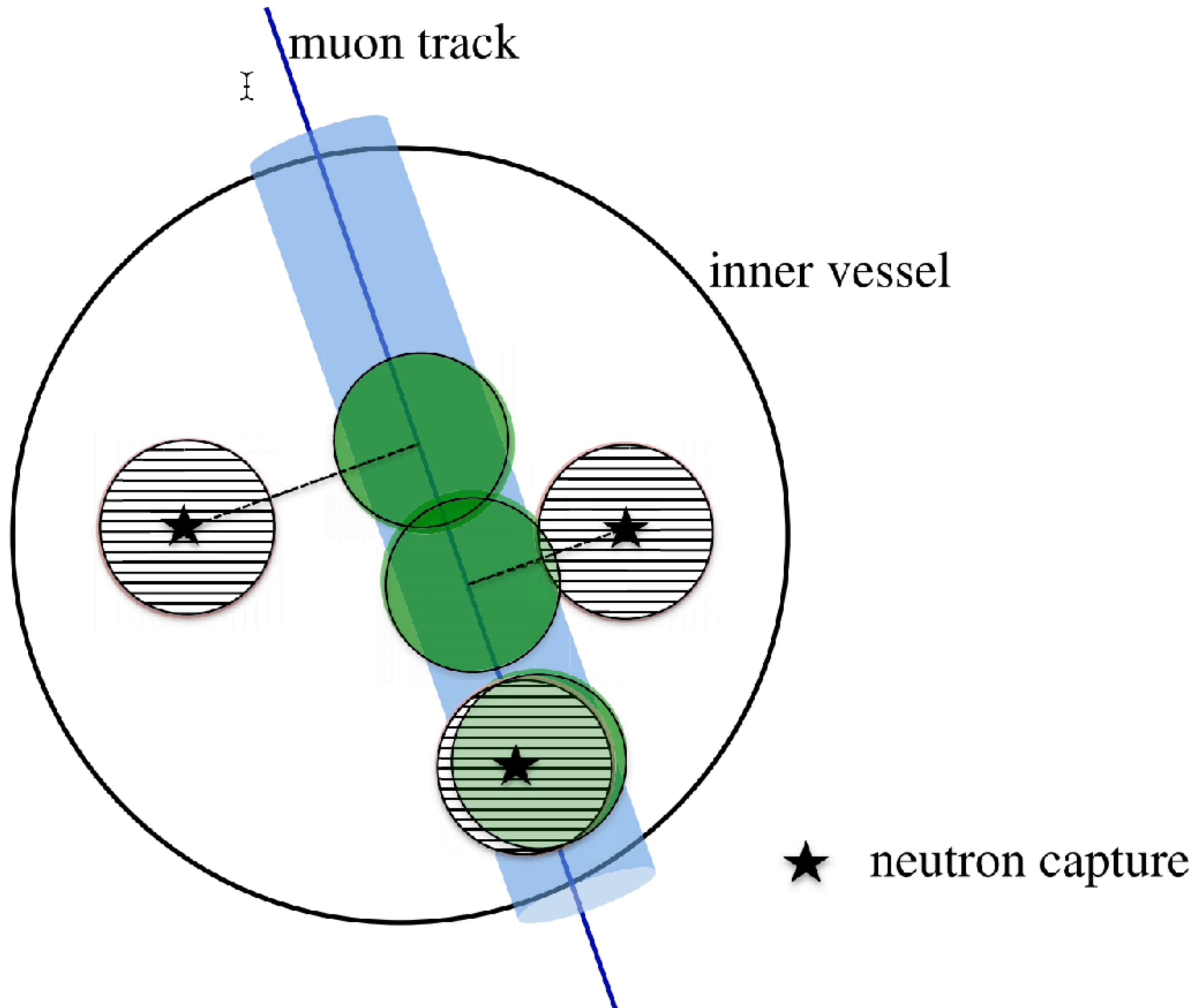
X	R_X^{tot} (day^{-1})	R_X^{ROI} (day^{-1})
^{8}B ν ES	90.55	13.23
^{10}C	760.4	447.85
^{11}Be	51.2	6.10
^{16}N	13[a]	0.39
^{6}He	1543	415.94
^{8}Li	560.2	37.38
^{8}B	387.2	$\ll 0.01$
^{9}Li	101.4	7.76
^{9}C	139.0	5.03
^{8}He	31.83	3.62
^{12}B	1968	112.17
^{13}B	12[a]	1
^{12}N	81.34	1.21
^{11}C	3.734×10^4	0
^{7}Be	5438[a]	0
^{10}Be	1419[a]	0
others	1.2×10^4[a]	0.10
neutrons	1.2798×10^5	1.2798×10^5

Normalized spectra



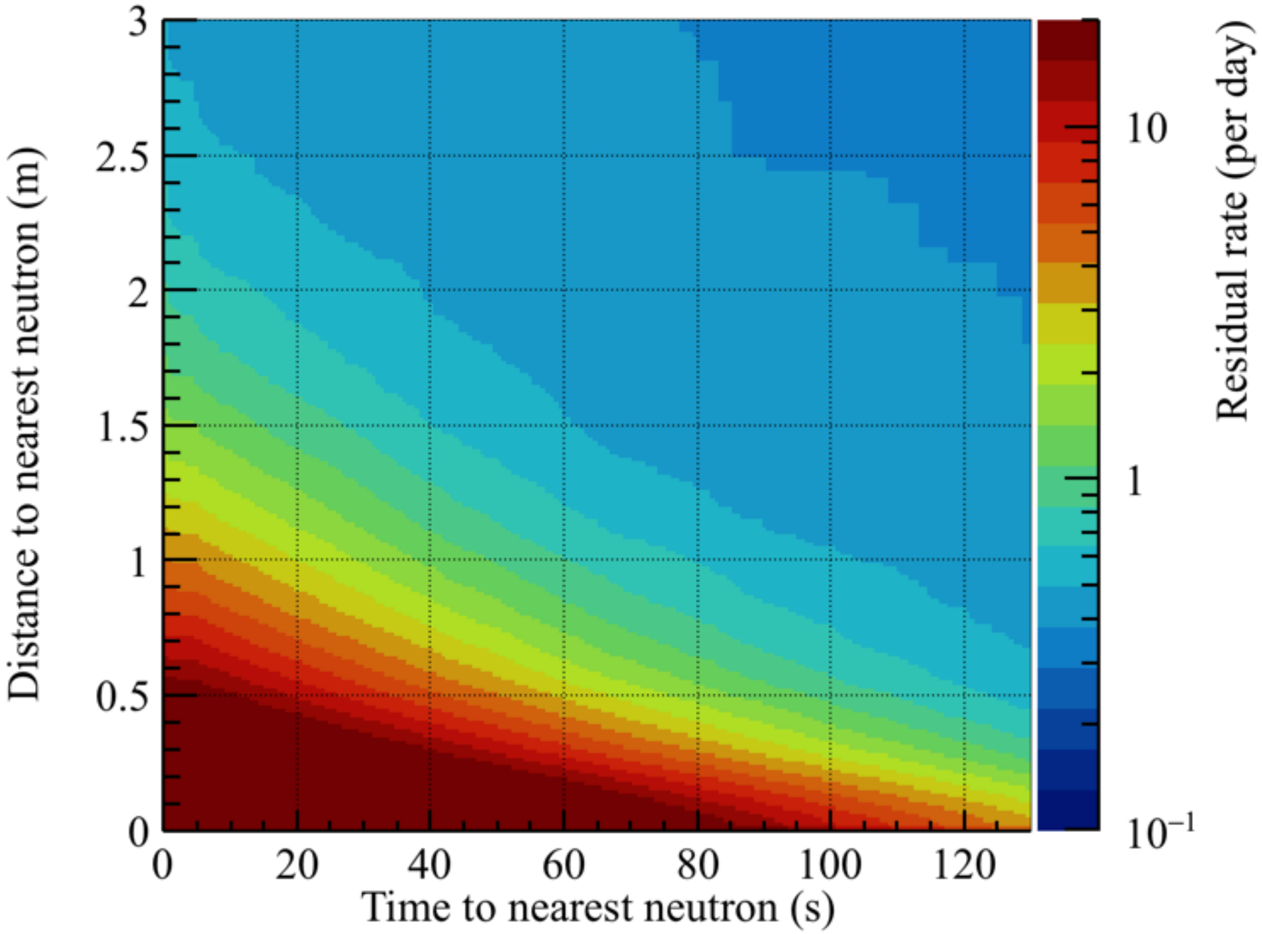
Three-Fold-Coincidence cut

- μ-associated n: $d_{n2\mu}$<2 ms, whole det.
- Definition of TFC: d_{x2n}<2 m and t_{x2n}<111 s

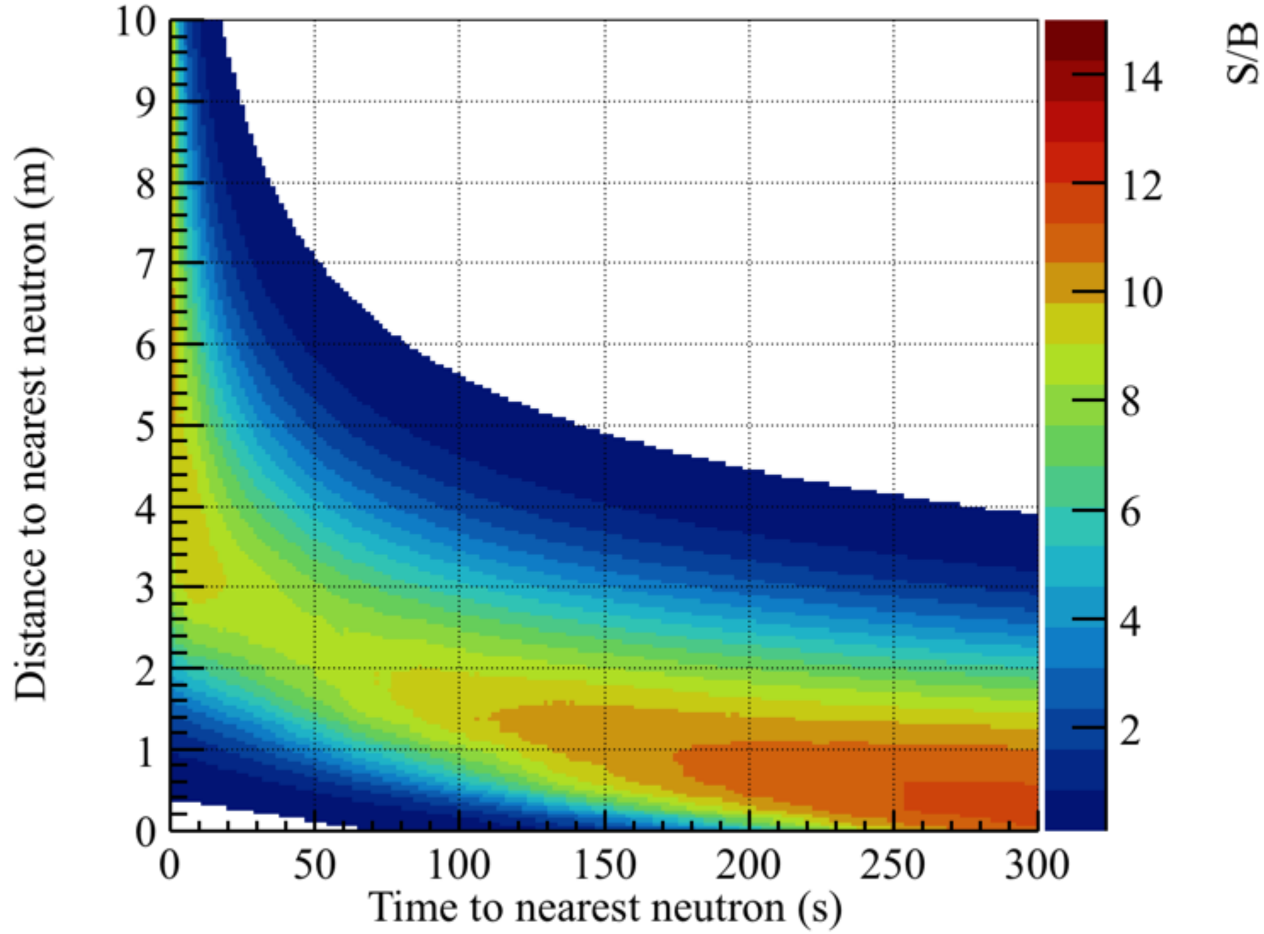


Borexino, "Final results of Borexino Phase-I on low-energy solar neutrino spectroscopy,"
Phys. Rev. D - Part. Fields, Gravit. Cosmol., vol. 89, no. 11, pp. 1–68, 2014.

Residual cosmogenic



S/B_{cos}



Other backgrounds

KamLAND 10.1103/PhysRevC.84.035804

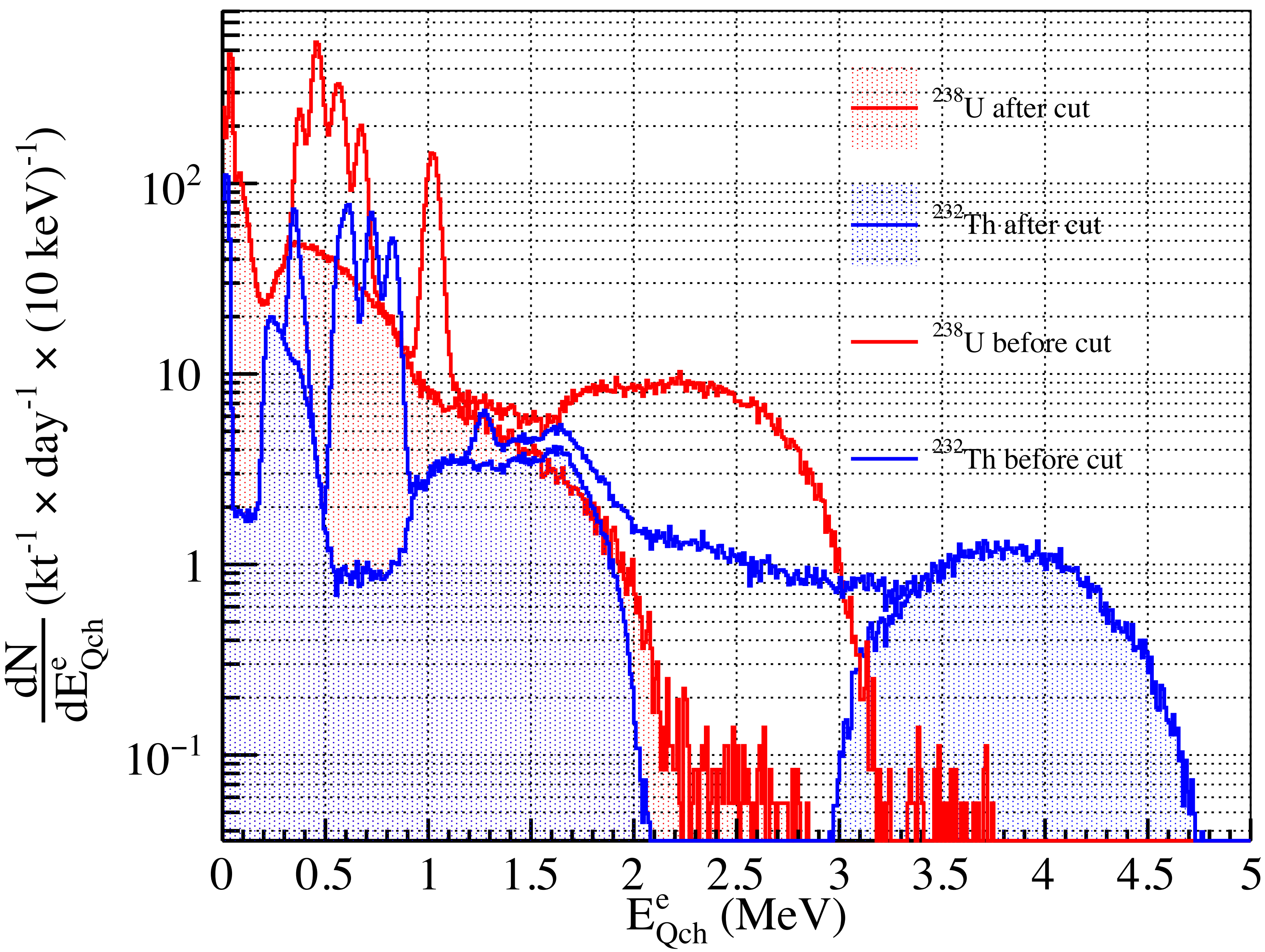
- atm/solar ν bkg scale from KamLAND ^{8}B solar ν paper
- Reactor IBD/ES taken from MH analysis
- Will be negligible after cut

Contribution to ROI (no cut)

X	R_X^{tot} (day^{-1})	R_X^{ROI} (day^{-1})
^{8}B ν ES	90.55	13.23
^{8}B CC 1	1.06	0.08
^{8}B CC 2	0.20	0.02
hep ES	0.11	0.01
atm ν ES	0.35	0.02
sum	1.72	0.13
Reactor $\bar{\nu}_e$ IBD p	83	12.5
Reactor $\bar{\nu}_e$ IBD d	83	83
Reactor $\bar{\nu}_e$ ES		0.1

radioactivity: α/β disc. + coincidence

- By rejecting ^{212}Bi—^{212}Po and ^{214}Bi—^{214}Po, we significantly reduce bkg. in ROI (2~3 MeV)



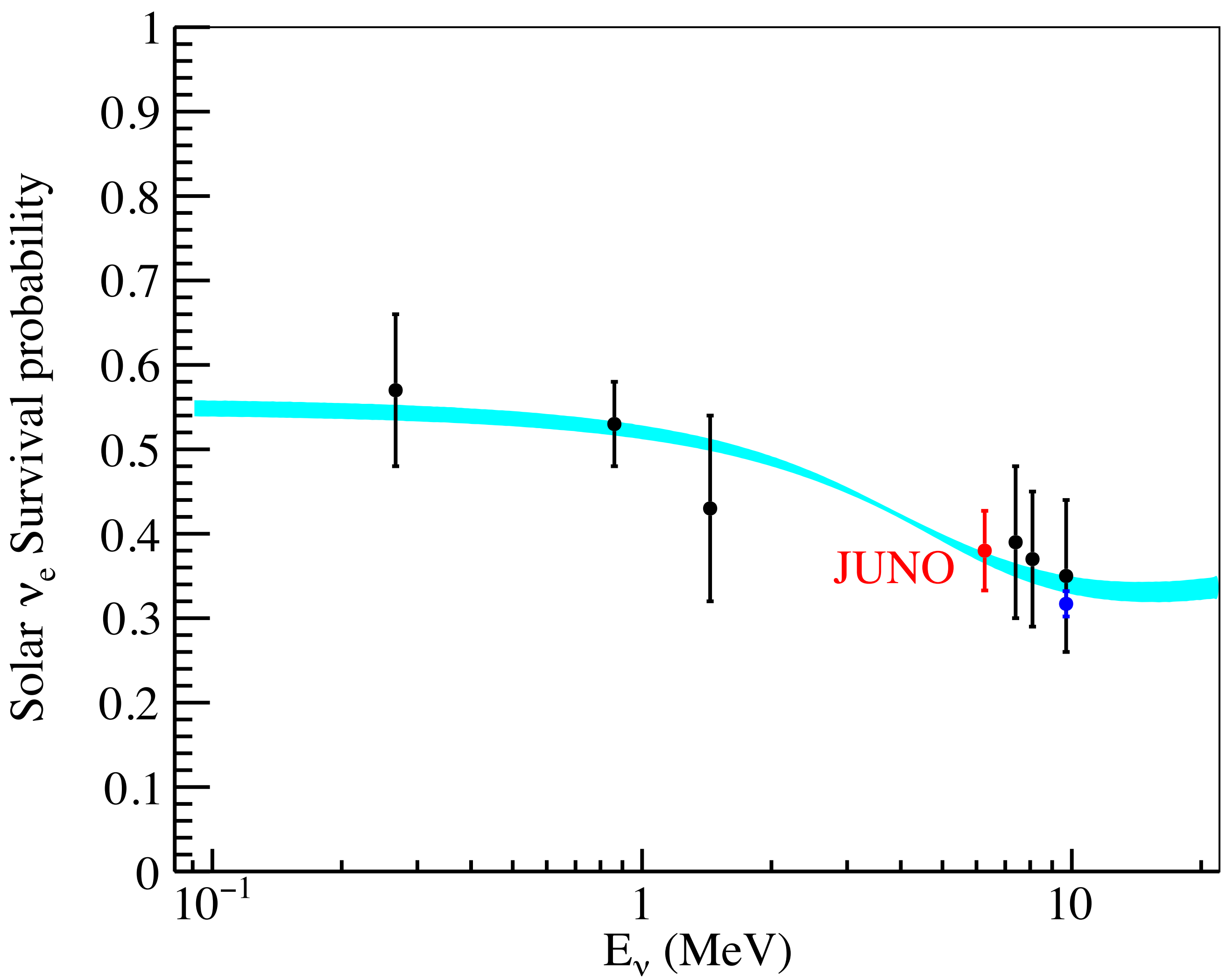
Summary of Signal and Backgrounds

Name	R_X^{tot}	R_X^{ROI}	FV cut	IBD cut	μ veto	TFC veto	α cut
^{8}B ν ES	90.55	13.23	6.546	6.546	4.639	3.659	3.659
External γs	3.333×10^7	9.105×10^5	0.055	0.055	0.039	0.031	0.031
(α, n)	$\mathcal{O}(10)$	$\mathcal{O}(10)$	0	-	-	-	-
^{238}U	3009.26	132.35	65.50	0.519	0.368	0.291	0.291
^{232}Th	656.28	24.44	12.10	12.10	8.58	6.76	0.102
^{10}C	760.4	447.85	221.69	221.69	186.05	0.033	0.033
^{11}Be	51.2	6.10	3.02	3.02	2.46	0.046	0.046
^{16}N	13	0.39	0.39	0.39	0.26	0.013	0.013
^{6}He	1543	415.94	205.90	205.90	11.99	0.212	0.212
^{8}Li	560.2	37.38	18.50	18.50	1.22	0.026	0.026
^{8}B	387.2	$\ll 0.01$	0	-	-	-	-
^{9}C	139.0	5.03	2.49	2.49	0.023	0	-
^{12}B	1968	112.17	55.53	55.53	1.58	0.018	0.018
^{13}B	12	1	0.50	0.50	0	-	-
^{12}N	81.34	1.21	0.60	0.60	0.006	0	-
^{9}Li	101.4	7.76	3.84	0.30	0.003	0	-
^{8}He	31.83	3.62	1.79	0.14	0.001	0	-
Rea $\bar{\nu}_e$ IBD p	83	12.5	6.19	0.14	0.099	0.078	0.078
Rea $\bar{\nu}_e$ IBD d	83	83	41	0.90	0.638	0.503	0.503
Rea $\bar{\nu}_e$ ES		0.1	0.050	0.050	0.035	0.028	0.028
others	3.2×10^4	0.23	0.114	0.114	0.081	0.064	0.064
bkg sum	3×10^7	9×10^5	639	523	213	8.102	1.444

S/B = 2.5

expected P_{ee}

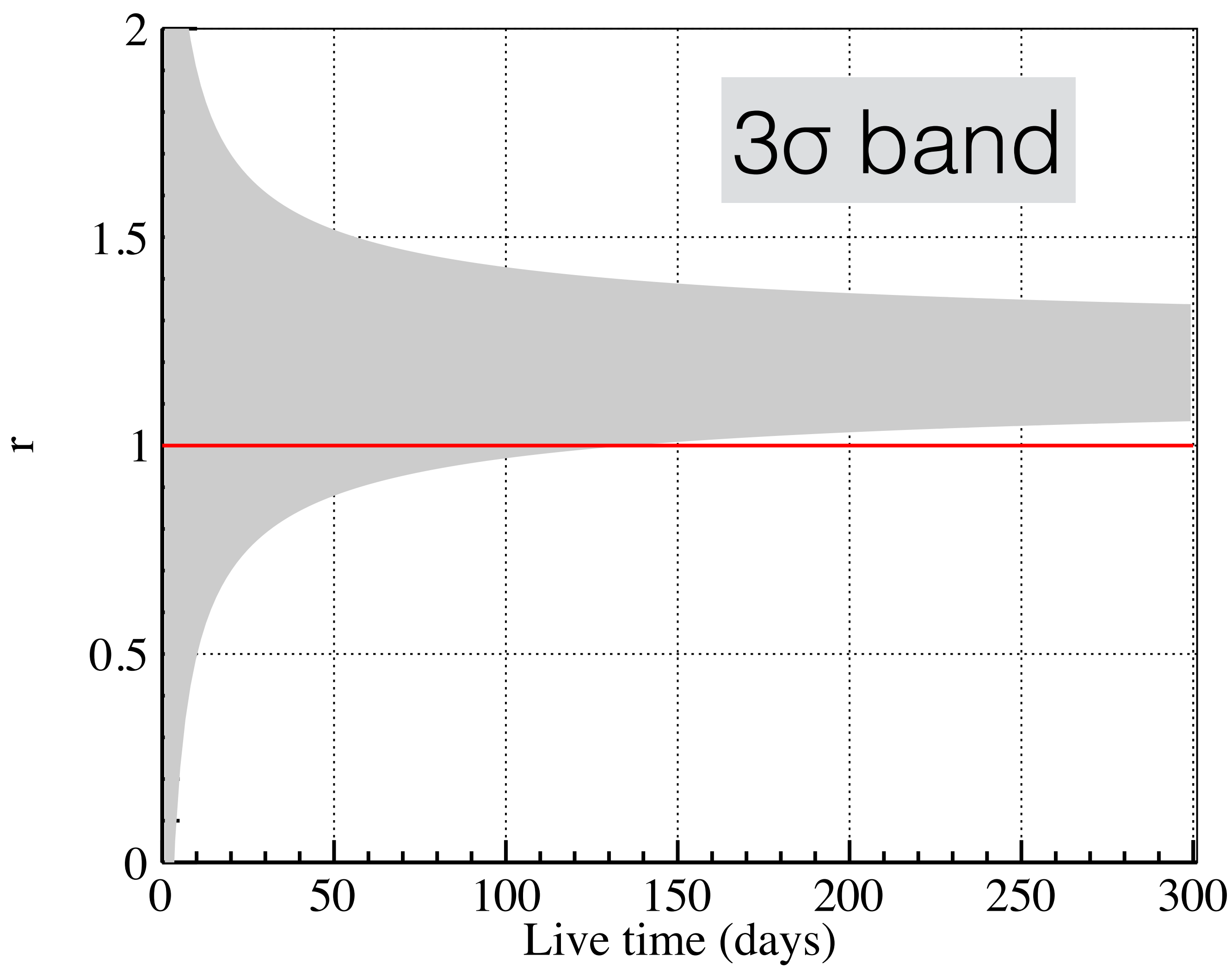
- ROI: Kinetic energy of electron ***T*** ~ [2, 3] MeV
- Average energy of contribution neutrinos: 6.18 MeV



1 year data: 14%
3.2% rate precision
12% theory uncertainty

Sensitivity to upturn

- Define ratio of avg P_{ee} between JUNO and Super-K
- r>1: evidence of upturn



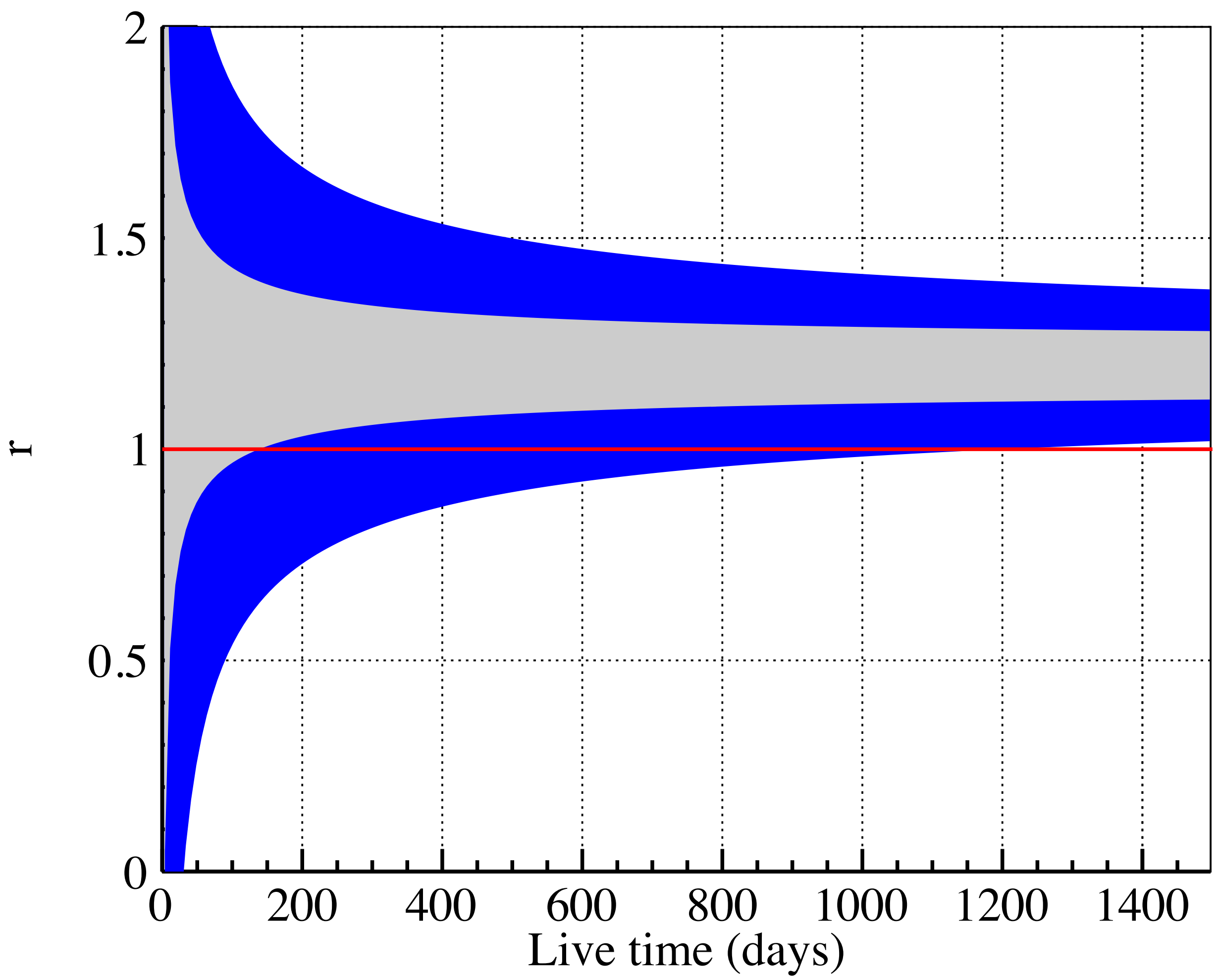
$$r^{SK/JUNO} = \frac{P_{ee}(\text{Super-K})}{P_{ee}(\text{JUNO})}$$

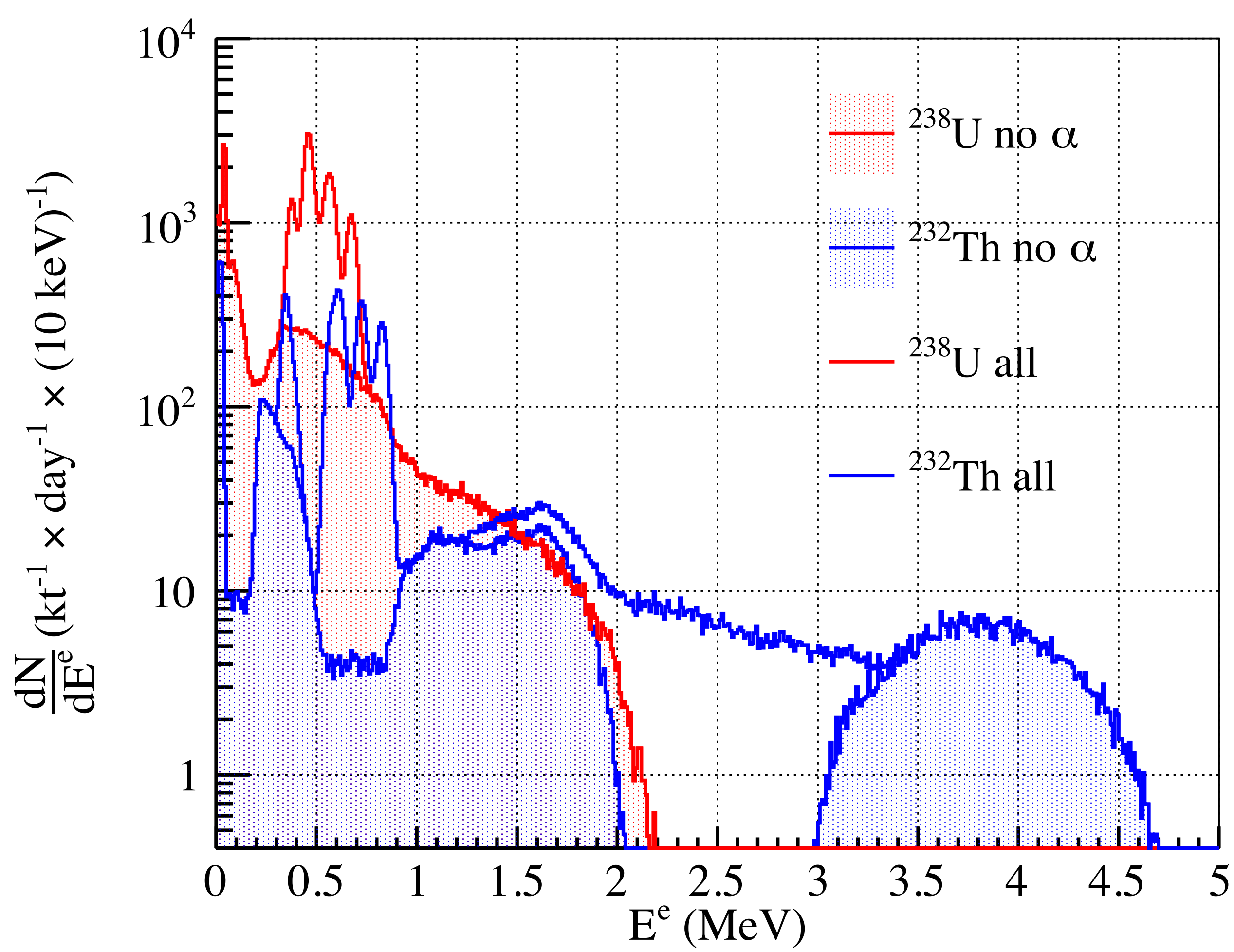
140 days of data:
>3σ rejection of H_0

Discussions

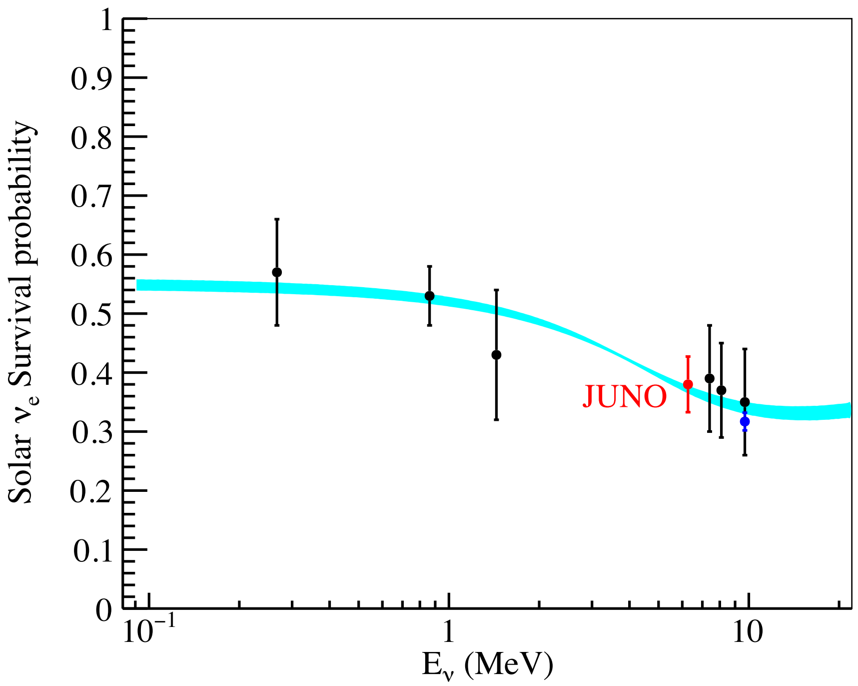
- ^{238}U & ^{232}Th ~ **10^{-15} g/g: 1200 days** to reach 3σ.
- However, the leakage mainly comes from **tail of ^{238}U**.

  A **shape** analysis or **higher energy threshold** can work.





Conclusions



- JUNO can uniquely detect ^8B solar neutrinos in the 2~3 MeV range (recoil electron energies). [Actually SNO can also do it..]
- S (3.6 per day) / B (1.4 per day) 2.5.
- This contribute to one data point at 6.2 MeV (neutrino energies) of neutrino survival probability. It's in the transition zone.
- JUNO can reject no-upturn hypothesis at 3σ within ~140 days.


Thanks
Dusk of L’Aquila
By Xuefeng Ding. All right reserved

Backup

External backgrounds: neutrons

- neutron capture γ can fall in ROI.
- neutron from (α,n) or Spontaneous Fission

Only Acrylic ball contribution considered (as major contribution)

(α,n) rate estimated using NEUCBOT based on TALYS

Type	^{238}U	^{235}U	^{232}Th
Concentration (g/g)	10^{-11}	10^{-13}	10^{-11}
(α, n) rate (n/decay)	1.2×10^{-6}	1.2×10^{-6}	1.4×10^{-6}
(α, n) n flux (per day)	7	0.5	3
SF rate $(n \cdot g^{-1} \cdot s^{-1})$	1.36×10^{-2}	3×10^{-4}	$< 1.32 \times 10^{-7}$
SF n flux (per day)	7	< 0.1	< 0.1

Contribution to ROI (no cut)

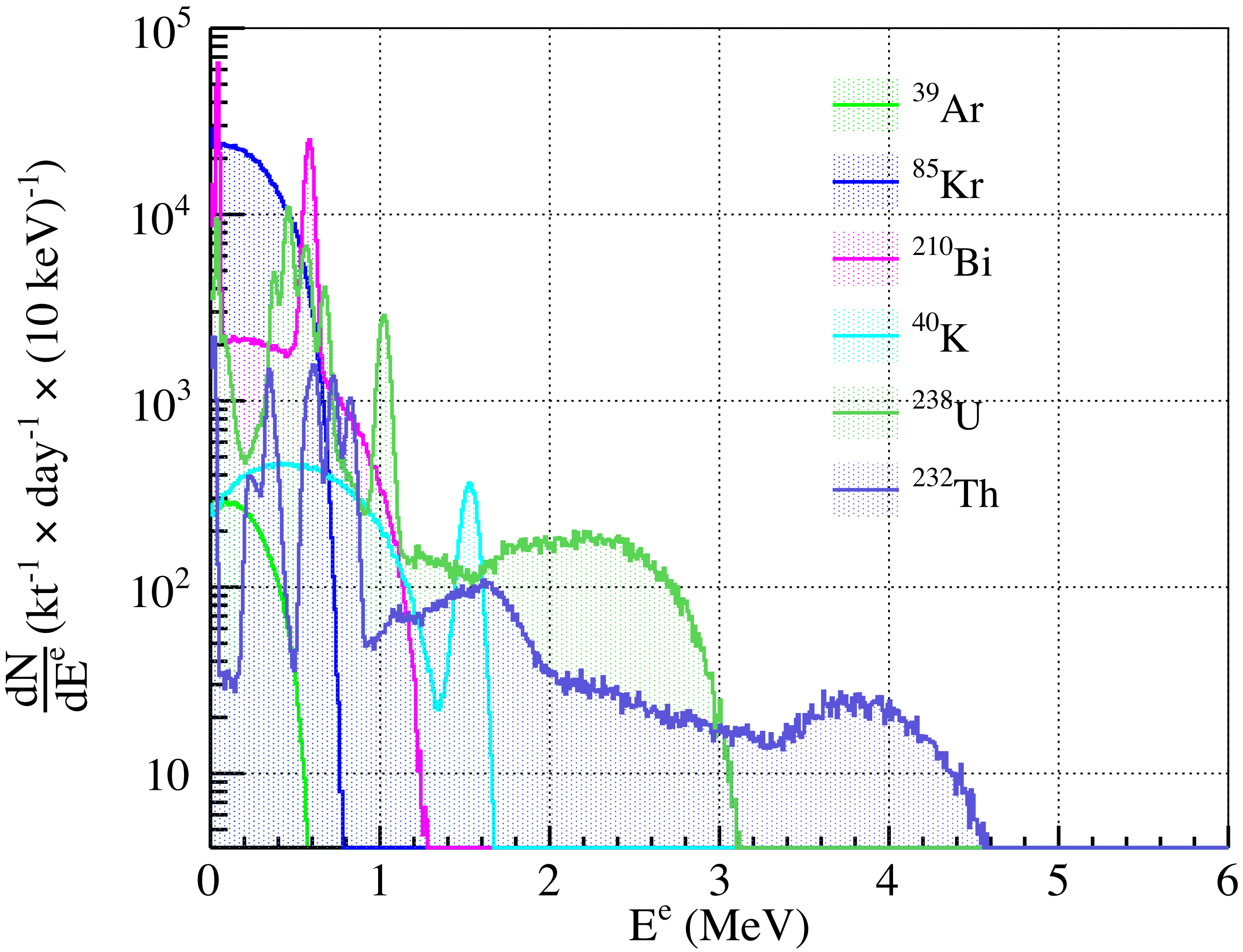
X	R_X^{tot} (day^{-1})	R_X^{ROI} (day^{-1})
^{8}B ν ES	90.55	13.23
(α, n)	$\mathcal{O}(10)$	$\mathcal{O}(10)$

LS internal backgrounds

- Based on F.P. An et al, 10.1088/0954-3899/43/3/030401
- 10^{-17} g/g ^{238}U, ^{232}Th (^{40}K, ^{210}Bi, ^{39}Ar, ^{85}Kr not contributing)

Contribution to ROI (no cut)

X	R_X^{tot} (day^{-1})	R_X^{ROI} (day^{-1})
^{8}B ν ES	90.55	13.23
External γs	3.333×10^7	9.105×10^5



Cosmogenic: scaling MC

- MC are biased
- Naive correction

$$R_X^{\mathrm{JUNO}} = R_X^{\mathrm{JUNO}}(\mathrm{MC}) \cdot \frac{R_X^{\mathrm{BX}}(\mathrm{data})}{R_X^{\mathrm{BX}}(\mathrm{MC})}$$

Borexino 10.1088/1475-7516/2013/08/049

	FLUKA	Borexino
	3 ± 19 GeV	—
Isotopes	ield $[10^{-7}\,(\mu\,\mathrm{g/cm^2})^{-1}]$	
^{12}N	0.5 ± 0.2	< 1.1
^{12}B	28.8 ± 1.9	56 ± 3
^{8}He	0.30 ± 0.15	< 1.5
^{9}Li	3.1 ± 0.4	2.9 ± 0.3
^{8}B	6.6 ± 0.6	14 ± 6
^{6}He	17.3 ± 1.1	38 ± 15
^{8}Li	28.8 ± 1.0	7 ± 7
^{9}C	0.91 ± 0.10	< 16
^{11}Be	0.59 ± 0.12	< 7.0
^{10}C	14.1 ± 0.7	18 ± 5
^{11}C	467 ± 23	886 ± 115
Neutrons	ield $[10^{-4}\,(\mu\,\mathrm{g/cm^2})^{-1}]$	
	2.46 ± 0.12	3.10 ± 0.11

Cosmogenic backgrounds

- Results

Isotope Unit	R^{BX}_{scaled} day^{-1}	R^{KL}_{scaled} day^{-1}	R^{FL}_{scaled} day^{-1}	R^{G4}_{scaled} day^{-1}	used day^{-1}
^{10}C	$(7 \pm 2) \times 10^2$	$(7.6 \pm 0.9) \times 10^2$	$(6.4 \pm 0.8) \times 10^2$	$(7.4 \pm 0.9) \times 10^2$	760.4
^{11}Be	$< 2.9 \times 10^2$	$(5.1 \pm 0.9) \times 10$	$(5 \pm 2) \times 10$	$(3 \pm 2) \times 10$	51.2
^{16}N	-	-	-	-	13
^{6}He	$(1.6 \pm 0.6) \times 10^2$	-	$(1.2 \pm 0.5) \times 10^3$	$(7 \pm 4) \times 10^2$	1543
^{8}Li	$(3 \pm 3) \times 10^2$	$(6 \pm 1) \times 10^2$	$(4.5 \pm 1.0) \times 10^2$	$(2.6 \pm 0.6) \times 10^2$	560.2
^{8}B	$(6 \pm 3) \times 10^2$	$(4 \pm 1) \times 10^2$	$(3.2 \pm 1.0) \times 10^2$	$(4 \pm 2) \times 10^2$	387.2
^{9}Li	$(1.2 \pm 0.2) \times 10^2$	$(1.02 \pm 0.09) \times 10^2$	$(7 \pm 2) \times 10$	$(2.1 \pm 0.4) \times 10^2$	101.4
^{9}C	$< 6.6 \times 10^2$	$(1.4 \pm 0.6) \times 10^2$	$(1.1 \pm 0.5) \times 10^2$	$(3 \pm 2) \times 10^2$	139.0
^{8}He	< 59	$(4 \pm 2) \times 10$	$(2 \pm 3) \times 10$	< 82	31.83
^{12}B	$(2.3 \pm 0.2) \times 10^3$	$(2.0 \pm 0.2) \times 10^3$	$(1.6 \pm 0.2) \times 10^3$	$(1.3 \pm 0.2) \times 10^3$	1968
^{13}B	-	-	-	-	12
^{12}N	< 44	$(8 \pm 2) \times 10$	$(6 \pm 4) \times 10$	$(9 \pm 3) \times 10$	81.34
^{11}C	$(3.7 \pm 0.5) \times 10^4$	$(4.1 \pm 0.7) \times 10^4$	$(3.1 \pm 0.5) \times 10^4$	$(2.5 \pm 0.4) \times 10^4$	37344
^{7}Be	-	-	-	-	5438
^{10}Be	-	-	-	-	1419
neutron	$(1.28 \pm 0.05) \times 10^5$	$(1.3 \pm 0.2) \times 10^5$	$(2.0 \pm 0.2) \times 10^5$	$(1.87 \pm 0.08) \times 10^5$	127975

Over-efficiency of TFC: ^{10}C

"TFC **CAN** removed **0-neutron-proc.** cosmogenic"

Borexino	$\epsilon_{\mu}^{\text{track}}$	$\epsilon_{n}^{\text{tag}}$	$\epsilon(^{10}\text{C})$ (%)
	99.99	94	$92.5^{+7.5}_{-20.0}$

Borexino, 10.1088/1475-7516/2013/08/049

TFC effciency: $$\frac{N\times 92.5\%}{N\times 90\%\times 94\%} = 109\%$$

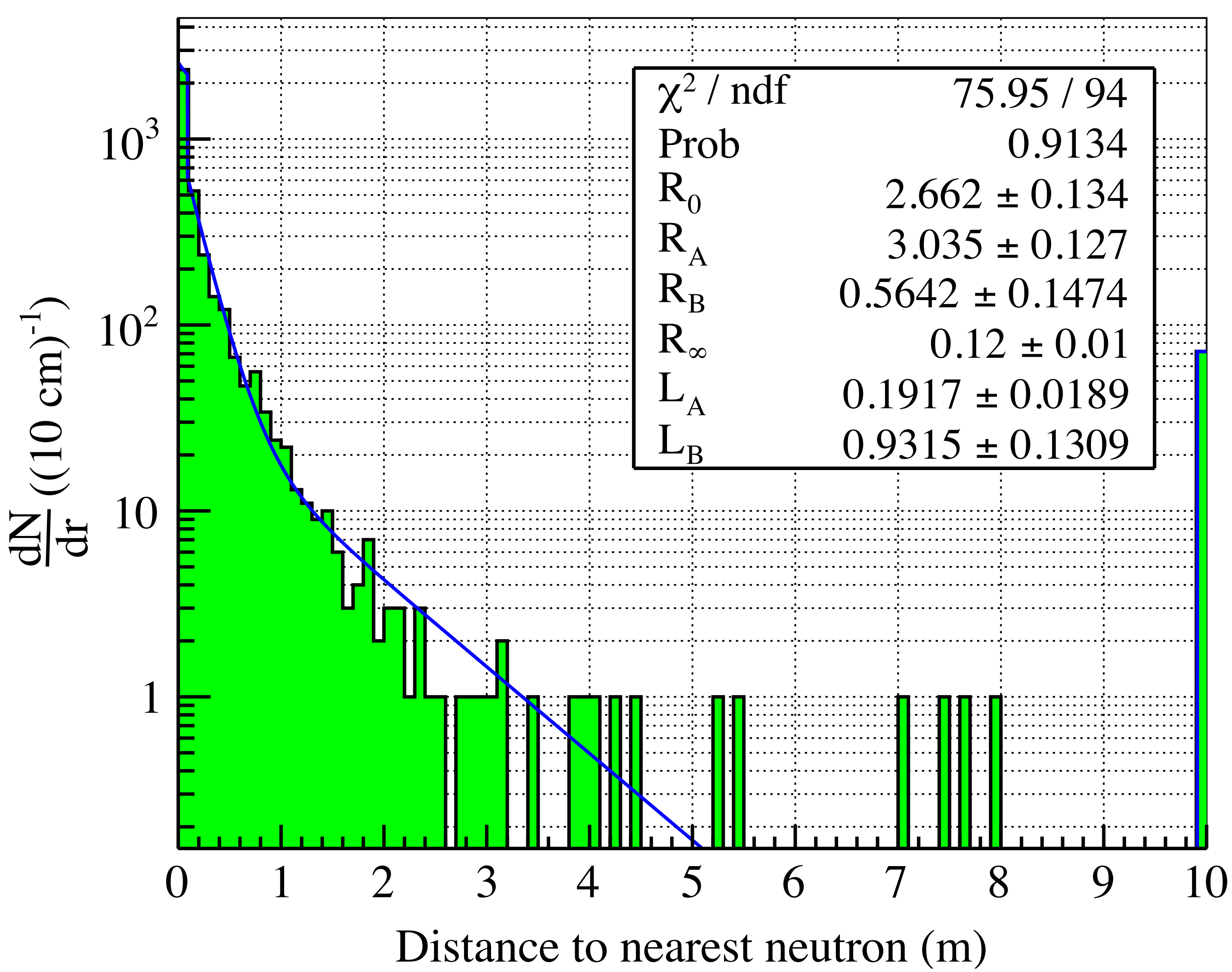
>1n ratio

DocDB 1486

Over-efficiency of TFC: ^{11}Be

"TFC **CAN** removed **0-neutron-proc.** cosmogenic"

Simulation by Geant4



^{11}Be

- main ch: ^{12}C(n, 2p)^{11}Be
- only 12% prod. is with n
- <-dist. to nearest neut.
- **2% μ track: no neut**.
- **97% nearest n <2 m**