Supernova Relic Neutrino Search with Hyper Kamiokande

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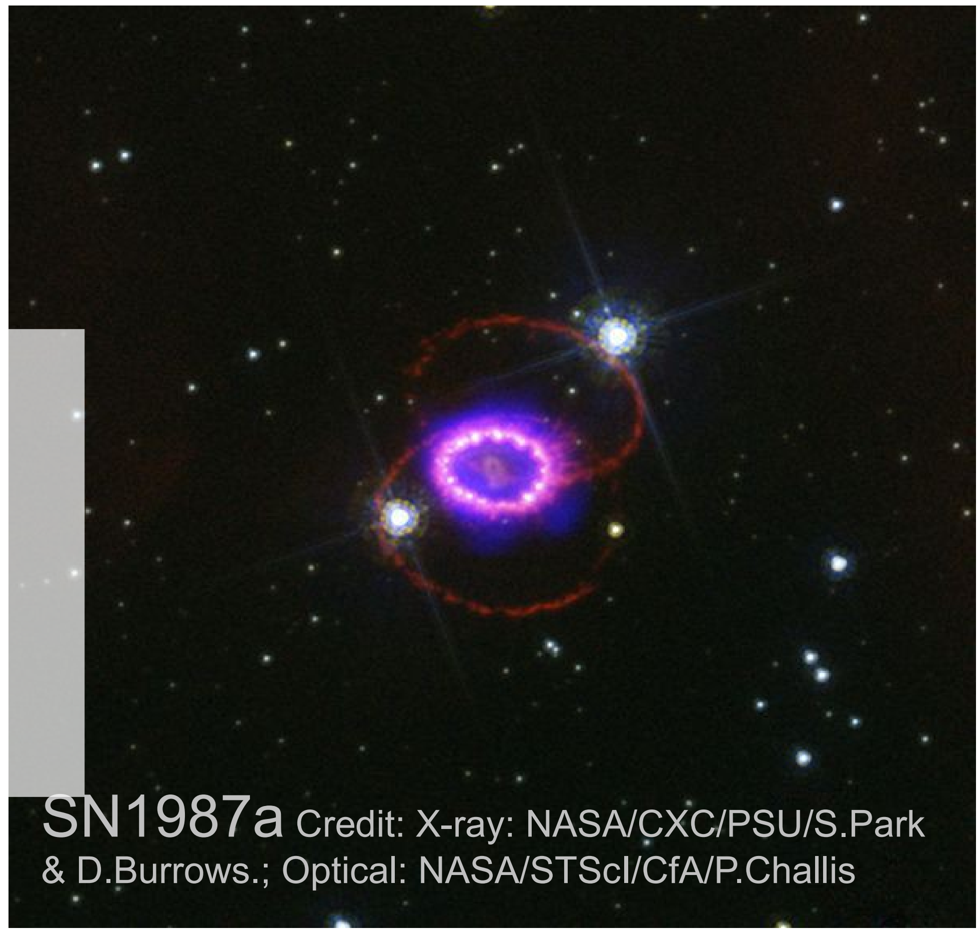
for HK-Astro WG



3rd Open Meeting for
Hyper Kamokande

21th June 2013.
At Kavli IPMU, Tokyo Univ.

Motivation of this study

- **Motivation**

  To study the effect of the location (depth) on SRN search with HK.

  Spallation rate ×1, ×3, ×4, ×5 and ×7 of SK case are studied.

  Shimizu-san studied HK will have ×5 μ rate and ×4 spallation rate.

- **Contents**

  1. Updates
     - Signal efficiency with more muons.
     - Remaining spallation events with 80% signal efficiency.
  2. SRN spectrum sensitivity with Hyper Kamiokande.

Current status of SRN search with SK

Supernova Relic Neutrino is diffused neutrino background from supernovae > ~Mpc.

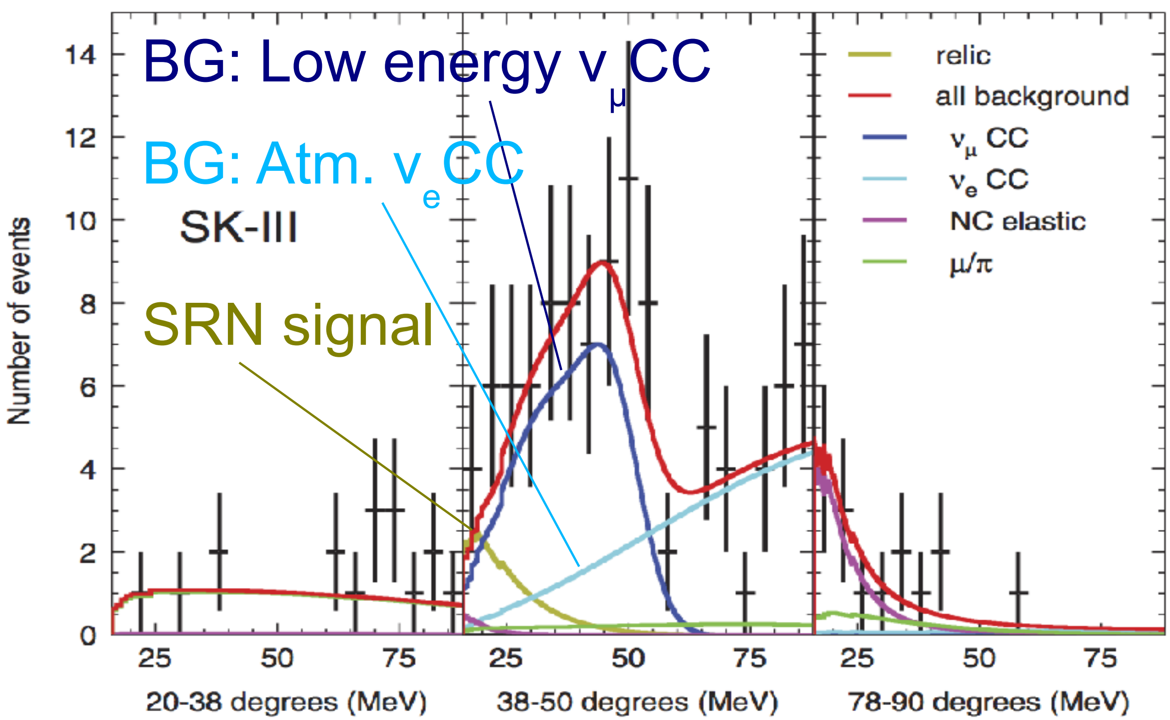
Recent SRN search was done with single positron tag analysis.

(K.Bays et al., Phys.Rev.D85, 052007 (2012))

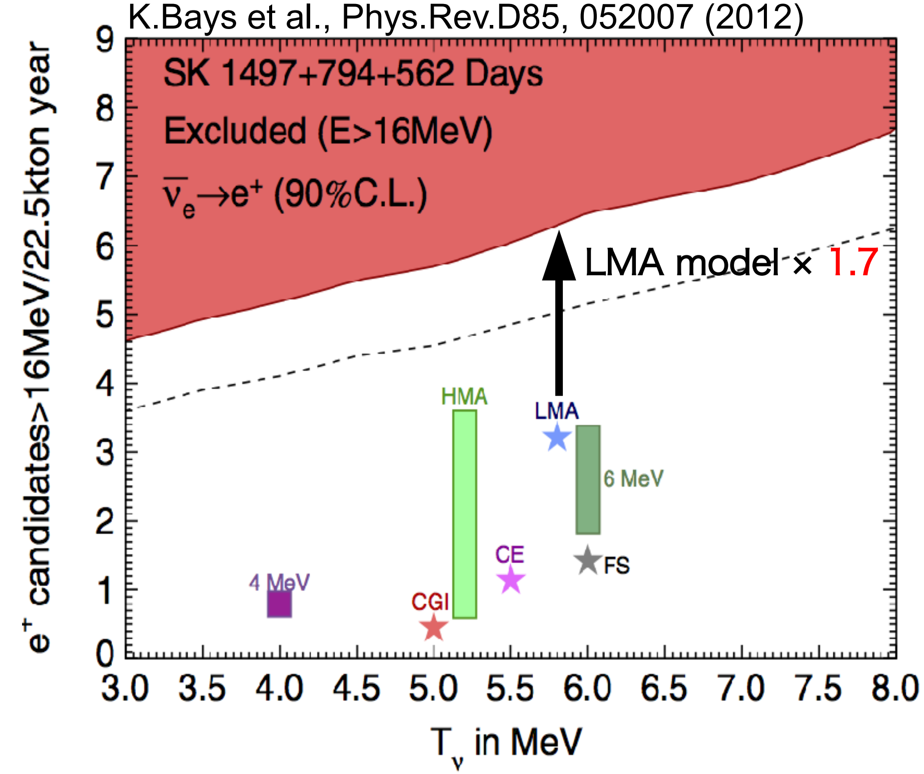
- SRN Flux < 1.7× LMA Flux (90%CL)

A new spallation likelihood cut (**relic spallation cut**) was applied.

The effect of more spallation on the new cut was studied last time.



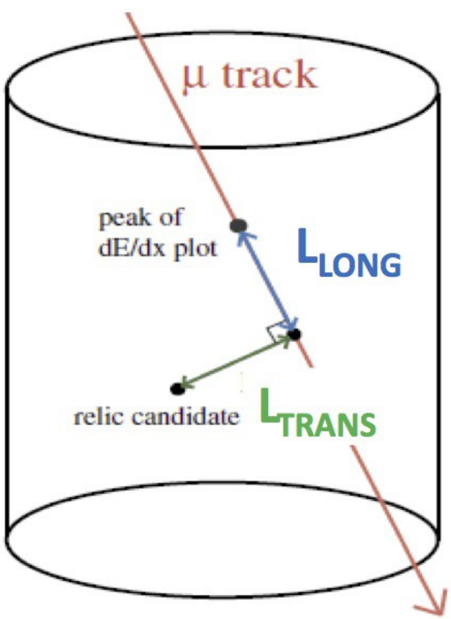
K.Bays et al., Phys.Rev.D85, 052007 (2012)

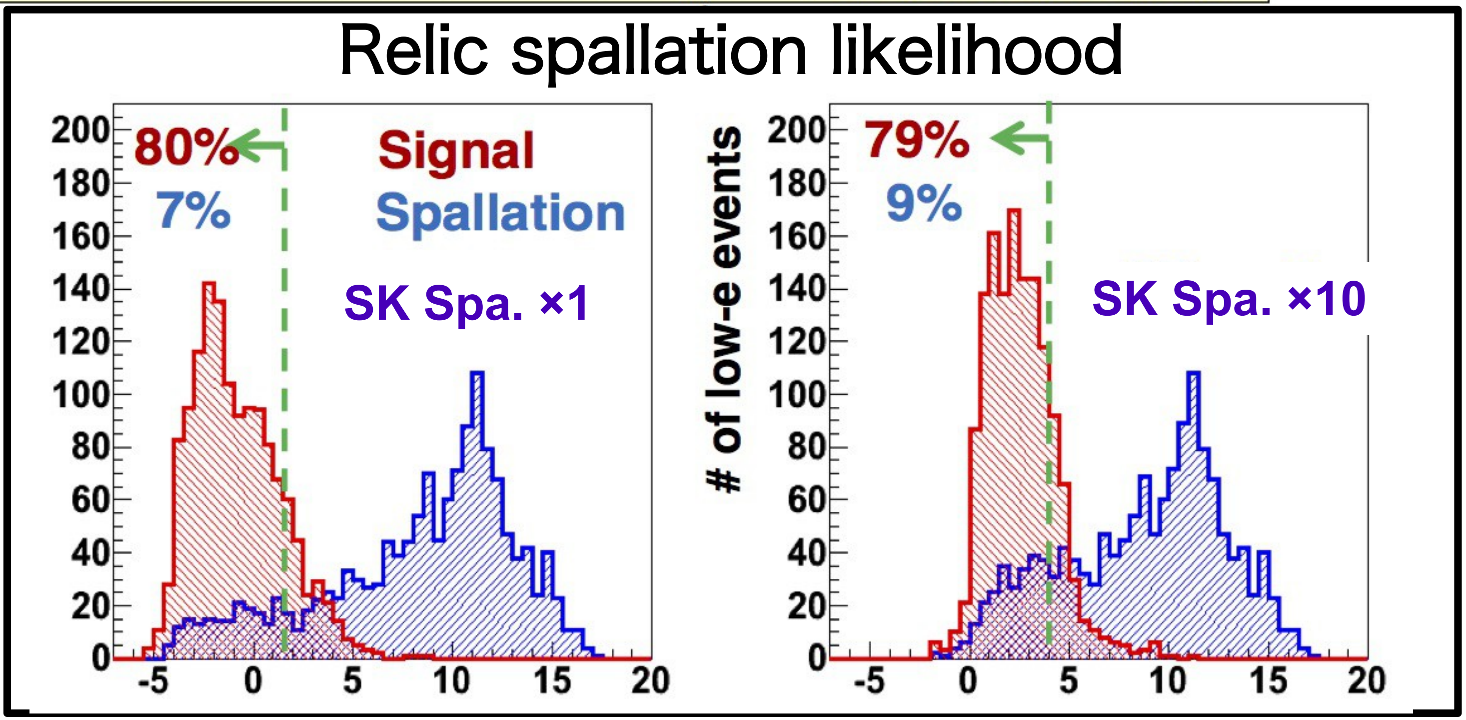


Spallation cut in SK

Y. Takeuchi,
2nd HK
open meeting

- Likelihood method is used to reduce spallation products in SK
- "Solar spallation cut" (in PRD73, 112001)
  - *Likelihood* = PDF(Q_{RES}) * PDF(ΔT) * PDF(L_{TRANS})
- "(supernova) relic spallation cut" (in PRD85, 052007)
  - *Likelihood* = PDF(Q_{PEAK}) * PDF(ΔT) * PDF(L_{TRANS}) * PDF(L_{LONG})
- Improved likelihood function is used in "relic spallation cut"





SK-II relic spallation likelihood and event samples are used for estimating HK. (SK-II: photo coverage 19%)

Remaining spallation events

- **Keep ~80% signal efficiency in 17.5 – 20 MeV**
  - Omit some cuts (Dt, Lt, gof cuts), then just use likelihood distribution.
  - At moment, we assumed <17.5 MeV region is same

	Mu*1	Mu*2	Mu*3	Mu*5	Mu*7	Mu*10
Signal efficiency	80%	79%	78%	78%	79%	77%
Remaining spallation products	7%	7%	8%	9%	9%	10%

Factor ~1.4 increase

Stat. errors are ~10%
Used for Solar study (Y. Koshio)

Cf.: solar spallation cut: factor ~3 increase

8

Y. Takeuchi,
2^{nd} HK open meeting

More muons mean worse separation of ν signal and spallation products.

- Solar ν
- Atmospheric ν
- Spallation

were counted.
= **overestimated**.

Update : Solar neutrino events in remaining samples are removed, with directional and multiple scattering goodness cut.

Remaining spallation events (Updated)

2nd HK open meeting

	spallation ×1	×2	×3	×5	×7	×10
Signal Efficiency	80%	79%	78%	78%	79%	77%
Remaining spallation rate	7%	7%	8%	9%	9%	10%

Updated

New

	spallation ×1	×2	×3	×4	×5	×7
Signal Efficiency	80%	81%	81%	80%	80%	81%
Remaining spallation rate	1.2%	2.1%	2.5%	3.0%	3.9%	4.6%

Current SK (solar) : 5~6%

Factor ×2.5 increase

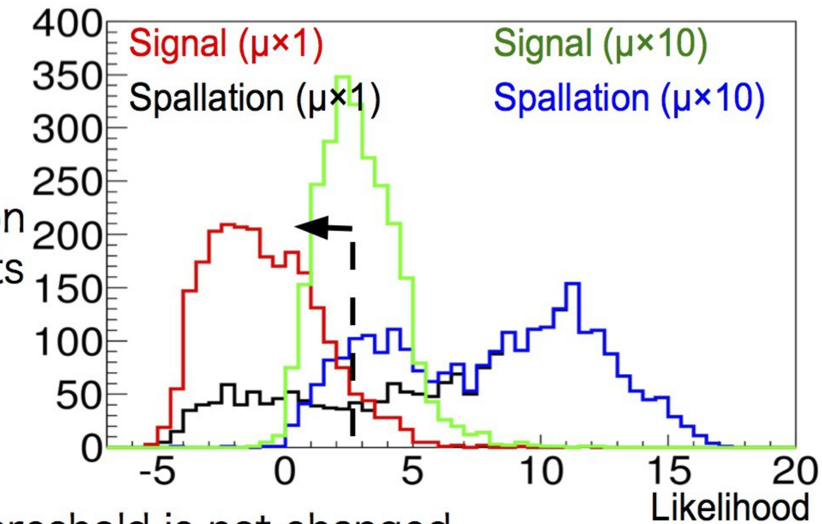
- With ×4 spallation events, the remaining spallation rate will be increased by a factor of 2.5.
- Considering the cosmic muon rate of ×5, the remaining spallation products in HK after relic spallation cut will be **15%**.
- With current SK and solar spallation cut, the remaining spallation products is **5~6%**.

Corresponding study (e.g. solar neutrino analysis) will be done.

Signal efficiency with more cosmic μ

T. Yano,
2nd HK open meeting

- The more cosmic muons result in the worse separation between the spallation events and the others.



- For SRN study, Likelihood threshold is not changed.
- It retains same spallation reduction efficiency.
  = Negligible spallation events after spacut.
- But **it reduces the signal efficiency**.

Signal Efficiency	Cosmic μ ×1	×2	×3	×5	×7	×10
17.5-20MeV	81%	65%	52%	33%	21%	11%
20-26MeV	90%	81%	74%	59%	46%	35%

More cosmic muons, worse signal efficiency

Update :

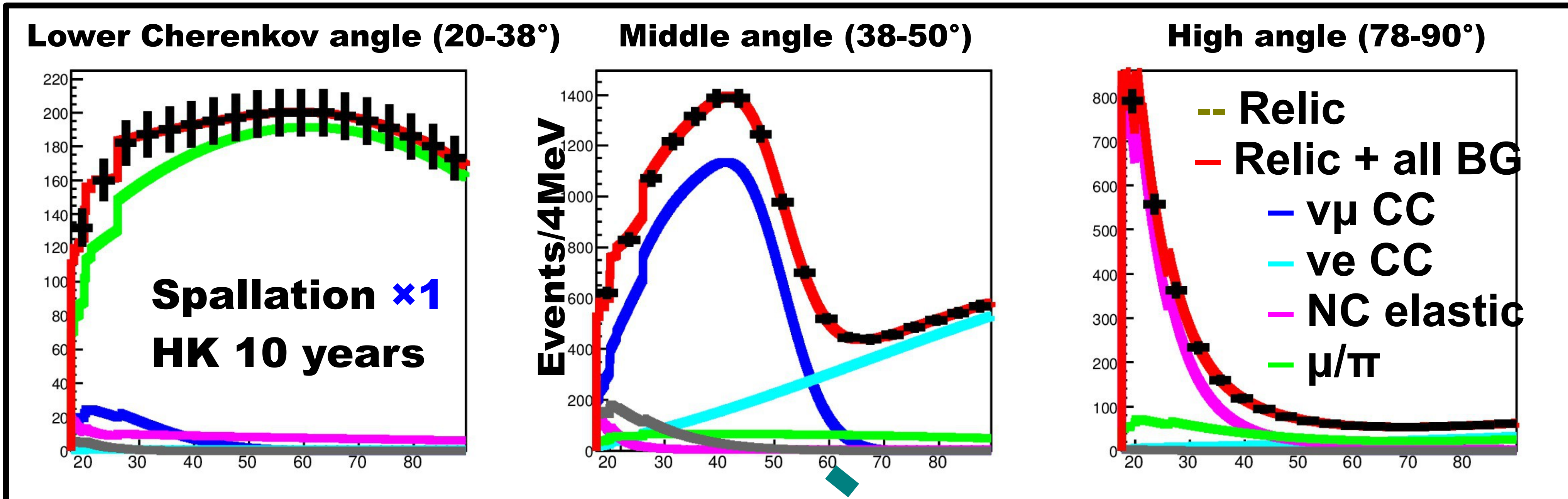
- Effect of solar ν is removed.
  It doesn't affect to signal efficiency.
- μ×4 case is studied.

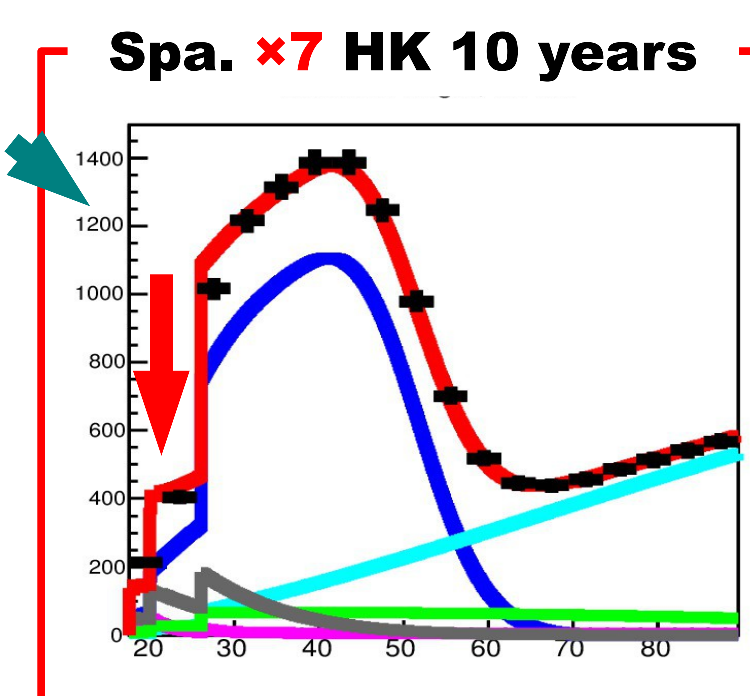
Updated

Signal Efficiency	spallation ×1	×2	×3	×4	×5	×7
17.5-20MeV	79%	62%	50%	39%	29%	17%
20-26MeV	90%	77%	73%	67%	54%	43%

New!

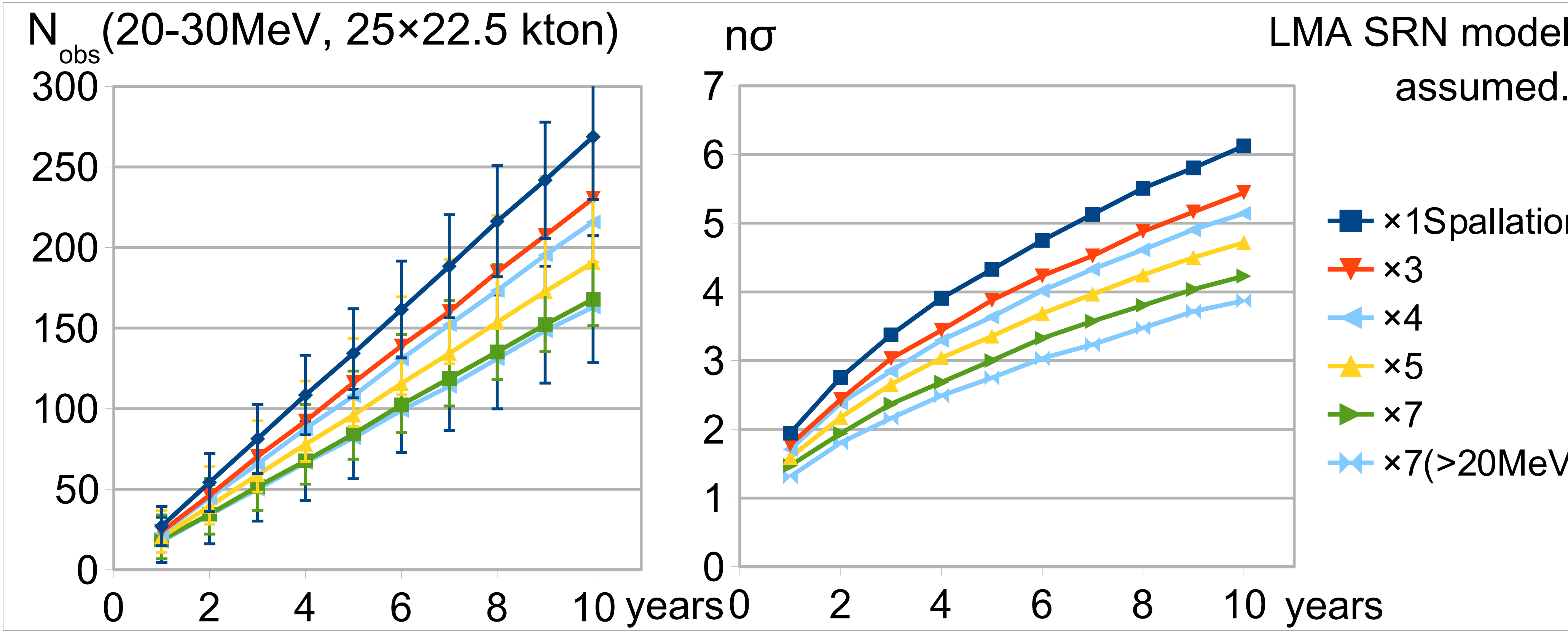
Update : non-0 significance of SRN





1. Event samples are made from SK-II best fit **BG** spectrum and expected **SRN** spectrum (LMA model, Ando et al. 2003).
2. Signal efficiency of **relic spallation cut** and **other cuts (e.g. solar ν cut)** are considered. **(Updated)**
3. The event samples are fitted with **BG** and **LMA** spectra, using MINUIT2 (ROOT).

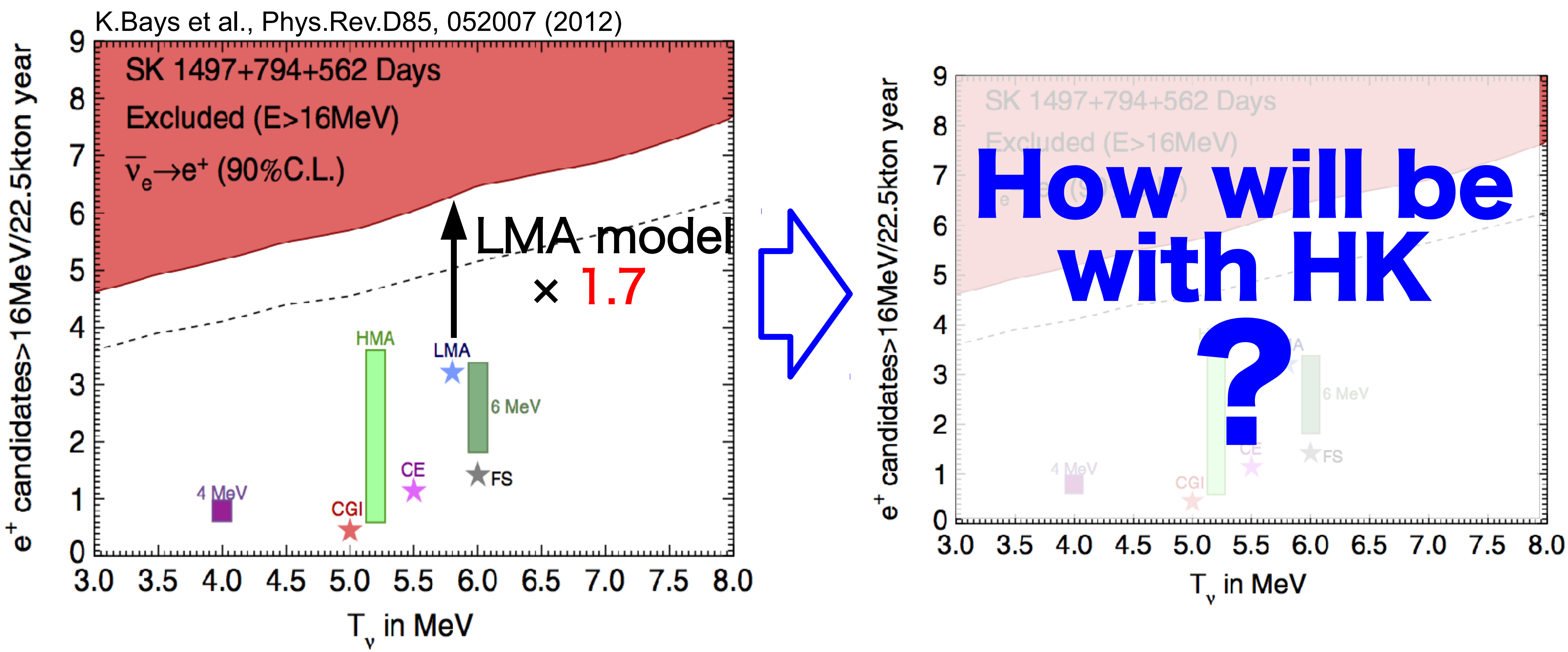
of SRN events and non-0 significance



The numbers of observed SRN events (20 - 30 MeV) and the non-zero significances (n = N_{obs}/[fit error σ]) are shown.

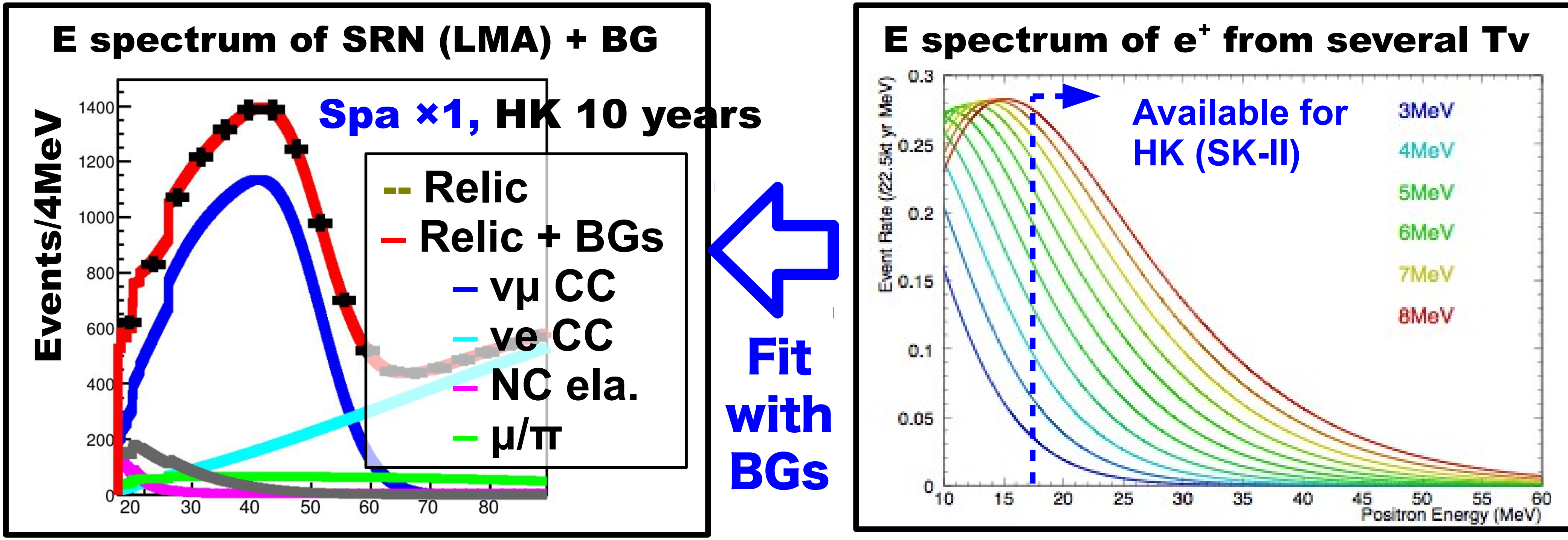
- In ×1spallation case (same rate as SK), the significance will be ~6σ after 10 years. (It was 7σ at HK 2nd open meeting.)
- In ×4 spallation case, it stays at ~5σ after 10 years. 4σ for ×7 case.
- The worst case, if only >20 MeV is available for ×7 spallation, it stays below 4σ.

Limit on SRN emitting spectrum



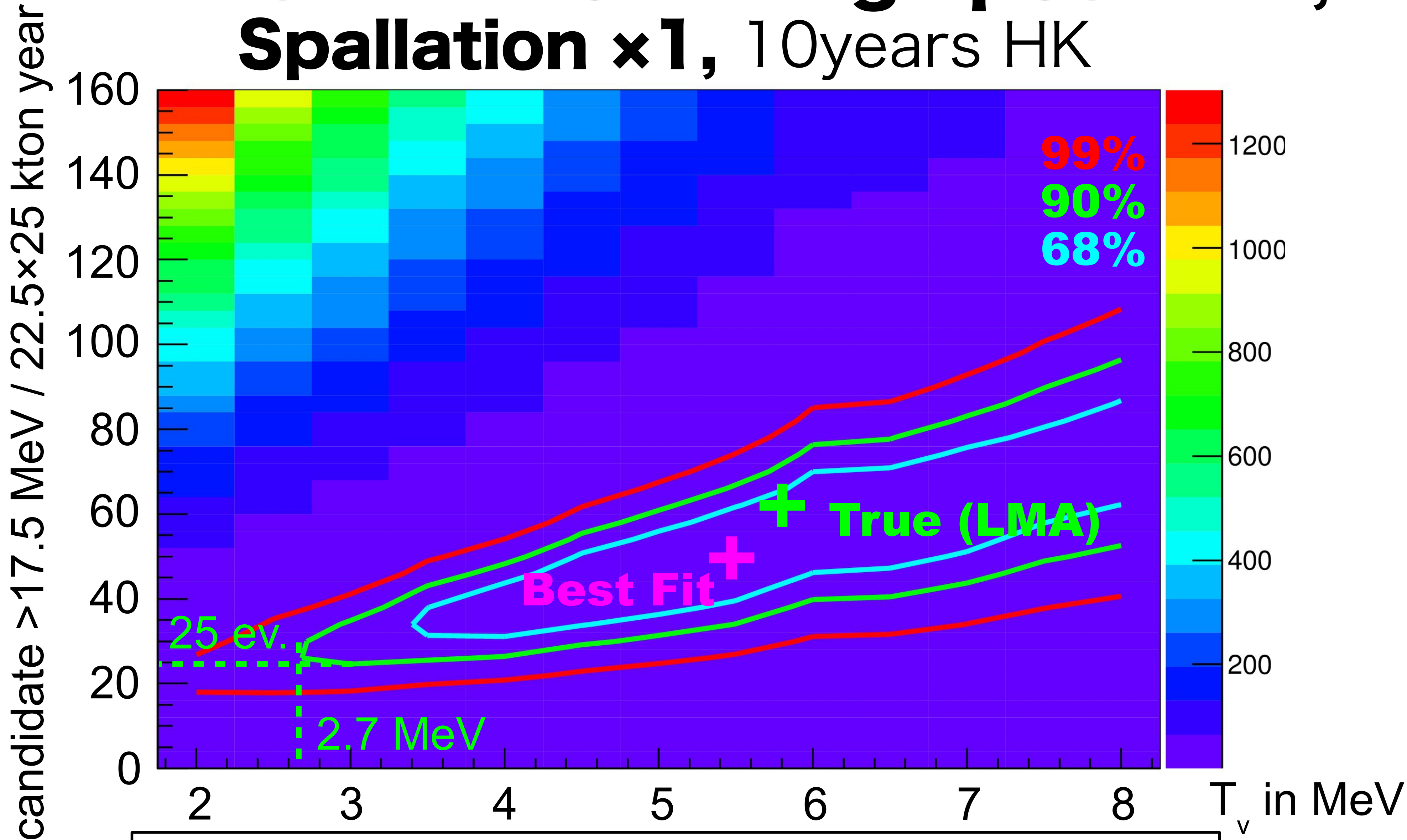
- SK-I, II and III 7.8 years got close to LMA SRN model by factor of 1.7.
- With HK, how close to SRN can we get?

Limit on SRN emitting spectrum
Method:



1. Fit LMA + BG model with general SRN model with SN ν temperature of 2 to 8 MeV and SN ν intensity.
2. Calculate -2 log likelihood for each ν temperature and intensity.
   - Only statistic error is considered here.
3. Plot 2D allowed regions for 66%, 90% and 99% C.L..

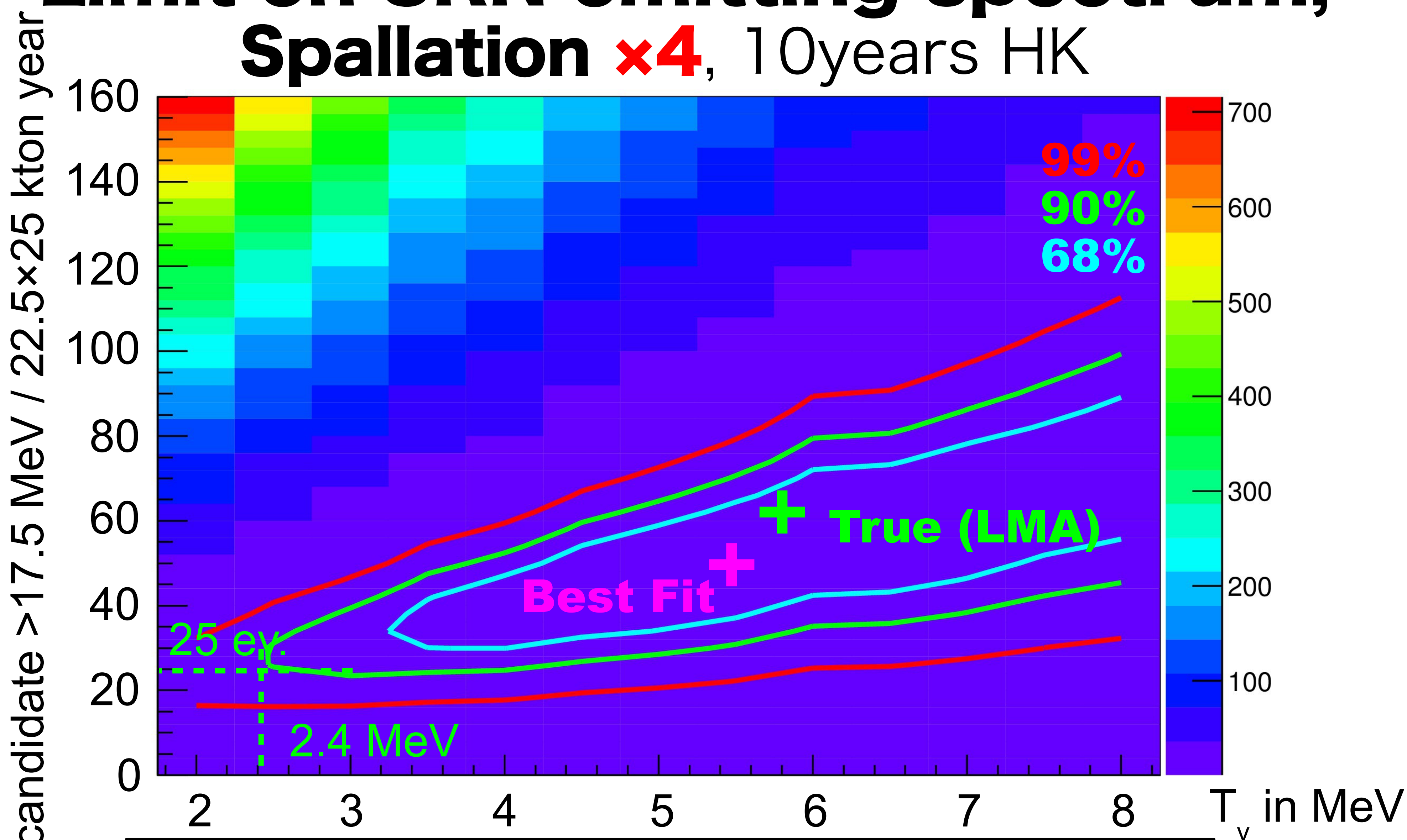
Limit on SRN emitting spectrum, Spallation ×1, 10years HK



Lower limit : T_ν > 2.7 MeV and N_{e+} > 25 events
(for E_{e+}>17.5MeV, 90% C.L.)

True (LMA) : T_ν = 5.8 MeV, N_{e+} = 58 events

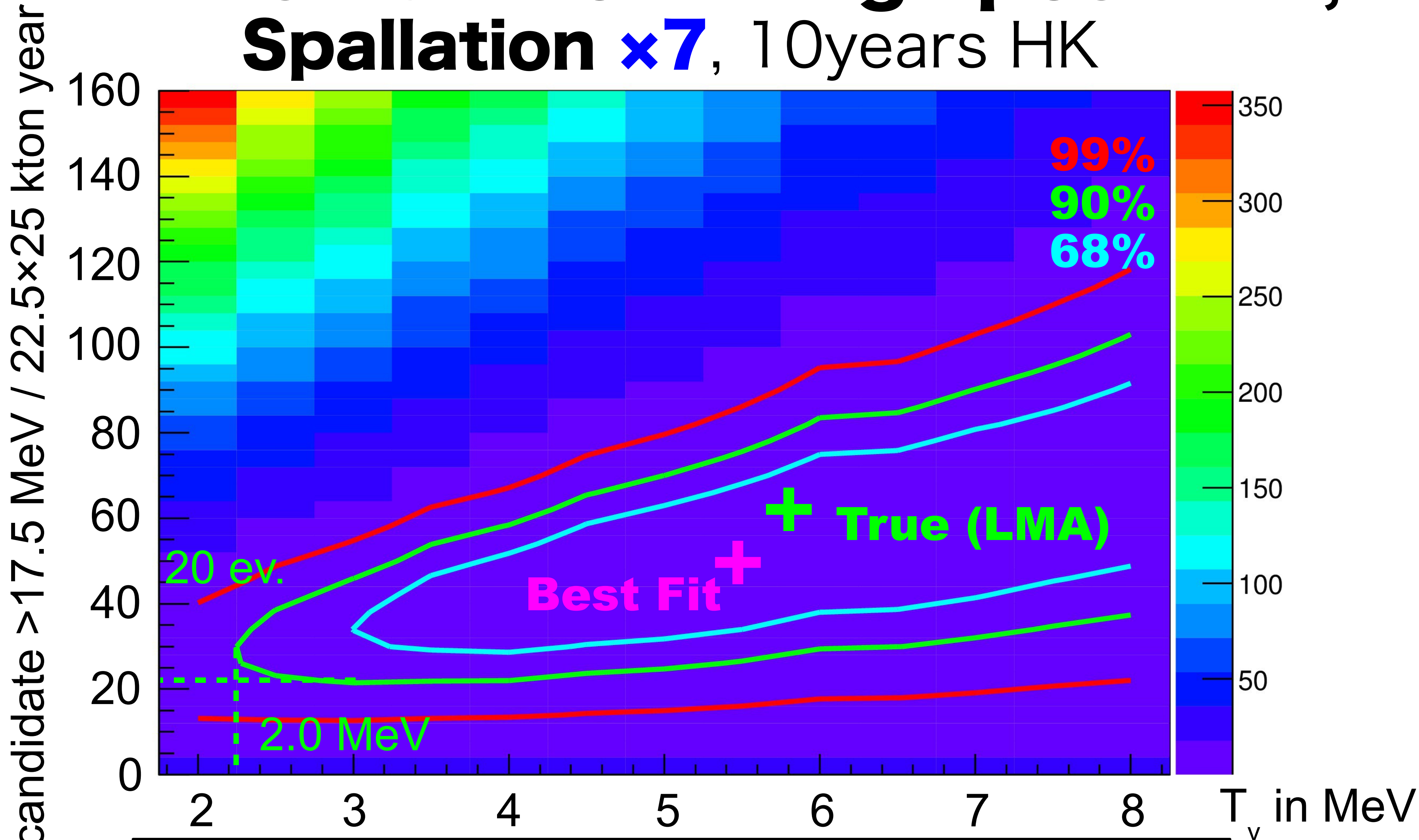
Limit on SRN emitting spectrum, Spallation ×4, 10years HK



Lower limit : T_ν > 2.4 MeV and N_{e+} > 25 events (for E_{e+}>17.5MeV, 90% C.L.)

True (LMA) : T_ν = 5.8 MeV, N_{e+} = 58 events

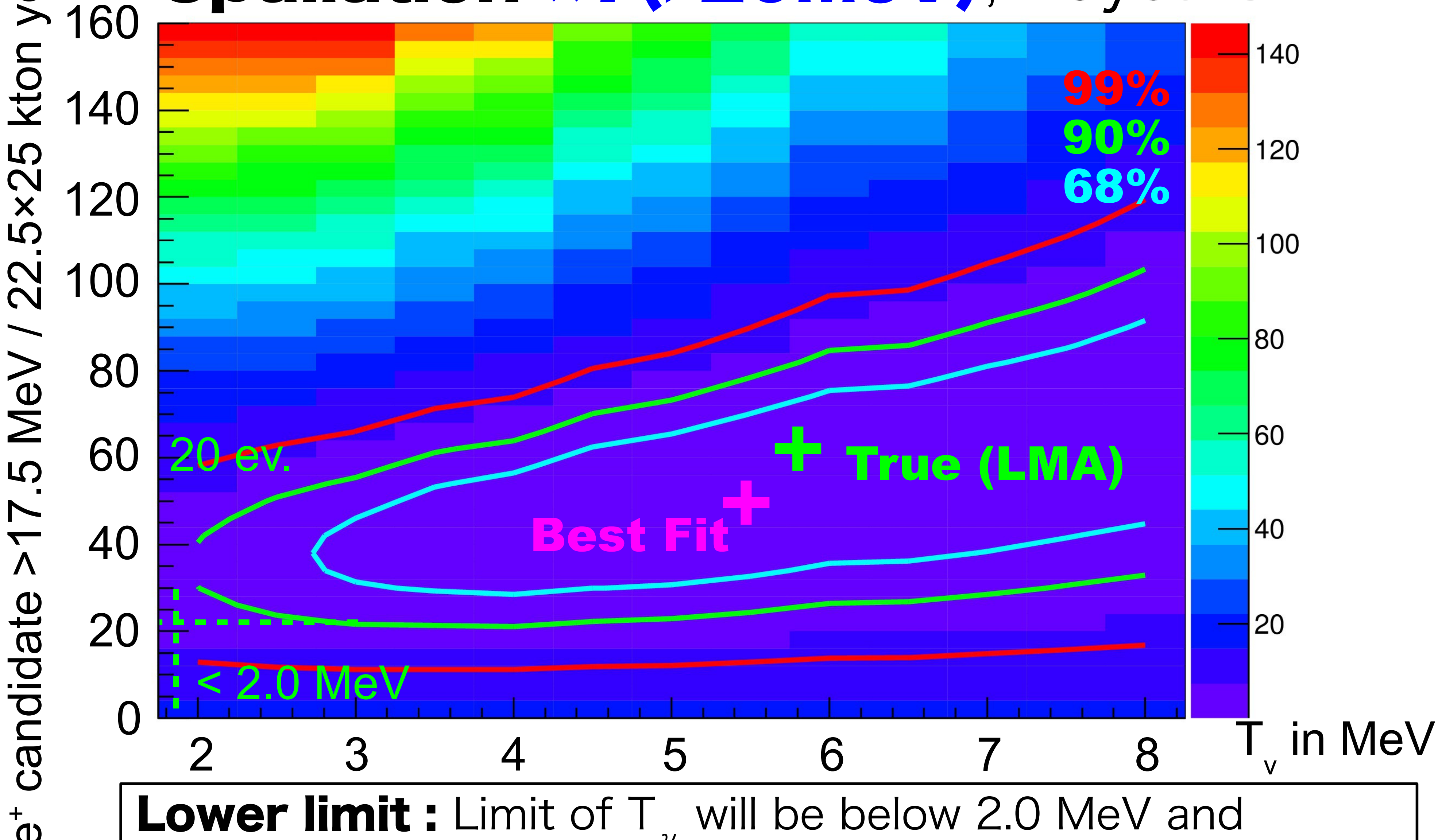
Limit on SRN emitting spectrum, Spallation ×7, 10years HK



Lower limit : T_ν > 2.0 MeV and N_{e+} > 20 events
(for E_{e+}>17.5MeV, 90% C.L.)

True (LMA) : T_ν = 5.8 MeV, N_{e+} = 58 events

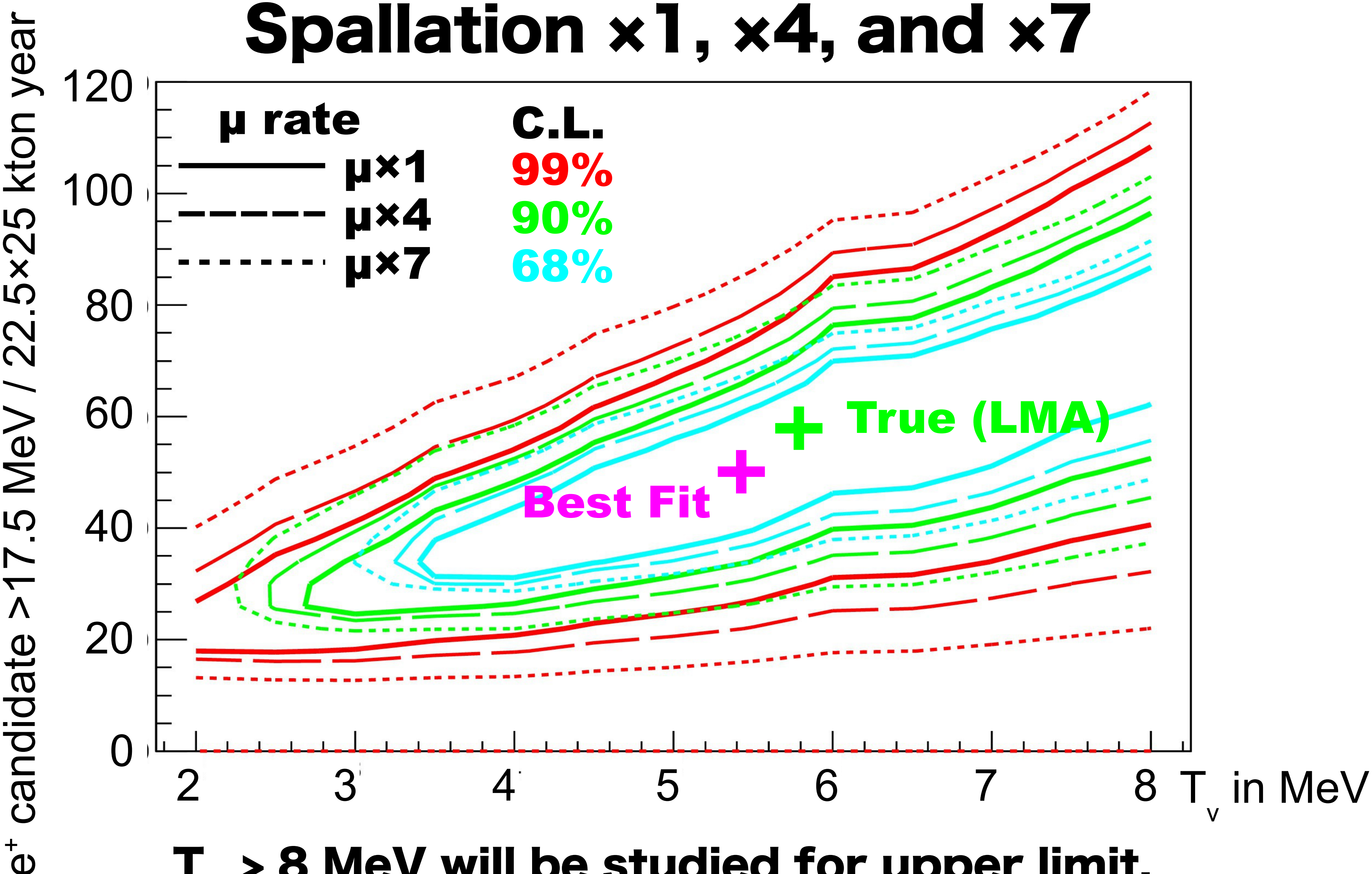
Limit on SRN emitting spectrum, Spallation ×7(>20MeV), 10years HK



Lower limit : Limit of T_ν will be below 2.0 MeV and N_{e+} > 20 events (for E_{e+}>17.5MeV, 90% C.L.)

True (LMA) : T_ν = 5.8 MeV, N_{e+} = 58 events

Limit on SRN emitting spectrum, Spallation ×1, ×4, and ×7



T_ν > 8 MeV will be studied for upper limit.
HK+Gd option will improve the limits.

Summary

- The effect of HK location (more cosmic muon rate) is studied.

- The remaining spallation events, while keeping the signal efficiency at 80%, will be increased to × 2.5 of ×1 spallation case in ×4 spallation case.

  In total, 15% remaining spallation events are expected for ×5μ and ×4 spallation.

- The significance of SRN will be 6σ after 10 years with HK, if the muon rate is same as SK.

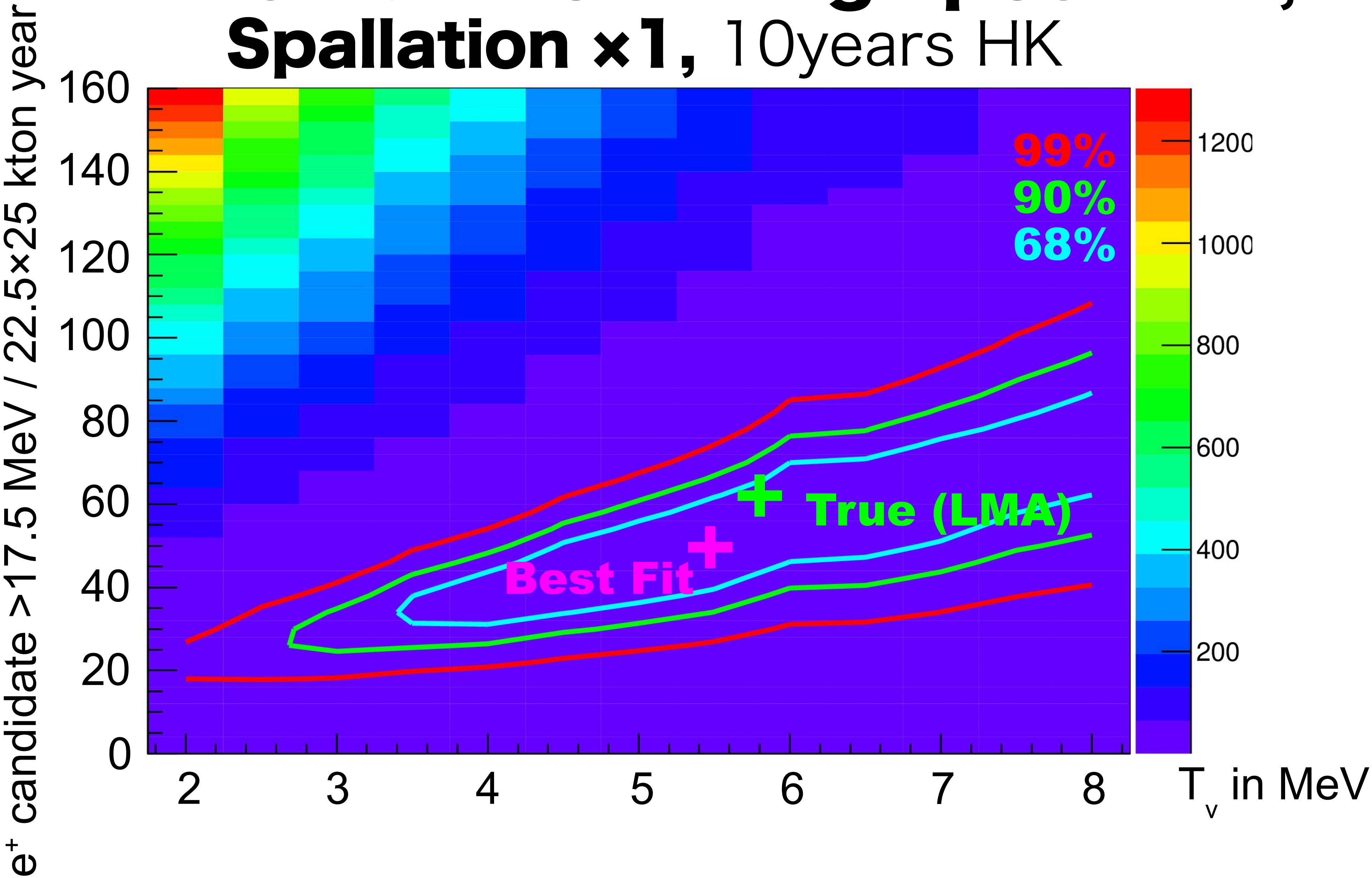
  In Tochibora, where the muon rate is ×4 of SK, the significance will be 5σ.

- HK's capability for limiting on SRN emitting spectrum is firstly studied.

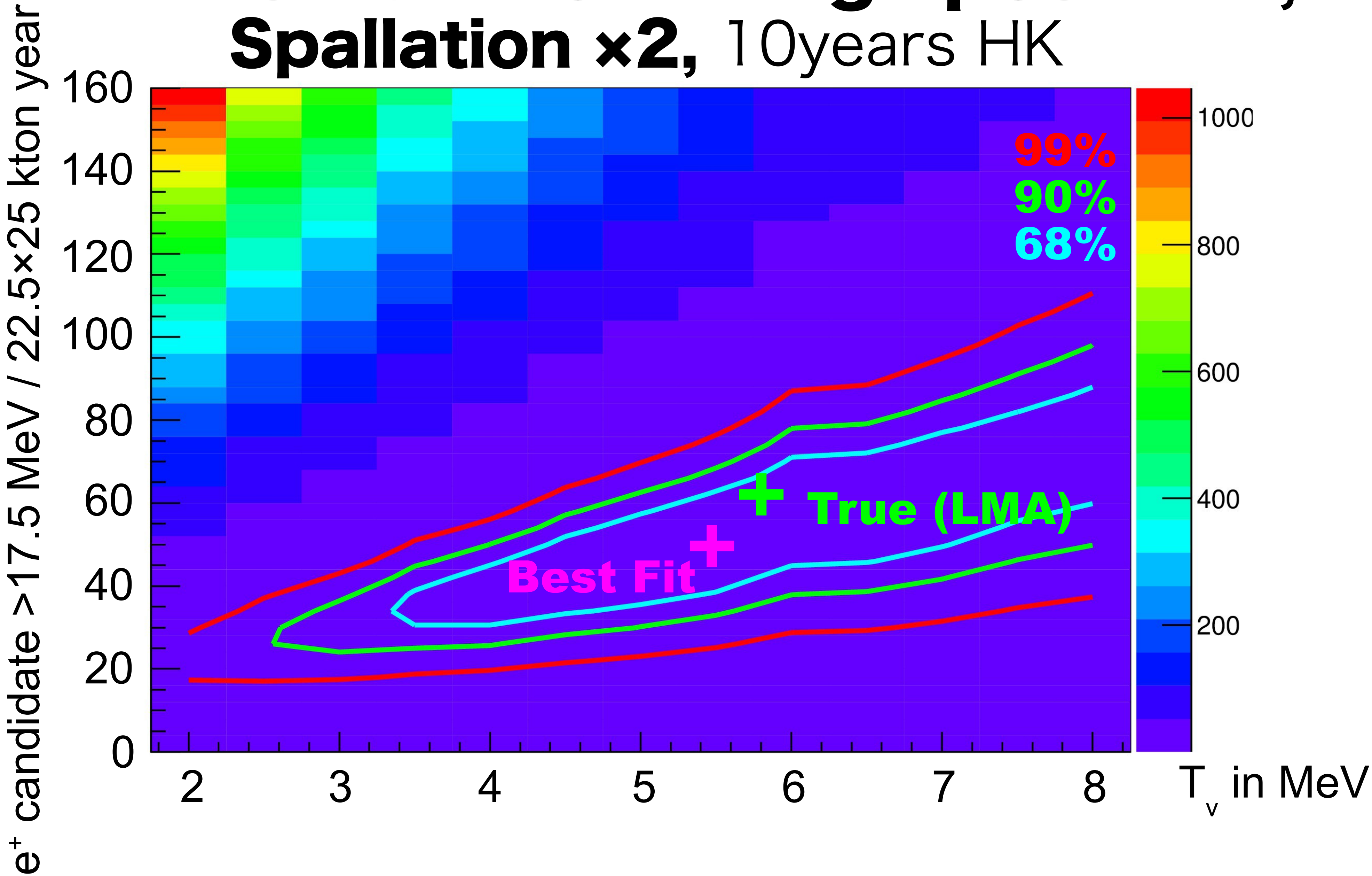
Lower limit : T_ν > 2.7 MeV and N_{e+} > 25 events (×1 μ)
T_ν > 2.4 MeV and N_{e+} > 25 events (×4 μ)
(for E_{e+}>17.5MeV, 90% C.L.)

True (LMA) : T_ν = 5.8 MeV, N_{e+} = 58 events

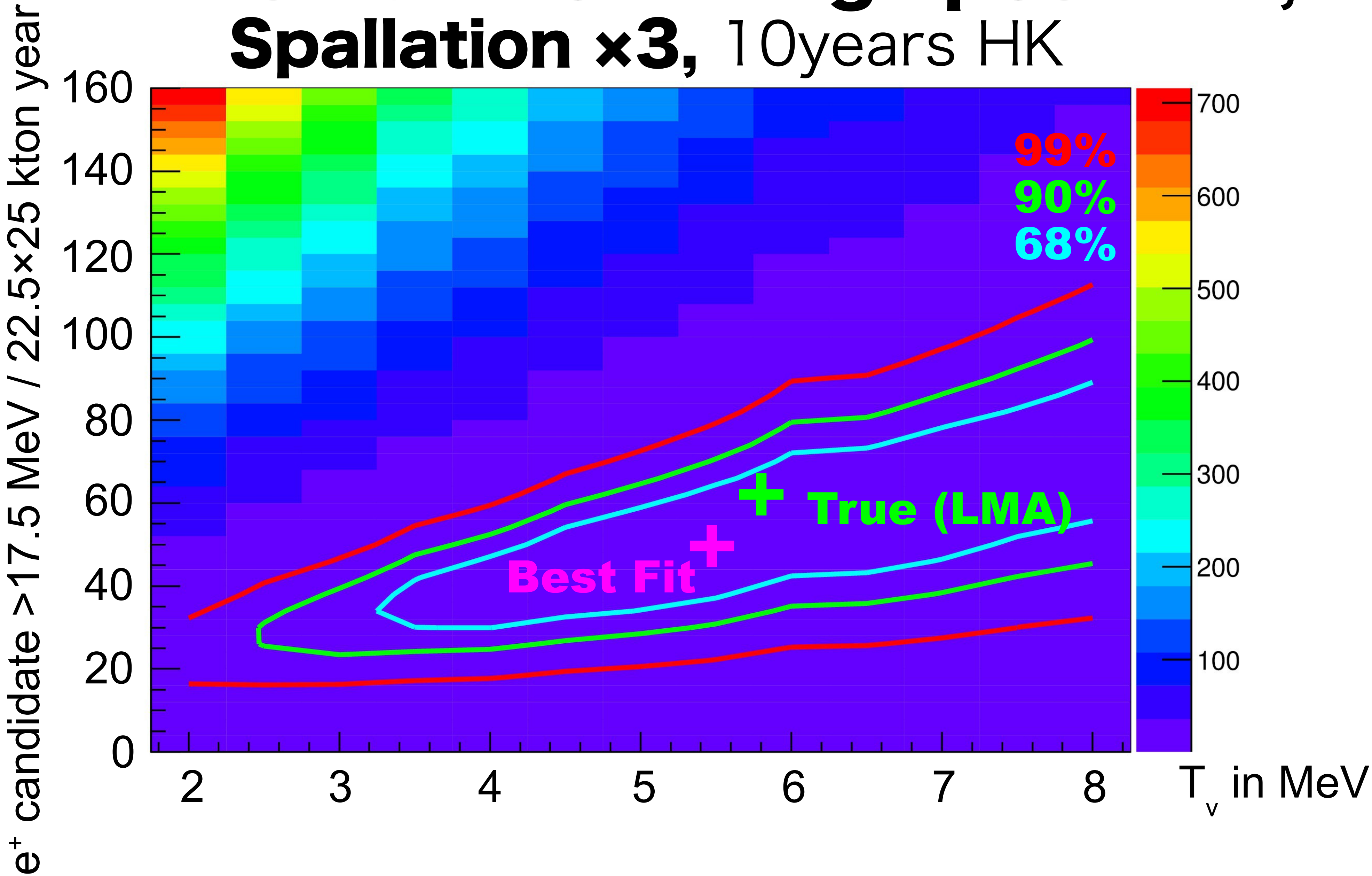
Limit on SRN emitting spectrum,
Spallation ×1, 10years HK



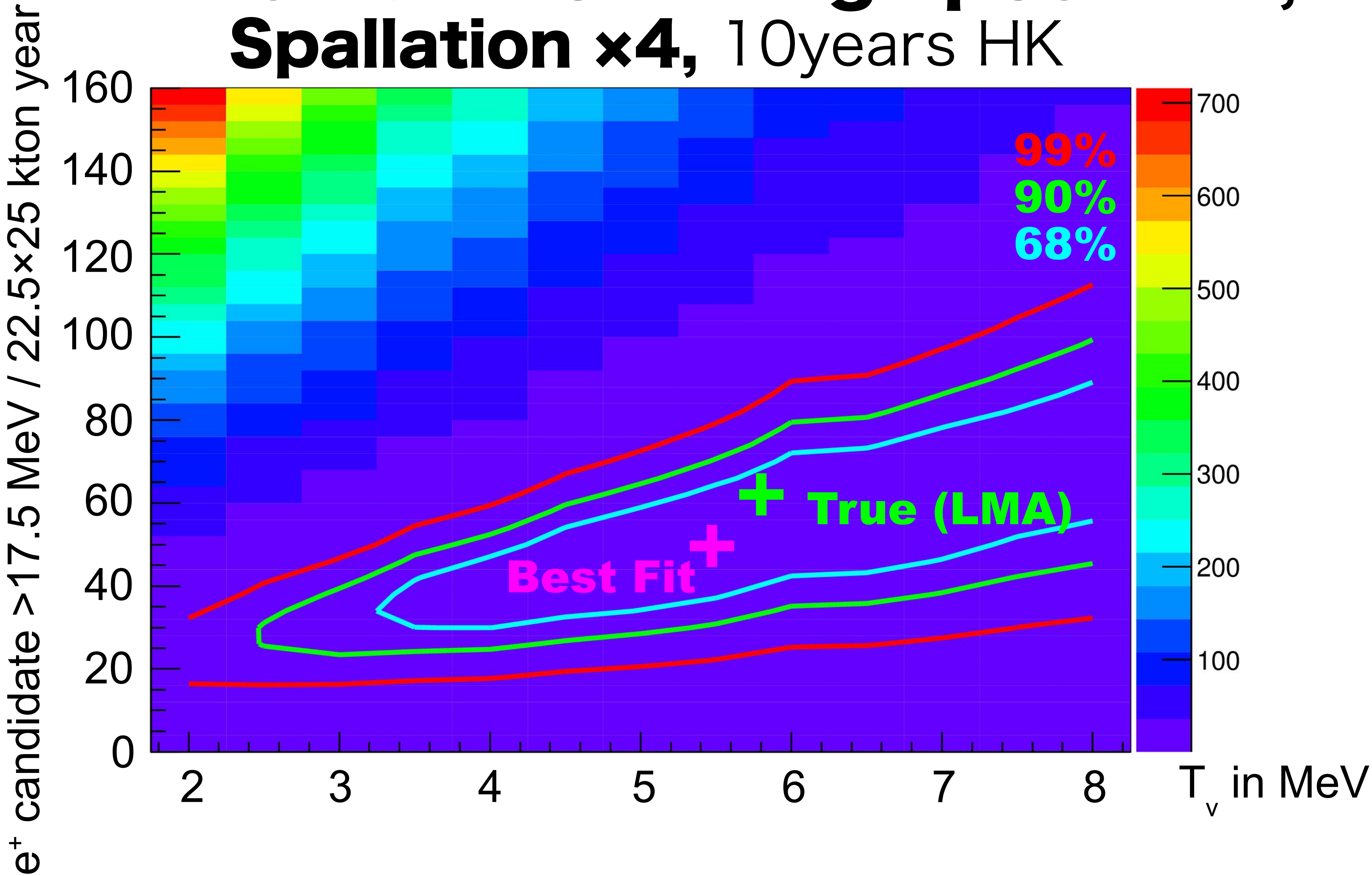
Limit on SRN emitting spectrum, Spallation ×2, 10years HK



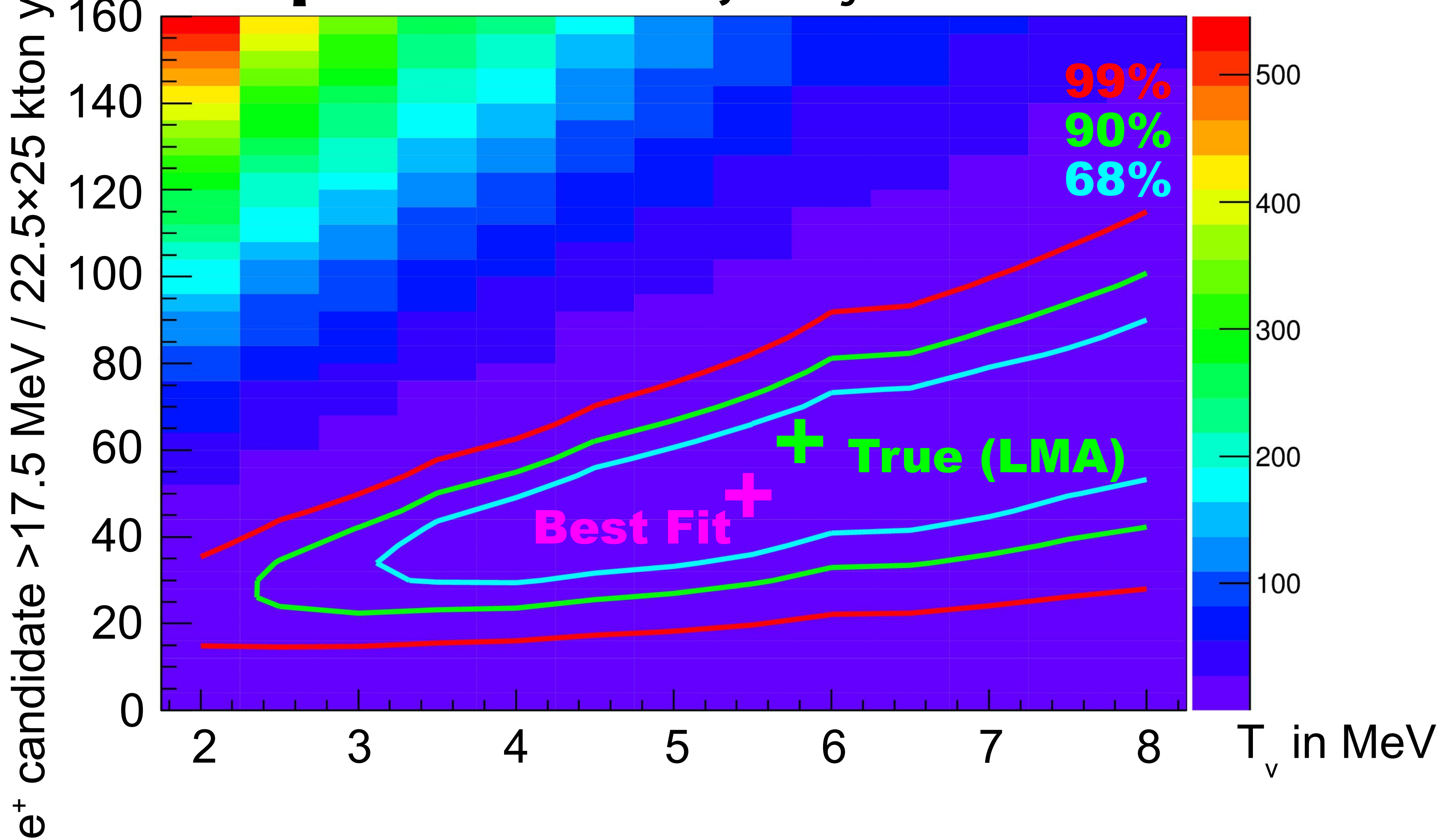
Limit on SRN emitting spectrum, Spallation ×3, 10years HK



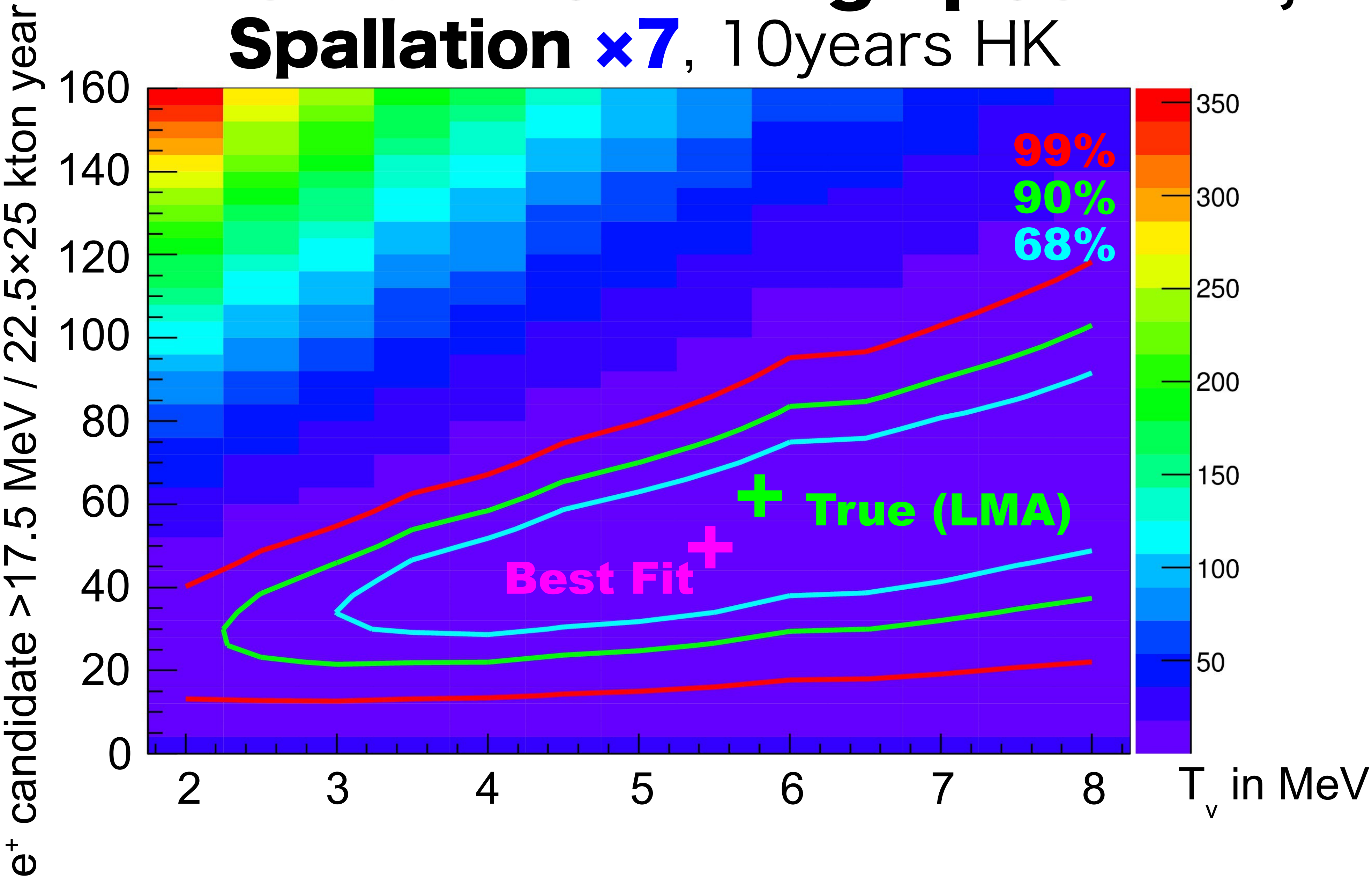
Limit on SRN emitting spectrum, Spallation ×4, 10years HK



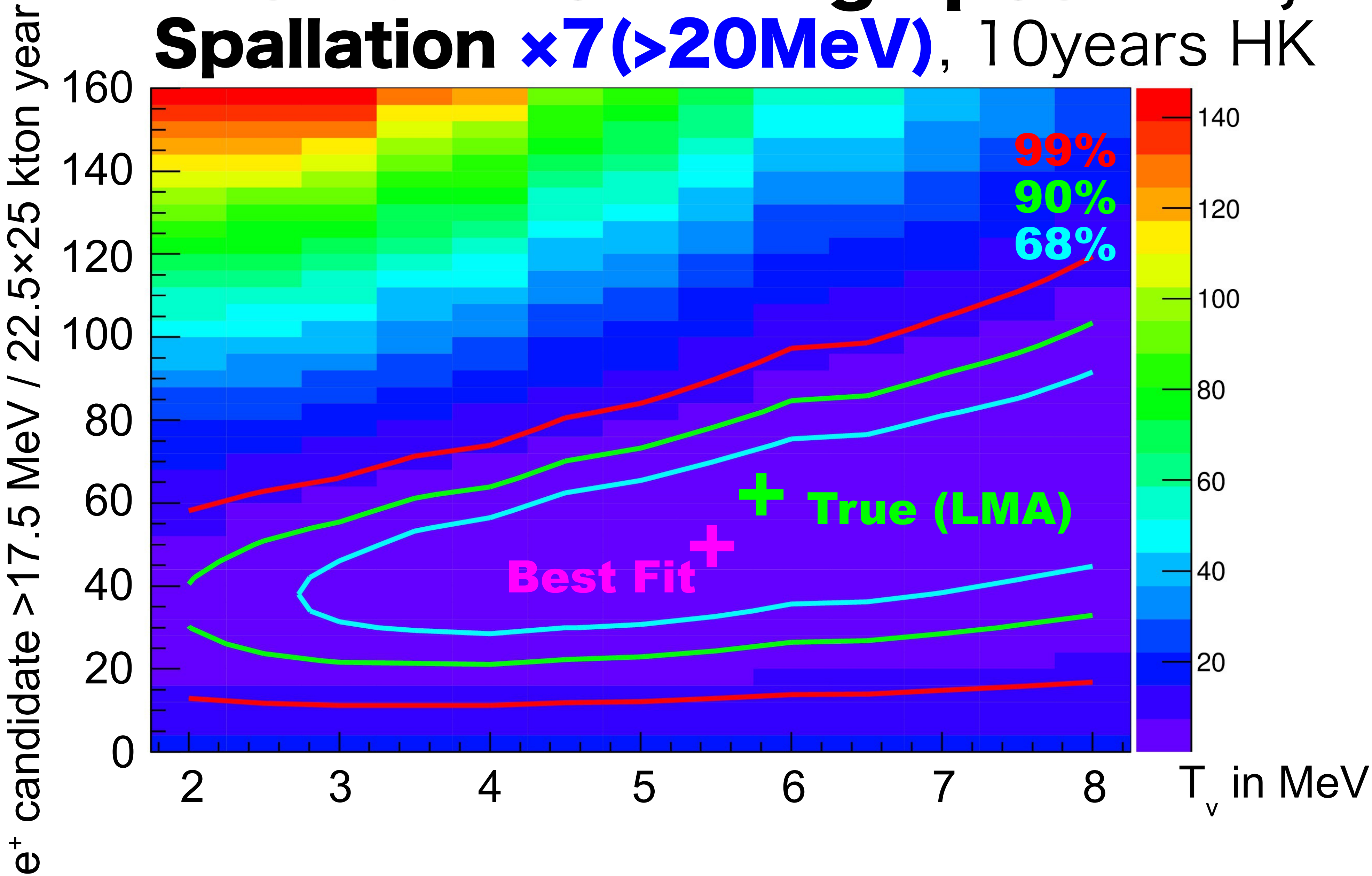
Limit on SRN emitting spectrum, Spallation ×5, 10years HK



Limit on SRN emitting spectrum,
Spallation ×7, 10years HK



Limit on SRN emitting spectrum, Spallation ×7(>20MeV), 10years HK

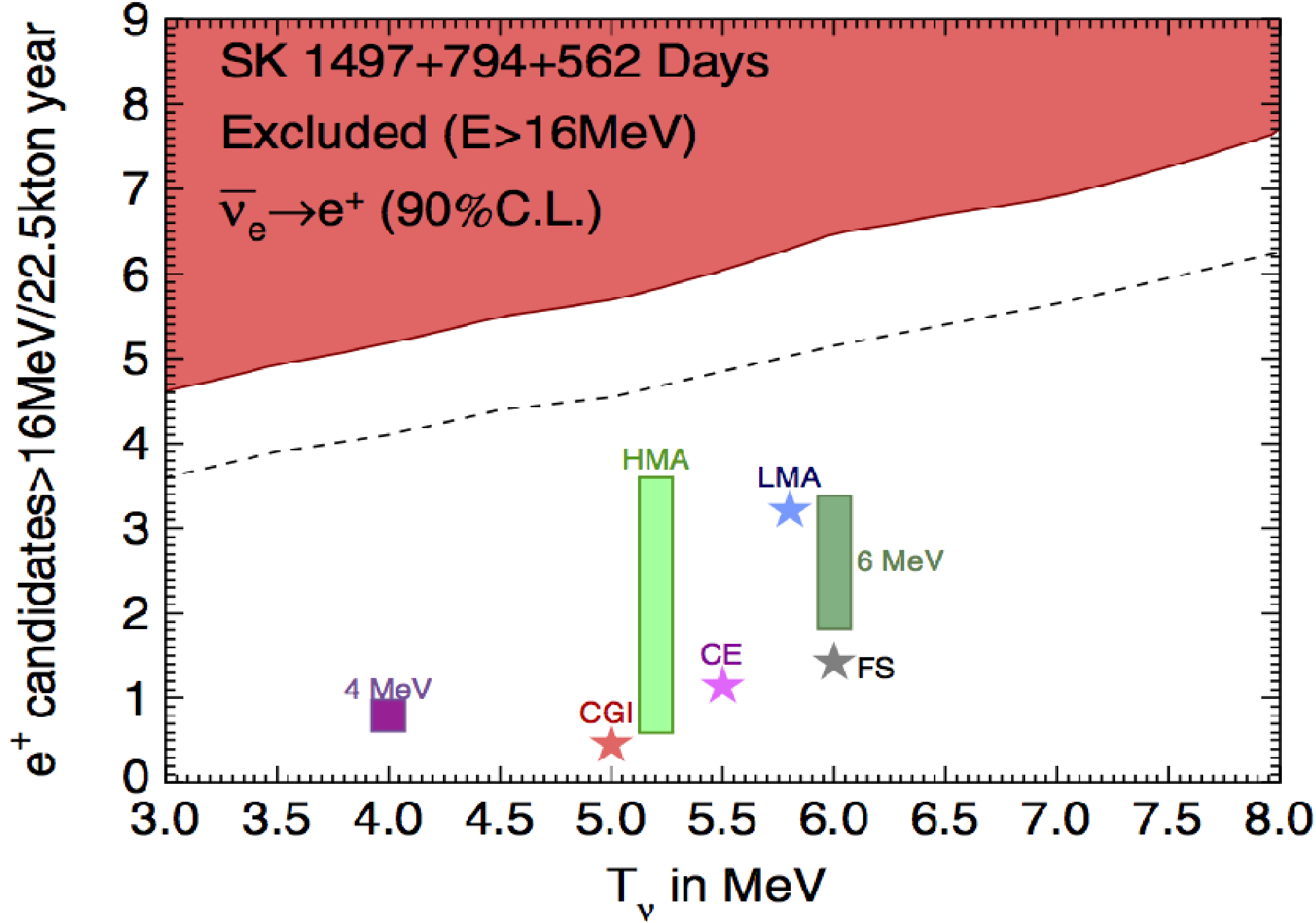


Appendix

Table 8.1: 90 % CL flux limit ($\bar{\nu}$ cm^{-2} s^{-1}), $E_\nu > 17.3$ MeV

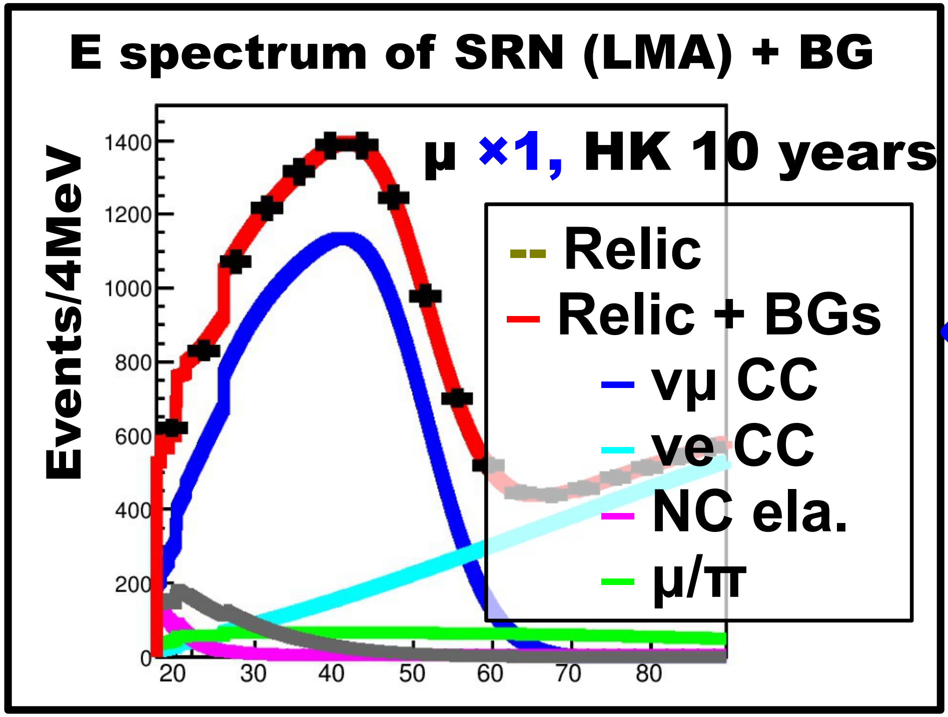
Model	SK-I	SK-II	SK-III	All	Predicted
Gas Infall (97)	<2.1	<7.5	<7.8	<2.8	0.3
Chemical (97)	<2.2	<7.2	<7.8	<2.8	0.6
Heavy Metal (00)	<2.2	<7.4	<7.8	<2.8	< 1.8
LMA (03)	<2.5	<7.7	<8.0	<2.9	1.7
Failed SN (09)	<2.4	<8.0	<8.4	<3.0	0.7
6 MeV (09)	<2.7	<7.4	<8.7	<3.1	1.5

Appendix

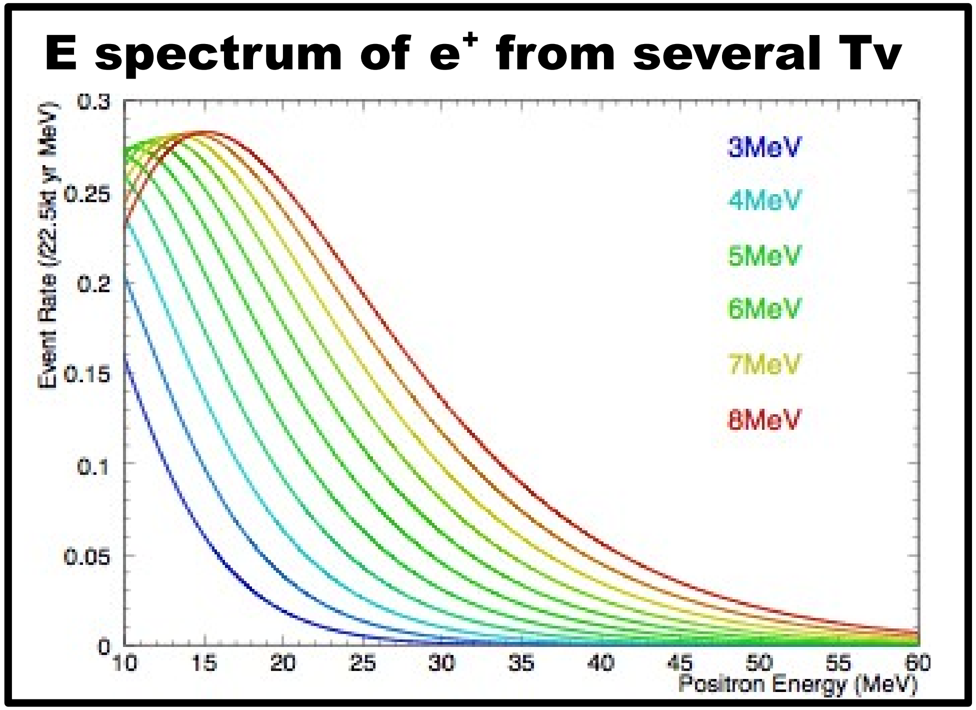


SK 1497+794+562 Days
Excluded (E>16MeV)
$\overline{\nu}_e \rightarrow e^+$ (90%C.L.)
HMA
LMA
6 MeV
CE
FS
4 MeV
CGI
e^+ candidates>16MeV/22.5kton year
T_ν in MeV
0
1
2
3
4
5
6
7
8
9
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0

Limit on SRN emitting spectrum



Fit with BGs



1. Fit LMA + BG model with general SRN model with SN ν temperature of 2 to 8 MeV and SN ν intensity.
   - Only statistic error is considered.
2. Calculate -2 log likelihood for each ν temperature and intensity.
3. Plot 2D allowed regions for 66%, 90% and 99% C.L..

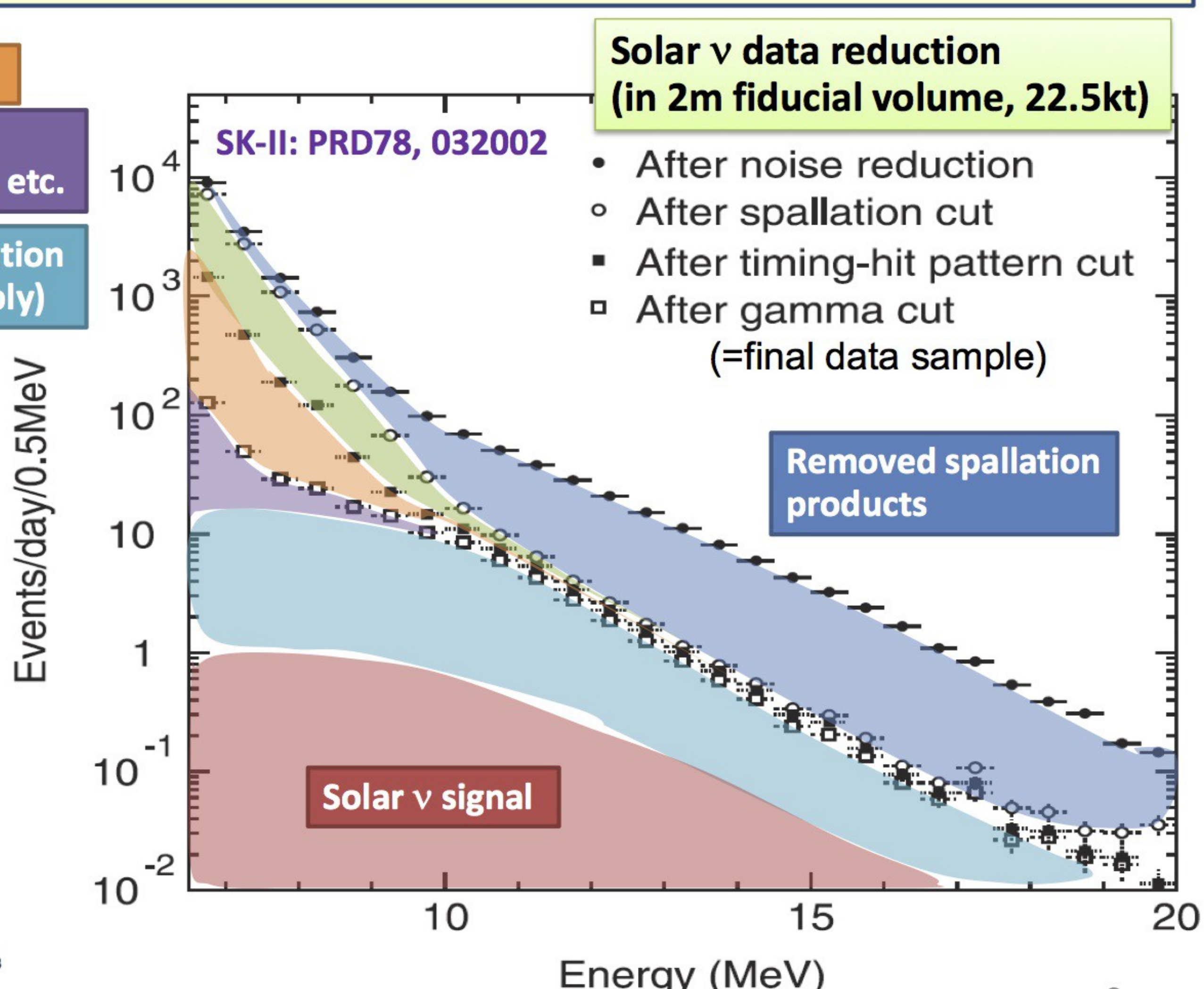
Probability density function

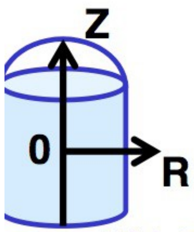
$$PDF = \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{(N_{Data} - N_{Model})^2}{2\sigma^2}\right)$$

$$Likelihood = \sum_{Low,Med,High} \left(2\log\sqrt{2\pi\sigma} + \frac{(N_{Data} - N_{Model})^2}{\sigma^2}\right)$$

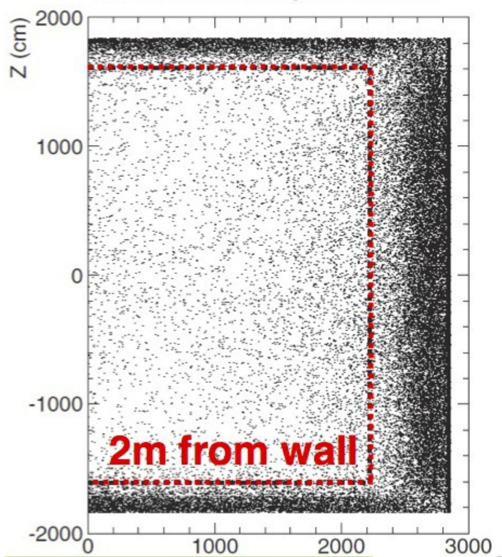
Low-energy backgrounds in SK

Spallation is dominant BG source in ~10-20MeV





SK-I: PRD73, 112001



Low-e vertex dist.

Y. Takeuchi, 2nd HK Open Meeting

Spallation products will be increased in HK due to high cosmic-ray muon flux.

Cosmic μ量のSignal Efficiencyへの影響

- Sol cut 前 (HK Collab. Jan. 2013)

Signal Efficiency	Cosmic μ ×1	×2	×3	×5	×7	×10
17.5-20MeV	81%	65%	52%	33%	21%	11%
20-26MeV	90%	81%	74%	59%	46%	35%

- Sol cut, FV cut等 ほぼ全てのcut後 (new)

	1倍	2倍	3倍	5倍	7倍	10倍
17-20MeV	79 ±4%	62 ±3%	50 ±3%	29 ±2%	17 ±2%	9 ±1%
20-26MeV	90 ±9%	77 ±9%	73 ±8%	54 ±7%	43 ±6%	34 ±6%