The 7th Supernova Neutrino Workshop (January 7–8, 2021)

Supernova Relic Neutrino Search at Super-Kamiokande and Future Prospects

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Supernova Relic Neutrinos

- Neutrinos from all past CCSNe are accumulated to form an integrated flux.

  = **Supernova Relic Neutrinos (SRNs)** or **Diffuse Supernova Neutrino Background (DSNB)**

- Various factors affect the SRN flux on Earth.
  - Neutrino oscillation (mass hierarchy)
  - Galactic evolution (star formation rate, initial mass function, binary interactions, etc)
  - Black hole formation rate (metallicity, equation-of-state, etc)
  - etc

SRN flux

$$\frac{d\Phi(E_\nu)}{dE_\nu} = c\int_0^\infty \frac{dz}{H_0\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}} \times \left[R_{\mathrm{CCSN}}(z) \int_0^{Z_{\max}} \Psi_{\mathrm{ZF}}(z,Z) \left\{ \int_{M_{\min}}^{M_{\max}} \Psi_{\mathrm{IMF}}(M) \frac{dN(M,Z,E'_\nu)}{dE'_\nu} dM \right\} dZ \right].$$

cosmological parameters: $H_0\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}$

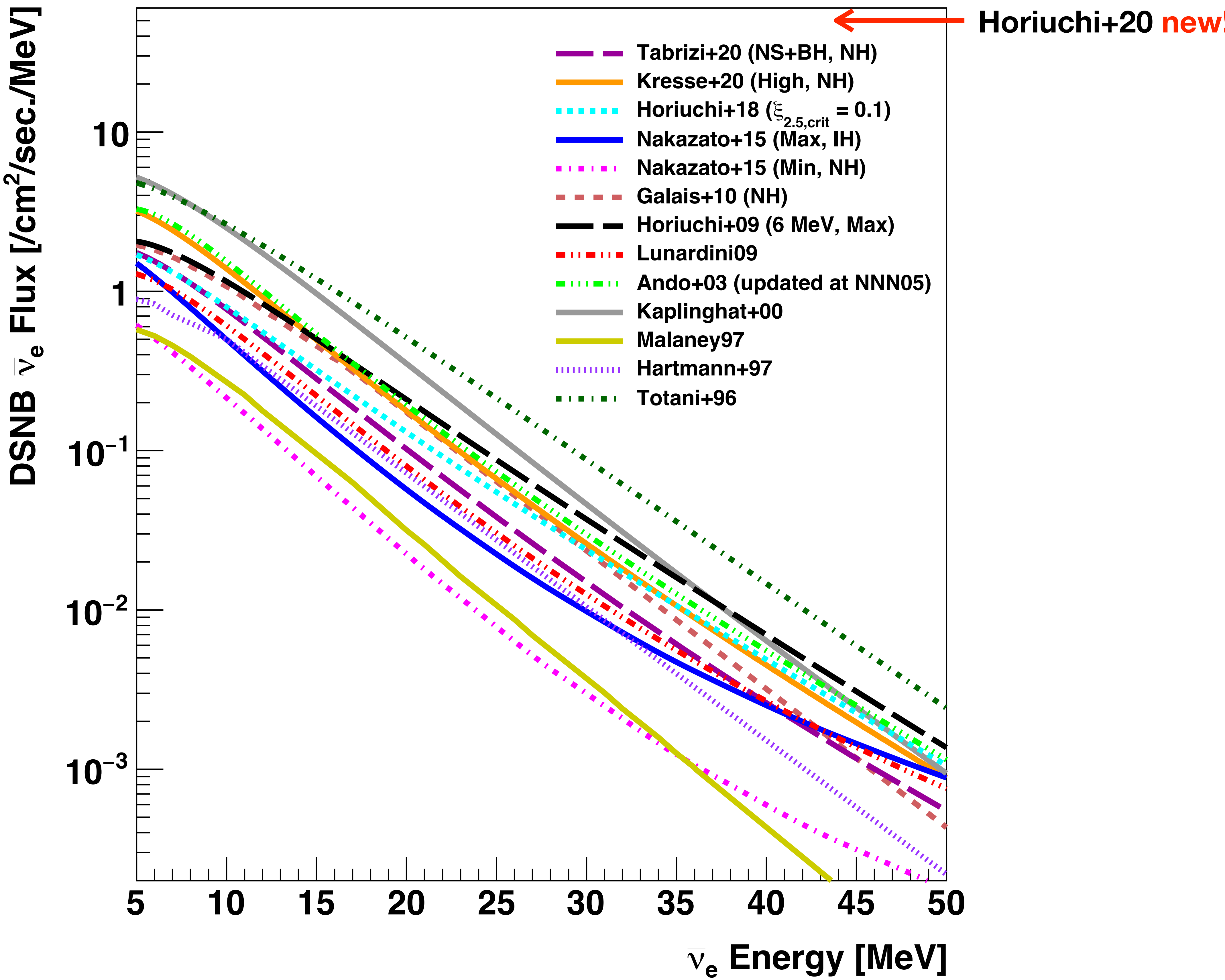
CCSN rate: $R_{\mathrm{CCSN}}(z)$

metallicity distribution of progenitors: $\Psi_{\mathrm{ZF}}(z,Z)$

initial mass function of progenitors: $\Psi_{\mathrm{IMF}}(M)$

neutrino number spectrum per CCSN: $\frac{dN(M,Z,E'_\nu)}{dE'_\nu}$

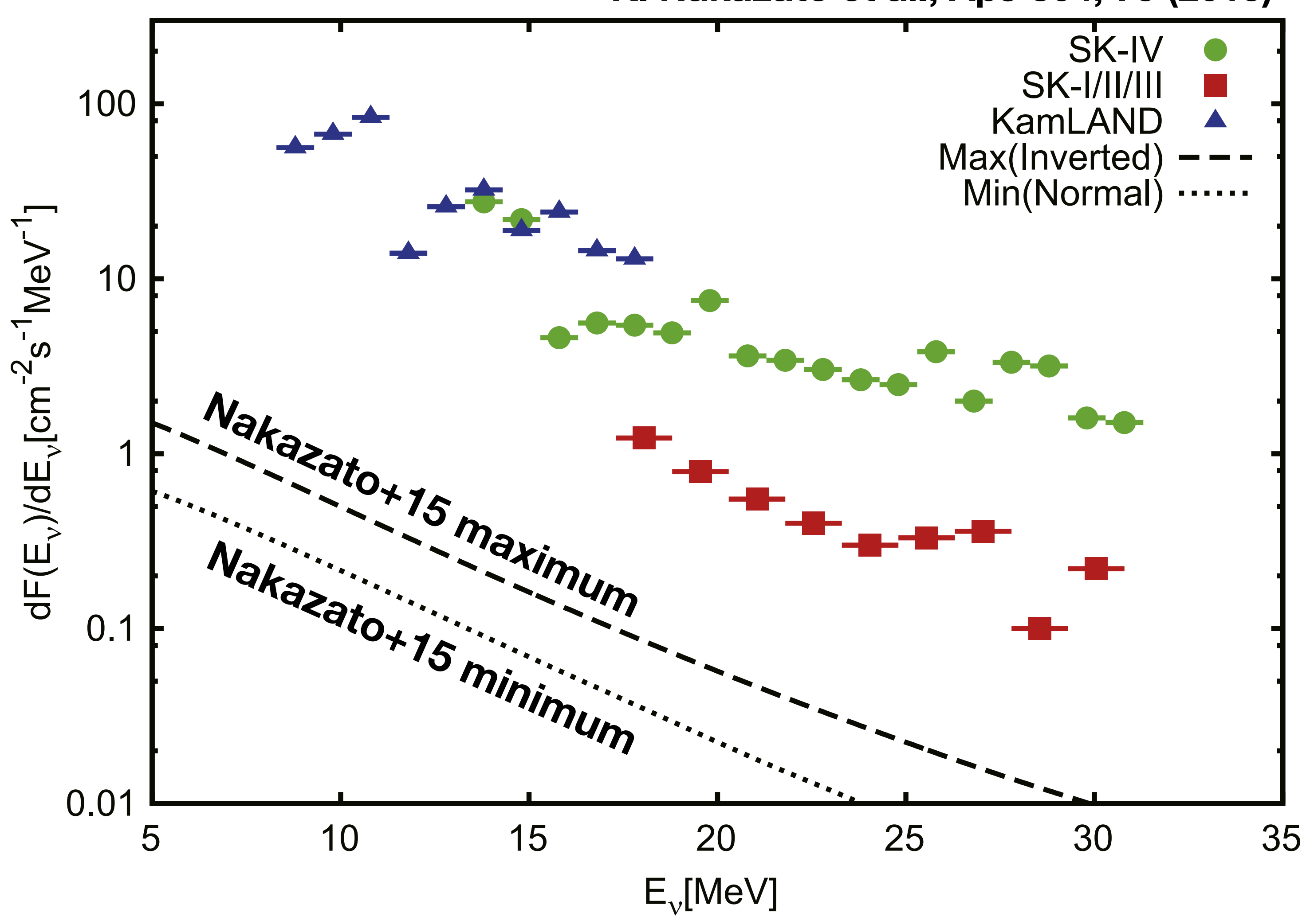
Model Predictions (See Backup for Refs.)



Previous Searches

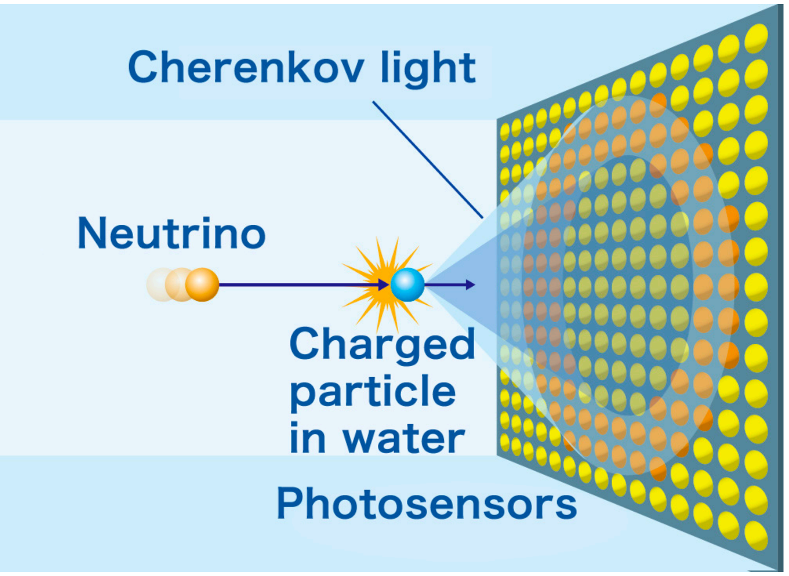
- **Signal in experimental searches** = inverse beta decay (**$\bar{\nu}_e + p \rightarrow e^+ + n$**)
- Most sensitive searches have been performed at **Super-Kamiokande** and **KamLAND**.
- Search at SK (water)
  - SK-I/II/III (spectral fitting analysis): fitting by atmospheric spectra for $E_\nu > 17.3$ MeV
  - SK-IV (neutron tagging analysis): low energy threshold, tagging efficiency ~20%
- Search at KamLAND (oil)
  - very low energy threshold, tagging efficiency ~ 100%

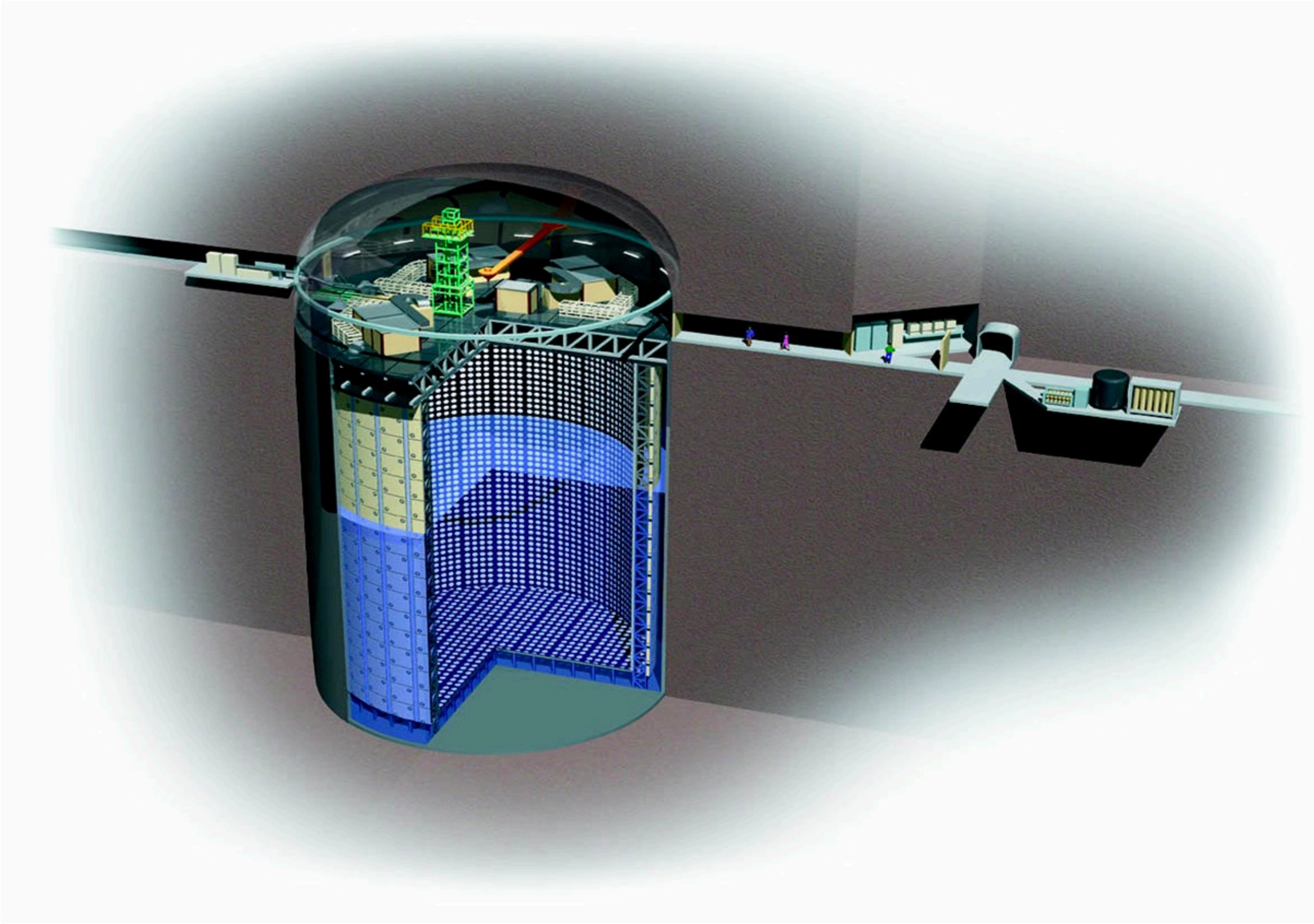
K. Nakazato et al., ApJ 804, 75 (2015)

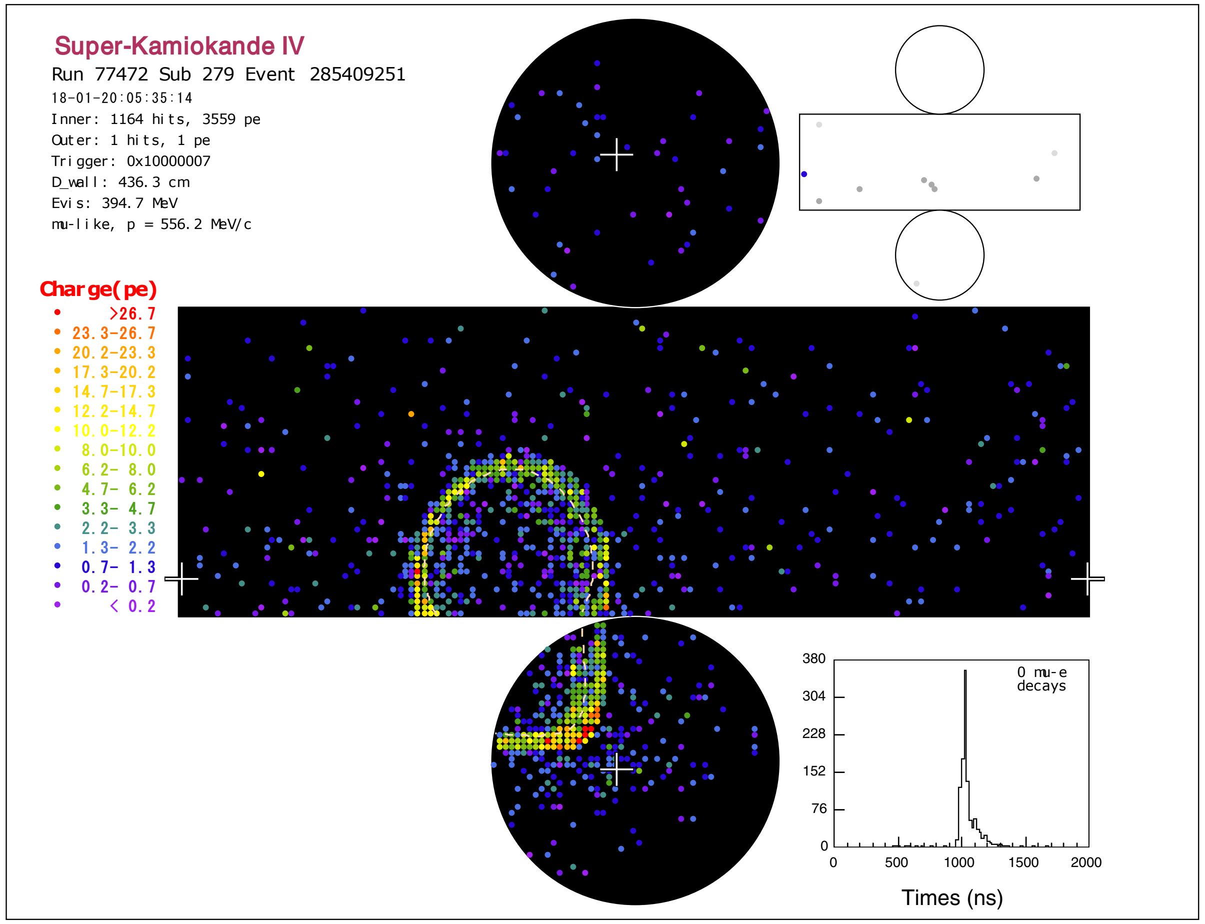


Super-Kamiokande

- A water Cherenkov detector located 1,000 m under the mountain.
- Fiducial volume: 22.5 kton
- Inner detector: 11,129 20-inch PMTs
- Outer detector: 1,885 8-inch PMTs, used for cosmic muon veto
- Operated since 1996 in five periods.
  - This work uses data from **SK-IV** (2008–2018).

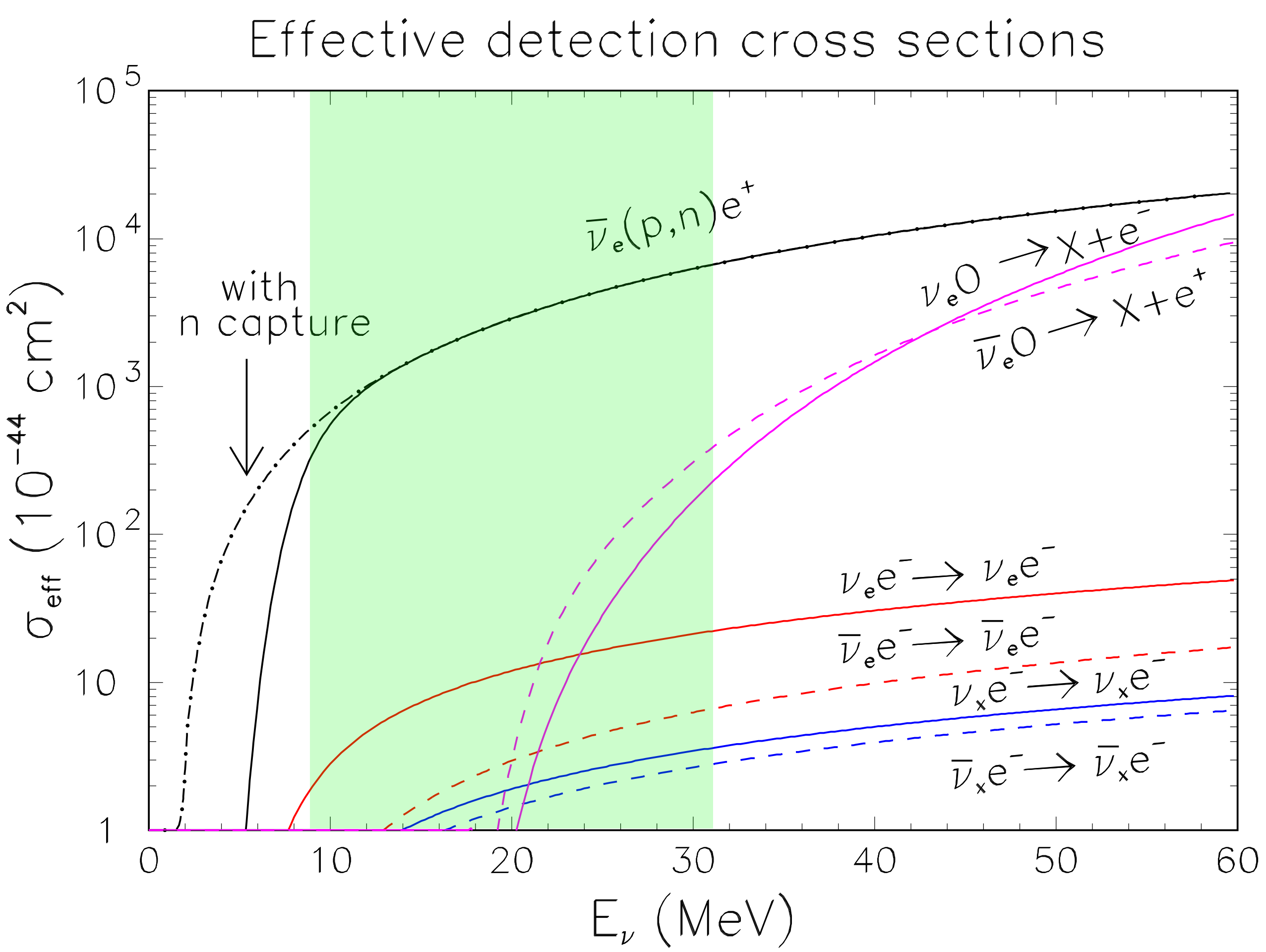


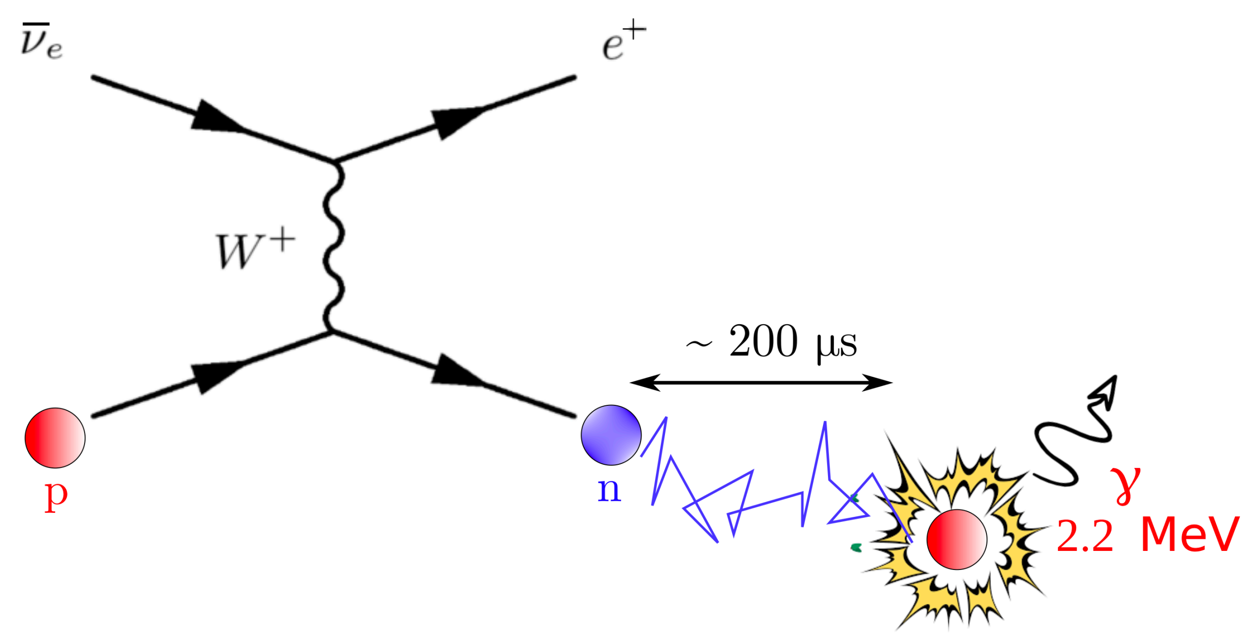




Signal

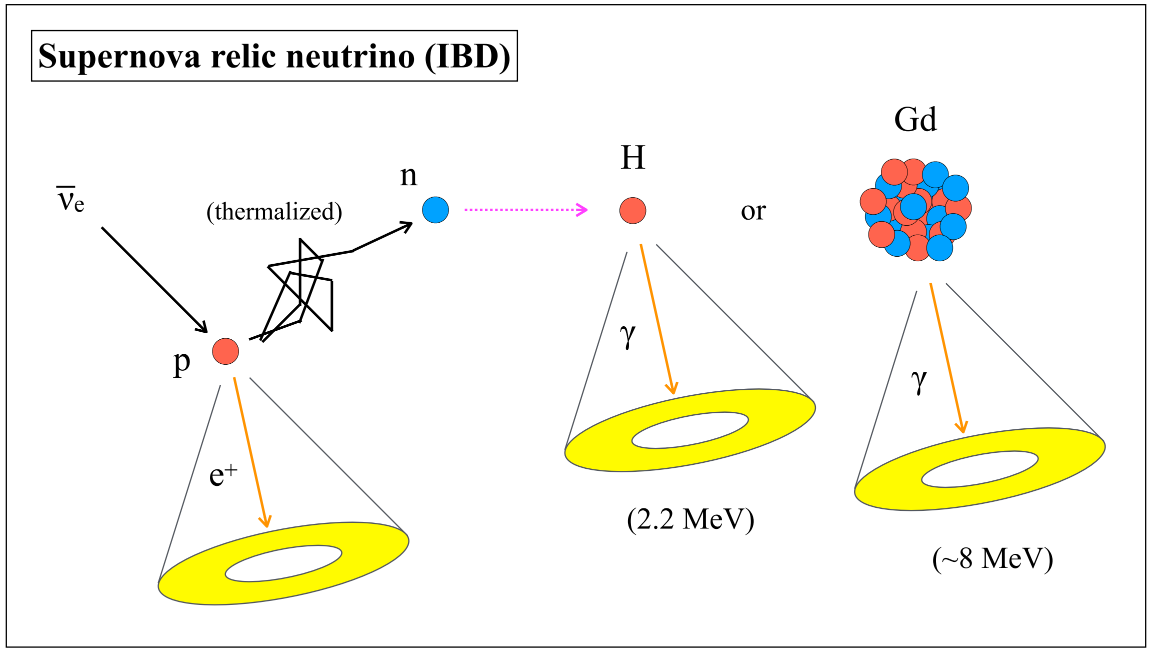
- Inverse beta decay of electron antineutrinos (**$\bar{\nu}_e + p \rightarrow e^+ + n$**) is searched.
  - Larger than the other mode by >2 orders of magnitude.
  - Search region: $E_{rec} > 7.5$ MeV ($E_\nu > 9.3$ MeV)
- Signal: "**β+n**" events
  - Prompt signal = β
  - Delayed signal = **2.2 MeV γ** from neutron capture

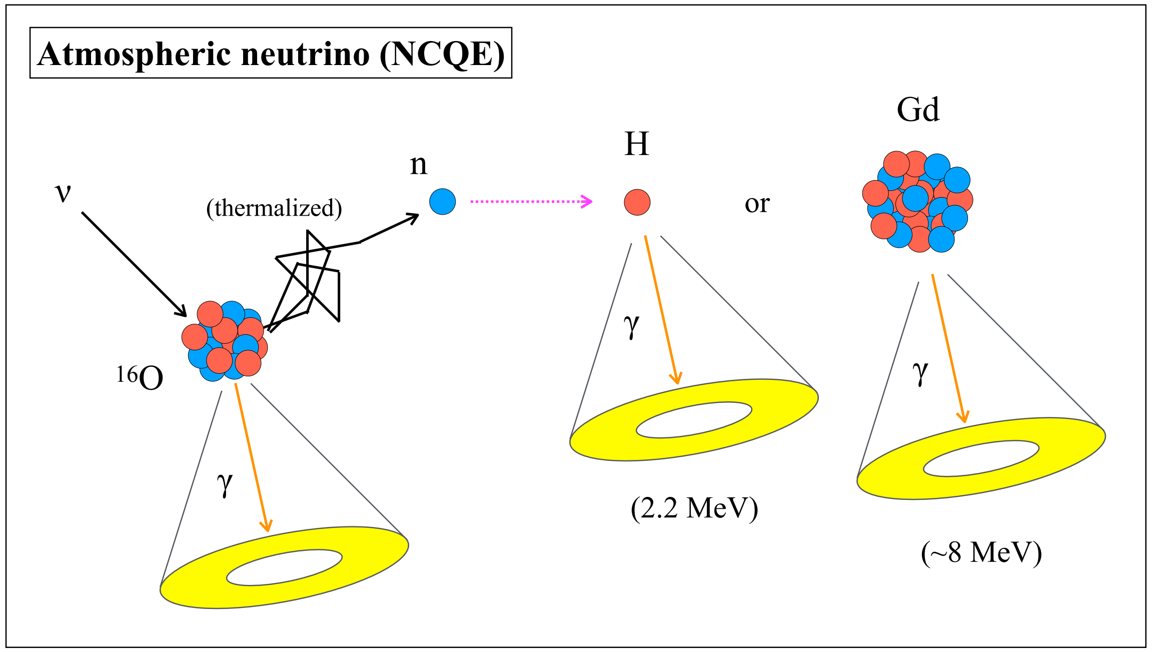




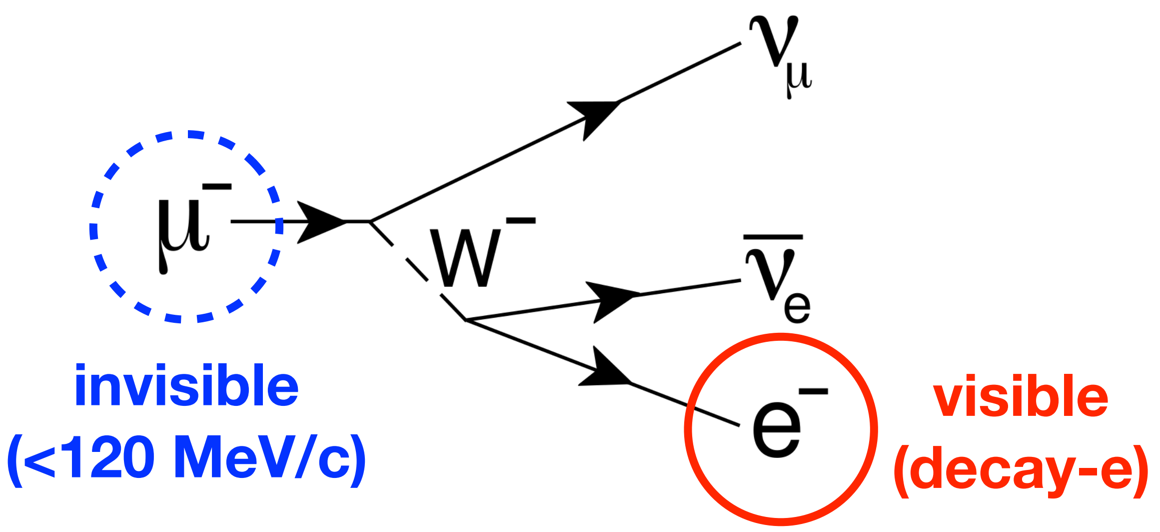
Background: Atmospheric Neutrinos

- **Neutral-current quasielastic (NCQE) interactions**
  - de-excitation γ-ray (+ n)
  - dominant below ~20 MeV





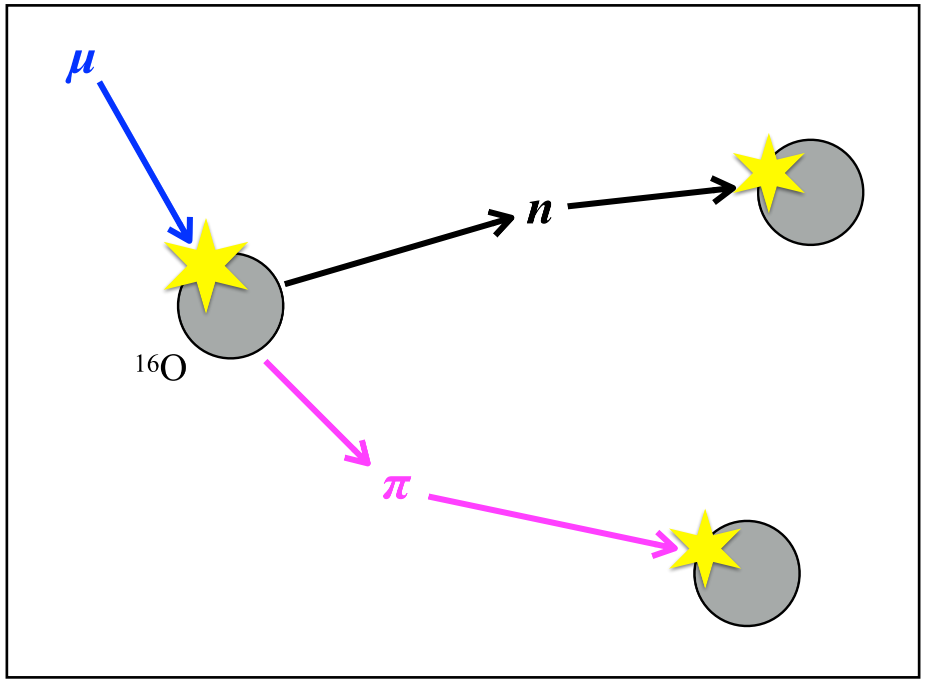
- **Other interactions (CC & NC1π)**
  - (invisible muon →) decay electron (+ n)
  - dominant above ~20 MeV
  - Michel spectrum >30 MeV

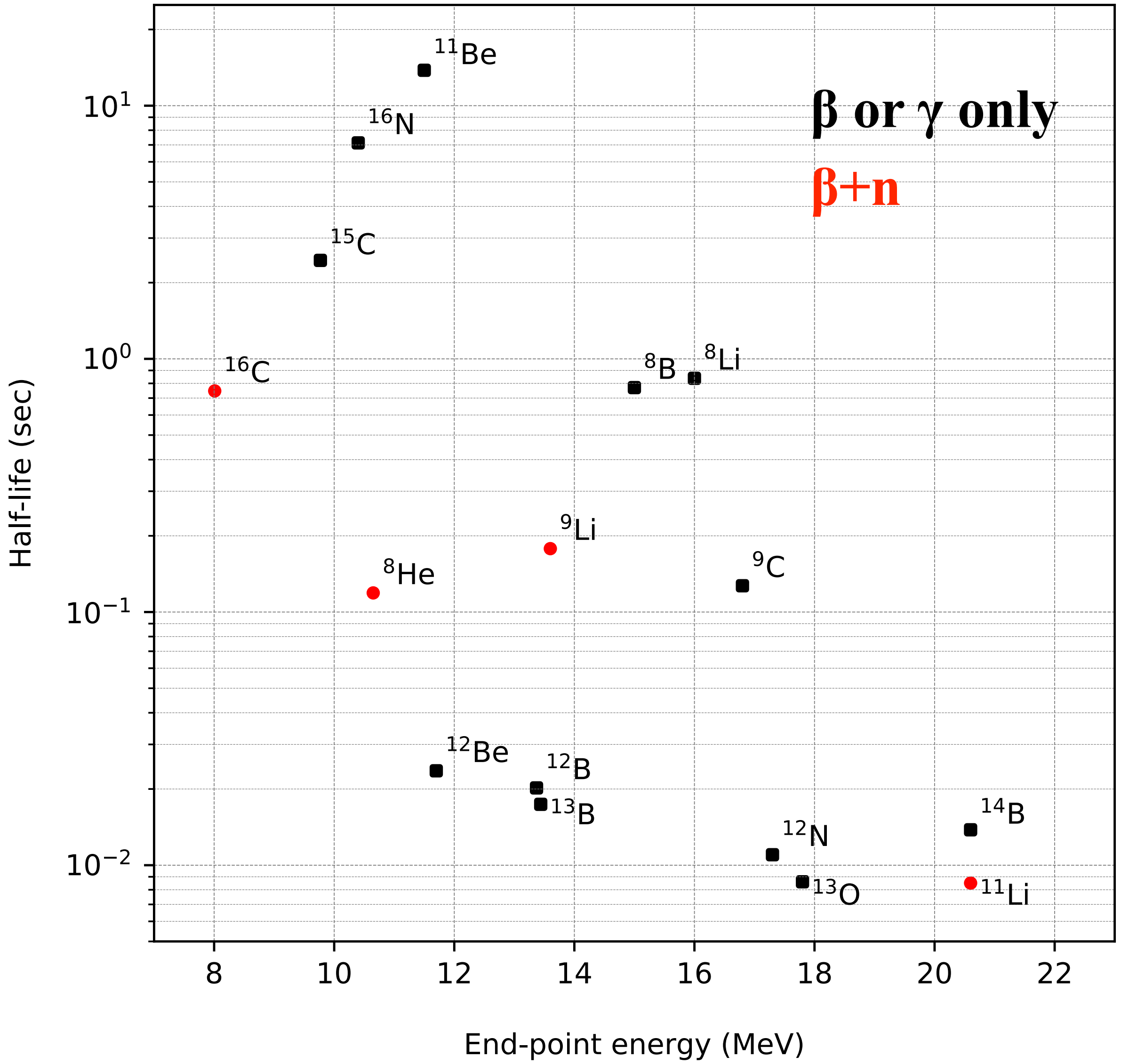


Background: Spallation Products

- **Cosmic-ray muon spallation**
  - ~2 Hz cosmic-ray muons at SK.
  - Radioactive isotopes are produced by muons, some of which decay into β/γ(+n).
  - Estimated with data-driven method.

- **Spallation ^{9}Li**
  - Most annoying background in the analysis.
  - Up to E_{rec} ~ 14 MeV

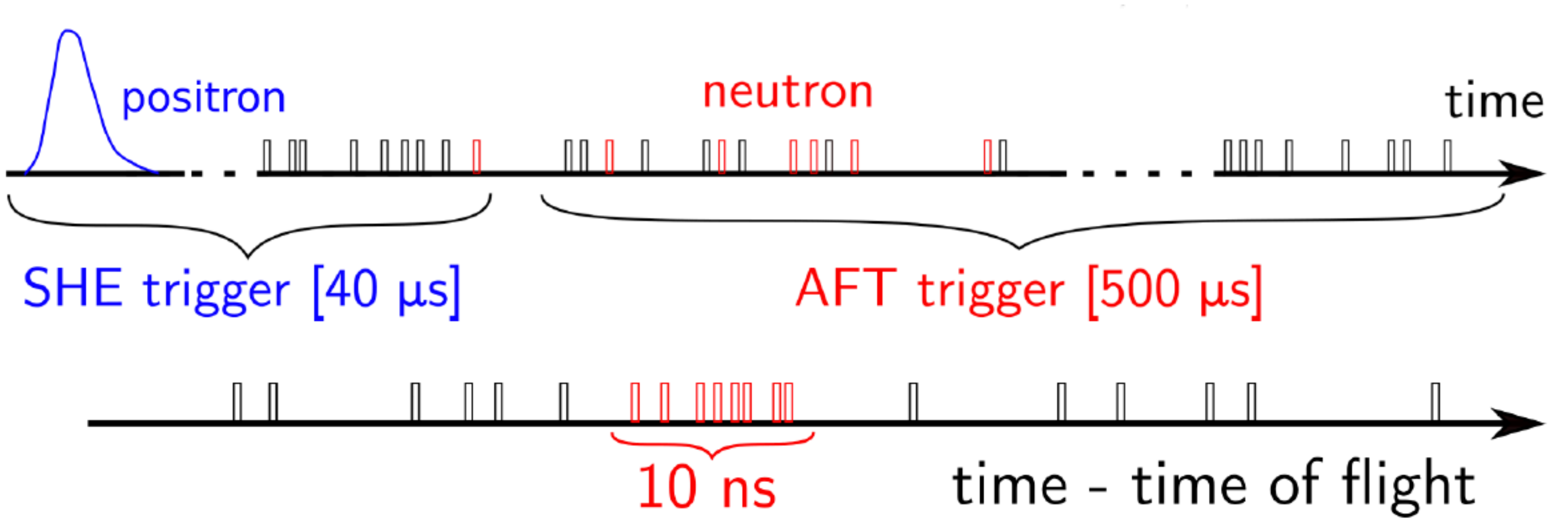




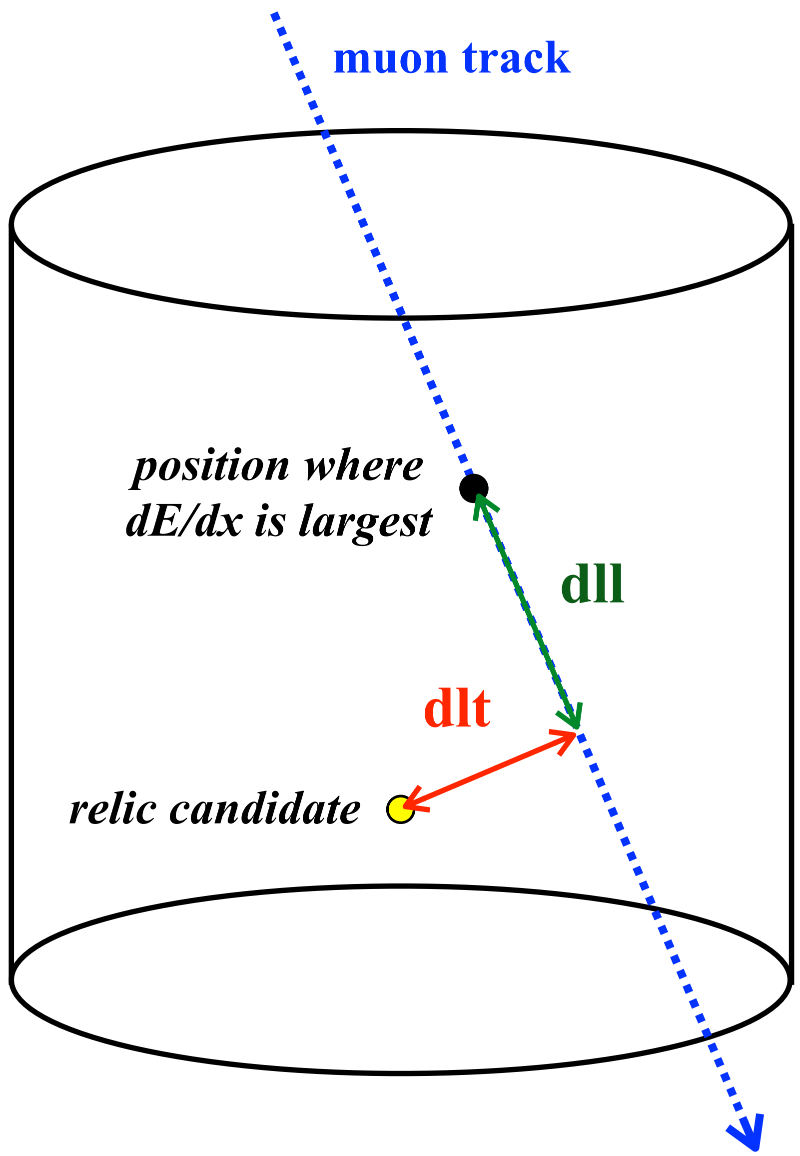
Background: Others

- **Reactor neutrinos**
  - Only below $E_{\mathrm{rec}} \sim 10$ MeV (lowest region in the analysis window).
  - Estimated with the IAEA Database.

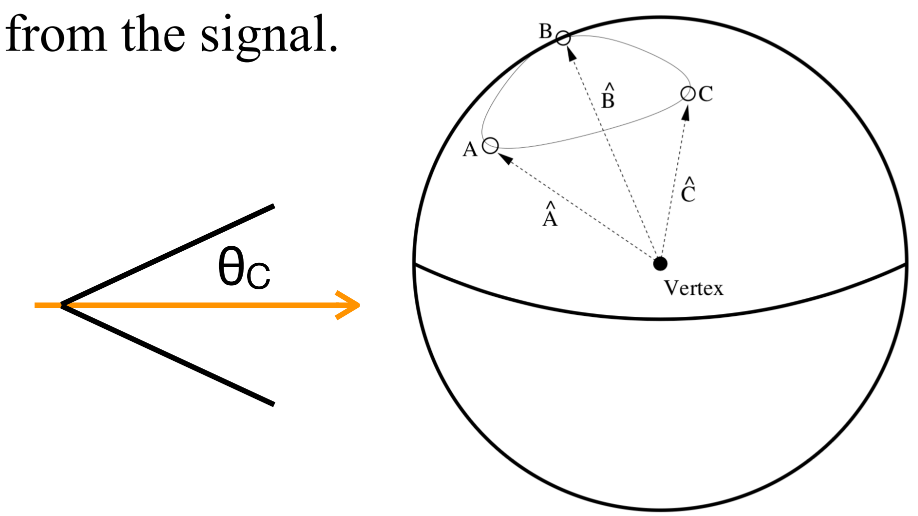
- **Accidental coincidence**
  - β-like + neutron-like
  - Primary = spallation, solar neutrinos, etc
  - Delayed = PMT noise, radioactive γ, etc
  - Estimated with the background data and BDT.



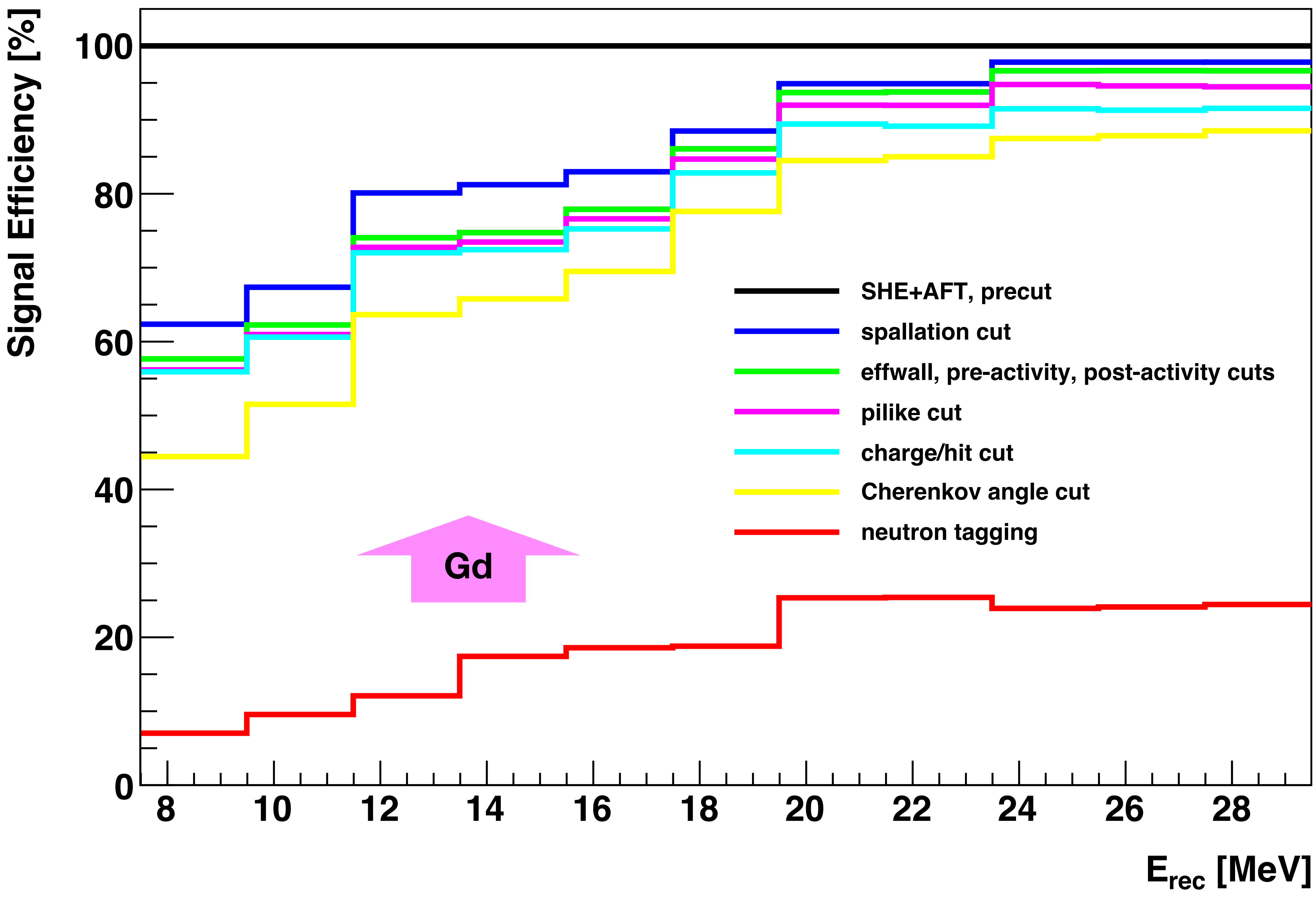
Data Reduction



1. **Noise reduction**
   - Bad runs, calibration runs, poor quality events, etc
2. **Spallation cut**
   - Use correlations between each low energy event and preceding muons.
   - Events close to muons in time and space are likely to be spallation.
3. **Positron identification**
   - Wall-originated events removed.
   - Decay-e events are searched seeing pre or post activities.
   - Cherenkov angle cut (signal = 38~50 deg)
4. **Neutron tagging**
   - Utilize boosted-decision-tree (BDT) to separate fake coincidences from the signal.



Signal Efficiency



Two Analysis Streams

A. Model-independent differential upper limit

- Differential upper limits calculated for each 2-MeV bin.
- E_ν = [9.3, 31.3] MeV
- Less sensitive to spectral shape uncertainties.
- Atmospheric non-NCQE estimated by fitting MC to data for >30 MeV.
- Atmospheric NCQE estimated referring to the T2K results.

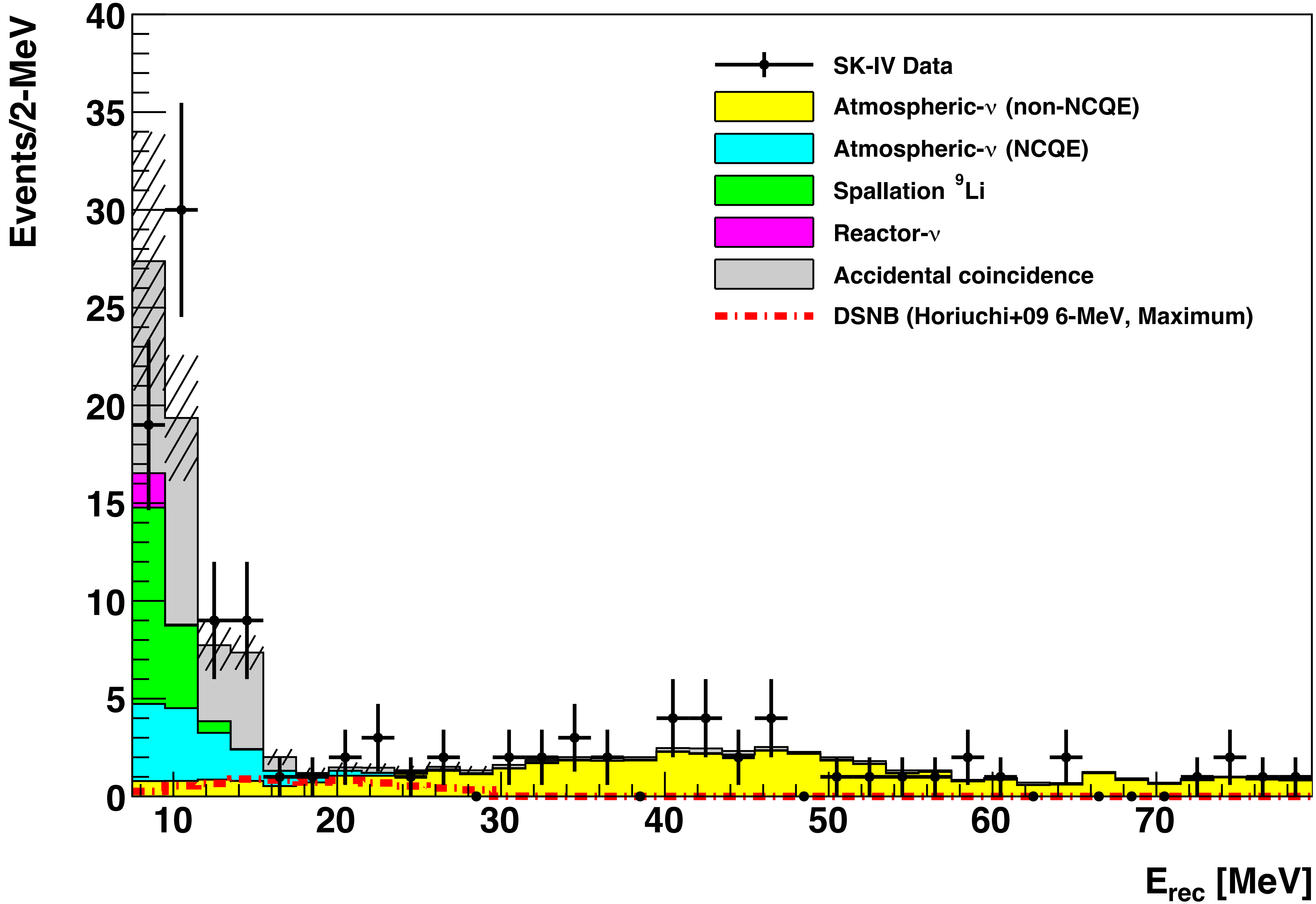
B. Spectral fitting

- Unbinned maximum likelihood fit by signal + atmospheric background PDFs.
- Fitting done separately for signal models.
- E_ν = [17.3, 81.3] MeV (w/ ntag), E_ν = [21.3, 81.3] MeV (w/o ntag)
- Combined with the SK-I/II/III results.

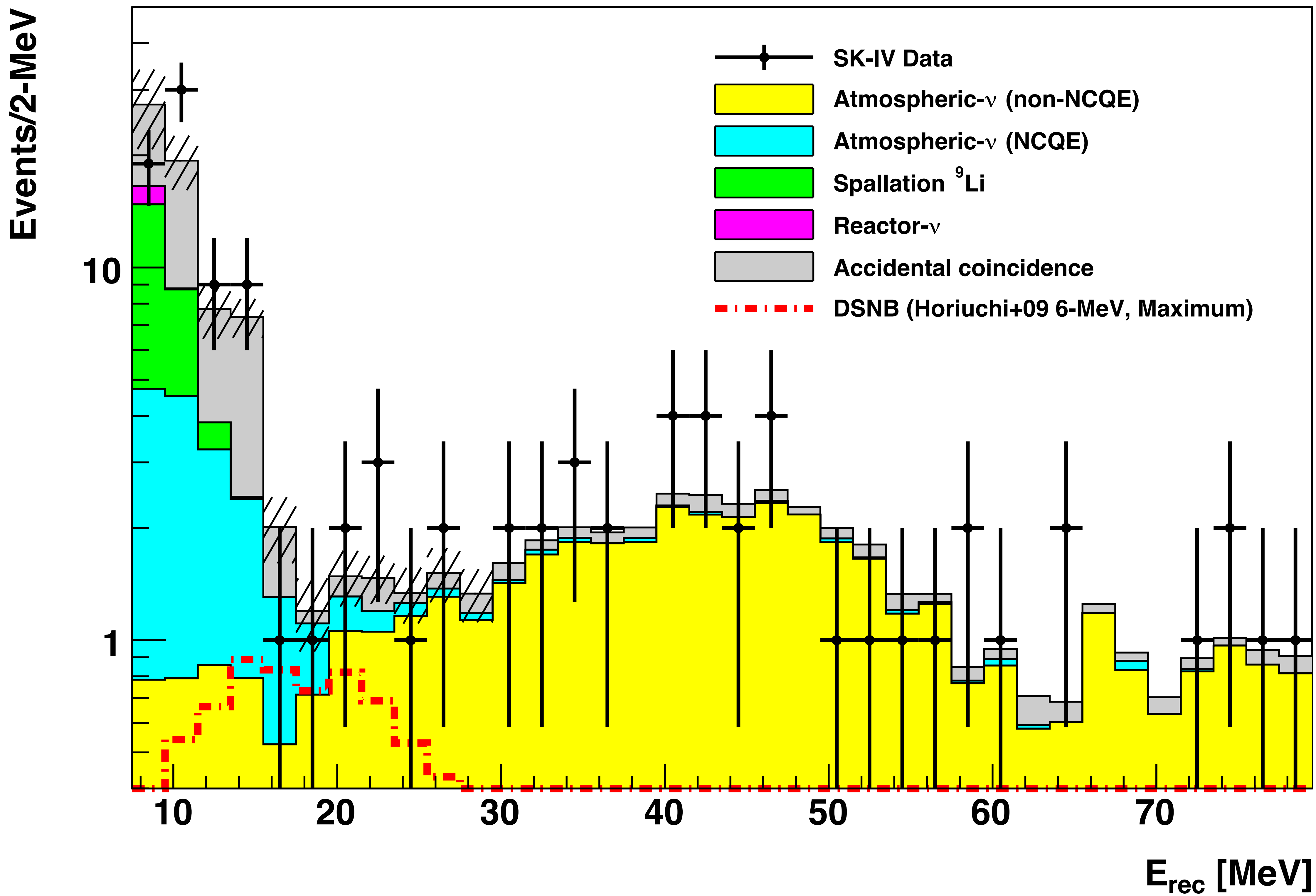
PDF region

	Cherenkov angle		
Neutrons	$[20, 38]^\circ$	$[38, 50]^\circ$	$[78, 90]^\circ$
1	μ/π	Signal	NC
0 or >1	μ/π	Signal	NC

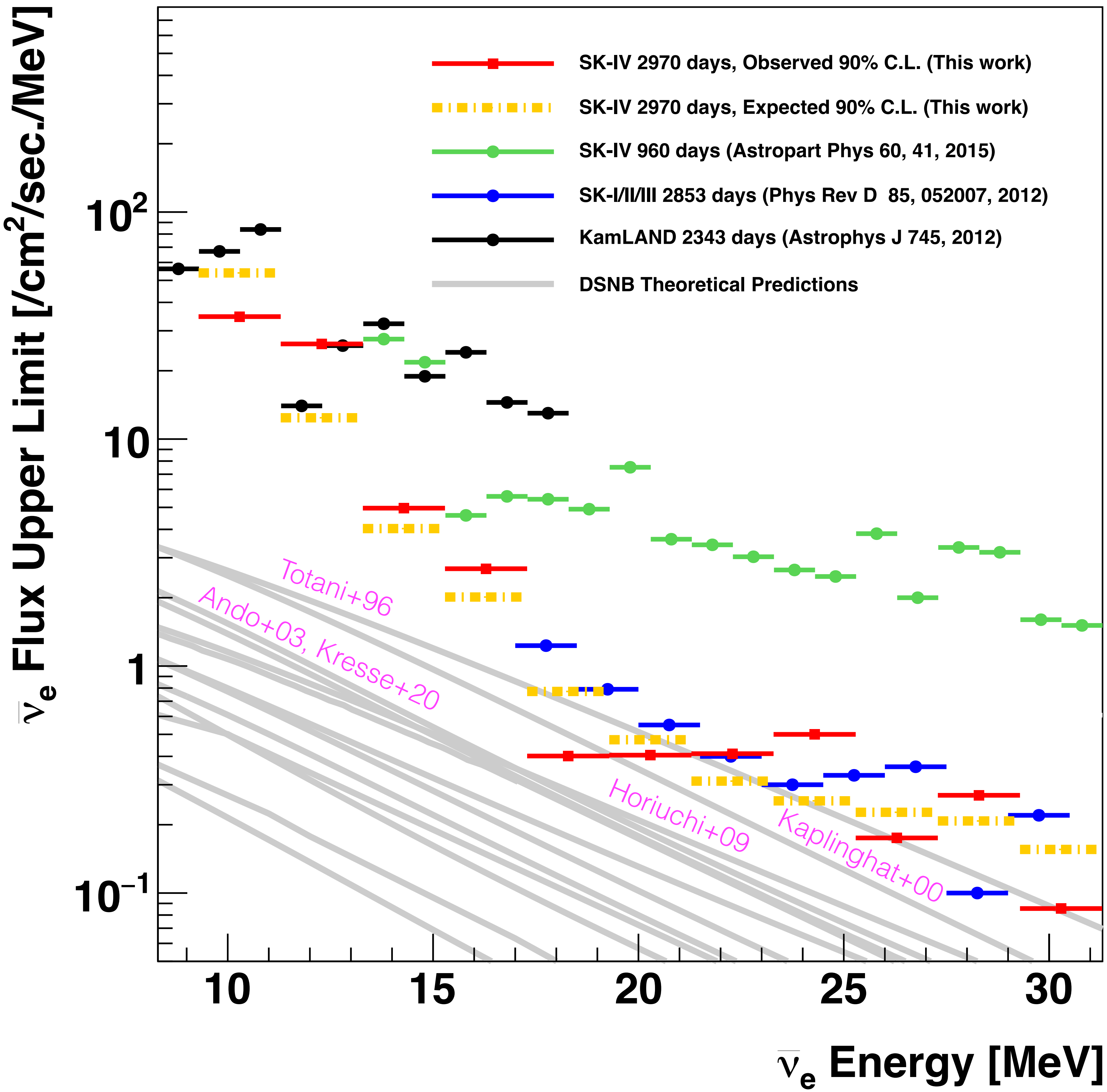
(A) Observation vs. Prediction



(A) Observation vs. Prediction

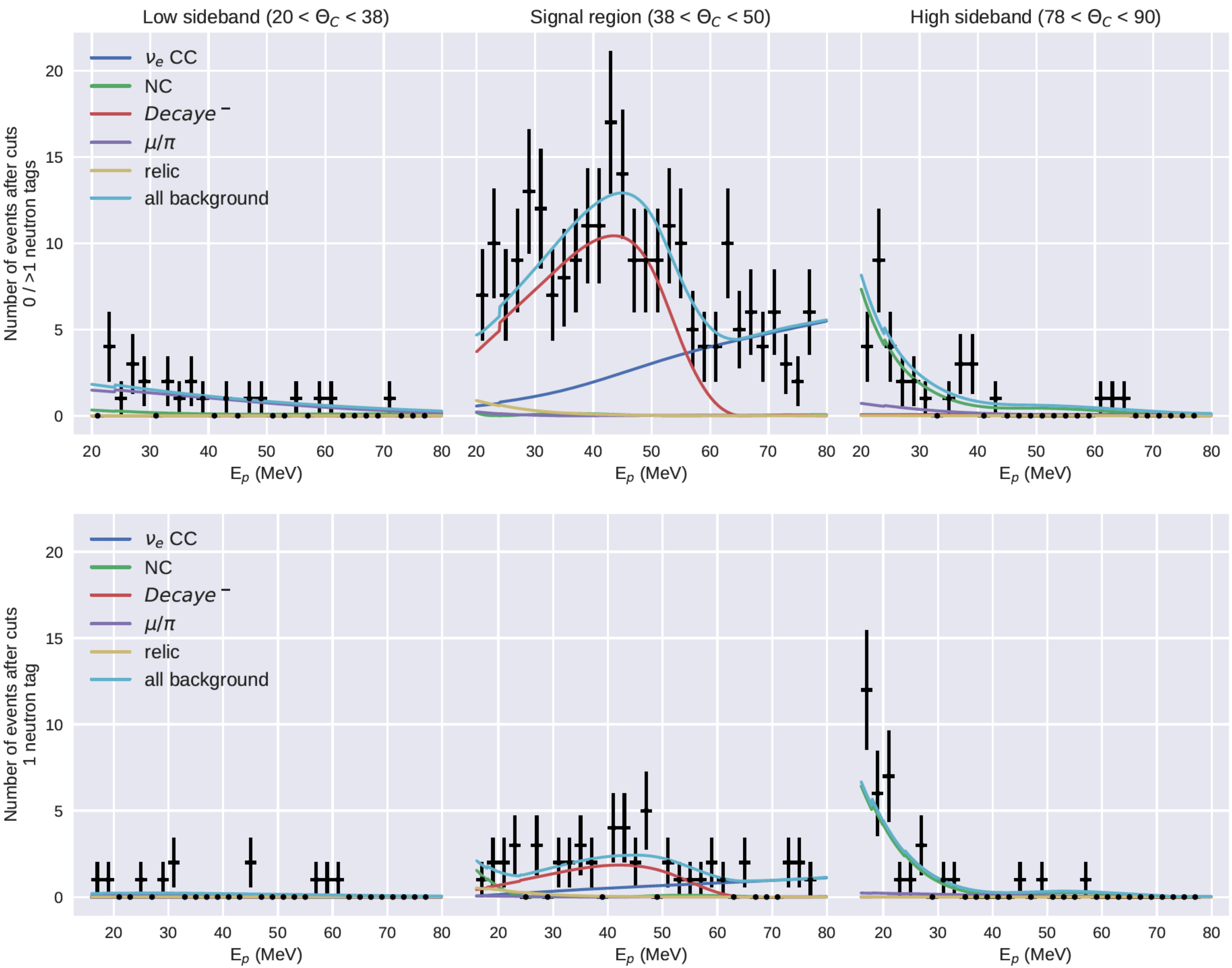


(A) Differential Upper Limit



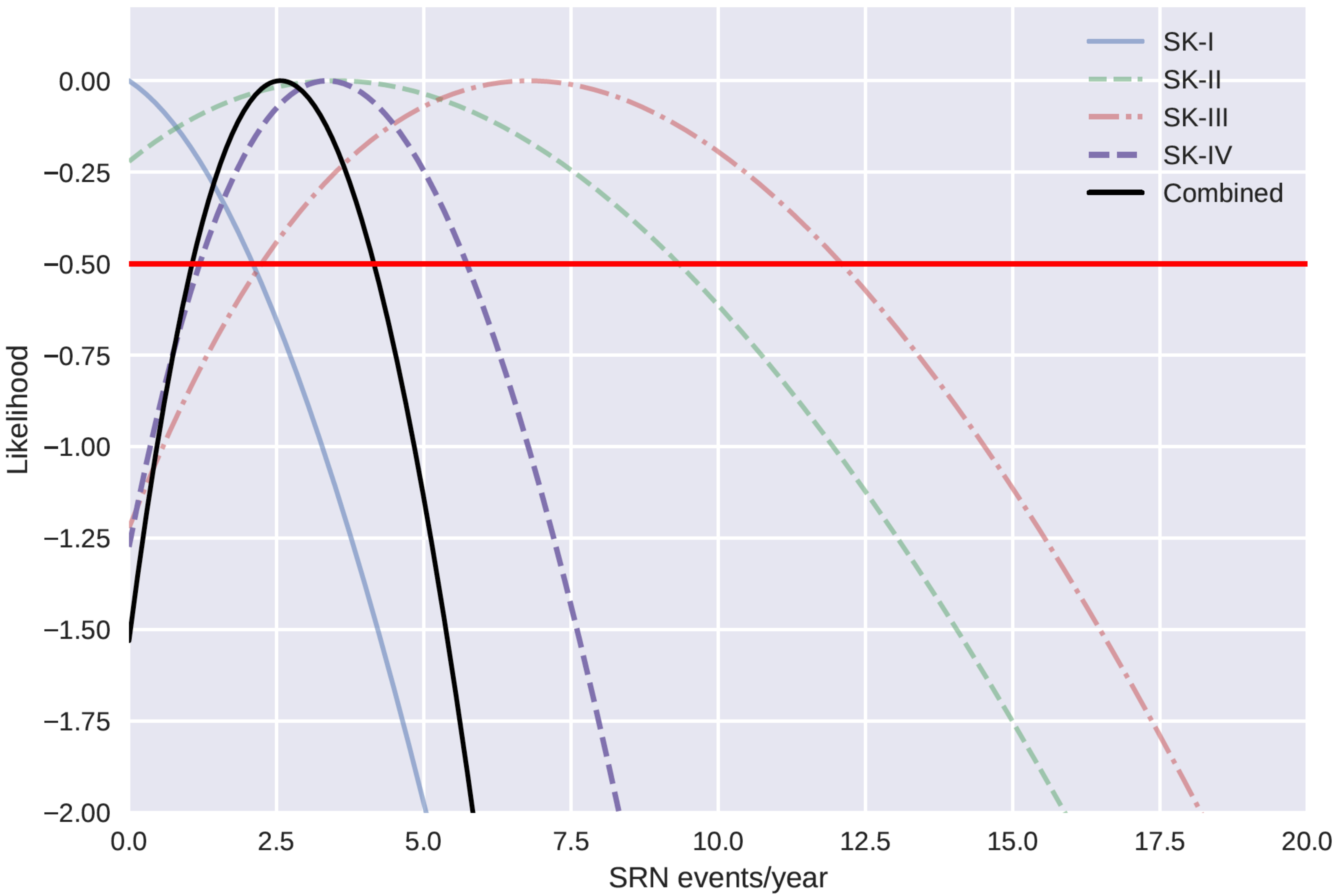
(B) Fitted Spectrum [Ando+03]

A. Giampaolo & S. El Hedri



(B) Combined Results

A. Giampaolo & S. El Hedri



(B) Upper Limits for Signal Models

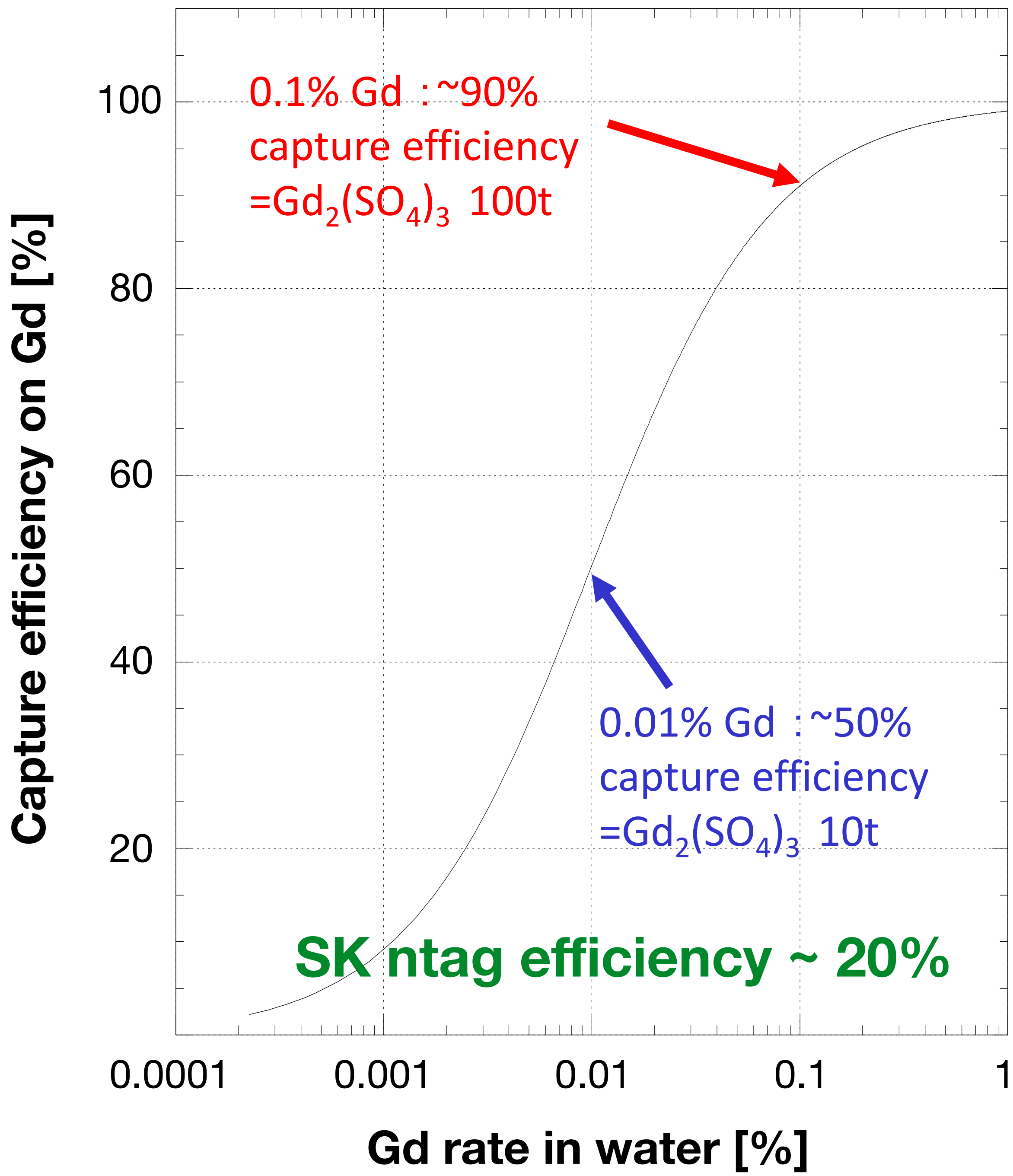
A. Giampaolo & S. El Hedri

Φ_ν [cm^{-2} sec^{-1}] (for E_ν>17.3 MeV)	Best fit		90% CL limit					Pred.
Model	SK4	All	SK1	SK2	SK3	SK4	All	
Totani+96 Constant	$1.9^{+1.3}_{-1.1}$	$1.4^{+0.8}_{-0.8}$	2.4	6.8	7.9	3.7	2.6	4.67
Malaney97 CGI	$1.8^{+1.3}_{-1.8}$	$1.4^{+0.8}_{-0.8}$	2.3	7.2	7.7	3.7	2.6	0.26
Hartmann+97 CE	$1.9^{+1.3}_{-1.2}$	$1.4^{+0.8}_{-0.8}$	2.4	7.0	7.8	3.7	2.6	0.63
Kaplinghat+00 HMA	$1.8^{+1.3}_{-1.2}$	$1.4^{+0.8}_{-0.8}$	2.3	7.1	7.8	3.7	2.6	3.00
Ando+03 (updated 05)	$1.9^{+1.3}_{-1.2}$	$1.5^{+0.9}_{-0.8}$	2.5	7.1	7.9	3.8	2.7	1.74
Lunardini09 Failed SN	$1.9^{+1.3}_{-1.2}$	$1.5^{+0.9}_{-0.8}$	2.5	7.5	8.1	3.8	2.7	0.72
Horiuchi+09 6 MeV, max	$1.9^{+1.3}_{-1.2}$	$1.5^{+0.9}_{-0.9}$	2.5	6.9	8.0	3.8	2.7	1.94
Galais+10 (NH)	$1.9^{+1.3}_{-1.2}$	$1.4^{+0.8}_{-0.8}$	2.3	7.1	7.8	3.7	2.6	1.49
Nakazato+15 (min, NH)	$1.8^{+1.3}_{-1.2}$	$1.4^{+0.9}_{-0.8}$	2.4	7.3	7.8	3.7	2.7	0.19
Nakazato+15 (max, IH)	$1.9^{+1.3}_{-1.2}$	$1.5^{+0.9}_{-0.9}$	2.5	7.1	8.0	3.8	2.7	0.53
Horiuchi+18 $\xi_{2.5} = 0.1$	$1.9^{+1.3}_{-1.2}$	$1.5^{+0.9}_{-0.9}$	2.5	6.9	8.1	3.8	2.7	1.23
Horiuchi+18 $\xi_{2.5} = 0.5$	$1.7^{+1.3}_{-1.2}$	$1.4^{+0.8}_{-0.8}$	2.3	7.6	7.5	3.6	2.5	0.55
Kresse+20 (High, NH)	$1.9^{+1.3}_{-1.2}$	$1.5^{+0.9}_{-0.8}$	2.4	7.2	7.9	3.7	2.7	1.57

Next Generation Detectors

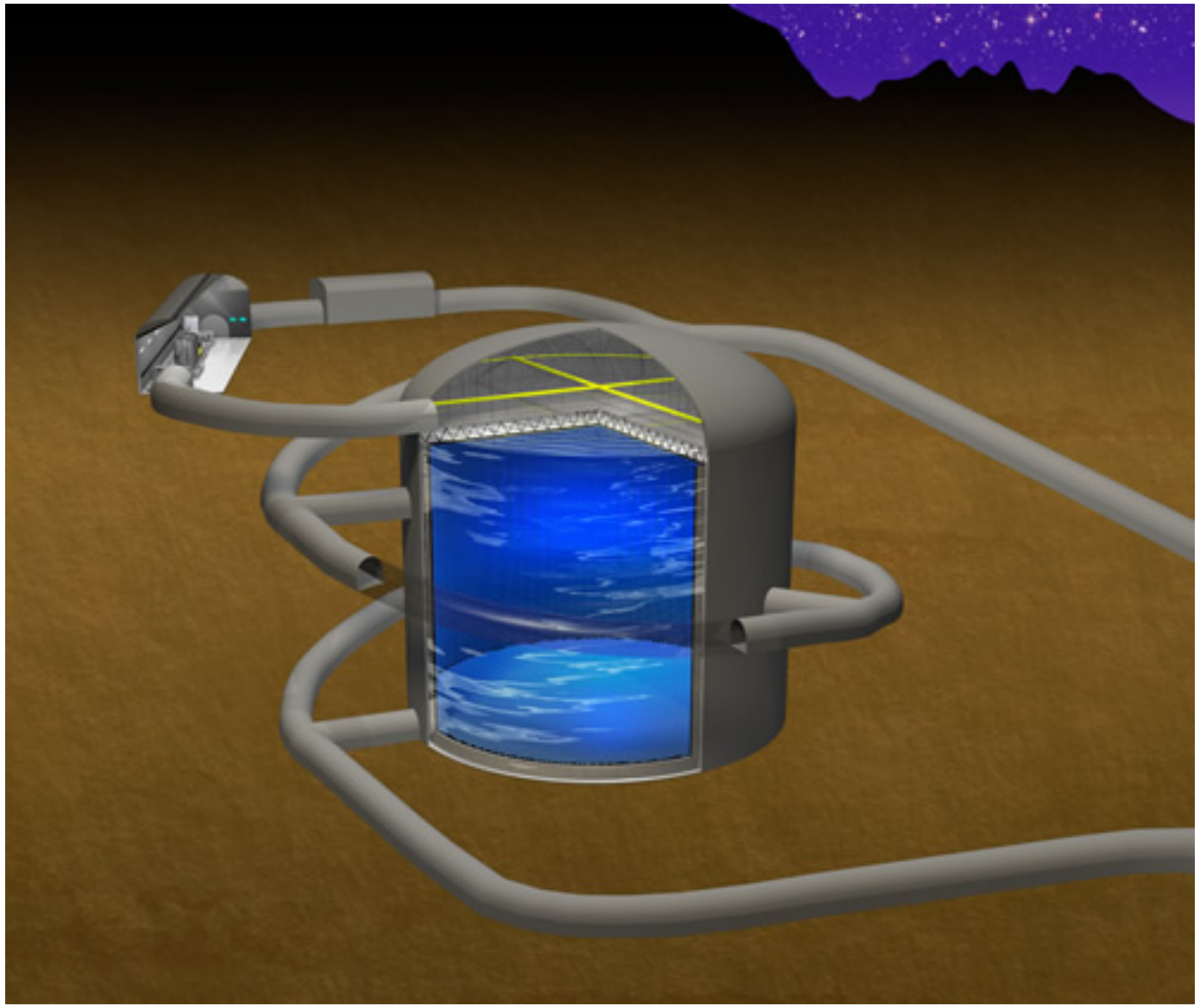
J. Beacom and M. Vagins, PRL 93, 171101 (2004)
K. Abe et al. (HK Proto-Collaboration), arXiv:1109.3262

SK-Gd ("Detection")



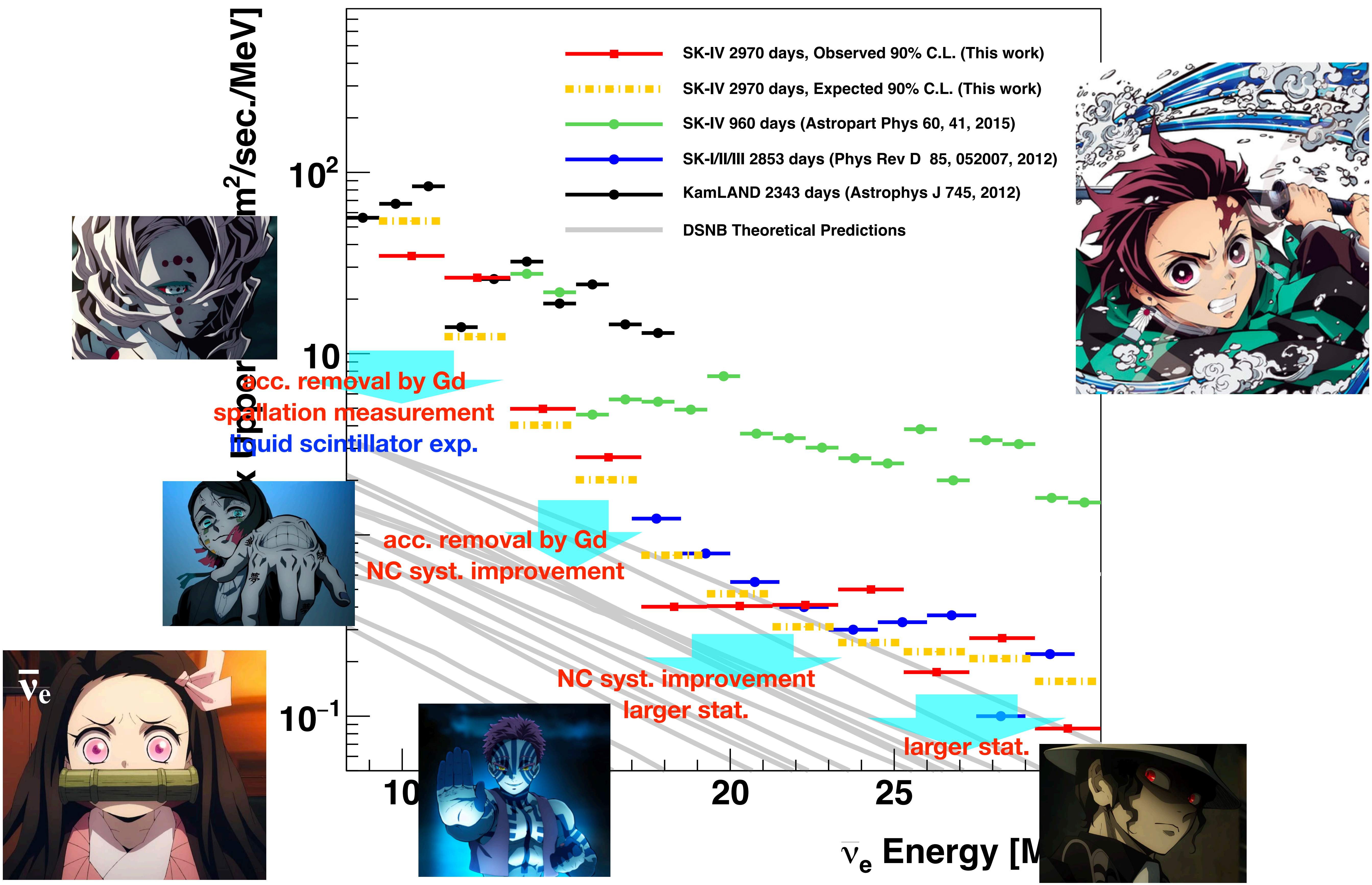
H: ~0.3 barn, 2.2 MeV γ
Gd: ~50 kbarn, ~8 MeV γ

Hyper-Kamiokande ("Measurement")



Fiducial mass: ~8.4 times larger than SK
Better photosensor: higher ntag efficiency
More spallation because of less overburden

“Demons” to be slain …



Summary

- The latest SRN search result from Super-Kamiokande is shown.
- Most optimistic models are disfavored by both analysis methods.
- Many models are within a factor of ~2 and reachable at SK-Gd.
- Spectral shape would be measured at further future detectors.

- A presentation focusing on atmospheric background to be at the Jan 12–13th atmospheric neutrino workshop (https://indico.cern.ch/event/873509/overview).

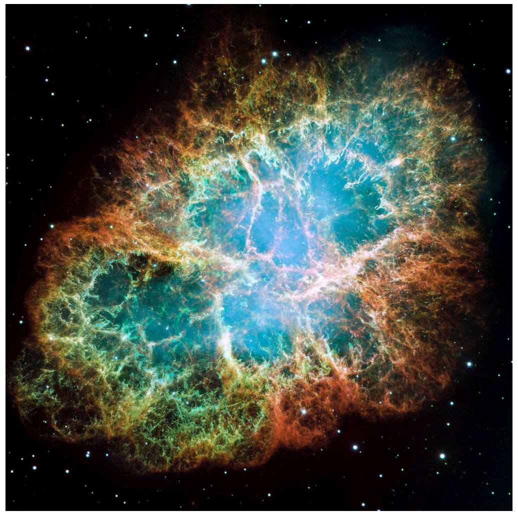
Backup Slides

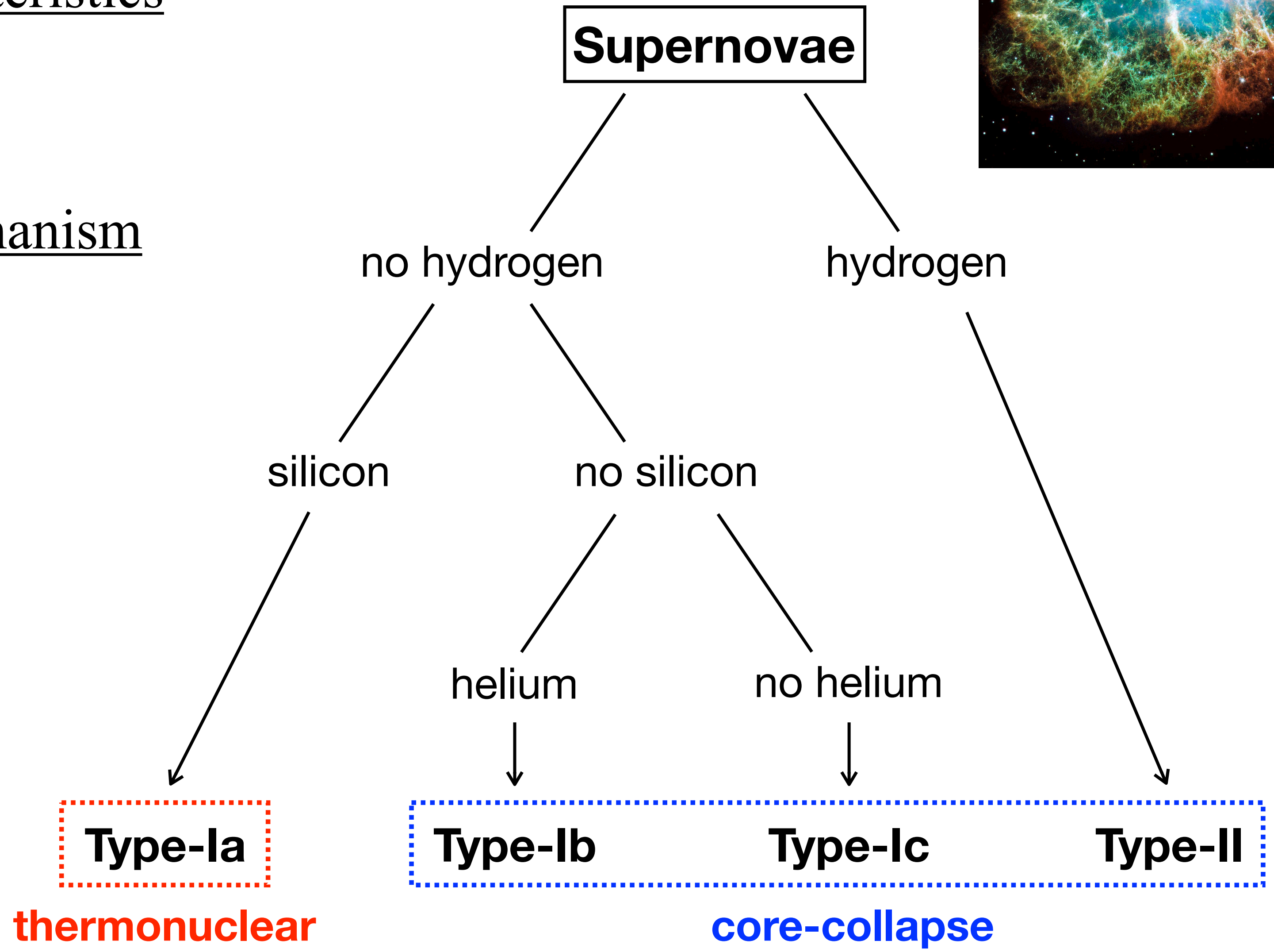
Supernova Explosion

- A Star which is more than ~8 times heavier than the Sun ends its life by an explosion.
  - kinetic energy: **~10^{51} erg** (1 erg = 1×10^{-7} J = 6.2×10^{11} eV)
  - luminosity: ~galaxy
  - rate: 1–3/century/galaxy
- Classification by spectral characteristics
  - Ia, Ib, Ic, II
- Classification by explosion mechanism
  - thermonuclear (= Ia)
  - **core-collapse** (= Ib, Ic, II)

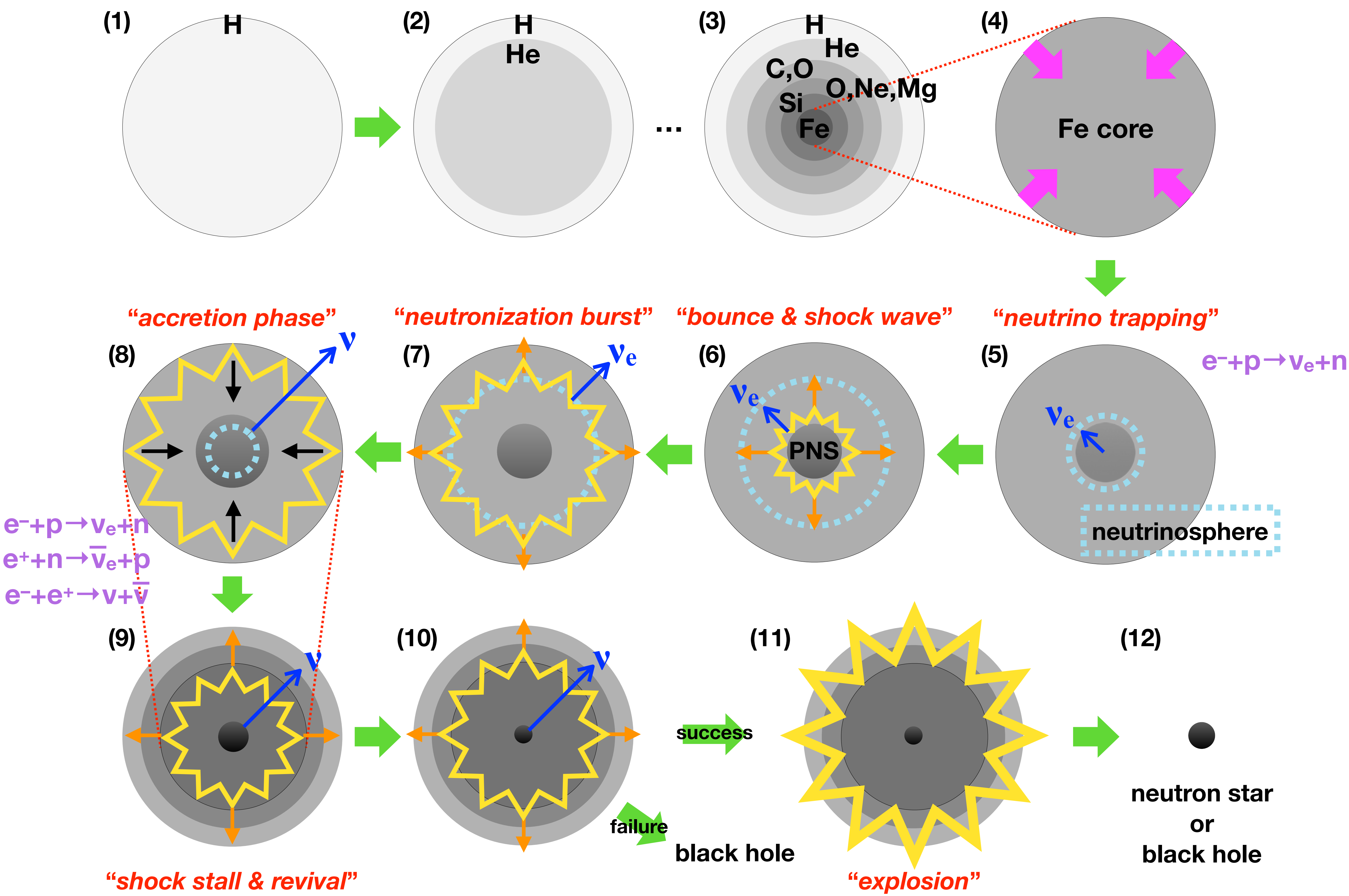
  → **neutrino emission**

Crab Nebula by NASA



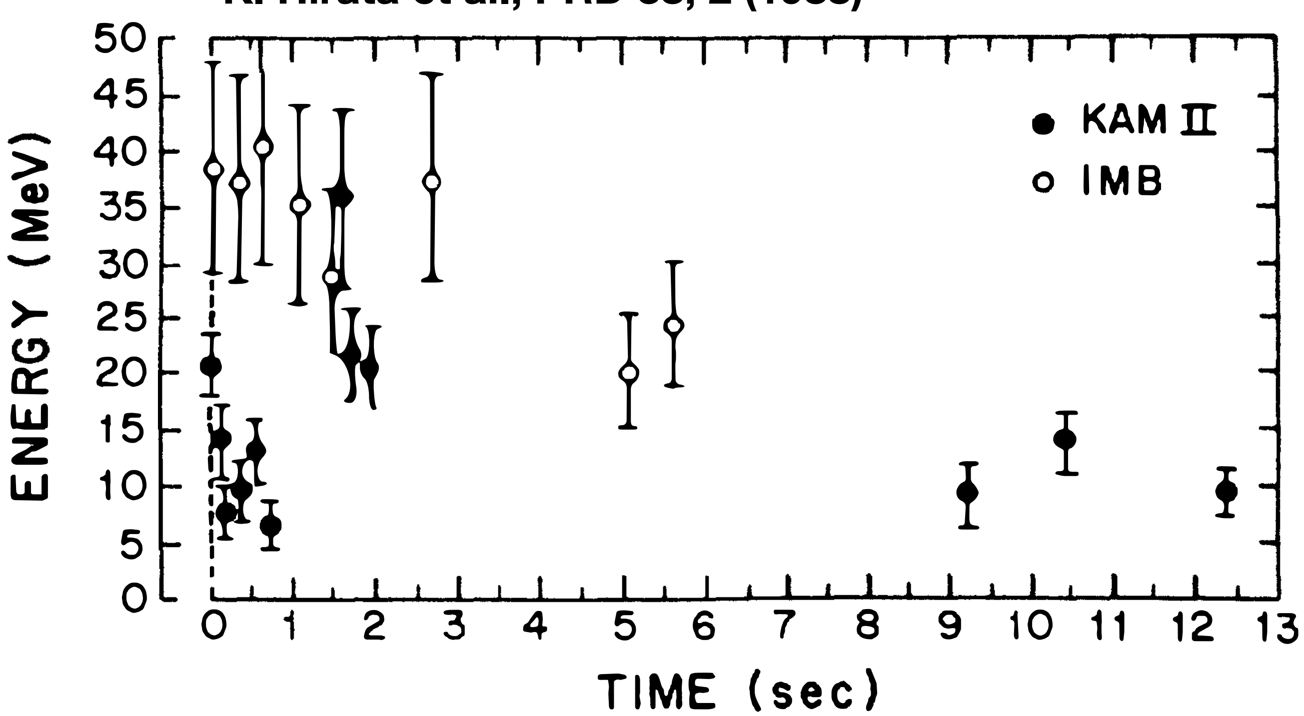


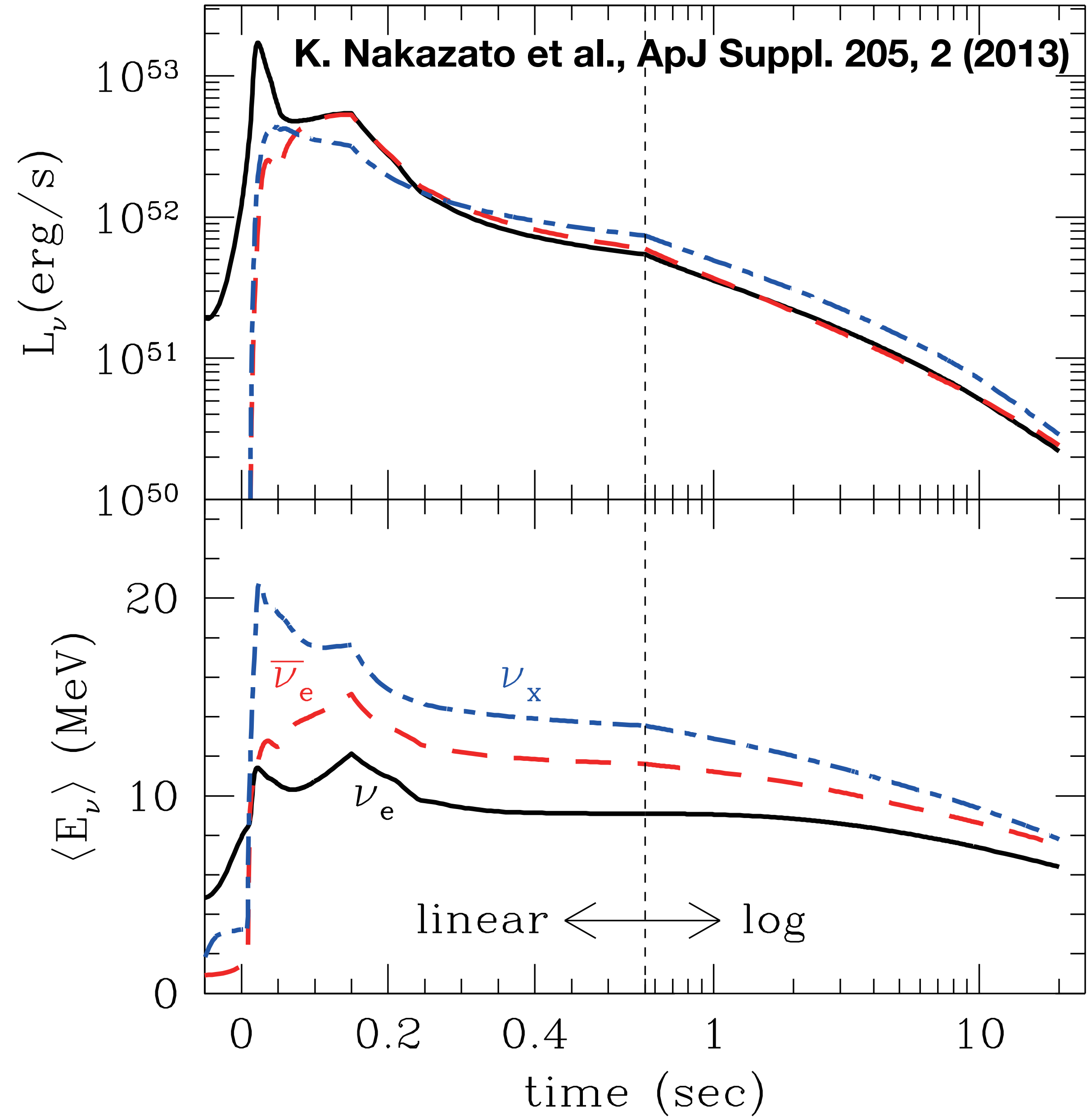
Neutrinos from Core-Collapse Supernovae



Neutrinos from Core-Collapse Supernovae

- ***Experiment*** There is only one observation of neutrinos from a supernova ("SN1987A" in the Large Magellanic Cloud).
- ***Theory*** There are many numerical simulations about CCSNe, but the explosion mechanism is not completely revealed.





Model Predictions: References

Horiuchi+20: arXiv:2012.08524

Tabrizi+20: arXiv:2011.10933

Kresse+20: arXiv:2010.0472

Horiuchi+18: Monthly Notice of the Royal Astronomical Society 475 (2018)

Nakazato+15: The Astrophysical Journal 804, 75 (2015)

Horiuchi+09 ("HBD"): Physical Review D 79, 083013 (2009)

Lunardini09 ("Failed SN"): Physical Review Letters 102, 231101 (2009)

Ando+03 ("LMA"): Astroparticle Physics 18, 307 (2003)

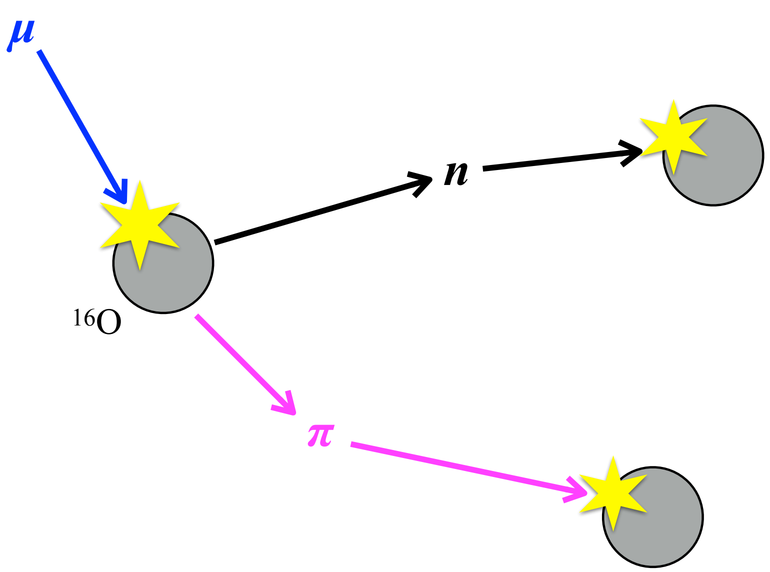
Kaplinghat+00 ("Heavy metal"): Physical Review D 62, 043001 (2000)

Malaney97 ("Cosmic gas"): Astroparticle Physics 7, 125 (1997)

Hartmann+97 ("Chemical evolution"): Astroparticle Physics 7, 137 (1997)

Totani+96 ("Constant SN"): The Astrophysical Journal 460, 303 (1996)

Spallation



Isotope	Half-life [sec.]	Decay mode	Yield [$\times 10^{-7}$muon^{-1}g^{-1}cm^2]	Primary process
n			2030	
^{18}N	0.624	β^-	0.02	^{18}O(n, p)
^{17}N	4.173	$\beta^- n$ ***low energy***	0.59	^{18}O$(n, n+p)$
^{16}N	7.13	$\beta^-\gamma$ (66%), β^- (28%)	18	(n, p)
^{16}C	0.747	$\beta^- n$ ***low energy***	0.02	(π^-, np)
^{15}C	2.449	$\beta^-\gamma$ (63%), β^- (37%)	0.82	$(n, 2p)$
^{14}B	0.0138	$\beta^-\gamma$	0.02	$(n, 3p)$
^{13}O	0.0086	β^+	0.26	$(\mu^-, p+2n+\mu^-+\pi^-)$
^{13}B	0.0174	β^-	1.9	$(\pi^-, 2p+n)$
^{12}N	0.0110	β^+	1.3	$(\pi^+, 2p+2n)$
^{12}B	0.0202	β^-	12	$(n, \alpha+p)$
^{12}Be	0.0236	β^-	0.10	$(\pi^-, \alpha+p+n)$
^{11}Be	13.8	β^- (55%), $\beta^-\gamma$ (31%)	0.81	$(n, \alpha+2p)$
^{11}Li	0.0085	$\beta^- n$ ***very short lifetime***	0.01	$(\pi^+, 5p+\pi^++\pi^0)$
^{9}C	0.127	β^+	0.89	$(n, \alpha+4n)$
^{9}Li	0.178	$\beta^- n$ (51%), β^- (49%)	1.9	$(\pi^-, \alpha+2p+n)$
^{8}B	0.77	β^+	5.8	$(\pi^+, \alpha+2p+2n)$
^{8}Li	0.838	β^-	13	$(\pi^-, \alpha+{}^2\mathrm{H}+p+n)$
^{8}He	0.119	$\beta^-\gamma$ (84%), $\beta^- n$ (16%) ***low energy***	0.23	$(\pi^-, {}^3\mathrm{H}+4p+n)$
^{15}O			351	(γ, n)
^{15}N			773	(γ, p)
^{14}O			13	$(n, 3n)$
^{14}N			295	$(\gamma, n+p)$
^{14}C			64	$(n, n+2p)$
^{13}N			19	$(\gamma, {}^3\mathrm{H})$
^{13}C			225	$(n, {}^2\mathrm{H}+p+n)$
^{12}C			792	(γ, α)
^{11}C			105	$(n, \alpha+2n)$
^{11}B			174	$(n, \alpha+p+n)$
^{10}C			7.6	$(n, \alpha+3n)$
^{10}B			77	$(n, \alpha+p+2n)$
^{10}Be			24	$(n, \alpha+2p+n)$
^{9}Be			38	$(n, 2\alpha)$
sum			3015	

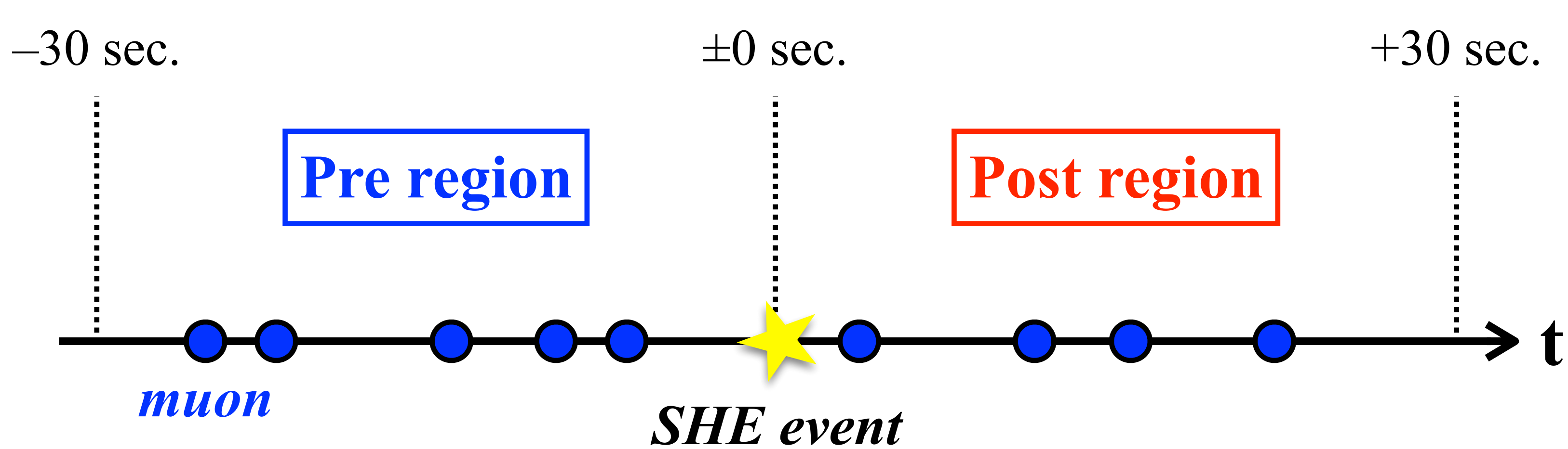
Not direct backgrounds in SK

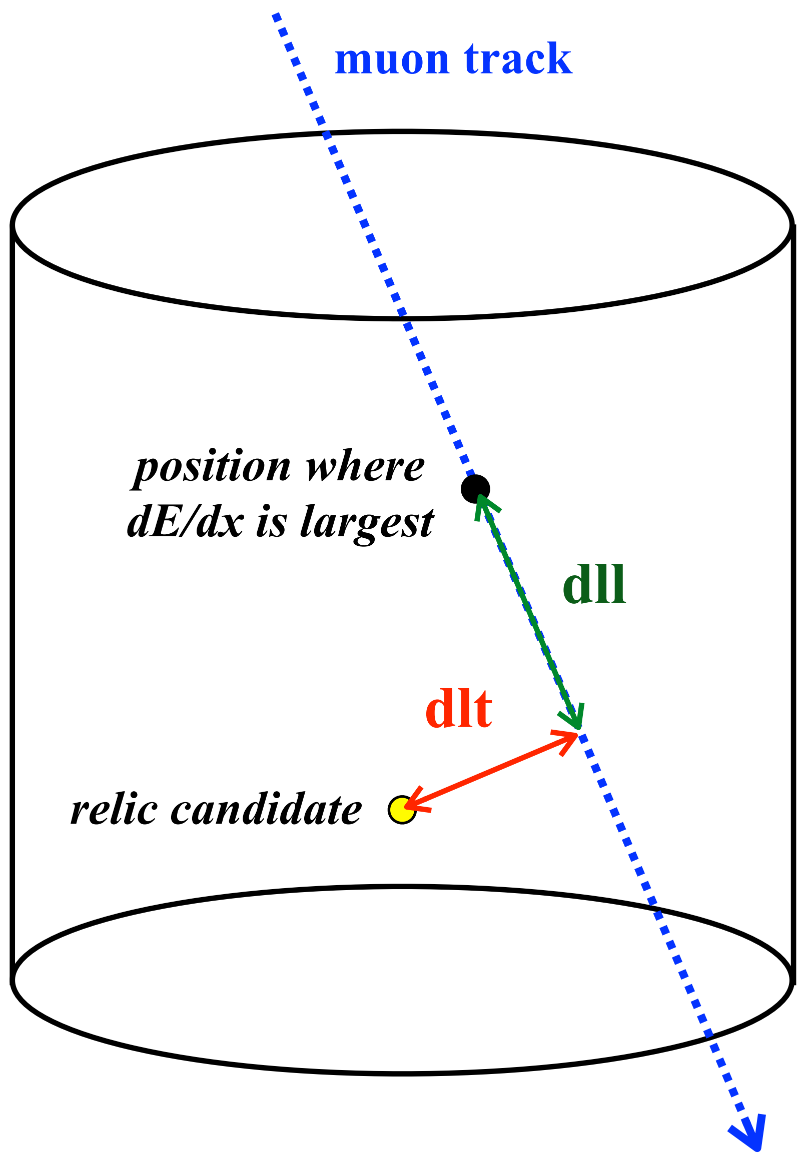
- **stable (no decay)**
- **long lifetime**
- **invisible decay**
- **very low energy**

Spallation Cut: Likelihood Cut

- Two samples
  - Pre sample (–30 ~ 0 sec.)
  - post sample (0 ~ +30 sec.)

- Five discriminating variables => make spallation likelihoods
  - **dt**: time difference between the relic candidate and muon
  - **dlt**: transverse distance
  - **dll**: longitudinal distance
  - **resq**: dE/dx related variable
  - **muqismsk**: total change deposit by muon

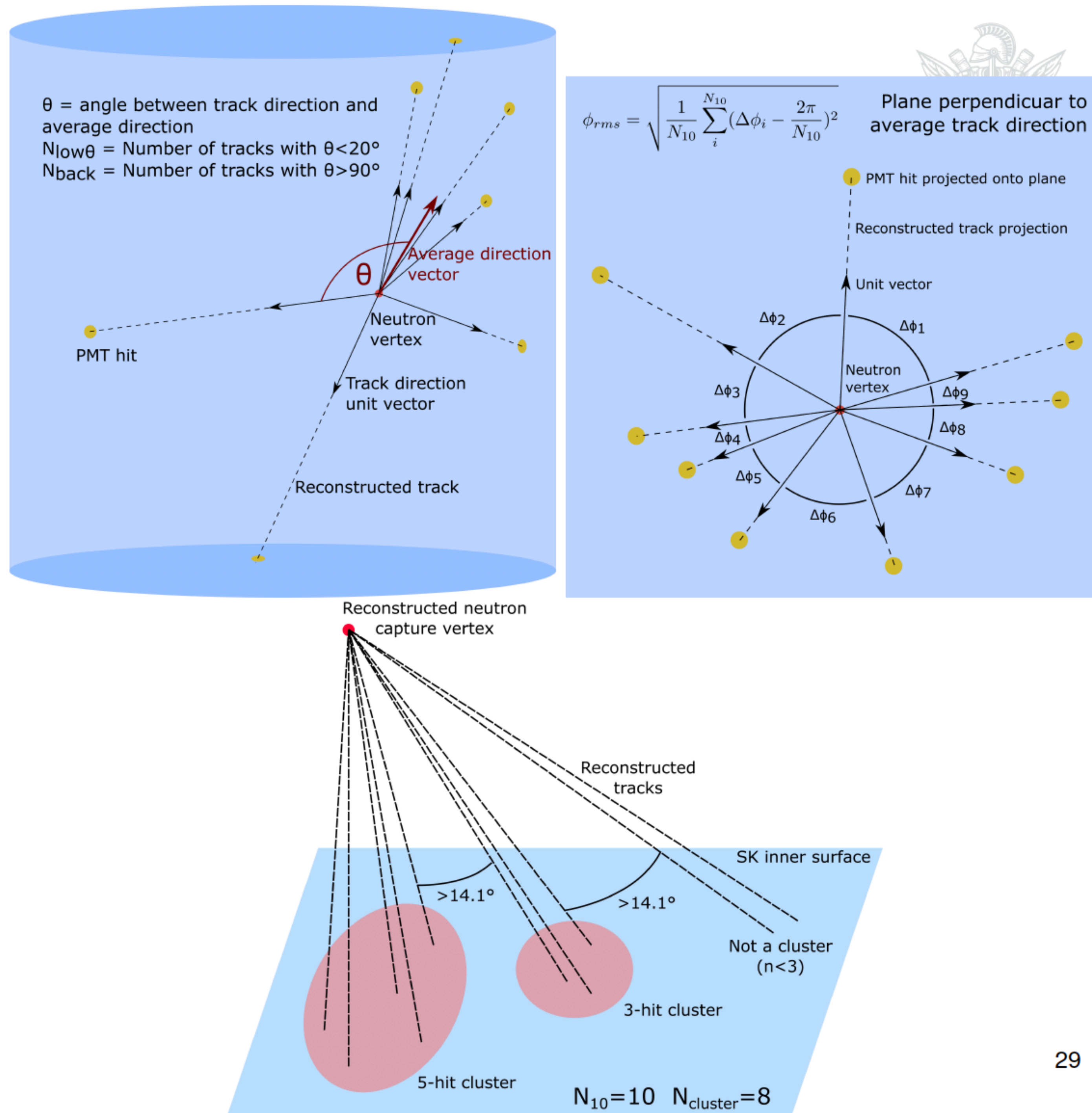




Neutron Tagging: The 22 Variables by Alberto

DISCRIMINATING VARIABLES (1)

- N_{10}: number of PMT hits in 10 ns window
- Geometrical variables
  - θ_{mean}, θ_{rms}
  - ϕ_{rms}
  - N_{low}
  - $N_{cluster}$
  - $N_{low\theta}$
  - N_{back}
- PMT noise variables
  - N_{300}
  - N_{highQ}
  - Q_{mean}, Q_{rms}
  - T_{rms}, minT_{rms}(3), minT_{rms}(6)



Neutron Tagging: The 22 Variables

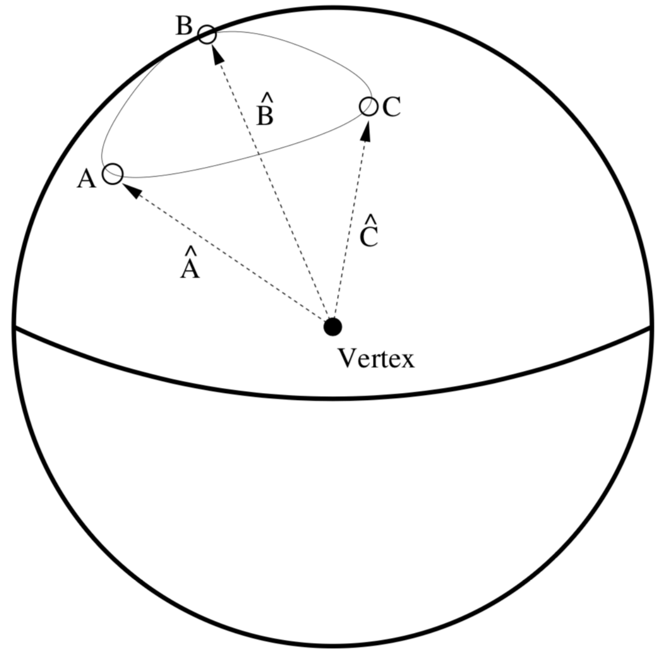
by Alberto

DISCRIMINATING VARIABLES (2)

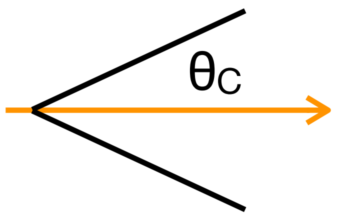
Additional variables to refine the zeroth-order vertex:

- Neut-Fit variables
  - NF_{wall}
  - $\delta \mathrm{N}_{10}$
  - $\delta \mathrm{T}_{rms}$
- BONSAI vertex fit Variables
  - BS_{wall}
  - BS_{energy}
- Fit agreement variables
  - BF_{dist}
  - FP_{dist}
- Combined-fit variables
  - $\mathcal{L}_{ratio} = \frac{\mathcal{L}_{combined}}{\mathcal{L}_{prompt} \times \mathcal{L}_{neutron}}$
  - $\mathcal{L}_{window}$

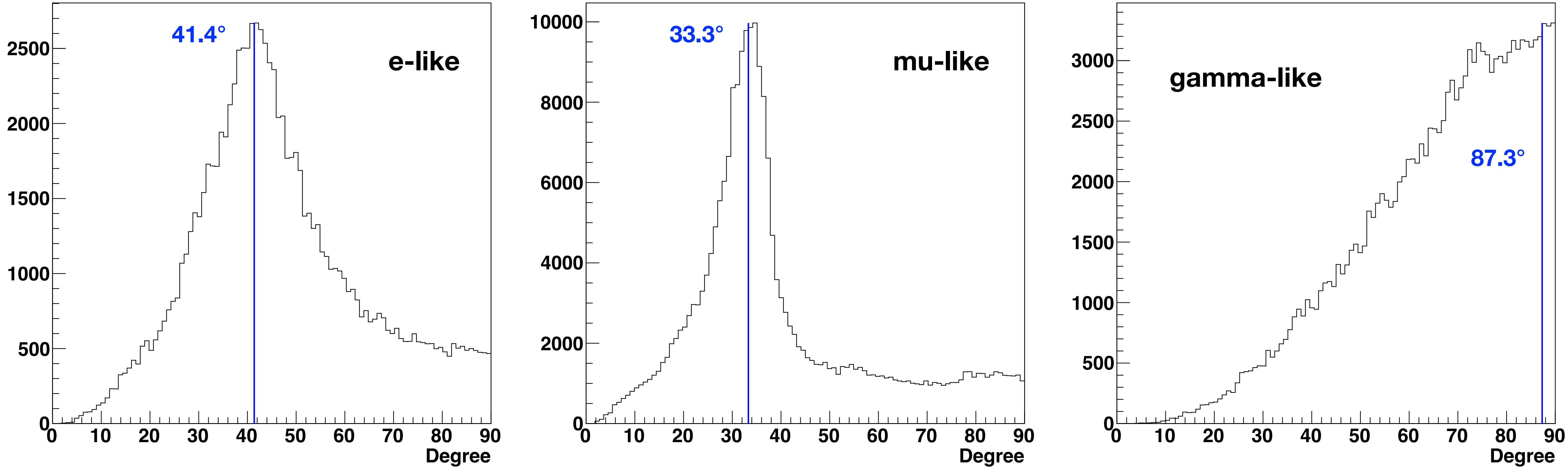
Particle Identification



- Particle ID is possible using "**Cherenkov opening angle**".
  - $\cos\theta_C = 1/n\beta$ (n ~ 1.33: refractive index)
  - θ_C ~ 42 deg. for relativistic particles
  - θ_C becomes larger for multiple γ-rays

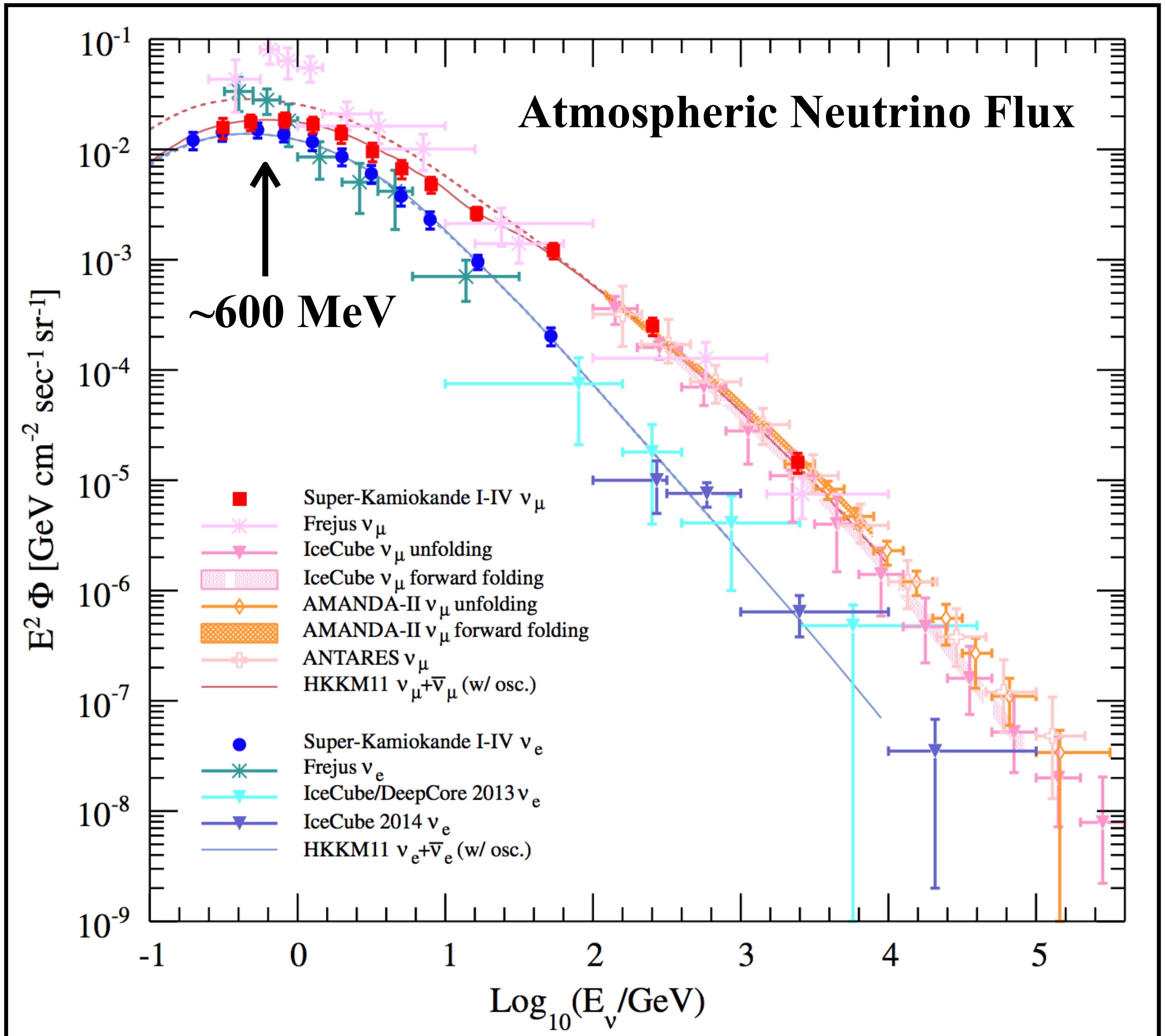


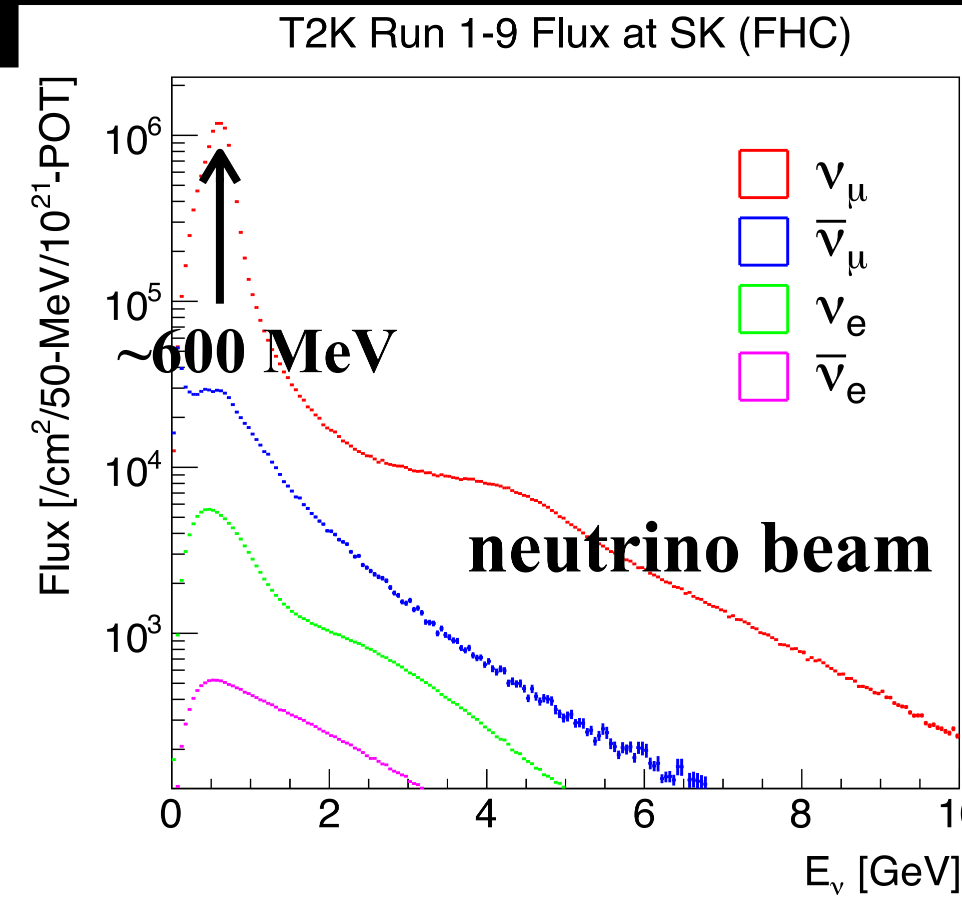
- This Cherenkov opening angle is reconstructed using triplet combinations of PMTs.
- In the SRN search, $38 < \theta_C < 50$ deg. is required to select e-like events.

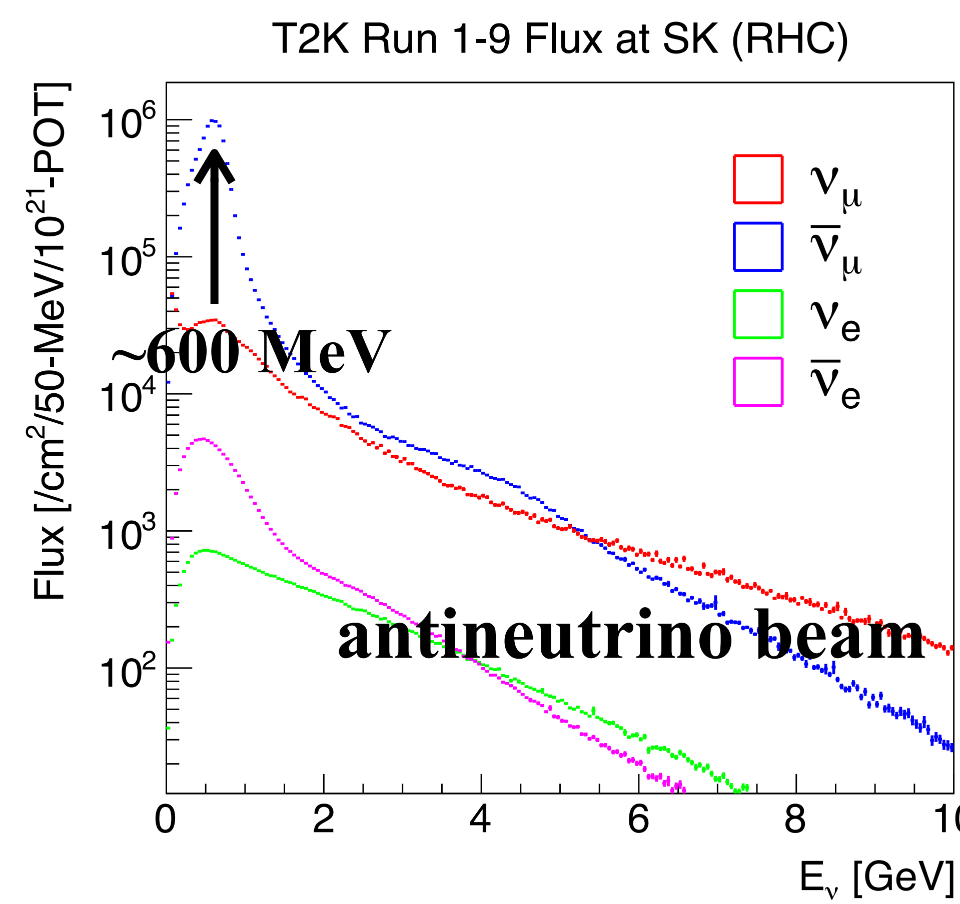


Flux: Atmospheric vs. T2K

E. Richard et al. (SK Collaboration), PRD 94, 052001 (2016).
K. Abe et al. (T2K Collaboration), PRD 100, 112009 (2019).







Background & Systematics

- ***Atmospheric-ν non-NCQE*** (**19% syst.**)
  - Fitting Monte-Carlo prediction to data in the sideband region (>30 MeV)

- ***Atmospheric-ν NCQE*** (**60~80% syst.**)
  - Xsec scaled by the T2K NCQE result (~25% syst)
  - Neutron multiplicity error estimated by the T2K Ntag result (~40% syst)
  - Spectrum shape error estimated by smearing method (30~60% syst)
  - Uncertainties from flux, flux shape, reduction etc (~20% syst)

- ***Spallation ^{9}Li*** (**60% syst.**)
  - Production rate taken from the ^{9}Li paper (22% syst)
  - Error on reduction (10~20% syst)
  - Study from Δt fit with no spacut + ntag (~50% syst)

- ***Reactor-ν*** (**100% syst.**)
  - Estimated referring to the IAEA Database

- ***Accidental coincidence*** (**6% syst.**)
  - Estimated using the T2K dummy trigger data

SK-I~IV Fit Results

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