ICEPP Symposium, 17th/February/2020)

Supernova Relic Neutrino Searches

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Supernova Explosion

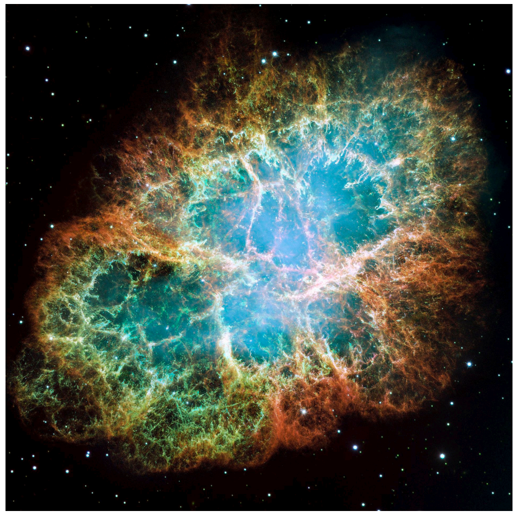
- A Star which is more than ~8 times heavier than the Sun ends its life by an explosion.
  - kinetic energy: **~10^{51} erg** (1 erg = 1 × 10^{-7} J = 6.2 × 10^{11} eV)
  - luminosity: ~galaxy
  - rate: 1–3/century/galaxy

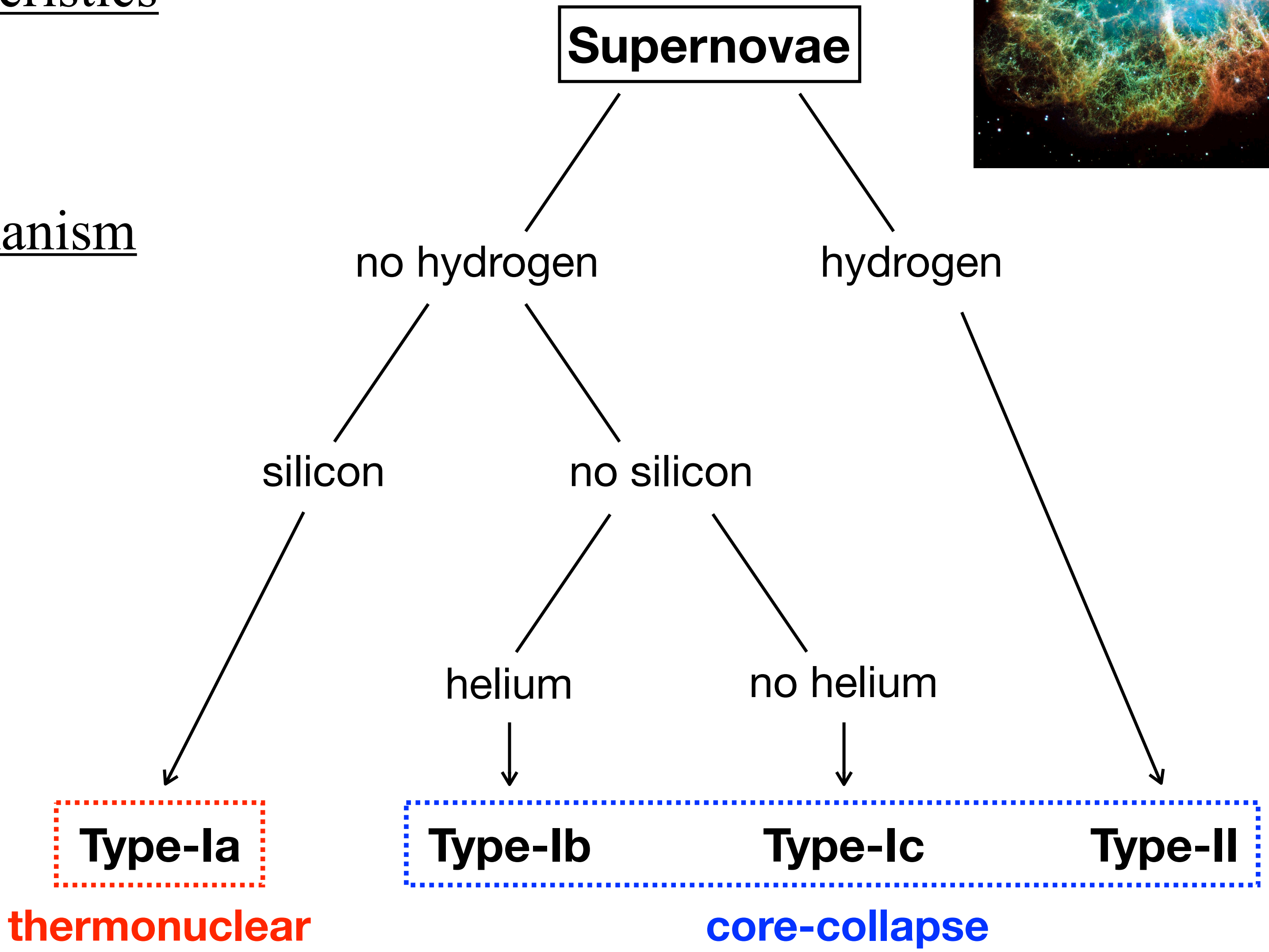
- Classification by spectral characteristics
  - Ia, Ib, Ic, II

- Classification by explosion mechanism
  - thermonuclear (= Ia)
  - **core-collapse** (= Ib, Ic, II)

  → **neutrino emission**

Crab Nebula by NASA

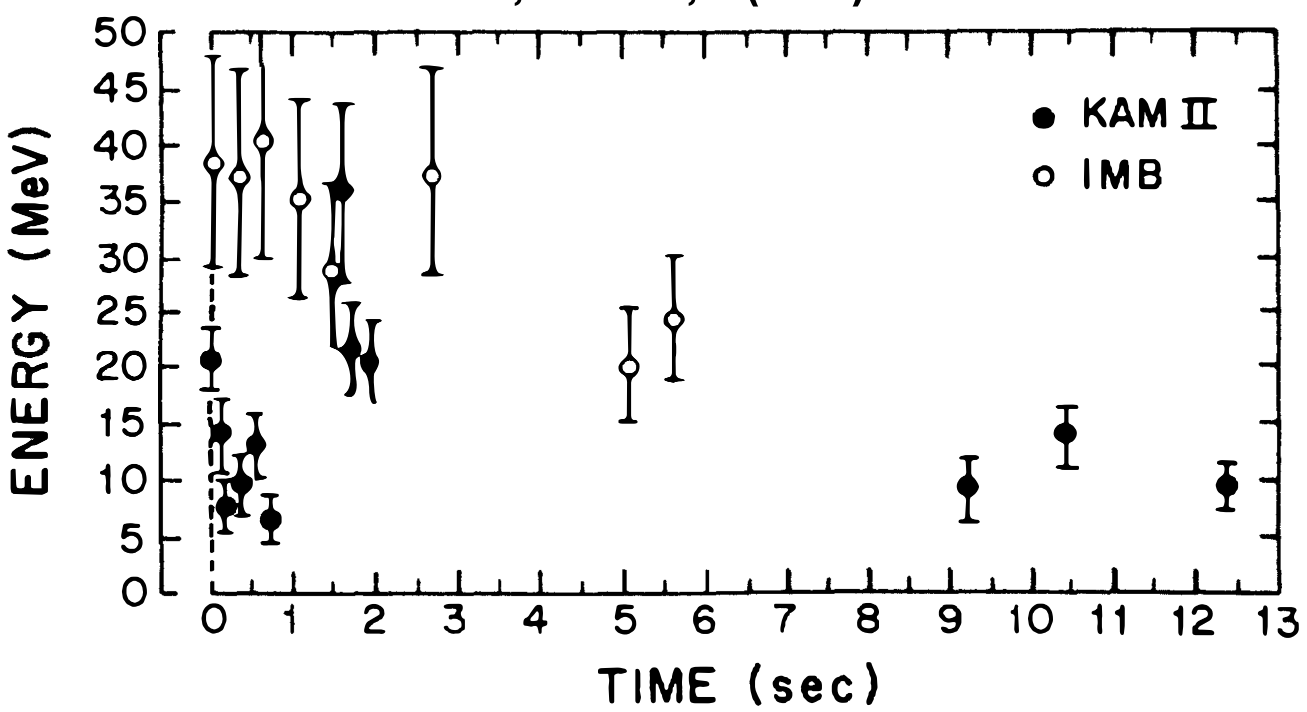




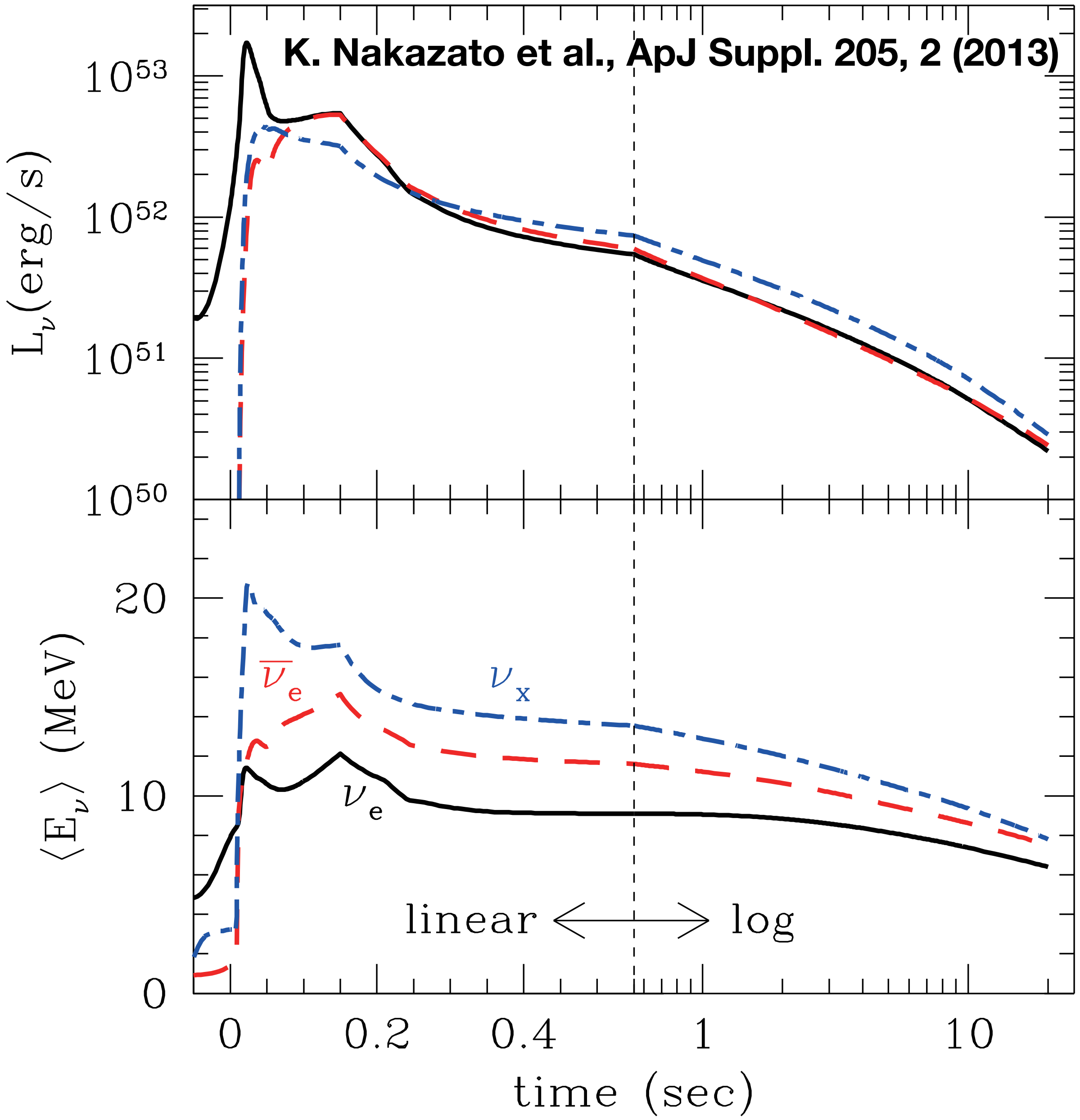
Neutrinos from Core-Collapse Supernovae

- ***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.

K. Hirata et al., PRD 38, 2 (1988)



K. Nakazato et al., ApJ Suppl. 205, 2 (2013)



Supernova Relic Neutrinos

- Neutrinos from all past CCSNe are accumulated to form an integrated flux.
  = **Supernova Relic Neutrinos (SRNs)**

- Various factors affect the SRN flux on Earth.
  - Neutrino oscillation (mass hierarchy)
  - Galactic evolution (star formation rate, initial mass function, 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

neutrino number spectrum per CCSN

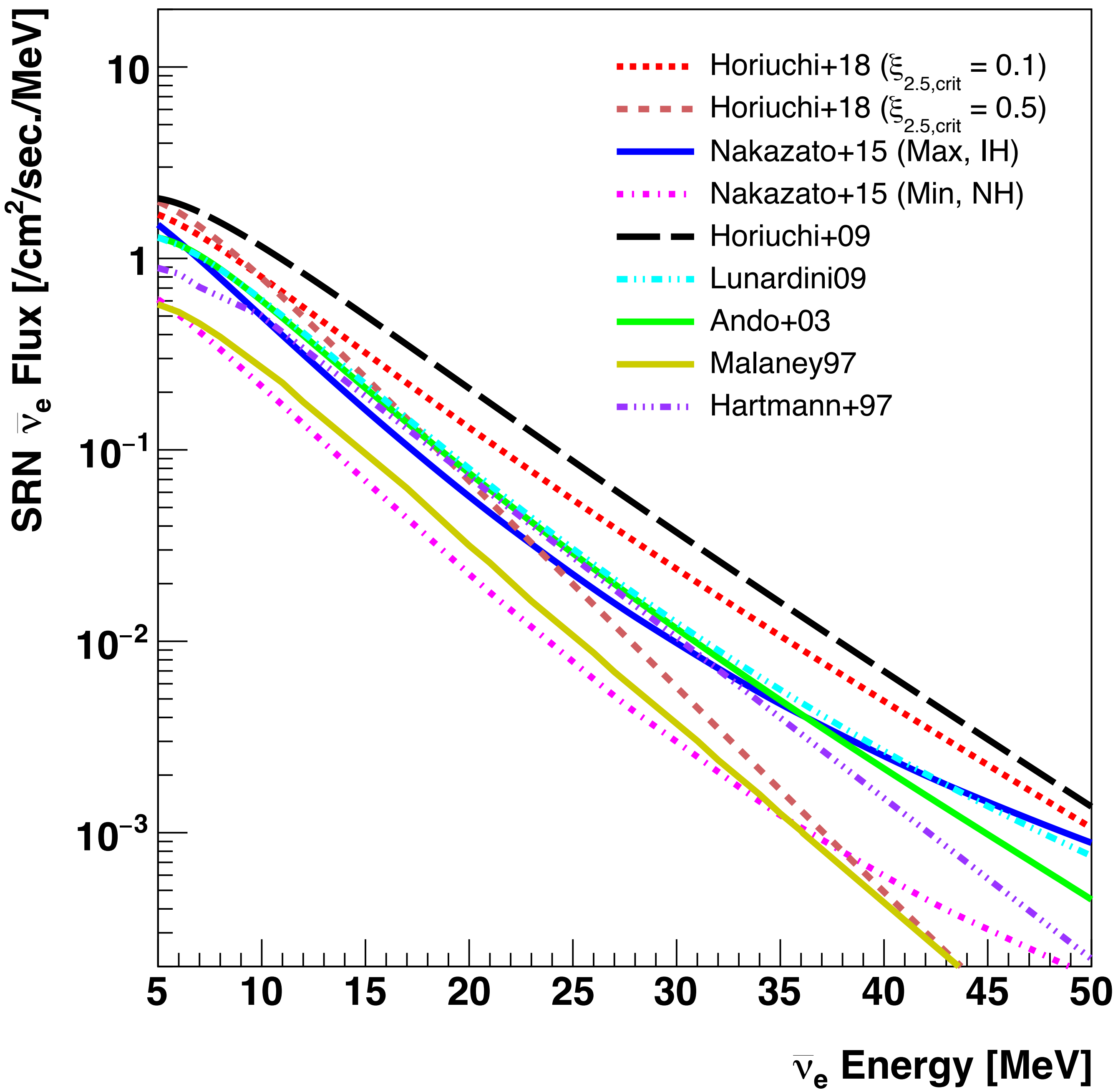
CCSN rate

metallicity distribution of progenitors

initial mass function of progenitors

Supernova Relic Neutrinos

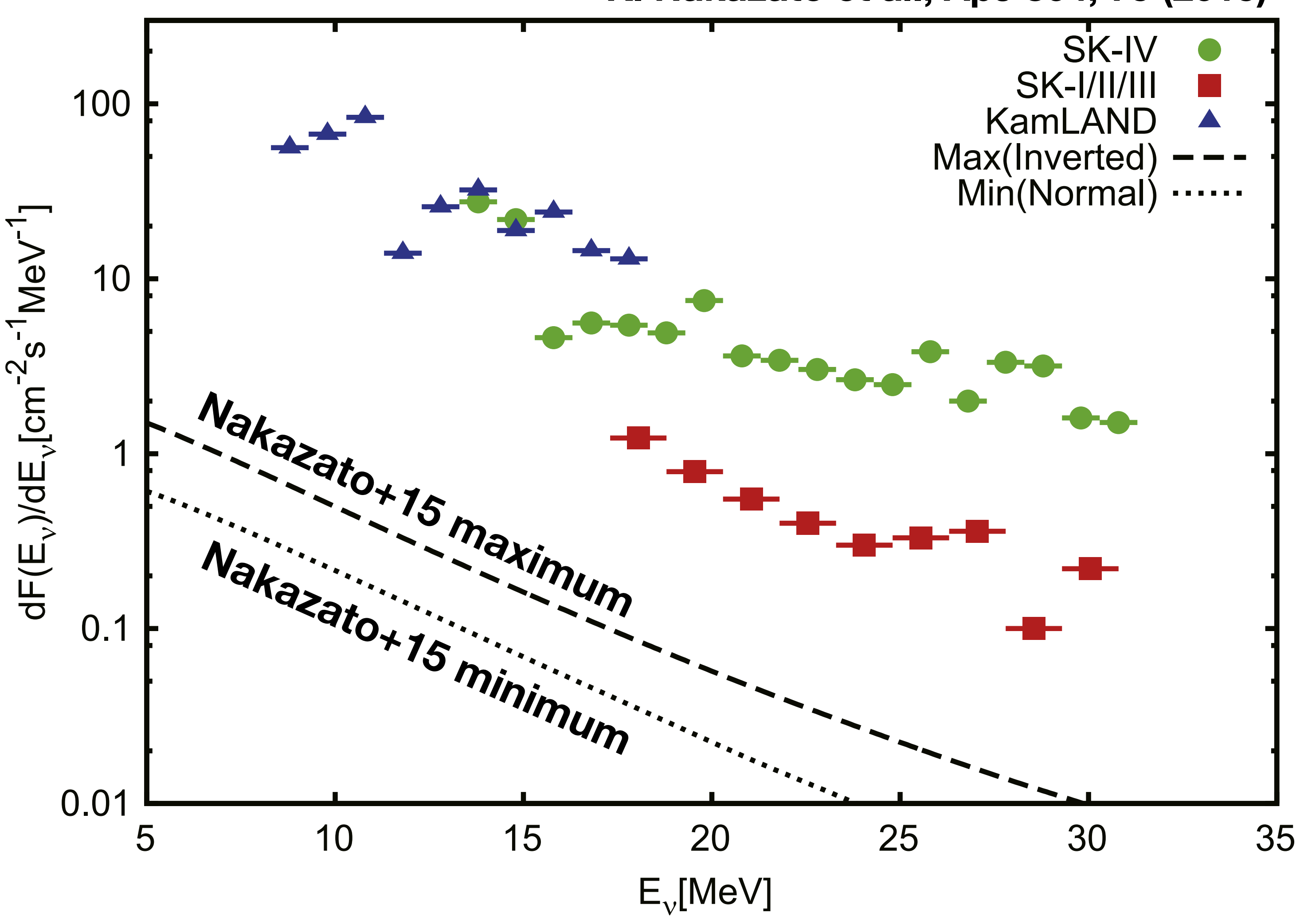
- There is nearly an order of magnitude difference in the flux depending on the model.
- Detecting SRNs would provide valuable information about the explosion mechanism as well as the star formation history.



Status of SRN Searches

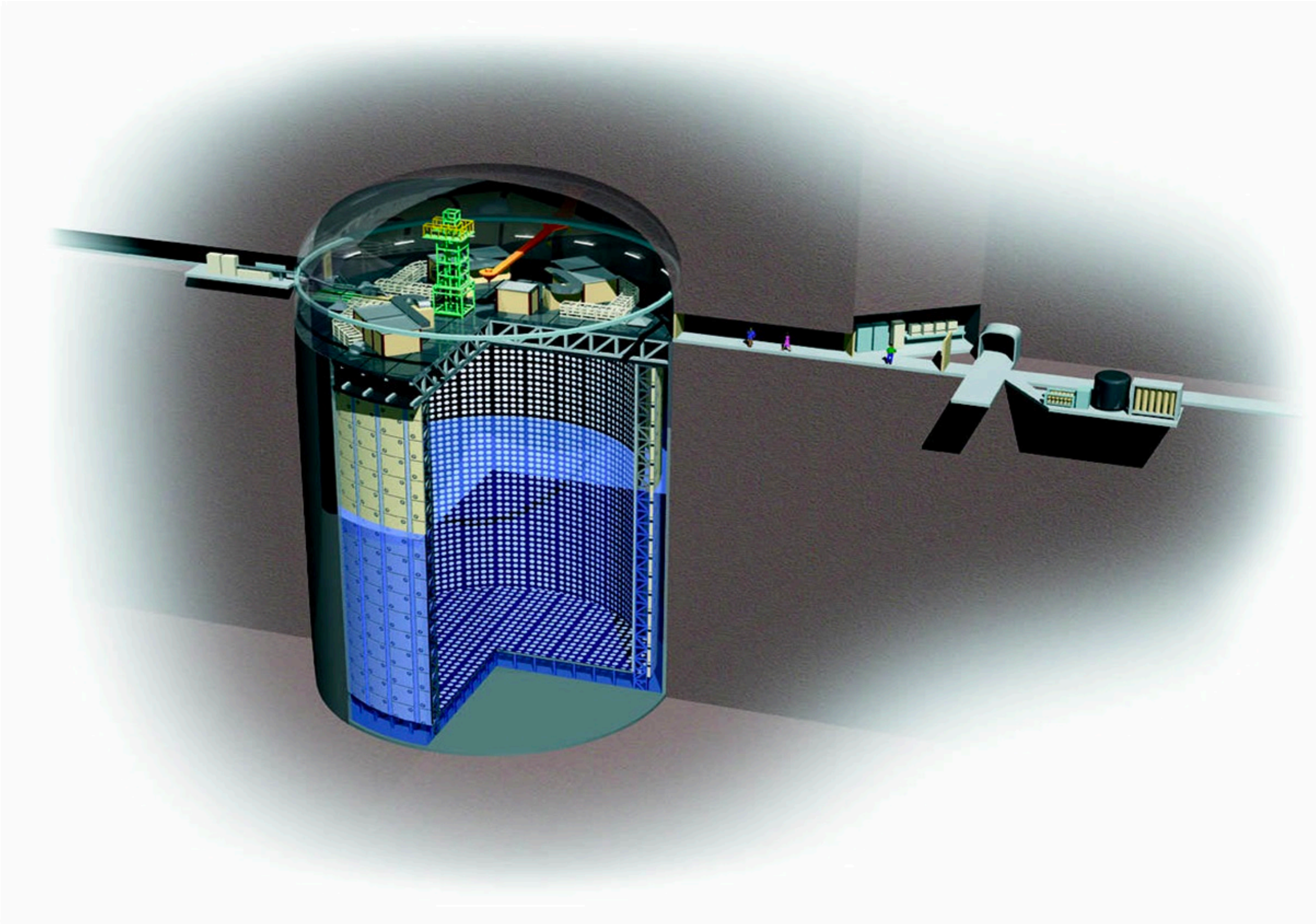
- **Signal in experimental search** = inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$)
- The most sensitive searches have been performed in Super-Kamiokande and KamLAND.
- Search at SK
  - SK-I/II/III (spectrum analysis): spectrum fitting to E_ν > 17.3 MeV
  - SK-IV (neutron tagging analysis): tagging efficiency ~20%
- Search at KamLAND
  - Delayed coincidence
    (tagging efficiency ~ 100%)

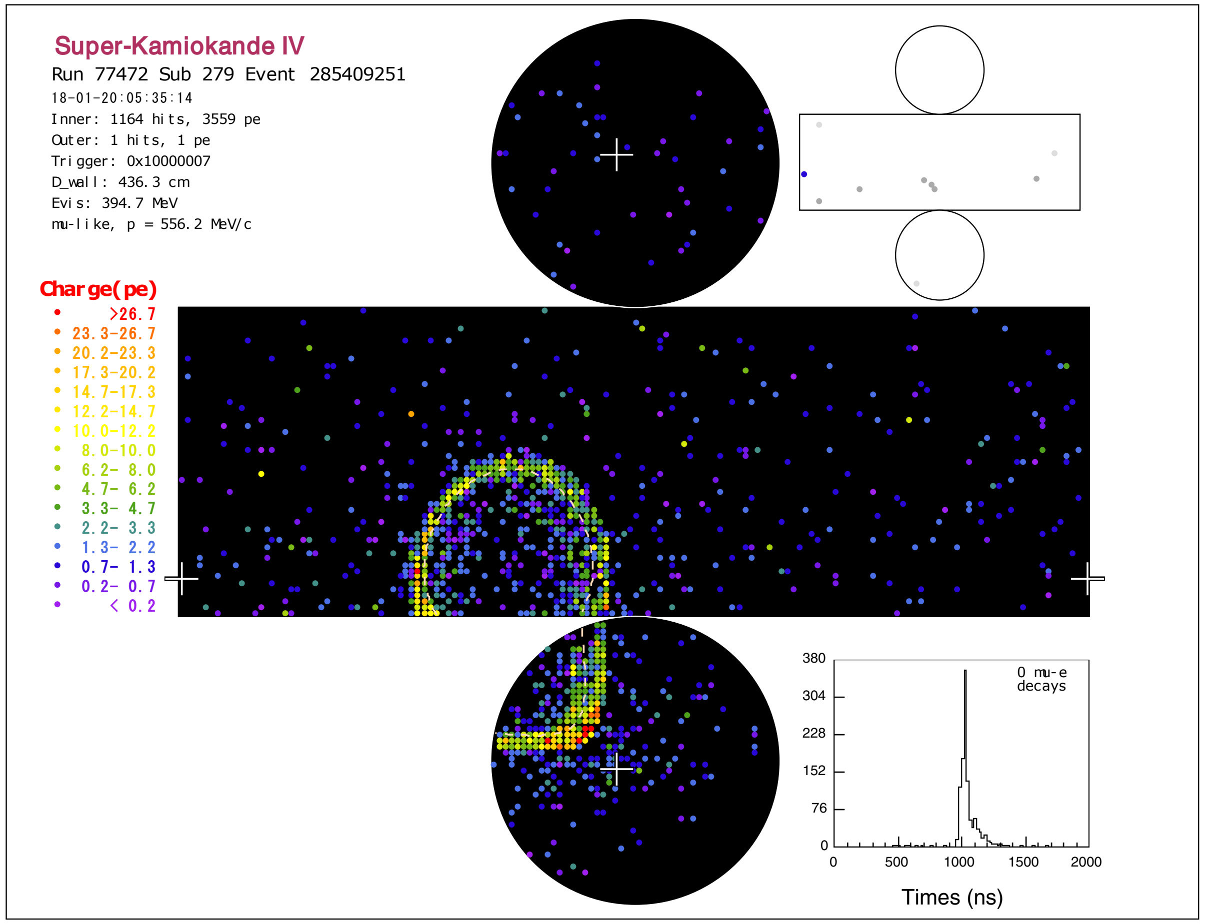
K. Nakazato et al., ApJ 804, 75 (2015)



Super-Kamiokande Detector

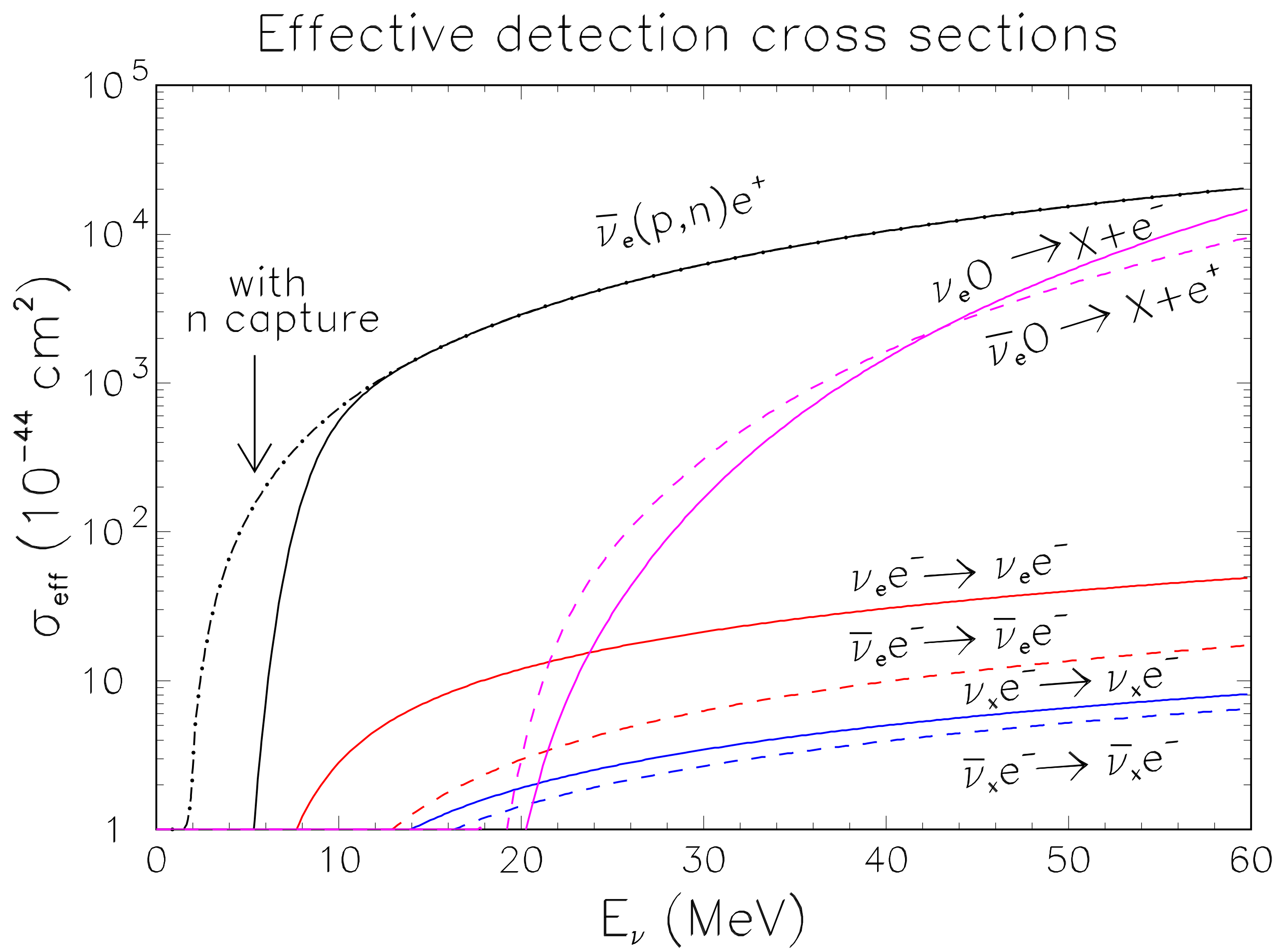
- A water Cherenkov detector located 1,000 m under the mountain.
- Fiducial volume: 22.5 kton
- Inner detector: 11,129 20-inch PMTs
- Outer detector: 1,885 8-inch PMTs, used for cosmic-ray muon veto
- Operated since 1996 in five periods.

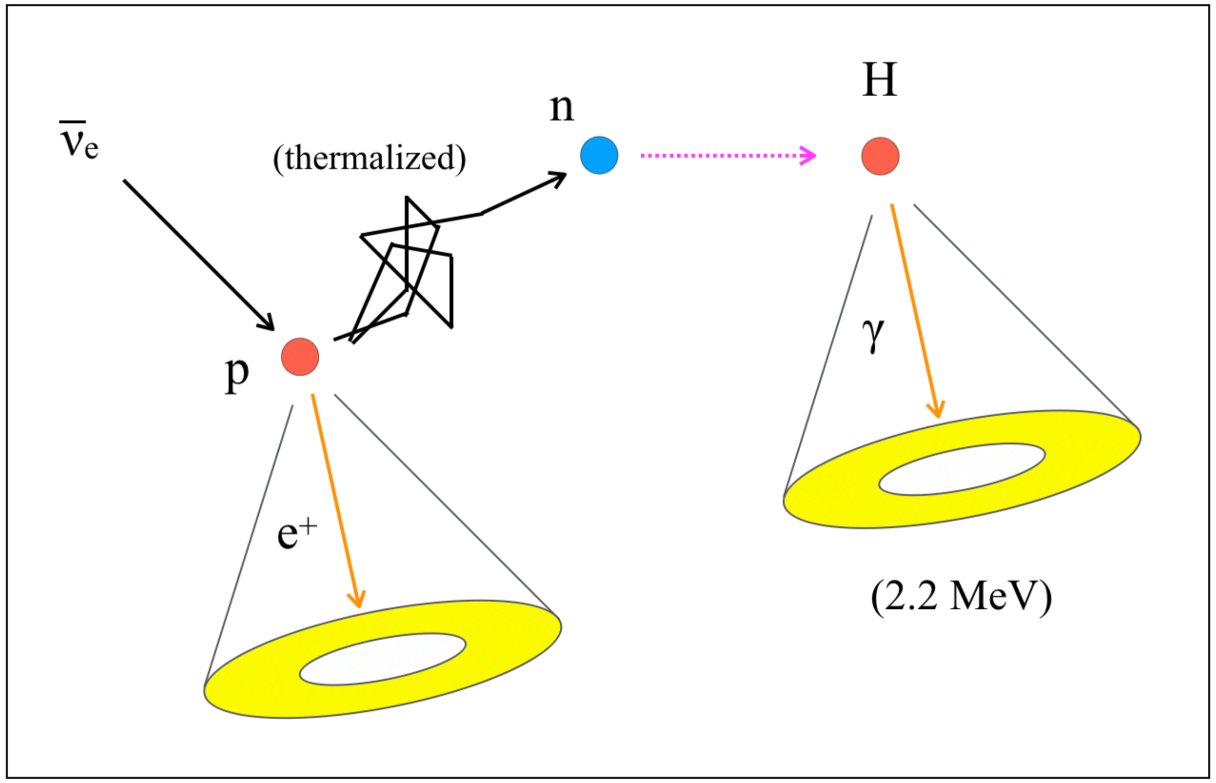




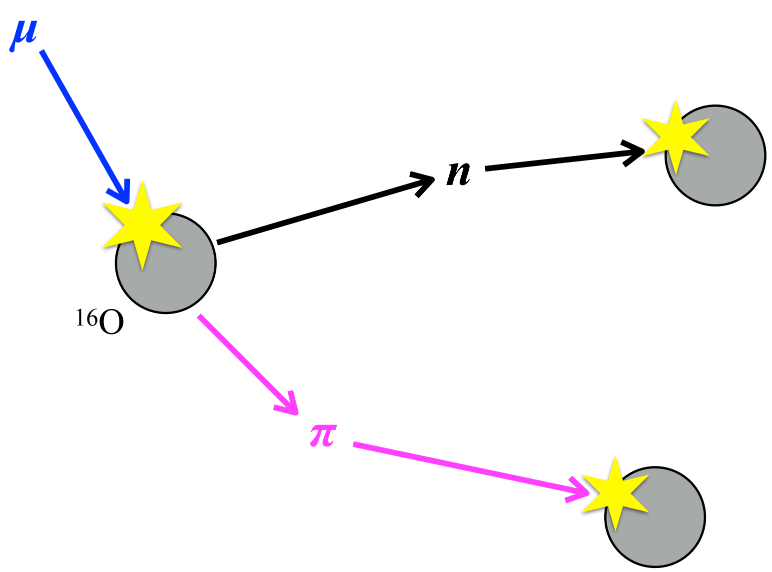
Signal

- 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 = [7.5, 29.5] MeV in visible energy (E_ν = [9.3, 31.3] MeV)
- Signal: "**β+n**" events
    - Prompt signal = β
    - Delayed signal = **2.2 MeV γ** from neutron capture





Background (1): Muon 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	$(\pi^-, \alpha+{}^2\text{H}+p+n)$
^{8}He	0.119	$\beta^-\gamma$ (84%), $\beta^- n$ (16%) *low energy*	0.23	$(\pi^-, {}^3\text{H}+4p+n)$
^{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	$(\gamma, {}^3\text{H})$
^{13}C			225	$(n, {}^2\text{H}+p+n)$
^{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	

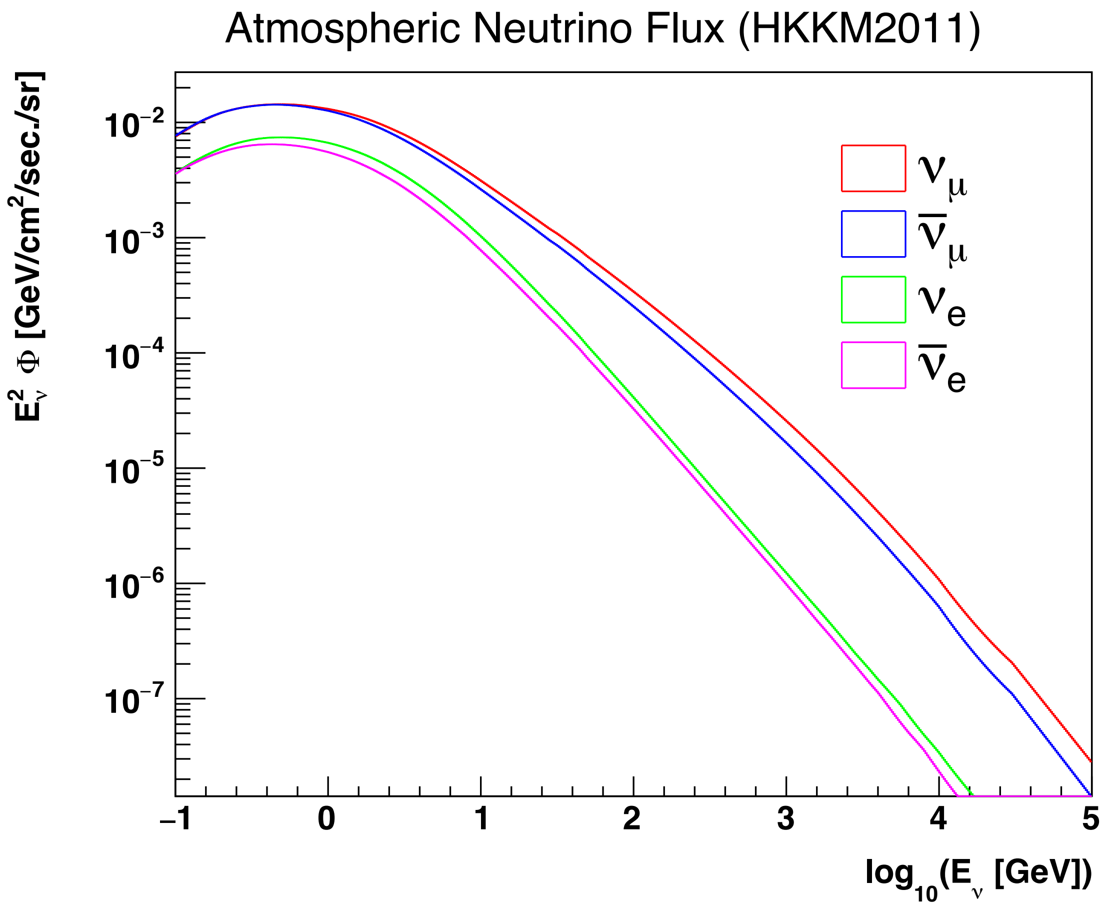
Not direct backgrounds in SK

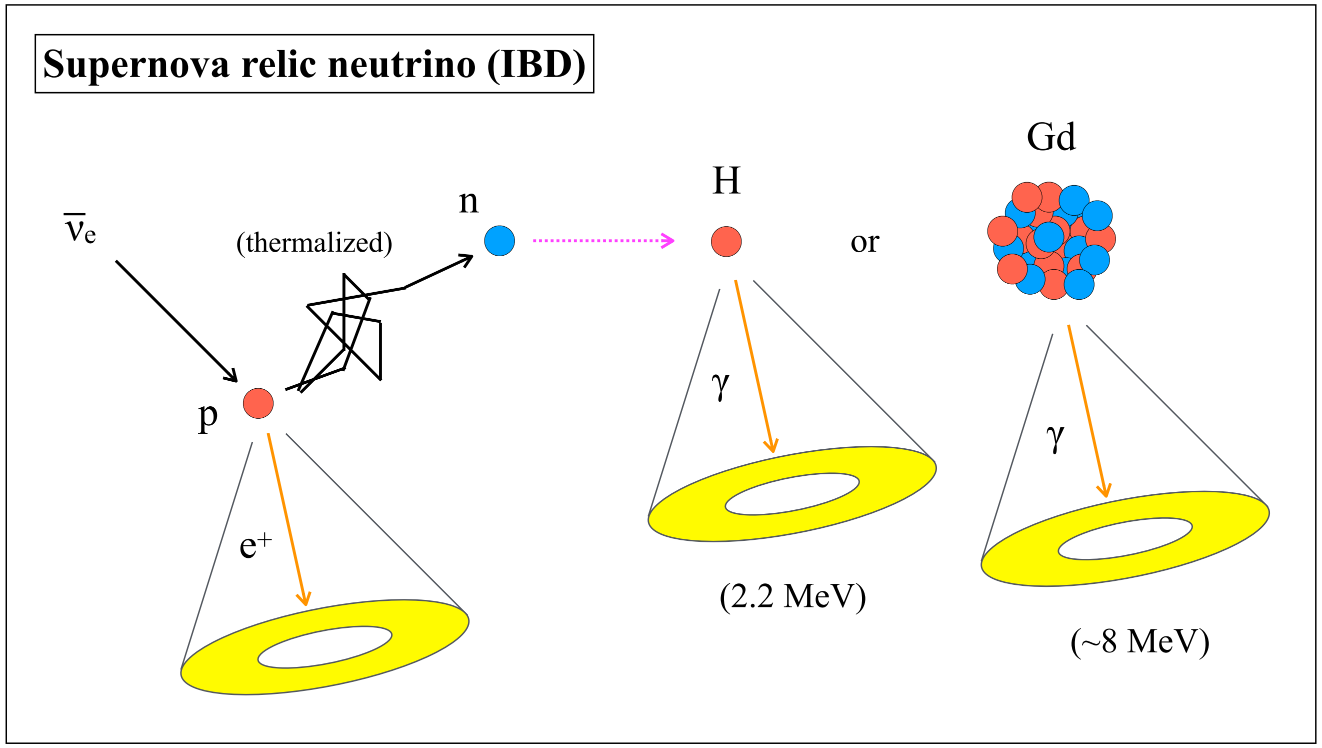
- **stable (no decay)**
- **long lifetime**
- **invisible decay**
- **very low energy**

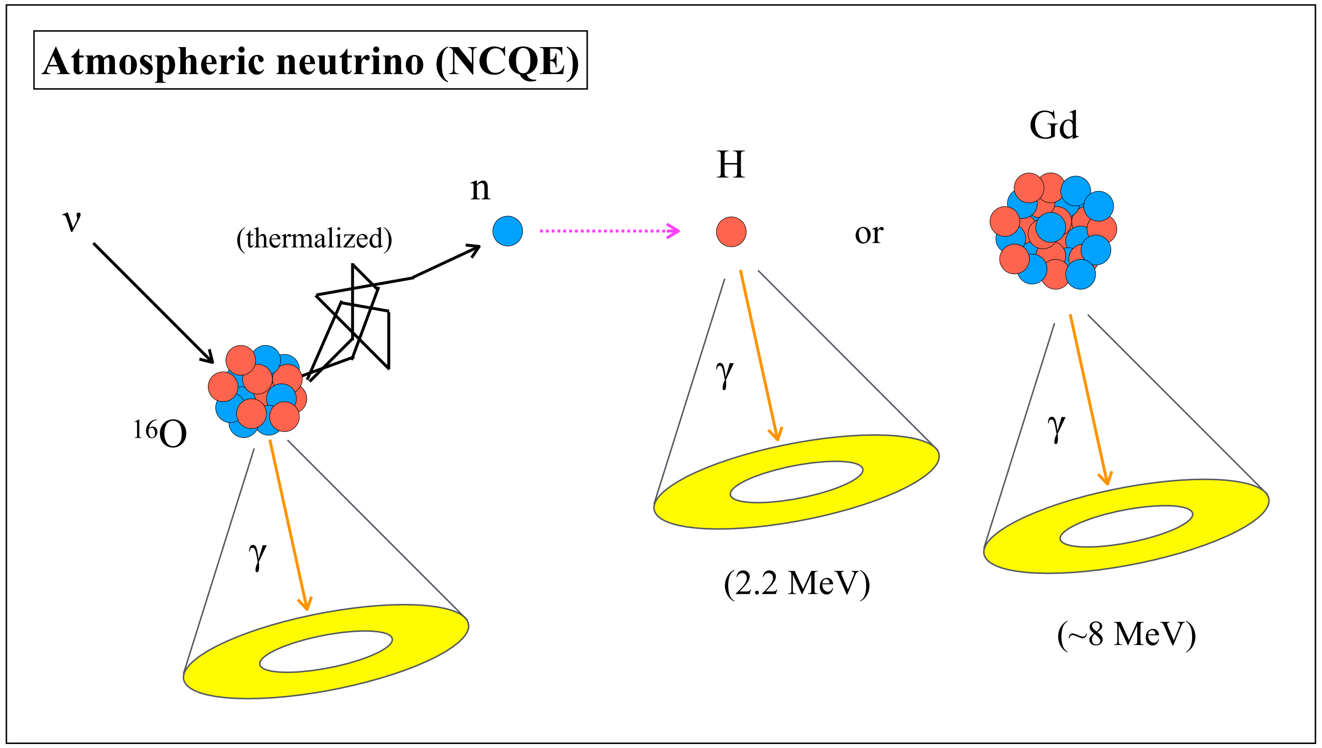
Background (2): Atmospheric Neutrinos

- **NCQE Interactions**
  - "γ+n" mimics "β+n".
  - Constrained by the recent T2K results.

    K. Abe et al. (T2K Collaboration), PRD 100, 112009
- **Other Interactions**
  - CC-induced muons, pion production, etc
  - These form a Michel spectrum then are estimated using the sideband region (>30 MeV).







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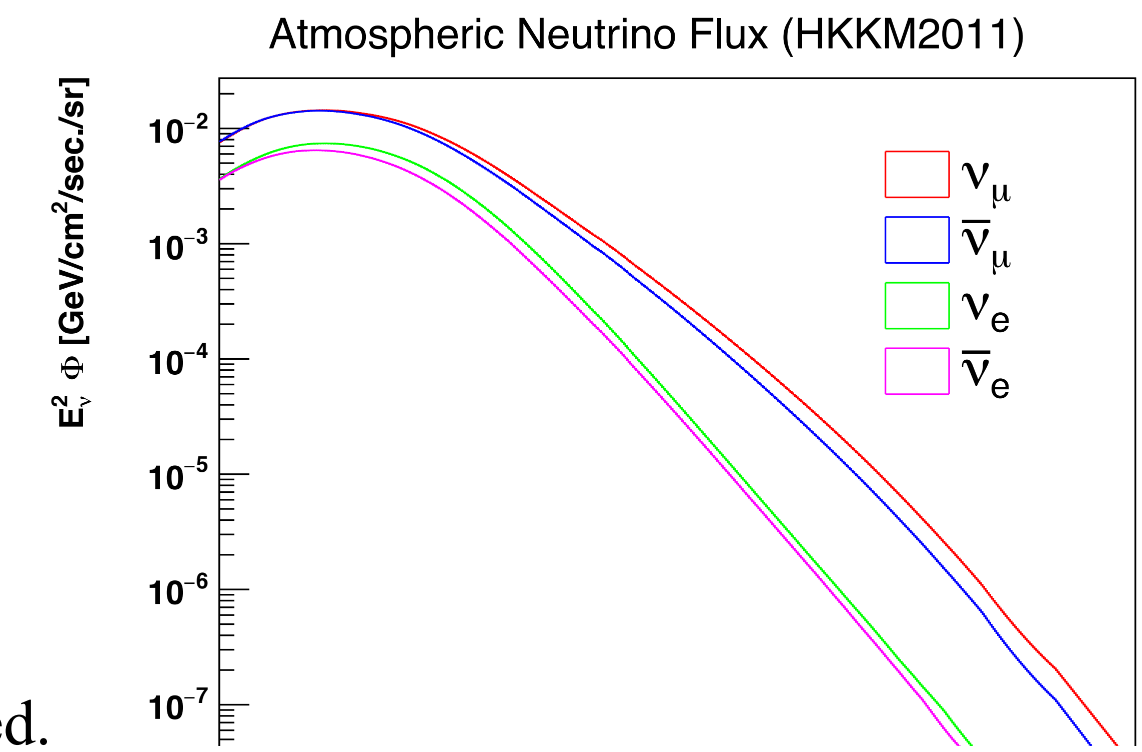

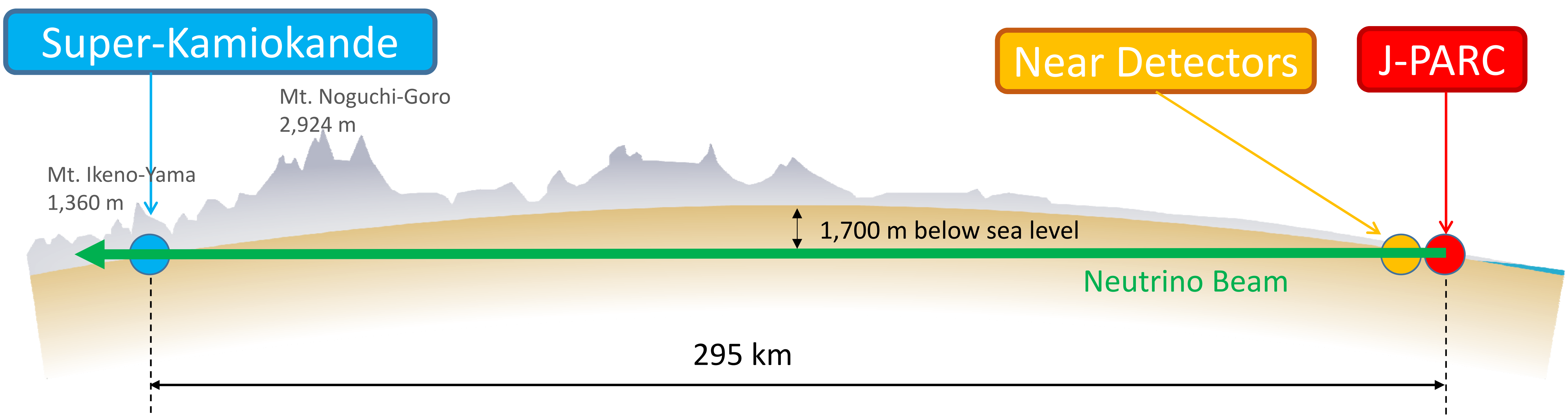

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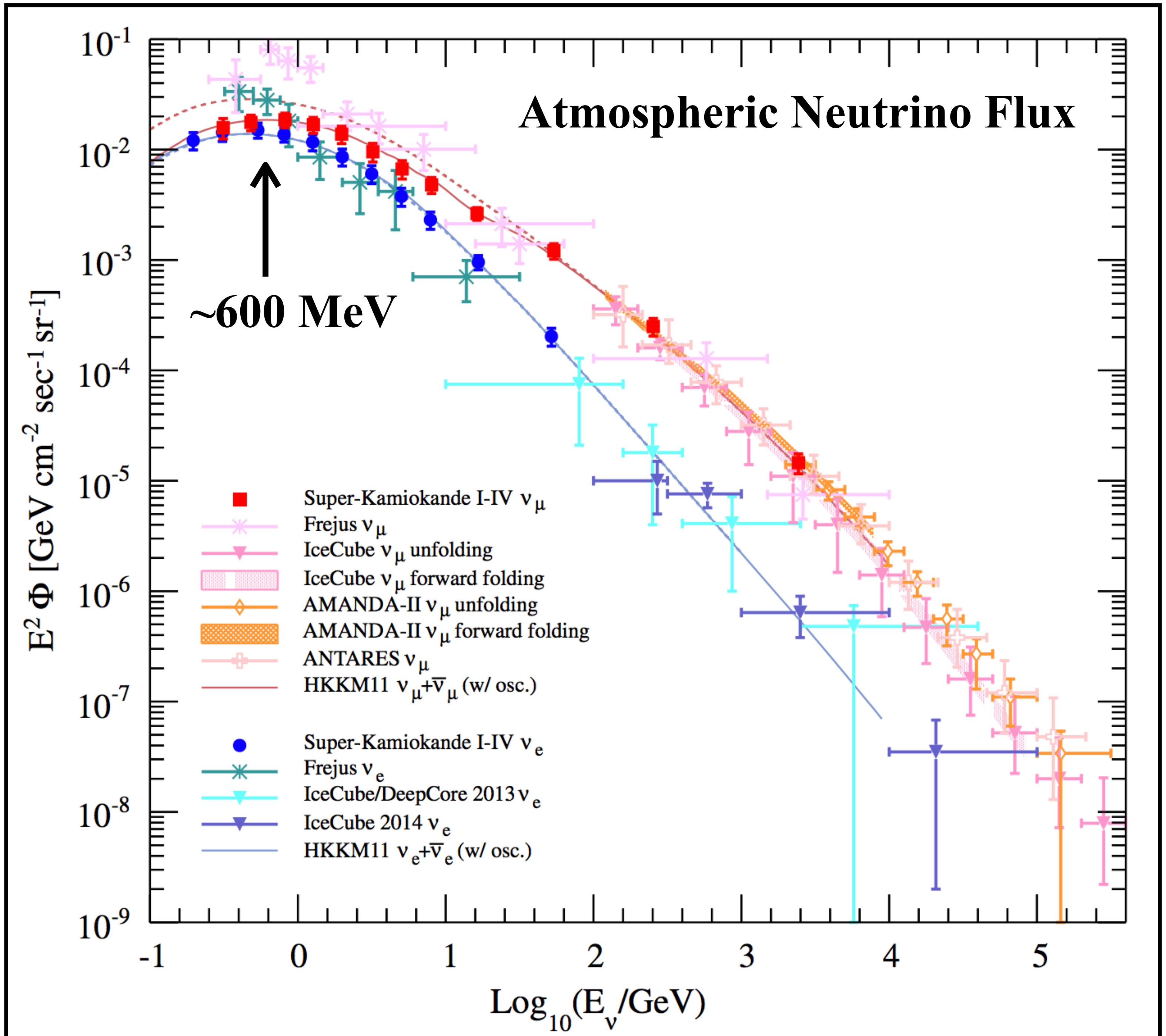
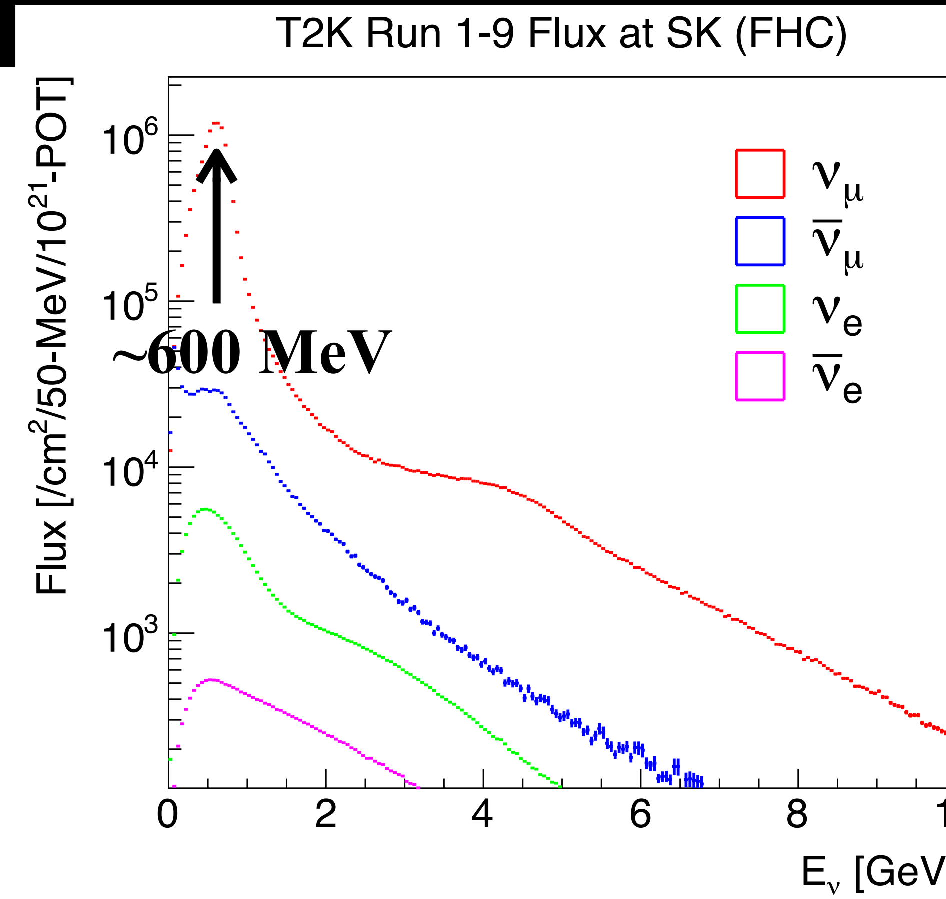
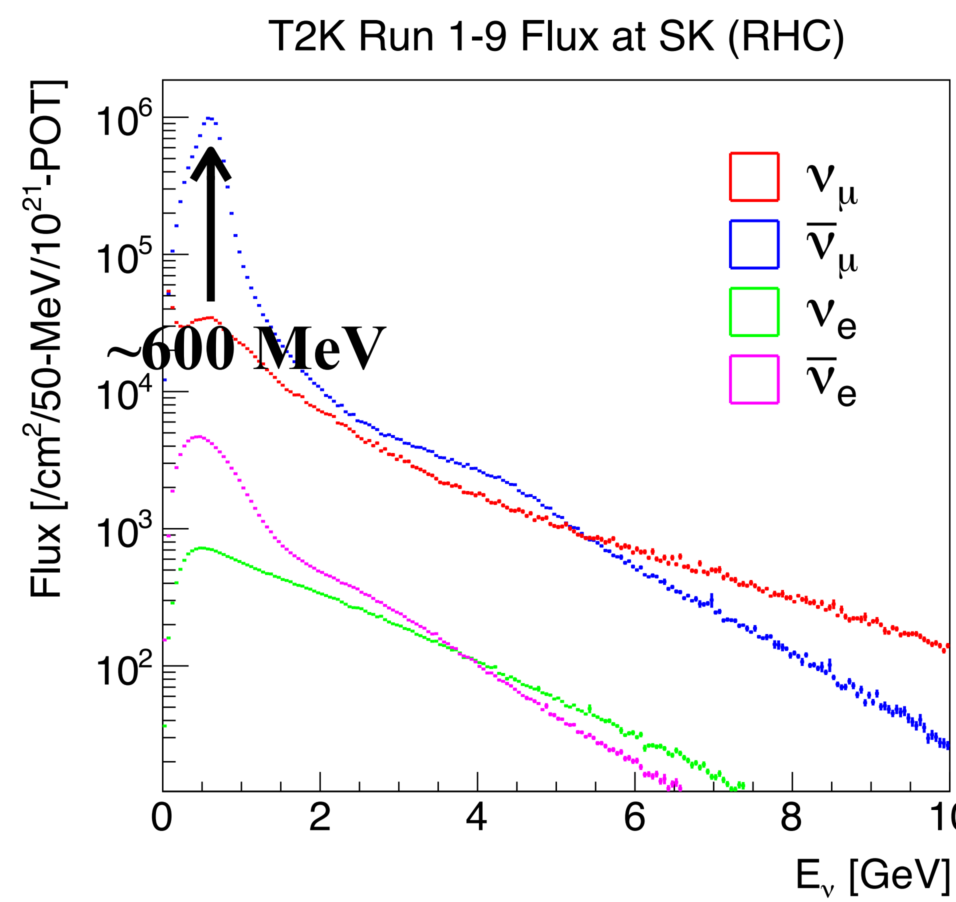


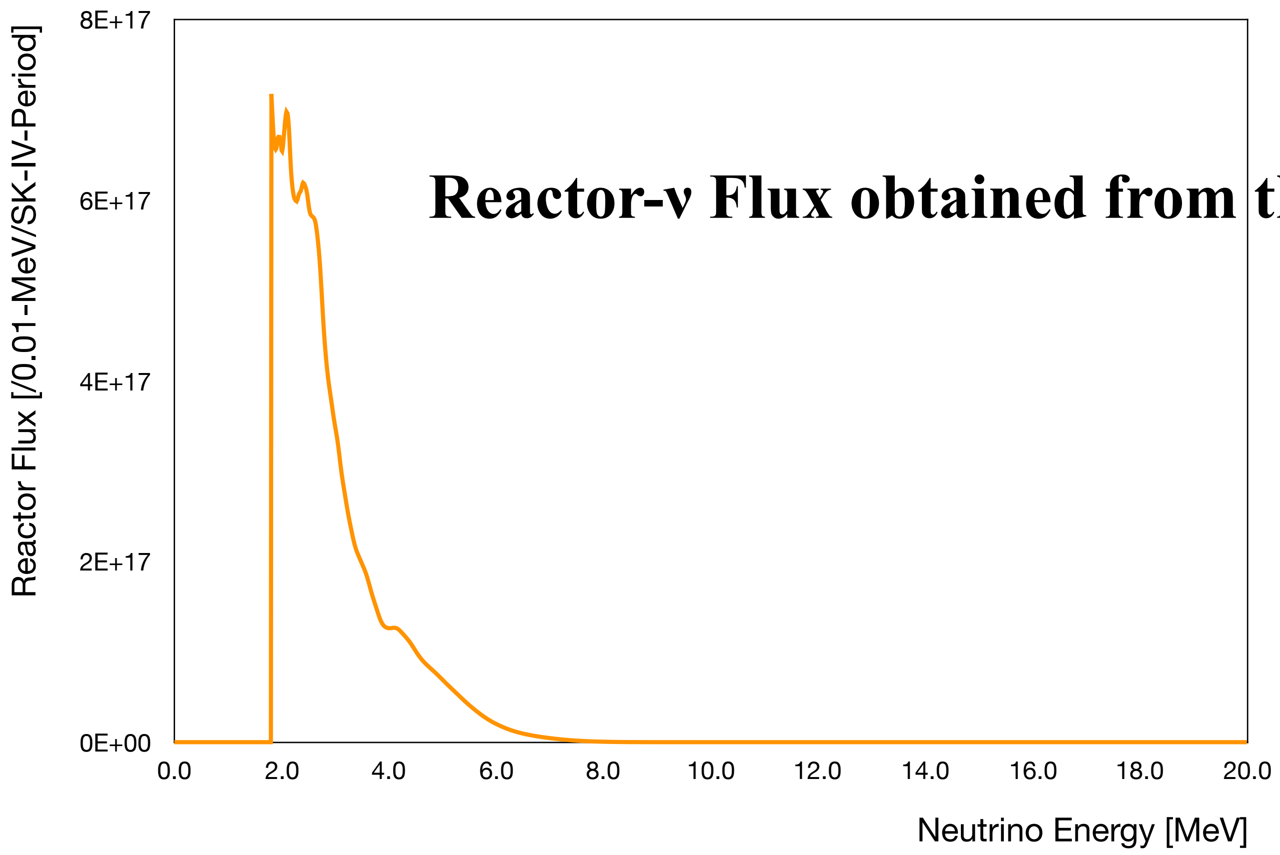




Background (3): Reactor & Accidental Events

- **Reactor neutrinos**
  - Electron antineutrinos from reactor plants.
  - IBD reaction is an irreducible background.

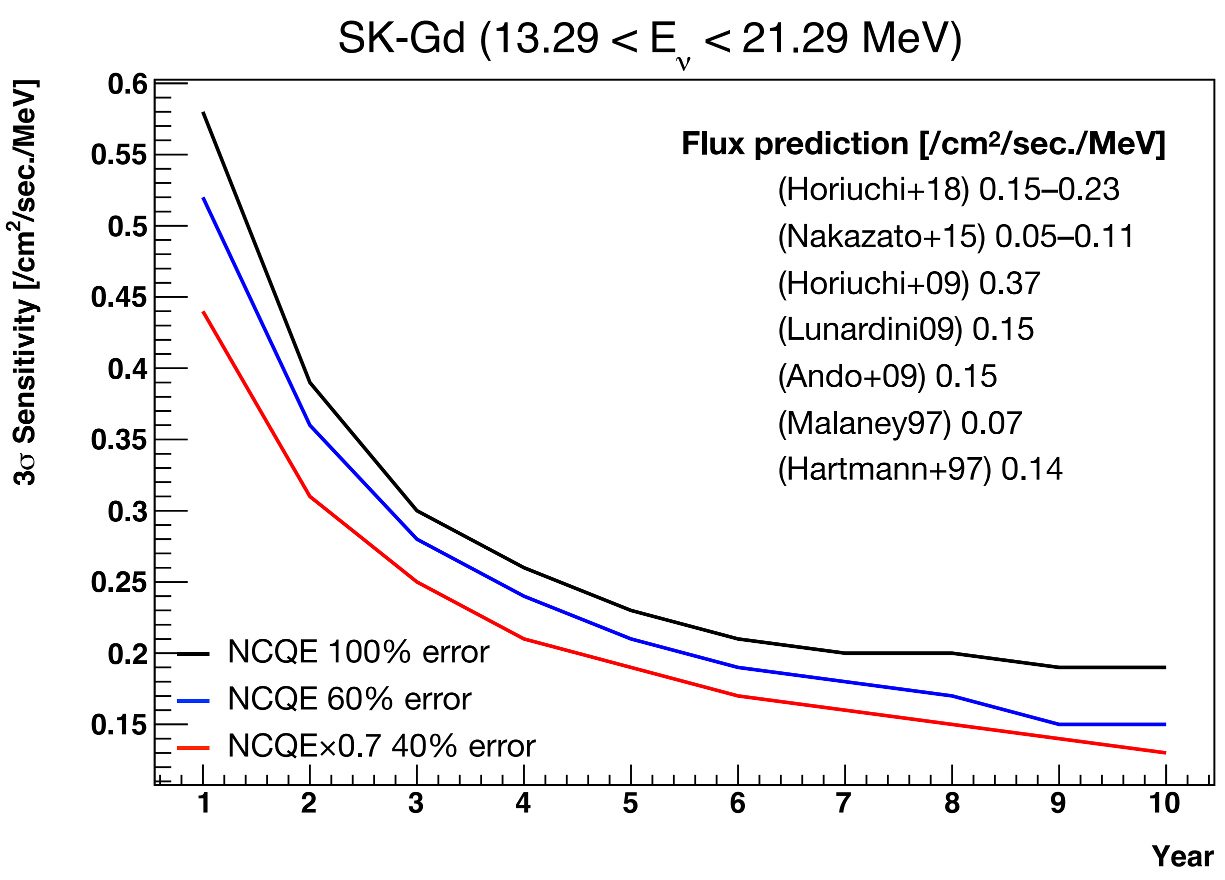
- **Accidental background events**
  - "True": β-like + neutron (due to muon spallation)
  - "Fake": β-like + neutron-like (due to PMT noise, radioactive γ, etc)

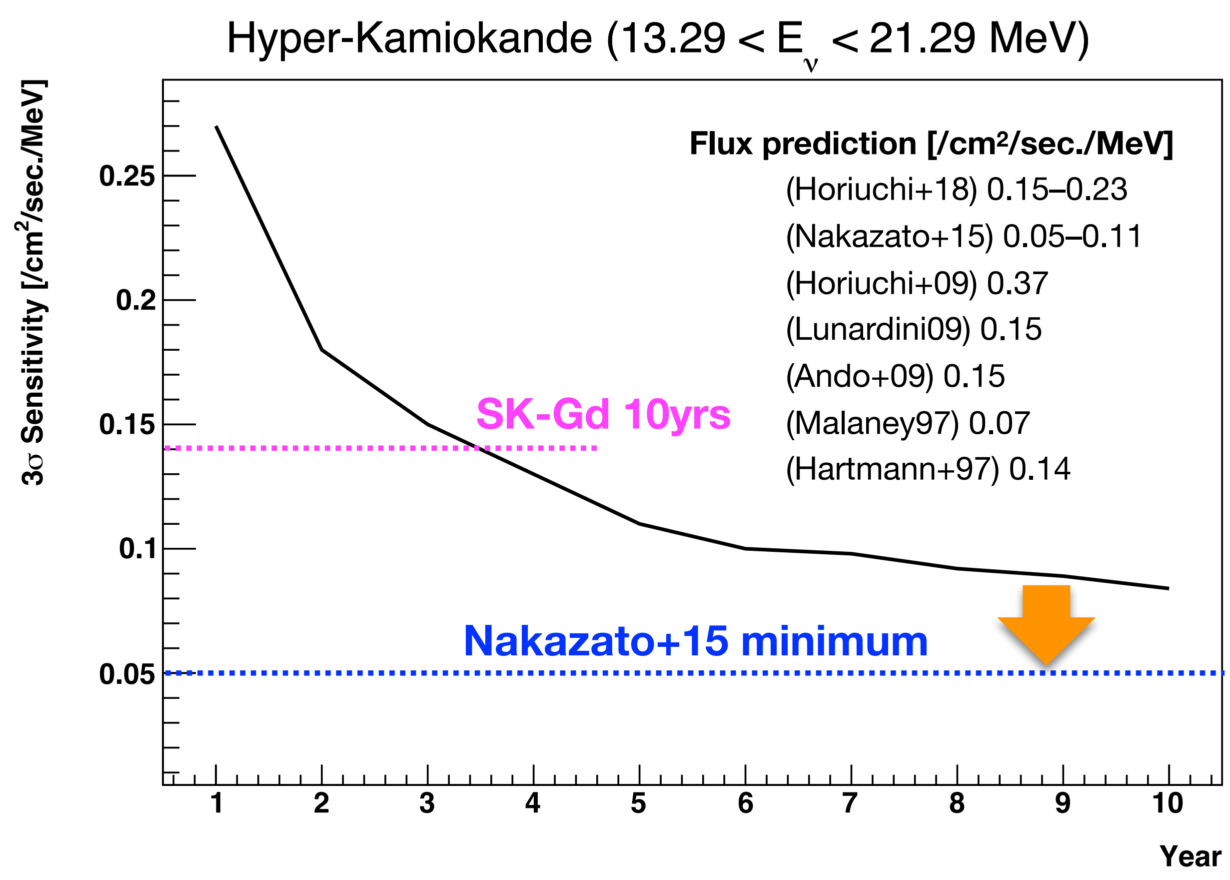


Reactor-ν Flux obtained from the IAEA database

3σ Sensitivities

- **SK-Gd** **J. Beacom and M. Vagins, PRL 93, 171101 (2004)**
  - ~90% neutron tagging efficiency with the Gd.
  - ~8 MeV γ-rays are emitted, then the search does not suffer from accidental backgrounds.
- **Hyper-Kamiokande** **K. Abe et al. (HK Proto-Collaboration), arXiv:1109.3262**
  - ~8.4 times larger fiducial mass.
  - Better photosensors and more coverage lead to doubled neutron tagging efficiency.



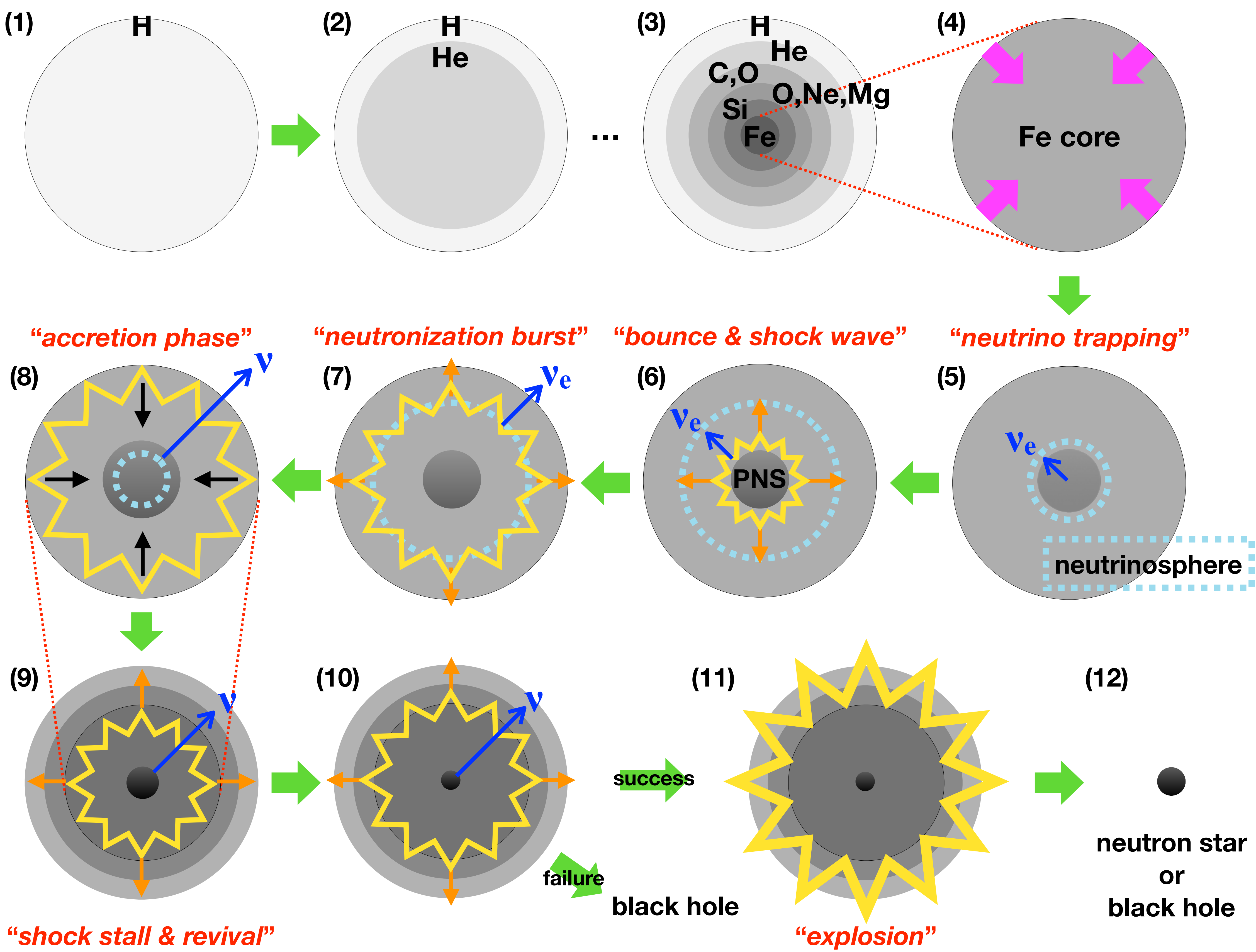


Summary

Let’s work forward to discovery!!

BACKUP SLIDES

Neutrinos from Core-Collapse Supernovae



Neutrino Oscillation Parameters (2018)

Table 1.1: Best-fit values of the neutrino oscillation parameters from PDG2018 [22]. NH and IH represent the normal and inverted neutrino mass hierarchy, respectively.

Oscillation parameter	Best-fit value
$\sin^2\theta_{12}$	0.307 ± 0.013
$\sin^2\theta_{23}$ (NH, Octant I)	$0.417^{+0.025}_{-0.028}$
$\sin^2\theta_{23}$ (NH, Octant II)	$0.597^{+0.024}_{-0.030}$
$\sin^2\theta_{23}$ (IH, Octant I)	$0.421^{+0.033}_{-0.025}$
$\sin^2\theta_{23}$ (IH, Octant II)	$0.592^{+0.023}_{-0.030}$
$\sin^2\theta_{13}$	$(2.12 \pm 0.08) \times 10^{-2}$
Δm^2_{12}	$(7.53 \pm 0.18) \times 10^{-5}$ eV^2
Δm^2_{32} (NH)	$(2.51 \pm 0.05) \times 10^{-3}$ eV^2
Δm^2_{32} (IH)	$(-2.56 \pm 0.04) \times 10^{-3}$ eV^2

CSFRD

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

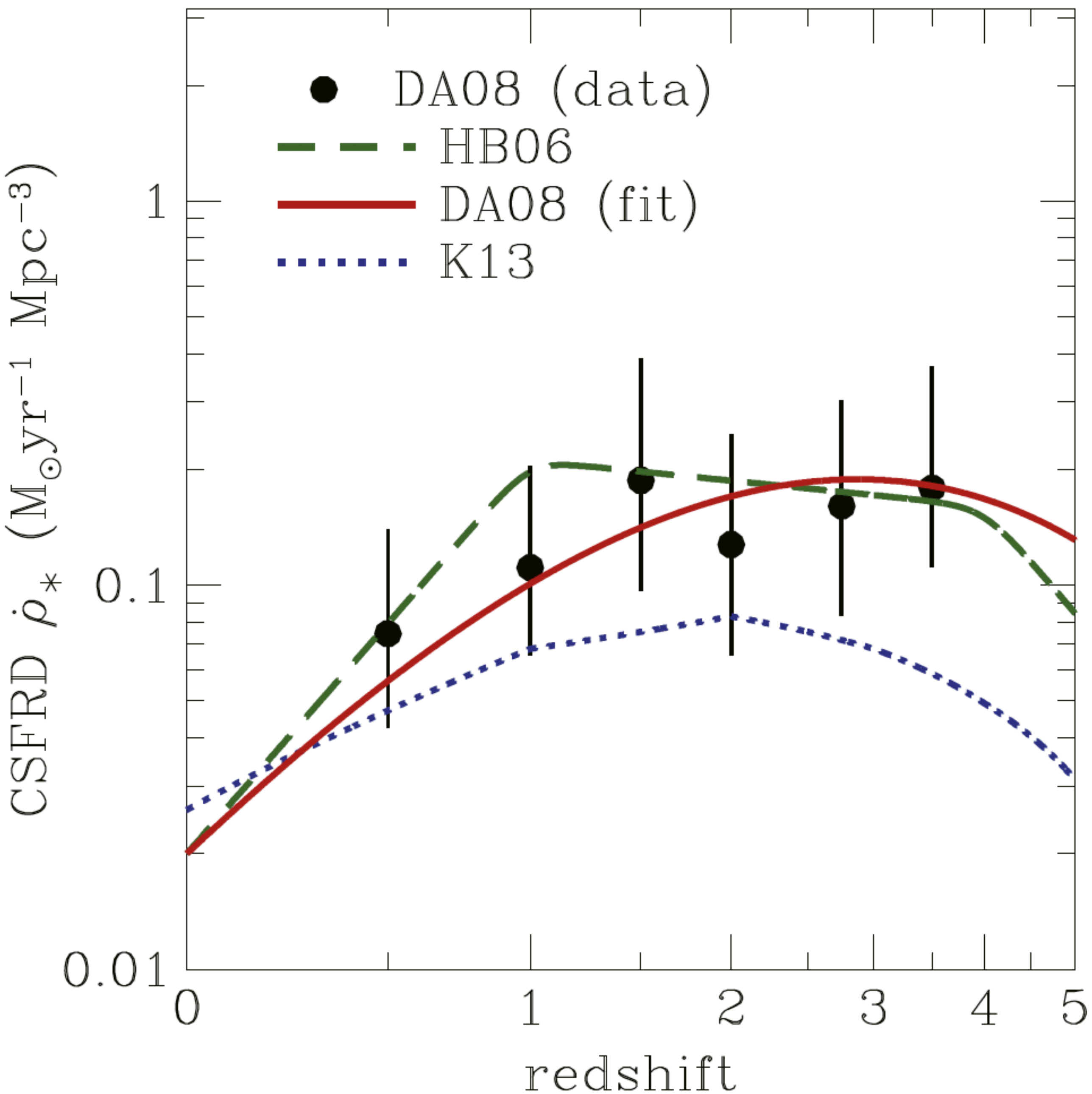


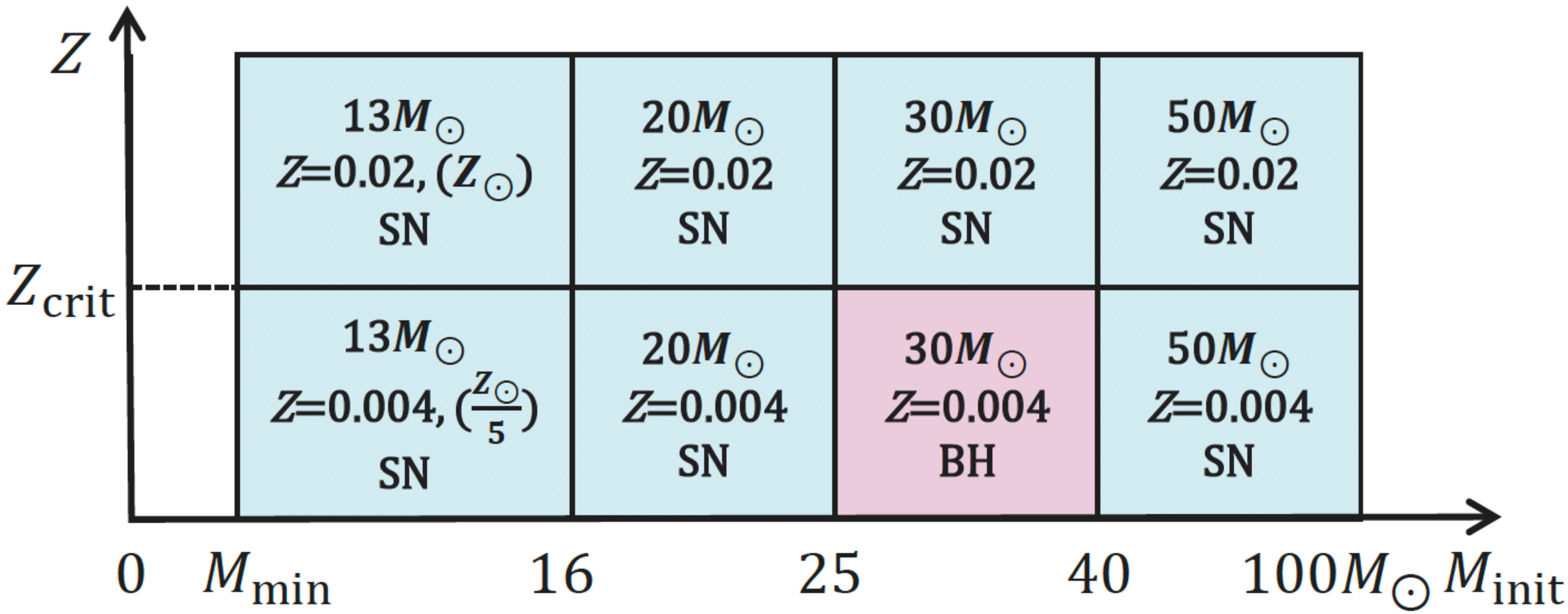
Figure 2. CSFRD as a function of redshift. Dashed, solid and dotted lines correspond to the models in HB06, DA08 and K13, respectively. Plots are calculated from the data in Tables 1 and 2 in DA08.

$$R_{\rm CCSN}(z) = \zeta_{\rm CCSN}\dot{\rho}_*(z),$$

$$\zeta_{\rm CCSN} = \frac{\int_{M_{\rm min}}^{M_{\rm max}} \Psi_{\rm IMF}(M)dM}{\int_{0.1M_{\rm sun}}^{100M_{\rm sun}} M\Psi_{\rm IMF}(M)dM},$$

BH Formation Criteria

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



Mass Hierarchy Effect

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

$$\begin{aligned}
\frac{dN_{\bar{\nu}_e}}{dE_\nu} &= |U_{e1}|^2\frac{dN_{\bar{\nu}_1}}{dE_\nu} + |U_{e2}|^2\frac{dN_{\bar{\nu}_2}}{dE_\nu} + |U_{e3}|^2\frac{dN_{\bar{\nu}_3}}{dE_\nu} \\
&= \cos^2\theta_{12}\cos^2\theta_{13}\frac{dN_{\bar{\nu}_1}}{dE_\nu} + \sin^2\theta_{12}\cos^2\theta_{13}\frac{dN_{\bar{\nu}_2}}{dE_\nu} + \sin^2\theta_{13}\frac{dN_{\bar{\nu}_3}}{dE_\nu} \\
&\sim 0.68\cdot\frac{dN_{\bar{\nu}_1}}{dE_\nu} + 0.30\cdot\frac{dN_{\bar{\nu}_2}}{dE_\nu} + 0.02\cdot\frac{dN_{\bar{\nu}_3}}{dE_\nu},
\end{aligned}$$

$$\frac{dN_{\bar{\nu}_e}}{dE_\nu} \sim 0.68\cdot\frac{dN^0_{\bar{\nu}_e}}{dE_\nu} + 0.32\cdot\frac{dN^0_{\bar{\nu}_x}}{dE_\nu}.$$

Normal Hierarchy

$$\frac{dN_{\bar{\nu}_e}}{dE_\nu} \sim \frac{dN^0_{\bar{\nu}_x}}{dE_\nu}.$$

Inverted Hierarchy

Shock Revival Time Effect

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

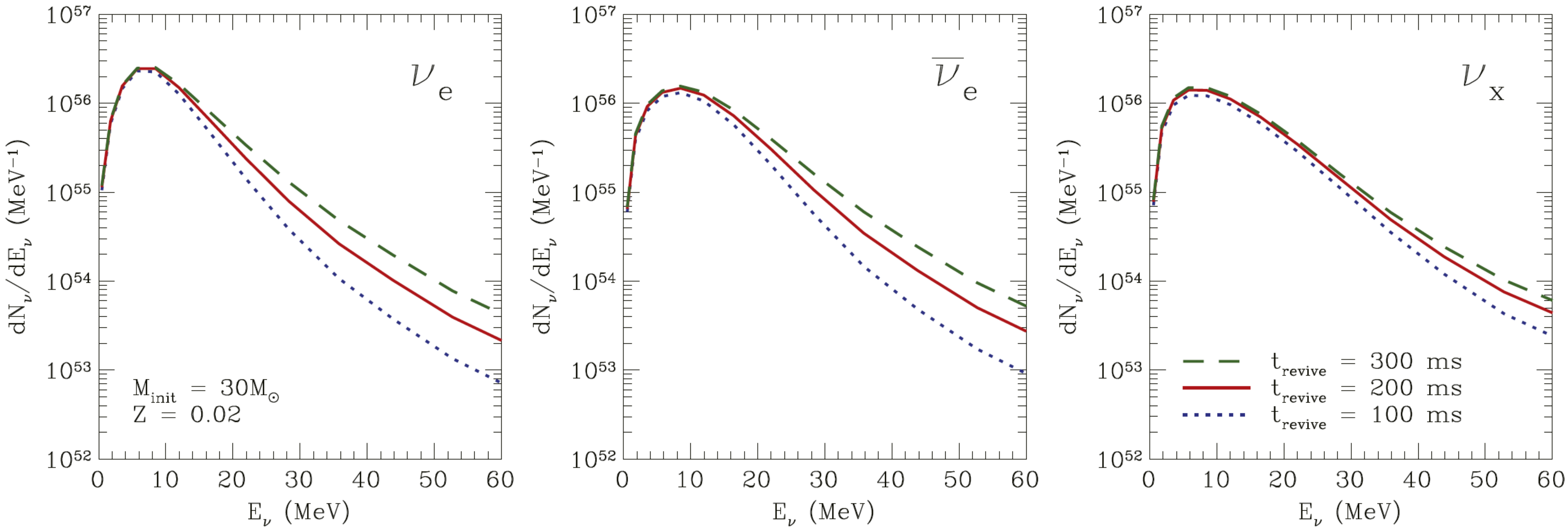


Figure 4. Neutrino number spectra of supernova with $30M_\odot$, $Z = 0.02$ and shock revival times of t_{revive} = 100 ms (dotted), 200 ms (solid), and 300 ms (dashed). The left, central, and right panels correspond to ν_e, $\bar{\nu}_e$, and ν_x ($=\nu_\mu = \bar{\nu}_\mu = \nu_\tau = \bar{\nu}_\tau$), respectively.

Equation-Of-State Effect

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

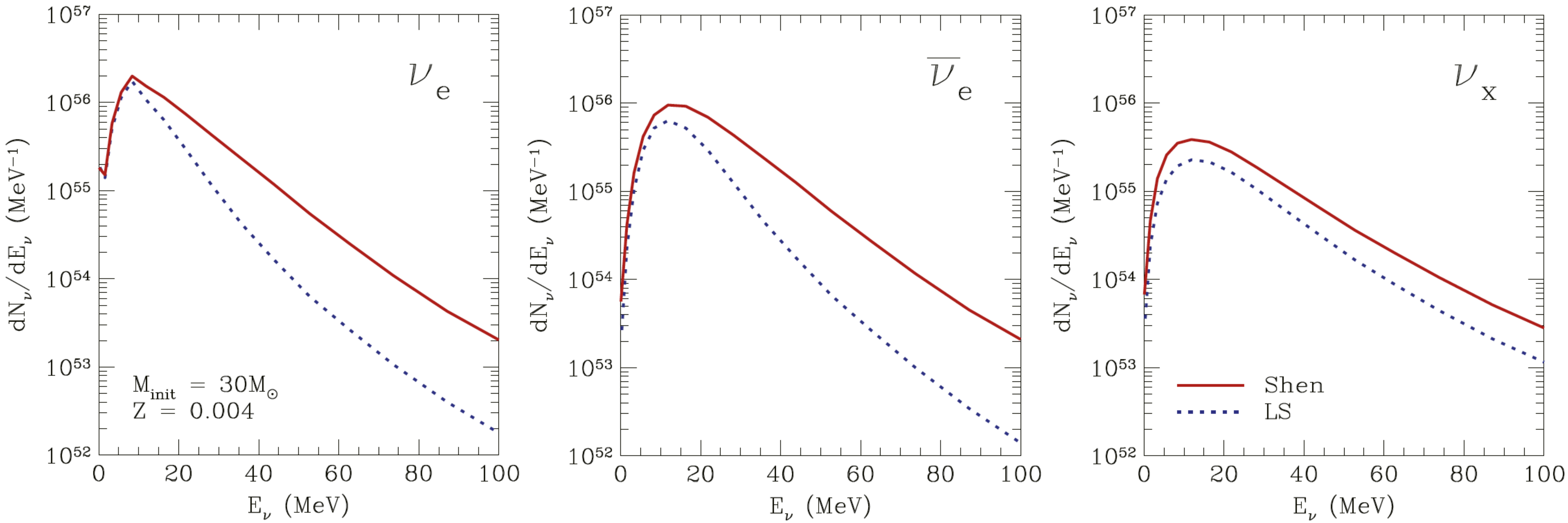


Figure 6. Neutrino number spectra for black hole formation with $30M_\odot$, $Z = 0.004$ and Shen EOS (solid) and LS EOS (dotted). The left, central, and right panels correspond to ν_e, $\bar{\nu}_e$, and ν_x $(=\nu_\mu = \bar{\nu}_\mu = \nu_\tau = \bar{\nu}_\tau)$, respectively.

Redshift Dependence

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

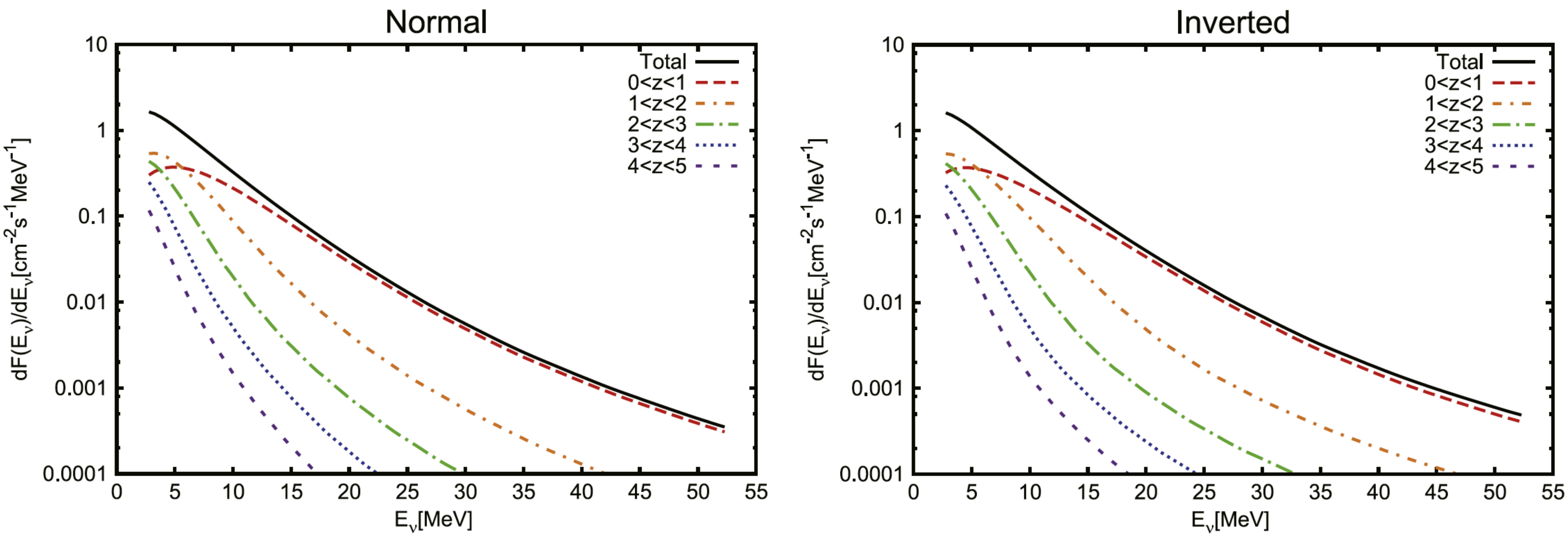
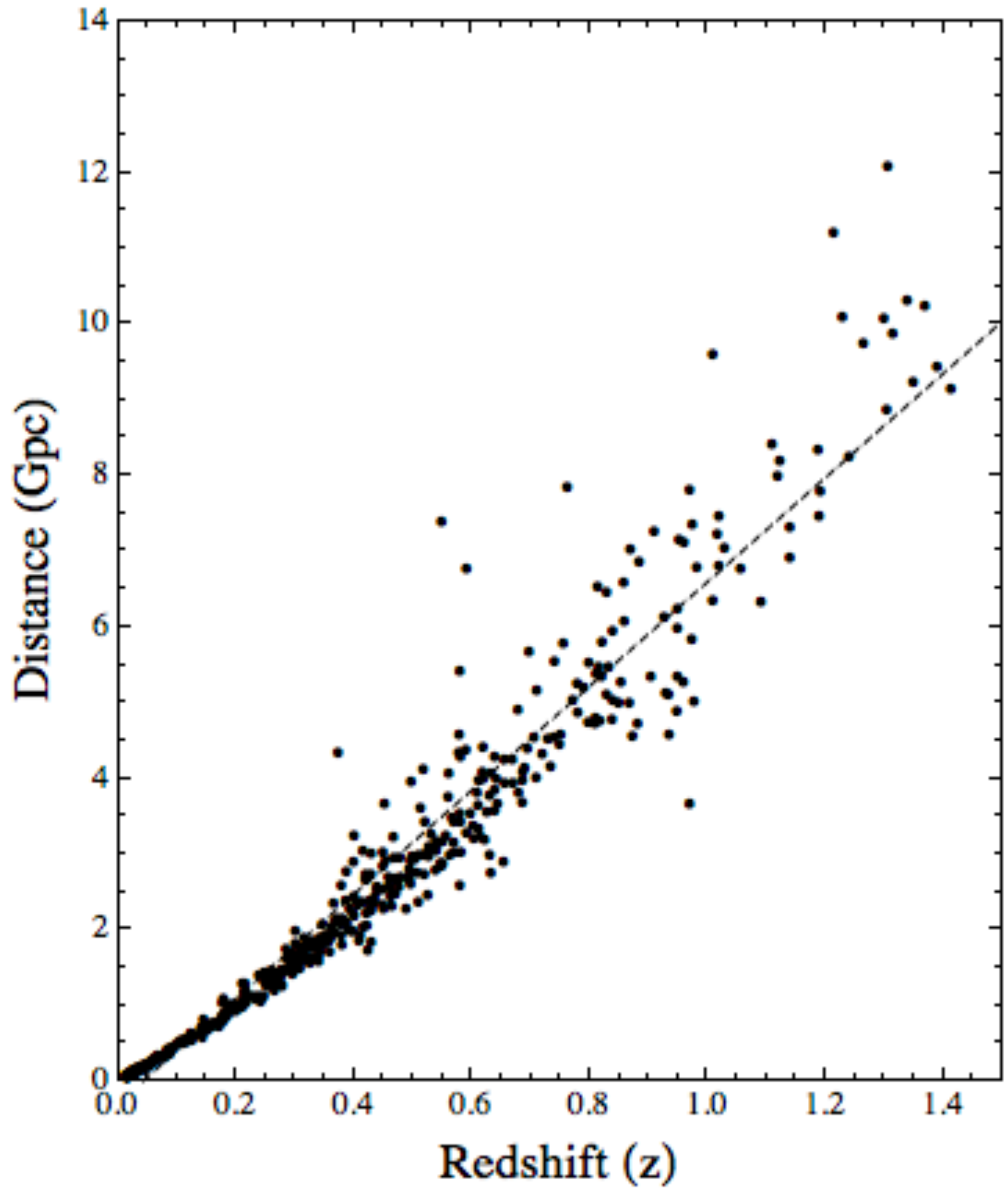


Figure 10. Total fluxes of SRNs (solid) and contributions from various redshift ranges for the reference model. The lines except for the solid line correspond, from top to bottom, to the redshift ranges $0 < z < 1, 1 < z < 2, 2 < z < 3, 3 < z < 4$, and $4 < z < 5$, for $E_\nu > 10$ MeV. The left and right panels show the cases for normal and inverted mass hierarchies, respectively.

Redshift

1 pc ~ 3.26 light-year



Nakazato+15 Flux Summary

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

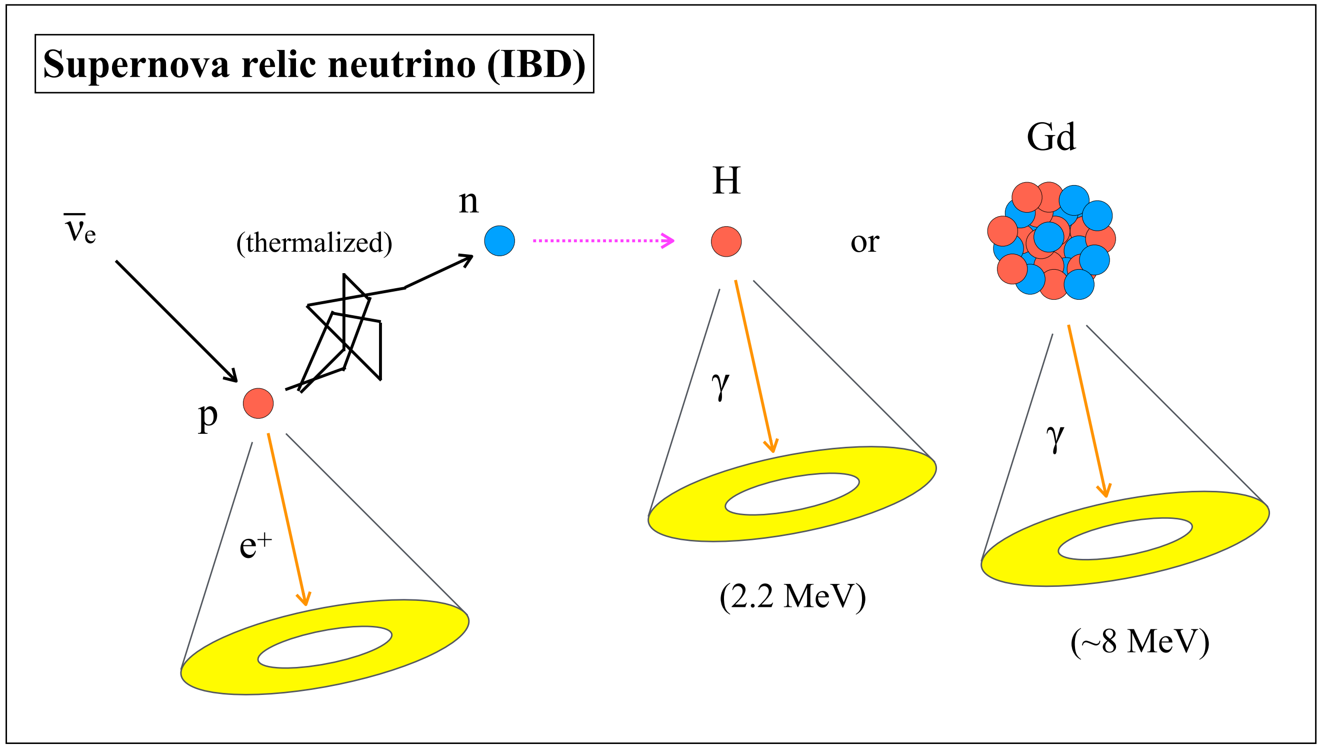
Table 3

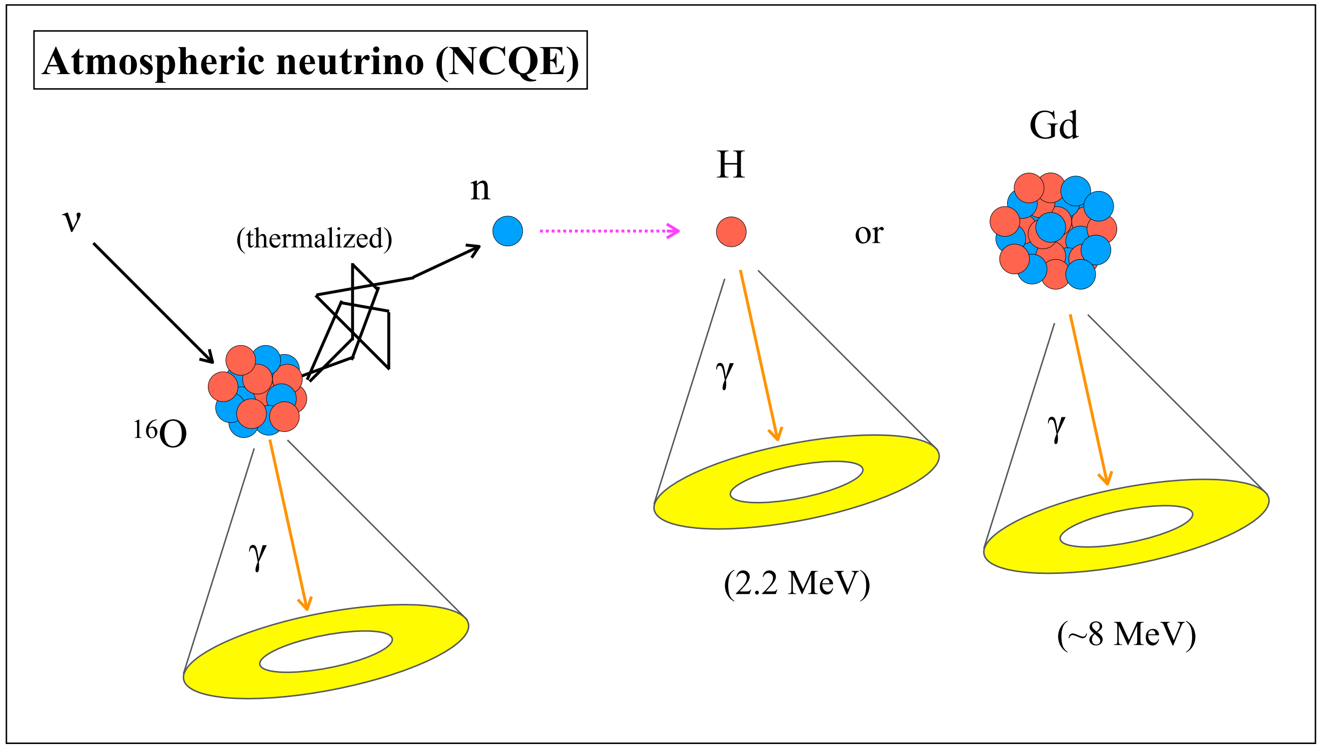
SRN Event Rates in Various Ranges of Positron Energy in Super-Kamiokande Over 1 yr (i.e., per 22.5 kton yr) for Models With Metallicity Evolution of DA08+M08

			Normal Mass Hierarchy			Inverted Mass Hierarchy			
CSFRD	t_{revive}	EOS for BH	18–26	10–18	10–26 MeV	18–26	10–18	10–26 MeV	Figure 12
HB06	100 ms	Shen	0.286	0.704	0.990	0.375	0.832	1.207	…
		LS	0.227	0.635	0.863	0.351	0.806	1.156	…
	200 ms	Shen	0.361	0.833	1.193	0.429	0.920	1.349	…
		LS	0.302	0.764	1.066	0.404	0.893	1.297	…
	300 ms	Shen	0.432	0.938	1.370	0.463	0.967	1.431	Maximum
		LS	0.374	0.869	1.242	0.439	0.941	1.379	…
DA08	100 ms	Shen	0.219	0.515	0.734	0.286	0.598	0.885	…
		LS	0.178	0.464	0.642	0.269	0.578	0.847	…
	200 ms	Shen	0.274	0.604	0.879	0.326	0.660	0.986	Reference
		LS	0.233	0.554	0.787	0.308	0.640	0.948	…
	300 ms	Shen	0.326	0.677	1.003	0.350	0.694	1.044	…
		LS	0.285	0.627	0.911	0.333	0.674	1.007	…
K13	100 ms	Shen	0.203	0.443	0.645	0.264	0.505	0.769	…
		LS	0.171	0.410	0.581	0.252	0.492	0.744	Minimum
	200 ms	Shen	0.252	0.514	0.767	0.298	0.554	0.853	…
		LS	0.221	0.482	0.703	0.286	0.542	0.827	…
	300 ms	Shen	0.298	0.570	0.868	0.319	0.580	0.899	…
	…	LS	0.266	0.537	0.804	0.306	0.568	0.874	…

NCQE Background

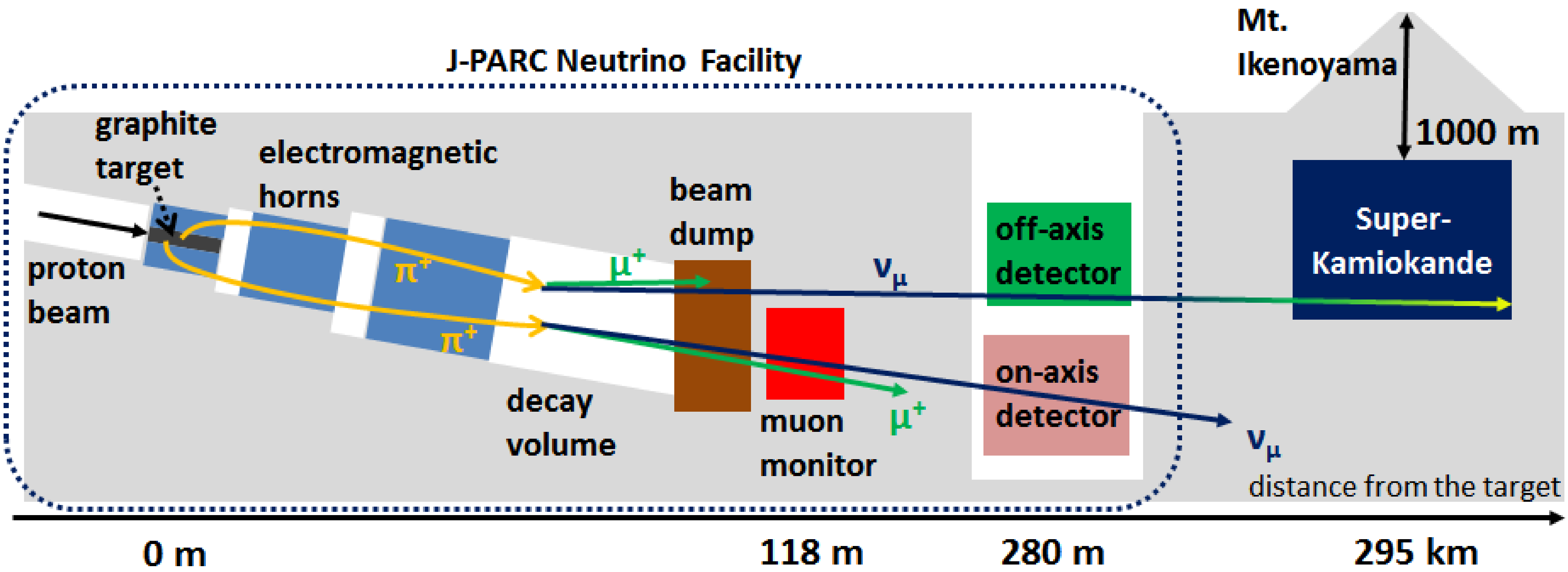
- At E_ν > ~200 MeV, neutrinos are likely to knock-out a nucleon in the NC interaction.
  = **NC quasielastic nucleon knock-out ("NCQE")**
- This mimics the SRN signal (IBD) and becomes a background (mainly E_ν = 12–20 MeV).
  So far the background was estimated by the simulation based on theories.
- **A 100% uncertainty was assigned to this channel because of little experimental data.**
- Previous measurements about this channel
  - SK: large uncertainty, mixture of neutrinos and antineutrinos — **L. Wan et al. (SK Collaboration), PRD 99, 032005 (2019)**
  - T2K: large uncertainty, only for neutrinos **K. Abe et al. (T2K Collaboration), PRD 90, 072012 (2014)**





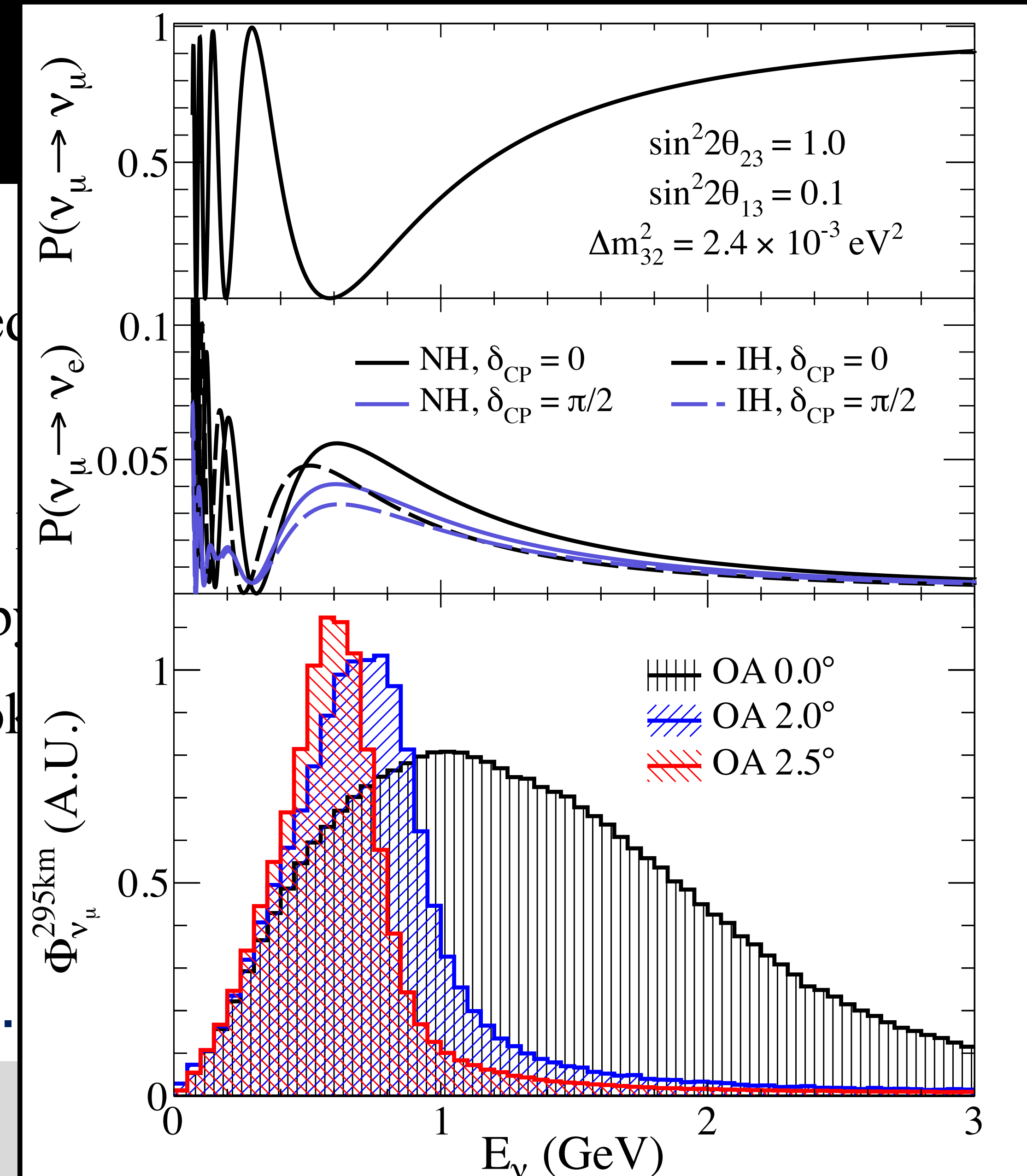
T2K Experiment

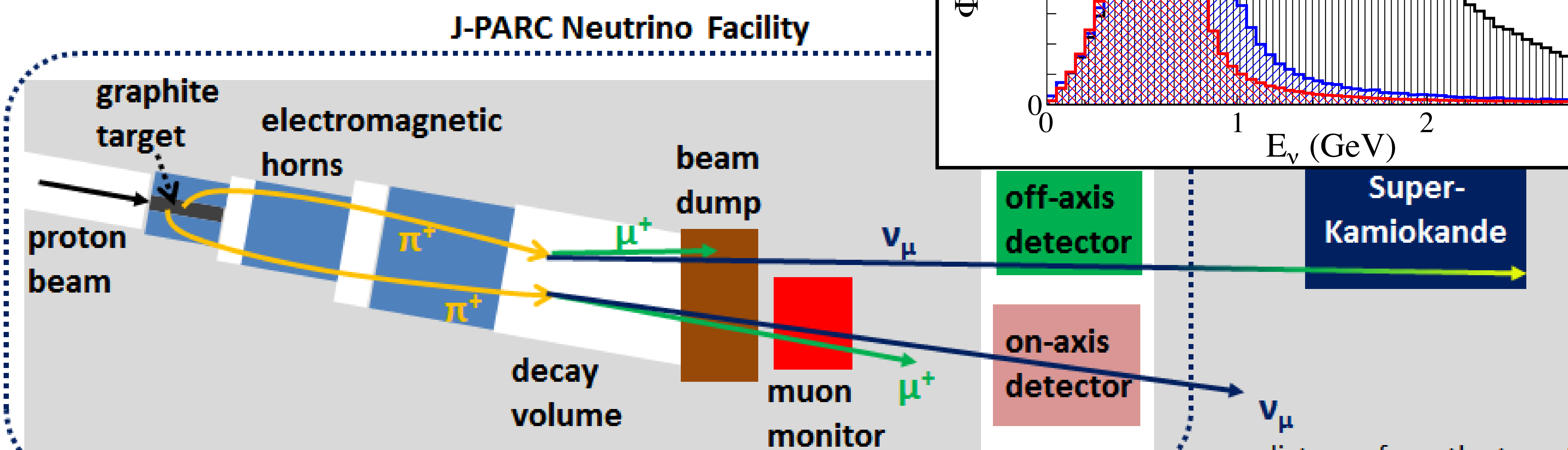
- Bunched proton beams (8 bunch per spill) are injected on the graphite target to produce hadrons (pions and kaons).
- Hadrons are focused by magnetic fields and decay to produce neutrino beams.
- Beam polarity (neutrino or antineutrino) is changed by the magnetic field direction.
- Neutrinos are detected at 295 km away Super-Kamiokande.



T2K Experiment

- Bunched proton beams (8 bunch per spill) are injected
  hadrons (pions and kaons).
- Hadrons are focused by magnetic fields and decay to
- Beam polarity (neutrino or antineutrino) is changed by
- Neutrinos are detected at 295 km away Super-Kamiok

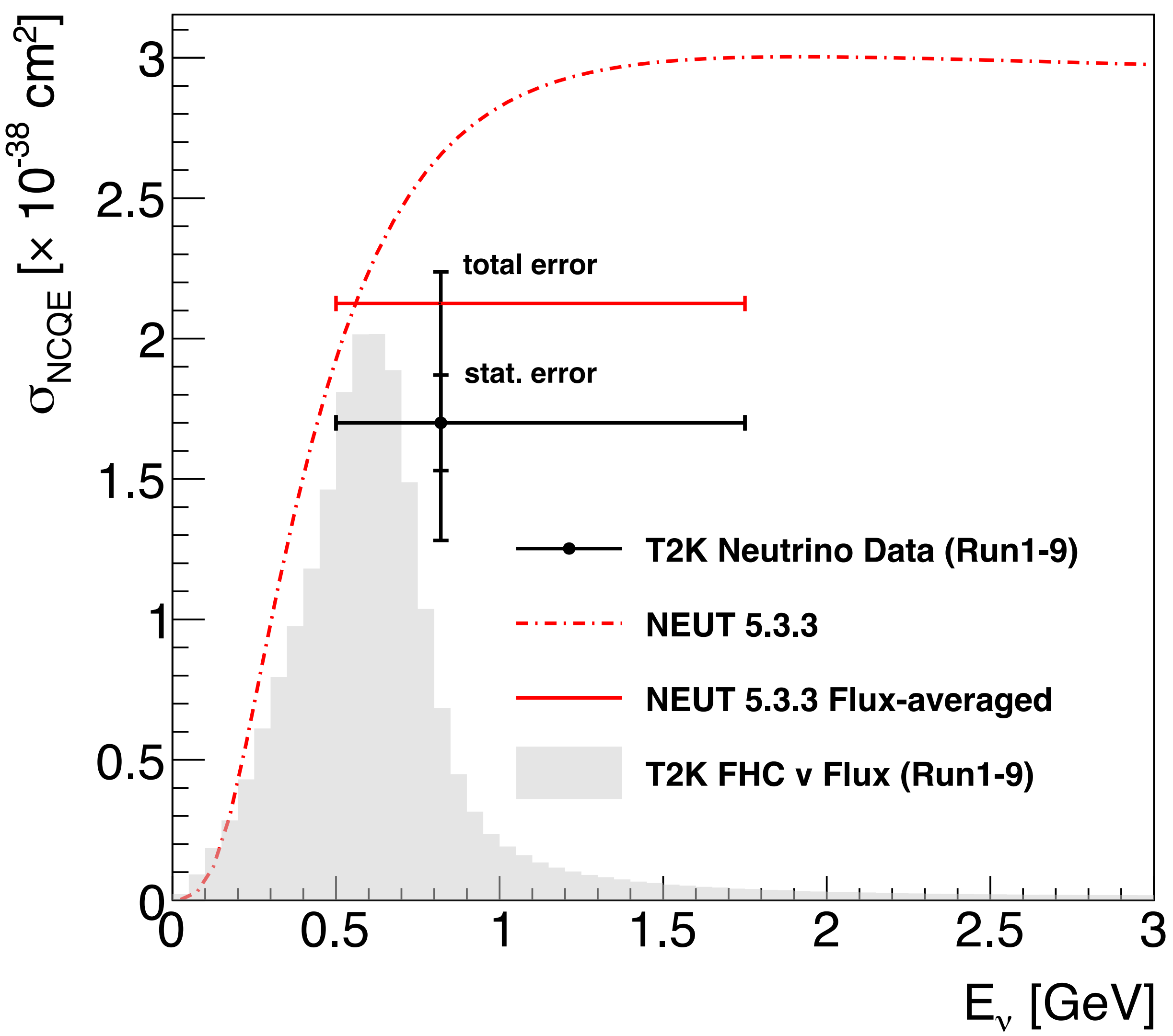




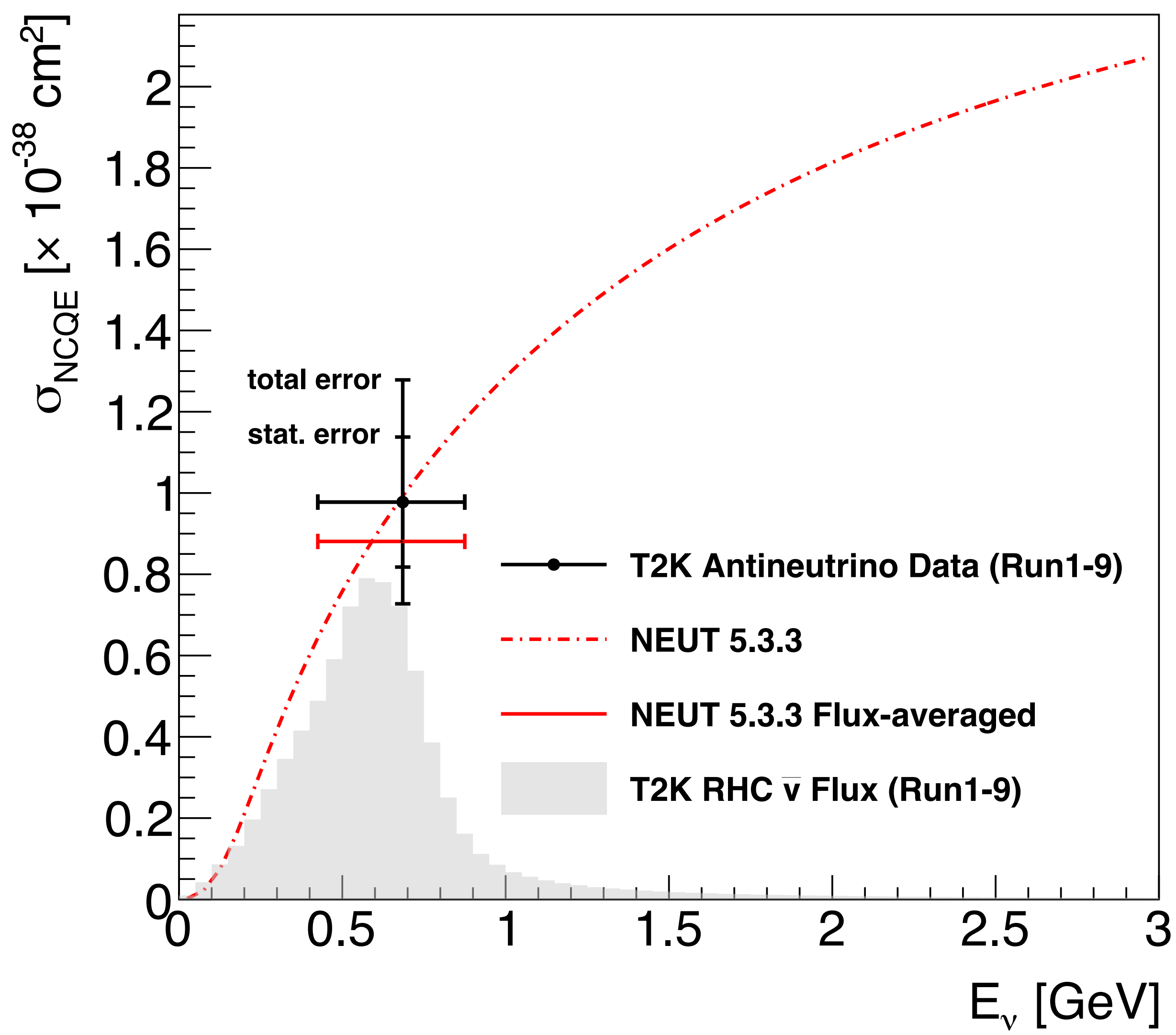
- **FHC (neutrino mode): 14.94×10^{20} protons-on-target** (Previous: 3.01×10^{20} POT)
- **RHC (antineutrino mode): 16.35×10^{20} protons-on-target**

NCQE Cross Sections in T2K

Neutrino



Antineutrino



$$\langle \sigma_{\nu\text{-NCQE}} \rangle = 1.70 \pm 0.17(\text{stat.})^{+0.51}_{-0.38}(\text{syst.}) \times 10^{-38}\ \text{cm}^2/\text{oxygen},$$

$$\langle \sigma_{\bar{\nu}\text{-NCQE}} \rangle = 0.98 \pm 0.16(\text{stat.})^{+0.26}_{-0.19}(\text{syst.}) \times 10^{-38}\ \text{cm}^2/\text{oxygen},$$

SK Operation Periods

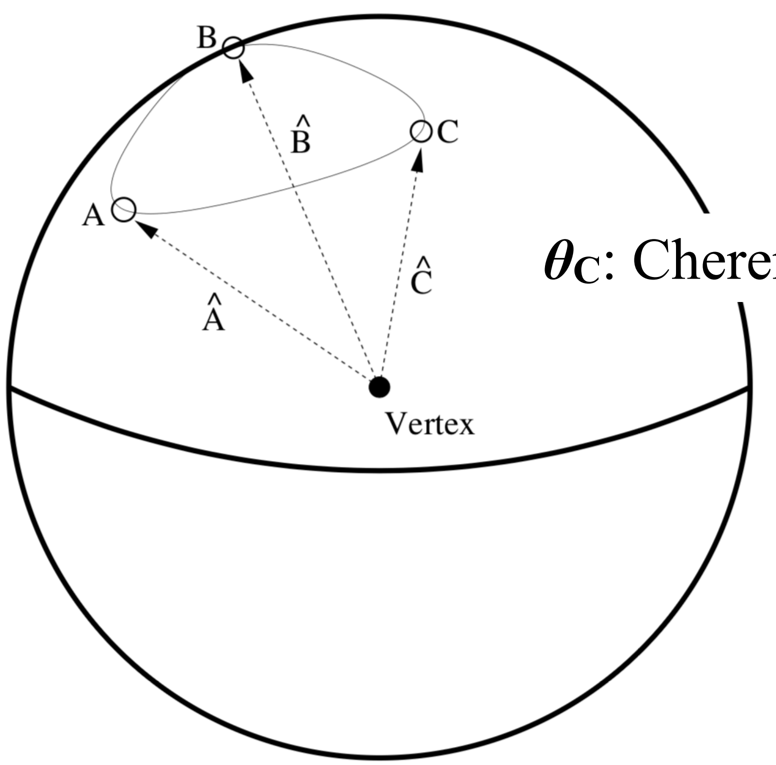
Phase	SK-I	SK-II	SK-III	SK-IV	SK-V
Start	Apr., 1996	Oct., 2002	Jul., 2006	Sep., 2008	Jan., 2019
End	Jul., 2001	Oct., 2005	Aug., 2008	May., 2018	(running)
Live time [days]	1496	791	548	2970	-
Number of ID PMTs	11,146	5,182	11,129	11,129	11,129
ID PMT coverage	40%	19%	40%	40%	40%
Number of OD PMTs	1,885	1,885	1,885	1,885	1,885
PMT protection	No	Yes	Yes	Yes	Yes
Neutron tagging	No	No	No	Yes	Yes
Threshold [MeV]	4.5	6.5	4.0	3.5	3.5

SK Triggers

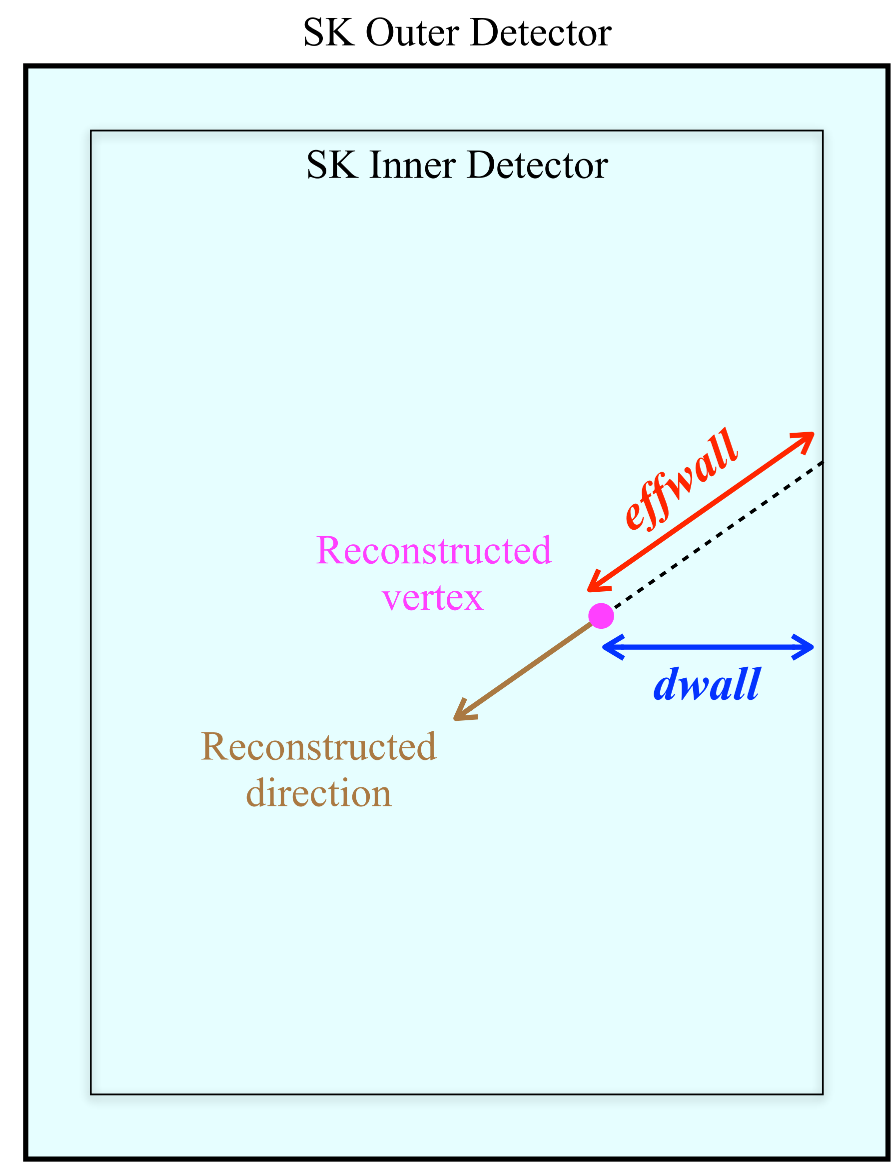
Trigger Type	Threshold	Time Window [μs]
SLE	$34 \rightarrow 31$ (after May of 2015)	$[-1.5, +1.0]$
LE	47	$[-5, +35]$
HE	50	$[-5, +35]$
SHE	$70 \rightarrow 58$ (after September of 2011)	$[-5, +35]$
OD	22 (in OD)	$[-5, +35]$
AFT	SHE + no OD	$[+35, +535]$
T2K	Beam on	$[-500, +535]$

Event Reconstruction in SK

- SK low energy fitter is used to reconstruct events.
  - **Vertex** ← PMT hit timing information
  - **Direction** ← Cherenkov ring pattern of hit PMTs
  - **Energy** ← Number of hit PMTs
  - **Cherenkov angle** ← Pattern of hit PMTs
- Fitter performance is checked by various calibrations.
- Important variables = { $\boldsymbol{E_{rec}}$, ***dwall***, ***effwall***, ***ovaQ***, $\boldsymbol{\theta_C}$ }.



θ_C: Cherenkov opening angle

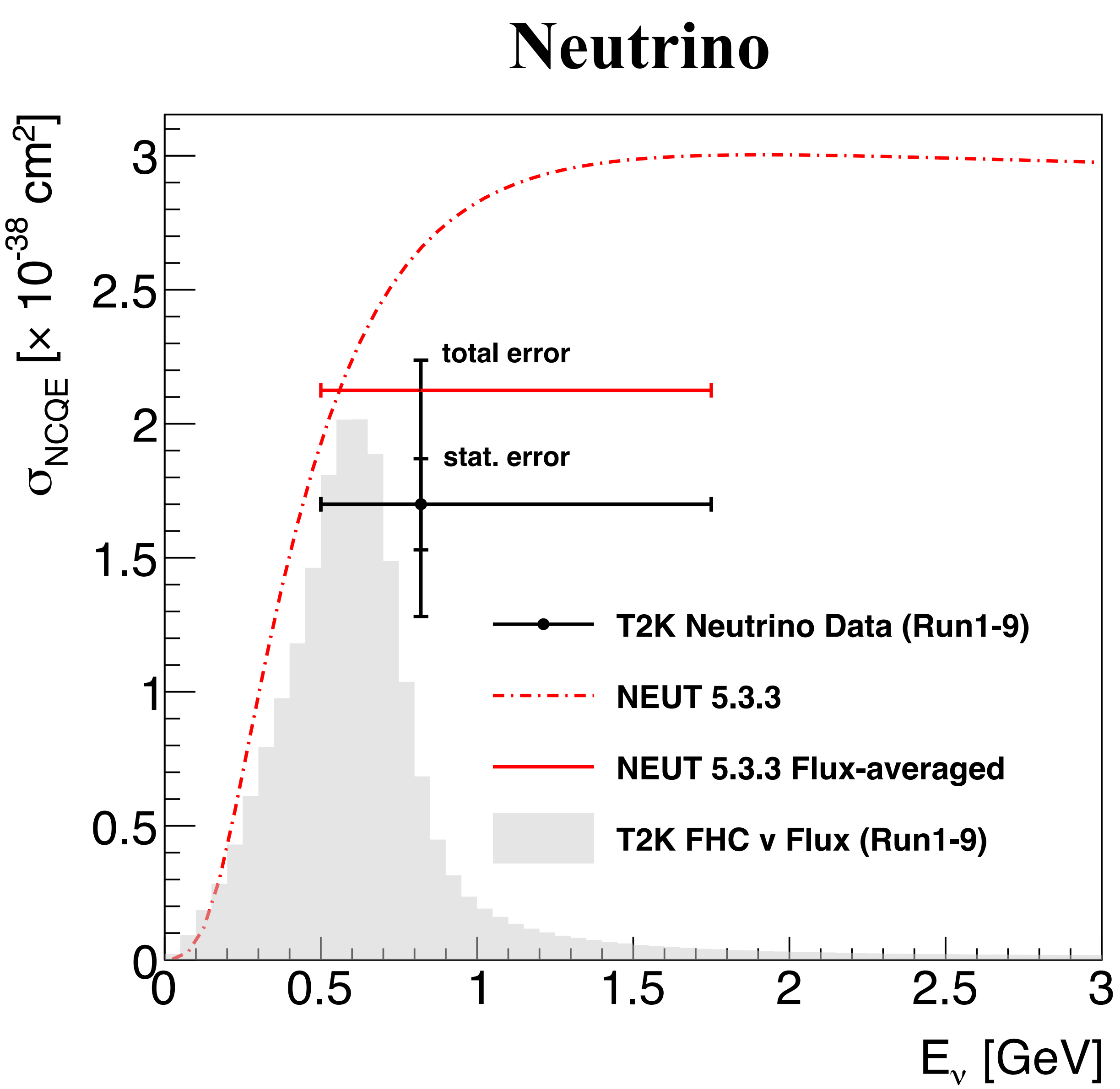


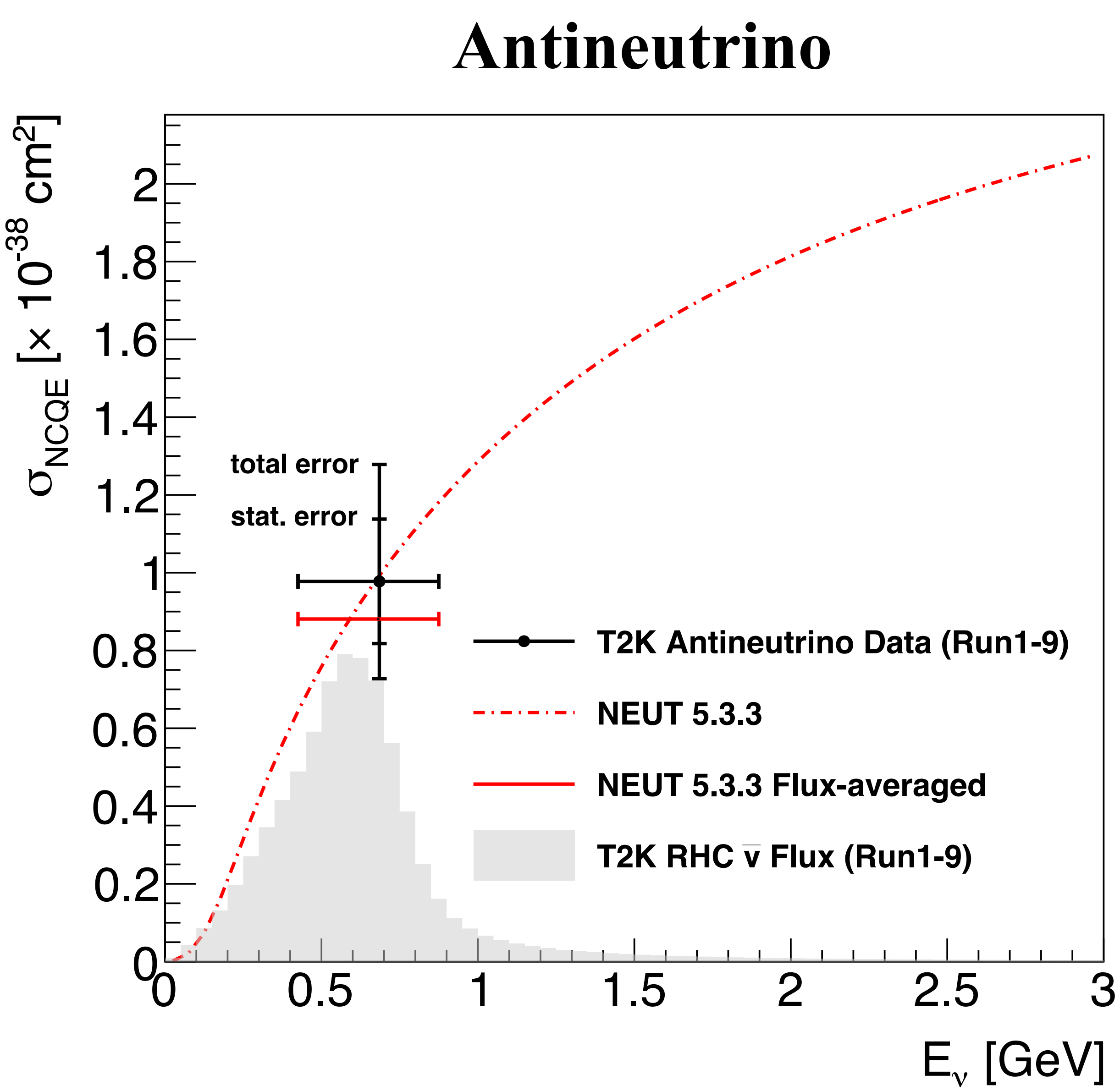
$\boldsymbol{ovaQ} = g_{vtx}^2 - g_{dir}^2$

g_{vtx} : Quality of reconstructed vertex

g_{dir} : Quality of reconstructed direction

Cross Sections Results





$$\langle \sigma_{\nu\text{-NCQE}} \rangle = 1.70 \pm 0.17(\text{stat.})^{+0.51}_{-0.38}(\text{syst.}) \times 10^{-38}\ \text{cm}^2/\text{oxygen},$$

$$\langle \sigma_{\bar{\nu}\text{-NCQE}} \rangle = 0.98 \pm 0.16(\text{stat.})^{+0.26}_{-0.19}(\text{syst.}) \times 10^{-38}\ \text{cm}^2/\text{oxygen},$$

Discussion

- **The measured cross sections are the most precise results to date.**
- **The antineutrino result is the first measurement of this channel.**
- Currently the dominant error source is the primary-/secondary-γ emission model.

- Secondary-γ emission model
  - Neutron experiment to measure **γ-rays from the neutron-oxygen reactions**.
  - The first beam test using an 80 MeV neutron beam was performed to ~20% precision.
  - Measurements with the similar sized precision over neutron energies would improve the current 13% uncertainty to <5%.

- Neutron information
  - Relation between neutrons and secondary-γ's
  - Event counting in the 2D E_{rec}–θ_{C} phase space with the neutron tagging

    → **direct estimation of the SRN background**
  - These are more plausible with higher statistics in SK-Gd and Hyper-Kamiokande.
    - >1000 events are expected in the SRN signal region with the neutron tagging.

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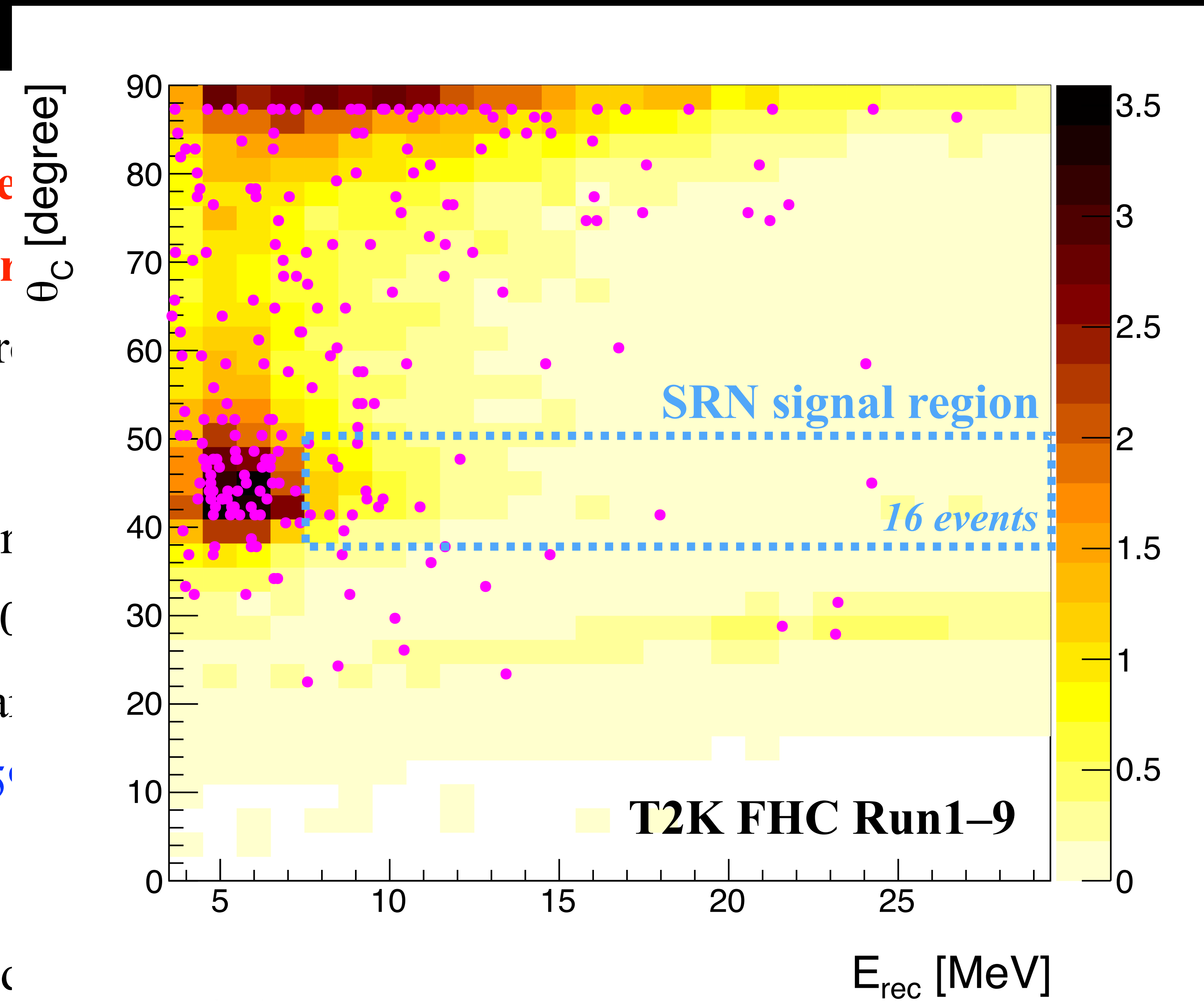
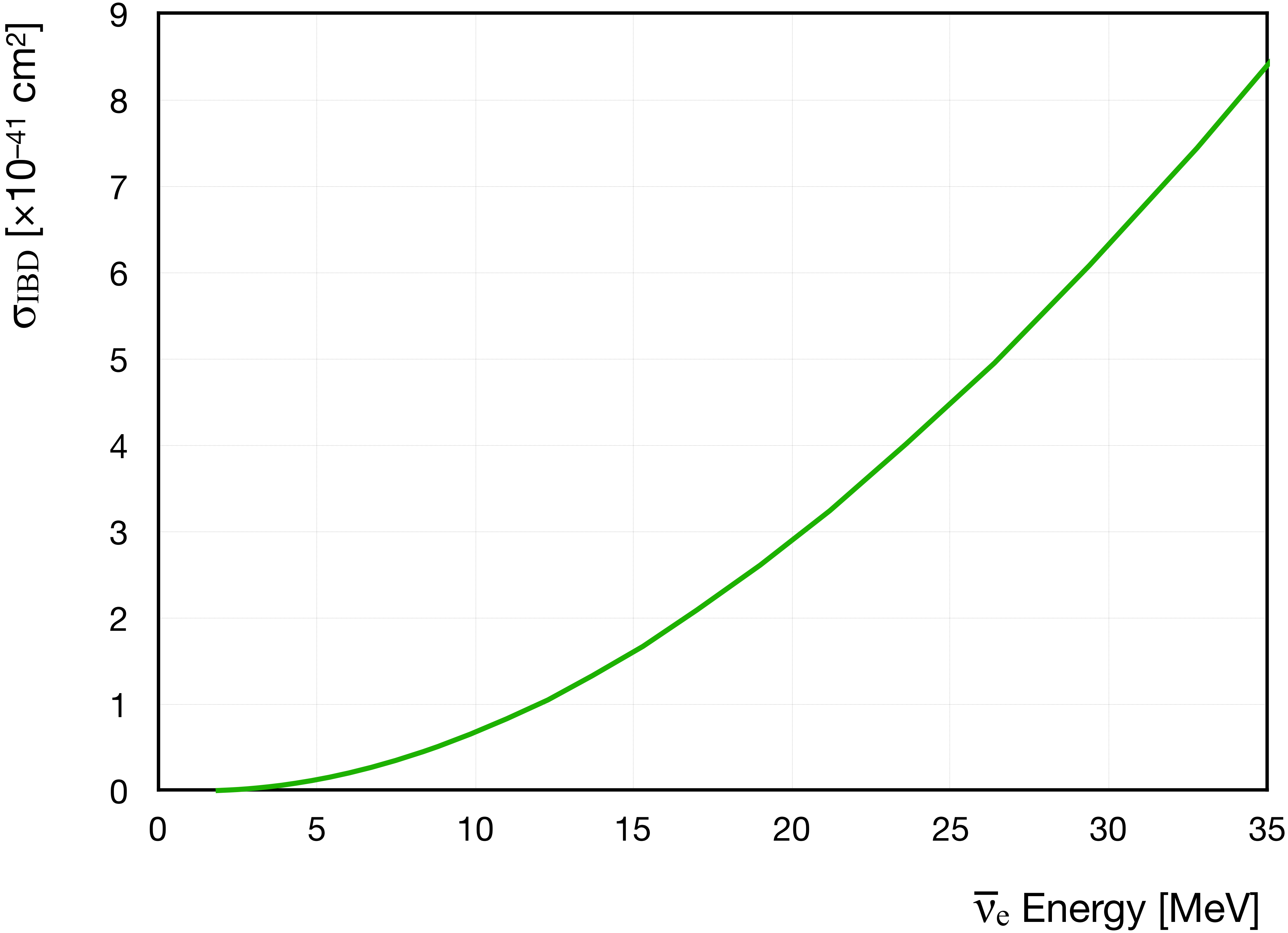


Search Overview

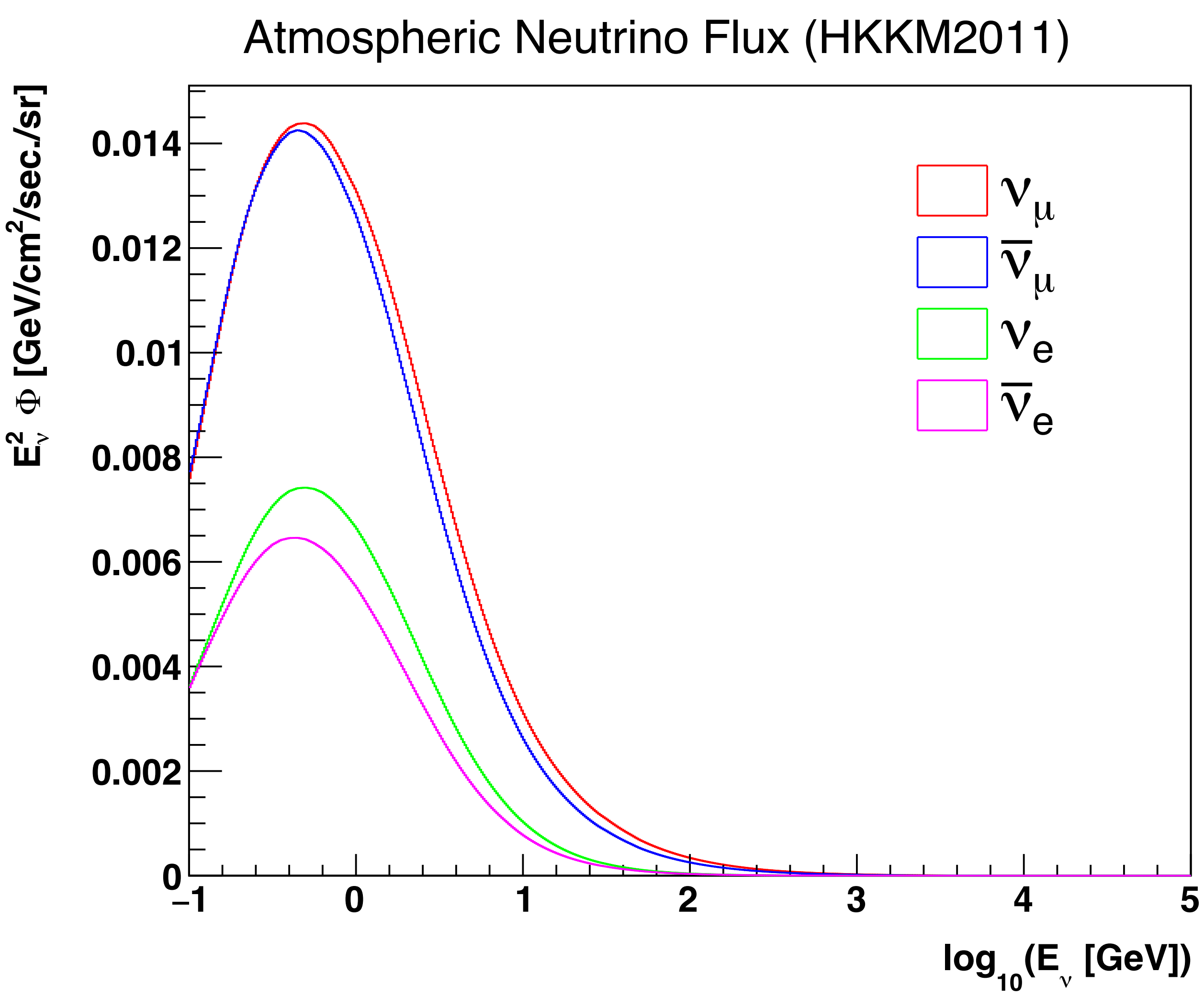
- **Data set**
  - Run 61525 – 77958 (**2790.1 live days**)
  - SHE+AFT events for relic candidates: >8(10) MeV before(after) Run 68670
  - HE+OD muons for spallation cut tuning
- **Software**
  - nuebar MC: new package made by Sonia (to be released)
  - atmospheric-ν MC: ATMPD production apr16 (no reduction)
  - reconstruction: lowfit_sk4 (w/o PMT gain correction), mufit_sk4
  - neutron tagging: new BDT package

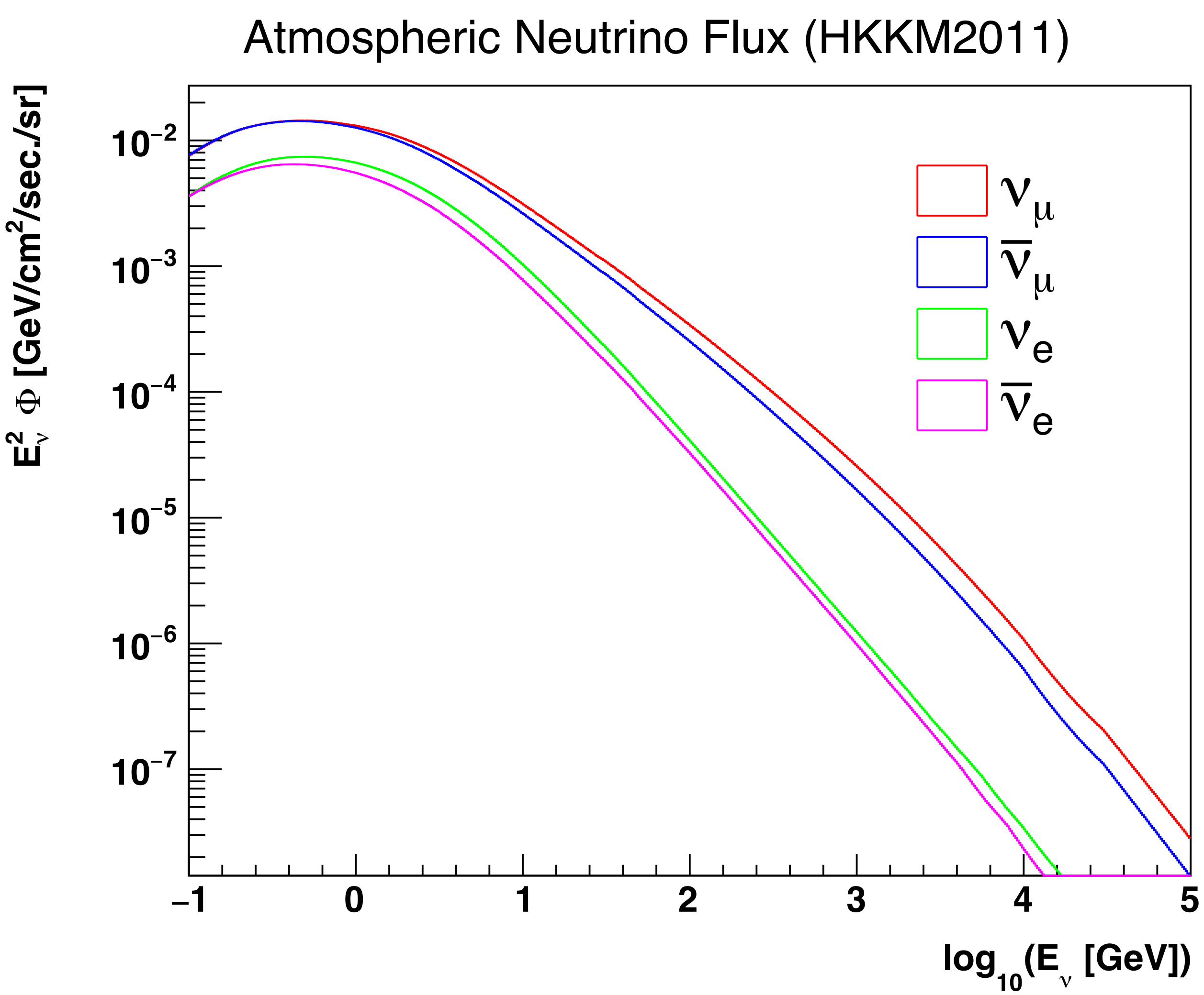
Start Date	End Date	Live time	SHE threshold	AFT window length
6th, Oct., 2008	22nd, Nov., 2008	25.0 days	70 hits	350 μs
22nd, Nov., 2008	9th, Sep., 2011	869.8 days	70 hits	500 μs
9th, Sep., 2011	31st, May., 2018	2075.3 days	58 hits	500 μs

Cross Section of IBD on Free Proton

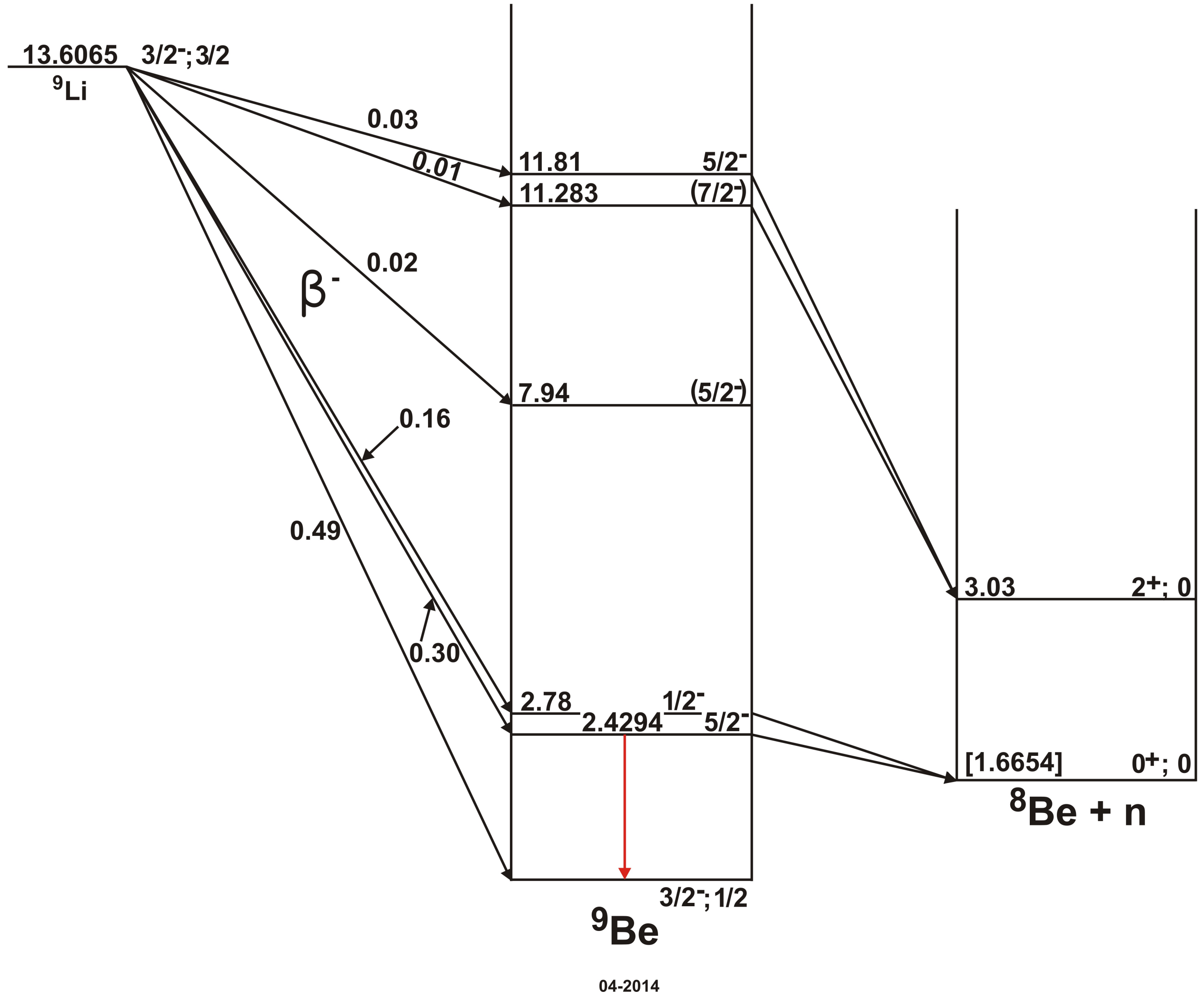


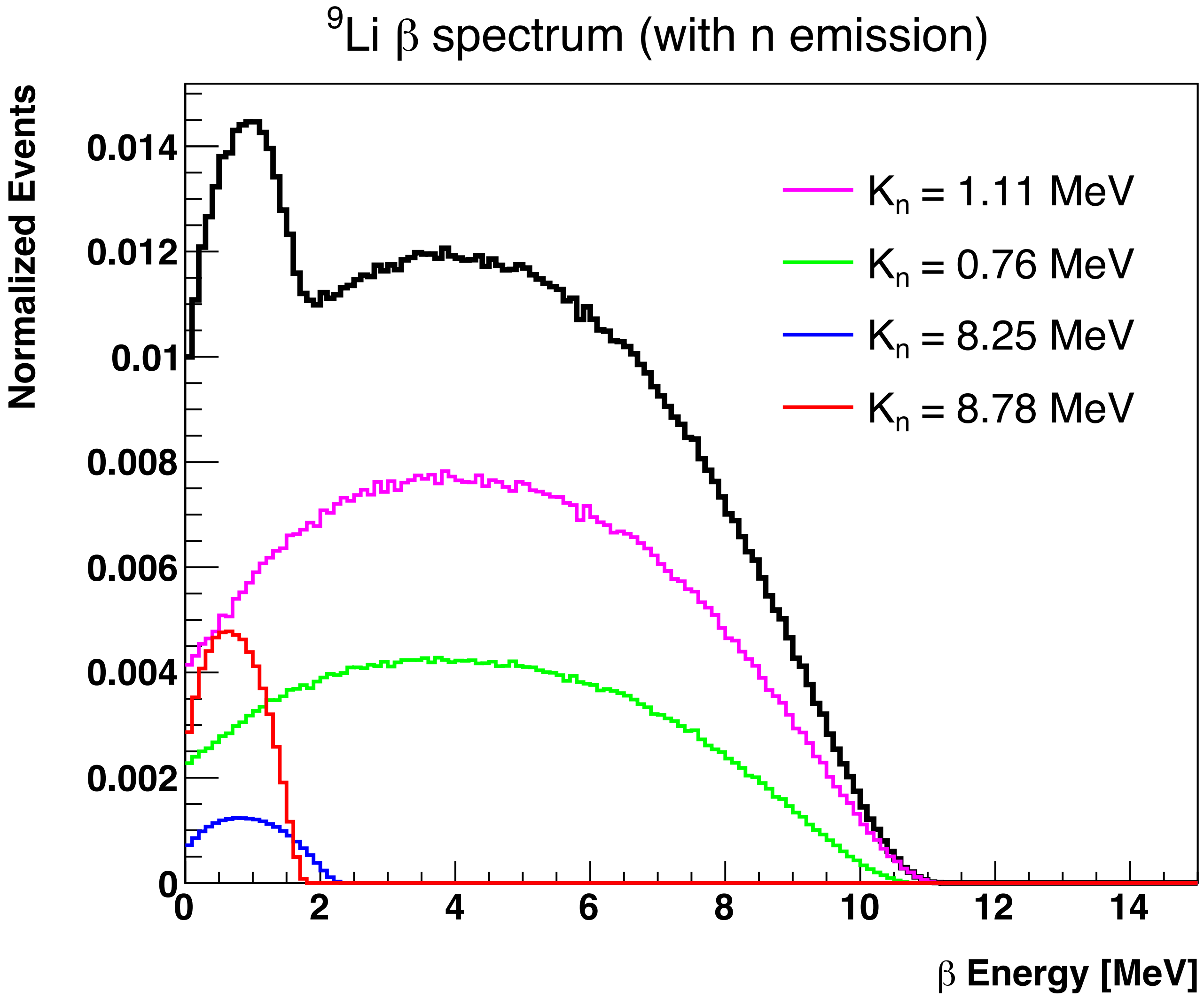
Atmospheric Neutrino Flux (HKKM2011)



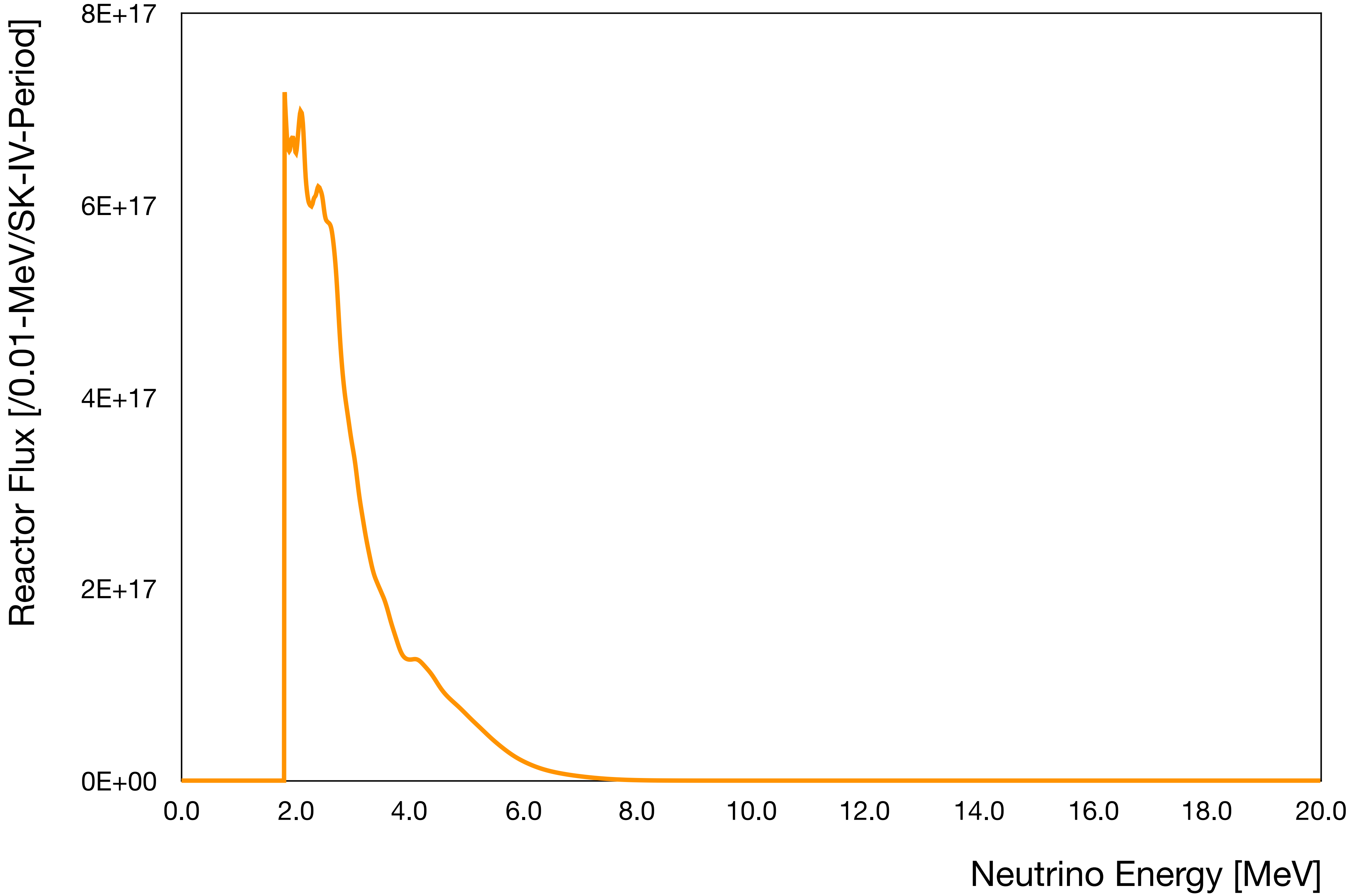


Lithium-9

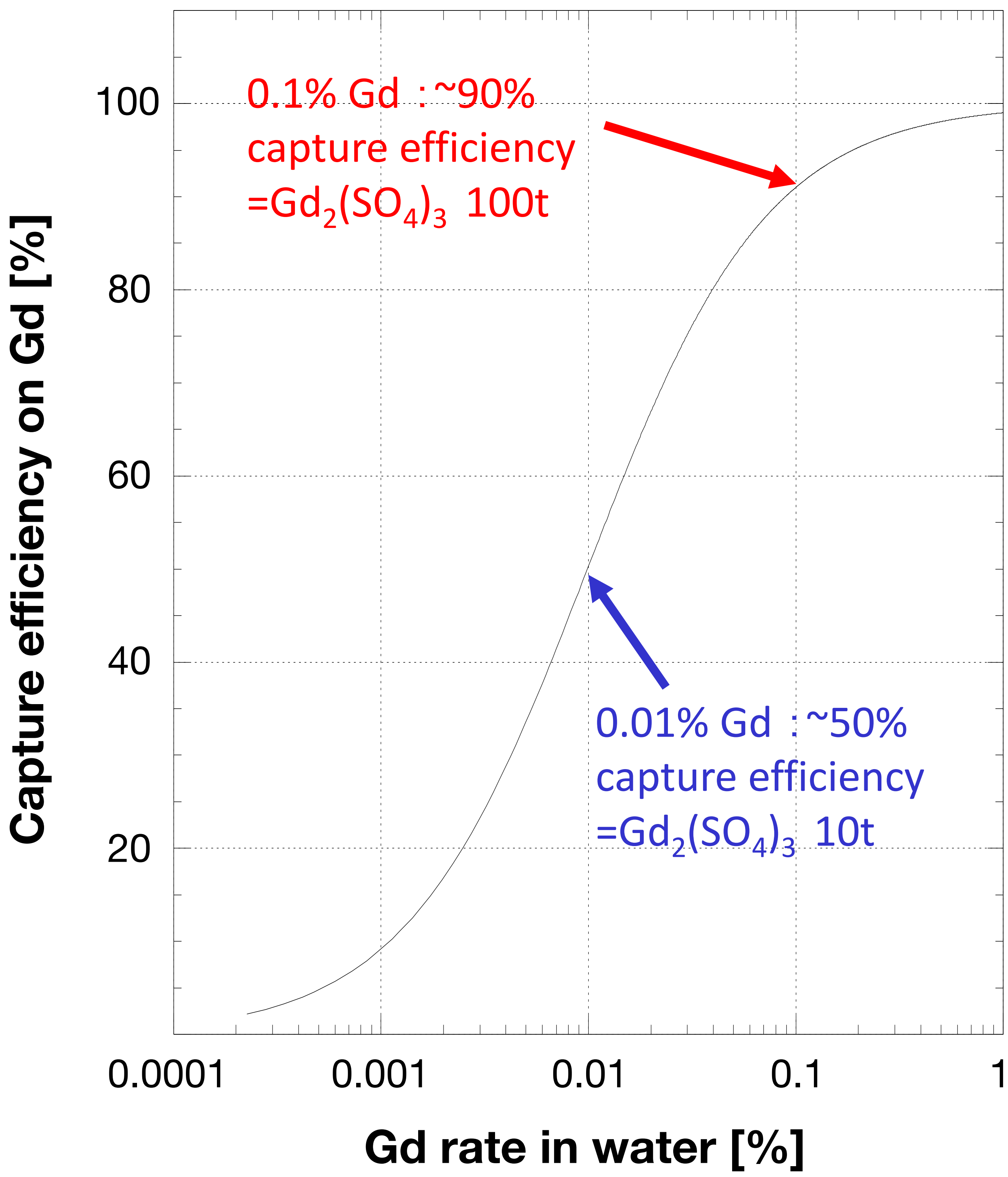

13.6065
3/2⁻; 3/2
9Li
β-
0.03
0.01
0.02
0.16
0.49
0.30
11.81
5/2⁻
11.283
(7/2⁻)
7.94
(5/2⁻)
2.78
1/2⁻
2.4294
5/2⁻
3/2⁻; 1/2
9Be
04-2014
3.03
2+; 0
[1.6654]
0+; 0
8Be + n


9Li β spectrum (with n emission)
Normalized Events
β Energy [MeV]
Kn = 1.11 MeV
Kn = 0.76 MeV
Kn = 8.25 MeV
Kn = 8.78 MeV
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0
2
4
6
8
10
12
14

Reactor Neutrino Flux



SK-Gd


0.1% Gd : ~90%
capture efficiency
=Gd2(SO4)3 100t
0.01% Gd : ~50%
capture efficiency
=Gd2(SO4)3 10t
100
80
60
40
20
0.0001
0.001
0.01
0.1
1
Capture efficiency on Gd [%]
Gd rate in water [%]

Hyper-Kamiokande