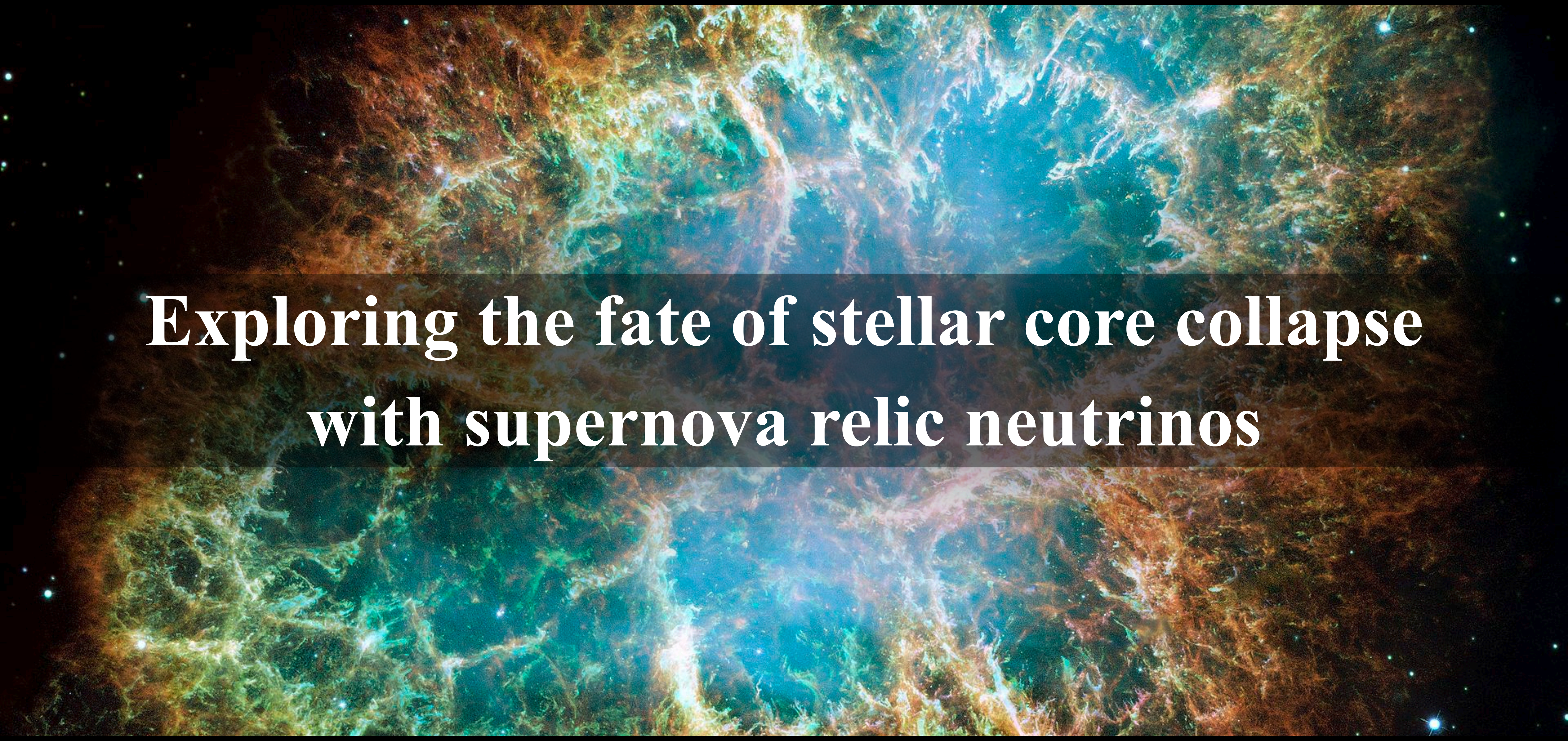
The 8th Supernova Neutrino Workshop (January 6–7th, 2022)



Exploring the fate of stellar core collapse with supernova relic neutrinos

Yosuke ASHIDA (University of Wisconsin-Madison)

Ken'ichiro NAKAZATO (Kyushu University)

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 ordering)
  - Galactic evolution (star formation rate, initial mass function, binary interactions, etc)
  - Black hole formation rate (metallicity, equation-of-state, etc)
  - etc

SRN flux

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

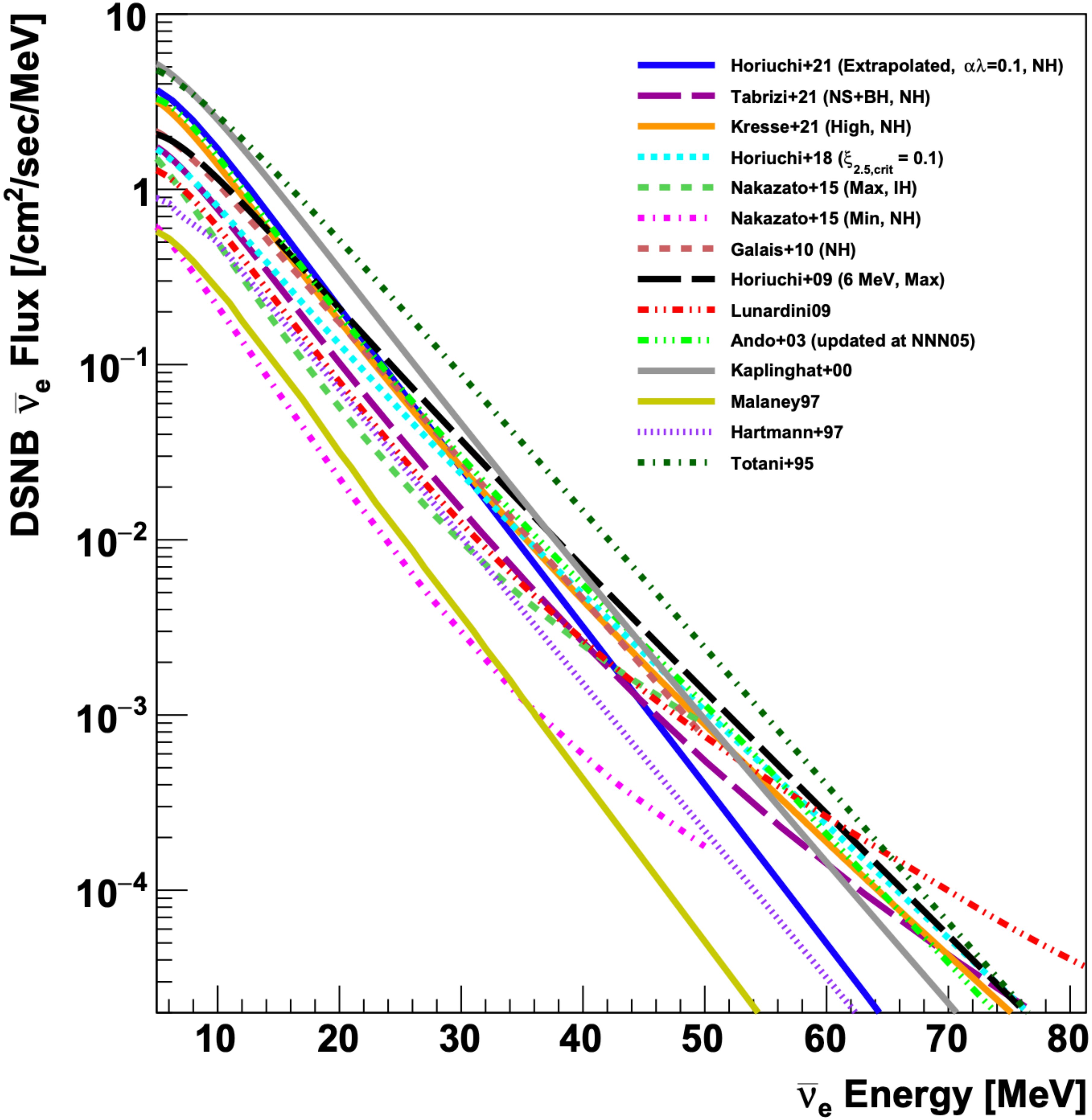
cosmological parameters: $H_0\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}$

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

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

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

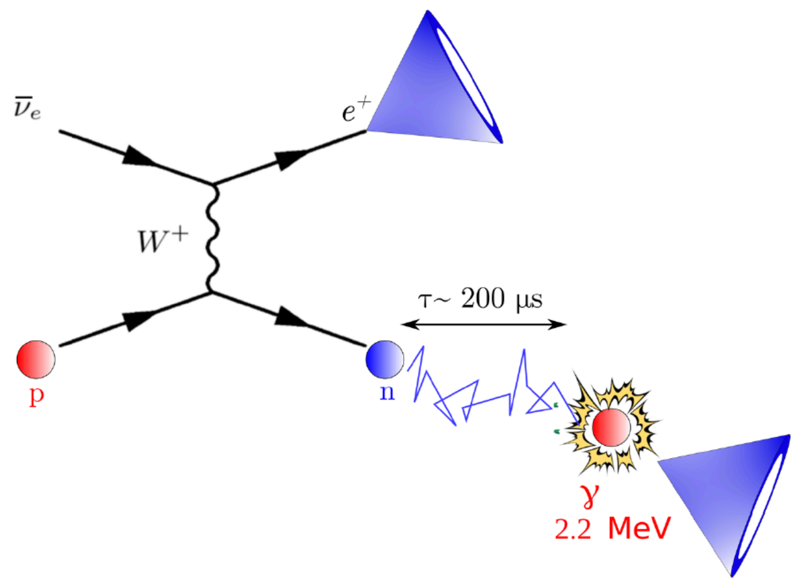
neutrino number spectrum per CCSN: $\frac{dN(M,Z,E'_\nu)}{dE'_\nu}$

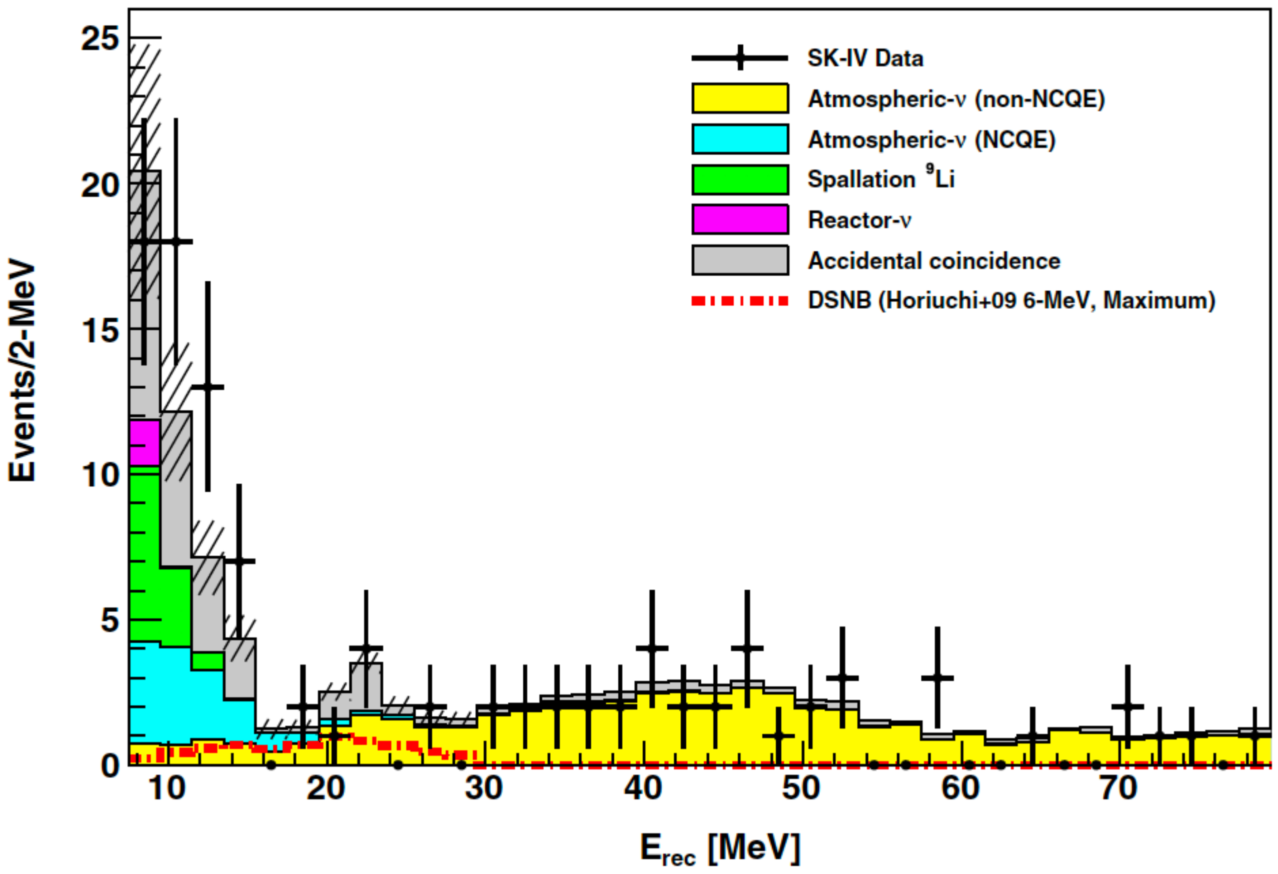


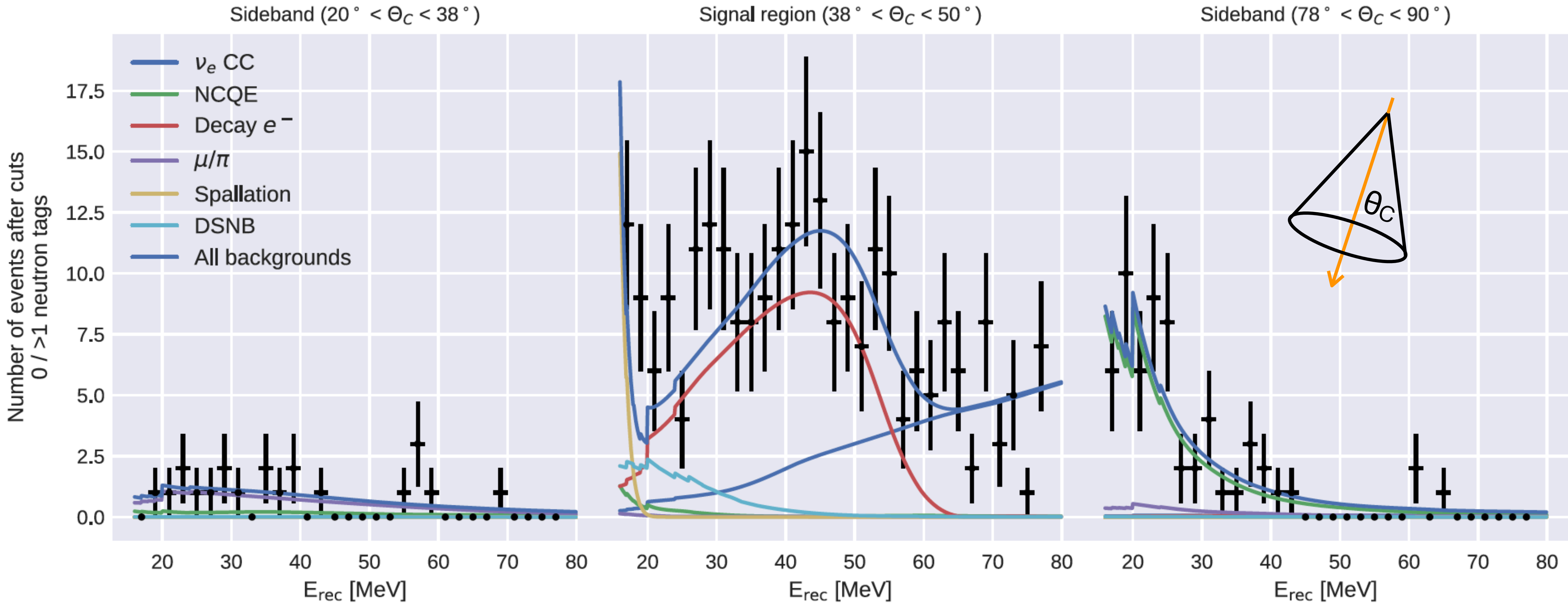
Horiuchi+21 (Extrapolated, αλ=0.1, NH)
Tabrizi+21 (NS+BH, NH)
Kresse+21 (High, NH)
Horiuchi+18 ($\xi_{2.5,crit}$ = 0.1)
Nakazato+15 (Max, IH)
Nakazato+15 (Min, NH)
Galais+10 (NH)
Horiuchi+09 (6 MeV, Max)
Lunardini09
Ando+03 (updated at NNN05)
Kaplinghat+00
Malaney97
Hartmann+97
Totani+95
DSNB $\bar{\nu}_e$ Flux [/cm^2/sec/MeV]
$\bar{\nu}_e$ Energy [MeV]
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10 20 30 40 50 60 70 80

Search at Super-K

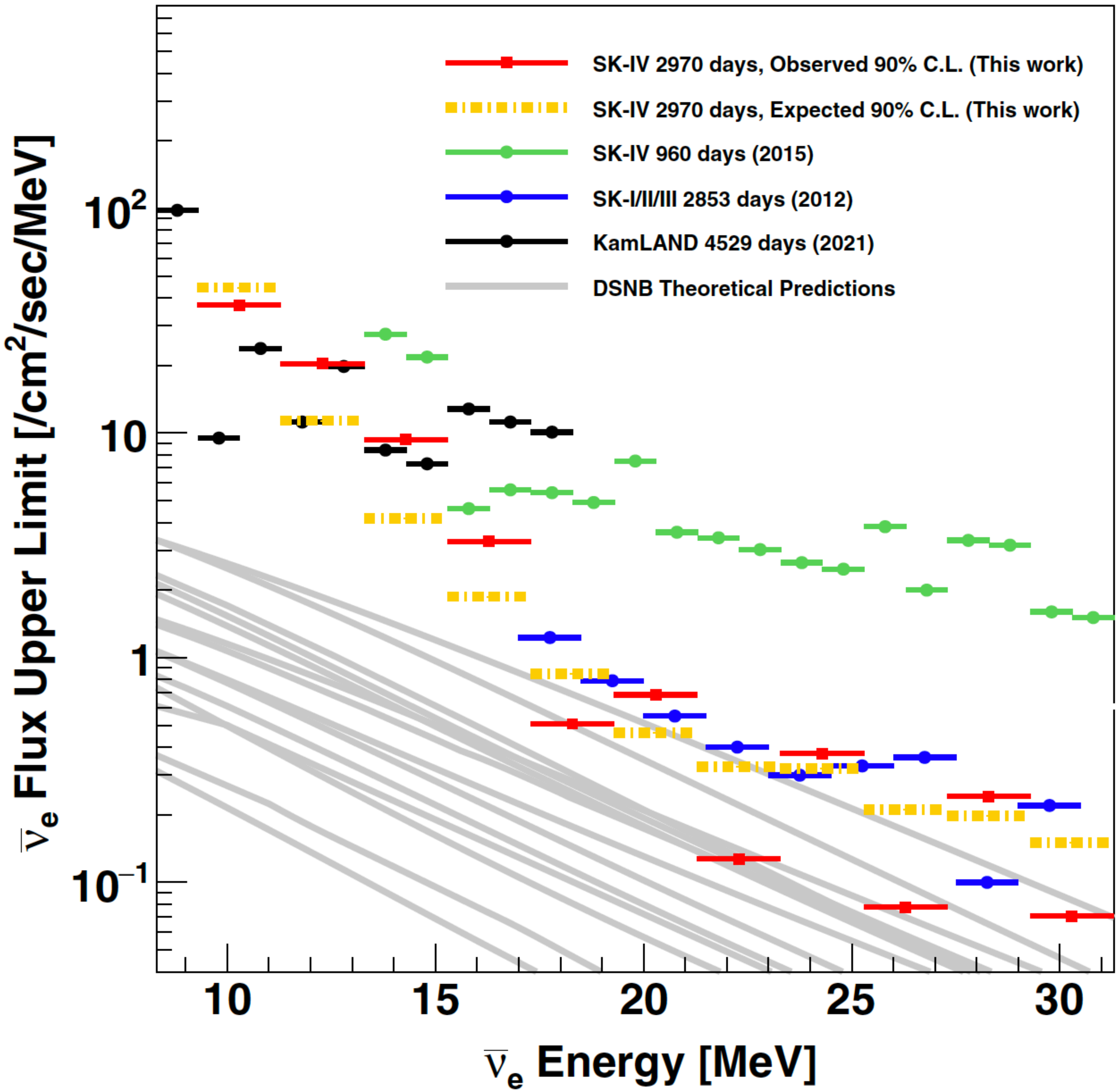
K. Abe et al. (SK Collaboration), PRD 104, 122002 (2021)



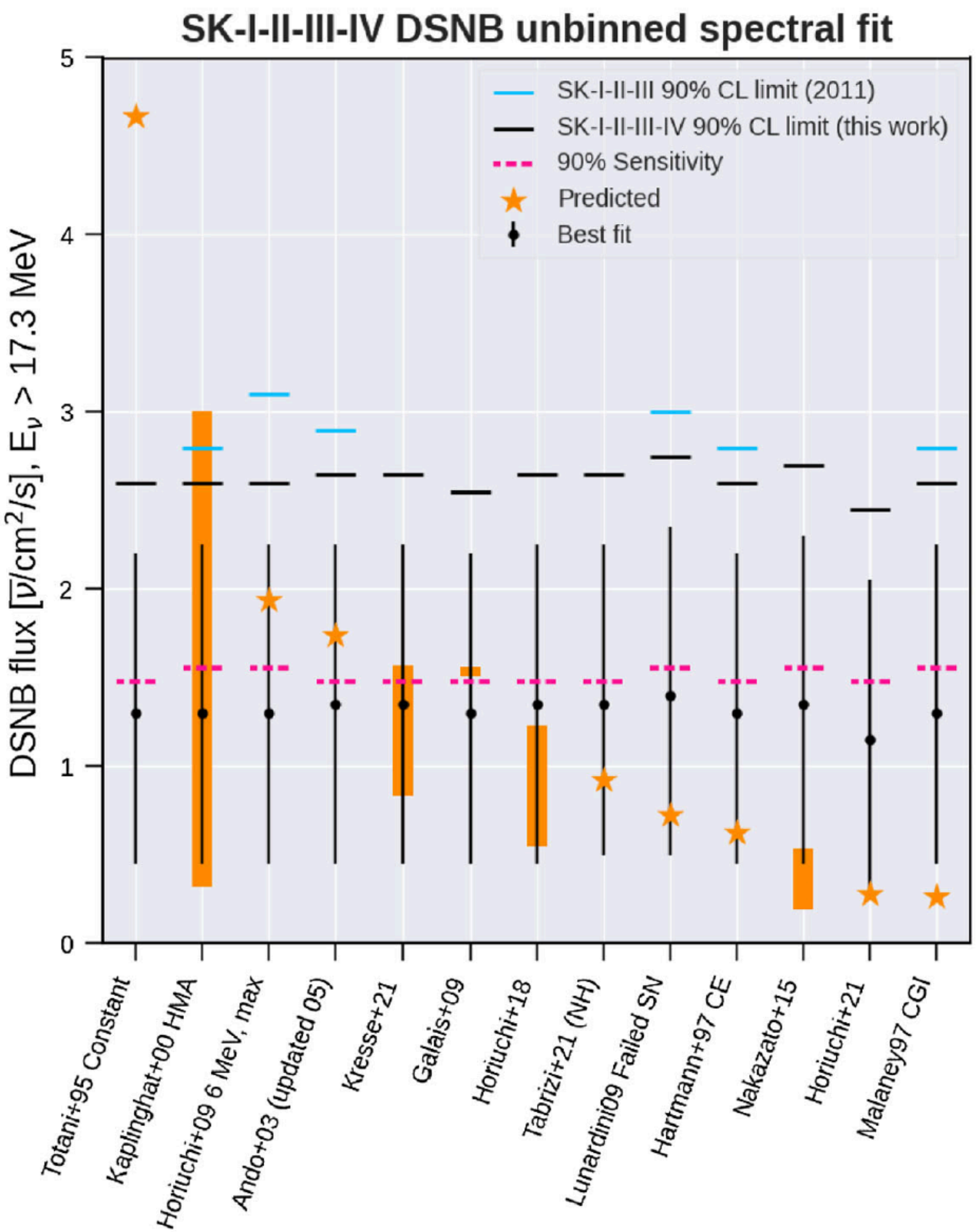




Model-Independent Upper Limit



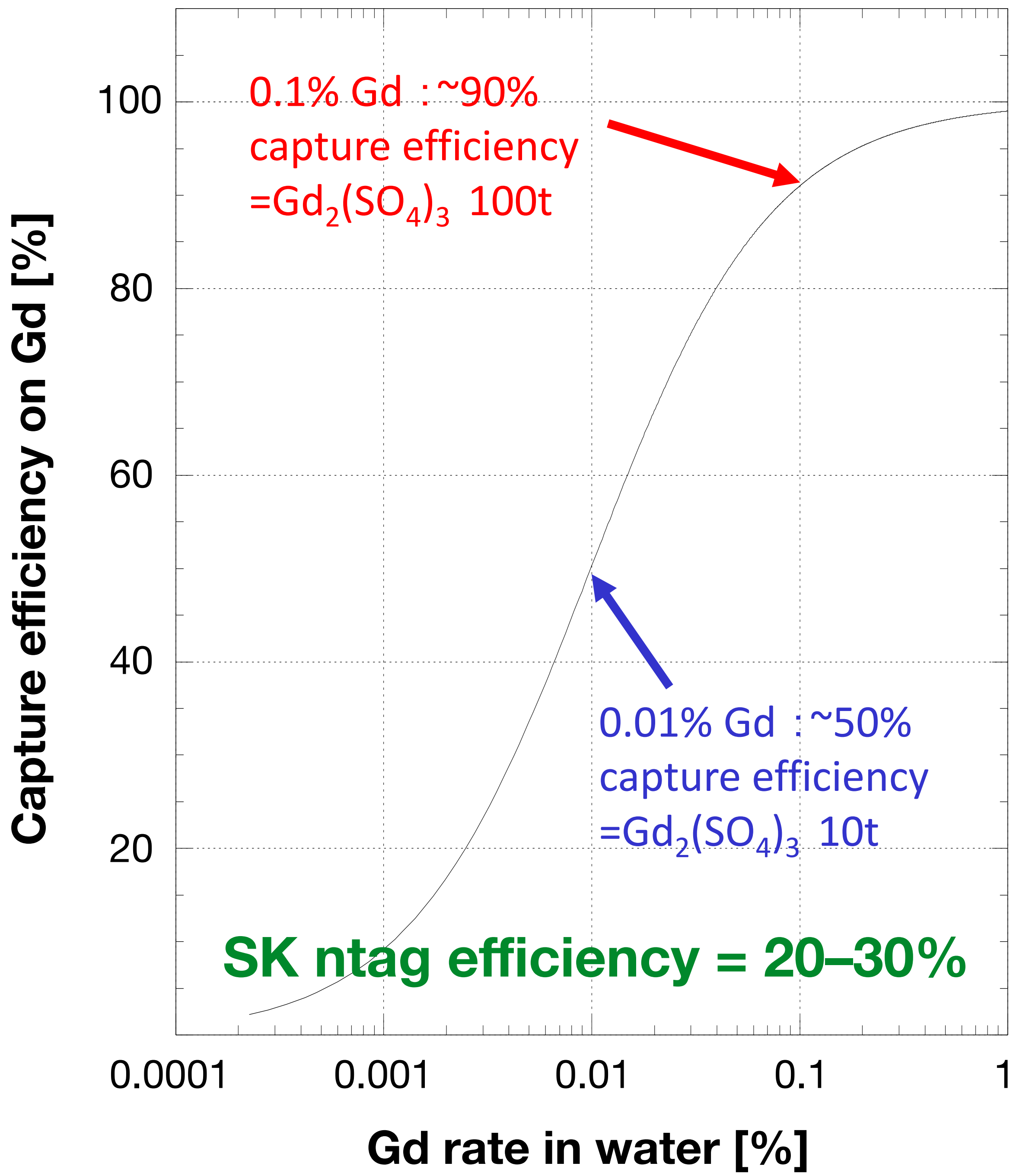
Model-Dependent Spectral Fitting Results



Next Generation Detectors

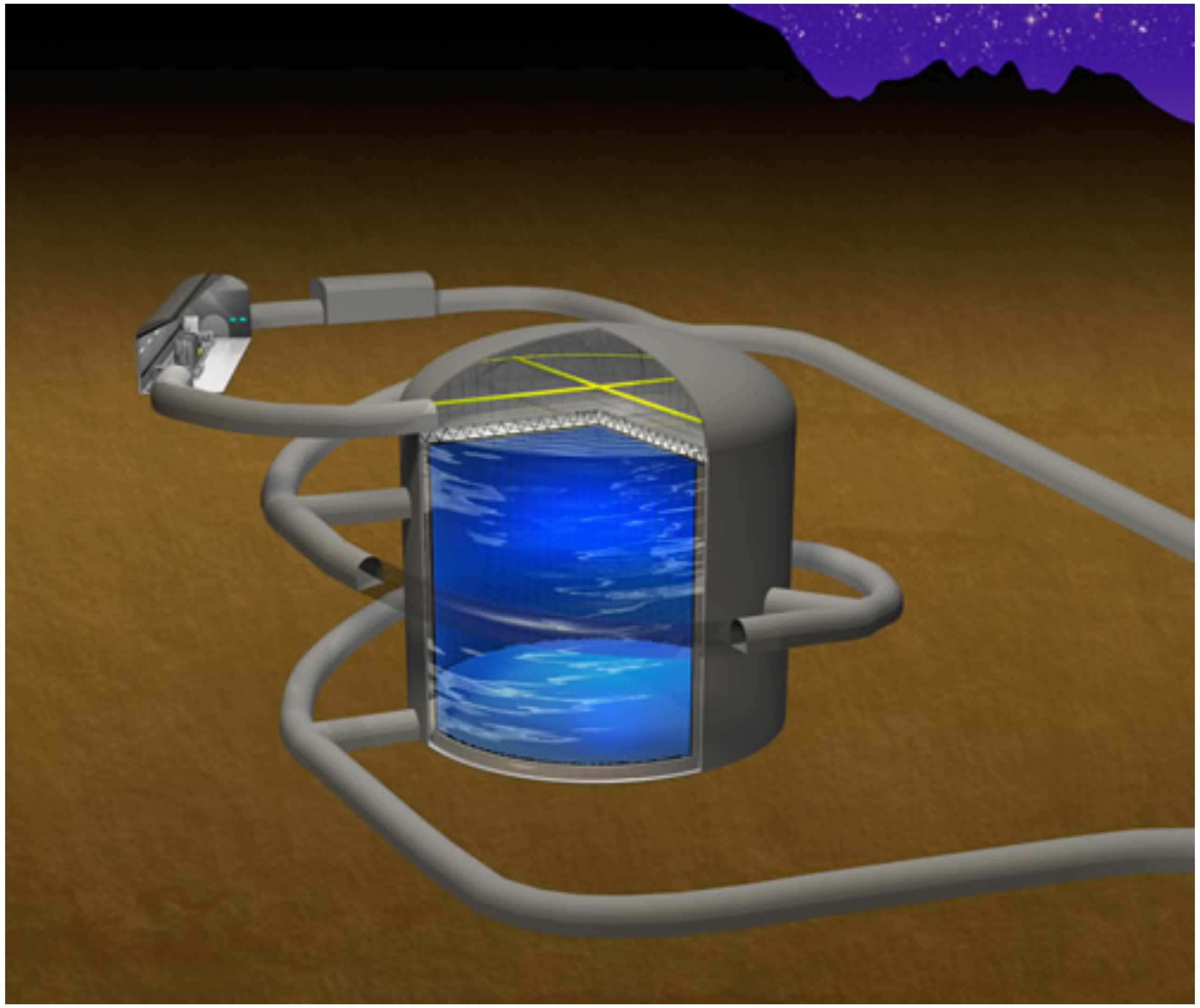
J. Beacom and M. Vagins, PRL 93, 171101 (2004)
K. Abe et al. (HK Proto-Collaboration), arXiv:1109.3262

SK-Gd



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

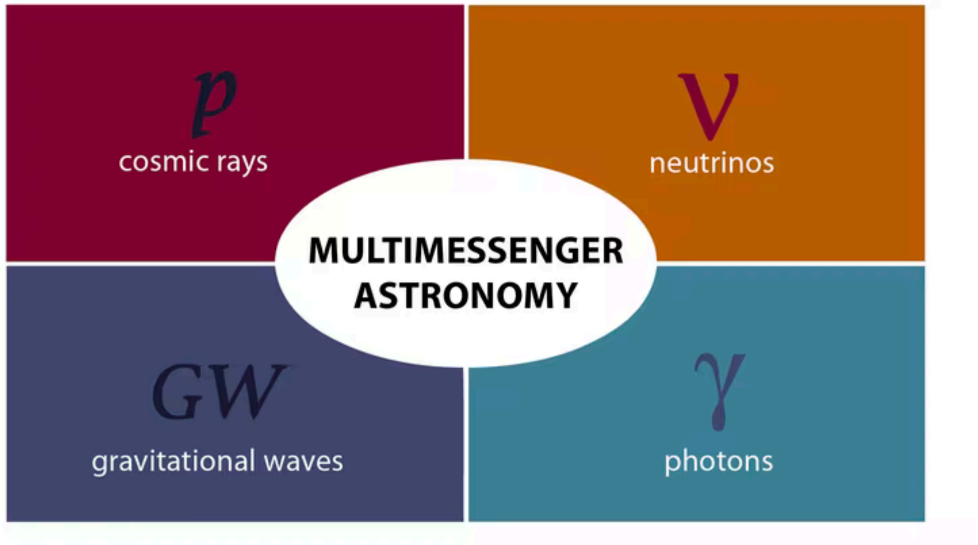
Hyper-Kamiokande



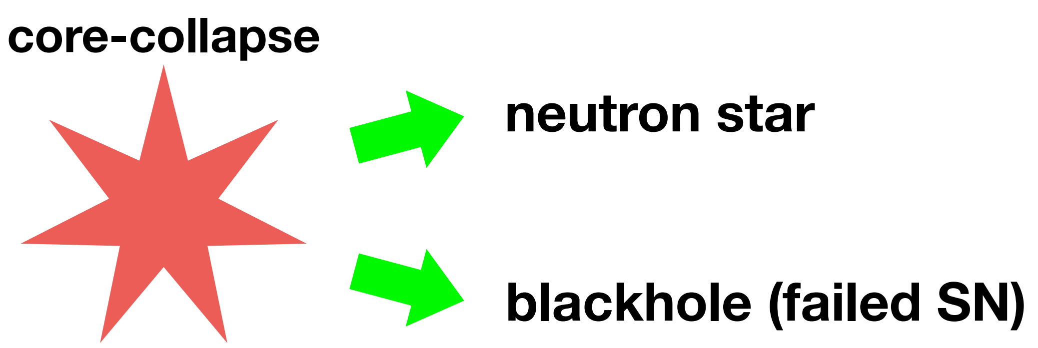
Fiducial mass: ~8.4 times larger than SK
Better photosensor → higher ntag efficiency
More spallation because of less overburden

Purpose of Present Study

- Last 20 years
  - Detector understanding
  - Understanding backgrounds
  - Establishing analysis methods



- Next 20 years
  - Extracting constraints on "physics"
  - Combination with other observations ("*multi-messenger astronomy*")
- We will show one demonstration.
  - Especially we focus on the fate of CCSNe in this study.



Model (See Nakazato-san's Talk for Details)

- Neutrino mass hierarchy: **normal** or **inverted**
- Neutron star EOS: **Togashi**, **LS220**, **Shen**
- Minimum mass of progenitors: $\mathbf{6}M_{\mathrm{sun}}$, $\mathbf{8}M_{\mathrm{sun}}$, $\mathbf{10}M_{\mathrm{sun}}$
- Fractions of the fate of CCSNe
  - Heavy neutron stars: f_{HNS}
  - Blackholes (failed SN): f_{BH} (= f_{FSN})

Flux from a CCSN

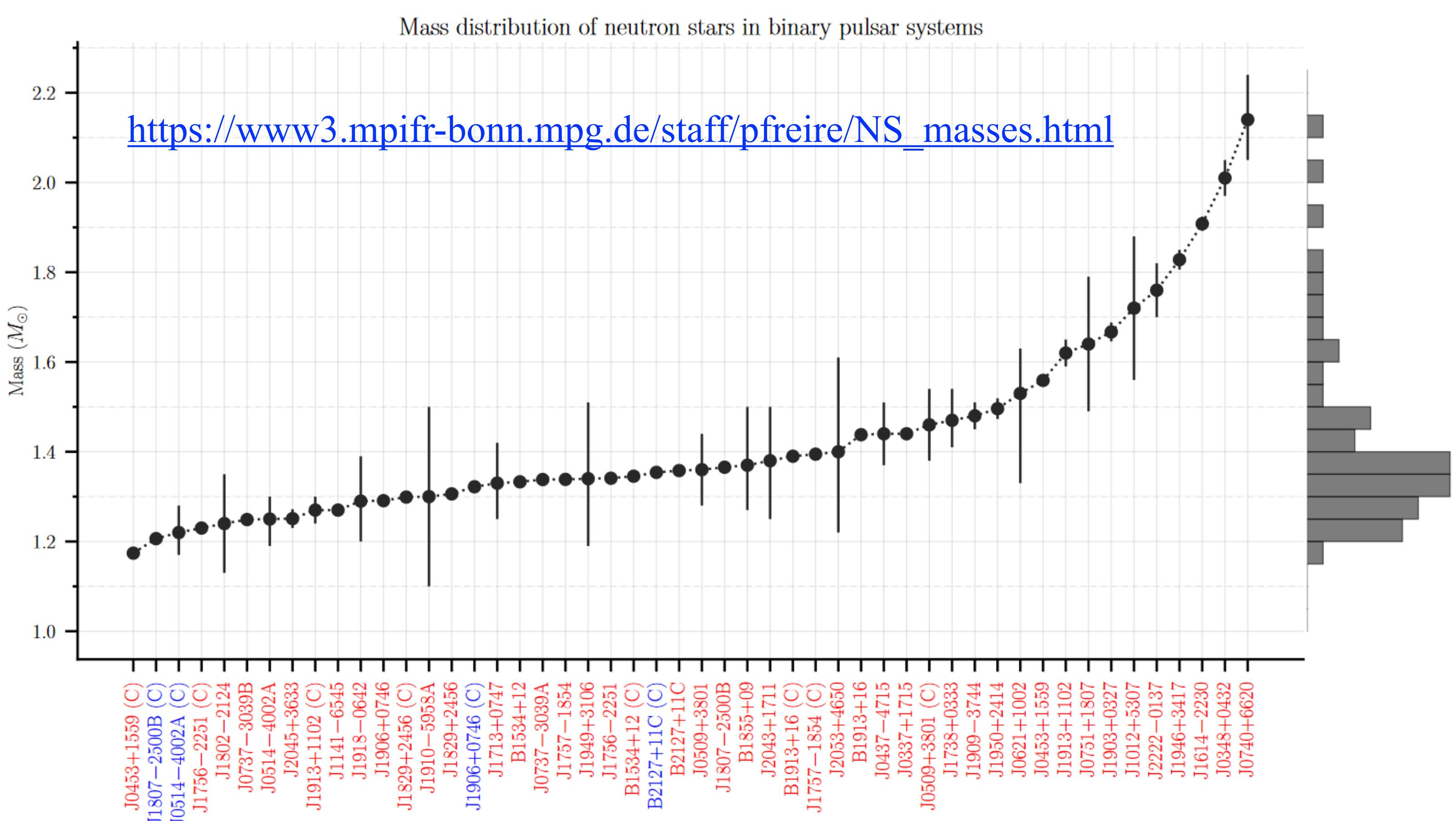
$$\frac{dF(E_\nu)}{dE_\nu} = c\int_0^{z_{\max}} R_{\mathrm{CC}}(z)\left\langle\frac{dN(z,E'_\nu)}{dE'_\nu}\right\rangle\frac{dz}{H_0\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}$$

$$\left\langle\frac{dN(z,E'_\nu)}{dE'_\nu}\right\rangle = \underbrace{f_{\mathrm{FSN}}(z)\frac{dN_{\mathrm{FSN}}(E'_\nu)}{dE'_\nu}}_{\text{BH}} + \left(1-f_{\mathrm{FSN}}(z)\right)\times\left[\underbrace{f_{\mathrm{HNS}}(z)\frac{dN_{\mathrm{HNS}}(E'_\nu)}{dE'_\nu}}_{\text{high-mass NS}} + \underbrace{\left(1-f_{\mathrm{HNS}}(z)\right)\frac{dN_{\mathrm{CNS}}(E'_\nu)}{dE'_\nu}}_{\text{canonical-mass NS}}\right]$$

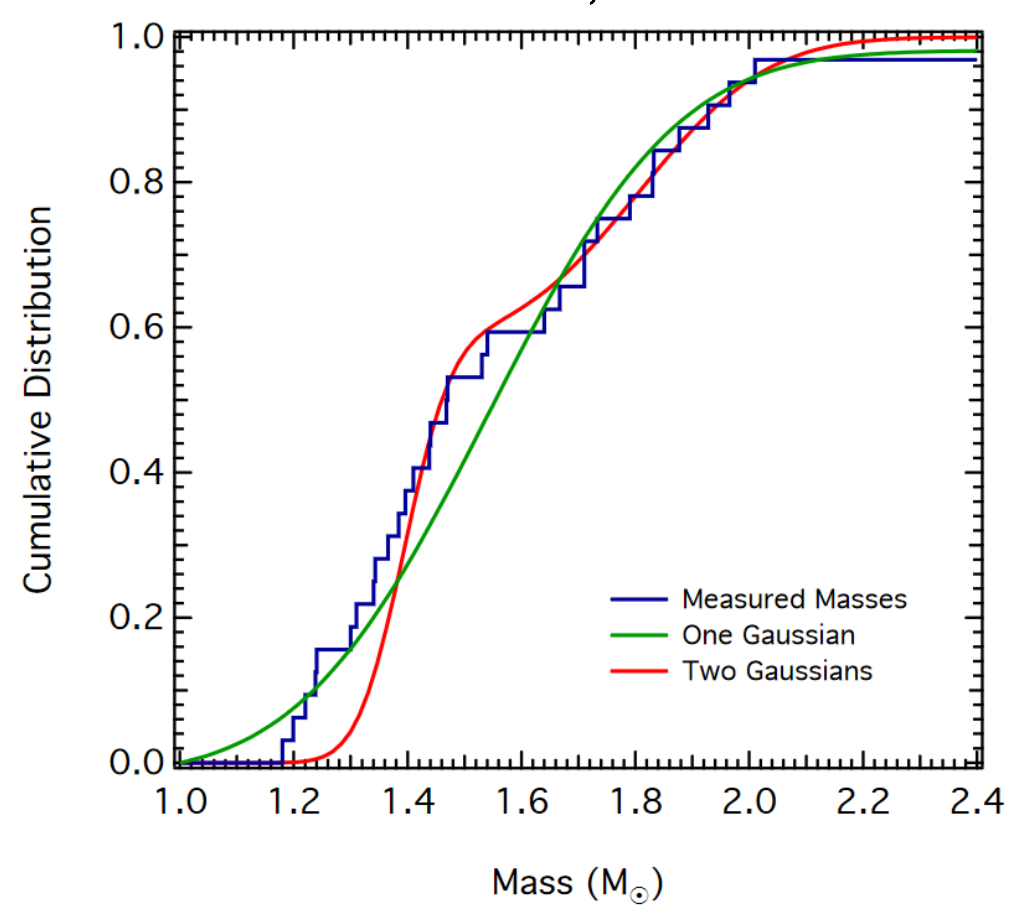
Neutron Star Mass

- From optical observations, we have a mass distribution of neutron stars in the binary.
  - Seems it has **two peaks**.
  - Natural-born heavy *or* became heavy through accretion from companion stars.

- Nakazato model
  - Canonical-mass NS: baryon mass = 1.47$M_{\rm sun}$, gravity mass ~ 1.34$M_{\rm sun}$
  - High-mass NS: baryon mass = 1.86$M_{\rm sun}$, gravity mass ~ 1.65$M_{\rm sun}$



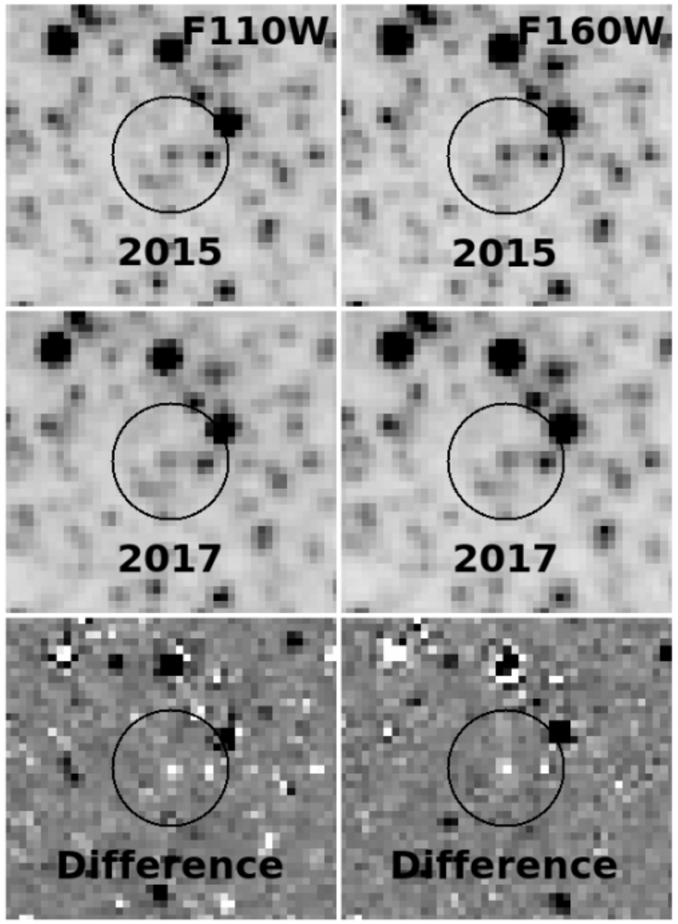
J. Antoniadis et al., arXiv:1605.01665



Failed SN (Blackhole Formation)

- Monitoring luminous stars gave constraints on failed SNe.
- 2 failed SN candidates (N6946-BH1, M101-OC1) out of 8 SNe.
  - **f_{BH} = 4–39% (90% C.L.)**, assuming $N_{FSN} = 1$ and $N_{SN} = 8$.

C. M. Basinger et al., arXiv:2007.15658



J. M. M. Neustadt et al., arXiv:2104.03318

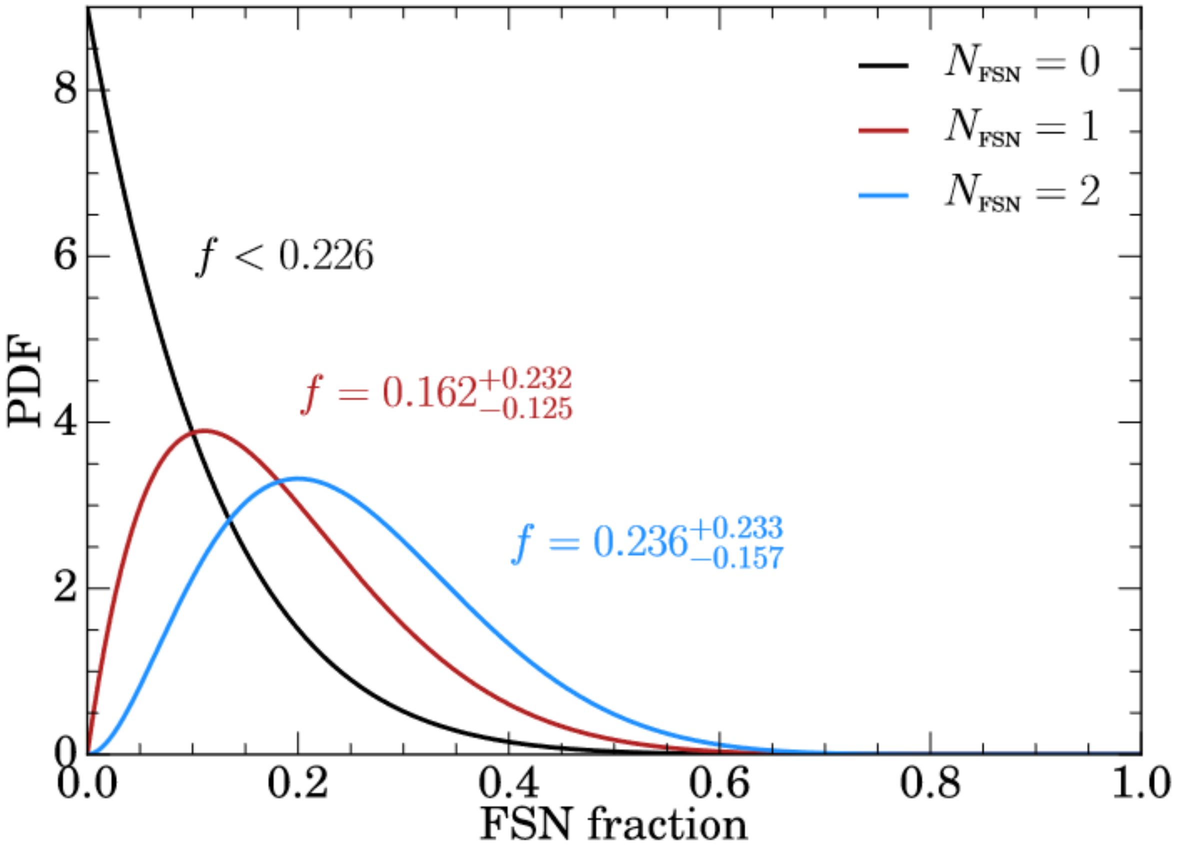


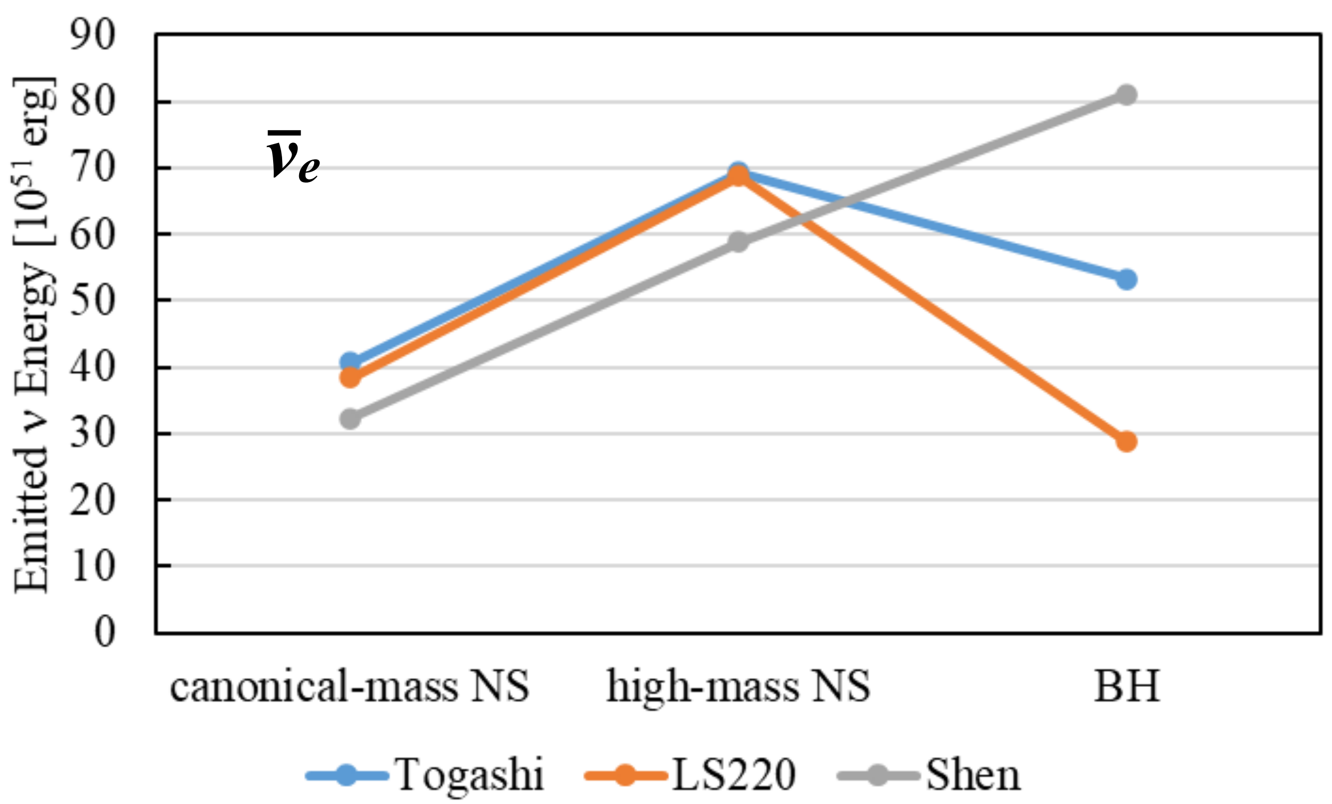
Table 5. Failed supernova/core-collapse fraction

N_{FSN}	Lower limit	Median	Upper limit
2	0.079	0.236	0.470
1	0.037	0.162	0.394
0	–	–	0.226

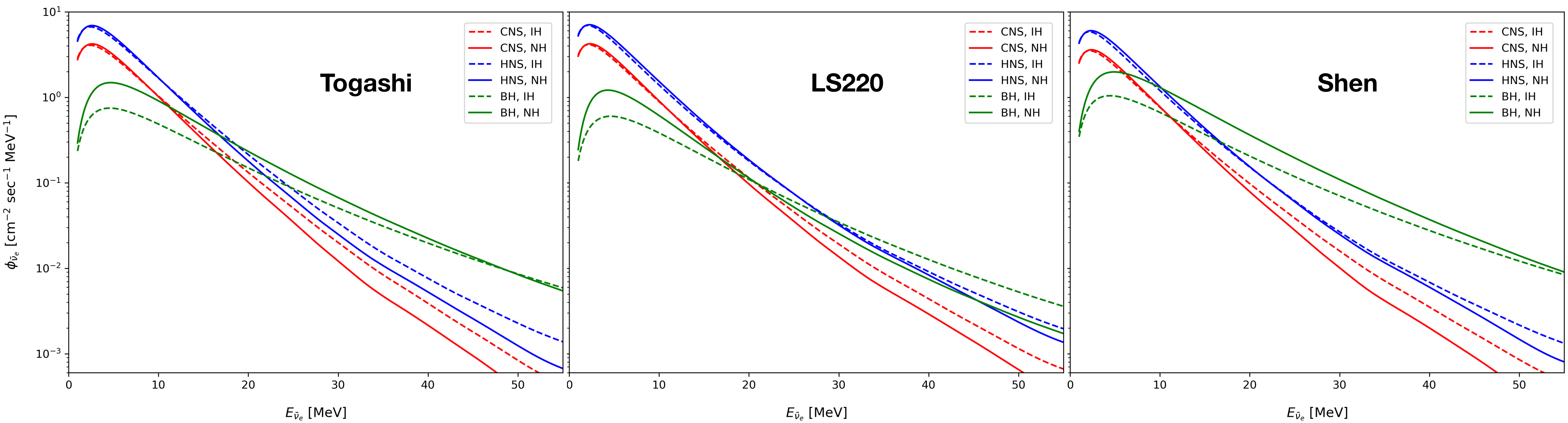
Notes: Limits are presented at the 90 per cent confidence level.

Neutrino Energy and Flux

- BH formation gives different average energy.
  → changes resulting SRN flux shape.
- Depends also on neutron star EOS.



canonical-mass NS, high-mass NS, BH



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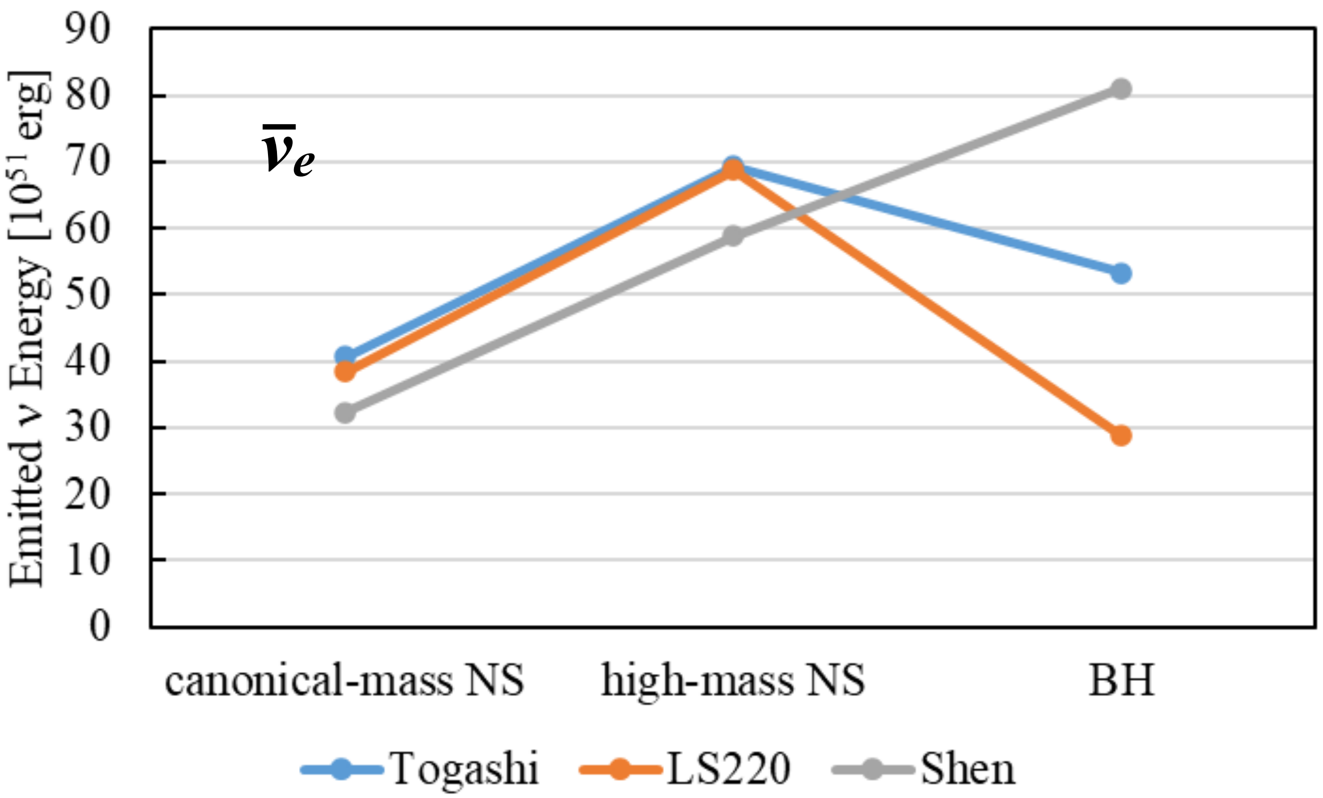
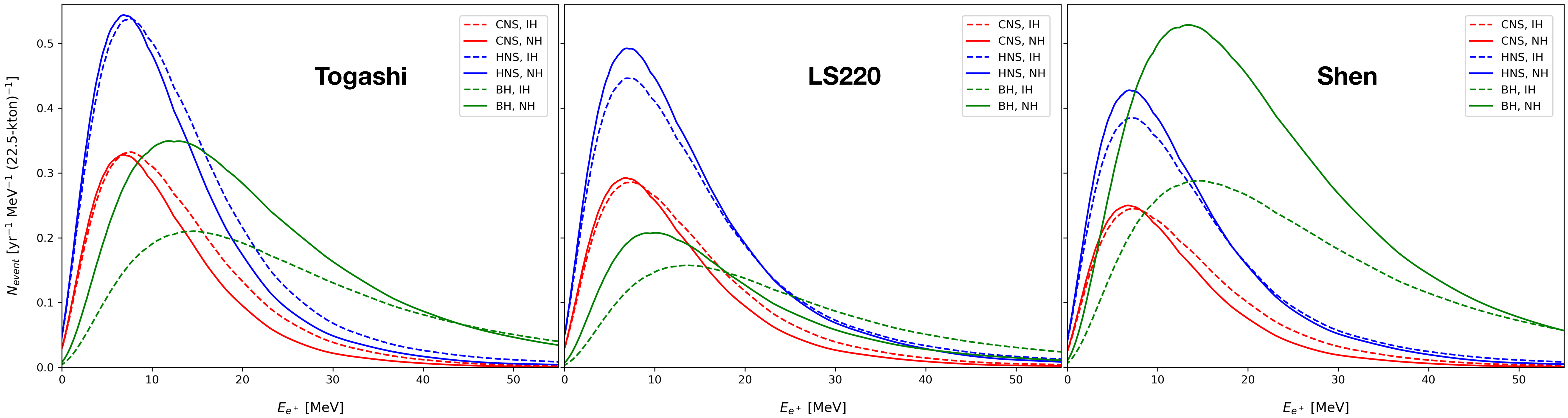
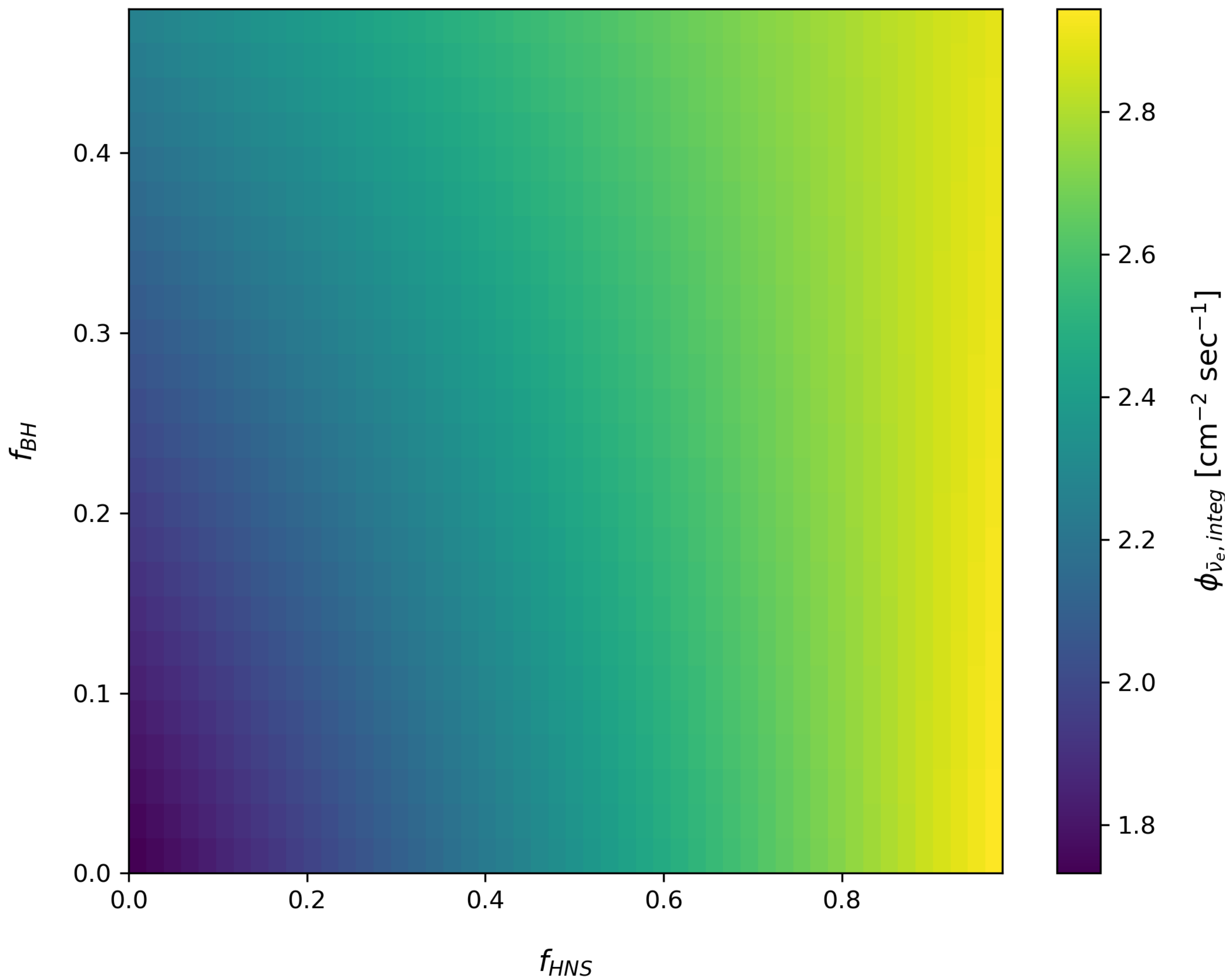


canonical-mass NS, high-mass NS, BH

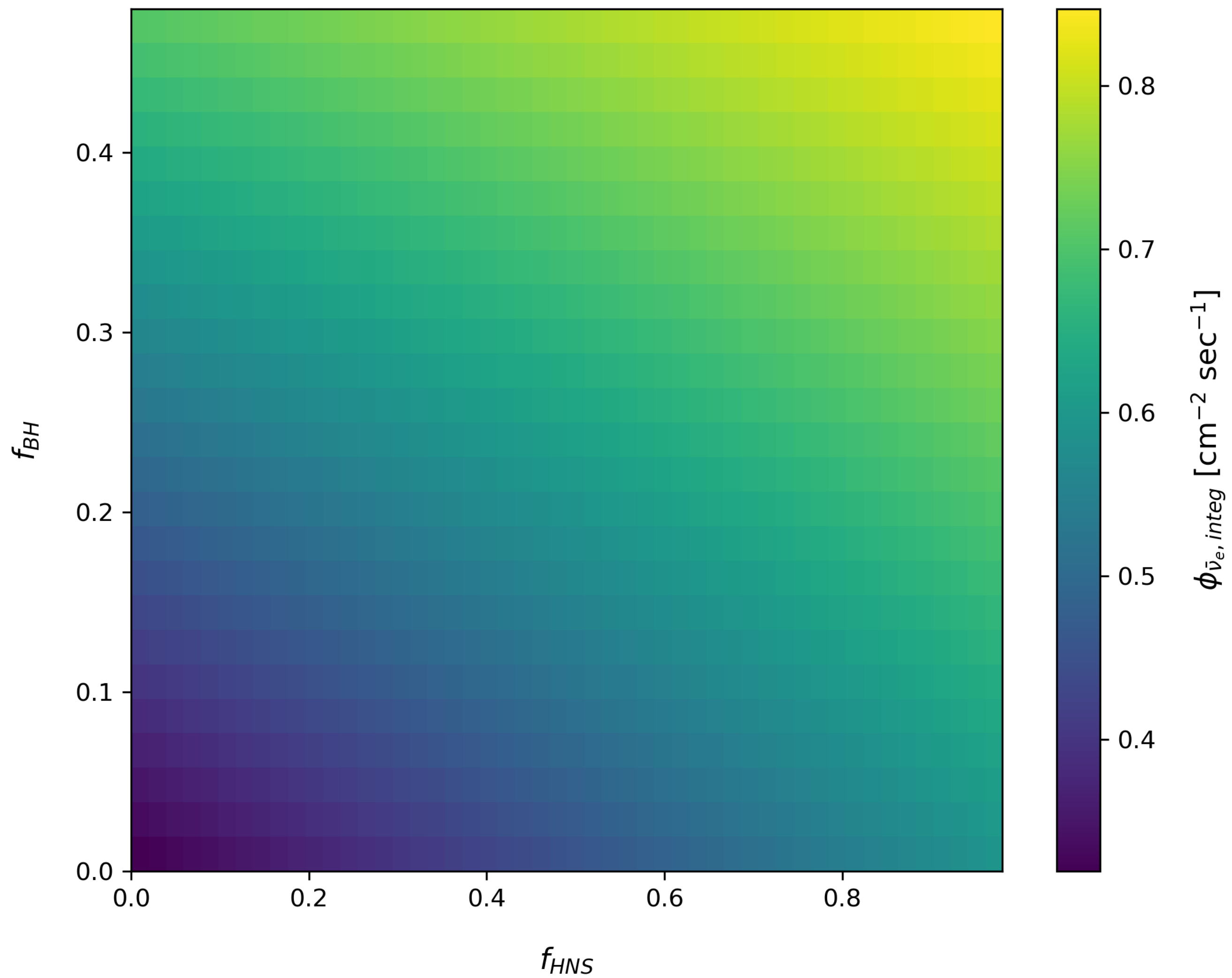


Integrated Flux for {$f_{\rm HNS}$, $f_{\rm BH}$}

13.3 < E_ν < 21.3 MeV



21.3 < E_ν < 31.3 MeV



mass hierarchy: normal, EOS: Togashi, minimal mass: 6$M_{\rm sun}$

Setup for Sensitivity Study

- **Extrapolated from SK-IV** about backgrounds, their systematics, and analysis efficiency.

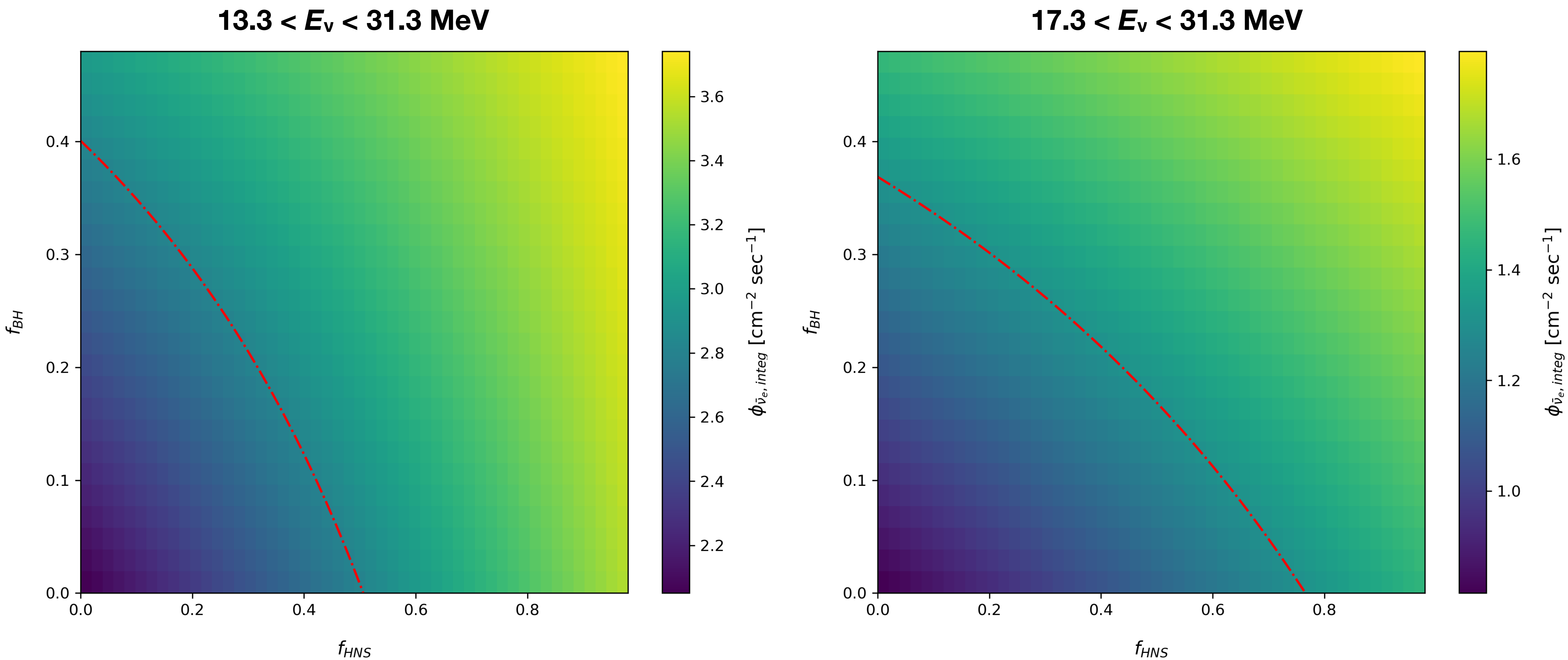
- SK-IV
  - 20~30% ntag efficiency
  - Systematics (CC: ~20%, NC: 60~80%)

- SK-Gd
  - Much less accidental background (×1/10)
  - Higher ntag efficiency (70% assumed)
  - Smaller atmospheric neutrino systematics (CC: ~15%, NC: 40~60%)

- Hyper-K
  - Much larger fiducial mass (×8.4)
  - Same ntag efficiency
  - Smaller atmospheric neutrino systematics (CC: ~5%, NC: 10~20%)

Results (Energy Range)

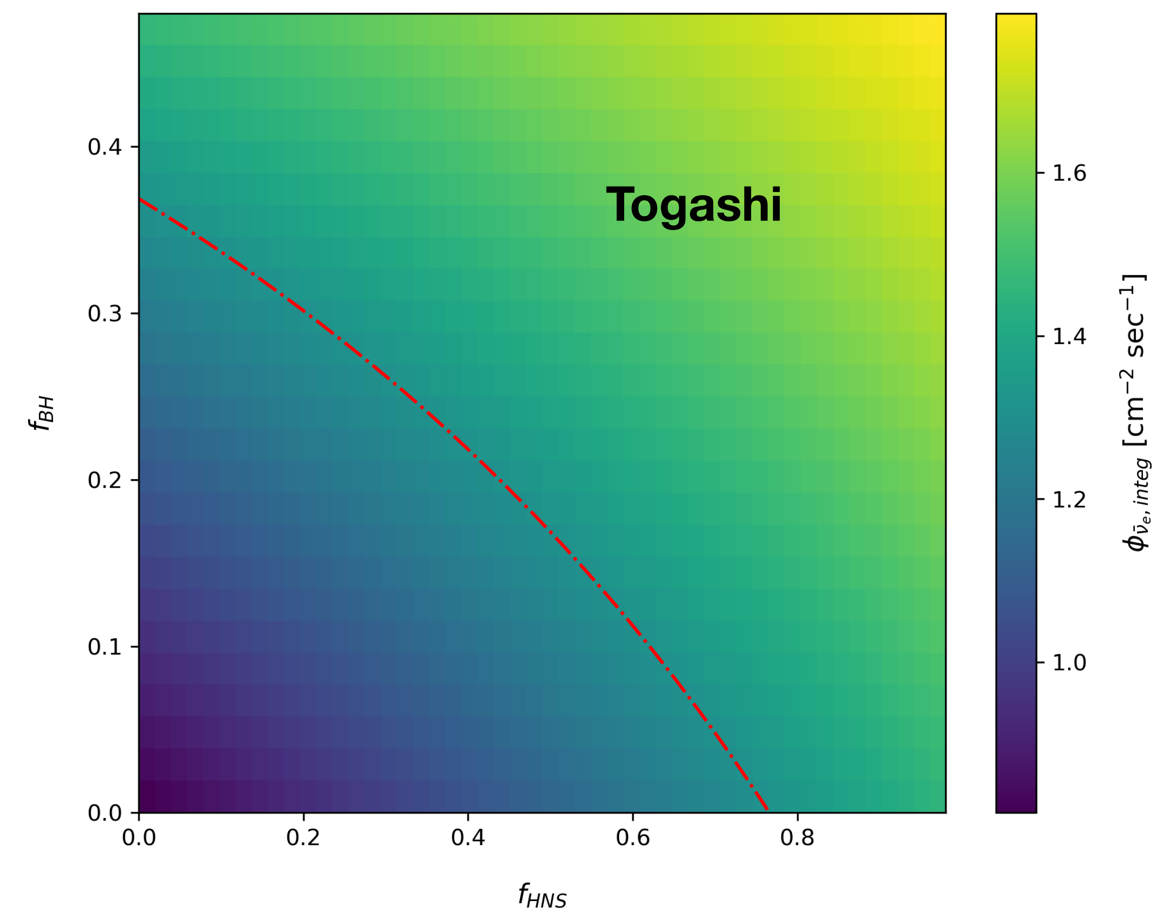
- Different analysis ranges cover different area in a 2D map.
- This would suggest a detailed *spectral shape analysis* along with a deep understanding of background shape.

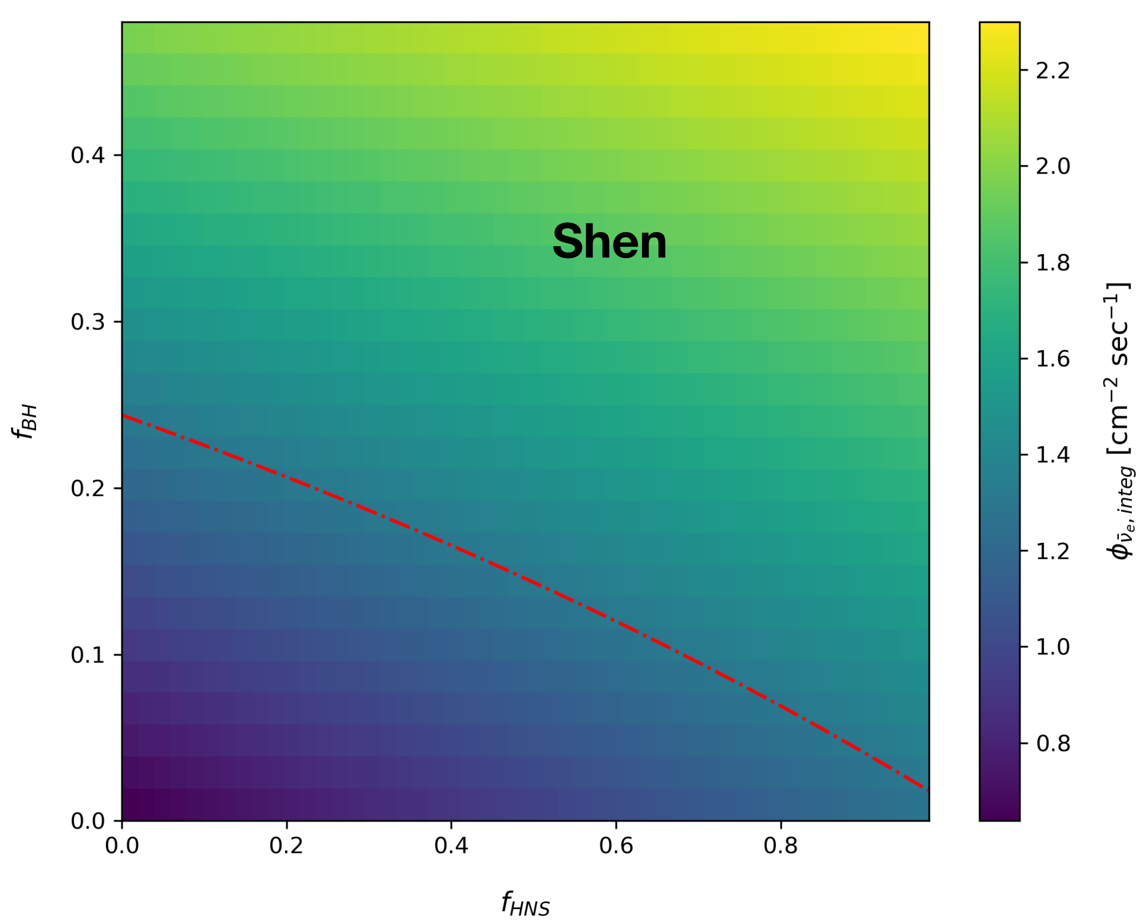


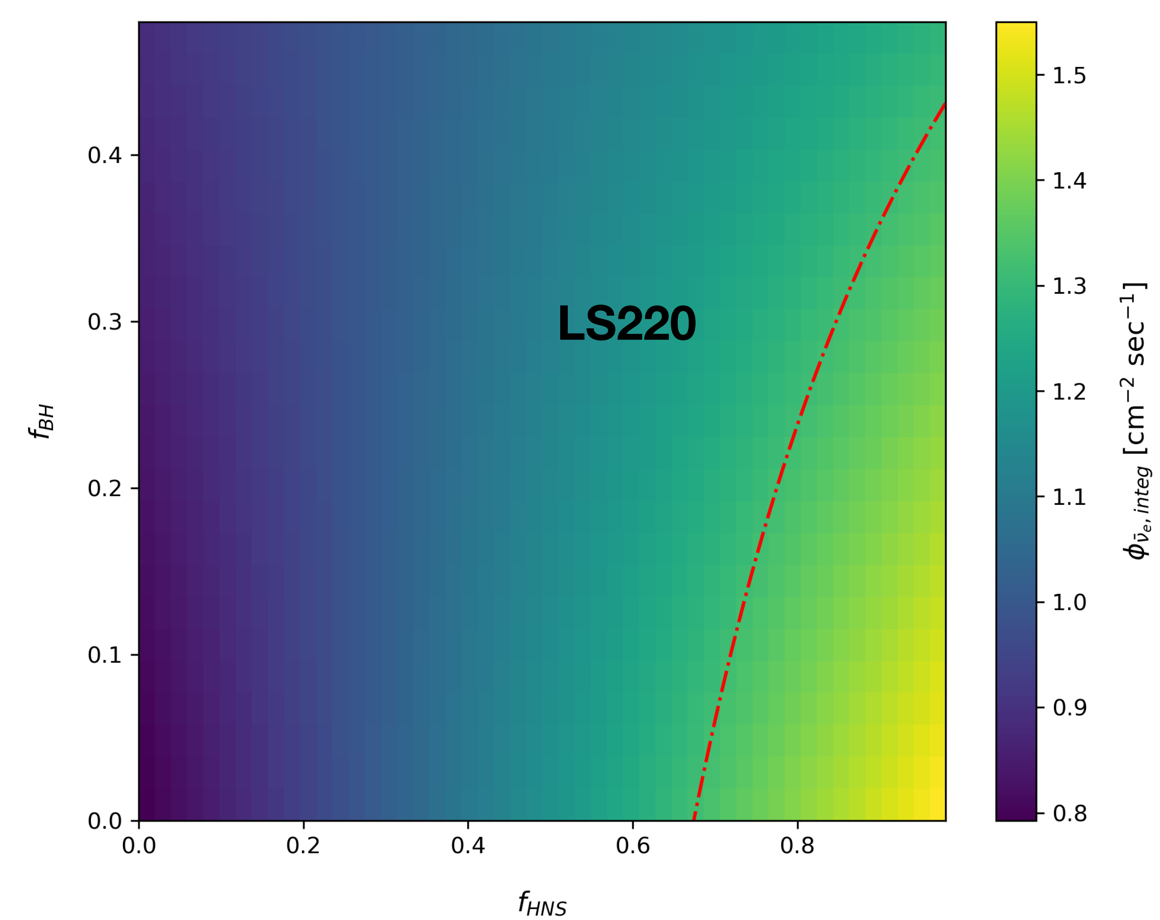
SK-Gd 10yr, 2σ C.L. (NH, Togashi, ≥6M_{sun})

Results (EOS)

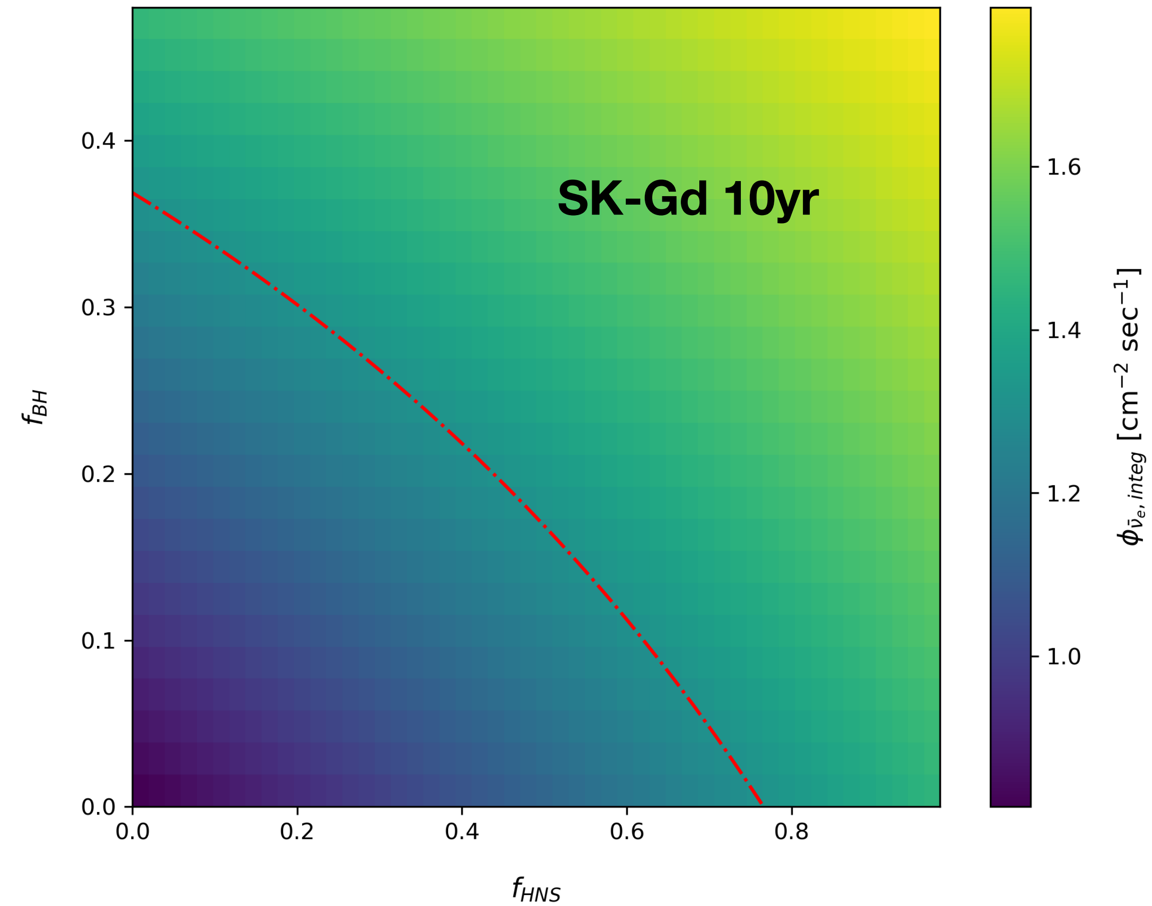
SK-Gd 10yr, 2σ C.L.
(17.3 < E_ν < 31.3 MeV, NH, ≥6M_{sun})





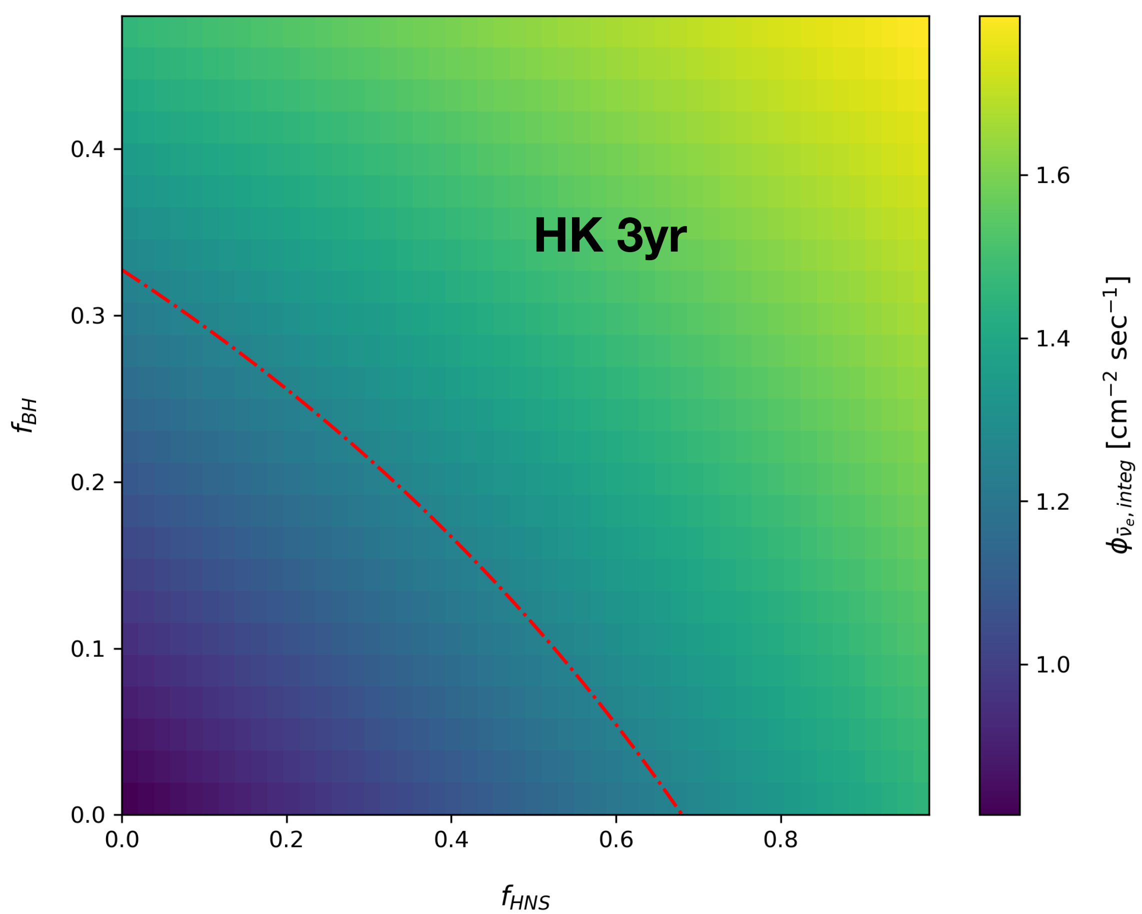


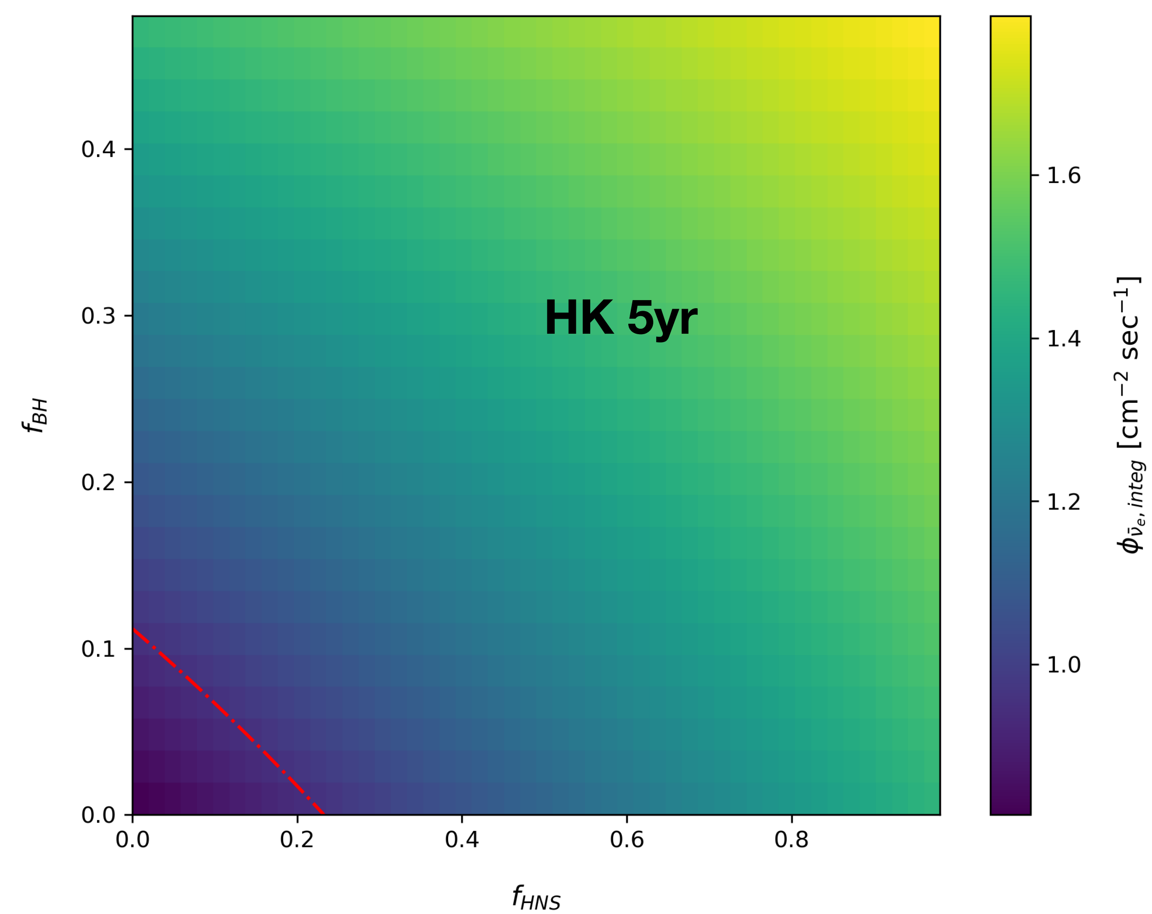
Results (Detector)



2σ C.L.

(17.3 < E_ν < 31.3 MeV, Togashi, NH, ≥6M_{sun})





Summary and Prospects

- SRN flux has footprints of various physics parameters.
- We are investigating the impact of the stellar core collapse fate (HNS, BH).
- Showed preliminary sensitivity results.
  - SK-Gd 10yr ~ HK 3yr
  - Spectral shape analysis seems nice to give a stronger constraint.
  - EOS dependence is strong, therefore inputs from external researches are important.

- Study background impacts depending on energy range.
- Plan to write a paper about this study.

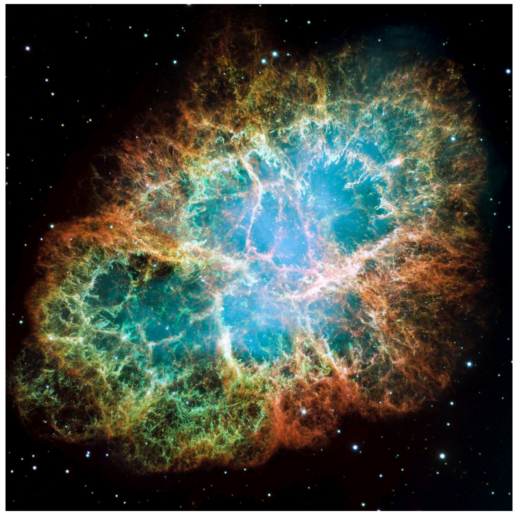
Backup Slides

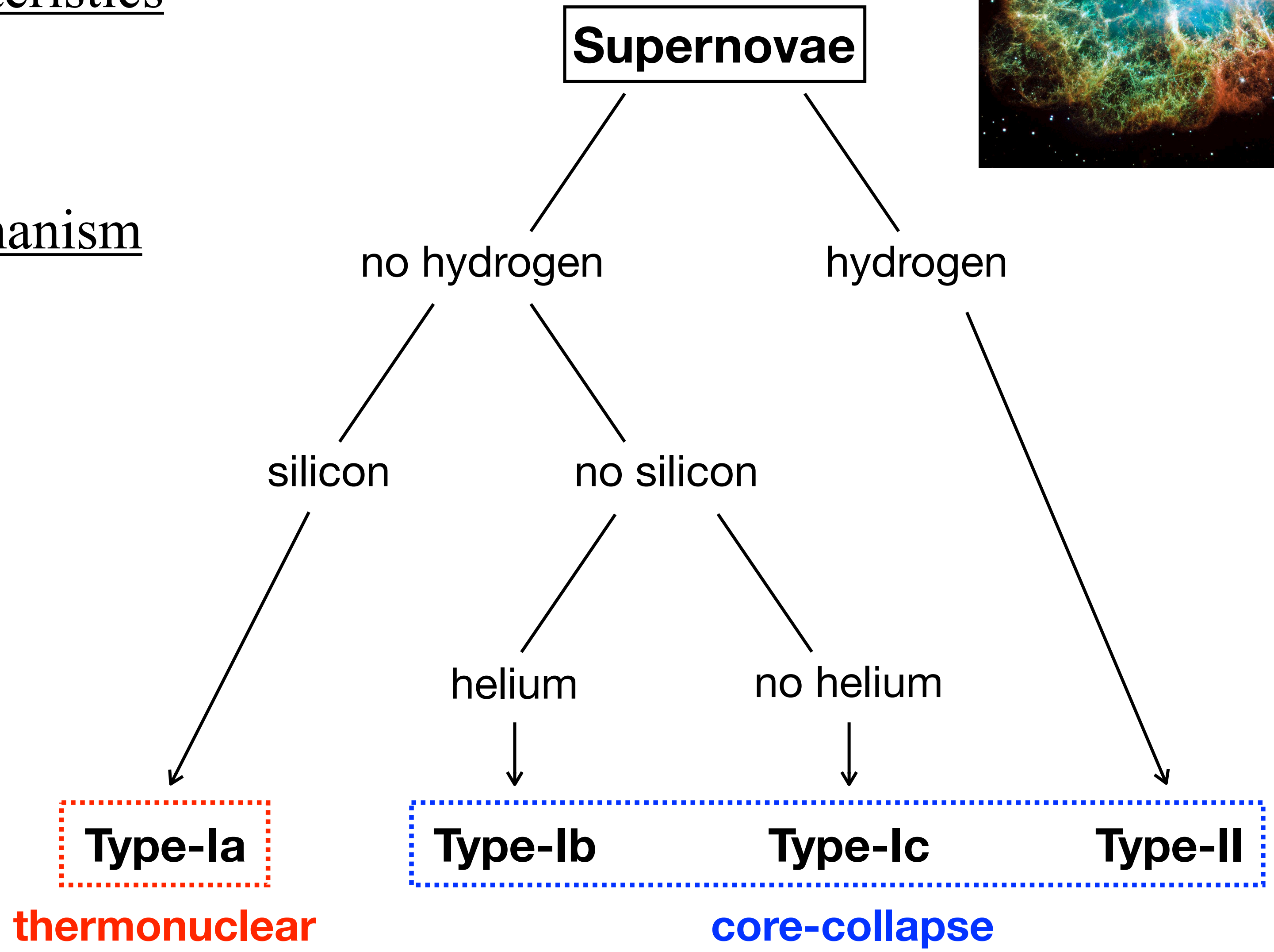
Supernova Explosion

- 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**

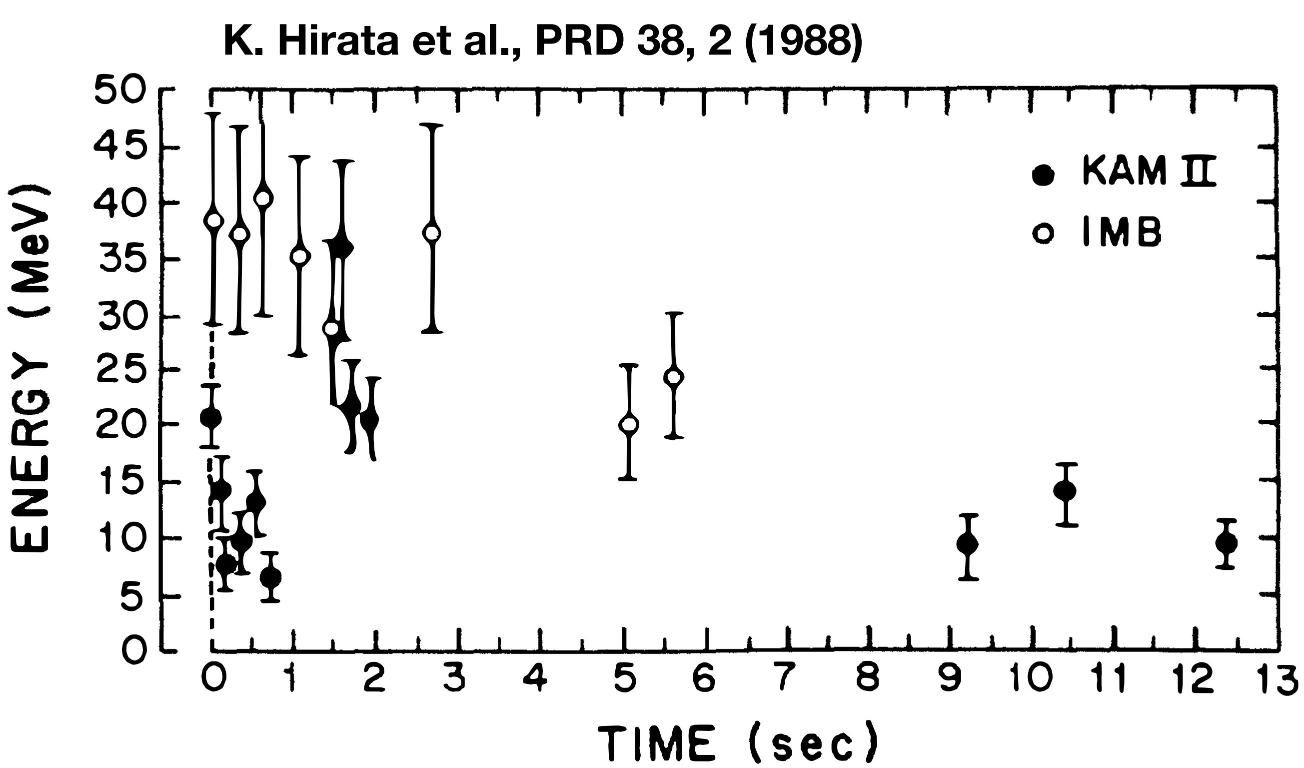
Crab Nebula by NASA

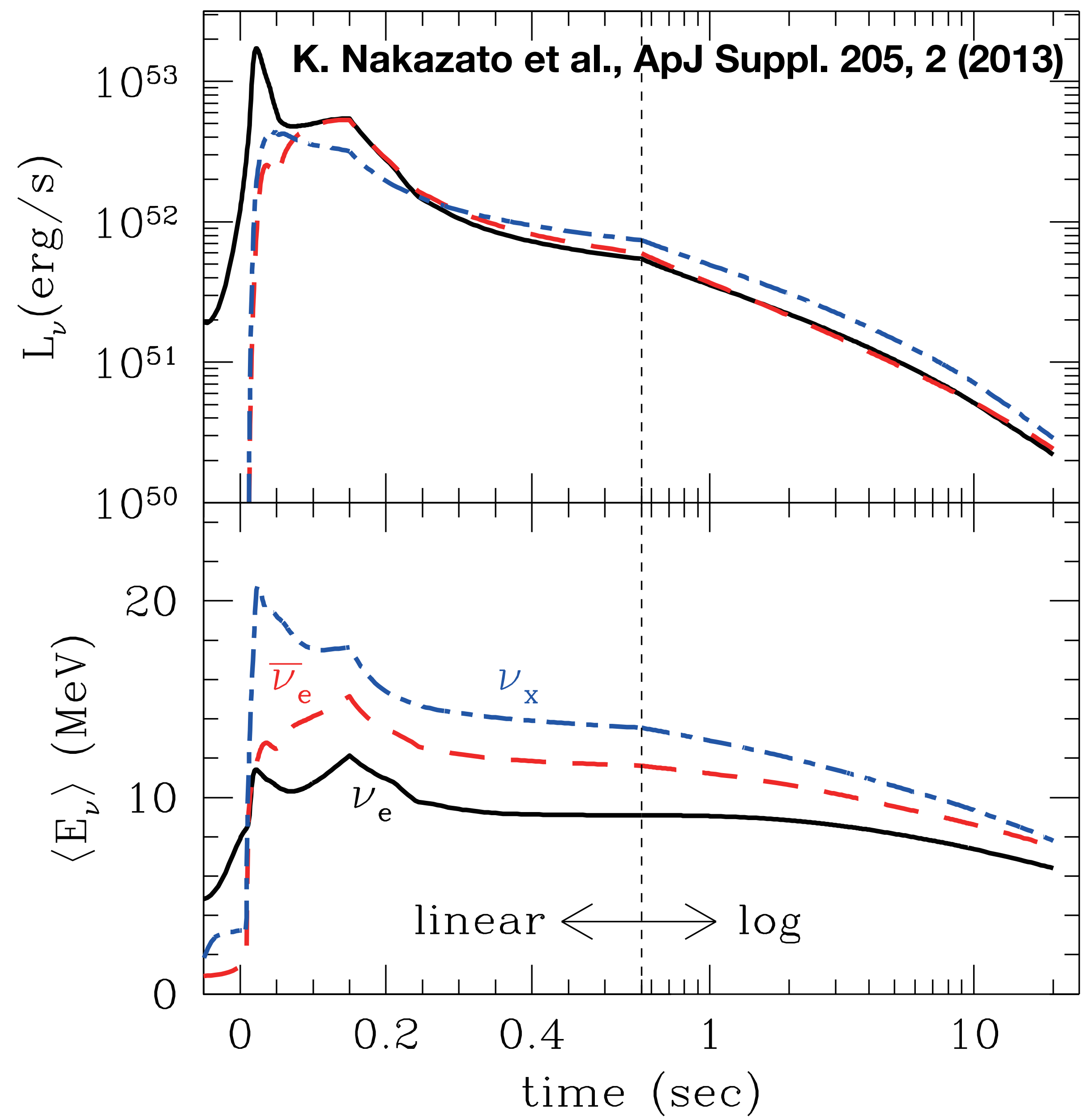




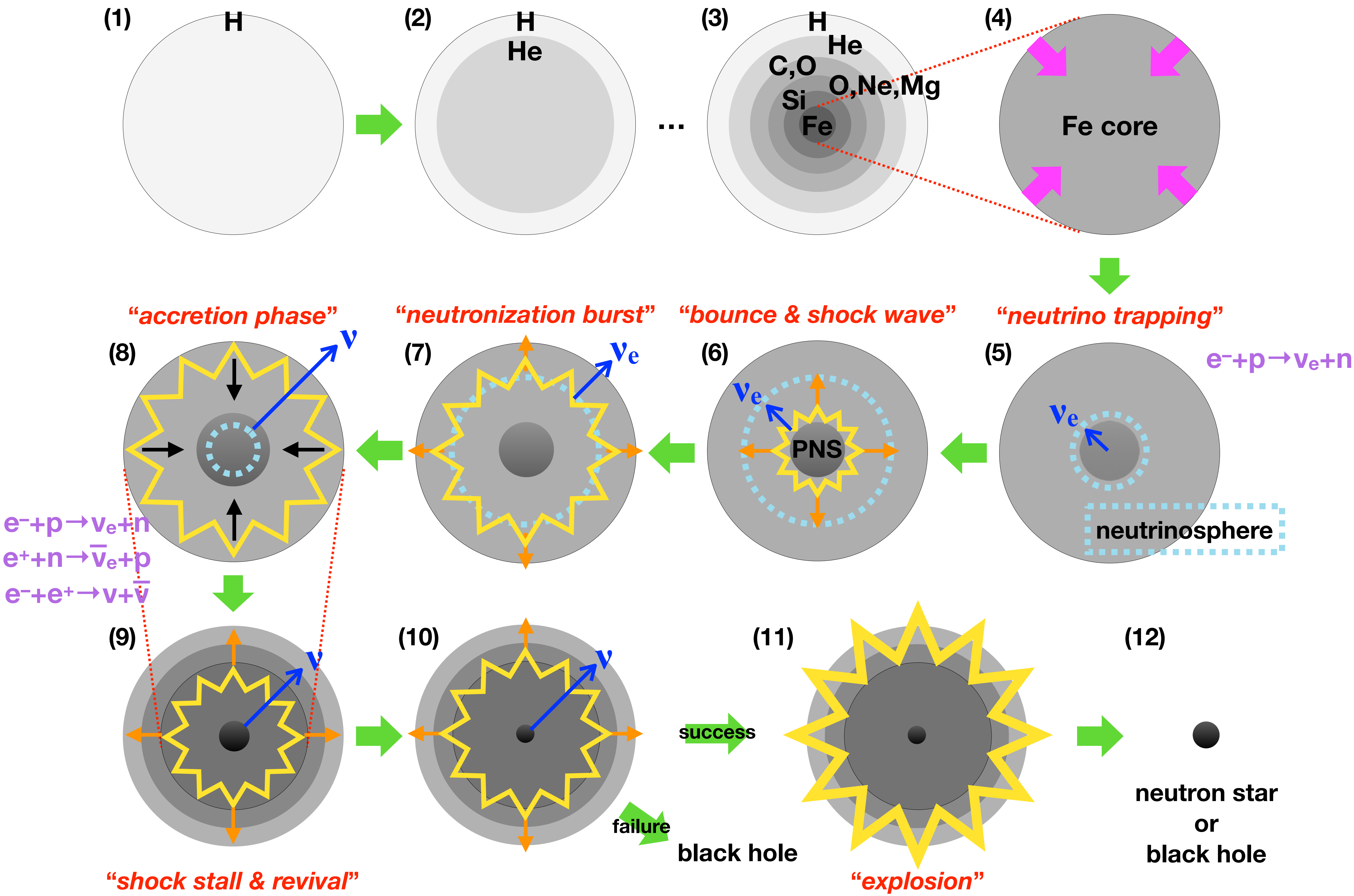
Neutrinos from Core-Collapse Supernovae

- ***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.





Neutrino Heating Scenario



CSFRD

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

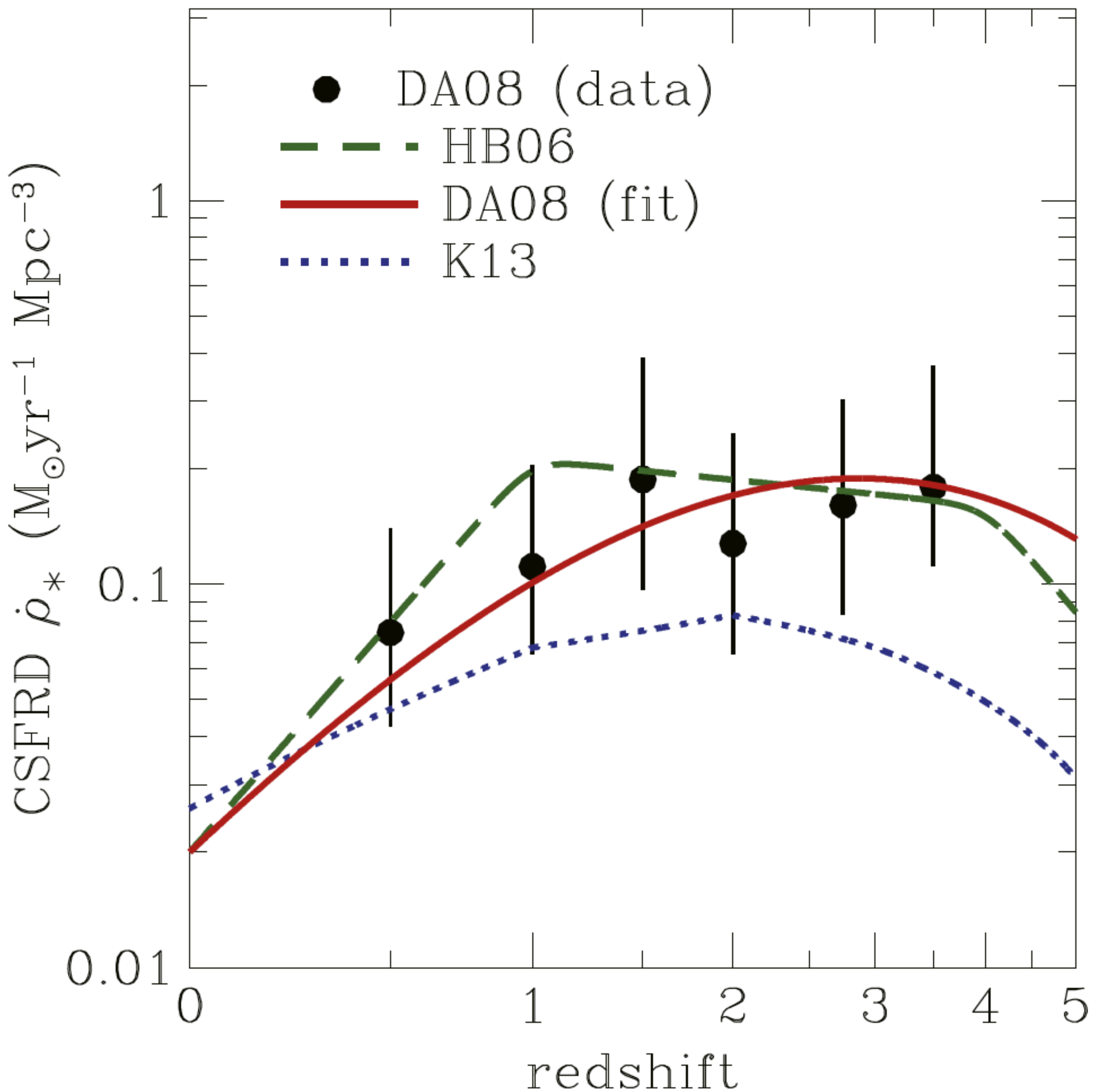


Figure 2. CSFRD as a function of redshift. Dashed, solid and dotted lines correspond to the models in HB06, DA08 and K13, respectively. Plots are calculated from the data in Tables 1 and 2 in DA08.

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

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

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**

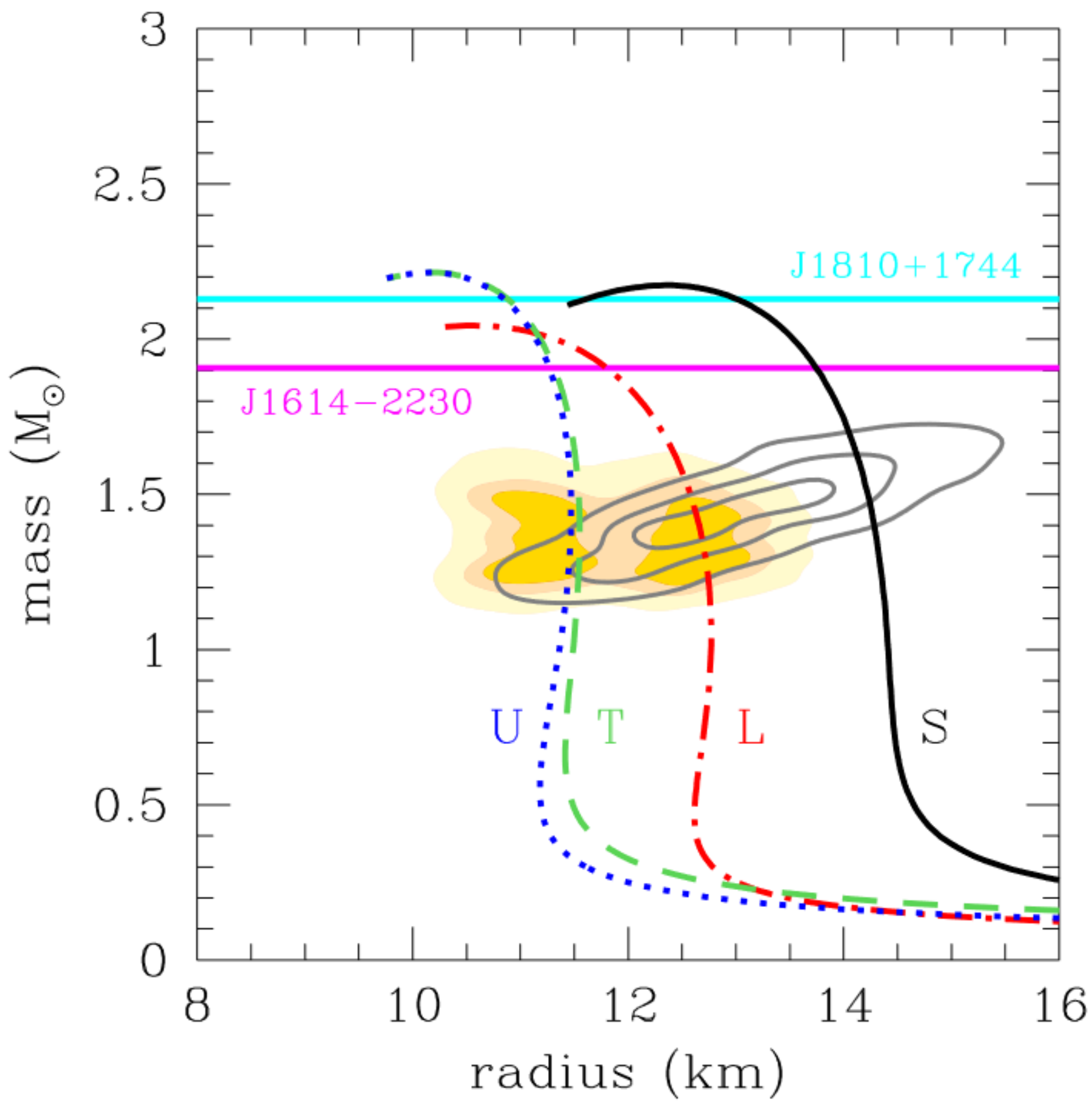
➡ $\frac{dN_{\bar{\nu}_e}}{dE_\nu} \sim \frac{dN^0_{\bar{\nu}_x}}{dE_\nu}.$ **Inverted Hierarchy**

EOS and Neutrino Emission

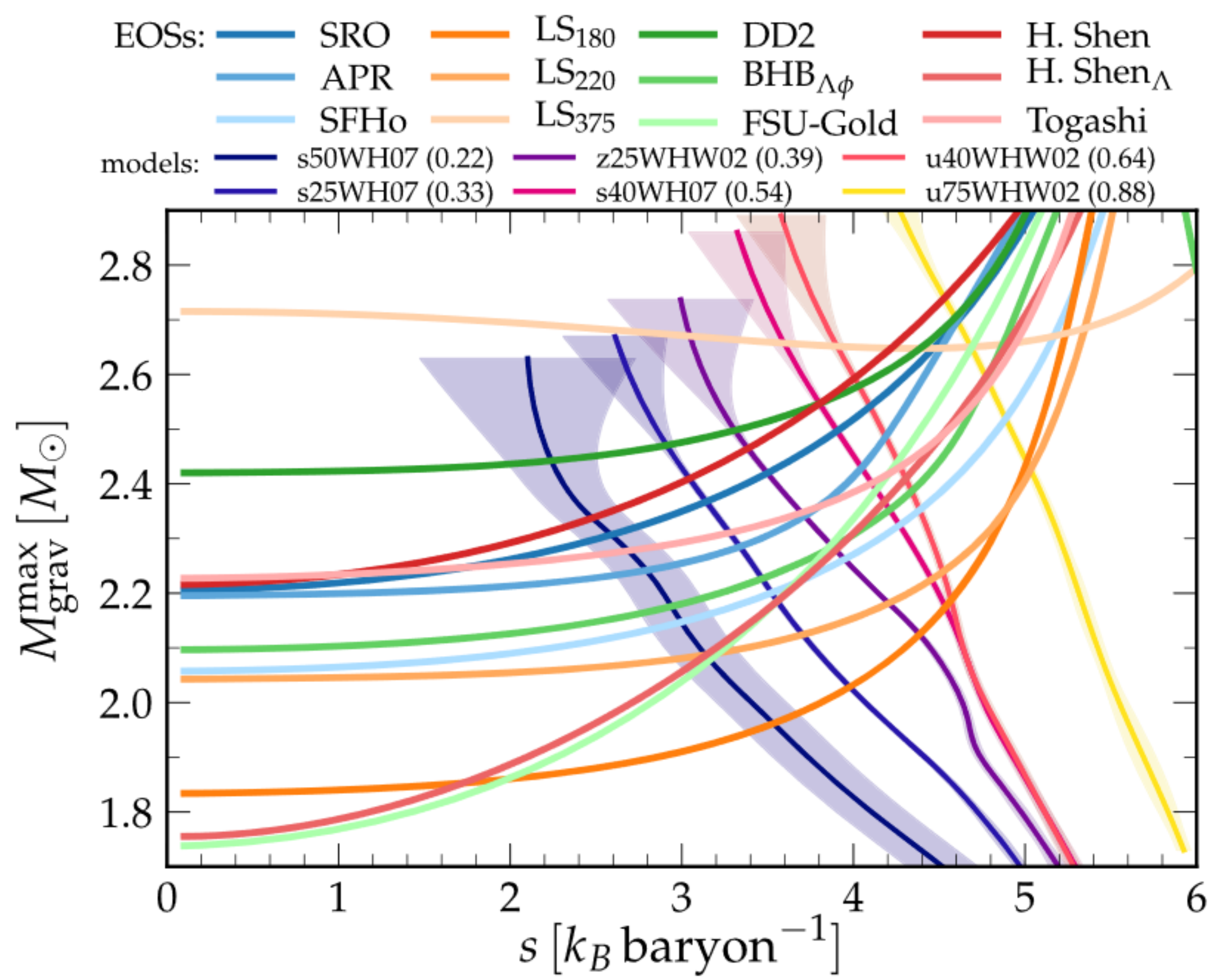
- In case of NS, neutrino emission amount depends on proto-NS radius.
- In case of BH formation, neutrino emission amount depends on maximal mass of proto-NS.

neutrinos from proto-NS

more ⟷ less



neutrinos from BH formation



Redshift Dependence

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

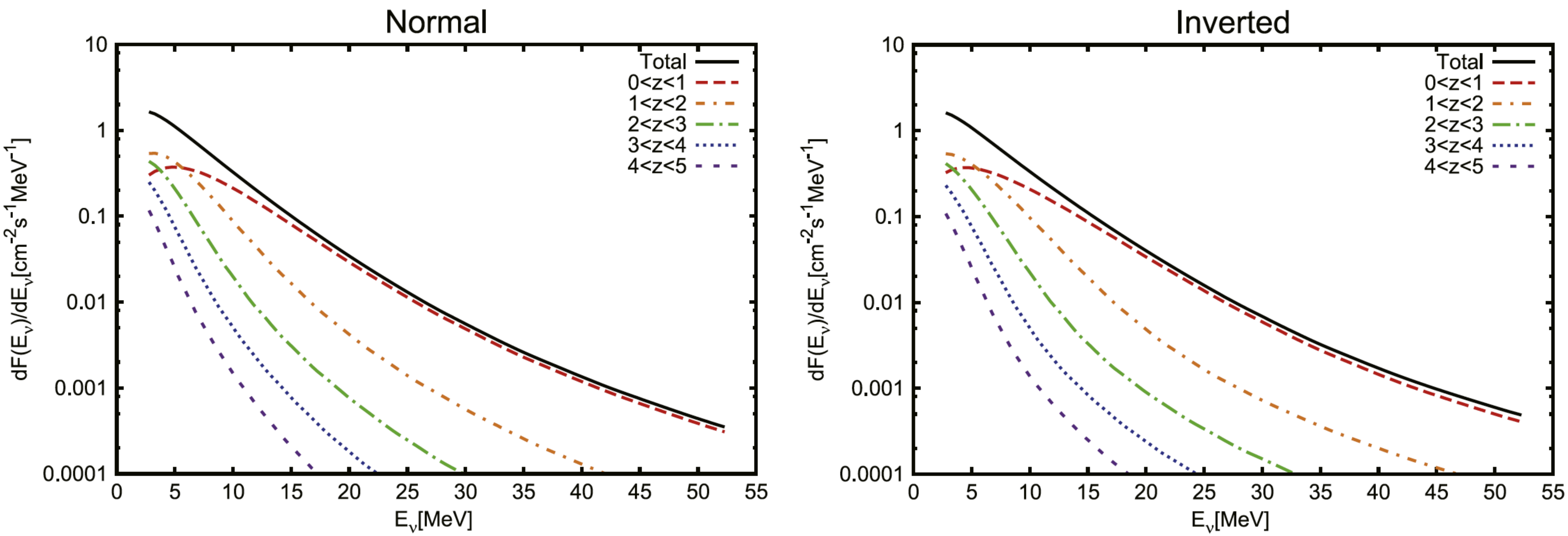
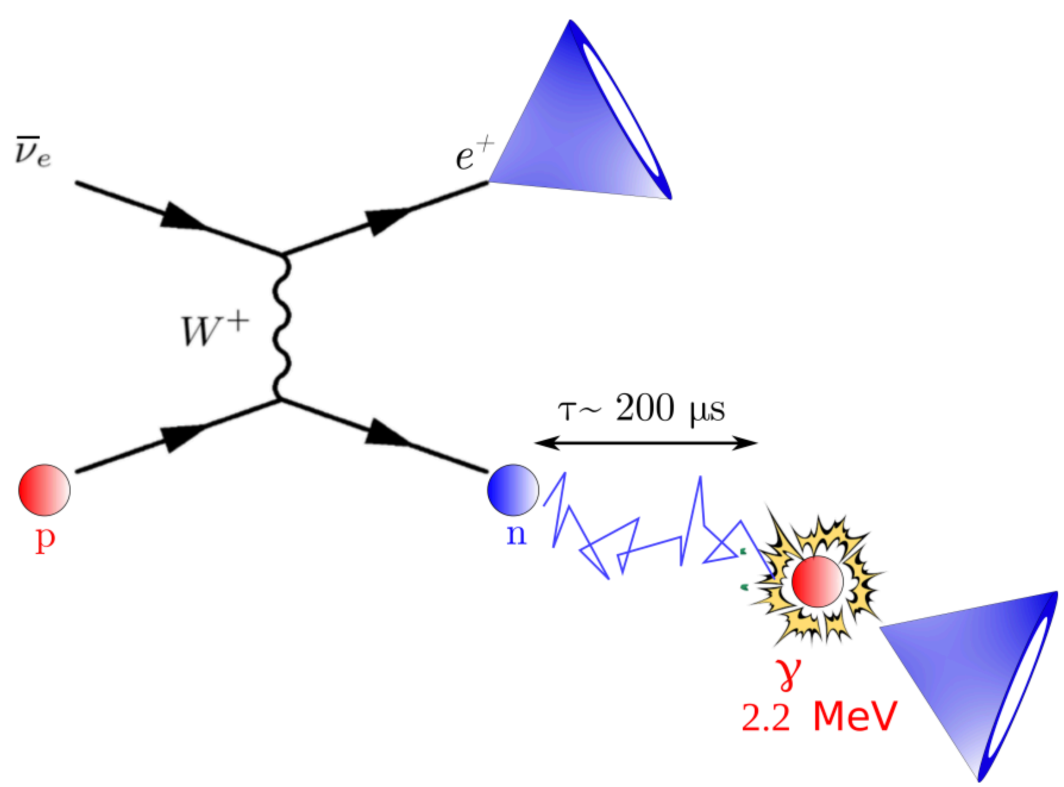
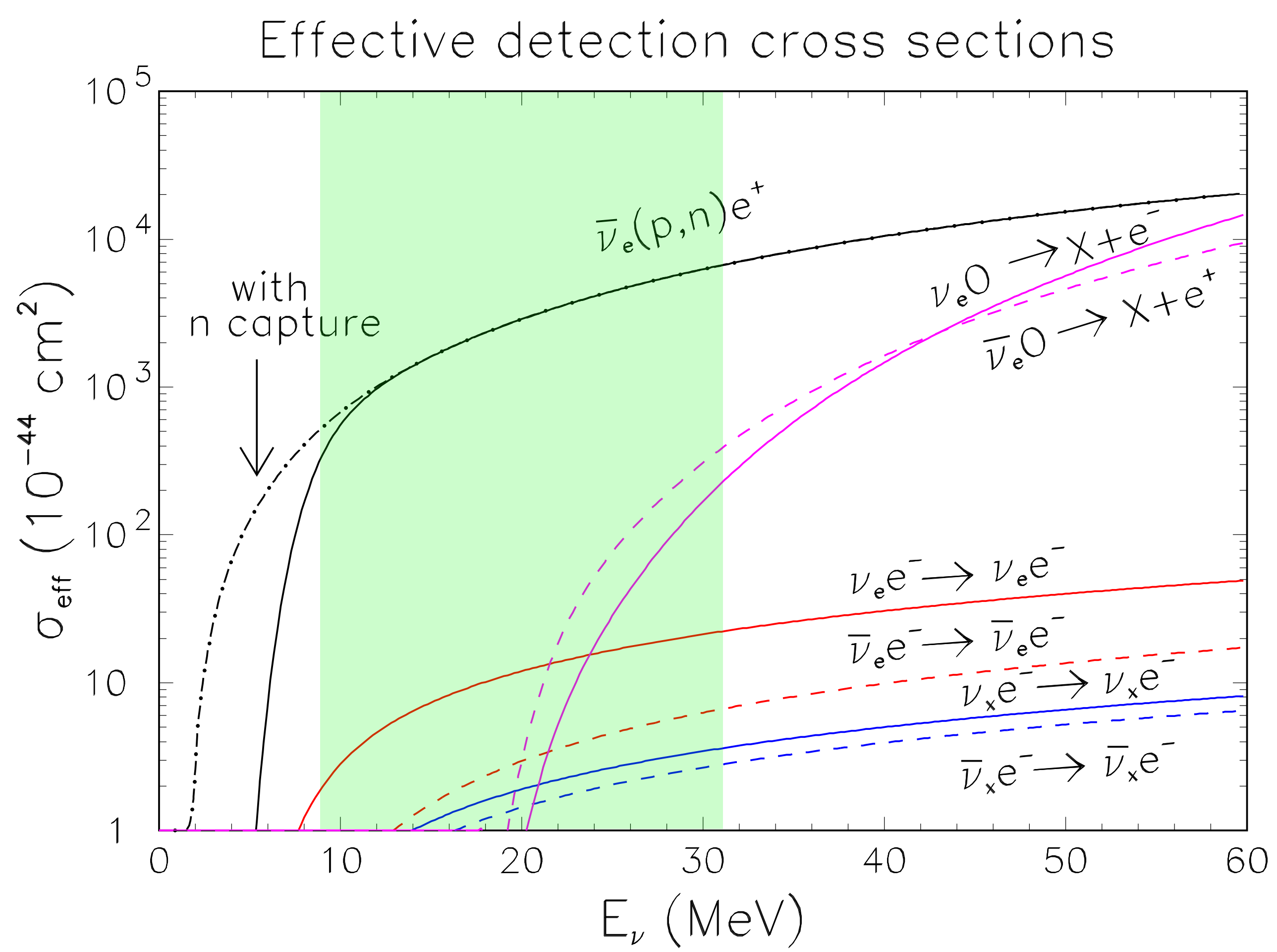


Figure 10. Total fluxes of SRNs (solid) and contributions from various redshift ranges for the reference model. The lines except for the solid line correspond, from top to bottom, to the redshift ranges $0 < z < 1$, $1 < z < 2$, $2 < z < 3$, $3 < z < 4$, and $4 < z < 5$, for $E_\nu > 10$ MeV. The left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

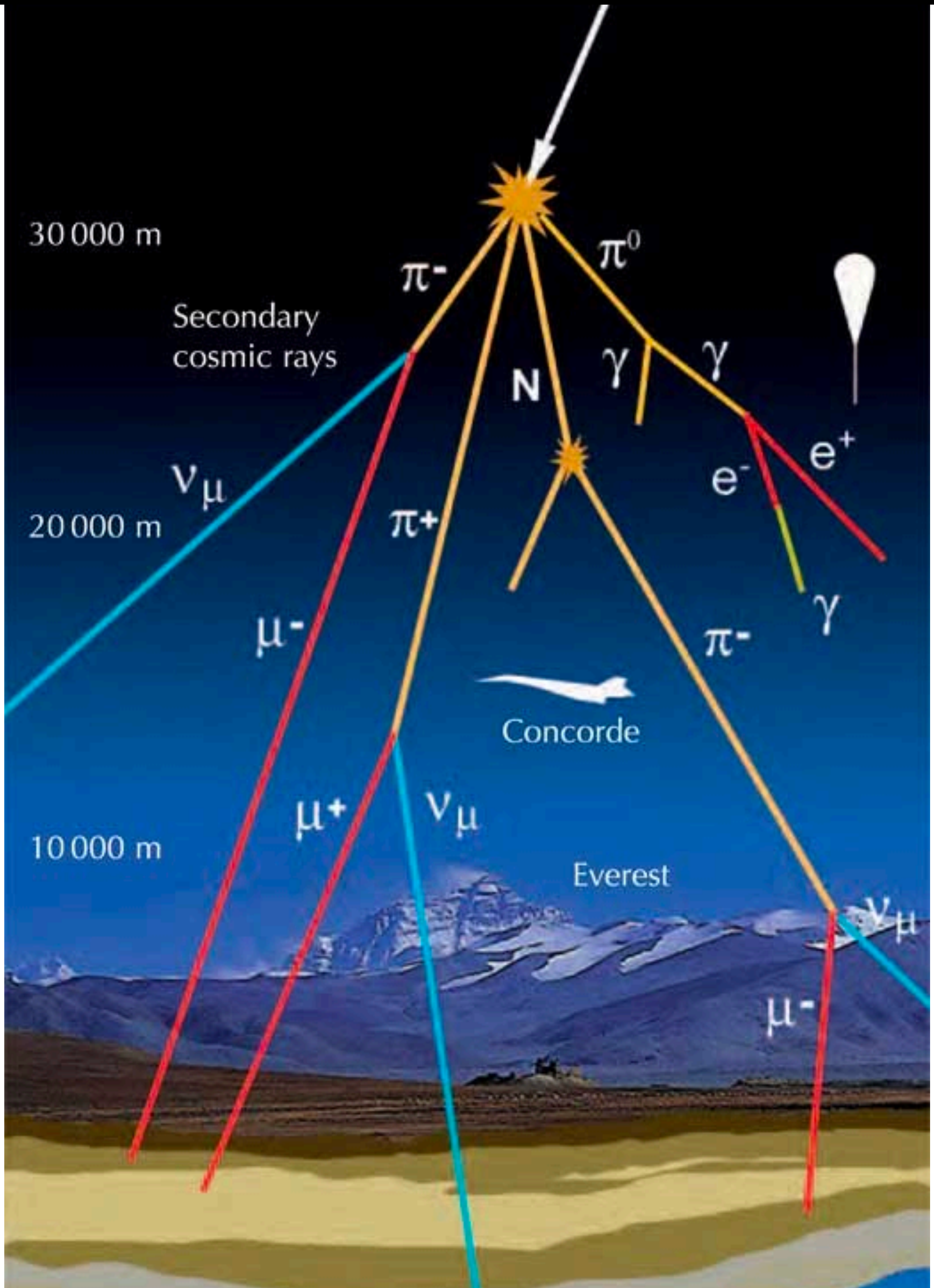
Detection Signal

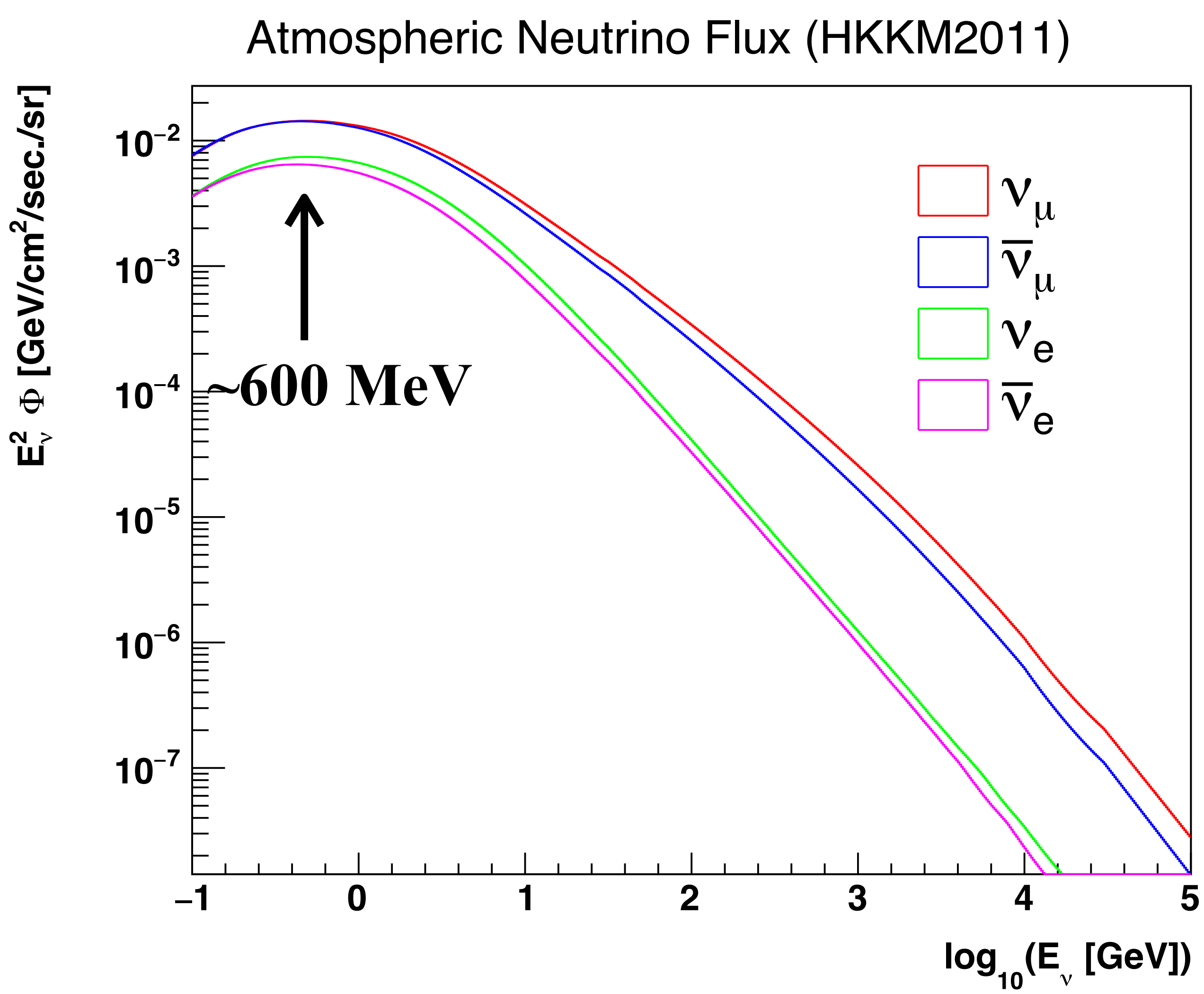
- Inverse beta decay of electron antineutrinos ($\bar{\nu}_e + p \rightarrow e^+ + n$) is searched.
  - Larger than the other mode by >2 orders of magnitude.
  - Search region = [7.5, 29.5] MeV in visible energy (E_ν = [9.3, 31.3] MeV)
- Signal: "β+n" events
  - Prompt signal = β
  - Delayed signal = **2.2 MeV γ** from neutron capture





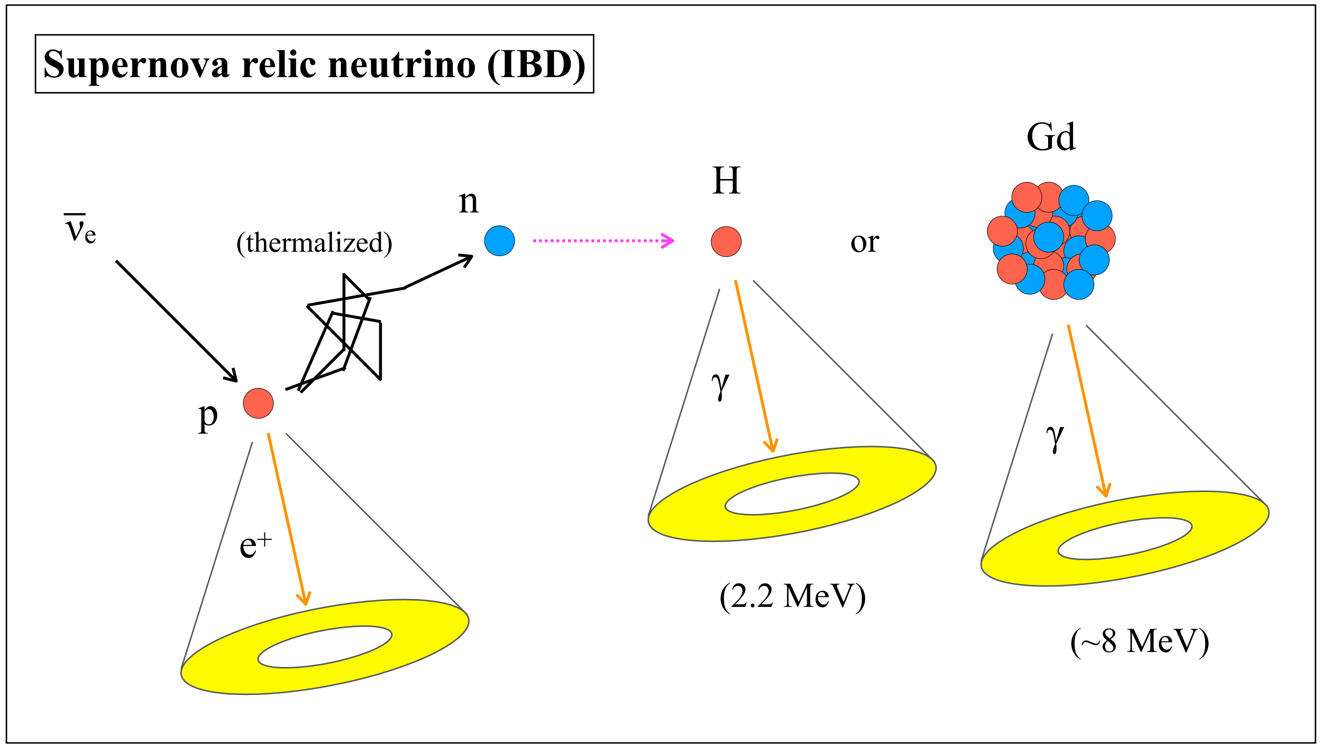
Background (1): Atmospheric Neutrinos

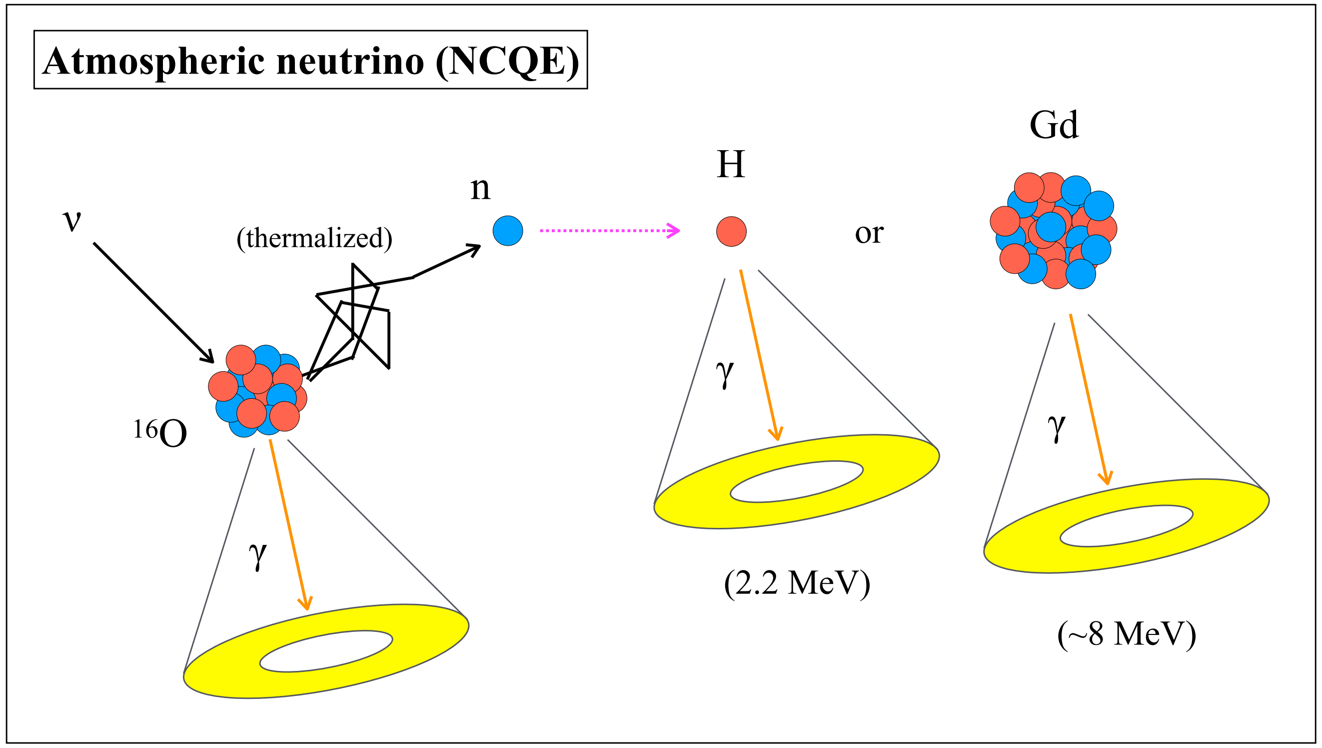




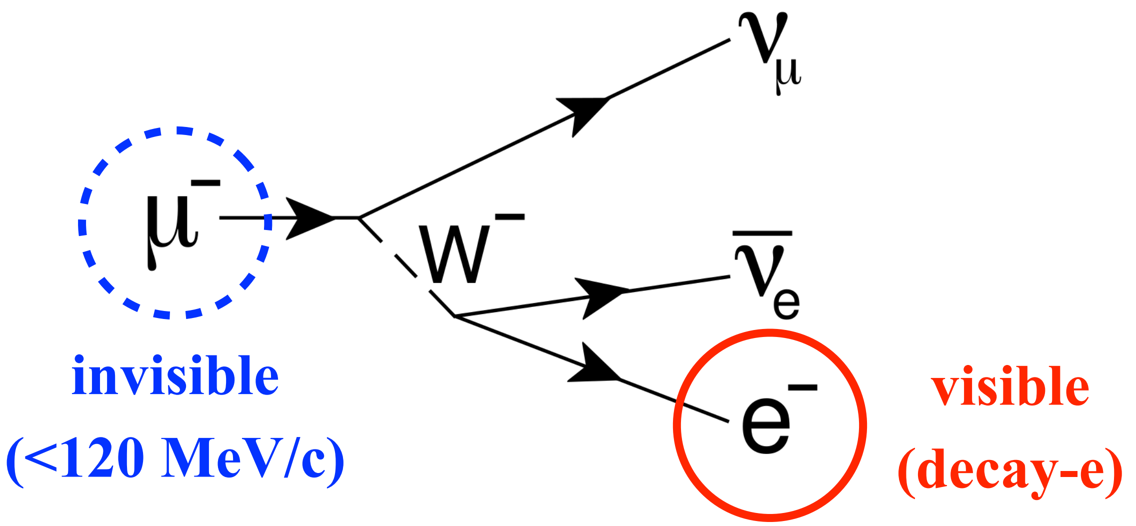
Background (1): Atmospheric Neutrinos

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



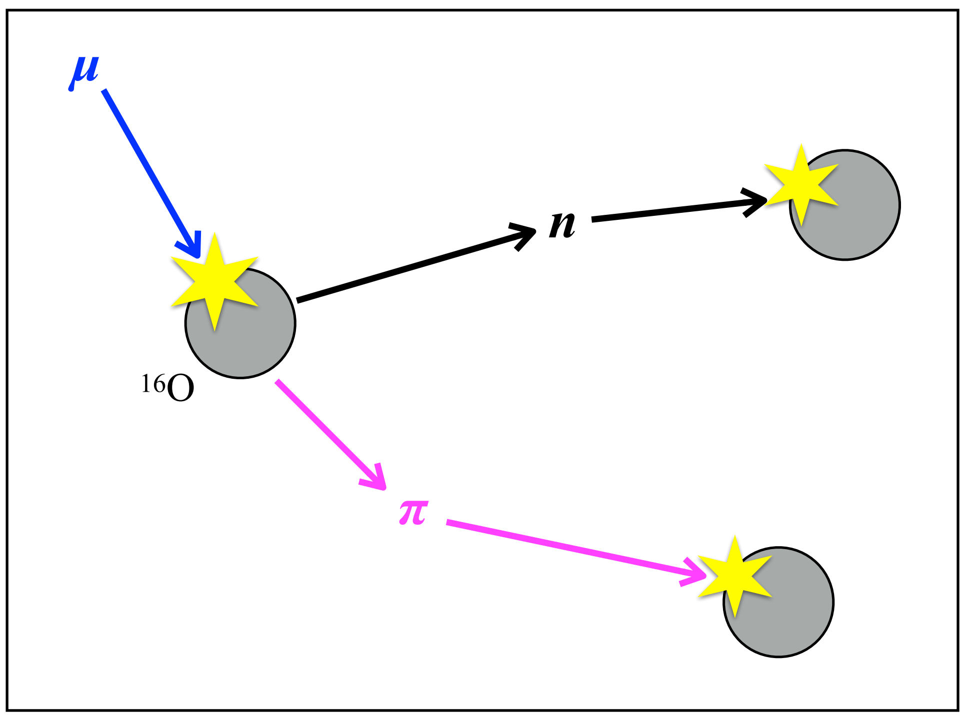


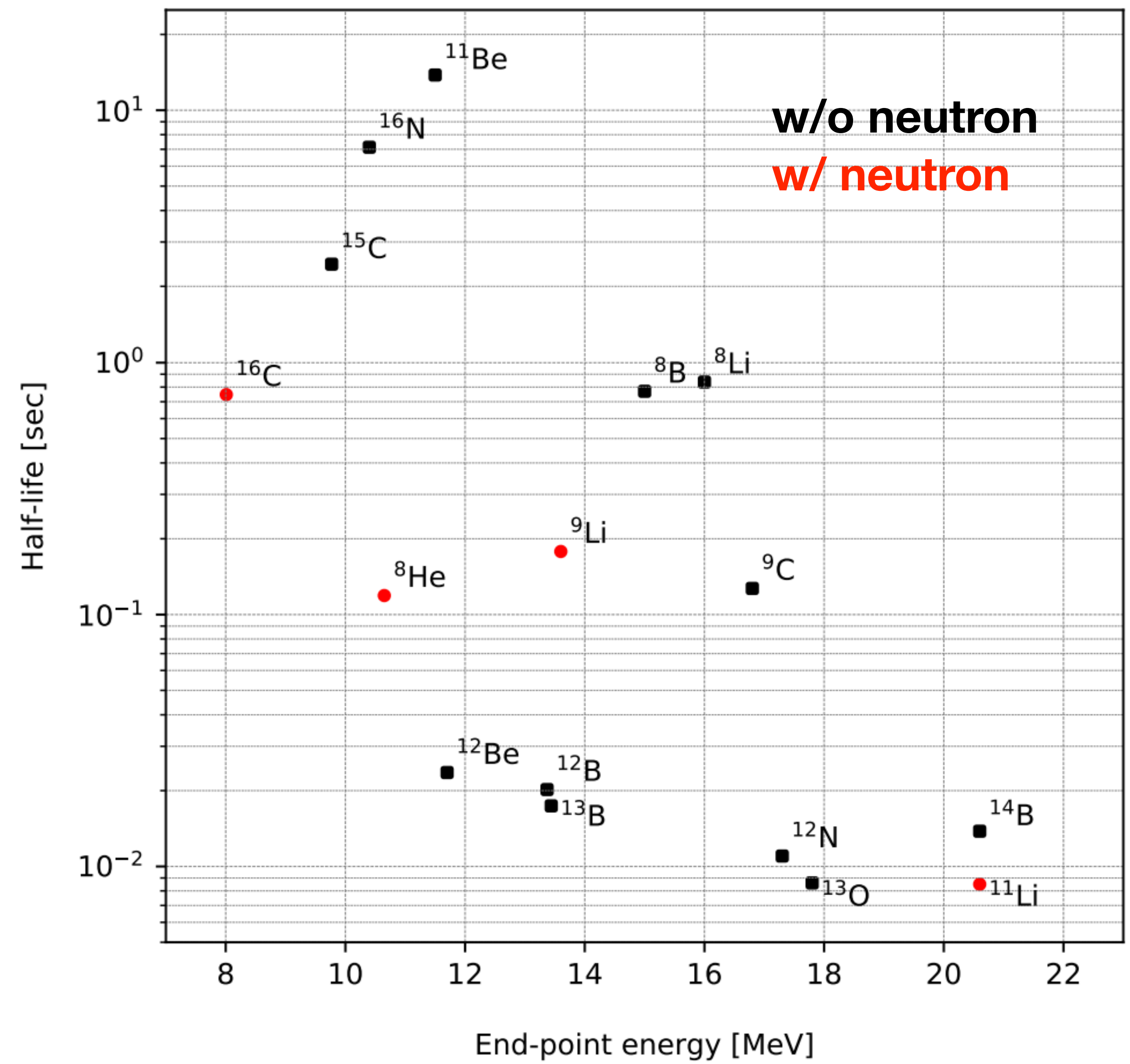
- **Muon-producing interactions (CC, NC)**
  - (invisible muon →) decay electron (+*n*)
  - dominant above ~20 MeV



Background (2): Muon Spallation

- Cosmic-ray muons are coming at Super-K with ~2 Hz.
- Some of them break nuclei in water, producing radioactive isotopes.
- This is huge below 20 MeV, and especially ^{9}Li decays into β+n.

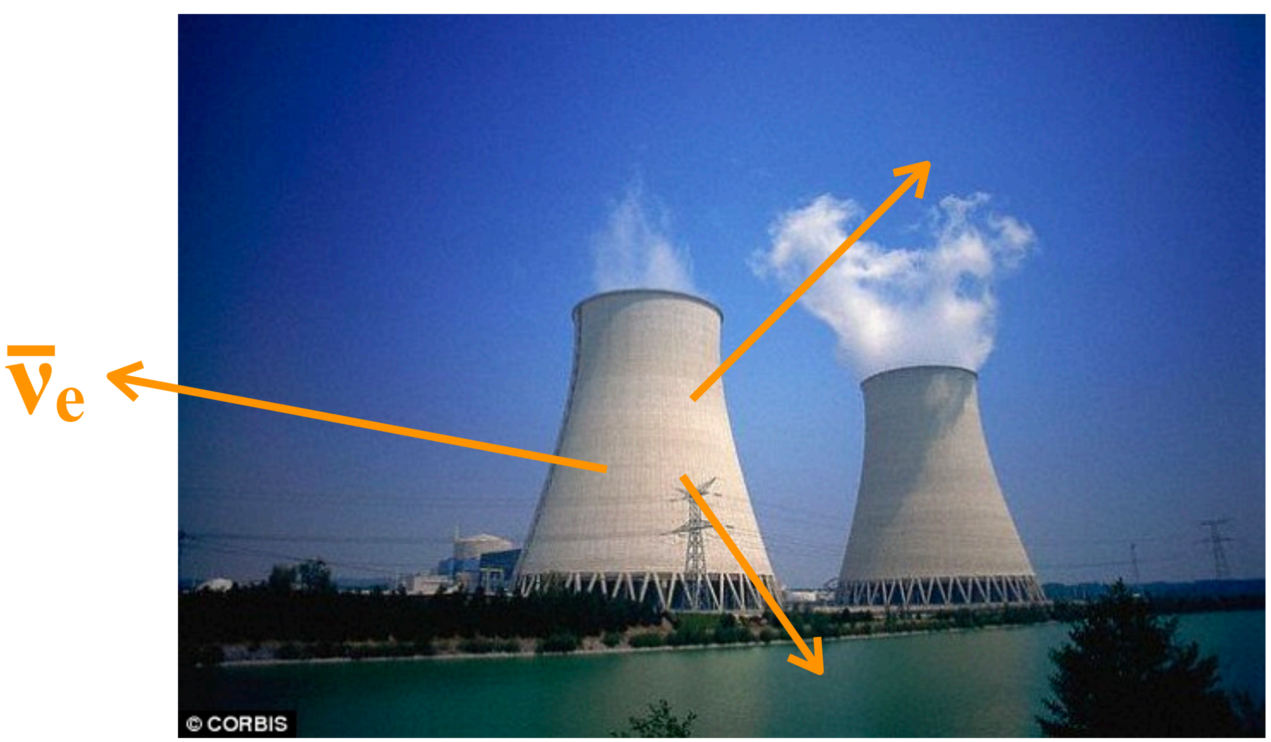


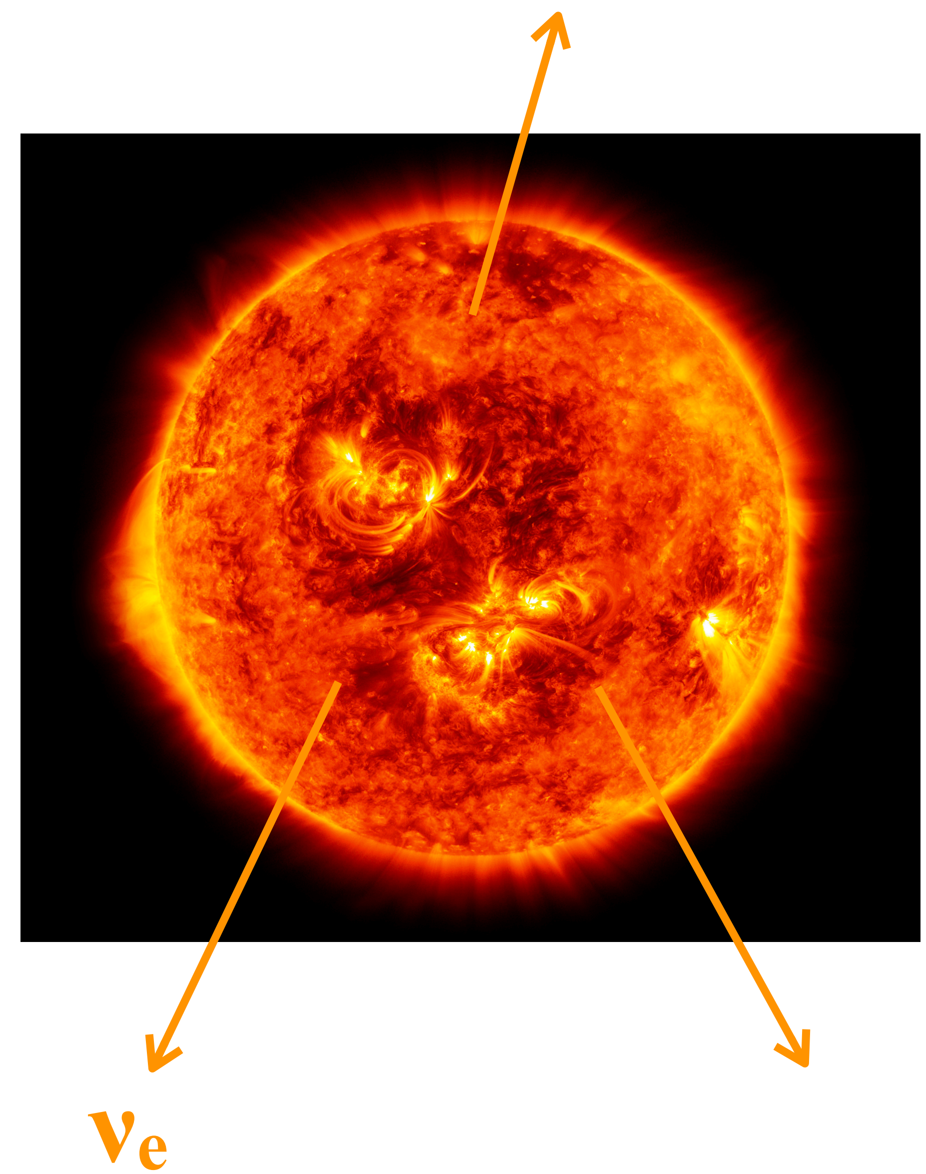


Background (3): Other Sources

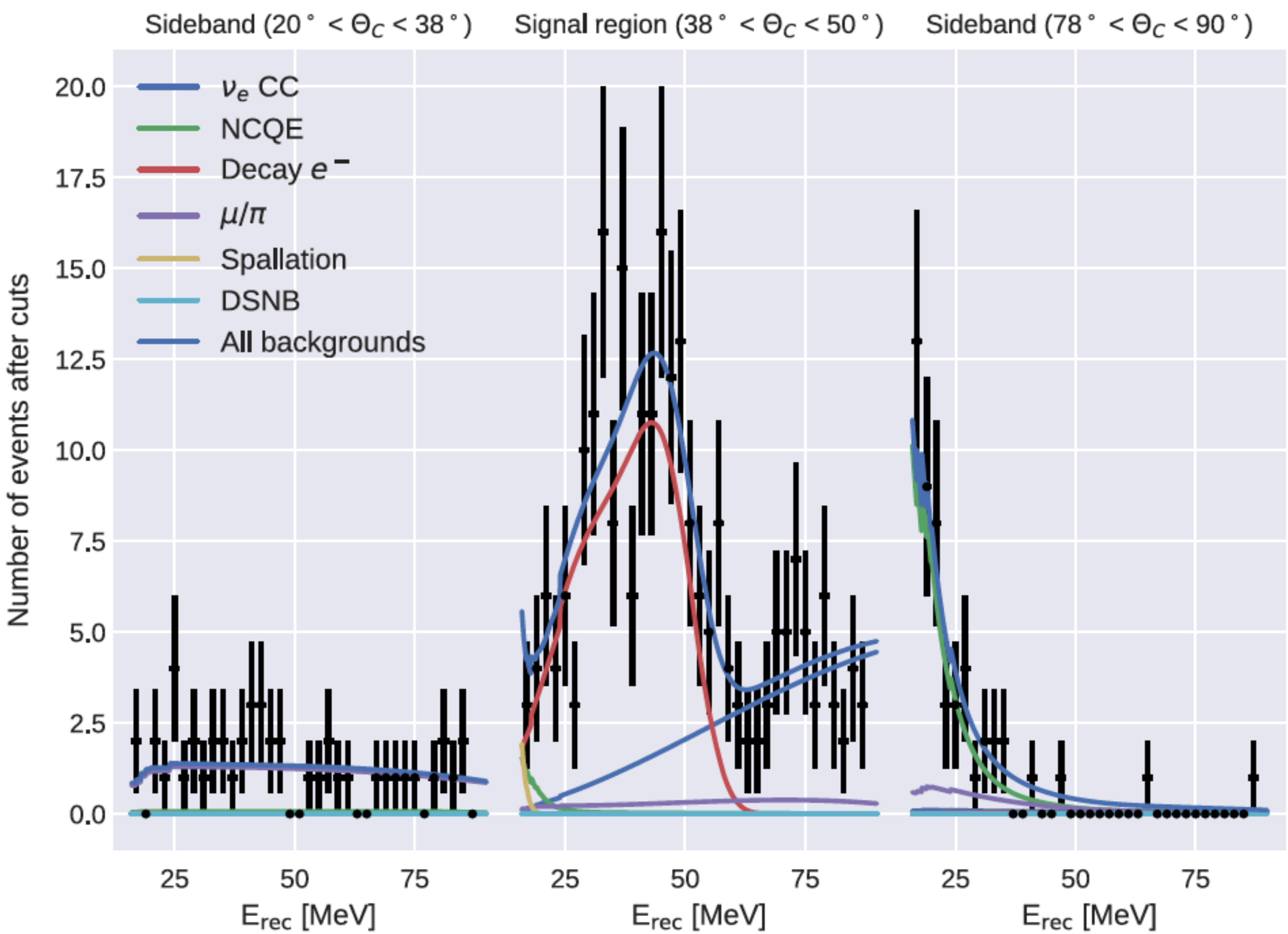
- **Solar neutrinos**
  - Electron neutrinos from Sun.
  - Would make an accidental pair with a neutron-like signal.

- **Reactor neutrinos**
  - Electron antineutrinos from reactor plants
  - Only below 10 MeV



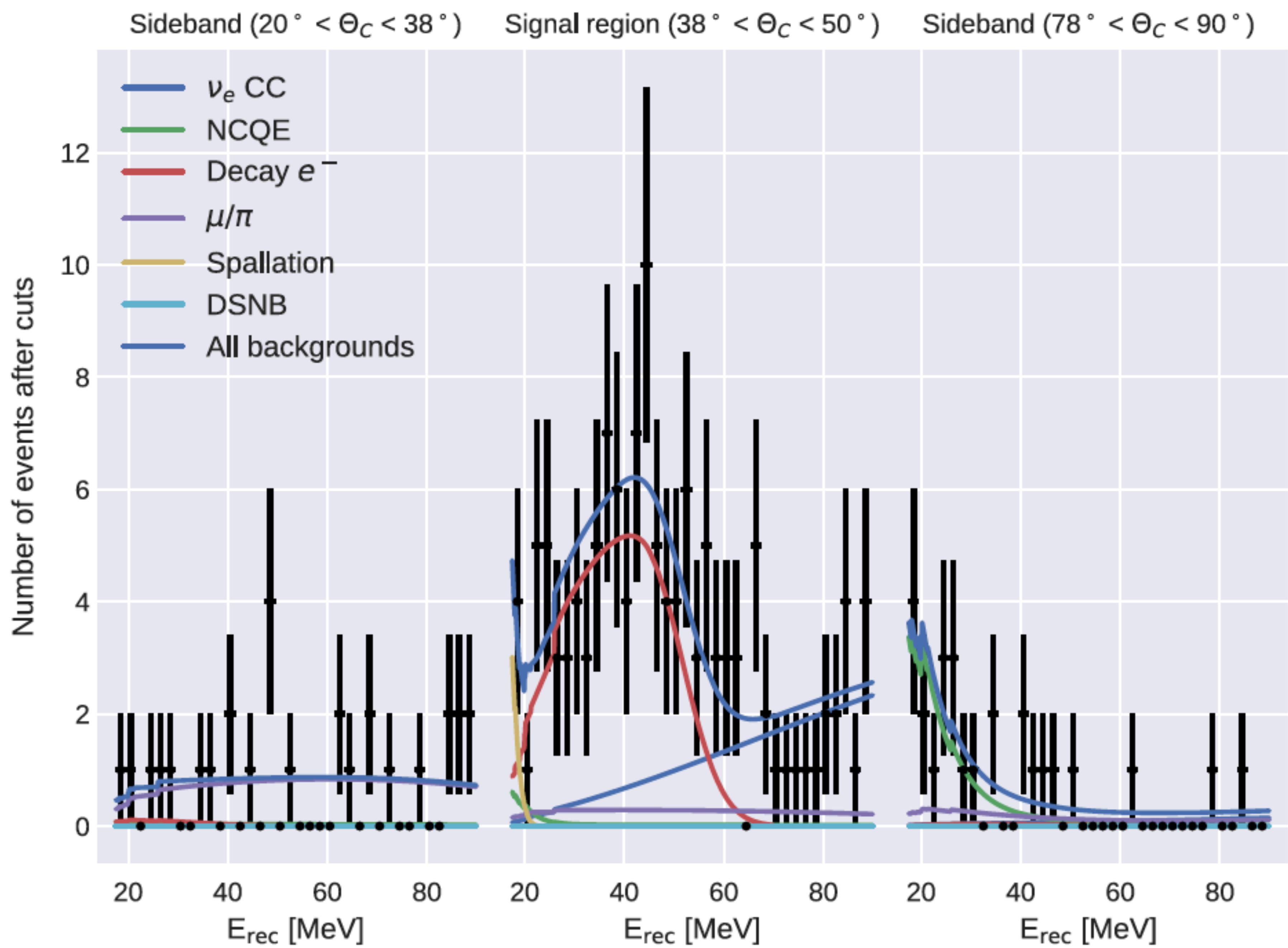


SK-I



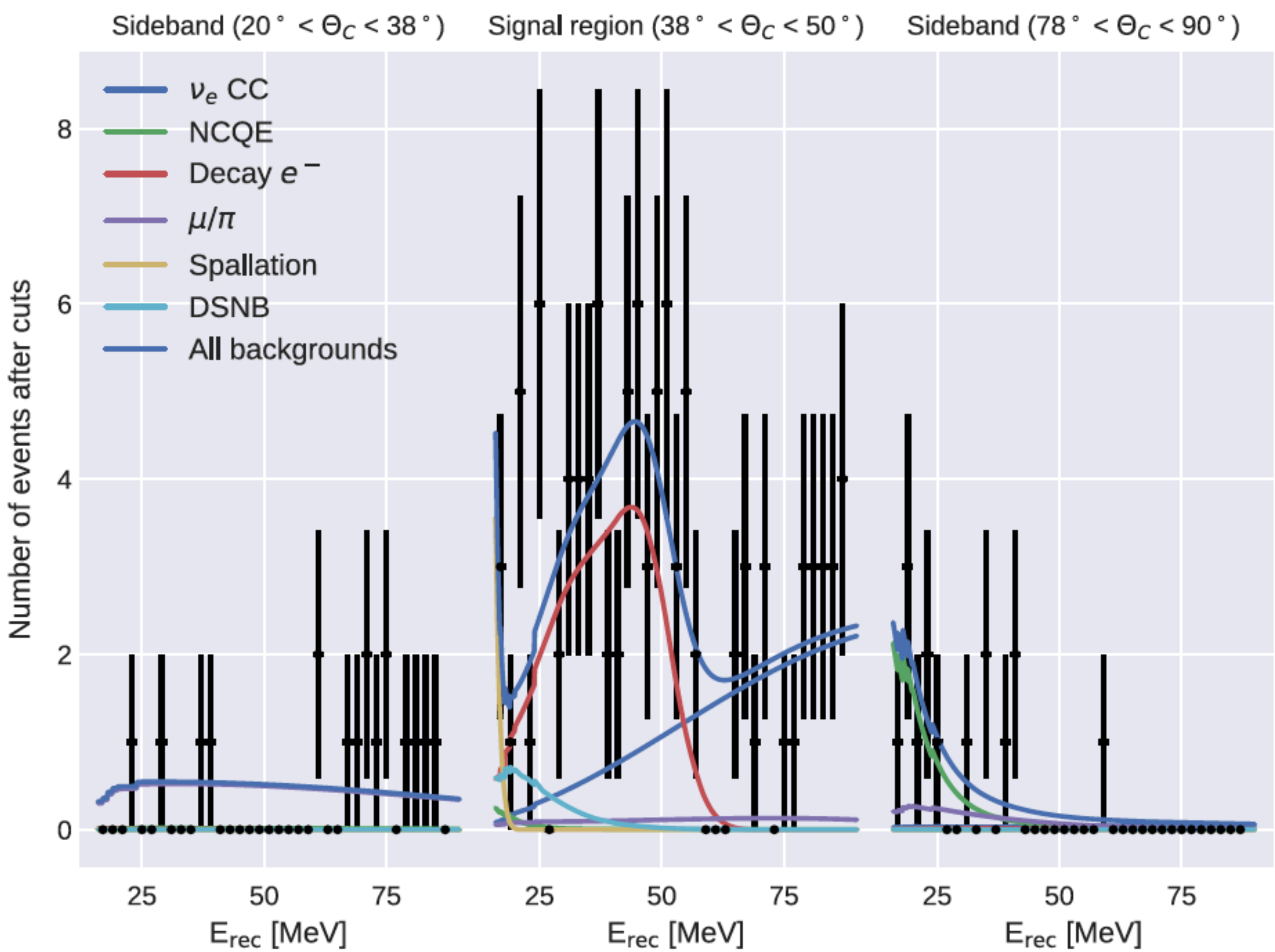
Sideband (20° < Θ_C < 38°)
Signal region (38° < Θ_C < 50°)
Sideband (78° < Θ_C < 90°)
ν_e CC
NCQE
Decay e⁻
μ/π
Spallation
DSNB
All backgrounds
Number of events after cuts
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
25
50
75
E_rec [MeV]

SK-II



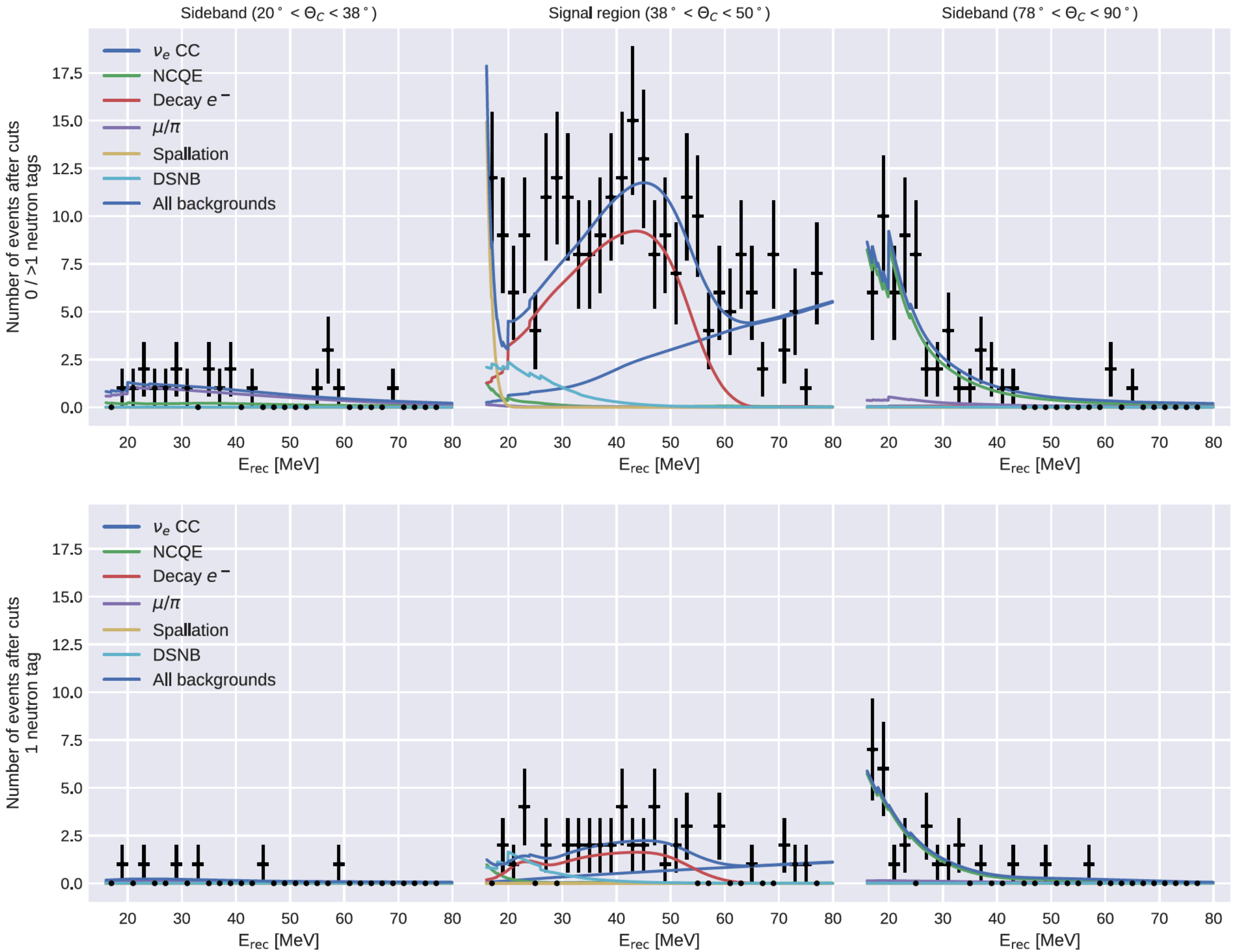
Sideband (20° < Θ_C < 38°)
Signal region (38° < Θ_C < 50°)
Sideband (78° < Θ_C < 90°)
ν_e CC
NCQE
Decay e⁻
μ/π
Spallation
DSNB
All backgrounds
Number of events after cuts
0
2
4
6
8
10
12
20
40
60
80
E_rec [MeV]
E_rec [MeV]
E_rec [MeV]

SK-III



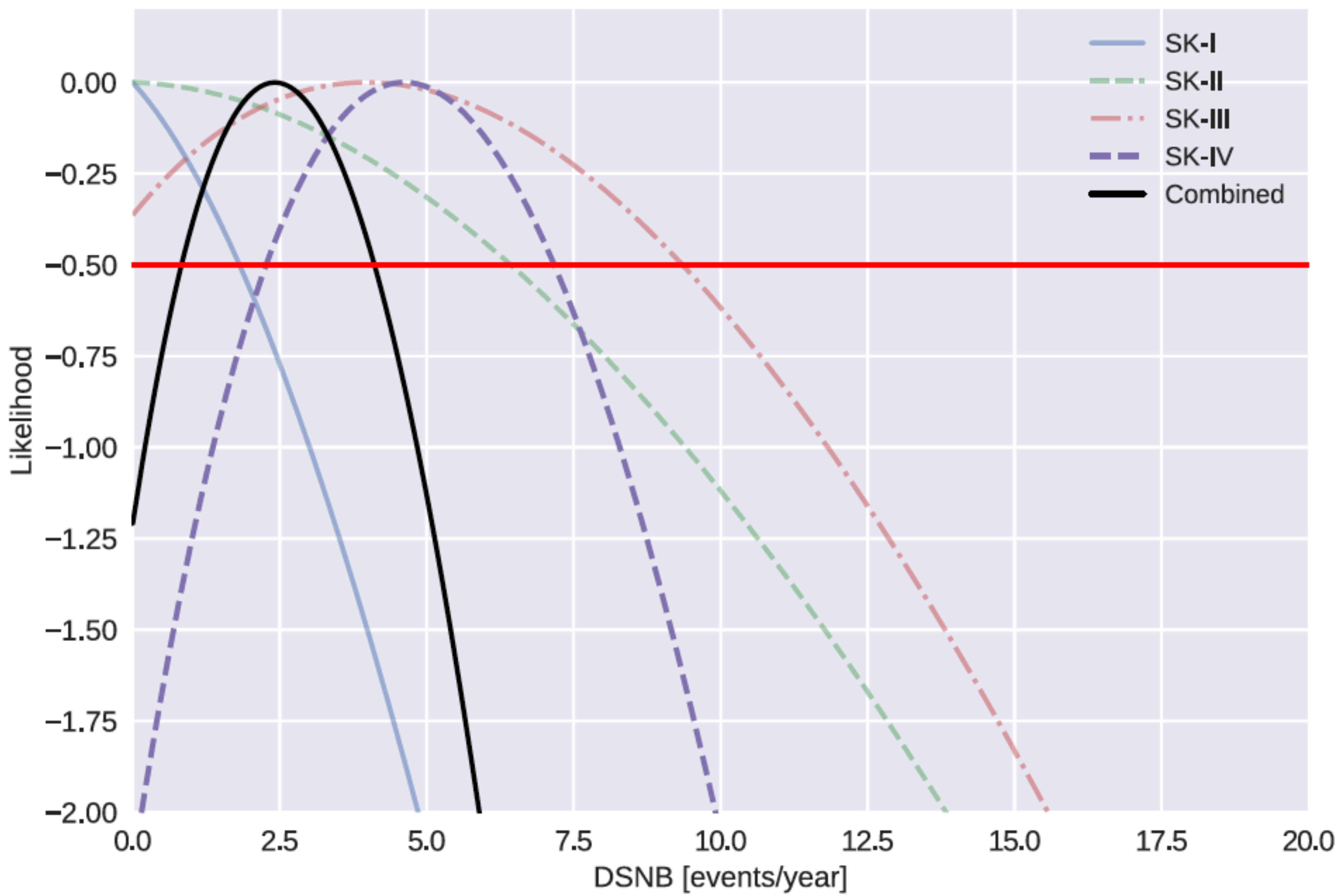
Sideband (20° < Θ_C < 38°)
Signal region (38° < Θ_C < 50°)
Sideband (78° < Θ_C < 90°)
ν_e CC
NCQE
Decay e^-
μ/π
Spallation
DSNB
All backgrounds
Number of events after cuts
0
2
4
6
8
25
50
75
E_{rec} [MeV]

SK-IV



Sideband (20° < Θ_C < 38°)
Signal region (38° < Θ_C < 50°)
Sideband (78° < Θ_C < 90°)
ν_e CC
NCQE
Decay e⁻
μ/π
Spallation
DSNB
All backgrounds
Number of events after cuts
0 / >1 neutron tags
1 neutron tag
E_rec [MeV]

Combination with SK-I,II,III



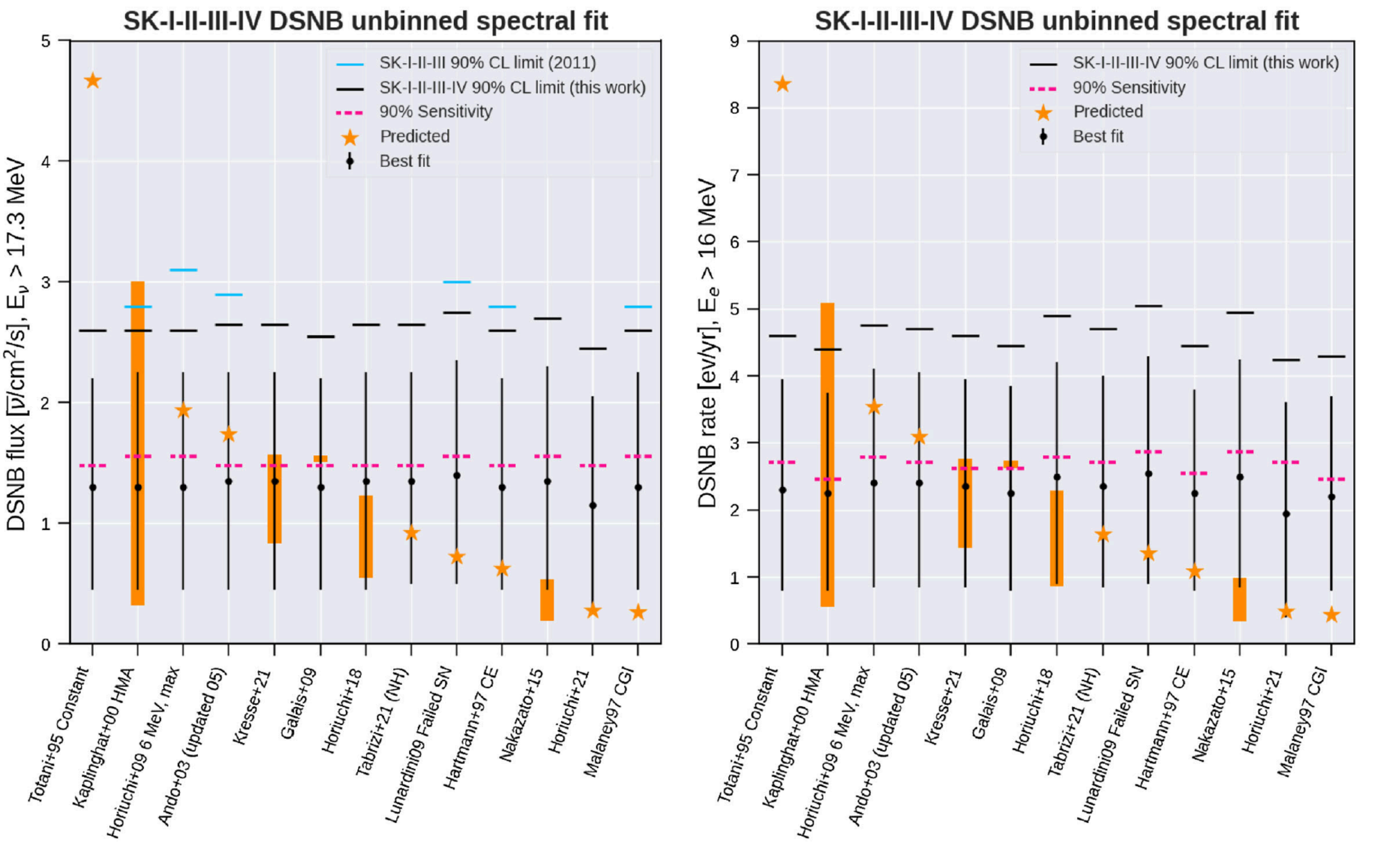


FIG. 29. The 90% CL upper limits, best-fit values, and expected sensitivities for the DSNB fluxes (left) and rates (right) associated with the models described in Sec. I. The best-fit rates and fluxes are shown with their associated 1σ error bars. This figure also shows the predictions for each models, either as a range or as one value. Note the stability of the expected and observed flux limits across all models.

TABLE VIII. Best-fit values and the 90% CL upper limits on the DSNB fluxes (in $cm^{-2} \cdot sec^{-1}$) for the theoretical models for phases SK-I to IV as well as for the combined analysis. Here the upper limits are given for $E_{\nu} > 17.3$ MeV. For the Kresse + 21 models, the "High," "Fid," and "Low" predictions correspond to the "W20-BH2.7-α2.0," "W18-BH2.7-α2.0," and "W18-BH2.7-α2.0-He33" models from Ref. [12], respectively.

	Best-fit		90% CL limit					
Model	SK4	All	SK1	SK2	SK3	SK4	All	Pred.
Totani + 95 Constant	$2.5^{+1.4}_{-1.3}$	$1.3^{+0.9}_{-0.9}$	2.3	6.3	7.0	4.5	2.6	4.67
Kaplinghat + 00 HMA (max)	$2.6^{+1.5}_{-1.3}$	$1.3^{+0.9}_{-0.9}$	2.3	6.7	7.1	4.7	2.6	3.00
Horiuchi + 09 6 MeV, max	$2.6^{+1.4}_{-1.3}$	$1.3^{+0.9}_{-0.9}$	2.4	6.0	7.0	4.6	2.6	1.94
Ando + 03 (updated 05)	$2.7^{+1.5}_{-1.4}$	$1.4^{+0.9}_{-0.9}$	2.3	6.6	7.2	4.7	2.7	1.74
Kresse + 21 (High, NO)	$2.7^{+1.5}_{-1.3}$	$1.4^{+0.9}_{-0.9}$	2.3	6.7	7.2	4.7	2.7	1.57
Galais + 09 (NO)	$2.5^{+1.4}_{-1.3}$	$1.3^{+0.9}_{-0.9}$	2.3	6.3	7.0	4.5	2.6	1.56
Galais + 09 (IO)	$2.6^{+1.4}_{-1.3}$	$1.3^{+0.9}_{-0.9}$	2.3	6.4	7.0	4.5	2.6	1.50
Horiuchi + 18 $\xi_{2.5} = 0.1$	$2.6^{+1.4}_{-1.3}$	$1.4^{+0.9}_{-0.9}$	2.4	6.1	7.1	4.6	2.7	1.23
Kresse + 21 (High, IO)	$2.7^{+1.5}_{-1.3}$	$1.4^{+0.9}_{-0.9}$	2.3	6.7	7.1	4.7	2.7	1.21
Kresse + 21 (Fid, NO)	$2.7^{+1.5}_{-1.3}$	$1.4^{+0.9}_{-0.9}$	2.3	6.8	7.2	4.7	2.7	1.20
Kresse + 21 (Fid, IO)	$2.7^{+1.5}_{-1.3}$	$1.4^{+0.9}_{-0.9}$	2.3	6.8	7.2	4.7	2.7	1.02
Kresse + 21 (Low, NO)	$2.7^{+1.5}_{-1.4}$	$1.4^{+0.9}_{-0.9}$	2.3	6.8	7.2	4.8	2.7	0.96
Tabrizi + 21 (NO)	$2.7^{+1.5}_{-1.3}$	$1.4^{+0.9}_{-0.9}$	2.4	6.6	7.1	4.7	2.7	0.92
Kresse + 21 (Low, IO)	$2.7^{+1.5}_{-1.4}$	$1.4^{+0.9}_{-0.9}$	2.3	6.8	7.2	4.8	2.7	0.84
Lunardini09 Failed SN	$2.8^{+1.5}_{-1.4}$	$1.4^{+0.9}_{-0.9}$	2.4	6.8	7.3	4.8	2.8	0.73
Hartmann + 97 CE	$2.6^{+1.4}_{-1.3}$	$1.3^{+0.9}_{-0.9}$	2.3	6.5	7.1	4.6	2.6	0.63
Nakazato + 15 (max, IO)	$2.7^{+1.5}_{-1.4}$	$1.4^{+1.0}_{-0.9}$	2.4	6.5	7.2	4.8	2.7	0.53
Horiuchi + 18 $\xi_{2.5} = 0.5$	$2.7^{+1.5}_{-1.4}$	$1.3^{+0.9}_{-0.9}$	2.2	7.1	7.1	4.8	2.6	0.55
Horiuchi + 21	$2.1^{+1.3}_{-1.2}$	$1.2^{+0.9}_{-0.9}$	3.4	4.3	5.9	3.9	2.5	0.28
Malaney97 CGI	$2.7^{+1.5}_{-1.3}$	$1.3^{+0.9}_{-0.9}$	2.3	6.8	7.1	4.7	2.6	0.26
Nakazato + 15 (min, NO)	$2.8^{+1.5}_{-1.4}$	$1.4^{+1.0}_{-0.9}$	2.3	6.8	7.2	4.8	2.7	0.19