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Dissecting the diffuse supernova neutrino background flux over wide energy range in upcoming era

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Higgstan

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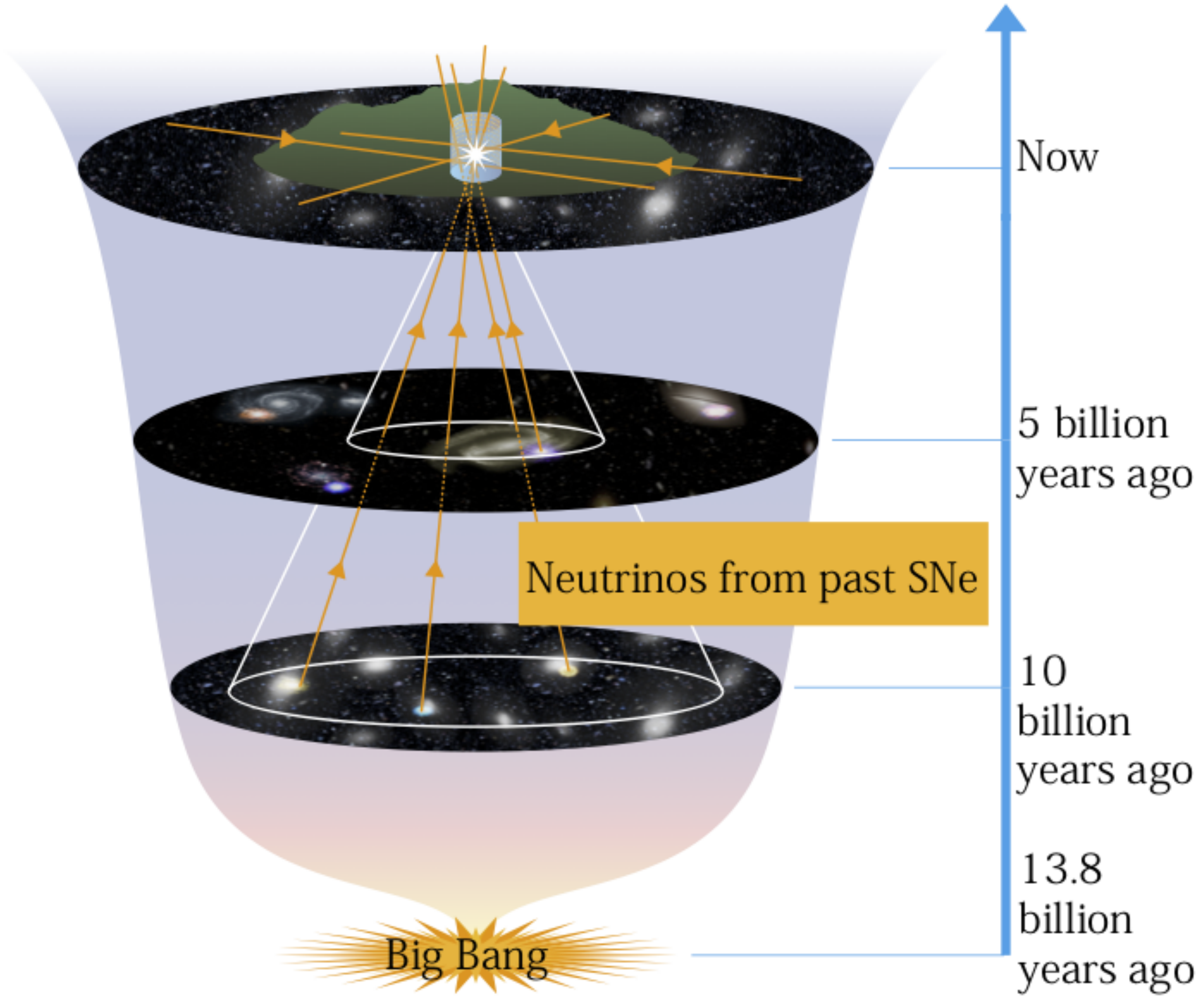
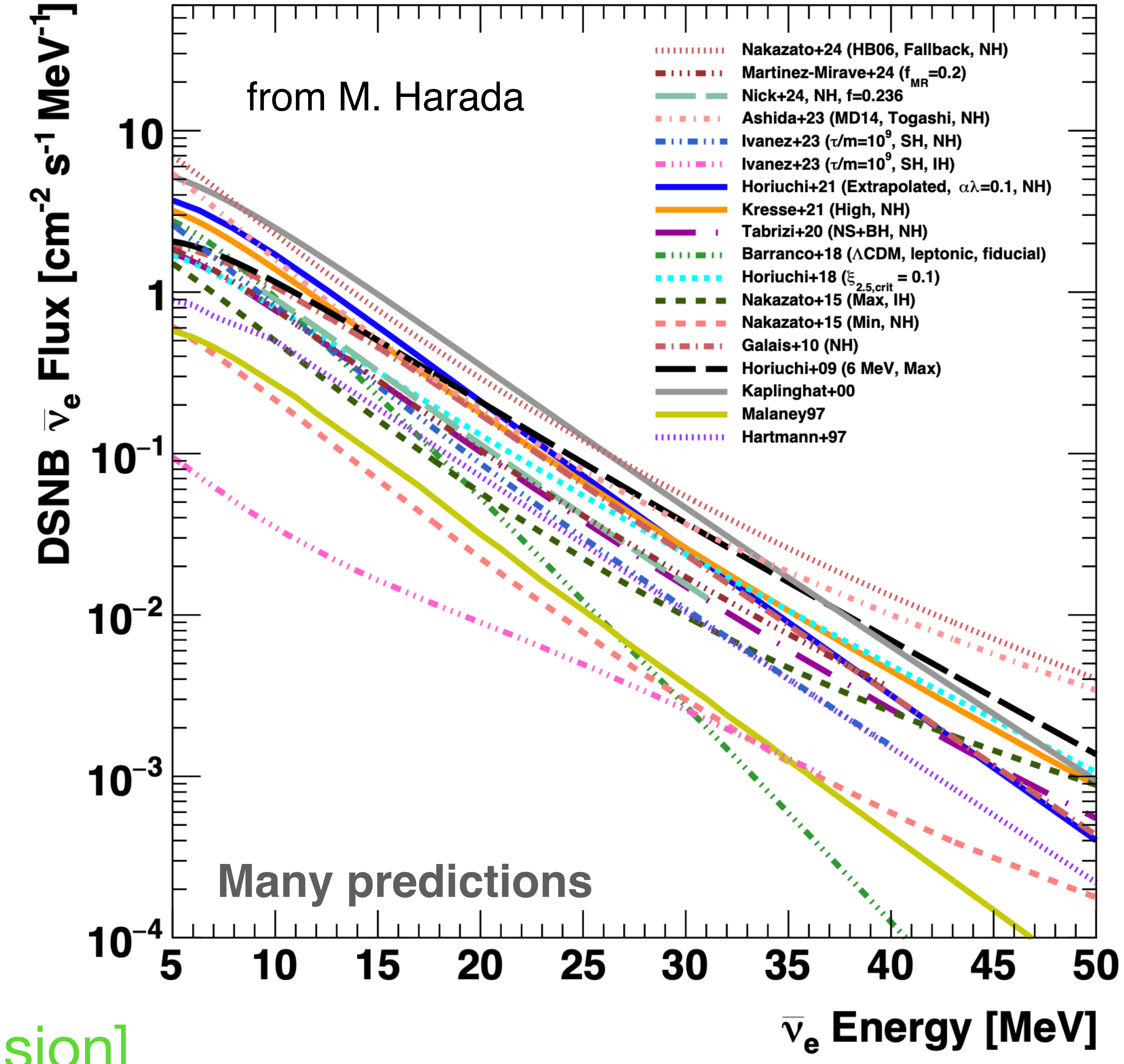
Message from Stars in the Past

The accumulated flux of neutrinos released from stellar core collapse over the cosmic history

= **Diffuse Supernova Neutrino Background; DSNB**



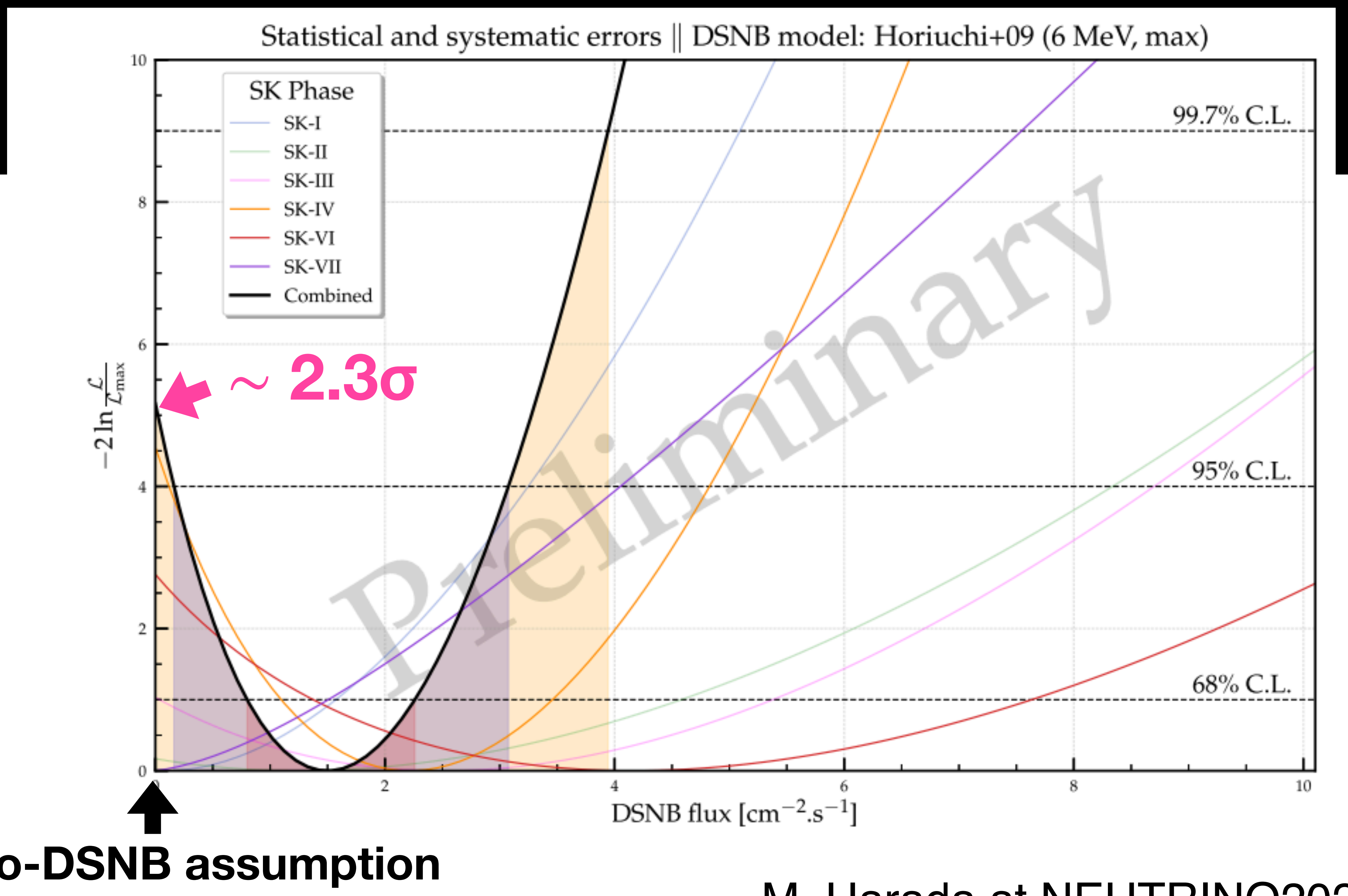


$$\Phi = \int [\nu \text{ emission}] \otimes [\text{Star formation}] \otimes [\text{Universe expansion}]$$

First Hint from Super-K?

- Best-fit DSNB $\overline{\nu}_e$ flux is **~1.4 cm^{-2} sec^{-1}** (>17.3 MeV).
- Null DSNB hypothesis is disfavored in both pure-water and Gd-water phases and is rejected at 2.3σ from the combined analysis.

They might catch the first hint of DSNB??



M. Harada at NEUTRINO2024

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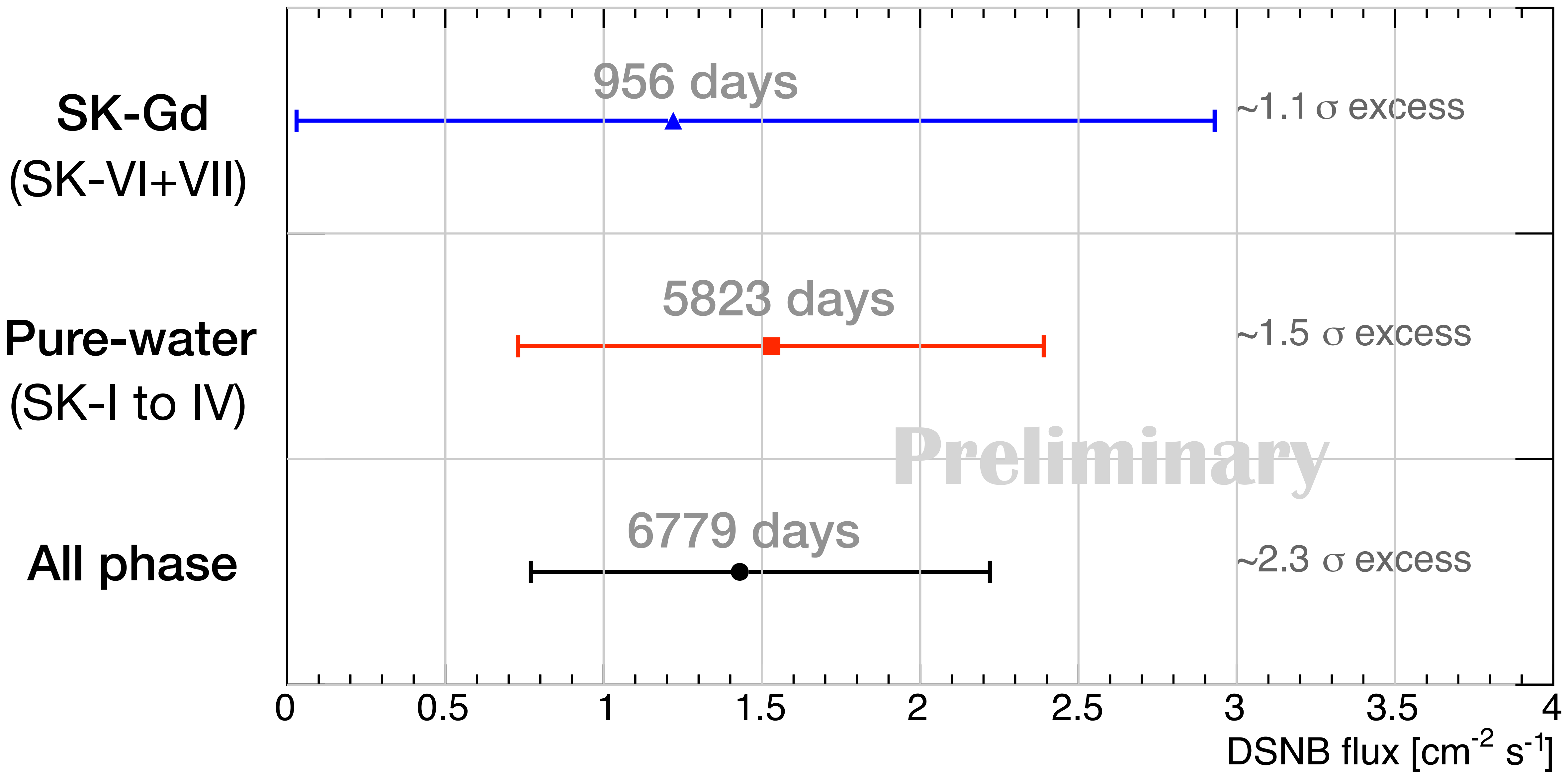
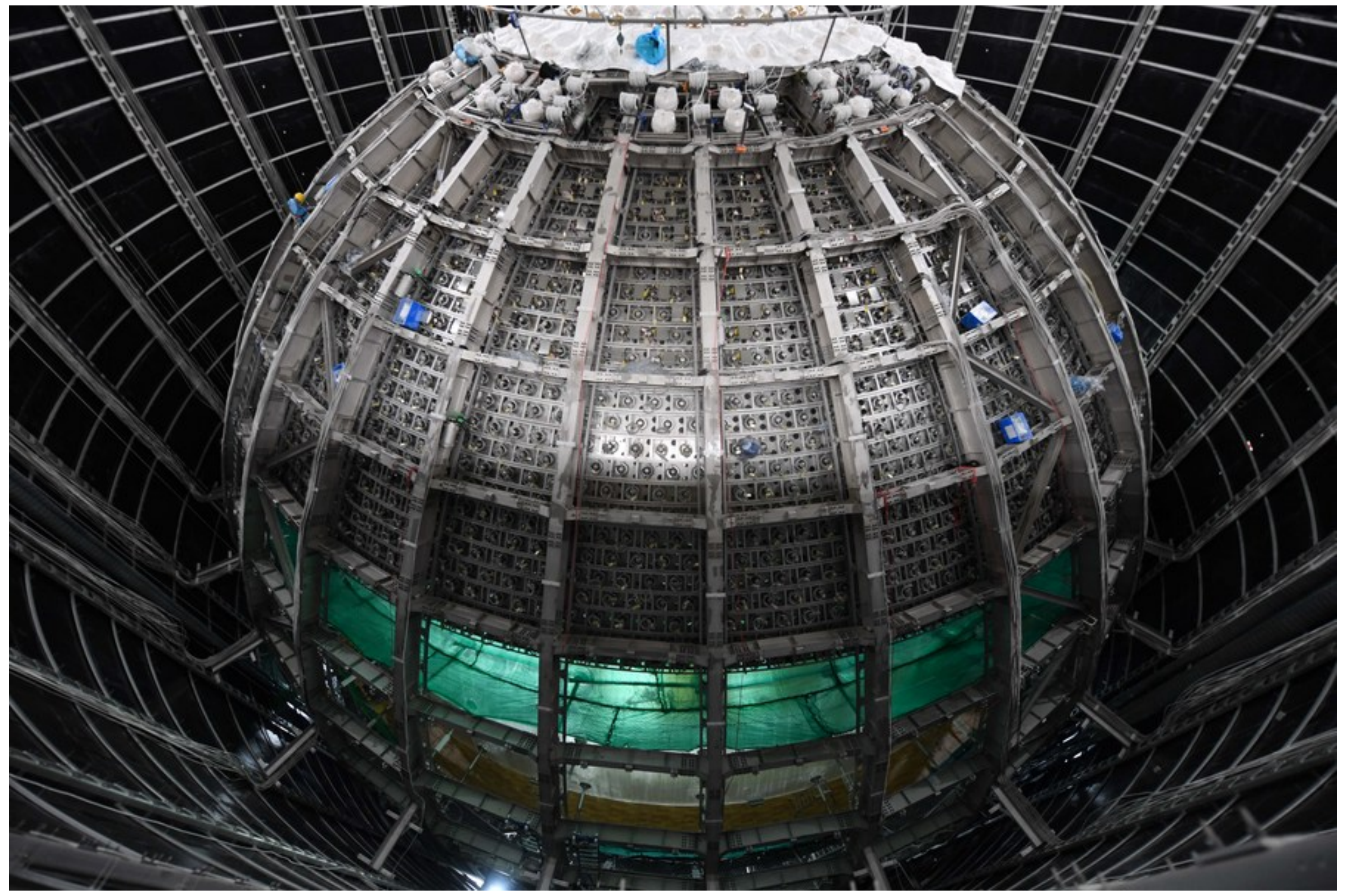
NEWS | 09 July 2024

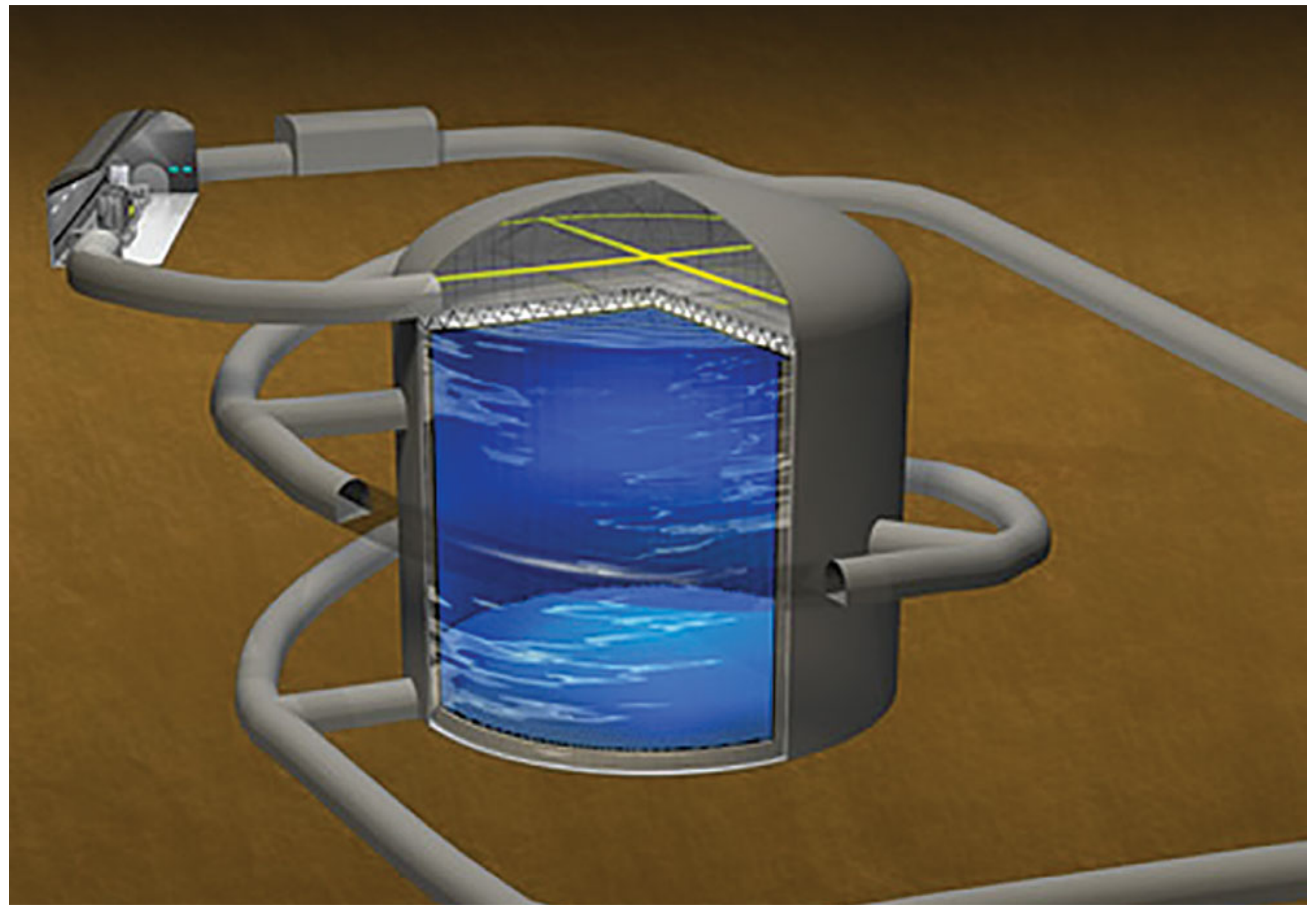
Huge neutrino detector sees first hints of particles from exploding stars

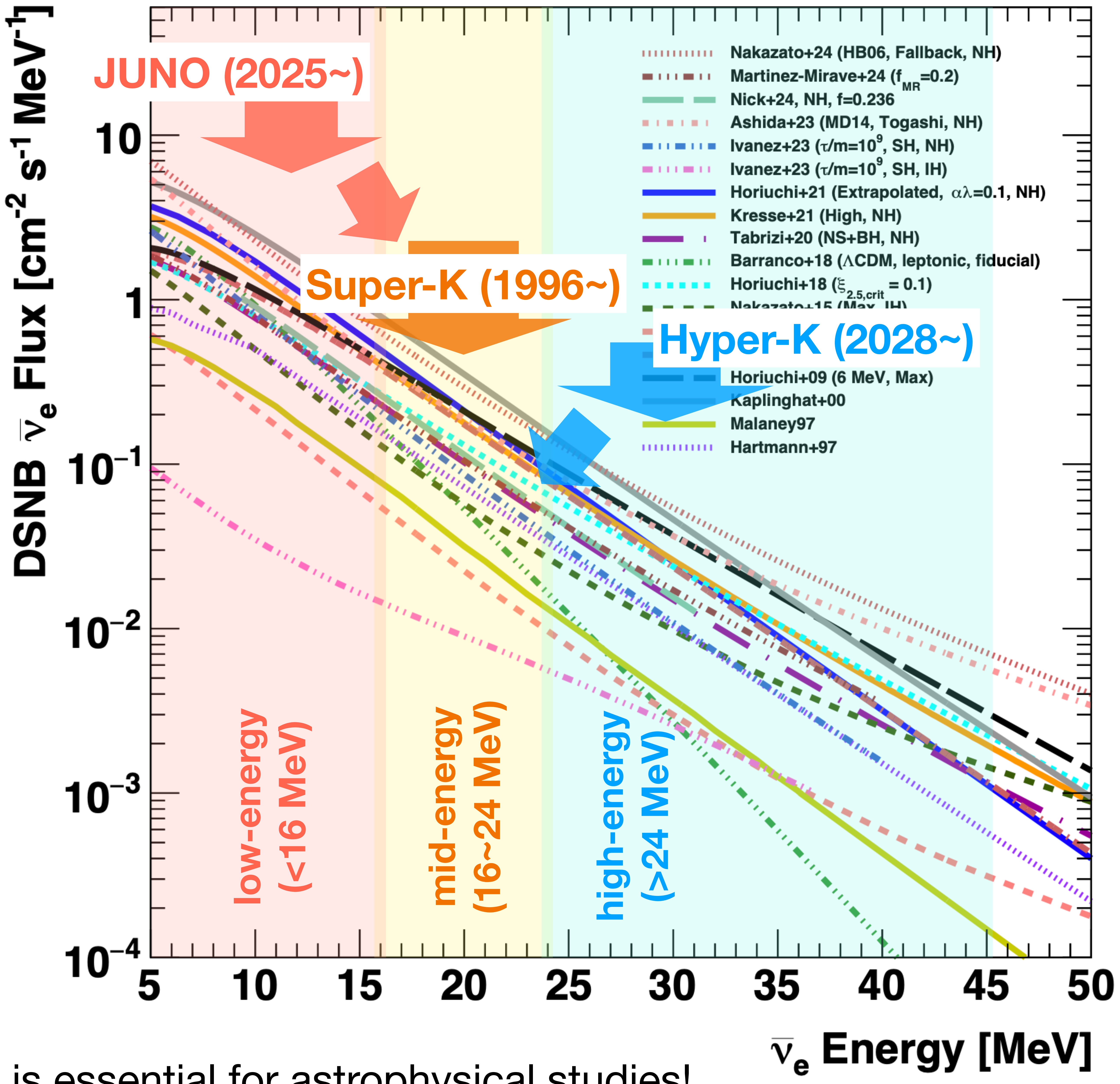
Japan's Super-Kamiokande observatory could be seeing evidence of neutrinos from supernovae across cosmic history.



Next Era





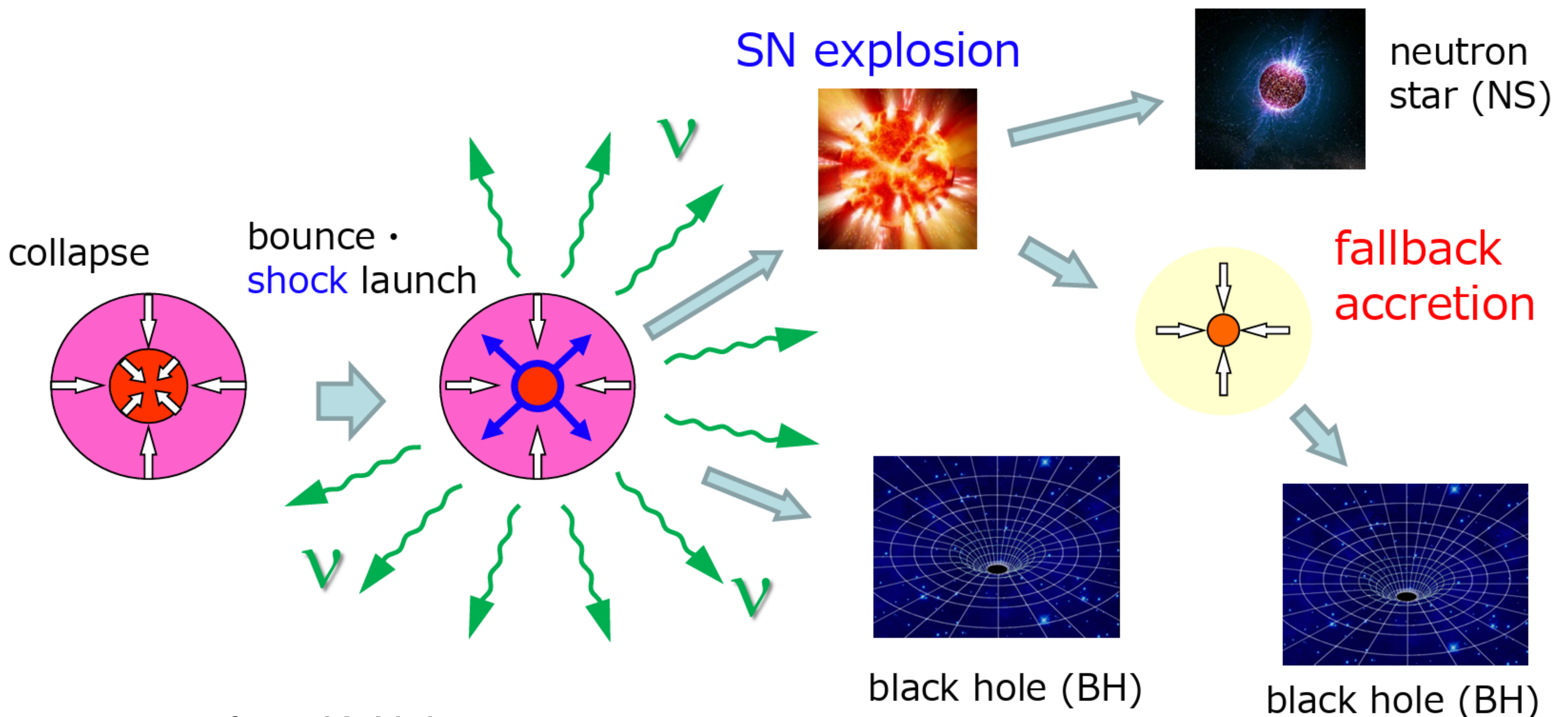


DSNB observation over the wide energy range is essential for astrophysical studies!

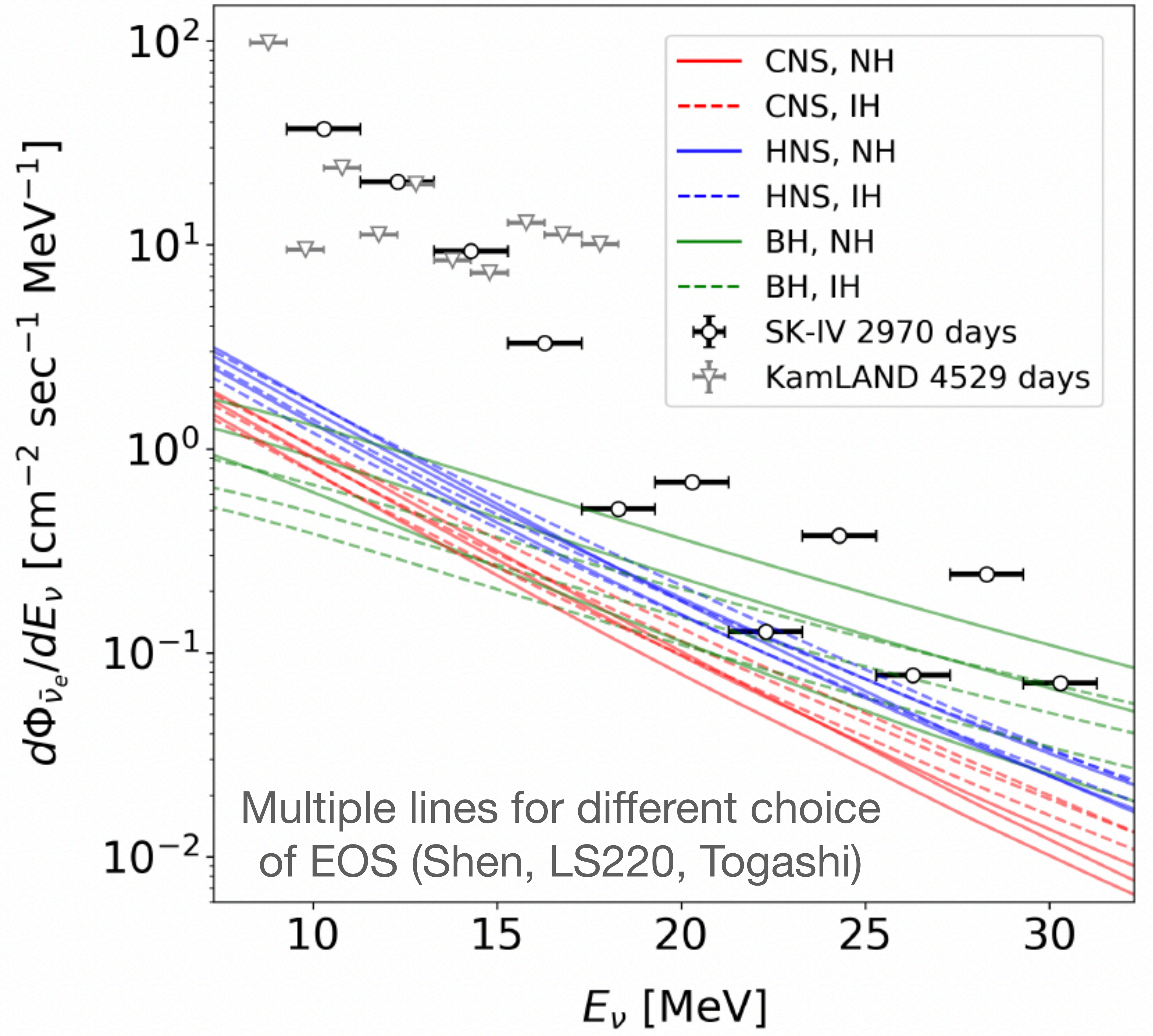
Contribution from Failed Explosion

Y. Ashida & K. Nakazato, ApJ 937, 1 (2022)

- Emitted ν spectrum is expected to depend on the remnant after core collapse ("*fate*").
  - Information about the fate are accessible by other observations (pulser, failed SN monitoring, GW etc).
- Consider three major cases as a fate and calculate DSNB flux for each.
  - Canonical mass neutron stars (~$1.4M_{sun}$)
  - High mass neutron stars (~$1.7M_{sun}$)
  - Black holes (failed SNe)



from K. Nakazato



Galactic Chemical Evolution and DSNB

Y. Ashida et al., ApJ 953, 2 (2023)

- Set the maximum mass of progenitors for successful explosions to **18M$_{sun}$** from both observational and theoretical findings.
- Proposed a new evolution model to compensate for the discrepancy in chemical abundance; categorize galaxies into five and assume different initial mass functions (IMF) depending types.

How star formation proceeds?

moderate mode

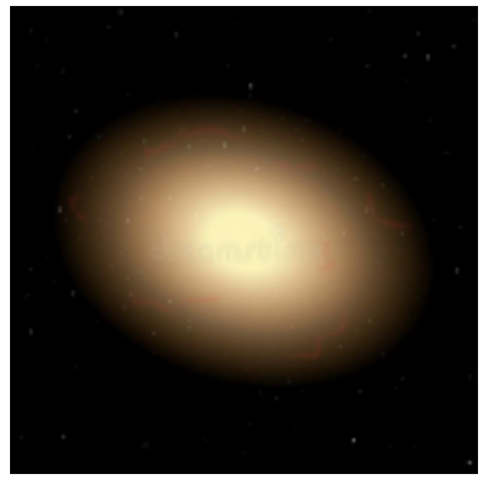
late-type galaxies (Sbc, Scd, Sdm)

Salpeter IMF

(x = −1.35)

bursting mode

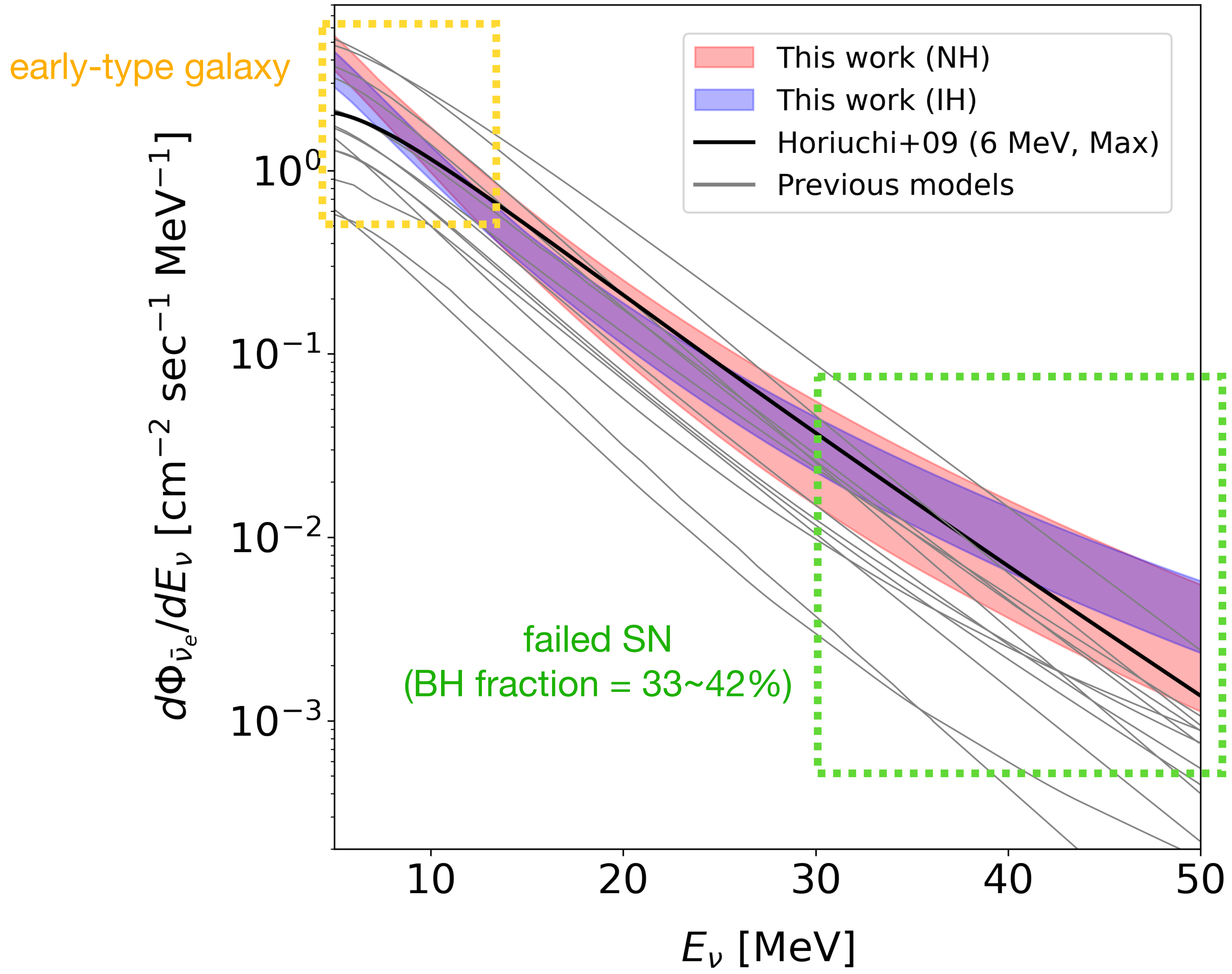
early-type galaxies (E/S0, Sab)



Flat IMF

(x = −0.9)

T. Tsujimoto, MNRAS 518, 3475 (2023)



CARNE

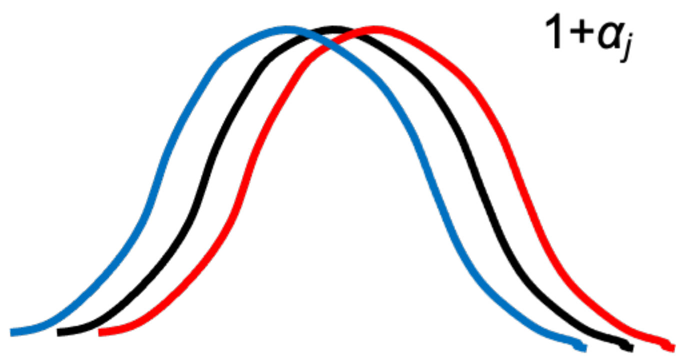
- Need to get prepared for making full use of available dataset from multiple future detectors.
- Another demand comes from the theoretical field as they would like to investigate their models with realistic experimental assumptions.

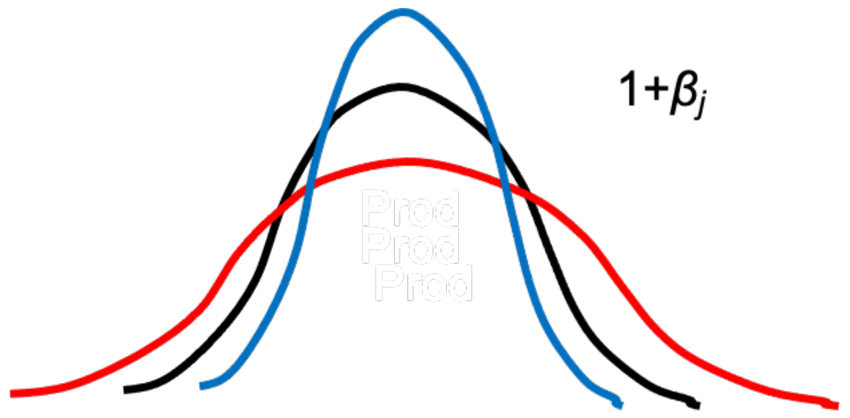
  → We are developing a dedicated spectral fitting code, *Code for Analyzing Relic NEutrinos* (**CARNE**).

- Philosophy
  - Detector type: water Cherenkov & liquid scintillator (primarily assume Hyper-K and JUNO)
  - Signal: inverse beta decay of electron antineutrinos
  - Background: realistic background incorporated from each group
  - Code access: public use for a wide use in the community; feedback reflected for improvement, making the code more matured to be referred as a basis for the actual use in future
  - Extension possibility: flexible design for potential extension, e.g., detector, observable

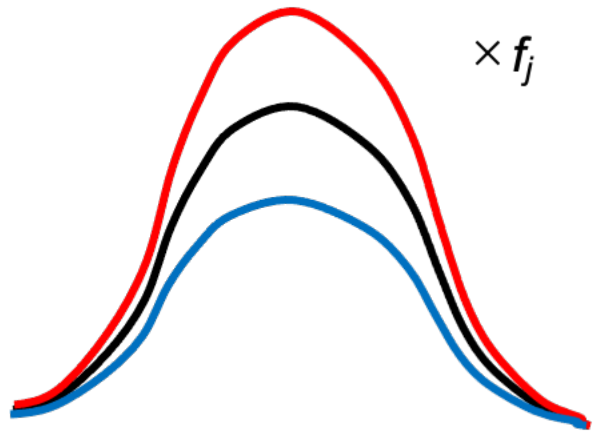
Scheme

- Statistical model: an extended unbinned likelihood
- Observable: detection energy
- Flow:





1. Prepare probability density functions (PDFs) of each signal and background; apply shift (energy scale) and shape (energy resolution) systematics here.
2. Produce N_{obs} events based on PDF, detector size, operation time, and analysis efficiency etc (as a toy dataset); in background-only hypothesis, $N_{\text{obs}} = N_{\text{bkg,nom}}$.
3. Calculate likelihood for each toy dataset by scanning N_{sig} and N_{bkg}, and normalize each likelihood by the maximum likelihood to obtain Test Statistic (TS).
4. From each toy dataset, obtain upper limits at different confidence levels (1σ: TS ≤ 1.00, 2σ: TS ≤ 3.84, 3σ: TS ≤ 6.63 based on Wilks' theorem).



$$L(E_i; N_{\text{sig}}, N_{\text{bkg}}) = \frac{e^{-(N_{\text{sig}}+N_{\text{bkg}})}}{N_{\text{obs}}!} \prod_{i=1}^{N_{\text{obs}}} \{N_{\text{sig}} P_{\text{sig}}(E_i) + N_{\text{bkg}} P_{\text{bkg}}(E_i)\} \times \prod_{\theta} exp\left\{-\frac{1}{2}\left(\frac{\theta - \theta_0}{\sigma_\theta}\right)^2\right\}$$

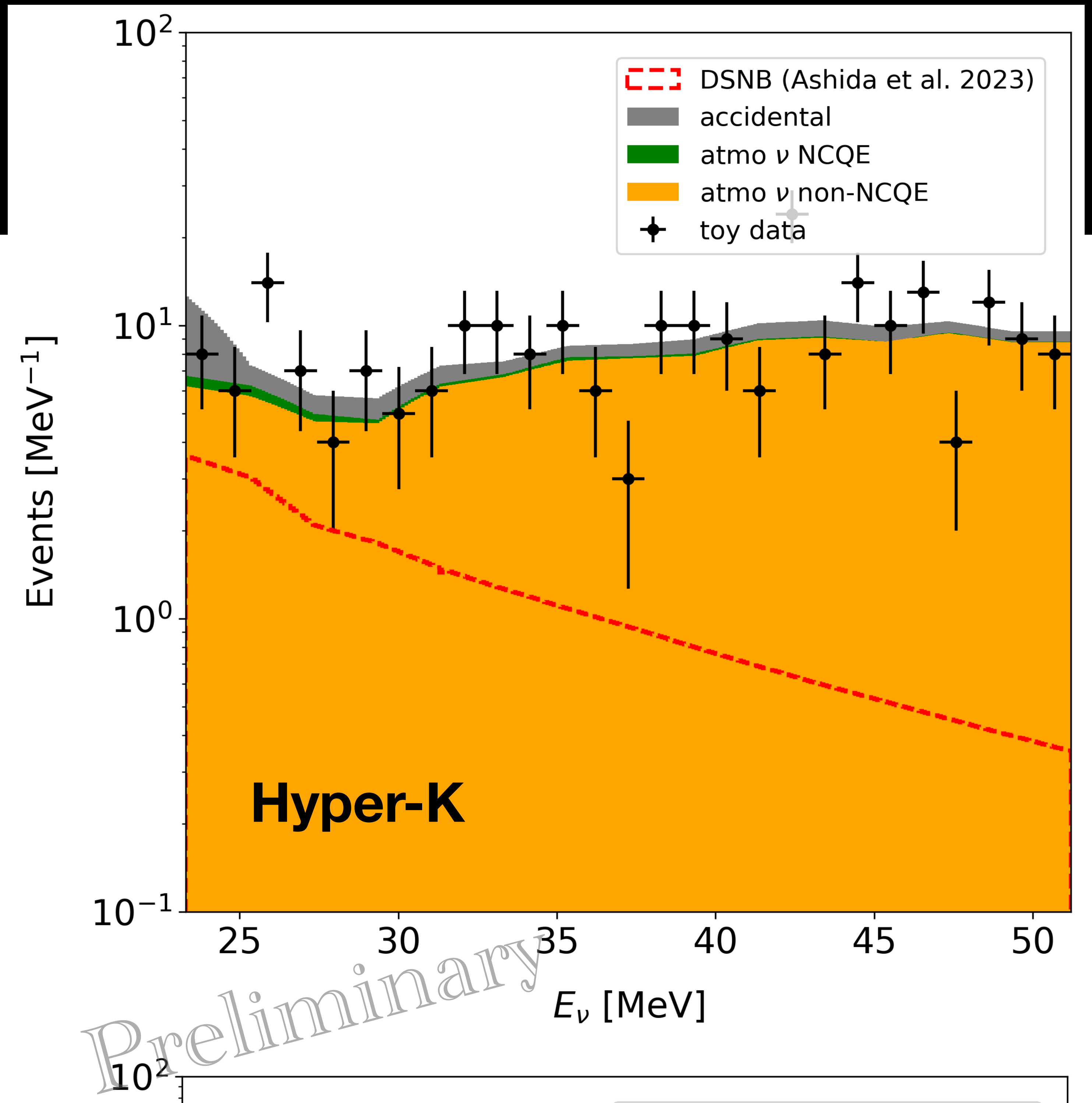
$$TS = -2\ln\left(\frac{L}{\hat{L}}\right)$$

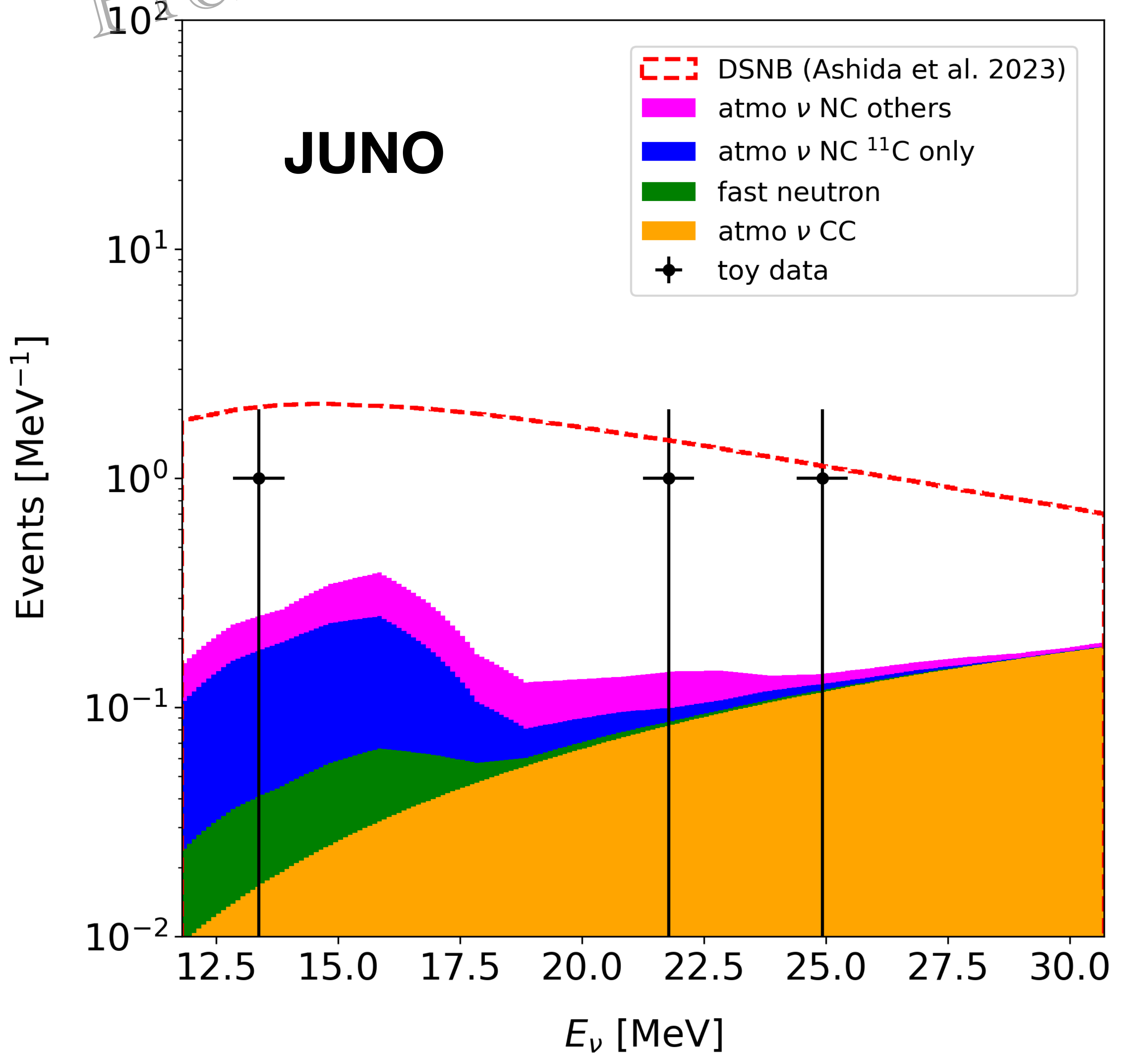
Poisson term for statistics
(i: event ID)

pull term for systematics
(θ ~ α_j, β_j, f_j: PDF shift/shape, bkg norm etc)

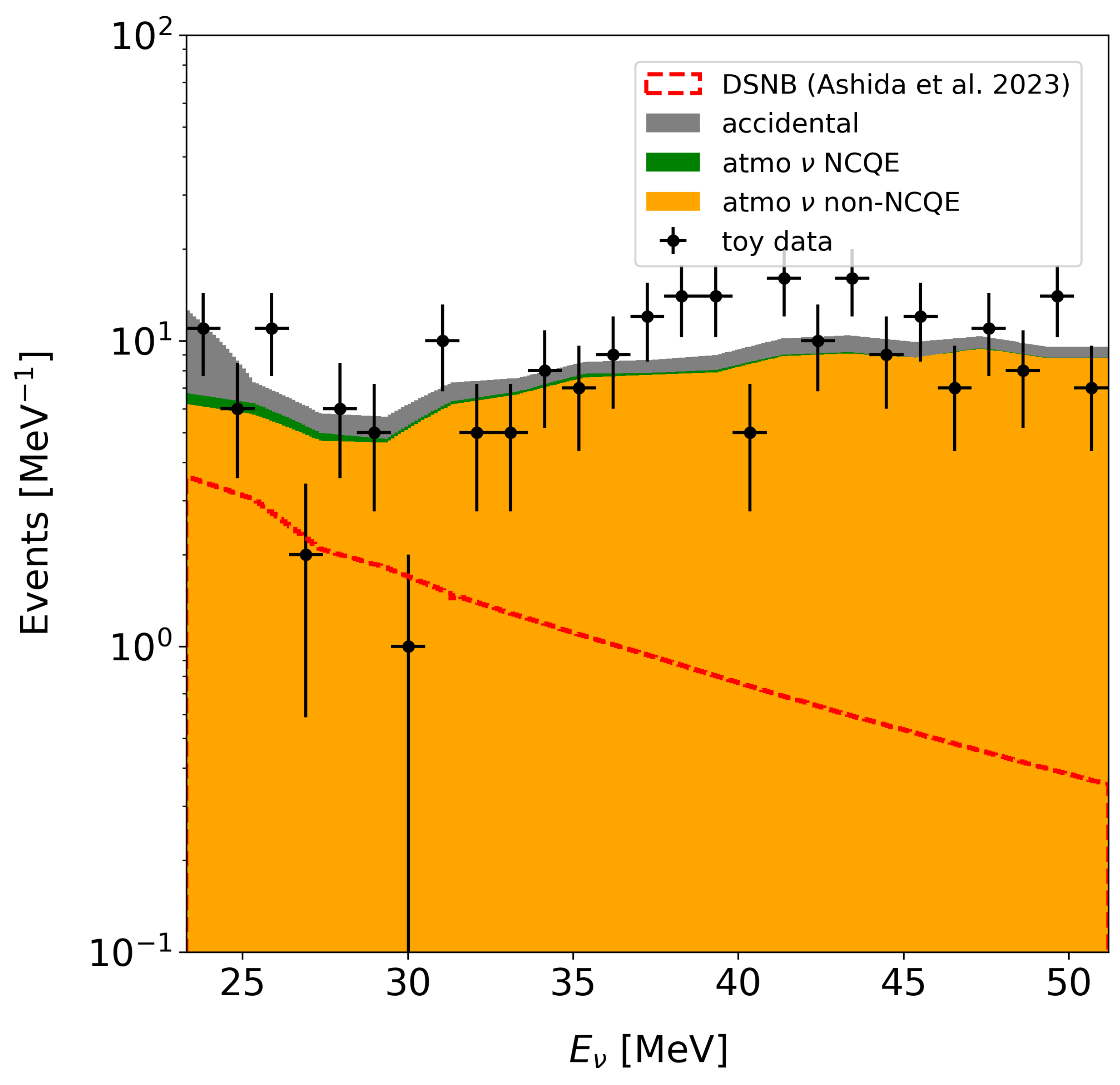
Demonstration Setup

- DSNB model: Y. Ashida et al., ApJ 953, 2 (2023)
- **Hyper-K**, extrapolated from SK-IV [K. Abe et al., PRD 104, 122002 (2021)]
  - Volume: 187 kton
  - Operation time: 7 years (2028~2035)
  - Background: non-NCQE (mainly CCQE), NCQE, accidental coincidence
  - Neutrino energy range: 23.3~51.3 MeV
- **JUNO**, taken from JUNO [A. Abusleme et al., JCAP 10, 033 (2022)]
  - Volume: 14.7 kton (FV1)
  - Operation time: 10 years (2025~2035)
  - Background: CC, NC, fast neutron, $^{9}Li/^{8}He$, reactor
  - Neutrino energy range: 11.8~30.8 MeV
- Systematics
  - 20% on total background scale (no others for now)

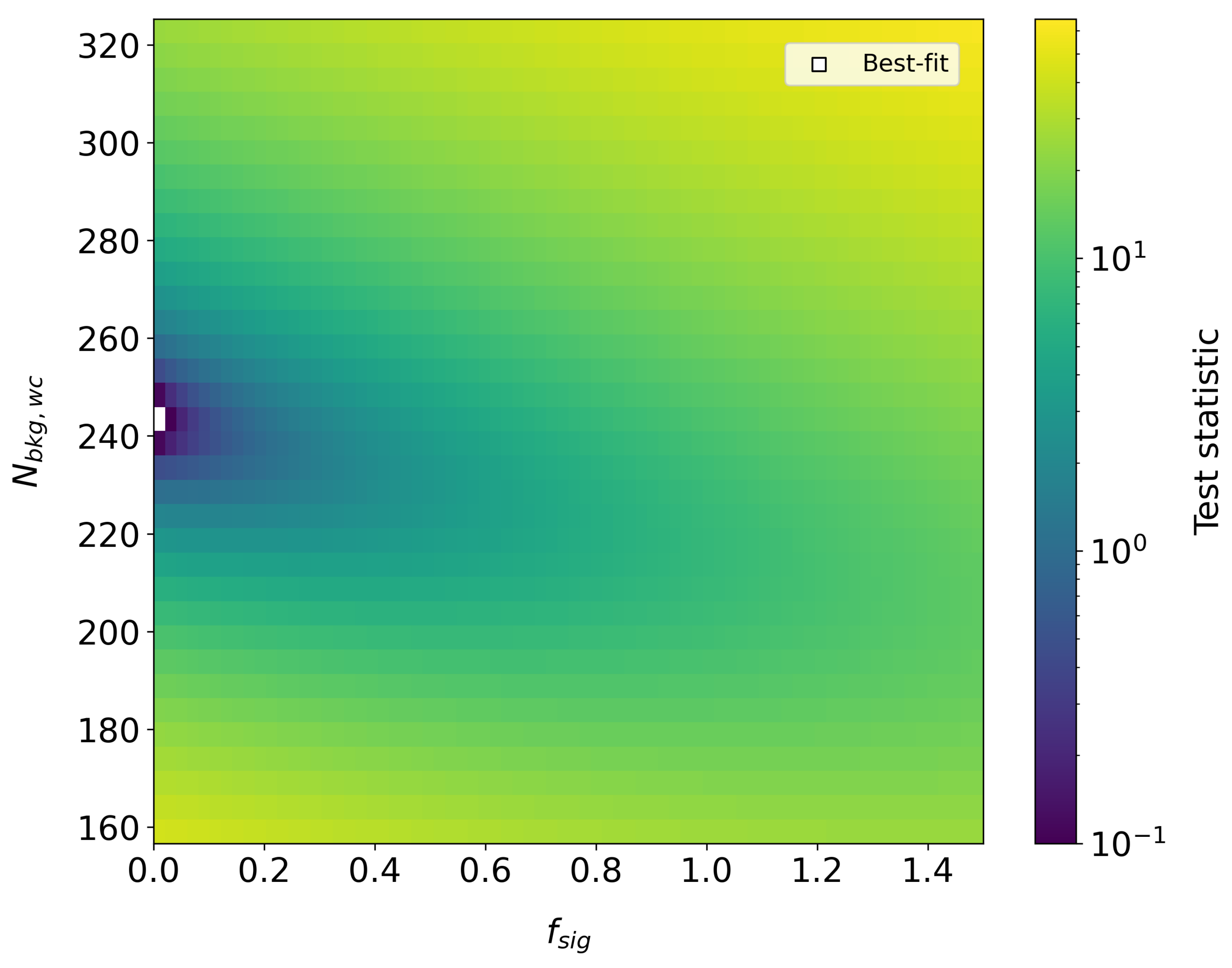




Example Trials



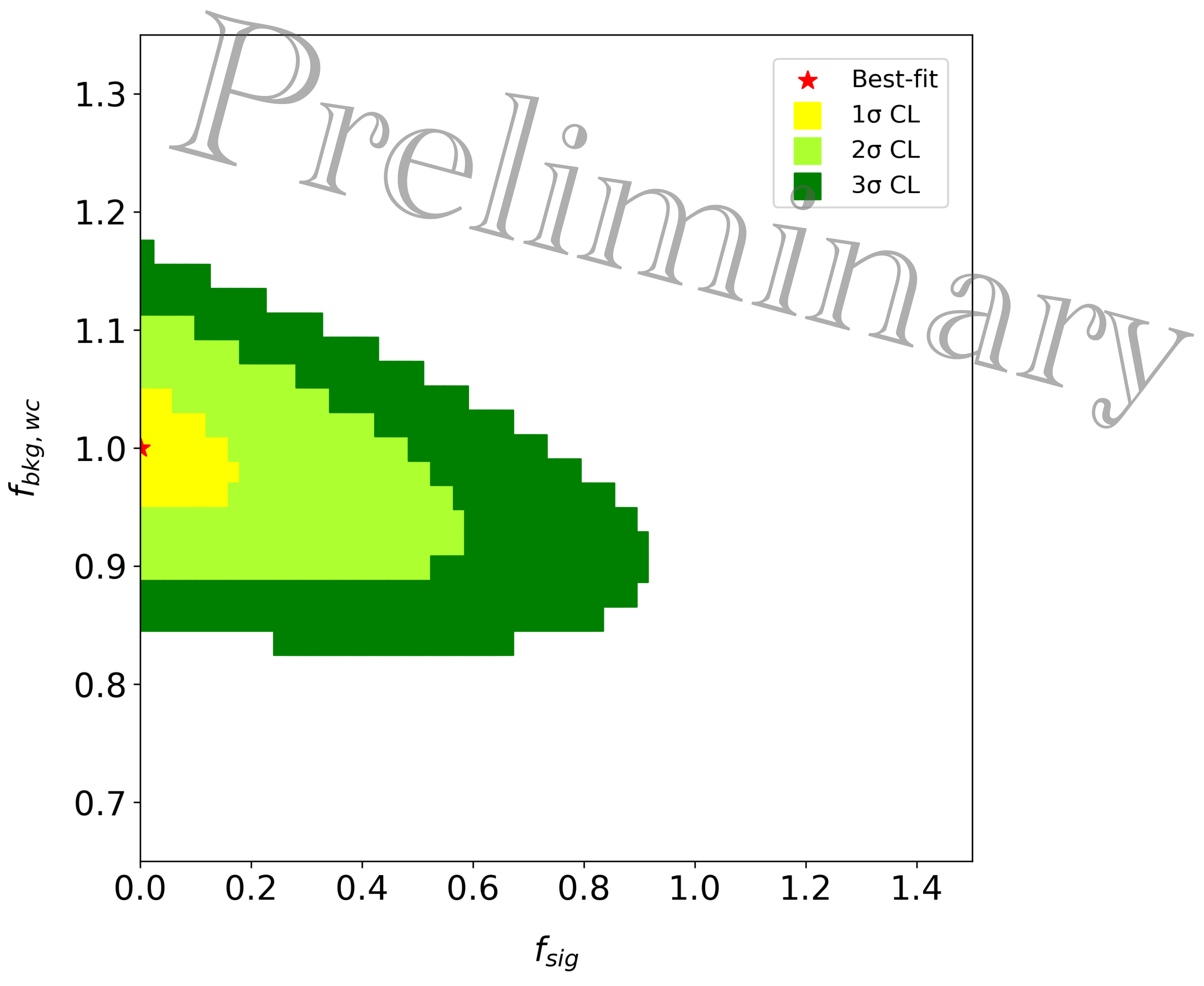
A certain toy sample with expectations



Test Statistic along scans

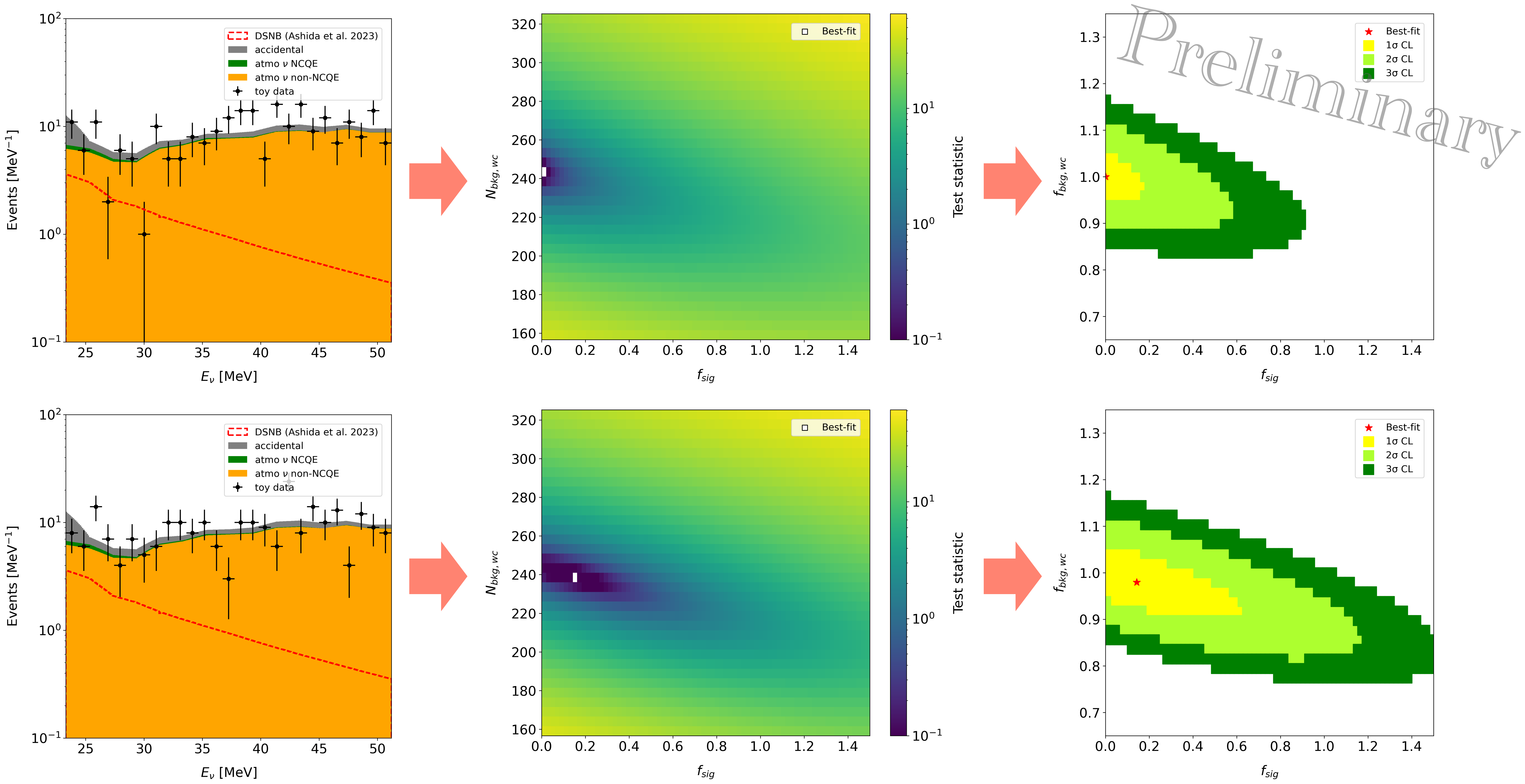
f_{sig}: scaling to nominal DSNB

$N_{\text{bkg,wc}}$: background at Hyper-K



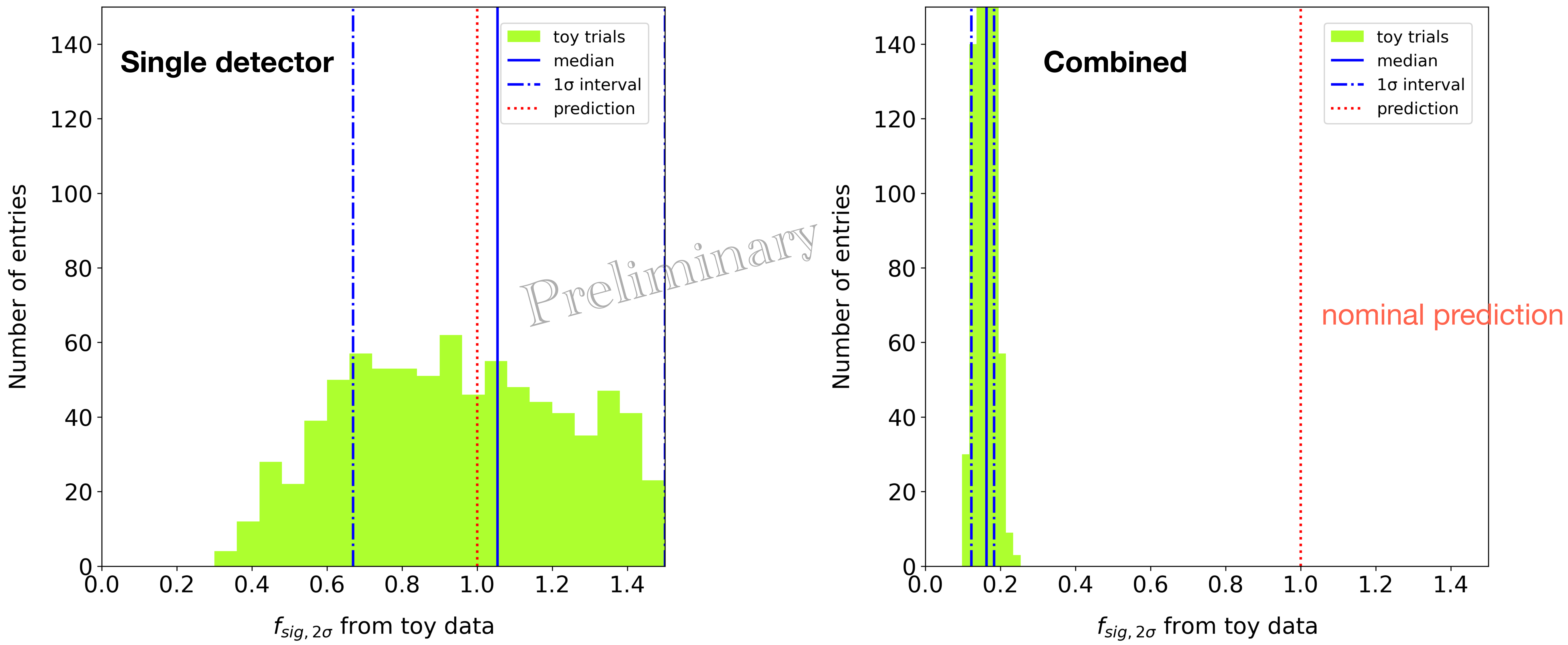
Allowed region based on TS

Example Trials



Expected Sensitivity

- Single detector cases are compared with a combined detector case.
- Multiple detector utilization provides a better sensitivity as expected.



NOTE: This is one test case. Please do not take them as official sensitivities from these detectors! We will check more on quantity!

Summary & Prospects

- DSNB is a unique probe of astrophysics and its discovery has been awaited for long.
- Next-generation detectors are operating soon with their own search window.
- Making full use of available data from multiple detectors is essential for astrophysical studies.
- We are developing a dedicated spectral fitting code CARNE for the future DSNB studies.
- An initial demonstration result is shown.
- Will sophisticate the code, aiming its public release of this year.

Thanks for your attention!

Supplements

Core Collapse Fate and DSNB

Y. Ashida & K. Nakazato, ApJ 937, 1 (2022)

- Emitted ν spectrum is expected to depend on the remnant after core collapse ("*fate*").
  - Information about the fate are accessible by other observations (pulser, failed SN monitoring, GW etc).

- Consider three major cases as a fate and calculate DSNB flux for each.
  - Canonical mass neutron stars (~1.4M_{sun})
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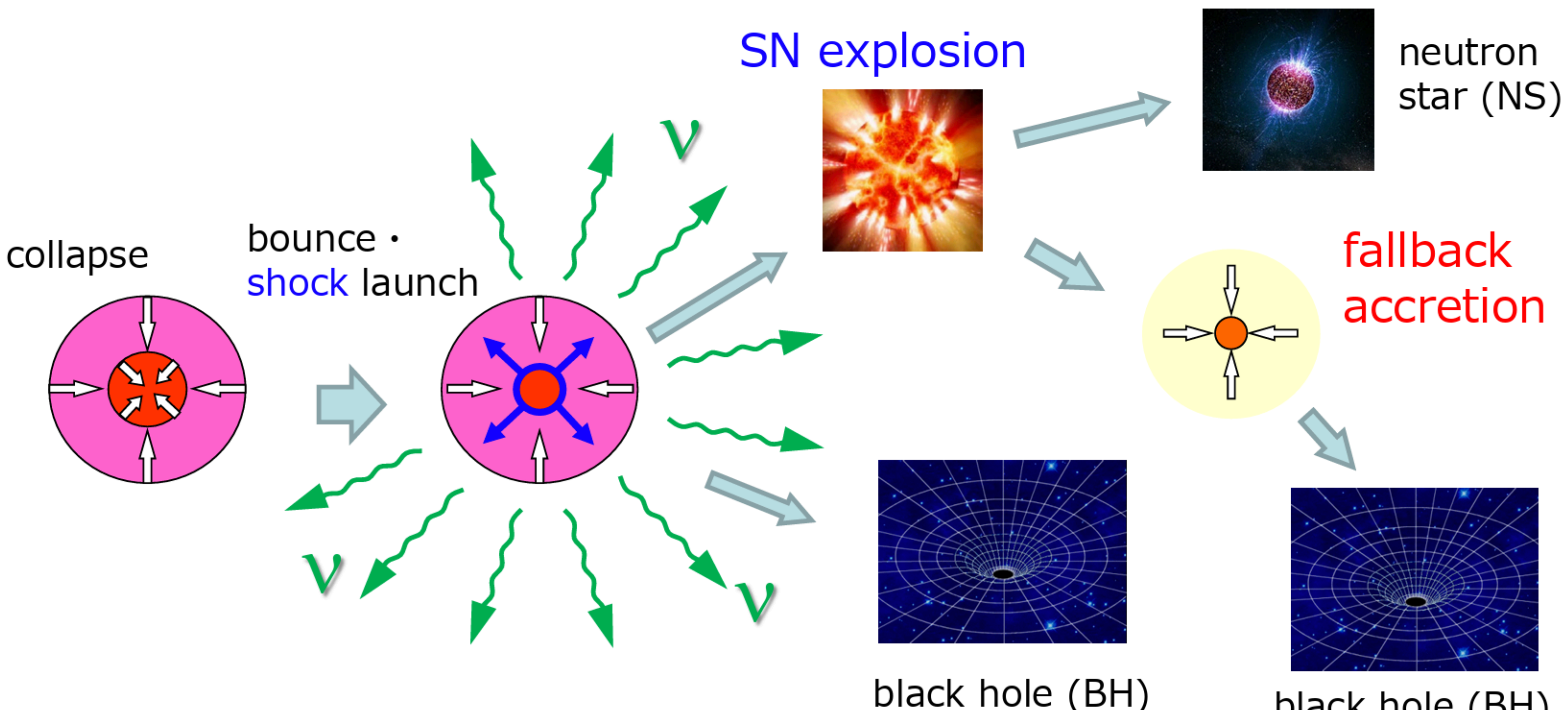
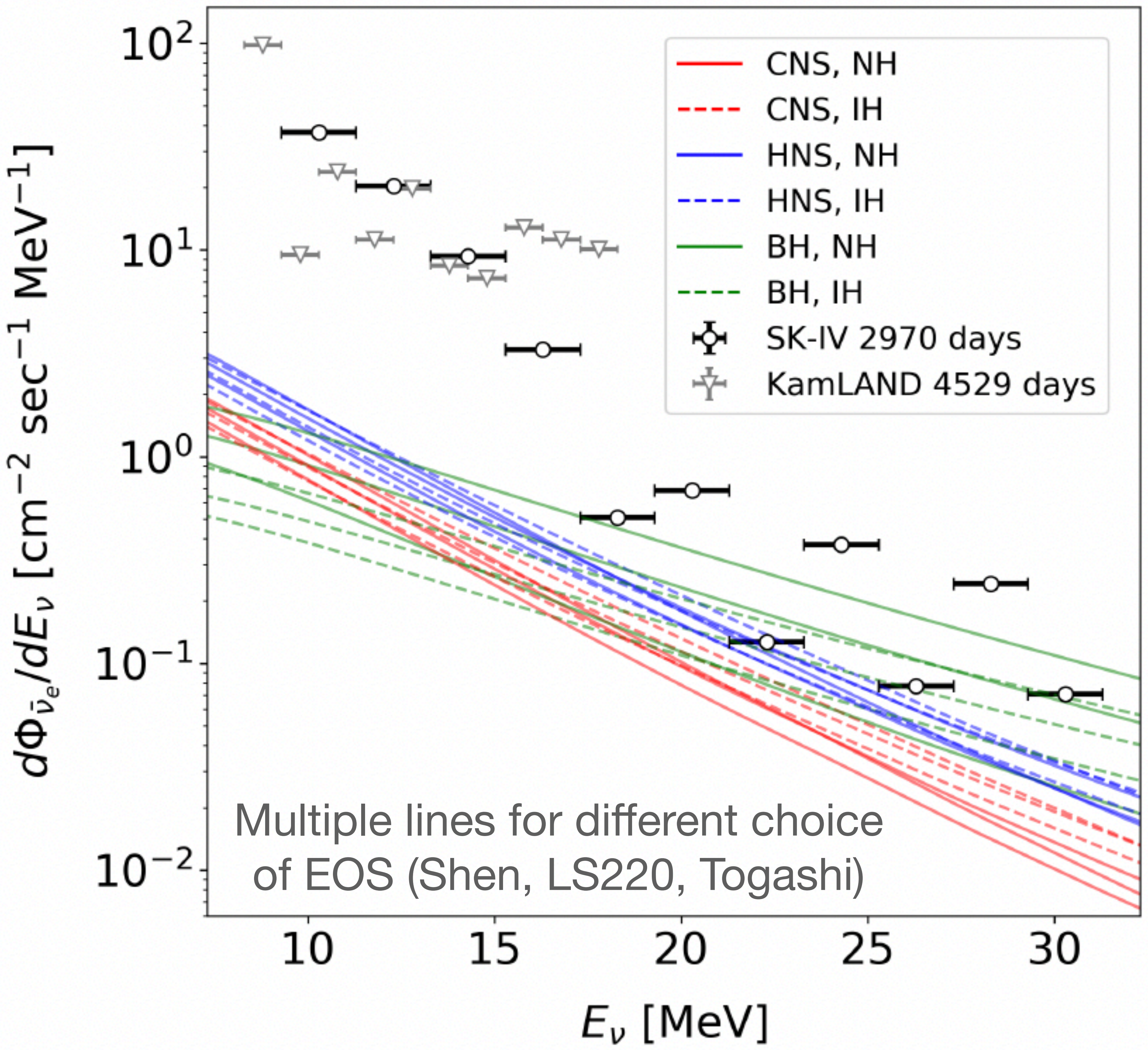
  - Black holes (failed SNe)



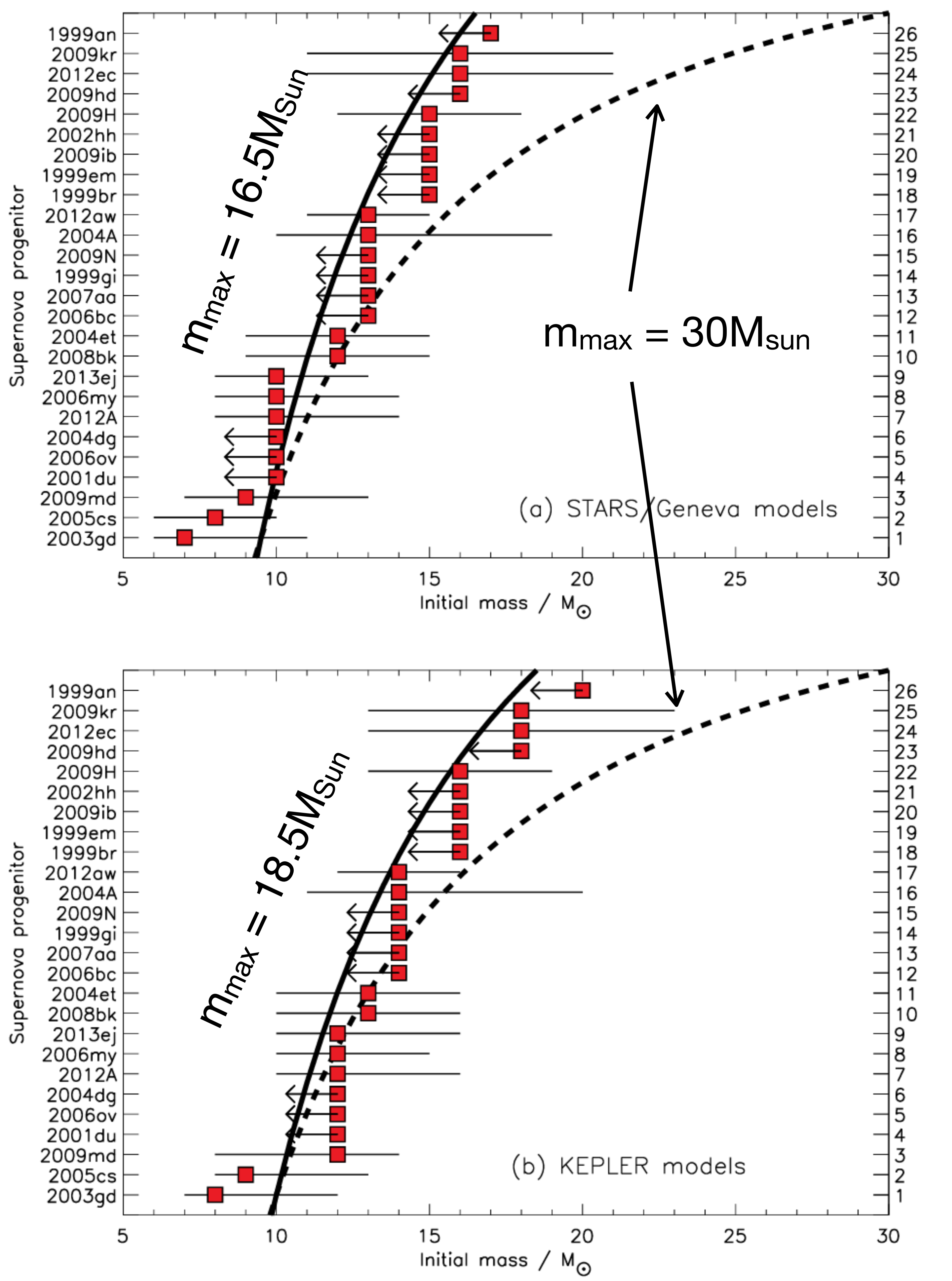
from K. Nakazato



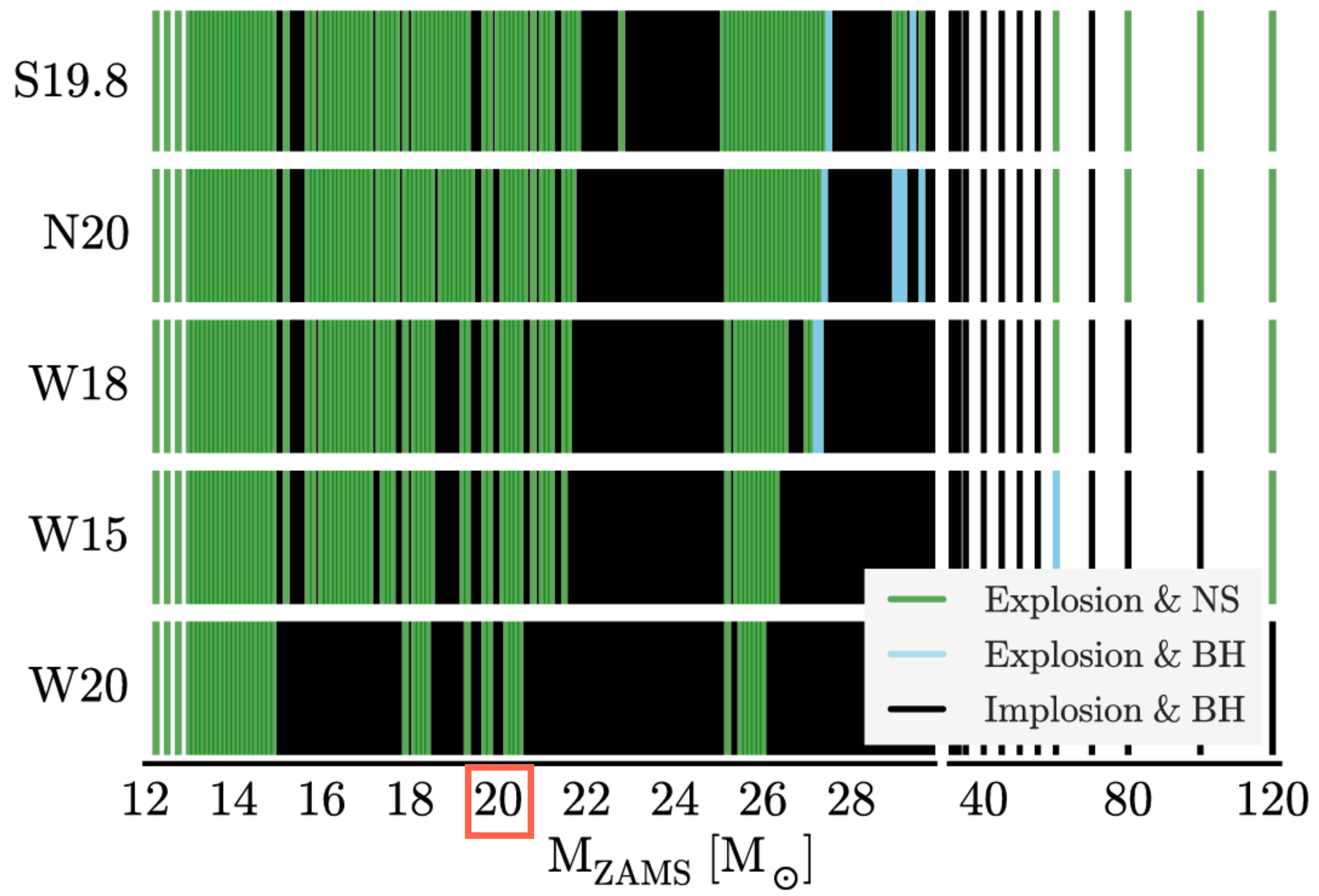
CCSN Mass Limit

- Set the maximum mass of progenitors for successful explosions to **18M$_{sun}$**.
  - Observationally, m_{min} ~ 8M$_{Sun}$ and m_{max} ~ 18M$_{sun}$ are supported.
  - There is a theoretical work that implies failed SNe above ~20M$_{sun}$.
- Many galactic chemical evolution schemes adopt a high m_{max} (50~100M$_{sun}$).
  - Our m_{max} =18M$_{Sun}$ assumption reduces the number of CCSNe to **~70%**.
  - Accordingly, the total amount of heavy elements is reduced to **~50%**.

S. J. Smartt, PASA 32 (2015)



T. Sukhbold et al., ApJ 821, 38 (2016)



New Chemical Evolution Model

- Proposed a new evolution model to compensate for the discrepancy in chemical abundance.
- Categorize galaxies into five and assume different initial mass functions (IMF) depending types.
- The fraction for BH formation from this model is **33~42%** (higher rate than many other DSNB models).

How star formation proceeds?

moderate mode

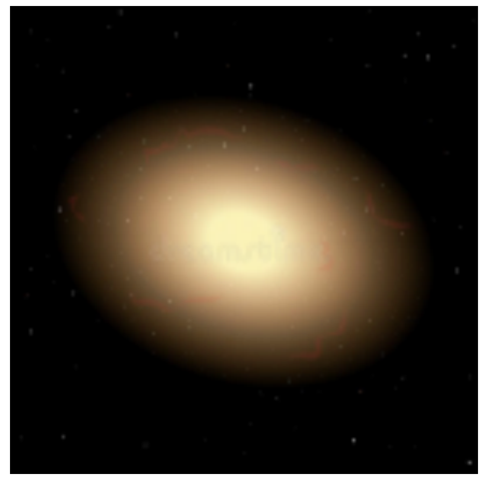
late-type galaxies (Sbc, Scd, Sdm)

Salpeter IMF

(x = −1.35)

bursting mode

early-type galaxies (E/S0, Sab)

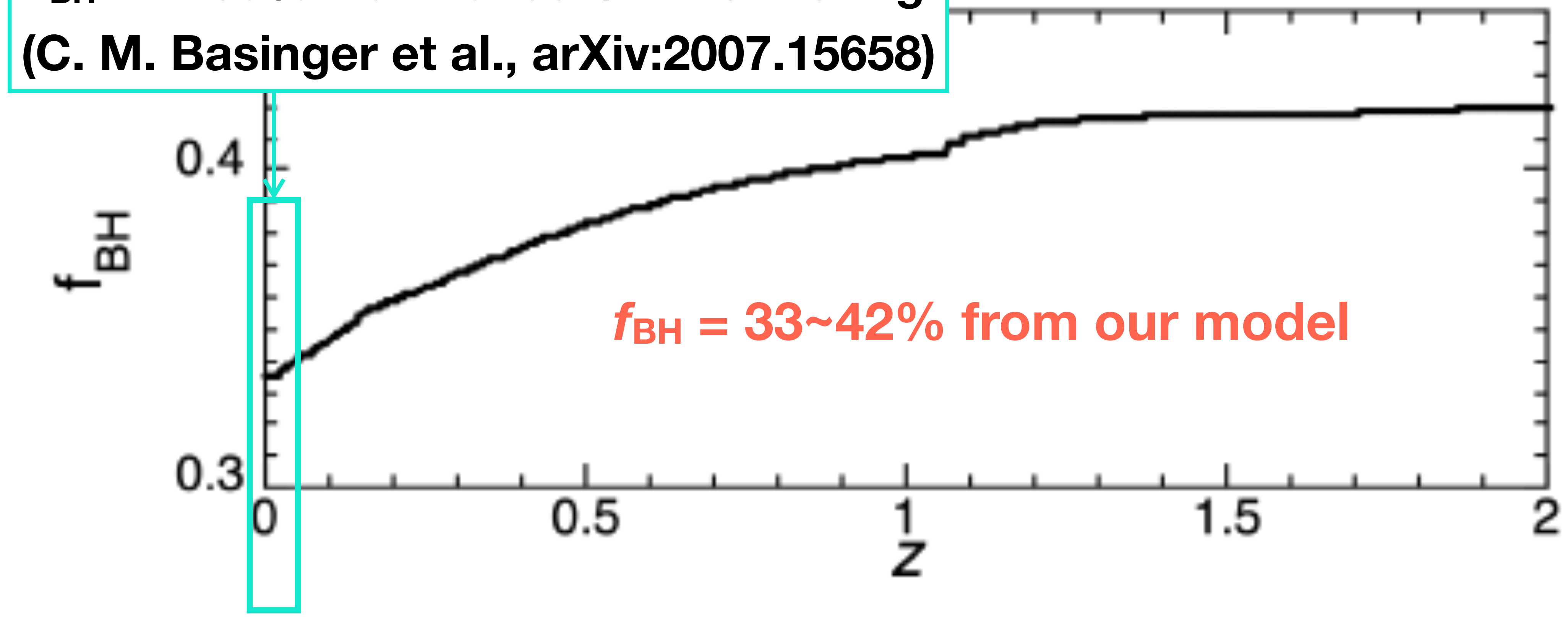


Flat IMF

(x = −0.9)

T. Tsujimoto, MNRAS 518, 3475 (2023)

f_{BH} = 4~39% from failed SN monitoring (C. M. Basinger et al., arXiv:2007.15658)

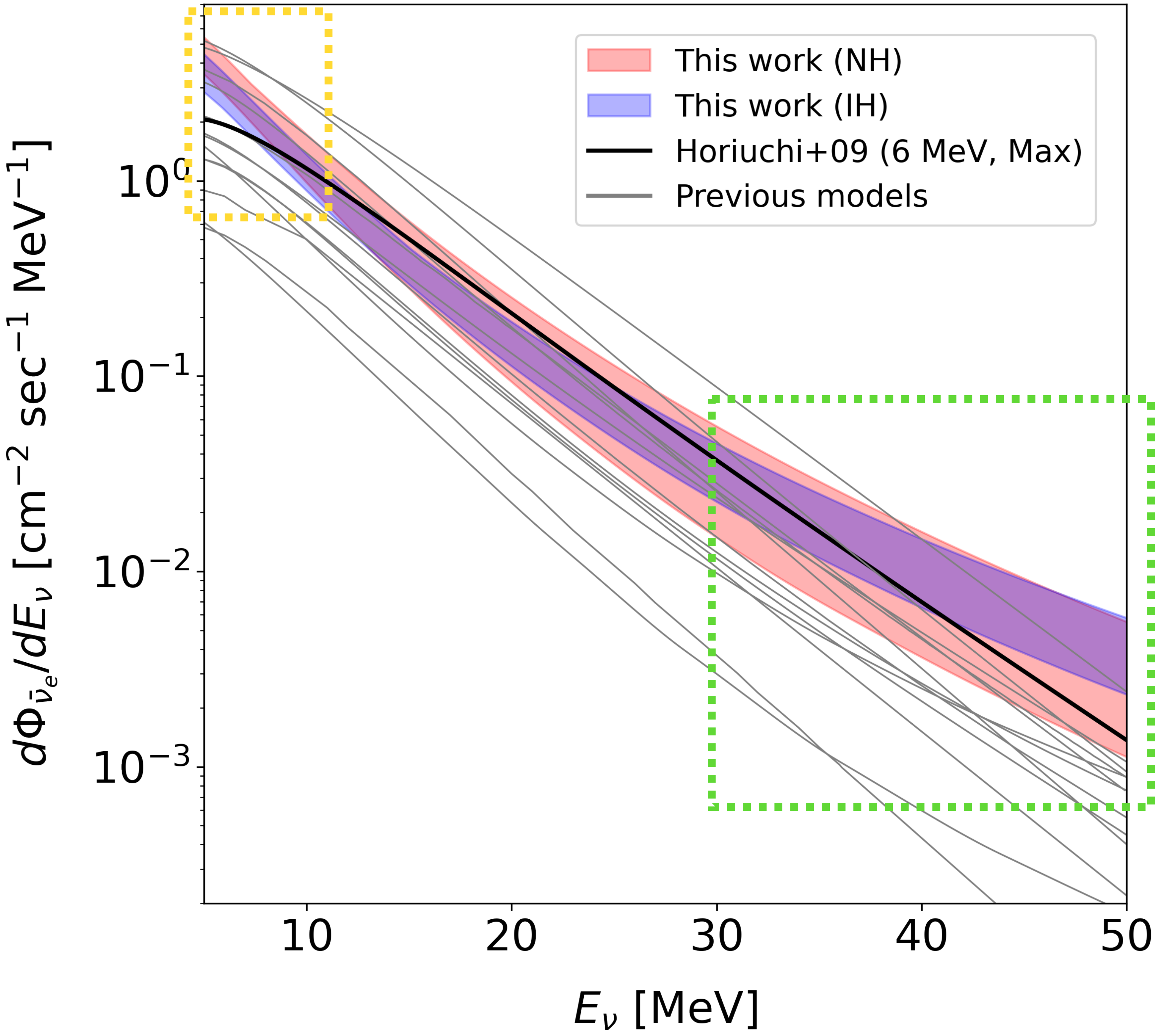


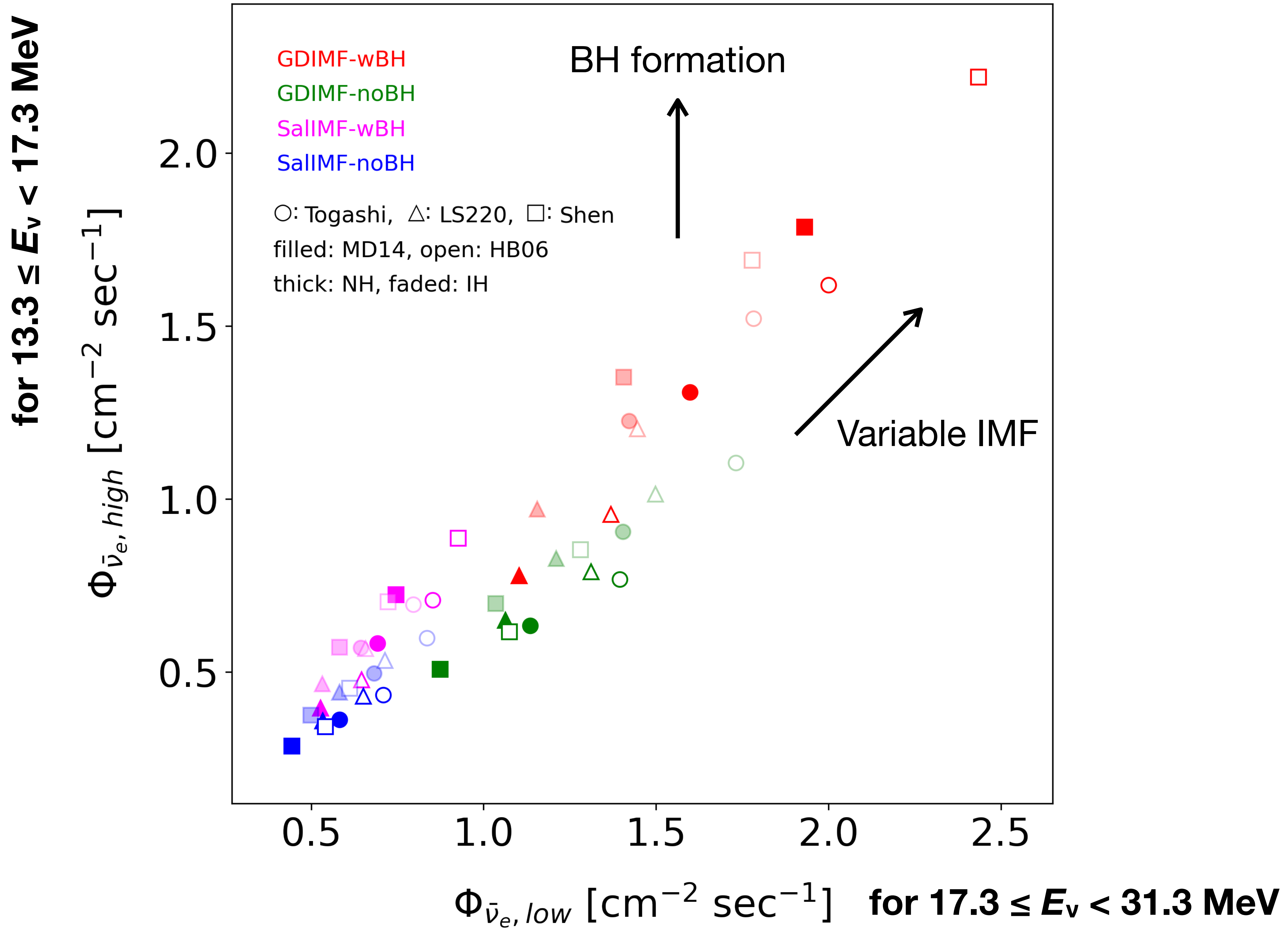
Our model nomenclature

Name	IMF form	BH treatment
GDIMF-wBH (ref.)	Variable	BHs for 18–100$M_\odot$
GDIMF-noBH	Variable	No BH
SalIMF-wBH	Salpeter	BHs for 18–100$M_\odot$
SalIMF-noBH	Salpeter	No BH

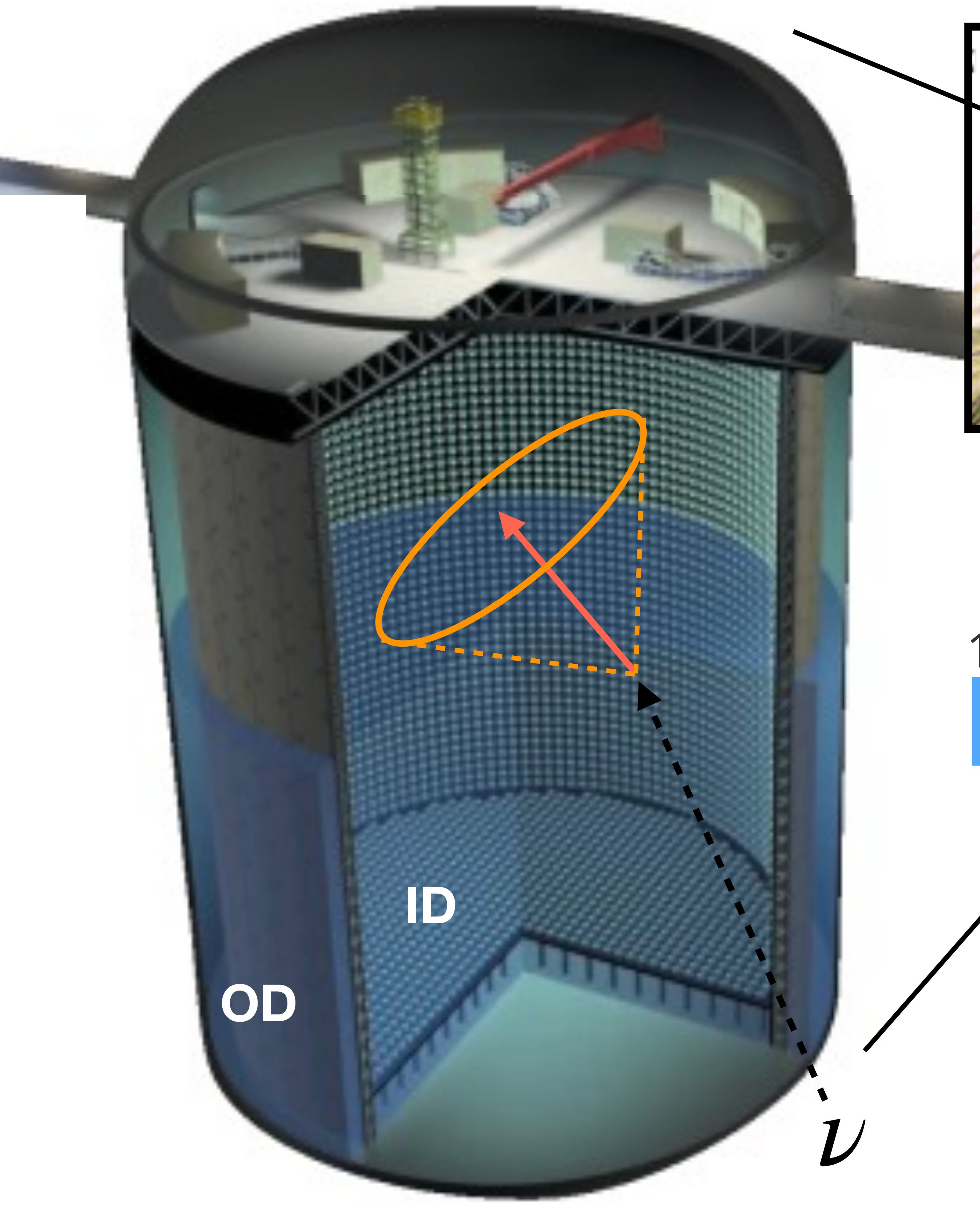
Resulting DSNB Flux

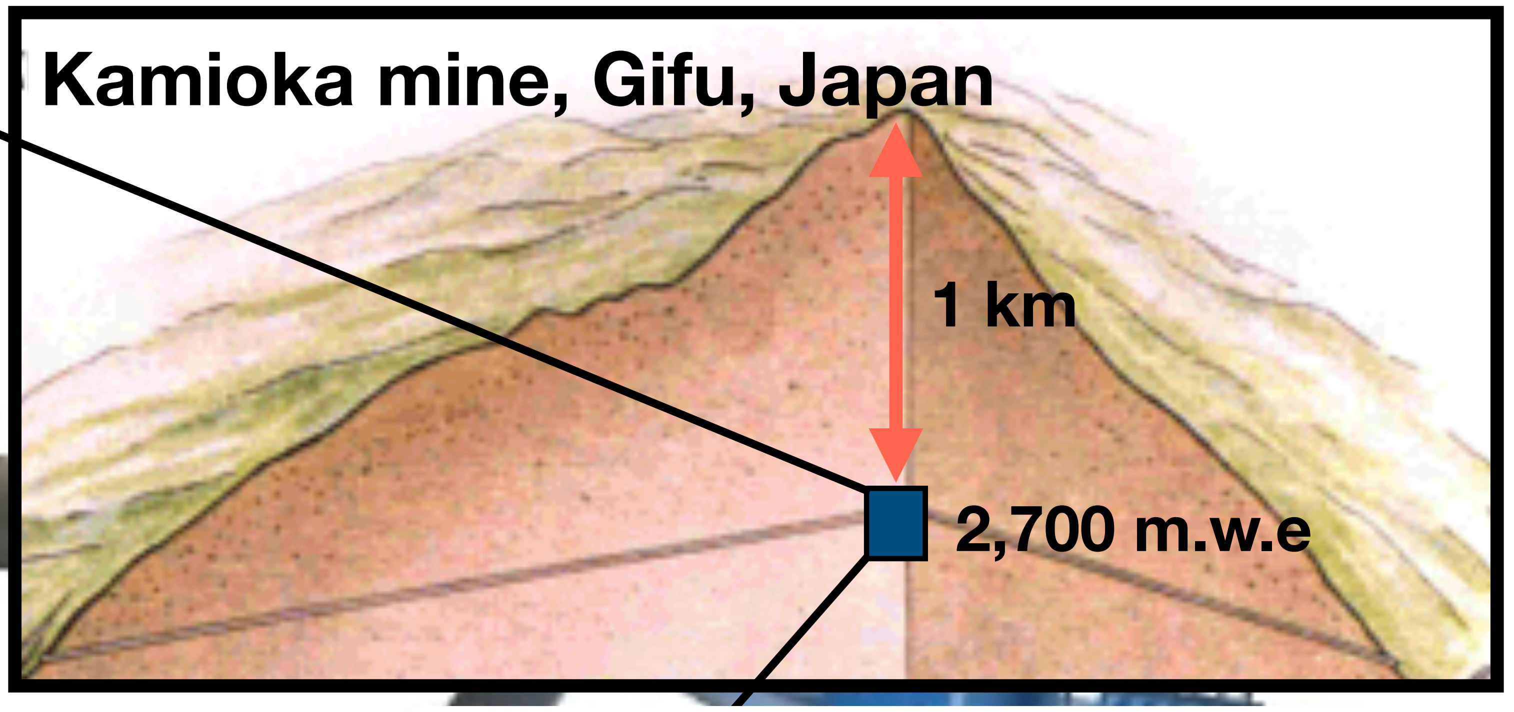
- Our model shows DSNB flux enhancements at high and low energies.
- High energy (>30 MeV): Large contribution from BH formation.
- Low energy (<10 MeV): Redshifted neutrinos from early-type galaxies with large CCSN rates.





Super-Kamiokande





Atmospheric muon rate ~2 Hz

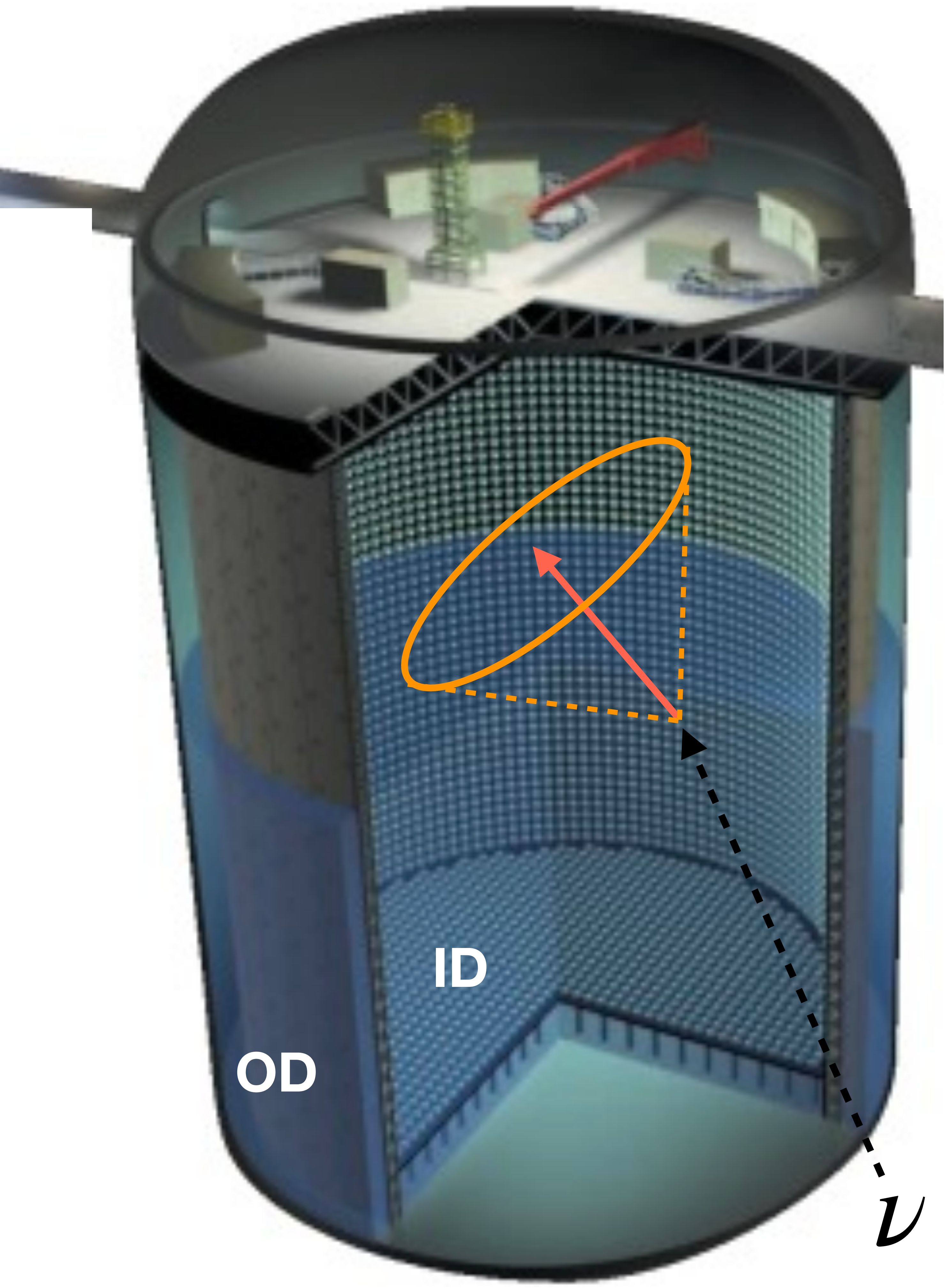
- 50 kton water (**22.5 kton** for analysis)
- **11,129** 20-inch PMTs (Inner Detector)
  → Physics event of interest
- **1,885** 8-inch PMTs (Outer Detector)
  → Background veto (muon etc)

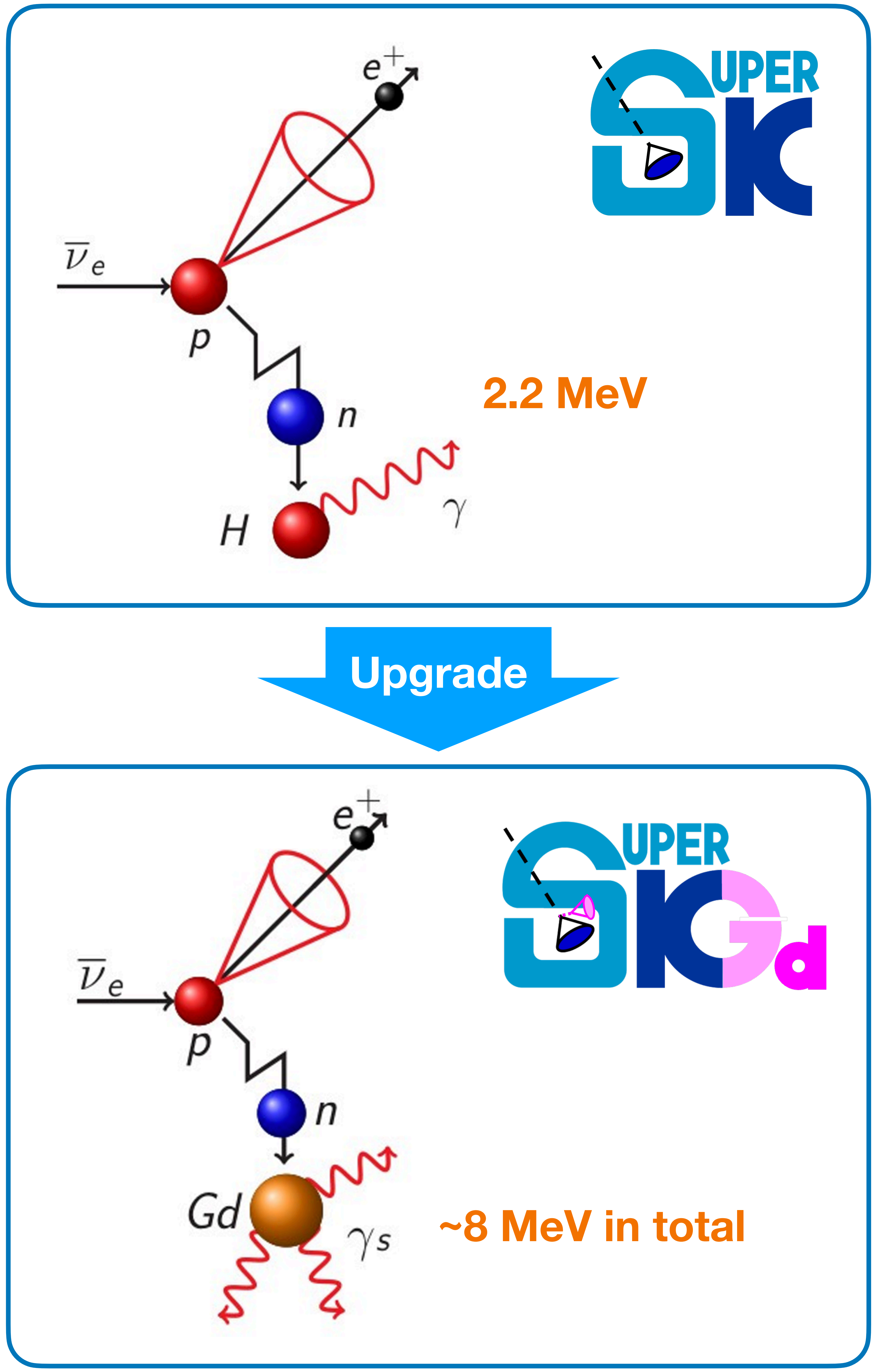
1996	2002	2006	2008	2019	2020	2022	2024
SK-I	SK-II	SK-III	SK-IV	SK-V	SK-VI	SK-VII	SK-VIII
	half photo coverage	·······→ ntag		·······→ Gd			

- 7 phases completed so far, and SK-VIII is on-going now.
- DSNB search performed multiple times.
  - SK-I to IV: published in [Physical Review D 104, 122002 (2021)]
  - SK-VI & VII: presented at [NEUTRINO 2024] (paper in prep)
  - SK-I through VIII: study in progress

Super-Kamiokande with Gadolinium

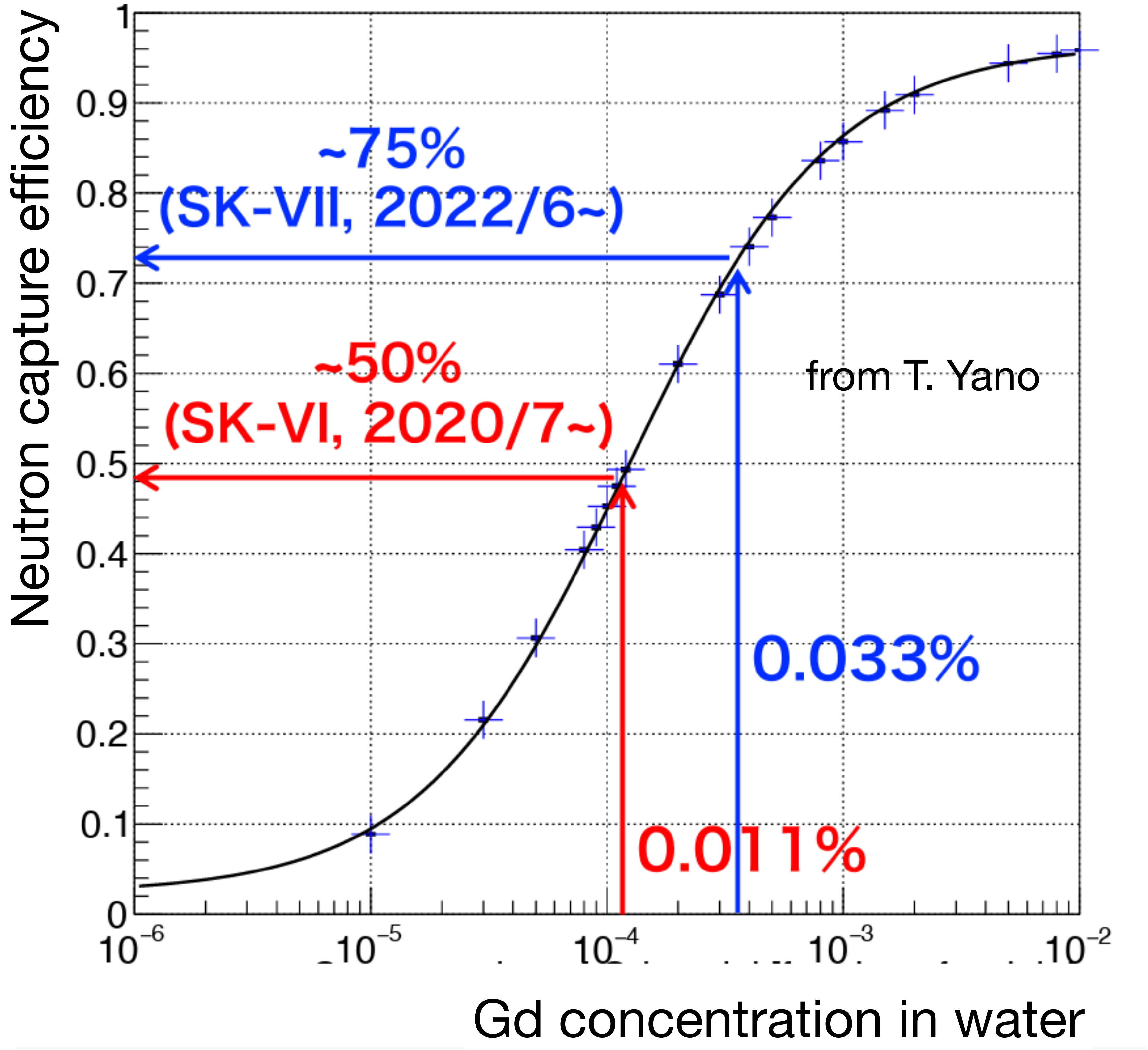
K. Abe et al. (SK Collaboration), NIMA 1027, 166248 (2022)
M. Harada et al. (SK Collaboration), ApJL 951, L27 (2023)
K. Abe et al. (SK Collaboration), NIMA 1065, 169480 (2024)





Gd loaded to improve neutron detection.

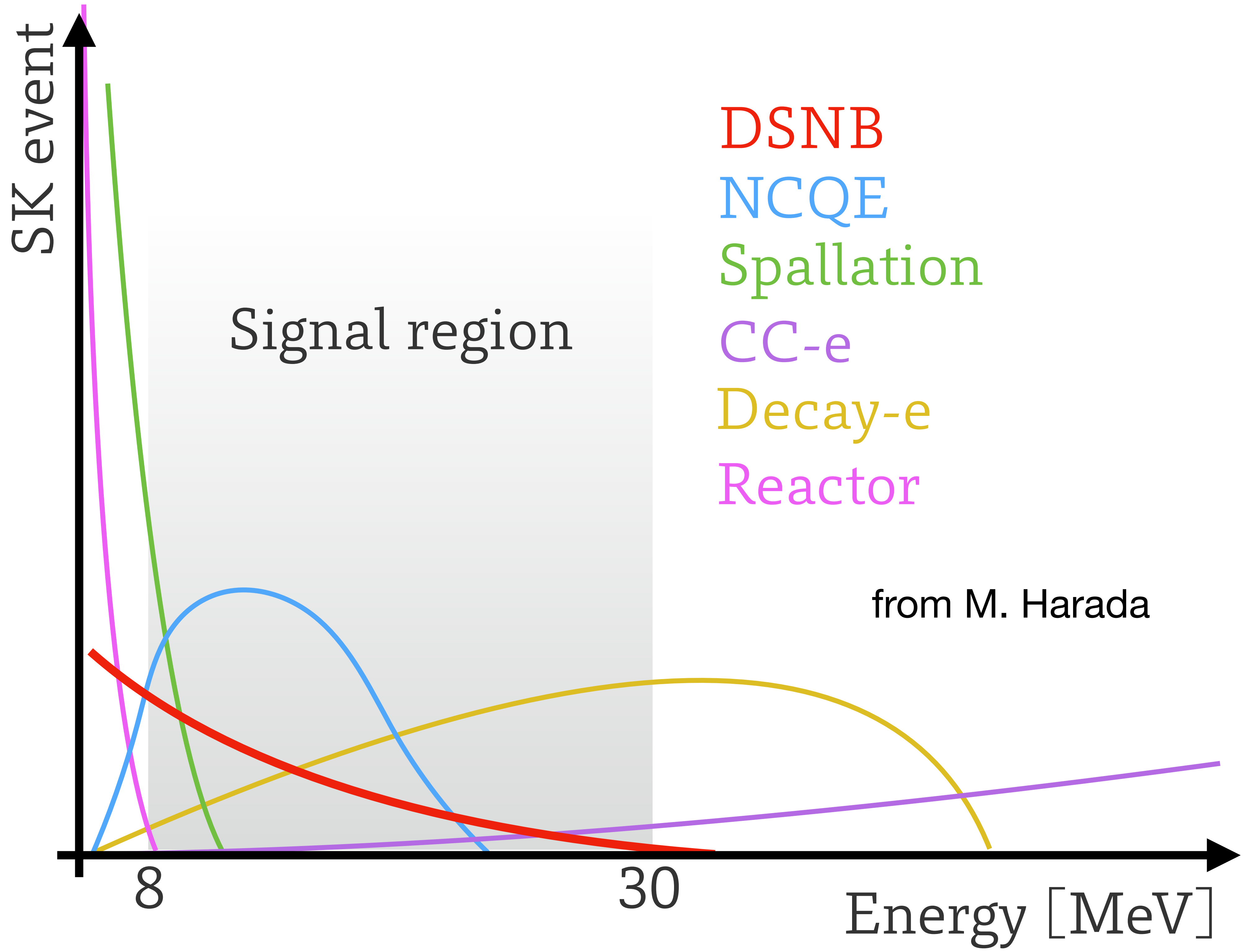
- Capture Xsec: 0.33 barn → **~49 kbarn**
- γ energy: 2.2 MeV → **~8 MeV**
- 0.011% (SK-VI), 0.033% (SK-VII~)



Signal and Background

- Signal = **inverse beta decay (IBD)**, $\bar{\nu}_e + p \rightarrow e^+ + n$ (dominant channel)
  - e^+ = "*prompt*" signal (main energy range: **8~30 MeV**)
  - **n** = "*delayed*" signal via **γ-ray(s)** from thermal capture on hydrogen or gadolinium

- Many types of backgrounds mimicking this signature.
  - Atmospheric neutrinos (NCQE, CC)
  - Radioactive isotopes produced by atmospheric muons
  - Solar neutrinos
  - Reactor neutrinos



from M. Harada