

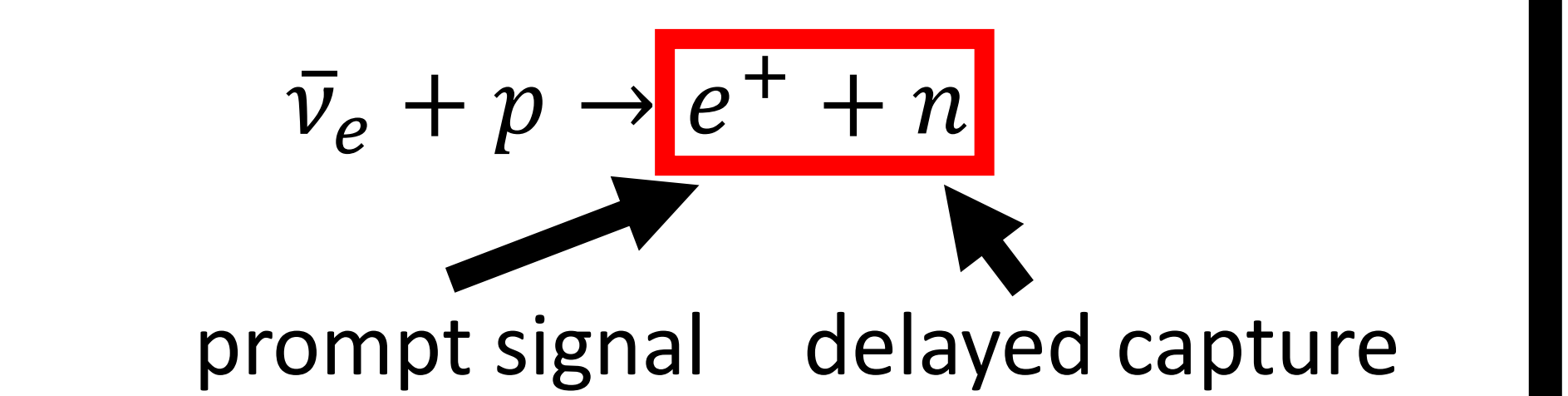
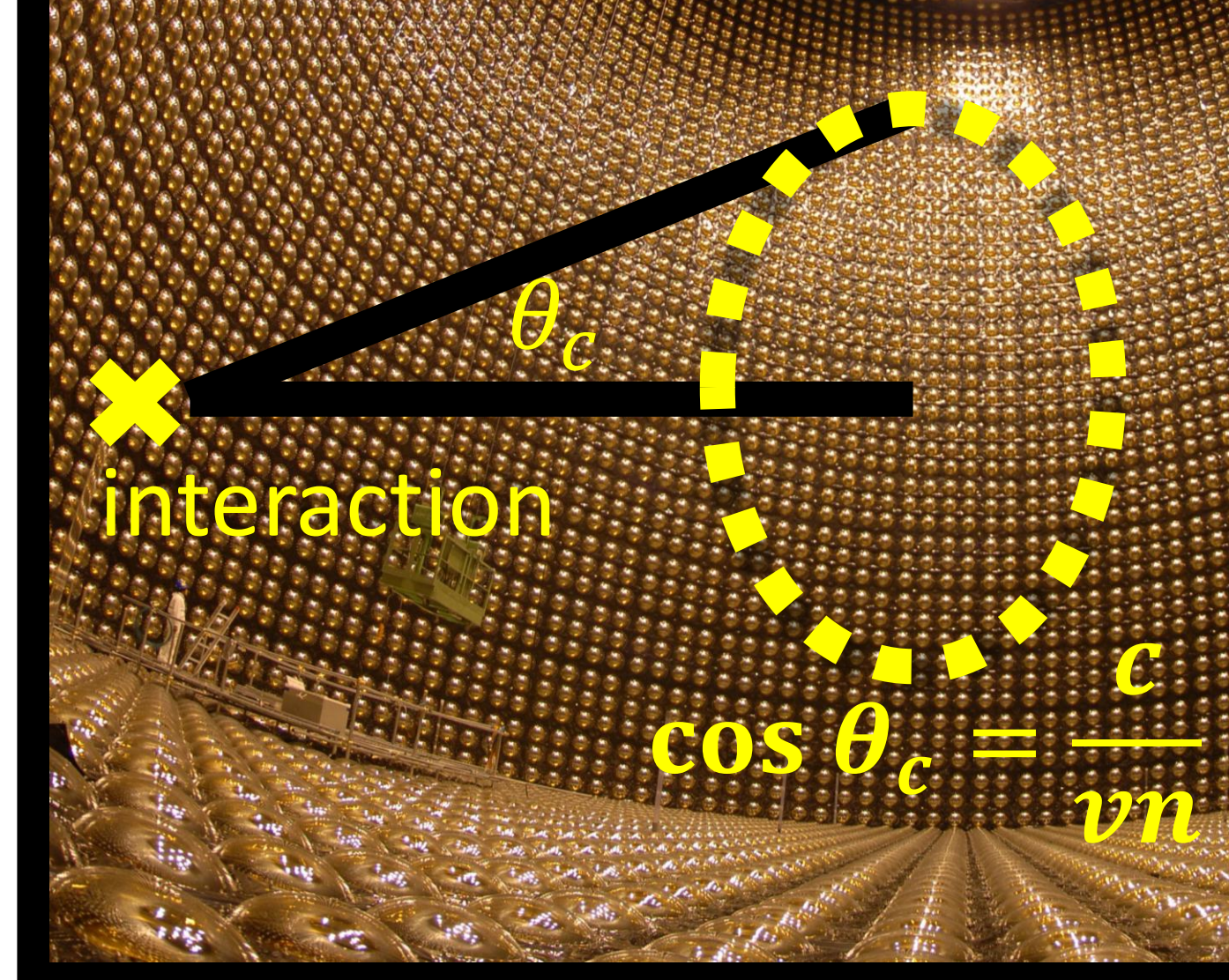


Neutrinos from every core-collapse supernova in the universe's history form the **Diffuse Supernova Neutrino Background (DSNB)**.

$$\frac{d\Phi_\alpha}{dE} = \int \int R_{SN}(z, M) \left[ \frac{dF_\alpha(E(1+z), M)}{dM} \right] \left| c \frac{dt}{dz} \right| dz dM$$

- The three main parts are the **supernova rate**, the neutrino **flux per supernova**, and the **cosmological expansion** of the universe.
- The **star formation history** of the universe directly impacts the CCSN rate, and the **fraction of CCSN forming black holes** impacts the shape of the DSNB spectrum.

Hyper-Kamiokande (HK) is the next-generation water Cherenkov experiment in Japan, aiming to **measure the DSNB** through inverse  $\beta$ -decay.



- With an analysis threshold at MeV-scale, the prompt **positrons create Cherenkov radiation** with large opening angle ( $\theta_c \approx 42^\circ$ ).
- Gammas released from **neutron captures** on free protons are observed  $\mathcal{O}(100)$   $\mu$ s later.

We **estimate the spallation backgrounds in HK**, leaning on our understanding of SK cosmic ray muon backgrounds.

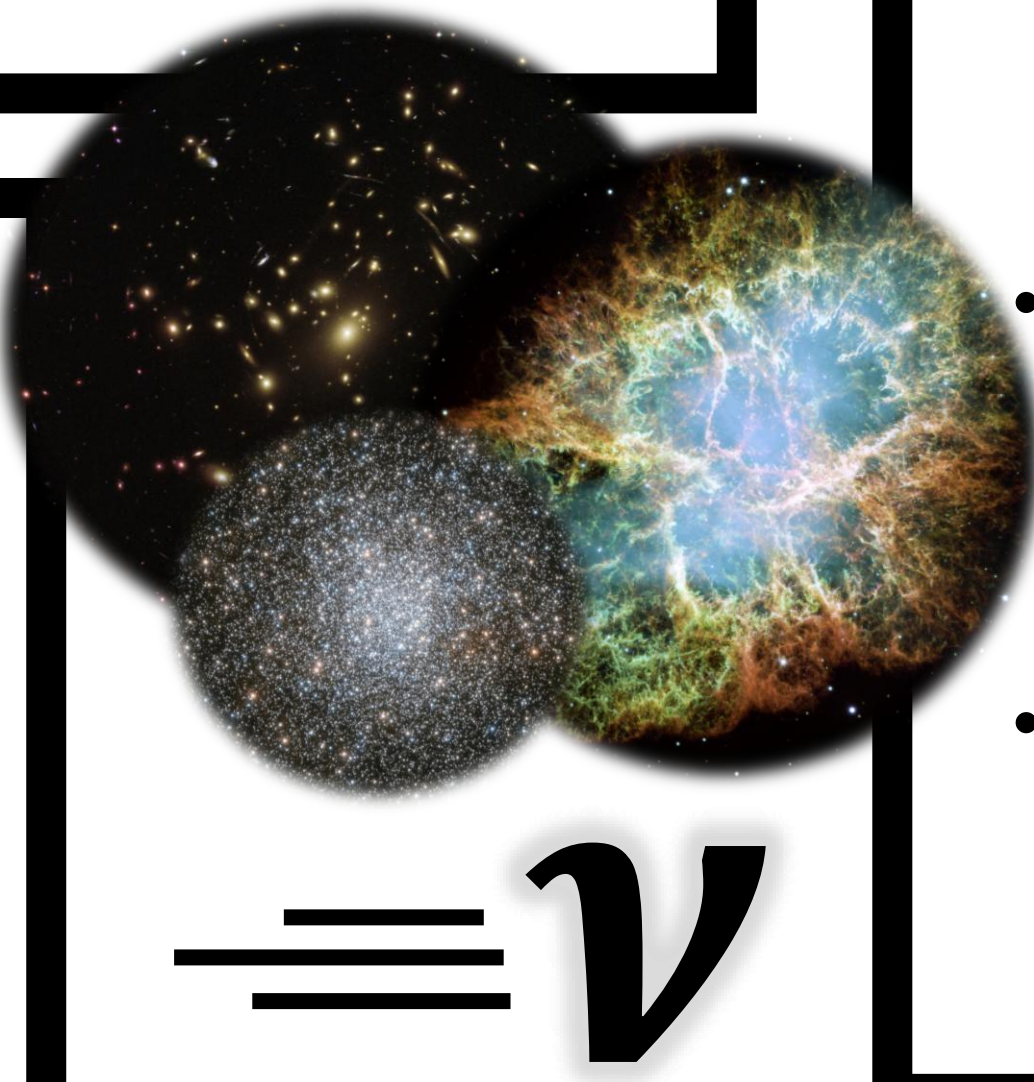
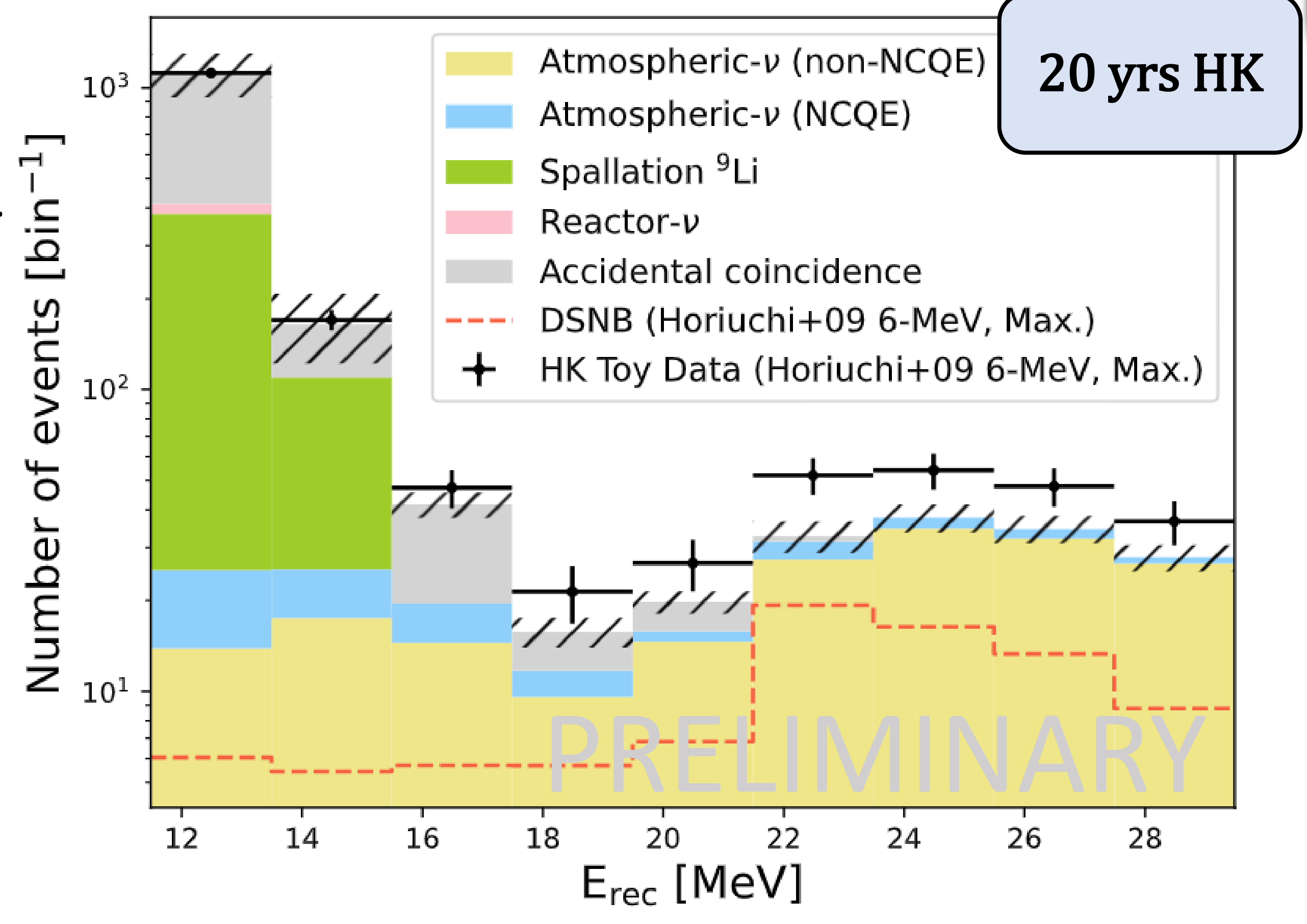
$$r_{\text{spall}} \equiv \frac{R_{\text{spall}}(\text{HK})}{R_{\text{spall}}(\text{SK})} = \frac{R_{\text{spall,prod}}(\text{HK})}{R_{\text{spall,prod}}(\text{SK})} \cdot \frac{f_{\text{spall}}(\text{HK})}{f_{\text{spall}}(\text{SK})} = (4 \pm 1) \left( \frac{0.039}{0.012} \right) = 13 \pm 3$$

- We should take into account the relative spallation production per unit volume and the efficacy of spallation reduction compared between HK and SK.
- The rate  $R_{\text{spall,prod}}$  of **spallation production per unit volume** in HK is expected to be around 4 times that of SK.
- Assuming a similar performance of background reduction as in SK solar neutrino analyses, **the remaining fraction of spallation  $f_{\text{spall}}$  in HK** will be around 3 times that of SK.
- The resulting  $r_{\text{spall}}$  ratio is around 13 times the spallation levels per unit volume in HK compared to SK.

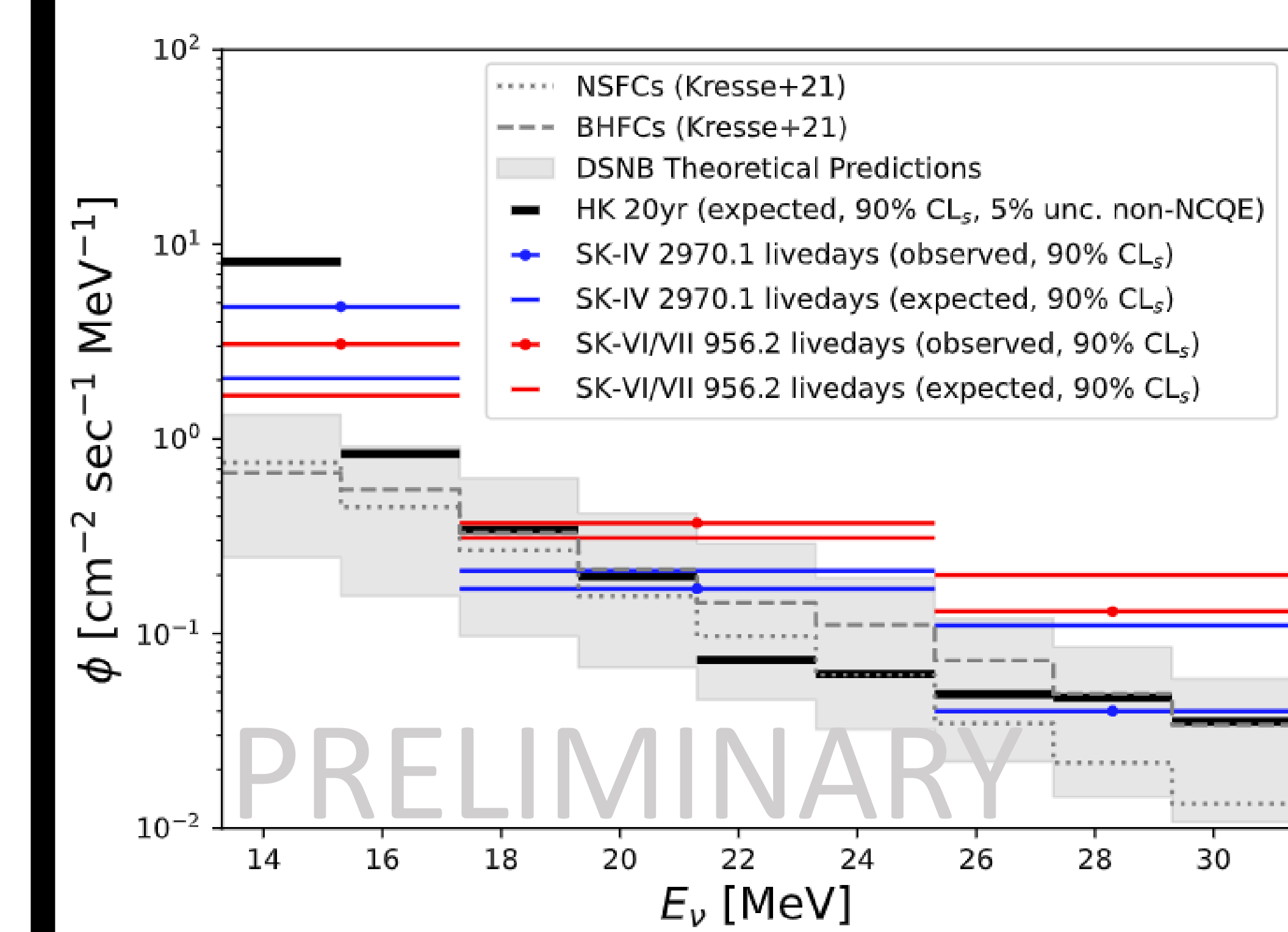
Four main reduction steps are dedicated to select final DSNB candidate events.

- 1st Reduction** • To **reduce radioactive backgrounds** (near detector walls) and **keep well-reconstructed events** (in **fiducial volume**).
- 2nd Reduction** • To remove events associated (in time and location) with cosmic ray muons generating **spallation backgrounds**.
- 3rd Reduction** • To target **atmospheric neutrino backgrounds** based on event topology, such as Cherenkov opening angle.
- 4th Reduction** • To select events having uniquely **one neutron capture**.

We show the **expected background levels** (stacked), a **nominal DSNB prediction** (red, dashed) in overlay, and a **toy dataset** given the expected backgrounds and nominal DSNB prediction for reference.



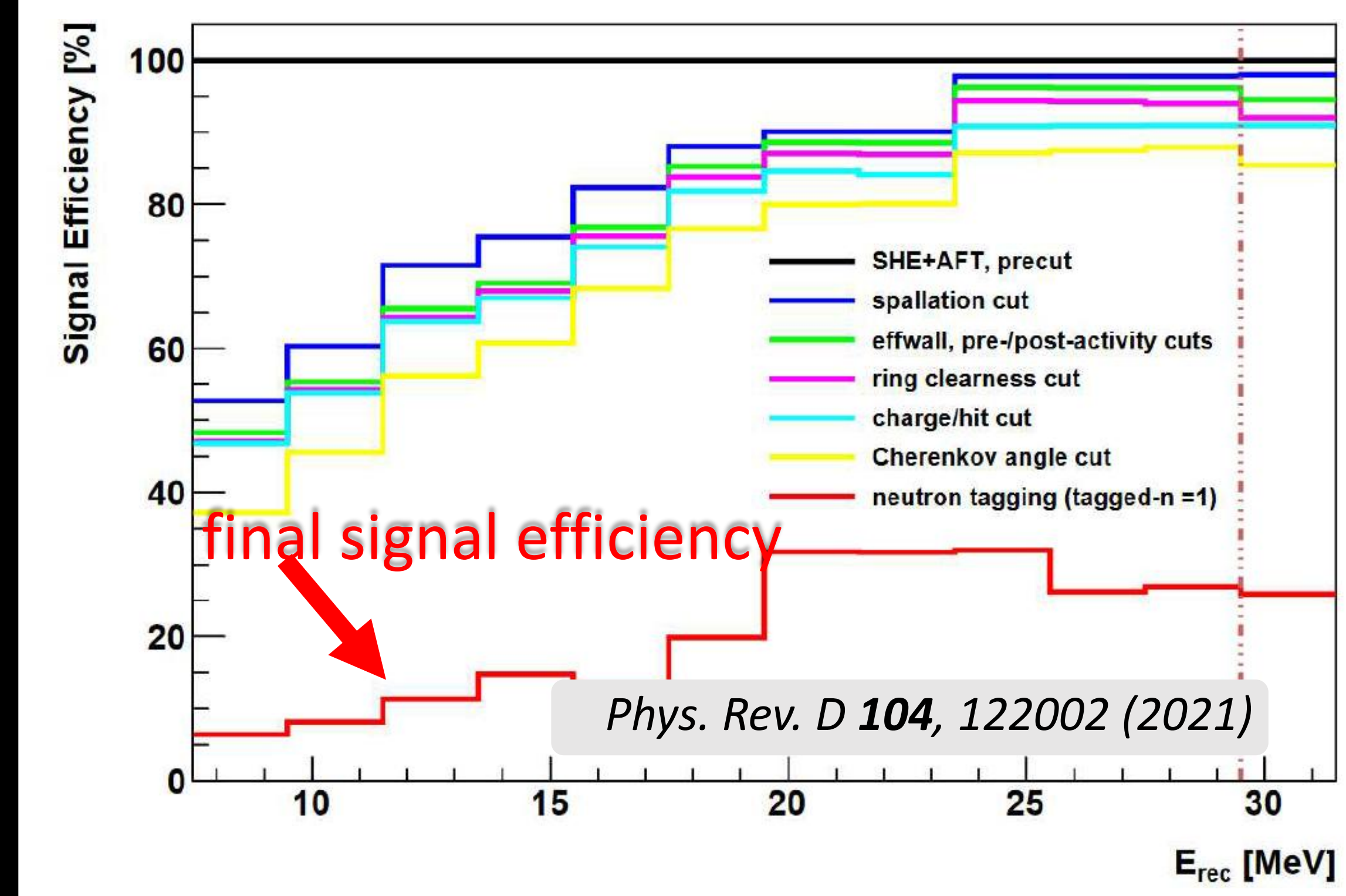
The **expected 90% C.L. upper limits per energy bin** are plotted against model predictions to demonstrate the **anticipated sensitivity of HK to the DSNB**.



- DSNB model predictions considering specifically **neutron star-forming (NSFCs)** and **black hole-forming collapses (BHFCs)** are in dotted and dashed lines, respectively.
- A band of **modern DSNB theoretical predictions** is given in gray.
- Assuming a 5% uncertainty on atmospheric neutrino backgrounds other than neutral-current quasi-elastic (NCQE) events, we **plot 20 years of HK (black)** against SK published expected and observed upper limits.

We expect HK to have **strong sensitivity** to the DSNB **between 20 and 30 MeV** where it can **probe the higher energies** at which NS-vs-BHFCs start to alter the DSNB spectrum.

We refer to the **neutron tagging performance, atmospheric backgrounds, and systematic uncertainties of Super-Kamiokande (SK) pure-water phases** as a **baseline for HK**.



- We take similar reduction cuts and their associated **signal/IBD final efficiencies** as the nominal predictions for the HK DSNB search. The final levels are shown as a red line after all other reduction steps.
- As in SK DSNB searches, we assume a 5% uncertainty on **neutron mis-tagging rates**, a 68% uncertainty on atmospheric neutral-current quasi-elastic (**NCQE**) **backgrounds**, and expect to do better than the  $\sim 20\%$  uncertainty on **non-NCQE backgrounds** from the SK pure-water phases.
- In SK pure-water phases, a Boosted Decision Tree (BDT) was employed to **tag neutrons**, and we assume its performance for this HK study.
- As in SK, an upgrade of HK to **gadolinium-doping** ("HK-Gd") would greatly enhance both IBD efficiency and background suppression.