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N°218

Diffuse Supernova Neutrino Background

Insights from Super-K & Prospects with Hyper-K

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on behalf of the Super-Kamiokande & Hyper-Kamiokande collaborations

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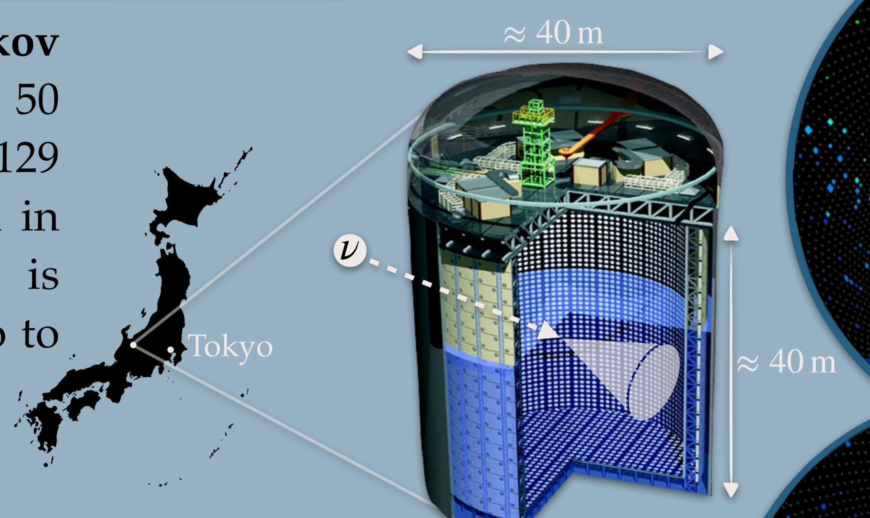
Super & Hyper-Kamiokande

SK is the world largest **Cherenkov detector**. The tank is filled with 50 kton of water surrounded by 11 129 **P**hoto**M**ultiplier **T**ubes of 50 cm in diameter in its inner part. It is located 1 km under the Mt. Ikeno to shield from cosmic muons.



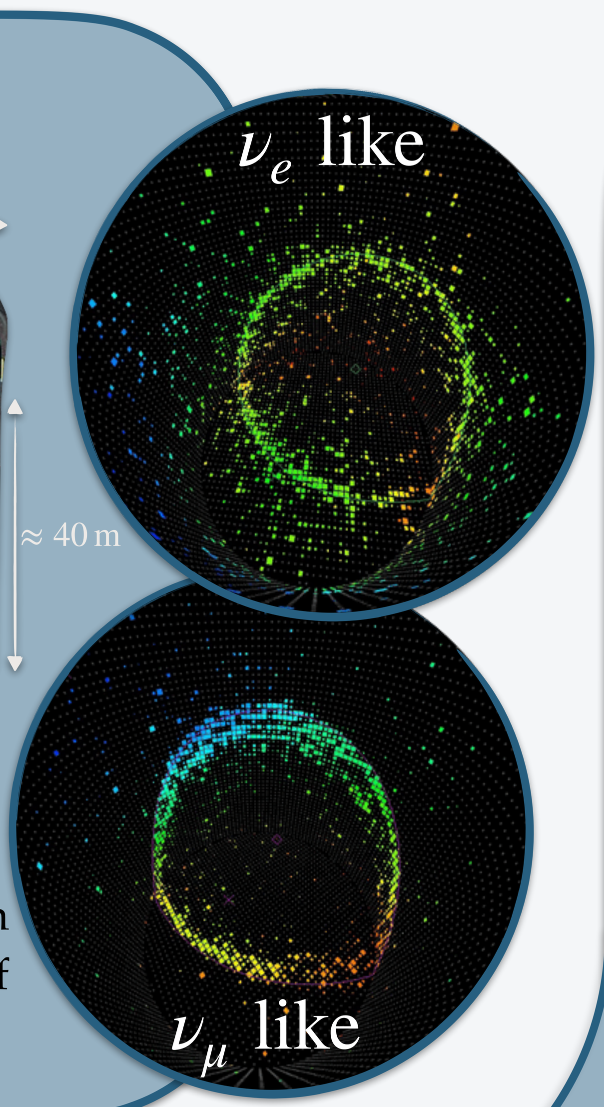
Since 2022:

0.03% **Gadolinium** by mass in water.

$\Longrightarrow$ **Improves neutron tagging efficiency**

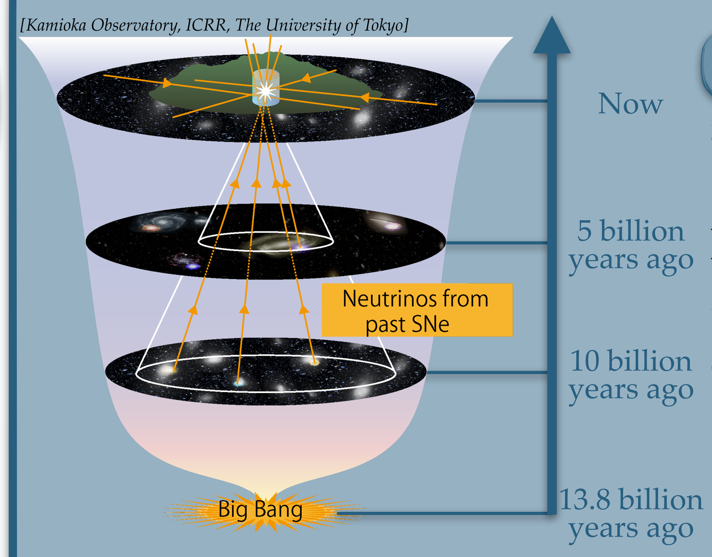
Kamiokande saga continues: HK (2027), will be its successor.

Features: 258 kton of water ($\times \approx 8$ in fiducial mass), $\approx$70 m in diameter and height. Inner detector equipped with 20 000 PMTs of 50 cm with improved performance.



Diffuse Supernova Neutrino Background

Explosion of a massive star with $M \gtrsim 8\ M_\odot \longrightarrow$ Neutron Star or Black Hole



Core-collapse SuperNovæ are powerful sources of ν! $\approx 99\,\%$ of the released energy ($\sim 10^{59}$ MeV) is carried by them, in just ~ 10 s. It emits $\sim 10^{58}$ ν but two factors make it difficult to detect a distant (CC)SN and constrain us to observe only galactic SNe:

- Flux decreases with distance ($\propto r^{-2}$)
- Small cross-section: $\sigma \approx \frac{p_e E_e}{\mathrm{MeV}^2}\ 10^{-43}\ \mathrm{cm}^2$

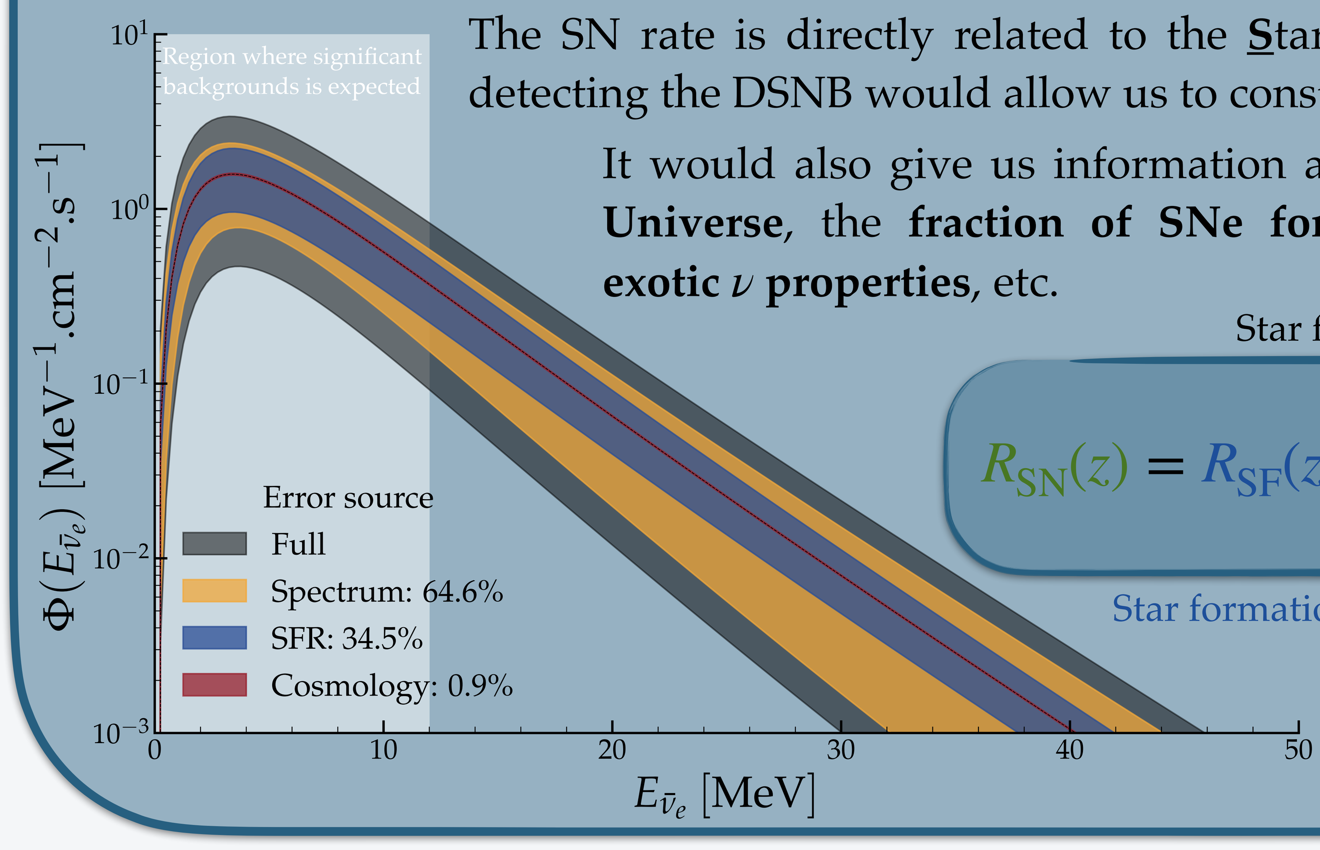
There is another source of astrophysical ν which is **isotropic** and **time-independent**.

$\Longrightarrow$ **Diffuse Supernova Neutrino Background** = ν_α and $\bar{\nu}_\alpha$ from every SN in the observable Universe since its beginning. Estimated modern rate of SNe since the beginning of the Universe: ~ 1 SN/s

SN neutrino emission spectrum

DSNB flux
$$\Phi(E_\nu) = \int_{z_{\text{today}}=0}^{z_{\max}} R_{\text{SN}}(z)\, \frac{\mathrm{d}N\left[E_\nu(1+z)\right]}{\mathrm{d}E_\nu}\, \frac{c\,\mathrm{d}z}{H(z)}$$

Redshift-dependent SN rate — Universe expansion



The SN rate is directly related to the **S**tar **F**ormation **R**ate. Thus, detecting the DSNB would allow us to constrain SFR models.

It would also give us information about the **history of our Universe**, the **fraction of SNe forming black holes** f_{BH}, **exotic ν properties**, etc.

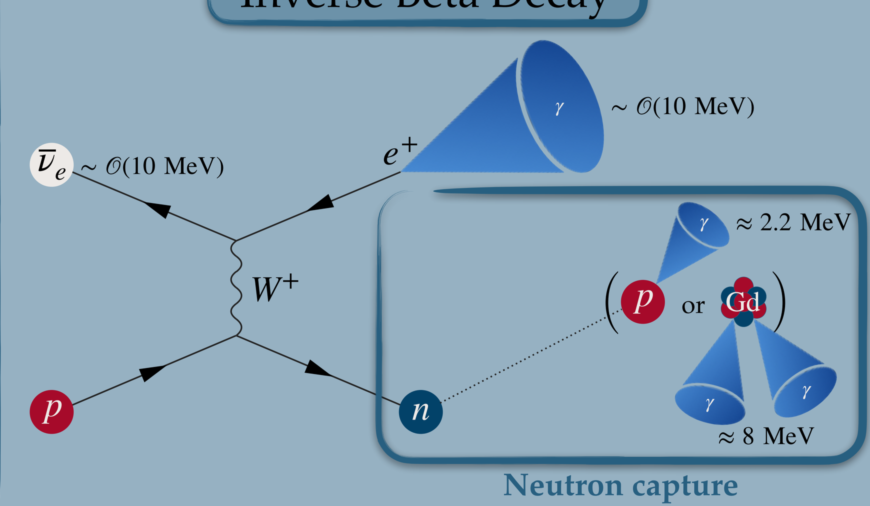
Star fraction that can generate SNe
$$R_{\text{SN}}(z) = R_{\text{SF}}(z) \frac{\int_{\text{SN}} \psi(M)\,\mathrm{d}M}{\int_{\text{Stars}} M\,\psi(M)\,\mathrm{d}M}$$
Star formation rate

DSNB Spectral Analysis with SK

Unbinned & model-dependent analysis. Goal: Fit **DSNB + expected background spectra** (atmospheric ν and spallation) to energy distribution of data.

The parameter space is divided into **6 regions** according to the **Cherenkov angle θ_C of the prompt e^+ event** (low, medium, high θ_C) and the **number of tagged neutrons** $N_{\text{tagged }n}$ ($\neq 1$, $= 1$).

Main detection channel
Inverse Beta Decay

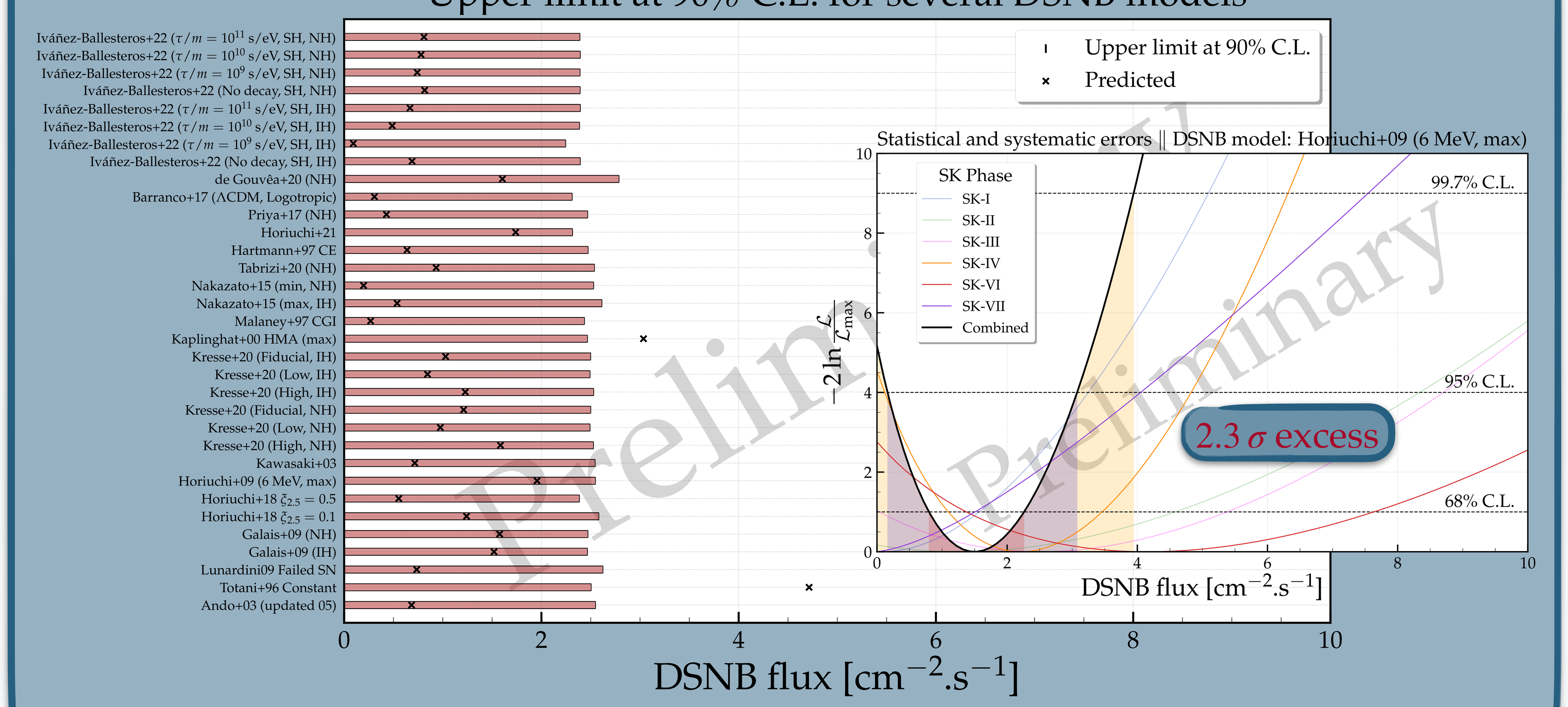


Once we have the PDF$_j$, we fit (simultaneously in the 6 regions) the number of observed events (N_s, $\vec{N}_b$) that maximizes the following extended likelihood:

$$\mathscr{L}\left(\vec{E}\,|\,N_s, \vec{N}_b, \vec{\varepsilon}\right) = e^{-\sum_{j\in s+b} N_j} \prod_{i=1}^{N_{\text{data}}} \sum_{j\in s+b} N_j\,\text{PDF}_j(E^i, \theta_C^i, N^i_{\text{tagged }n}\,|\,\vec{\varepsilon})$$

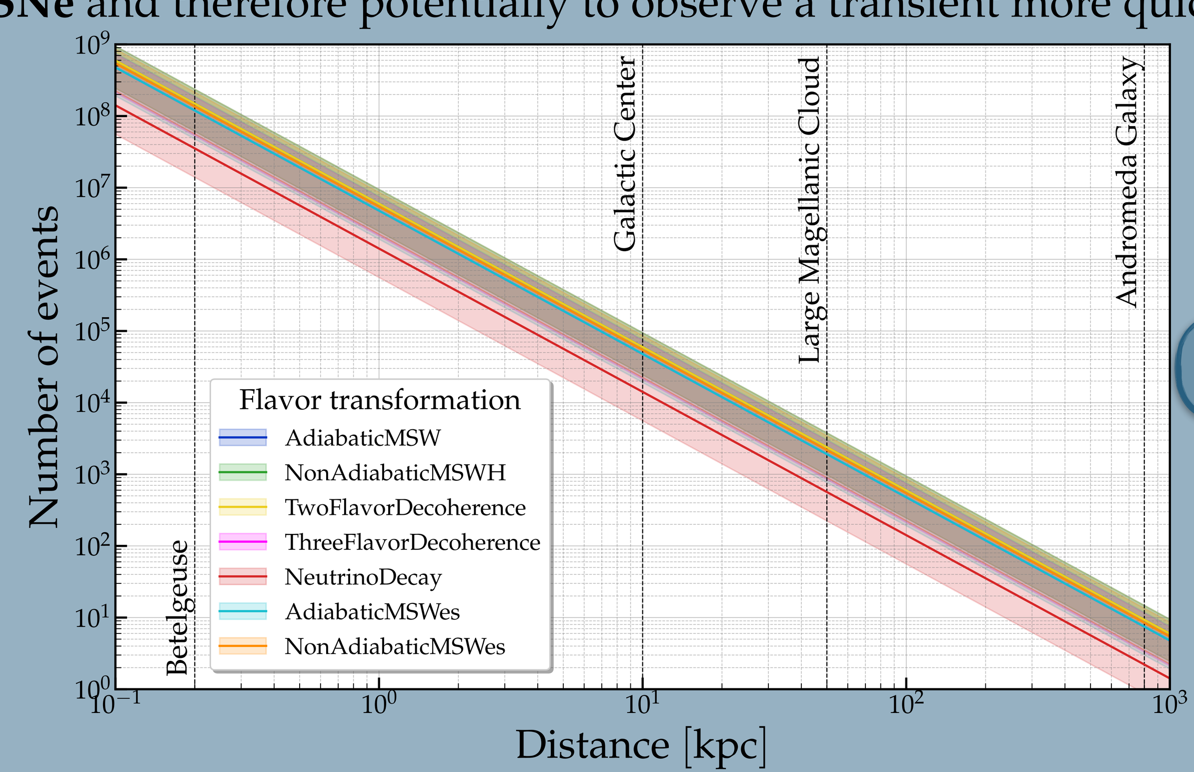
Systematics are encoded as **shape nuisance parameters**

Upper limit at 90% C.L. for several DSNB models



SK sees an excess above backgrounds but due to limited statistics, the **results are rather model-independent**. HK will enable us to push the limits of this study by **probing the shape of the spectrum** and **discriminating between models**.

Detecting the nearby SN would enable us to reduce the error we have on the ν emission spectra from a SN and therefore to discriminate the DSNB models much better and thus infer information about its component parameters. HK will enable us to be **sensitive to extra-galactic SNe** and therefore potentially to observe a transient more quickly.

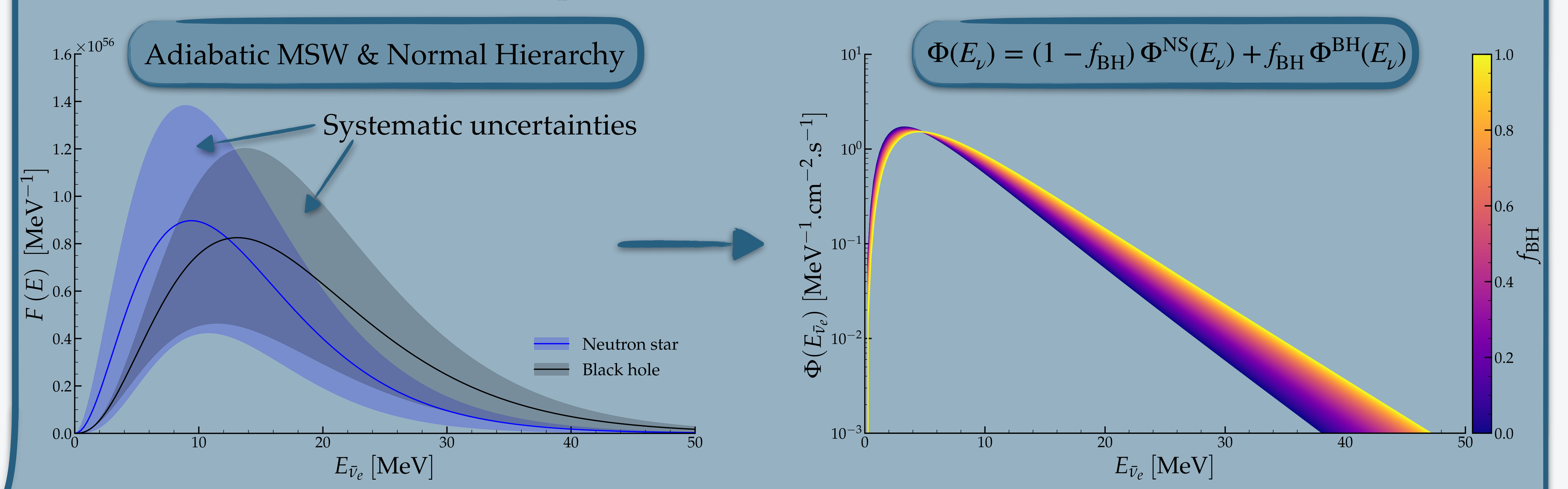


Black Hole & Normal Hierarchy

CCSN & DSNB Phenomenology with HK

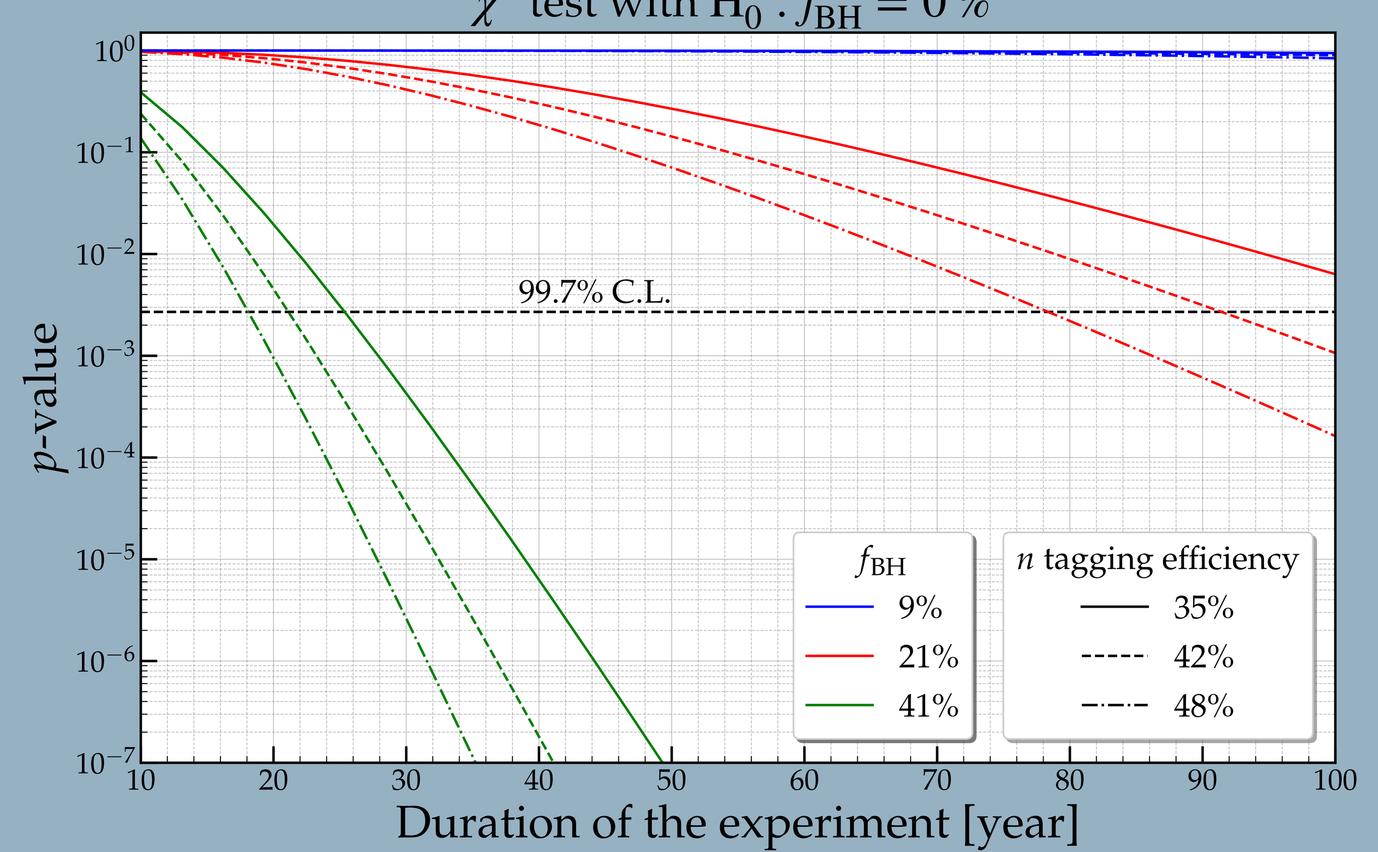
Hidden in $\int_{\text{SN}} \psi(M)\,\mathrm{d}M$

Rather than trying to distinguish between the different **SN mass sub-intervals** for Φ, we hide our lack of understanding of the SN mechanism in f_{BH}. In order to include knowledge of SN simulations in Φ, SNEWPY[1] ($\sim$ 700 simulations from 11 models) was used, from which two fiducial spectra (NS & BH) of ν emission were defined.



The only scenario that can be observed with a significance of $3\,\sigma$ in a reasonable time (18 years) is the most optimistic one[2] with a $f_{\text{BH}} = 41\,\%$.

χ^2 test with $\text{H}_0 : f_{\text{BH}} = 0\,\%$



Prospects: Re-evaluation of systematic uncertainties $\Rightarrow$ **Reduced by $\gtrsim 2$**, which would **proportionally reduce the durations required to exclude H_0**.

References: **[1]** A. L. Baxter et al., 2022 ApJ 925 107 | **[2]** P. Iváñez-Ballesteros and M. C. Volpe, Phys. Rev. D 107, 023017