High Energy Astrophysical Neutrino Flux and Galactic Center Dark Matter Annihilation Search with Hyper-Kamiokande

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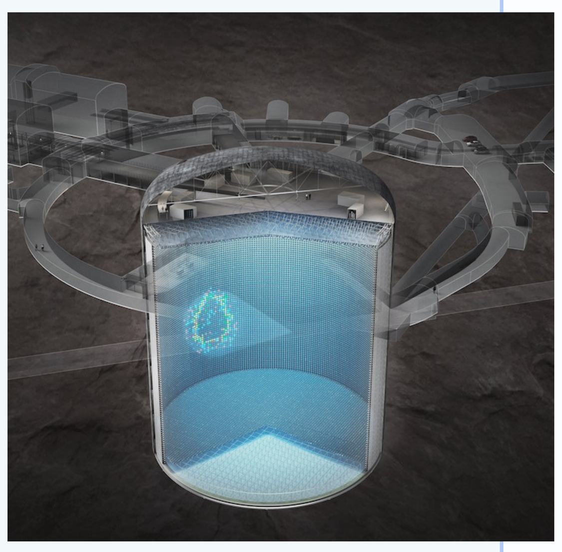
Introduction

- Hyper-Kamiokande (HK) is the next-generation underground water Cherenkov experiment.
- Far detector will be located in Mount Niyugo-yama, Tochibora site, Japan, overburden by 600 m of rock. It consists of a cylindrical tank with a diameter of 68 m and 71 m height, that will be filled with ∼260 kton of ultra-pure water, ∼190 kton of fiducial mass.
- 20,000 improved 50 cm PMTs will be installed, together with 800 mPMTs modules, each of which will allocate 19 8 cm PMTs, improving the direction reconstruction and the detector sensitivity.
- HK will have excellent sensitivity to ν oscillation parameters as well as to detect ν coming from different sources. We show here its **potential to study astrophysical high energy neutrinos up to TeV energy range.** HK will also be well positioned to perform **indirect Dark Matter (DM) searches** [1].
- Both, the astrophysical ν flux and DM searches, are limited by atmospheric neutrino background.
- Monte Carlo simulations from [3], enhanced with Super-Kamiokande (SK) reports [4] and [11] to study astrophysical flux and DM sensitivity.



Schematic view of HK.

Dark Matter Annihilation from Galactic Center

- Neutrinos can be generated when DM particles χ annihilate in dense regions, such as the Milky Way's Galactic Center (GC).
- The expected flux at Earth is

$$\frac{\mathrm{d}^2\Phi_\nu}{\mathrm{d}E_\nu\,\mathrm{d}\Omega} = \frac{\langle\sigma v\rangle}{2}\frac{1}{4\pi m_\chi^2}\sum_f B_f \frac{\mathrm{d}N_\nu^f}{\mathrm{d}E_\nu} J(\psi), \tag{1}$$

where $J(\psi)$ is the astrophysical J-factor, which captures how much DM is along the line of sight.

- Assuming Navarro-Frenk-White (NFW) profile [7] for the Galactic DM distribution with $r_s = 20$ kpc and $\rho_s \simeq 0.33\,\mathrm{GeV\,cm^{-3}}$, the average J-factor in a cone of 10^{-5} sr around the GC is $\bar{J}(10^{-5}sr) \sim 2\times10^{23}\,\mathrm{GeV^2\,cm^{-5}}$, value that normalizes the expected ν flux in HK.
- We compute ν spectra from DM annihilation using framework of PPPC4DMID [8].

Sensitivity Analysis: DM annihilation from GC

- We assume Majorana DM particles and consider only annihilation from the GC.
- **Fig. 5** Expected number of events in 10 years of HK for Multi-Ring τ-like sample.
- **Fig. 6** Expected number of events in 10 years of HK for μ-like PC sample.

For Fig. 5 & Fig. 6: $m_\chi = 50$ GeV≡ DM (χ) mass, $<\sigma v>= 10^{-25} cm^3\,s^{-1}$ ≡ velocity-averaged annihilation cross section, expected from thermal relic scenario [12].

- **Fig. 7** 90% C.L. sensitivity projections for $\chi\chi\to\nu\bar{\nu}$ velocity-averaged cross section.
- HK analysis compared to results from IceCube, SK, ANTARES [6] and KM3NeT [13].
- From Eq. (1) it is seen that DM ν flux depends on σ and m_χ. For higher $m_\chi \to$ more energetic events; for higher $\sigma v \to$ DM ν flux increases (higher prob. DM annihilation into neutrinos).

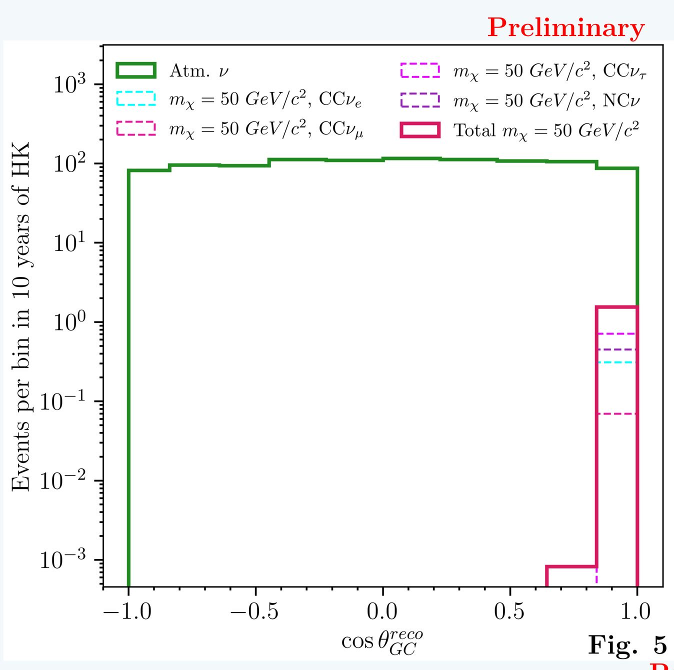
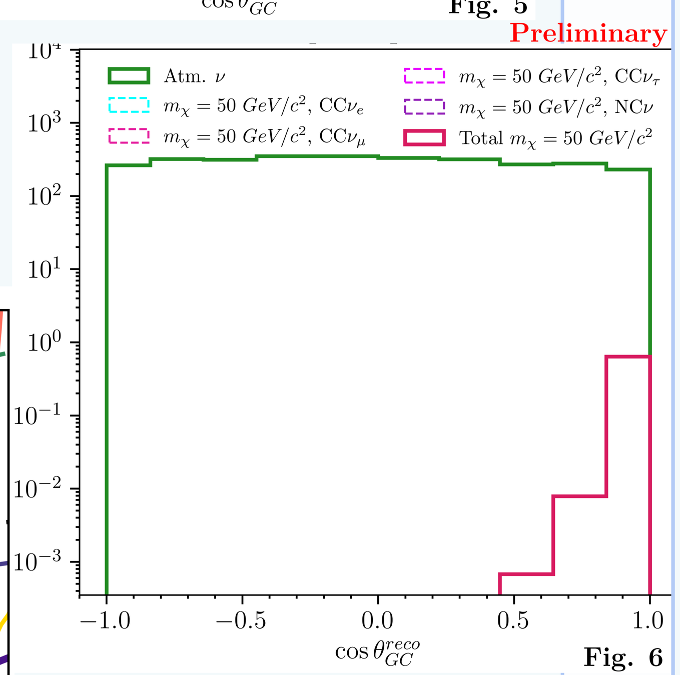


Fig. 5



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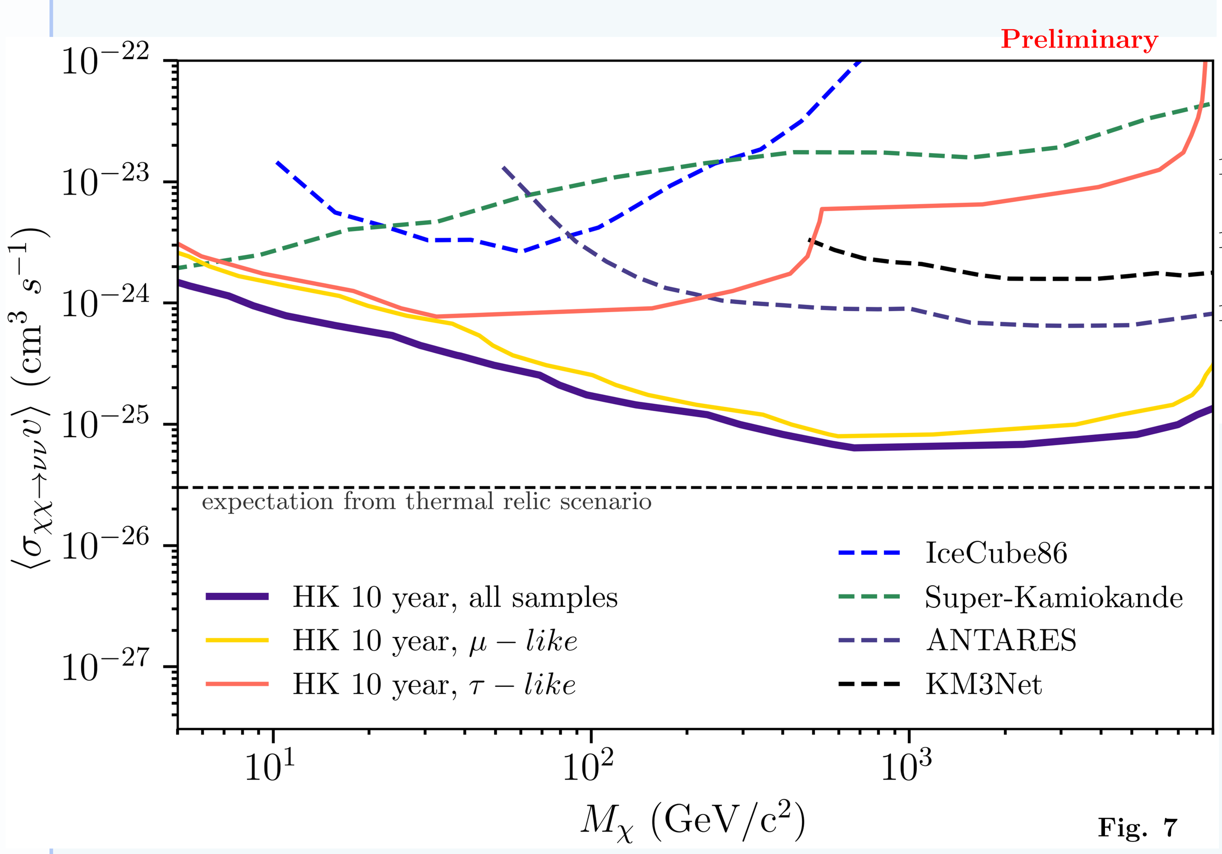

Fig. 7

Conclusions

⇒ This study shows that **HK has a promising sensitivity to astrophysical neutrinos at low energies, in the (10-10^4) GeV E range**. The sensitivity to ν_μ is significantly better than that to ν_τ for high-energy range in the HK's region studied in this work, due to PC and UpMu events, whereas **ν_τ allows us to probe an upper bound for the astrophysical ν flux from $\mathcal{O}(10)$ - 300 GeV**. Therefore, **astrophysical ν flux analysis with HK would provide a complementary measurement to IceCube's sensitivity at energies** $< 10^4$ **GeV**.

⇒ Additional high-energy neutrino sources, such as DM annihilation in the GC, can also be searched in HK. Assuming the null DM hypothesis ($<\sigma v>= 0$), we **found that HK will be able to potentially probe with best sensitivity DM annihilation in the (10–10^4) GeV/c^2 mass range for the $\chi\chi\to\nu\bar{\nu}$ channel**.

Astrophysical ν Flux

- Charged particles can be accelerated in astrophysical shock fronts up to relativistic velocities, resulting in a power-law energy distribution of the form $E^{-\gamma}$. We detect these highly relativistic charged particles directly, as cosmic rays (CRs), or indirectly, as synchrotron radio emission.
- Flux per flavor modeled considering a power-law spectrum:

$$\phi(E) = norm \times 2.40\times10^{-12}\times\left(\frac{E}{300\ \mathrm{GeV}}\right)^{-\gamma}. \tag{2}$$

- Observation of high-energy ν provides insight into the astrophysical ν production, closely related to the production and acceleration of CRs. The spectral index γ, together with the normalization factor, carries information about the ν sources and their environments.

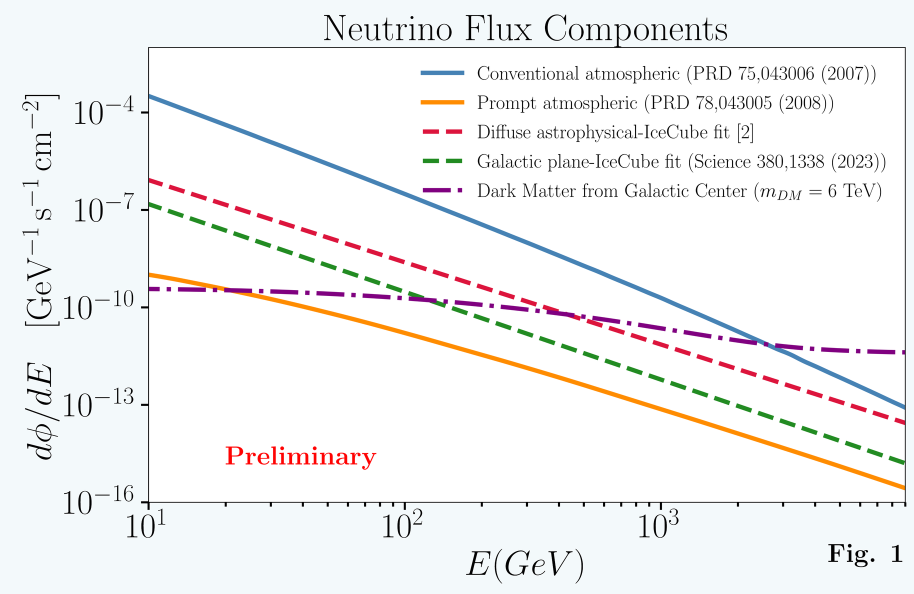

Fig. 1

Sensitivity Analysis: astrophysical ν flux

- $\mathcal{O}(TeV)$-$\mathcal{O}(10^2TeV) \to$ the measurement at HK is limited to the ν_μ component through the Partially Contained (PC) and Up-going muons (UpMu) samples (μ-like samples).
- $<\mathcal{O}(100GeV) \to$ ice- and water-based detector technologies have demonstrated the ability to identify ν_τ even in the presence of background [9],[10].
  - τ-like event tagging uses digitized output from SK's neural net classifier [11].
  - Zenith angle binning reduced to up-going (dominated by atmospheric ν oscillations) vs. down-going (mostly astrophysical ν_τ, isotropy assumed) for separation.
- **Fig.2** Expected number of events in 10 years of HK for Multi-Ring τ-like down-going sample.
- Note the 10x scaling for visualization purposes.

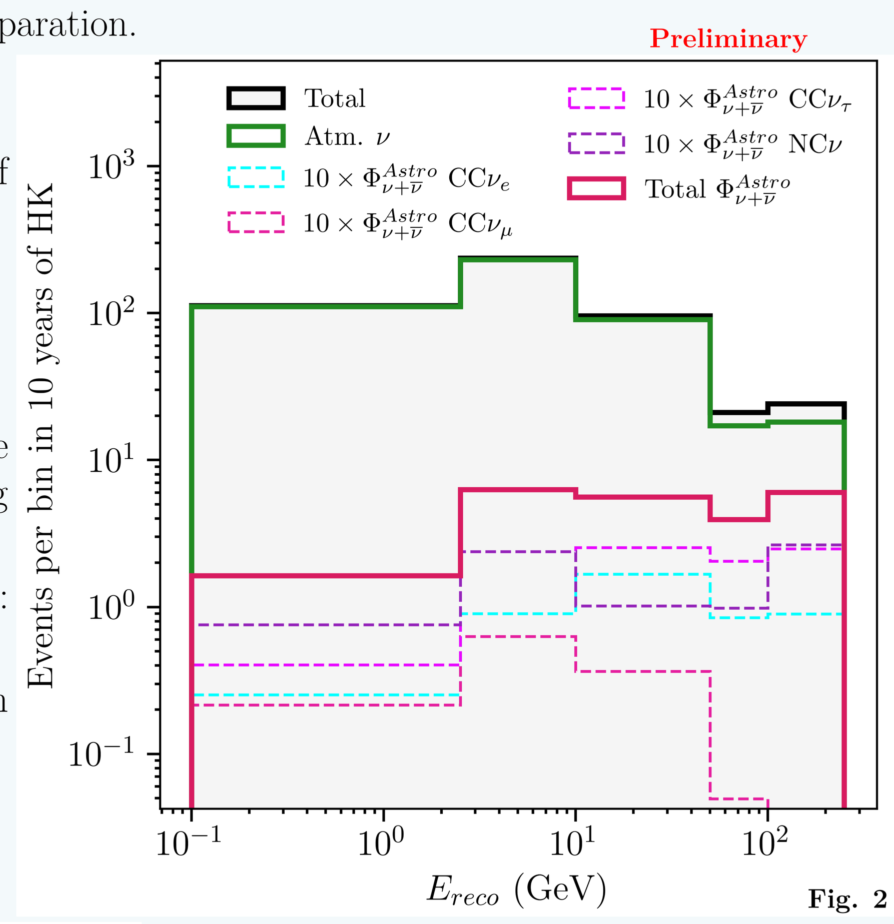

Fig. 2

- **Fig.3** Expected 1σ sensitivity contours for the astrophysical neutrino flux parameters, assuming 10 years of HK exposure.
- True parameter values used in the analysis (⋆): norm = 1.66, $\gamma = 2.53$ (IceCube best-fit [2]).
- $\nu_e:\nu_\mu:\nu_\tau = 1:1:1$ is assumed (expected from ν oscillations).

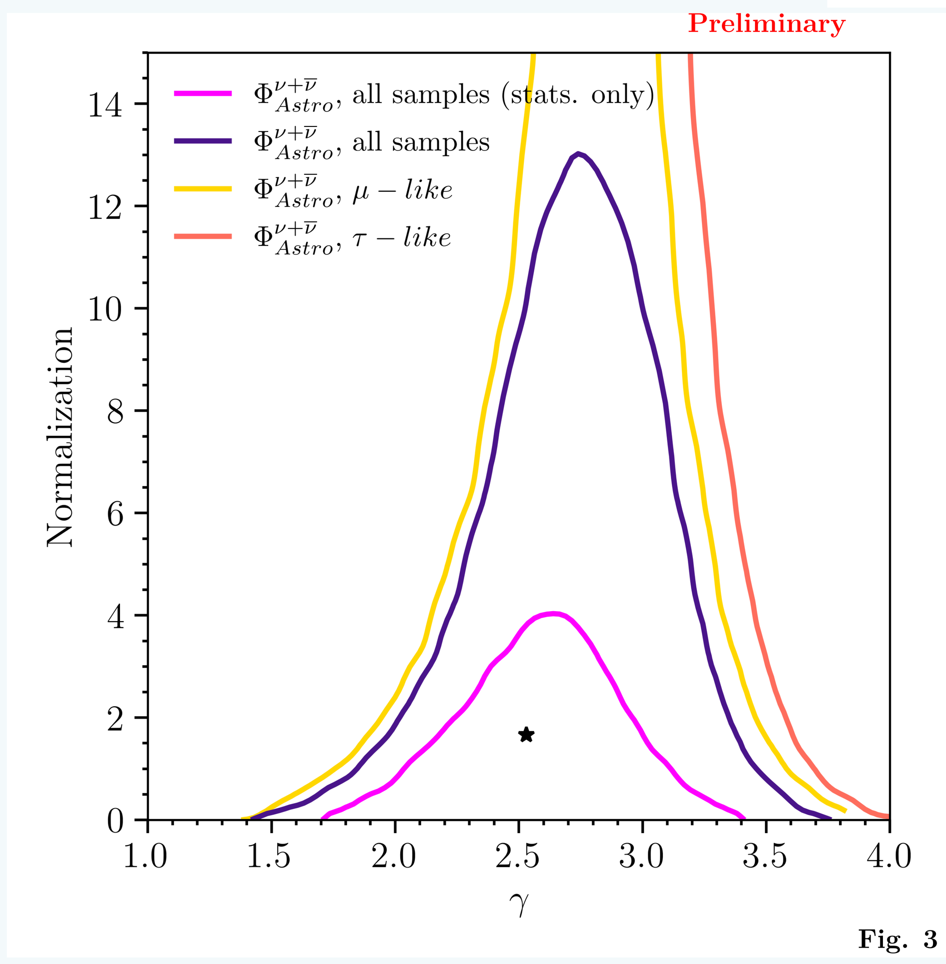

Fig. 3

- The fit explores how well HK could constrain the normalization and spectral index γ, assuming an astrophysical flux is present.
- **Fig. 4** Comparison of 1σ allowed regions for the astrophysical ν flux parameters between HK and IceCube, where IceCube data fit used is from [2]).

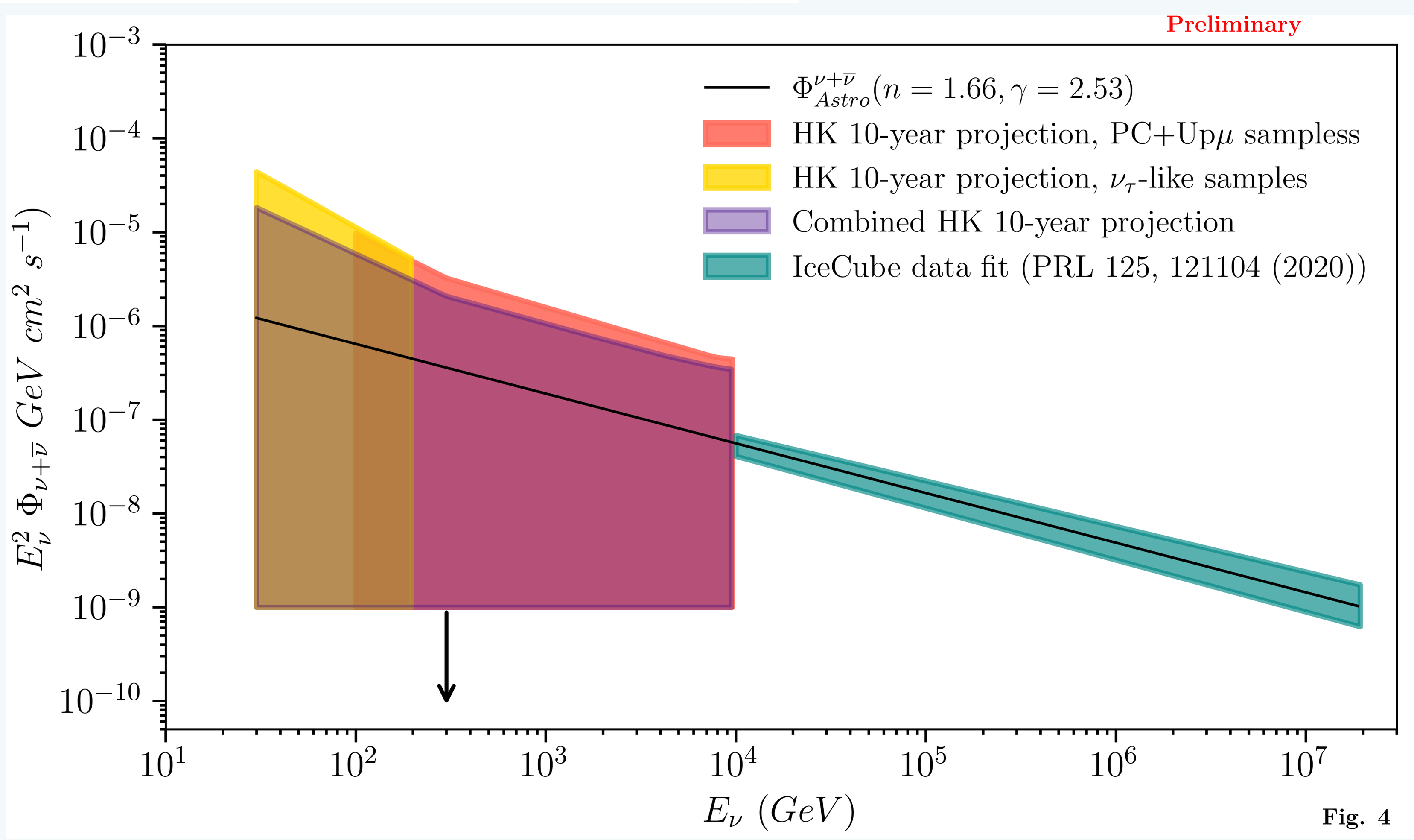

Fig. 4

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