Search for Neutrino Emission from X-ray Binaries with KamLAND

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Introduction

- **X-ray Binary (XRB):** A binary star system in which a **compact object** (neutron star or black hole) accretes matter from a **stellar companion**. Neutrino emission is predicted from the disk and the jet. Disk instabilities and enhanced mass transfer (**flare**) lead to X-ray brightening and increased hadronic acceleration. A **correlation** between **flares** and **neutrino emission** is therefore expected.

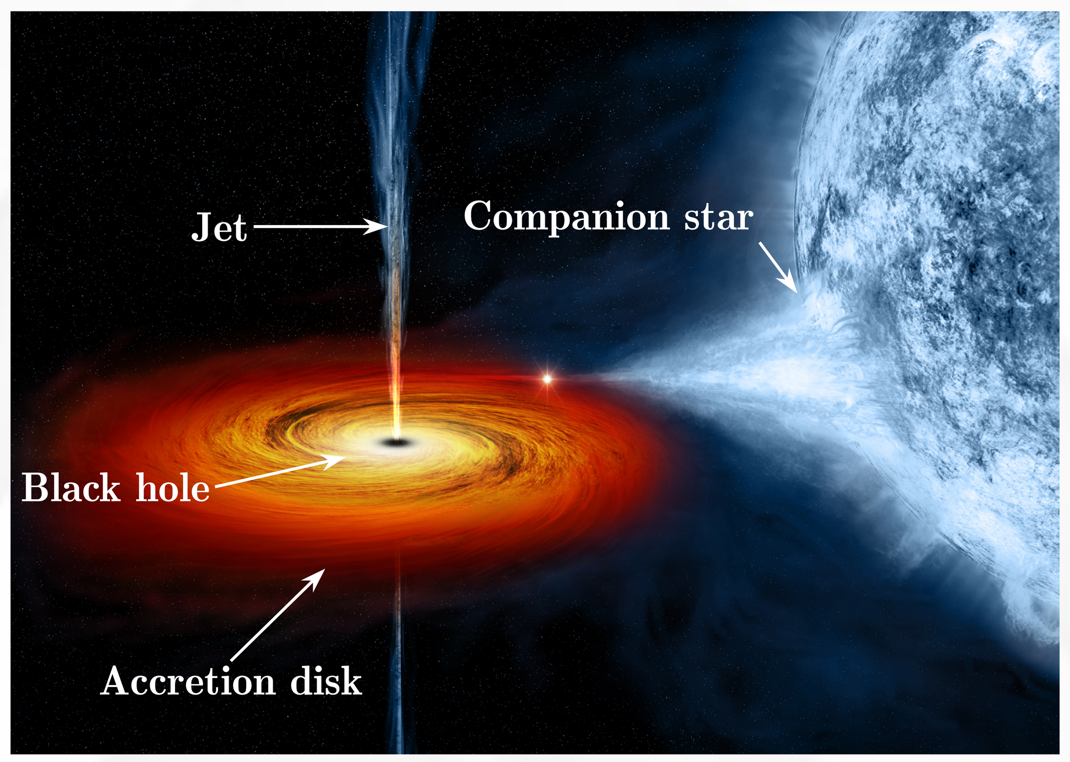

Figure 1: Schematic of an X-ray binary.

Credit: NASA/CXC/M. Weiss

- **KamLAND**: Short for Kamioka Liquid Scintillator Antineutrino Detector. It was designed to detect $\bar{\nu}_e$ primarily from surrounding nuclear reactors using **inverse beta decay**:

$$\bar{\nu}_e + p \rightarrow e^+ + n. \quad (1)$$

It contains 1 kiloton of ultra-pure liquid scintillator housed in a ∼13 m diameter nylon balloon inside a stainless-steel sphere.

- **KamLAND Periods:** The experiment is divided into **4 periods**, depending on whether the inner balloon (IB) is inserted:
  - Period I (2002–2011): without IB.
  - Period II (2011–2015): with IB; reactors shut down after the Fukushima accident, and the science goal shifted to neutrinoless double-beta decay.
  - Period III (2015–2016): without IB; outer-detector refurbishment.
  - Period IV (2016–2024): with IB; a cleaner, larger Xe-loaded IB was installed. DAQ ended in August 2024.

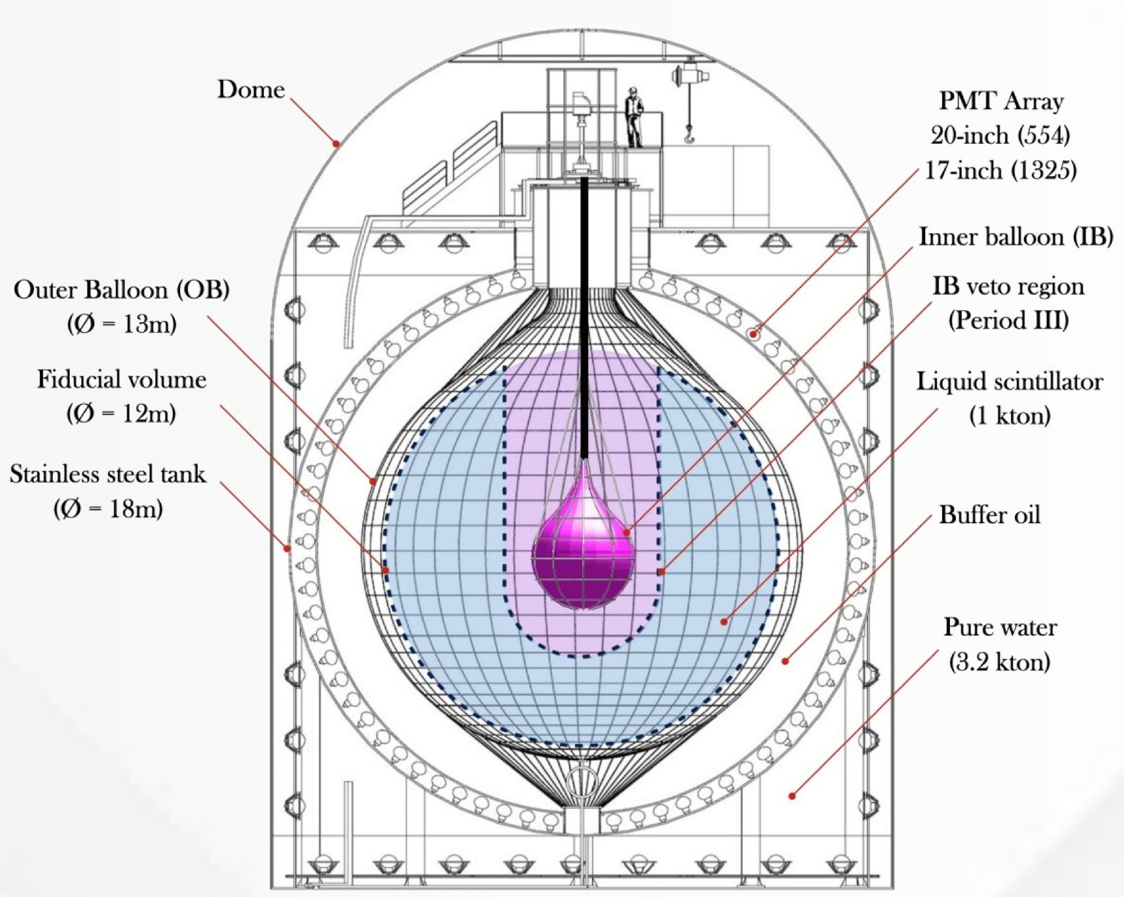

Figure 2: The KamLAND detector

Method

- **Source Selection:** Using publicly available Swift/BAT and MAXI data from the last 20 years, we found 94 high-mass XRBs and 165 low-mass XRBs.

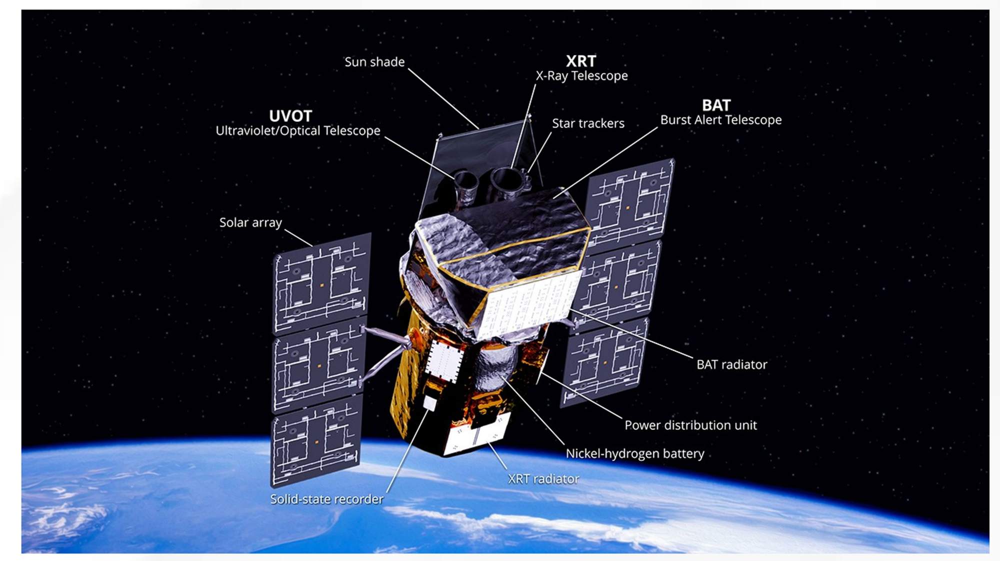

Figure 3: An artist's concept of the Neil Gehrels Swift Observatory.

Credit: NASA/Goddard Space Flight Center Conceptual Image Lab

- **Constructing the Likelihood:**

$$\mathcal{L}(n_s, f_{\rm th}, T) = \prod_{k=I}^{IV} \prod_{i=1}^{N_k} \left[\frac{w_k n_s}{N_k} \mathcal{S}_{ik} + \left(1 - \frac{w_k n_s}{N_k}\right) \mathcal{B}_{ik} \right], \quad (2)$$

  - k**:** index of KamLAND period.
  - i**:** index of the i-th neutrino in the dataset.
  - N_k**:** total number of neutrinos in period k.
  - n_s**:** number of neutrinos that come from XRBs.
  - $\mathcal{S}$**:** PDF of the signal neutrinos. $\mathcal{S} = \mathcal{S}^E \times \mathcal{S}^T \times \mathcal{S}^{\rm deff}$
    - $\mathcal{S}^E$**:** energy PDF of the signal neutrinos; a power law is assumed.
    - $\mathcal{S}^T$**:** assumed to be proportional to the X-ray intensity, obtained by applying Bayesian Blocks to the XRB light curve and setting a dynamic threshold, following the IceCube analysis [1].

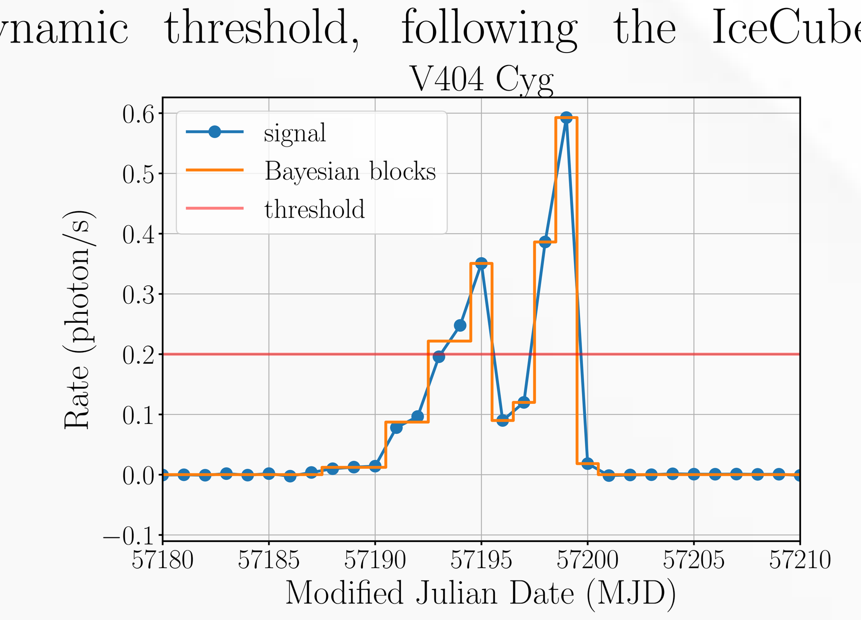

Figure 4: Example of converting the V404 Cyg light curve to a PDF.

    - $\mathcal{S}^{\rm deff}$**:** detector-efficiency PDF of the signal neutrinos; the efficiency is close to 100%.
  - $\mathcal{B}$**:** PDF of the background neutrinos. $\mathcal{B} = \mathcal{B}^E \times \mathcal{B}^T \times \mathcal{B}^{\rm deff}$.
    - $\mathcal{B}^E$**:** energy PDF of the background neutrinos; calculated by histogramming the neutrino energies measured by KamLAND.
    - $\mathcal{B}^T$**:** time PDF of the background neutrinos; calculated by averaging the number of neutrinos detected by KamLAND.
    - $\mathcal{B}^{\rm deff}$**:** detector-efficiency PDF; taken be the same as $\mathcal{S}^{\rm deff}$ as an approximation for now.
  - $f_{\rm th}$**:** threshold of the light curve (minimum 5% of the max).
  - T**:** maximum time lag allowed between the flare and the neutrino arrival time; set to ±7 days.
  - w_k**:** signal weight of period k; the fraction of $\mathcal{S}^T$ falling within period k.

Simulation & Summary

Varying n_s, $f_{\rm th}$, and T to maximize $\mathcal{L}$ gives the best-fit values of these three parameters, based on the PDFs described previously.

- **Injection Recovery Test:** Testing whether the algorithm can recover the number of signal neutrinos injected according to $\mathcal{S}$; each n_{inj} has 1000 trials.

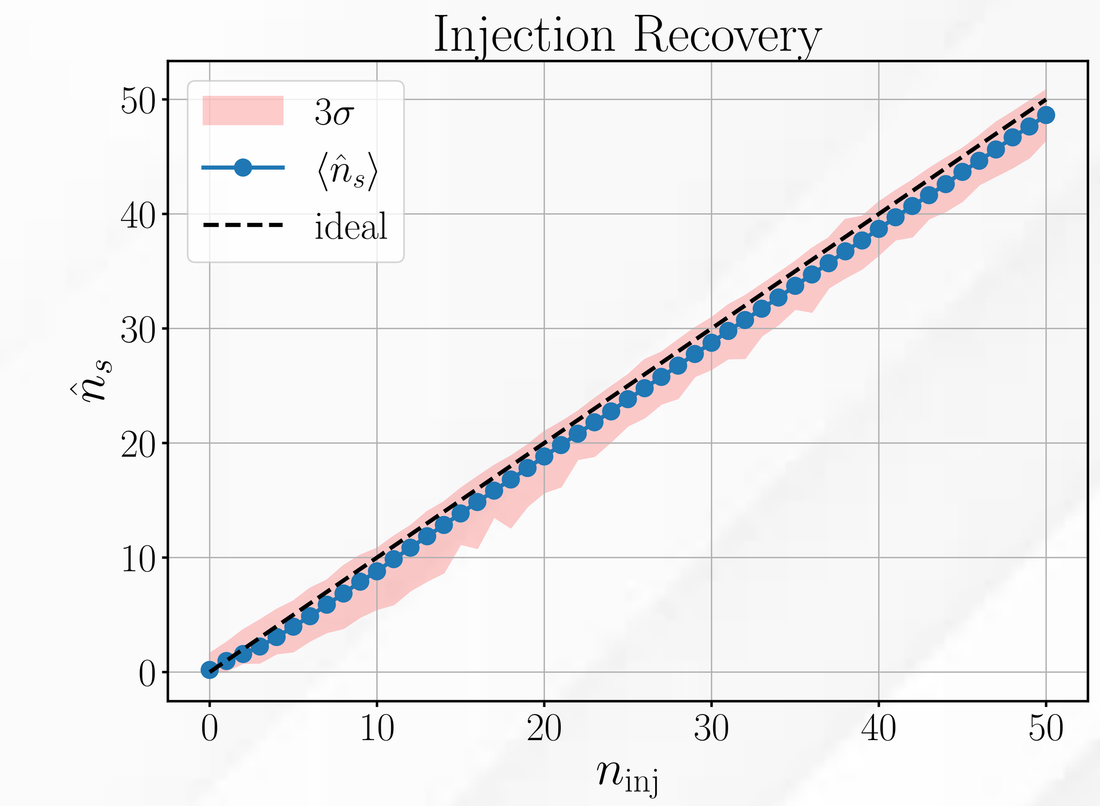

Figure 5: Recovering the injected signal neutrinos.

- **Significance:** Testing the detection potential of KamLAND for the XRB V404 Cyg for the energy range 10 - 150 MeV. Each tested point of flux has 10,000 trials (the uncertainty in B^E is not included for now). The flux is averaged over the flare period (9 days). Please note the 3σ line is calculated but the 5σ line is fitted due to an insufficient number of trials.

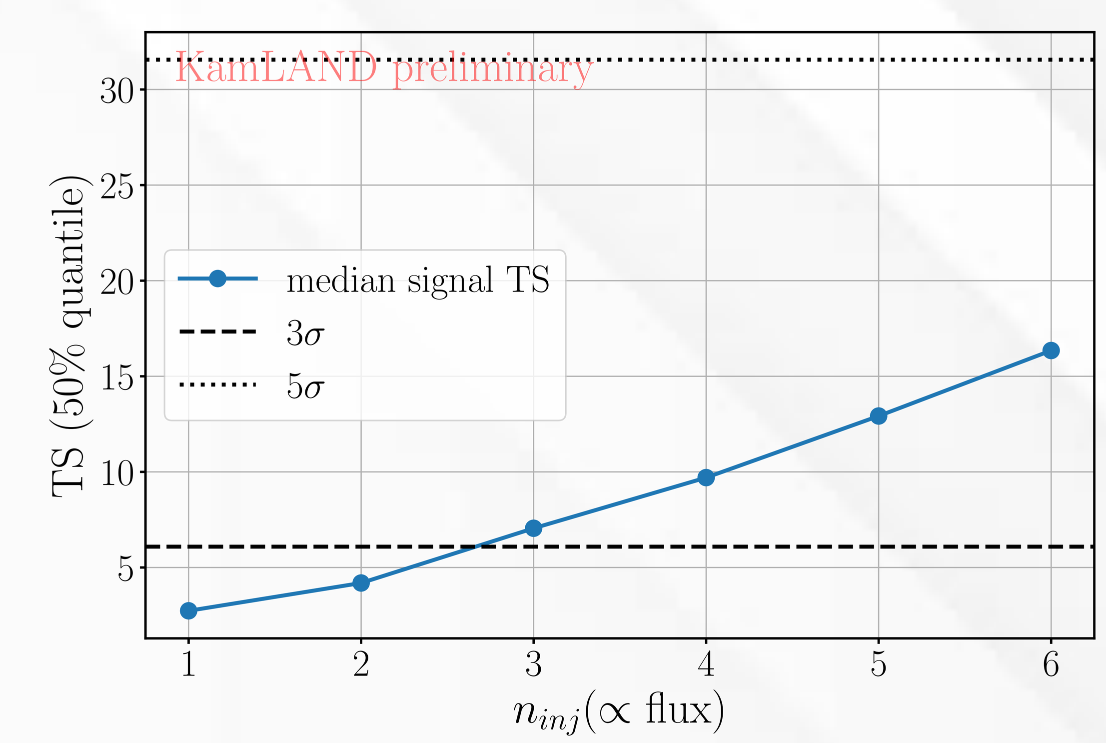

Figure 6: The detection potential of KamLAND for V404 Cyg.

- **Summary:** We have developed an unbinned likelihood search for MeV-scale neutrino emission from X-ray binaries, using KamLAND IBD events time-correlated with Swift/BAT and MAXI flare light curves. The method is validated by injection-recovery tests, and we estimate KamLAND's detection potential for V404 Cyg. The low IBD-like background in 10–150 MeV makes even a few flare-correlated events significant.

References

[1] R. Abbasi et al. Search for high-energy neutrino emission from galactic x-ray binaries with icecube. *The Astrophysical Journal Letters*, 930(2):L24, may 2022.