Searching for Neutrinos in KamLAND in Coincidence with the Brightest Gamma Ray Burst of All Time (BOAT)

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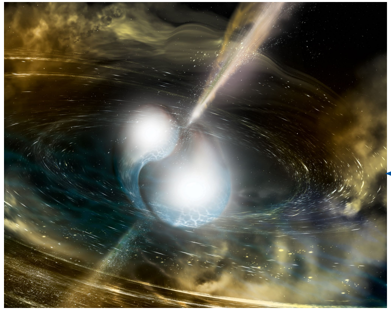
Zero neutrino double beta decay search

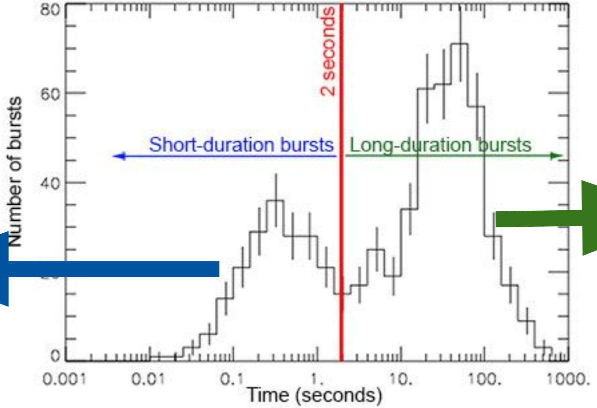
KamLAND-Zen

Gamma Ray Burst (GRB) Background

GRBs are the most energetic electromagnetic events in the universe, and as such are one of the prime candidates for multi-messenger searches.

Short GRBs (<2 sec):
BNS Mergers



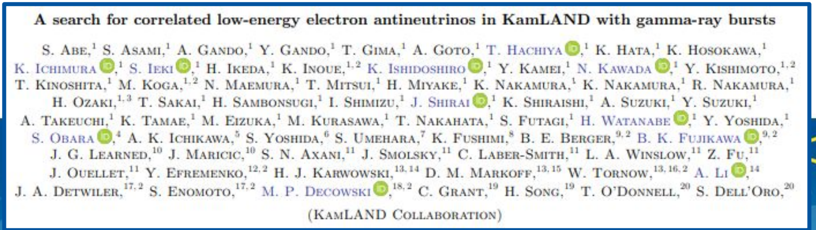


Long GRBs (>2 sec):
Core-Collapse Supernovae

Neutrino detectors have looked for neutrinos from GRBs before, including IceCube, SuperK, KamLAND

S. Abe et al 2022 ApJ 927 69, K. Asakura et al 2015 ApJ 806 87

- KamLAND has no significant observation, but able to place the strongest limits at low energies



A search for correlated low-energy electron antineutrinos in KamLAND with gamma-ray bursts

S. Abe,[1] S. Asami,[1] A. Gando,[1] Y. Gando,[1] T. Gima,[1] A. Goto,[1] T. Hachiya,[1] K. Hata,[1] K. Hosokawa,[1] K. Ichimura,[1] S. Ieki,[1] H. Ikeda,[1] K. Inoue,[1,2] K. Ishidoshiro,[1] Y. Kamei,[1] N. Kawada,[1] Y. Kishimoto,[1,2] T. Kinoshita,[1] M. Koga,[1,2] N. Maemura,[1] T. Mitsui,[1] H. Miyake,[1] K. Nakamura,[1] K. Nakamura,[1] R. Nakamura,[1] H. Ozaki,[1,3] T. Sakai,[1] H. Sambonsugi,[1] I. Shimizu,[1] J. Shirai,[1] K. Shiraishi,[1] A. Suzuki,[1] Y. Suzuki,[1] A. Takeuchi,[1] K. Tamae,[1] M. Eizuka,[1] M. Kurasawa,[1] T. Nakahata,[1] S. Futagi,[1] H. Watanabe,[1] Y. Yoshida,[1] S. Obara,[4] A. K. Ichikawa,[5] S. Yoshida,[6] S. Umehara,[7] K. Fushimi,[8] B. E. Berger,[9,2] B. K. Fujikawa,[9,2] J. G. Learned,[10] J. Maricic,[10] S. N. Axani,[11] J. Smolsky,[11] C. Laber-Smith,[11] L. A. Winslow,[11] Z. Fu,[11] J. Ouellet,[11] Y. Efremenko,[12,2] H. J. Karwowski,[13,14] D. M. Markoff,[13,15] W. Tornow,[13,16,2] A. Li,[14] J. A. Detwiler,[17,2] S. Enomoto,[17,2] M. P. Decowski,[18,2] C. Grant,[19] H. Song,[19] T. O'Donnell,[20] S. Dell'Oro,[20]
(KamLAND Collaboration)

The BOAT (GRB221009A)

Observed: Oct. 9, 2022

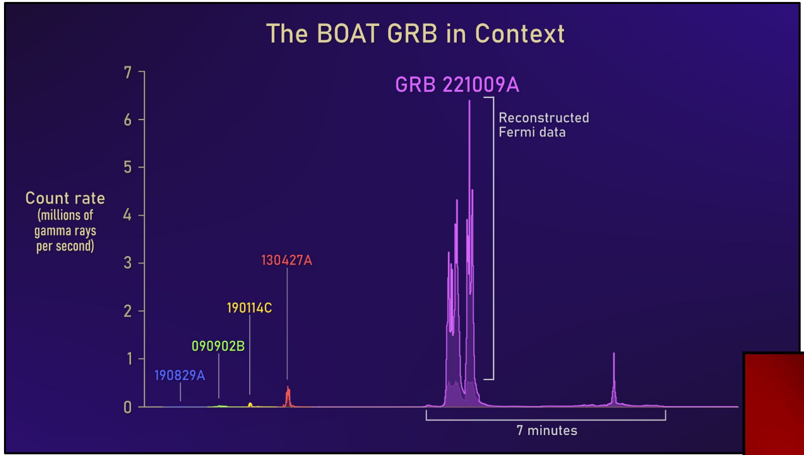
Location: Declination +19° 46′ 24.6″,

RA $19^h\ 13^m\ 03.48^s$

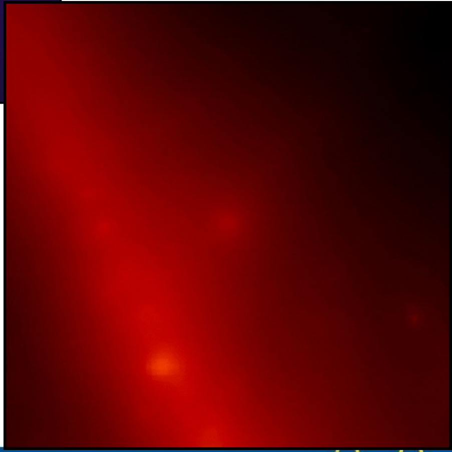
⟶ Just off of the Galactic Plane

Distance: 726 Mpc (z=0.151)

Prompt Emission: ~600s



GRB 221009A outshines the Milky Way in Gamma Rays (10 hr Timelapse)



Brightest GRB ever observed, by several metrics[1]:

- Fluence: 0.21 erg/cm^2 (46x previous record)
- Peak flux: 0.031 erg/s/cm^2 (25x previous record)
- Equivalent Isotropic Energy: ~$1.2*10^{55}$ erg (2x previous record)

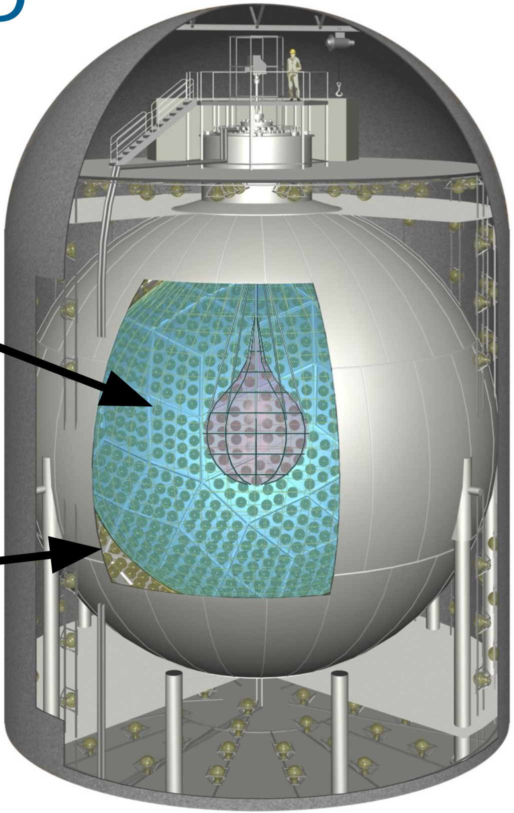
[1]Eric Burns *et al* 2023 *ApJL* 946 L31

KamLAND

KamLAND is a neutrino detector built 1 km underneath Mt. Ikenoyama in Gifu, Japan.

Inner Detector: outer balloon holding 1 kton ultrapure liquid scintillator

1879x Photomultiplier tubes for 34% PMT coverage

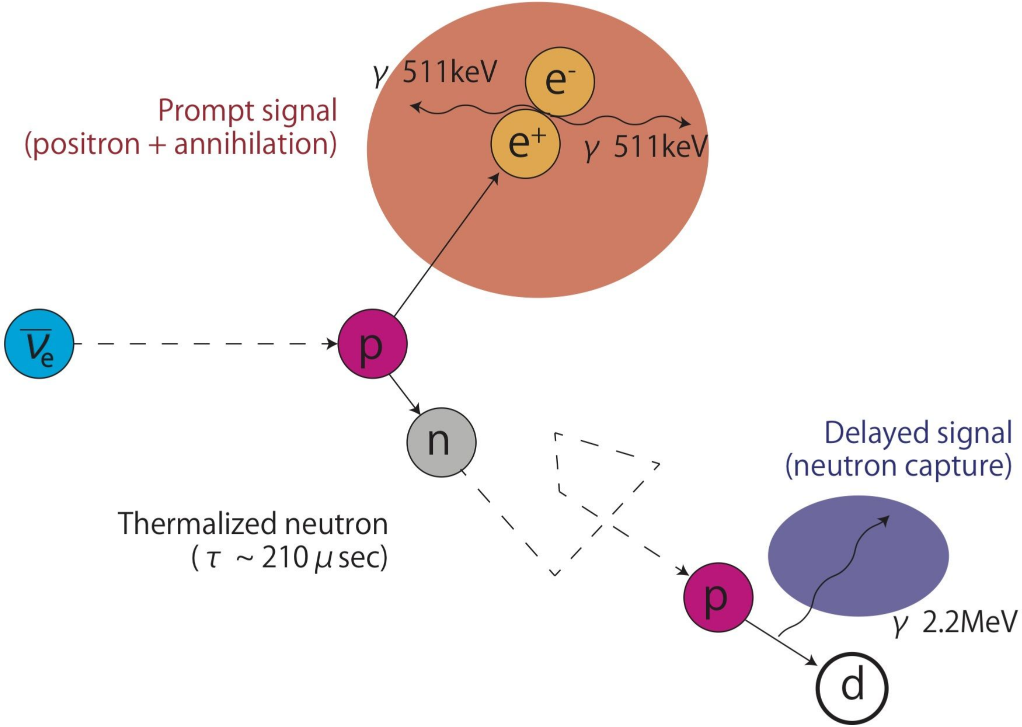


KamLAND Energy Resolution: $\frac{6.4\%}{\sqrt{E(MeV)}}$

Neutrino Detection with KamLAND

KamLAND detects antineutrinos through the Inverse Beta Decay (IBD) process, which leaves a very recognizable signal spatially and temporally.

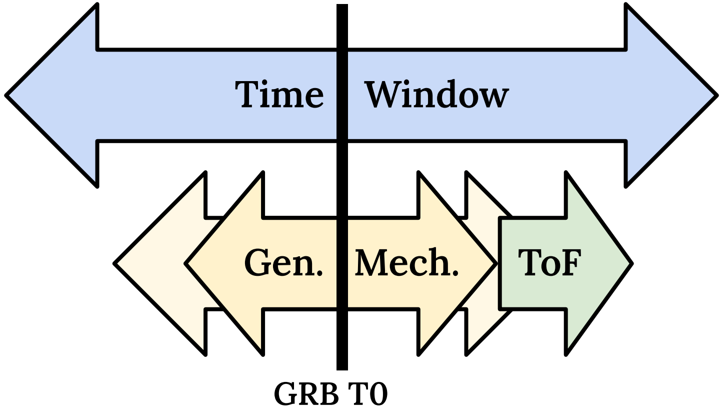
$$p^{+} + \overline{\nu}_{e} \rightarrow e^{+} + n^{0}$$

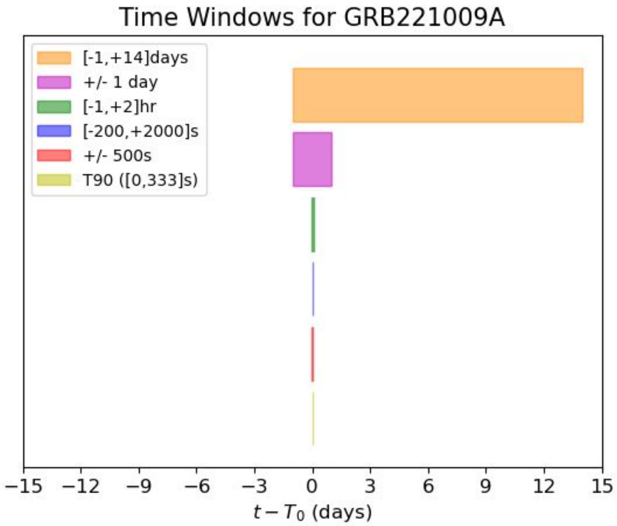


Analysis Techniques

To look for antineutrino candidates, we perform an IBD search in chosen time windows surrounding the GRB. Given the observed signal and background rate, we use the Feldman-Cousins method to calculate signal upper limits for each time window.

No neutrinos were observed in any of the time windows.

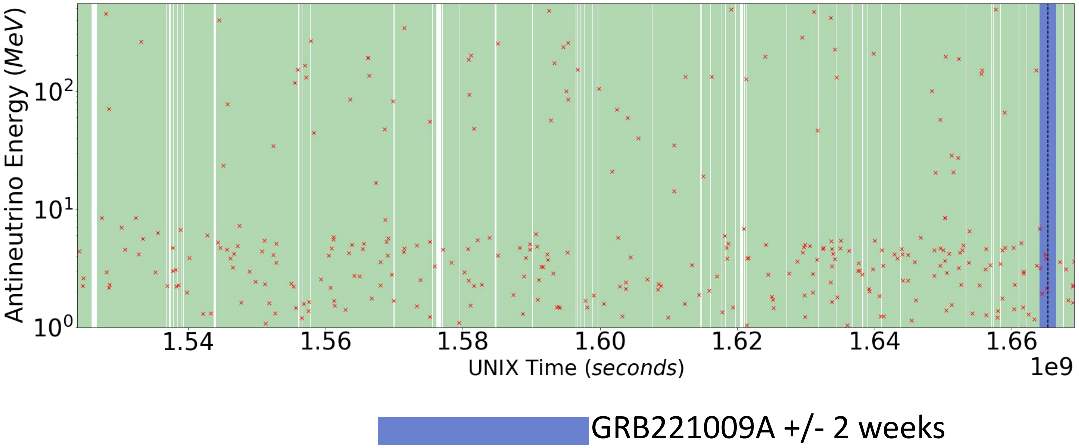


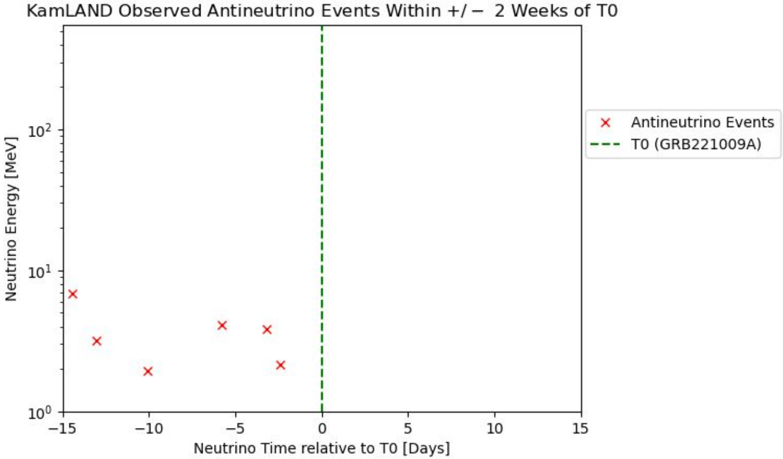


Analysis Techniques, cont.

Backgrounds are calculated by looking for antineutrinos over all of KamLAND-Zen 800 (Period IV):

- We calculate the background rate: total antineutrinos in Period IV / Period IV livetime
- We want to also calculate the expected number of background antineutrinos in the time window by randomly resampling IBD timestamps many times





Analysis Techniques, cont.

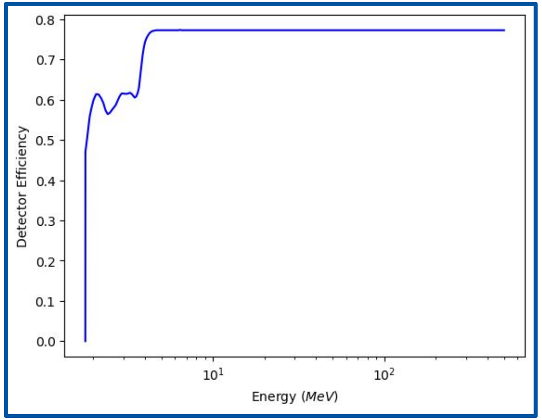
Using the signal upper limit, we can calculate electron antineutrino fluence using the model independent Green's Function, Ψ_{90}, as a function of the neutrino energy.

$$\Psi_{90}(E_{\bar{\nu}_e}) = \frac{N_{90}}{N_T \sigma(E_{\bar{\nu}_e}) \epsilon_{live}(E_{\bar{\nu}_e})}$$

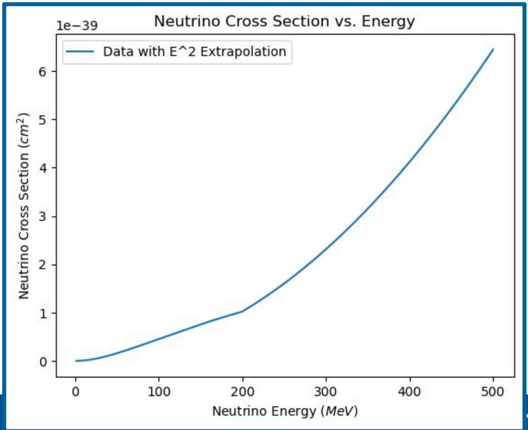
We also calculate the time-integrated antineutrino flux limit, F_{90}, assuming different power law models for emission at the source. We test $F(E) \propto E^{-1.5}$, E^{-2}, $E^{-2.5}$, and E^{-3}. $\lambda(E)$ is the power law normalized to 1 over the energy range, and N_{90} is the signal upper limit calculated for the different time windows.

$$F_{90} = \frac{N_{90}}{N_T \int \sigma(E_{\bar{\nu}_e}) \lambda(E_{\bar{\nu}_e}) \epsilon_{live}(E_{\bar{\nu}_e}) dE_{\bar{\nu}_e}}$$

$\epsilon_{live}(E)$: Detector Efficiency



$\sigma(E)$: IBD Cross Section



A. Strumia and F. Vissani, Precise quasielastic neutrino/nucleon cross-section, Phys. Lett. B 564 (2003) 42

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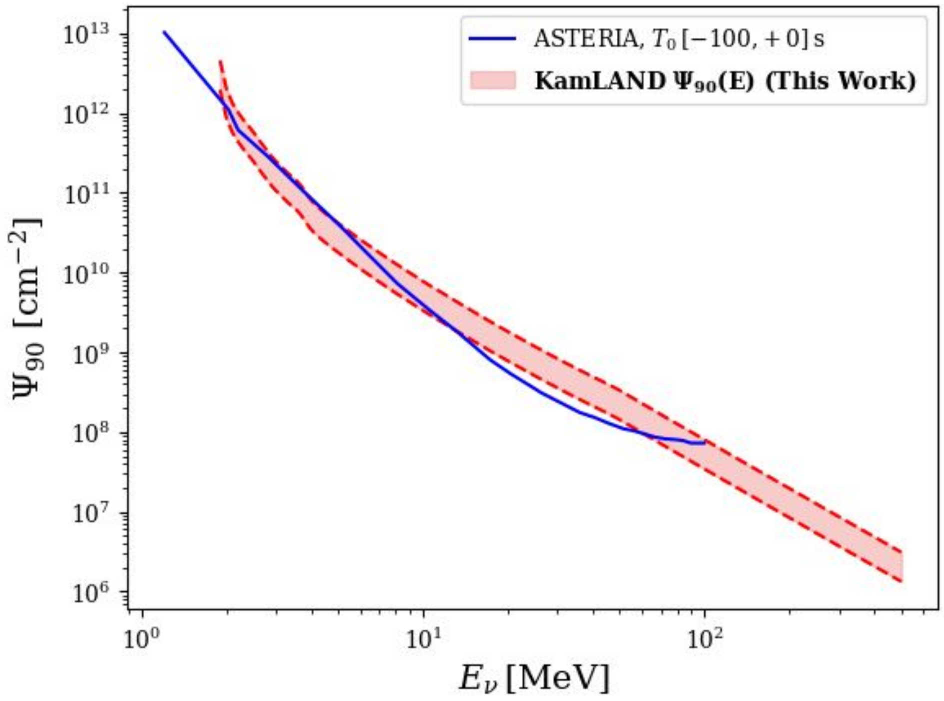
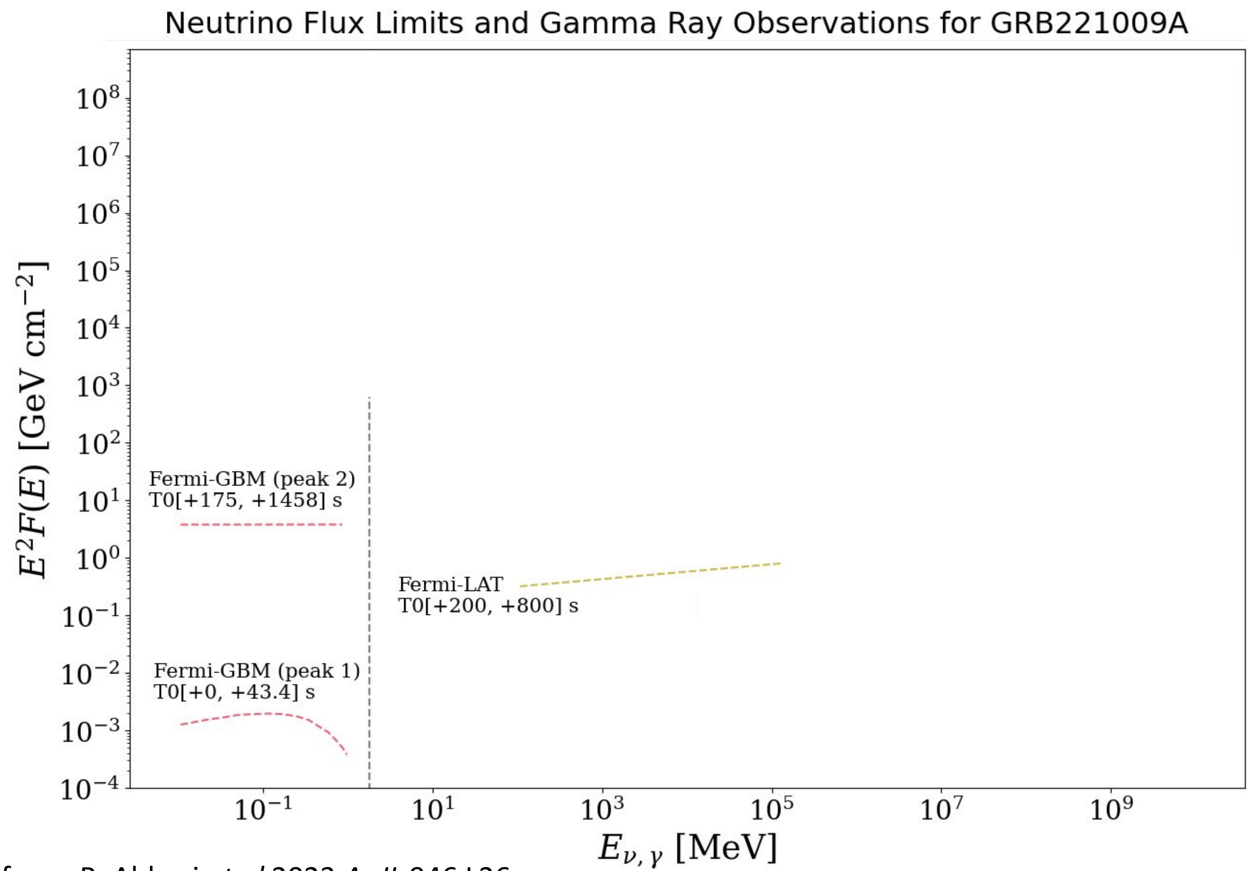
Fluence Upper Limit Result

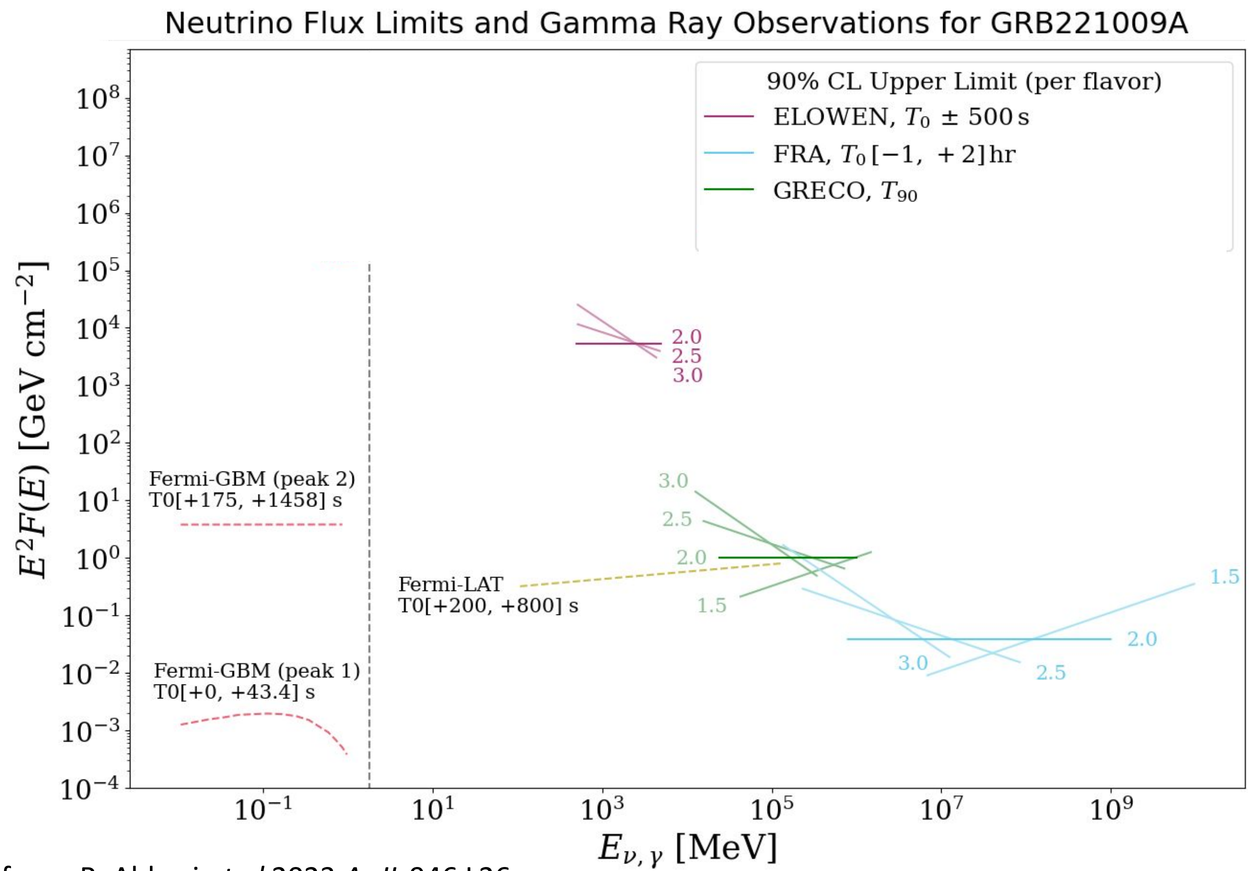


IceCube Low Energy Result (90% CL UL) in blue

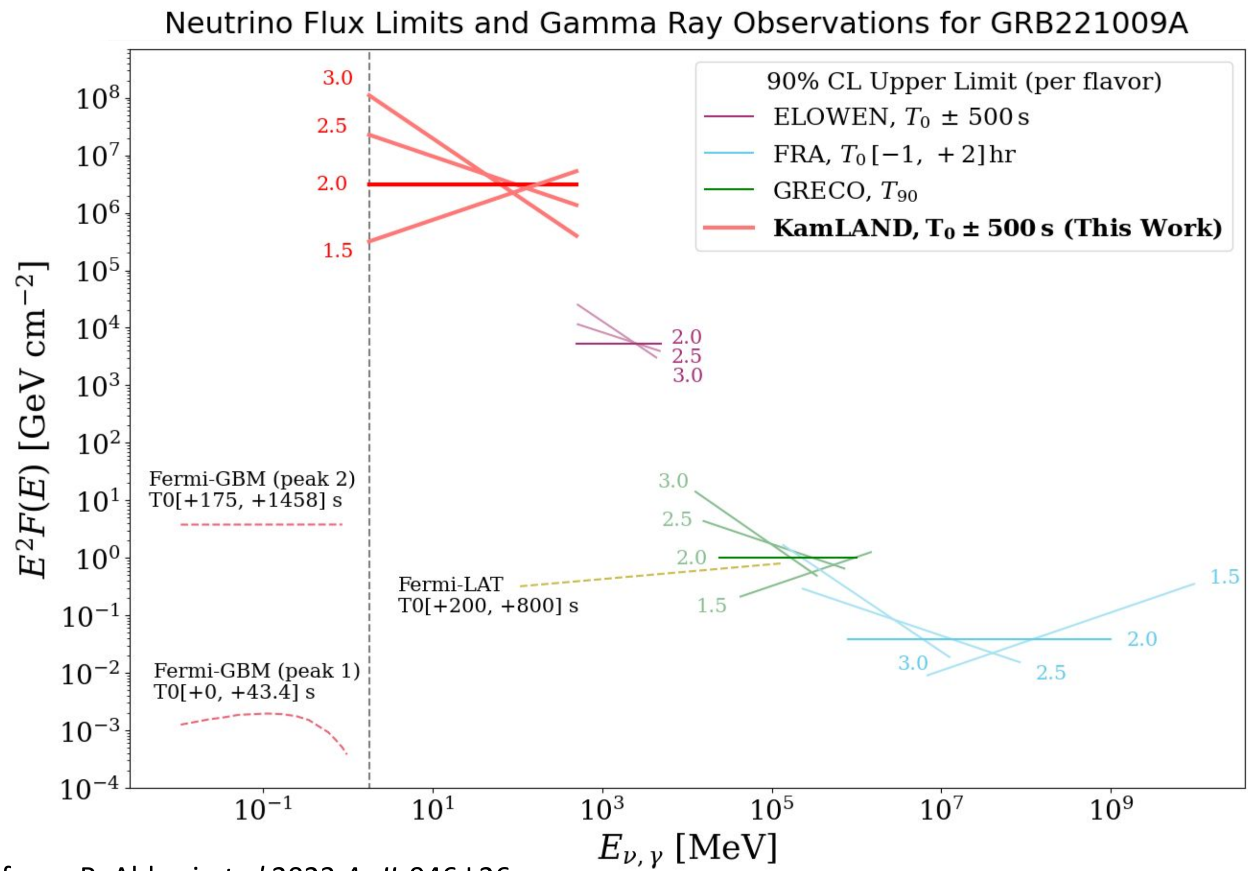
KamLAND shaded area is between the shortest and longest time windows used in the analysis.



IceCube and Fermi data from: R. Abbasi *et al* 2023 *ApJL* 946 L26



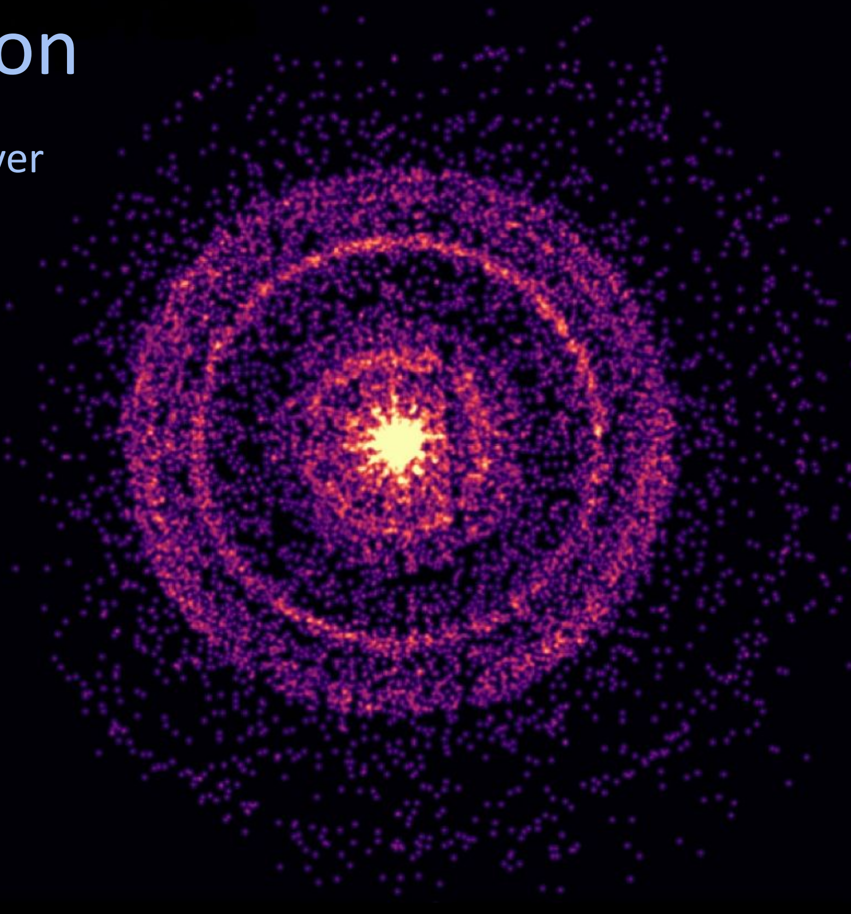
IceCube and Fermi data from: R. Abbasi *et al* 2023 *ApJL* 946 L26



IceCube and Fermi data from: R. Abbasi *et al* 2023 *ApJL* 946 L26

Conclusion

- GRB221009A is the brightest gamma ray burst ever observed, giving us a **1-in-10,000 year event** to search for neutrino emission.
- We perform an IBD search over various time windows surrounding the GRB event.
- No significant observations, but limits are placed on the antineutrino flux for various source emission models.
- These limits cover the low energy range down to the IBD limit, providing complementary results with IceCube's analysis.



Thanks for your attention!

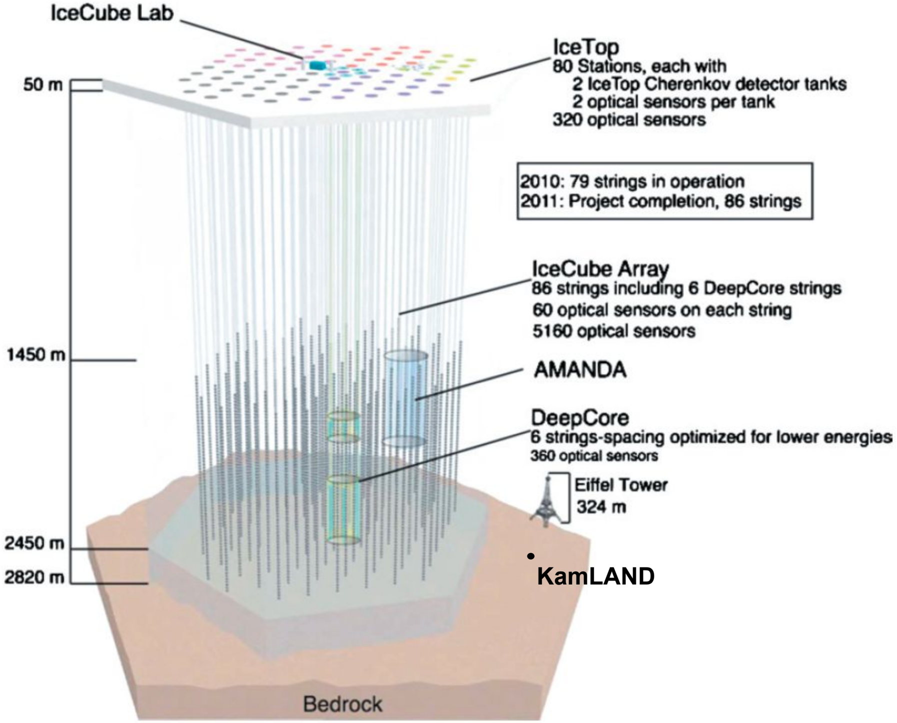
BACKUP SLIDES

Interest in the BOAT: IceCube

The IceCube Neutrino Observatory is a $1km^3$ neutrino detector built into the ice at the South Pole. It is the biggest and best neutrino detector for astrophysical neutrino searches.

- ~10^6x fiducial volume of KamLAND, but much lower detection efficiency
- Best at detecting high energy neutrinos, while KamLAND detects low energy neutrinos

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY



The Astrophysical Journal Letters, 946:L26 (10pp), 2023 March 20
https://doi.org/10.3847/2041-8213/acc077

Limits on Neutrino Emission from GRB 221009A from MeV to PeV Using the IceCube Neutrino Observatory

Event Selection

We also impose further cuts to improve data quality. These take into account spatial and temporal signals and reject backgrounds, such as cosmic ray muons.

Run Quality: <5 (half-good runs or better)

Fiducial Volume Cuts: Remove events close to (or inside) the inner balloon, as well as events close to the edge of the outer balloon

Delayed Energy: 1.8 (4.4) $< E_d <$ 2.6 (5.6) MeV for neutron capture on protons (carbon)

Muon Vetos: Remove events with muon within 2ms

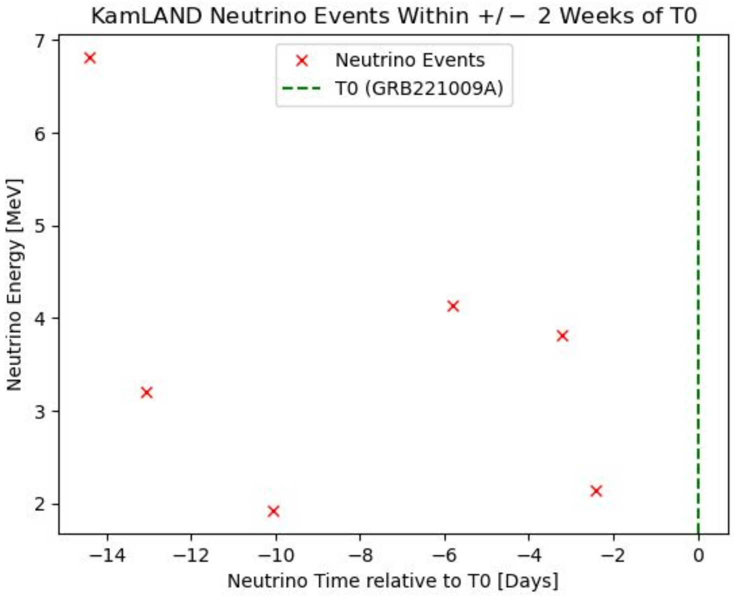
Likelihood Selection

Different cuts for low energy vs. high energy analysis

Observed Neutrinos

We find only 6 neutrinos within +/- 2 weeks of the GRB, all of them being at least 2 days before T0, and energies that are low.

Chance of seeing 6 antineutrinos in the 2 weeks before T0 and 0 in the 2 weeks after, given background rate, is about 1/400

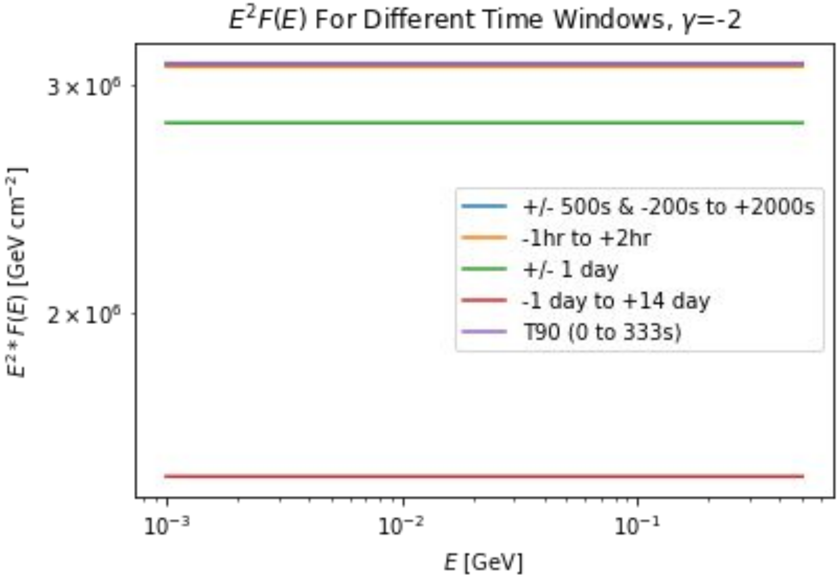


Time Window Uncertainty

The time window we should be looking for neutrinos in for a GRB is not exactly known.

We can define the uncertainty in our flux limit due to the choice of time window as the difference between the largest and smallest flux limits for different time windows.

This is approximately a factor of 2 difference.



KamLAND Live Time During GRB221009A

- KamLAND had very little dead time during the event, with the detector running about 96.5% of the time in the 2 weeks before and after the GRB.