# Search for X-ray transient counterparts for the IceCube neutrino events with MAXI

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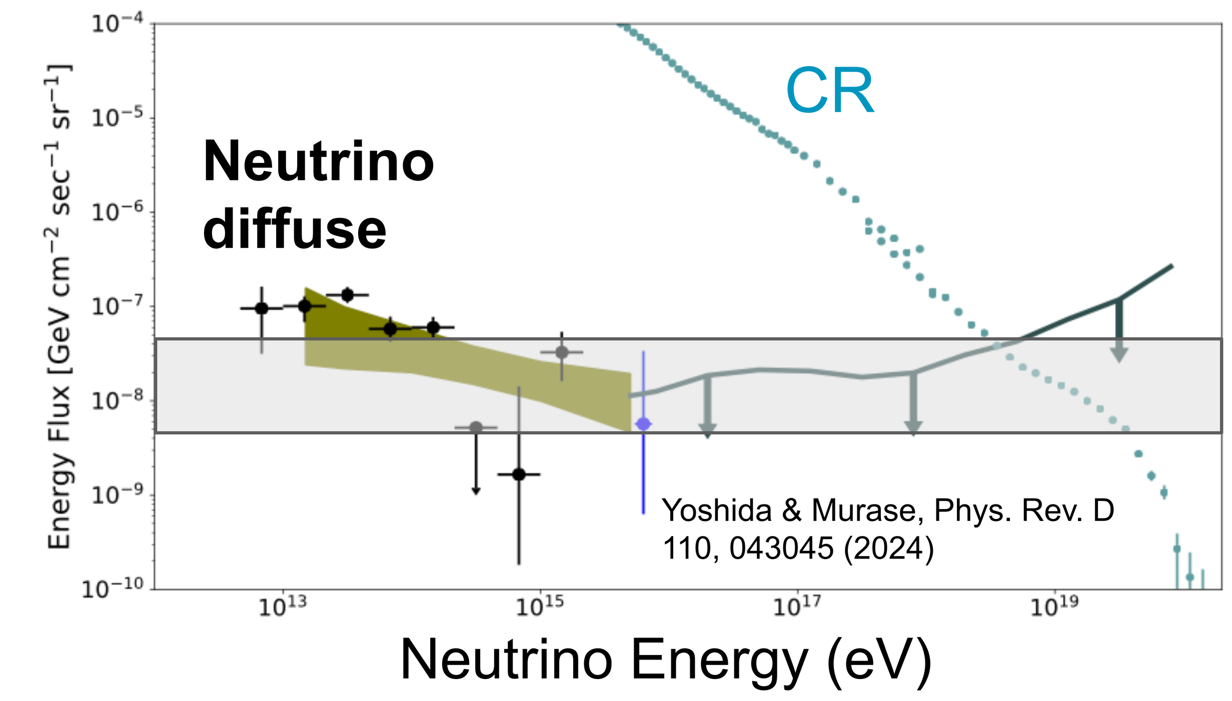
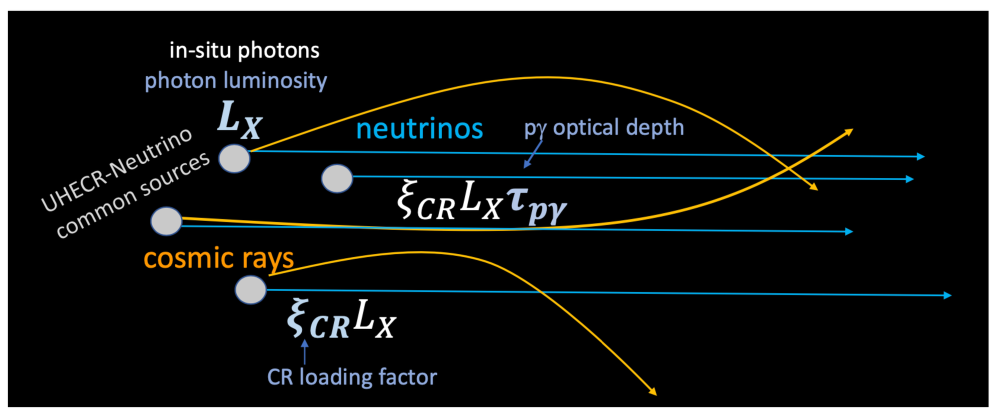
## Introduction




Detected astrophysical high-energy neutrinos by IceCube → **what is the origin of diffuse neutrino emissions?? unified origin of the UHECR??**
Hard X-ray transients origin, such as standard long GRBs, has been ruled out by MM analysis

## Soft X-ray transients are key




In-situ X-ray luminosity is the gauge of both the neutrino emission power via the optical depth $\tau p_\gamma$ and the UHECR emission power via the CR loading factor ($\xi_{CR}$).

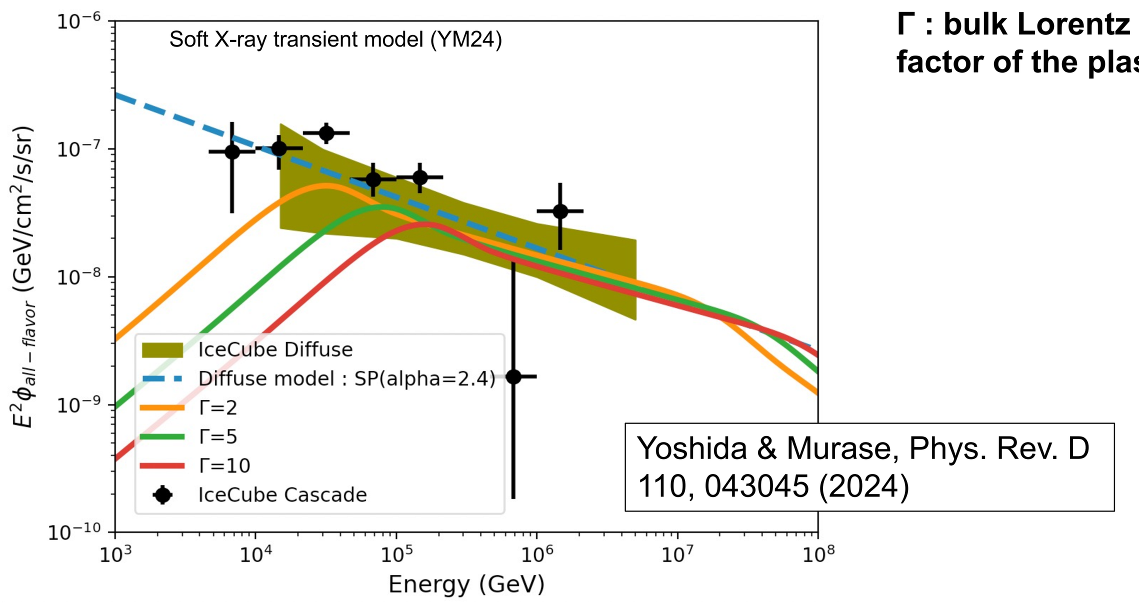
### Goals of our analysis :

- Detecting the X-ray counterpart of the neutrino signal using the new MM likelihood test
- If there is no sources, still we can provide lower-limit of the $\xi_{CR}$

- In relativistic plasma flows, **soft X-ray photons** are good targets for PeV protons via pγ reaction

$$\varepsilon_X = 15\left(\frac{\Gamma}{10}\right)^2\left(\frac{\varepsilon_p}{1PeV}\right)^{-1}\text{keV}$$

Γ : bulk Lorentz factor of the plasma




$$\Phi_\nu^{\text{Diffuse}} \propto n_0 \xi_{\text{CR}} L_X \tau_{p\gamma}[\sqrt{L_X}, B, \Gamma]$$

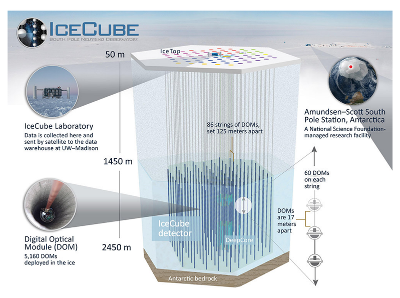
Scan a reasonable range to obtain the upper limit of Lx for each $n_0$ and Γ

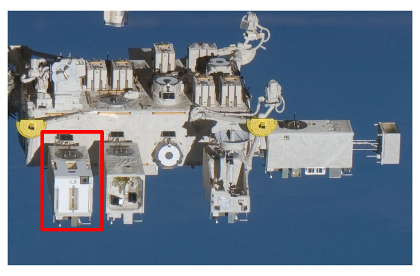
$n_0$ : Source density

**Lower limit** derived from constraints on the neutrino diffuse flux

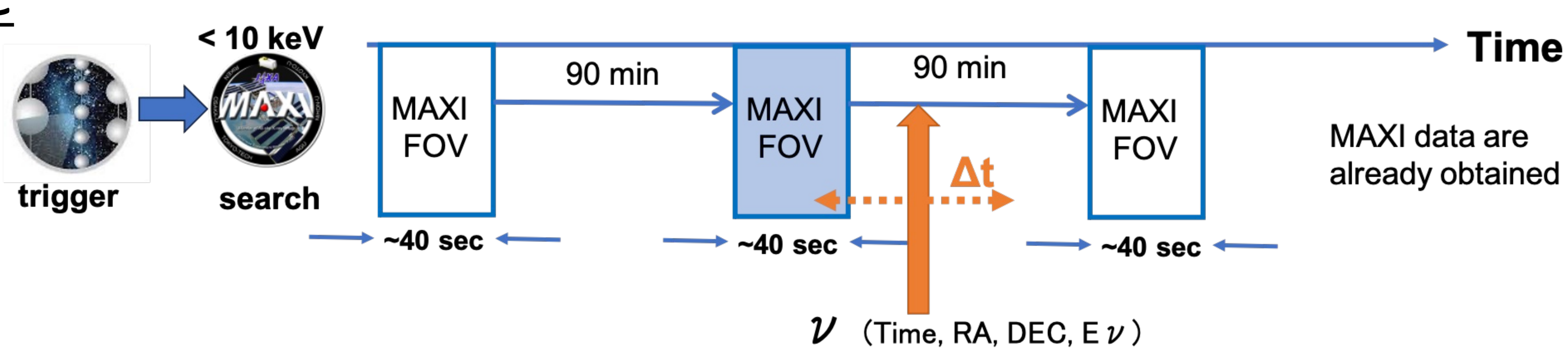
**Upper limit** by this X-ray counterpart search

## Data and Analysis – MAXI and IceCube





| | IceCube | MAXI |
|---|---|---|
| Energy range | TeV – PeV (ν) | 2 – 20 keV (photon) |
| FOV | All sky | All sky (80% in 92 min orbit) |
| Start date | April 2011 (IC86) | Aug 2009 |
| Angular resolution | ~1.0 deg (90% for track events) | 1.5 deg (FWHM) |
| Data processing | Real-time@South pole | Real-time@TKSC via TDRSS |




Both have over a 10-year overlap in their all-sky monitoring and similar angular resolution.

Check corresponding MAXI data for all neutrino track events and test for significance.
The rate is ~2 mHz and ~1/1000 of that is astrophysical-origin.
When Δt is set to 90 minutes, the number of coincident events over 10 years is ~200,000.

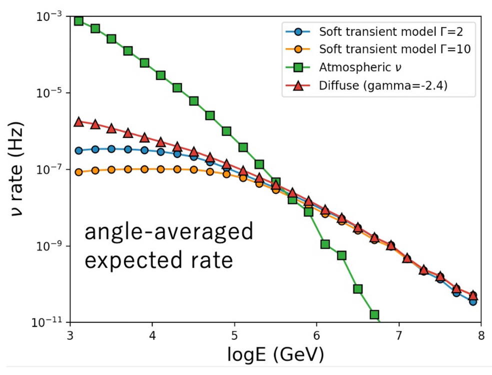
## Idea for MM likelihood test

ν signal related X-ray | ν signal "not" related X-ray

$$\mathcal{L}_{\text{sig+bgd}} = \left(\frac{n_{\text{sig}}}{n_{\text{atm}}+n_{\text{dif}}} P_\nu^{\text{sig}}(E_\nu,\delta) \times P_X^{\text{sig}}(N_X, \mu_{X\text{sig}(L_X,z)}) + \frac{1}{n_{\text{atm}}+n_{\text{dif}}}\left\{n_{\text{dif}} P_\nu^{\text{dif}}(E_\nu,\delta) - n_{\text{sig}} P_\nu^{\text{sig}}(E_\nu,\delta)\right\} P_{X_{\text{DB}}}^{\text{bgd}} + \frac{n_{\text{atm}}}{n_{\text{atm}}+n_{\text{dif}}} P_\nu^{\text{atm}}(E_\nu,\delta) P_{X_{\text{DB}}}^{\text{bgd}}\right)$$

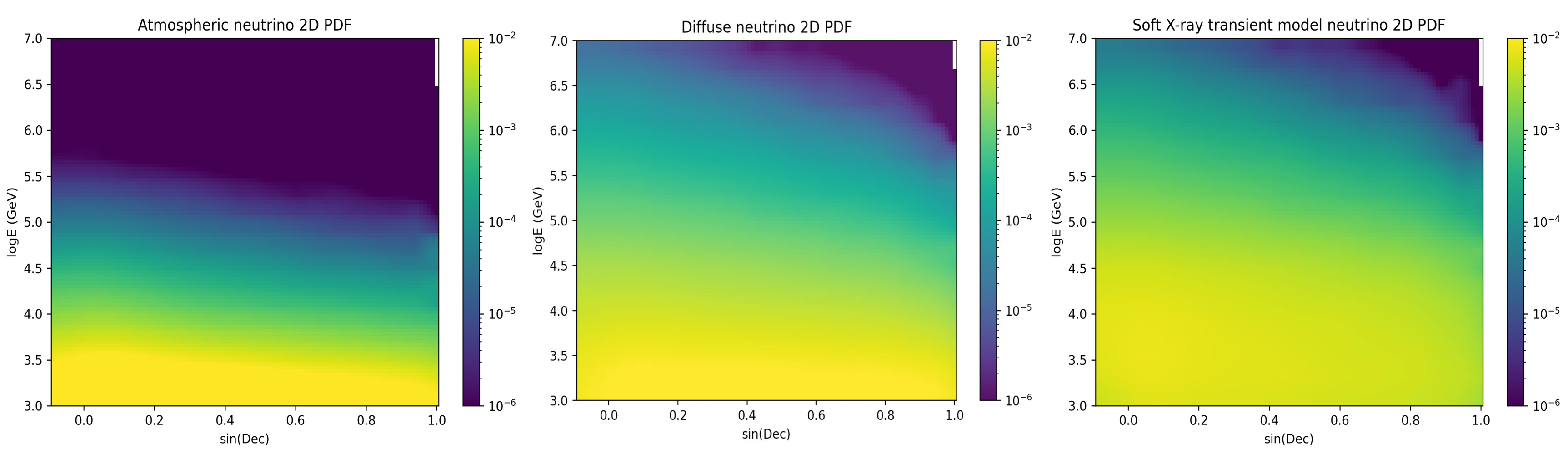
atmospheric ν bgd "not" related X-ray

n :Expected rate for each component
$P$ : Probability Density Function
$N_X$ : Number of X-ray events
$\delta$ : direction of the events
$\epsilon_\nu$ : energy of the events

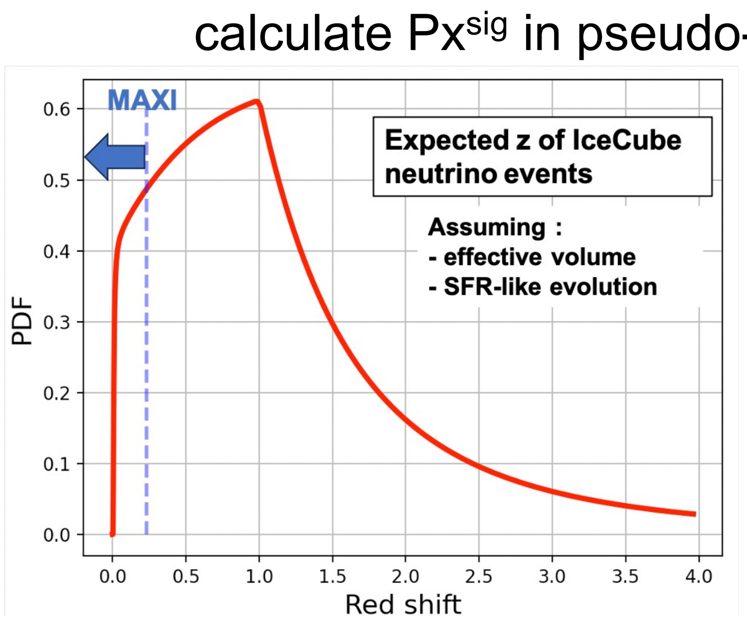


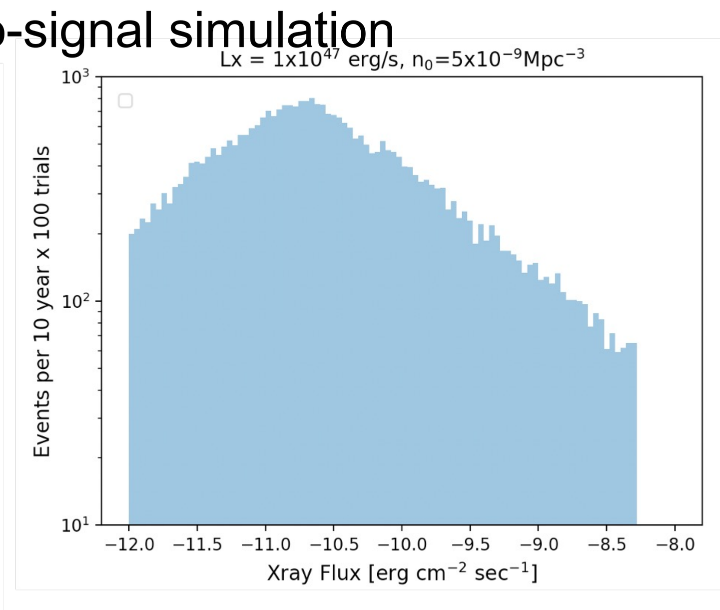

Using it for pseudo-signal simulation, sensitivity can be evaluated.

Pν : Two-dimensional PDFs of neutrino energy and angle (atmospheric, diffuse, soft x-ray transient model) estimated by MC simulation.



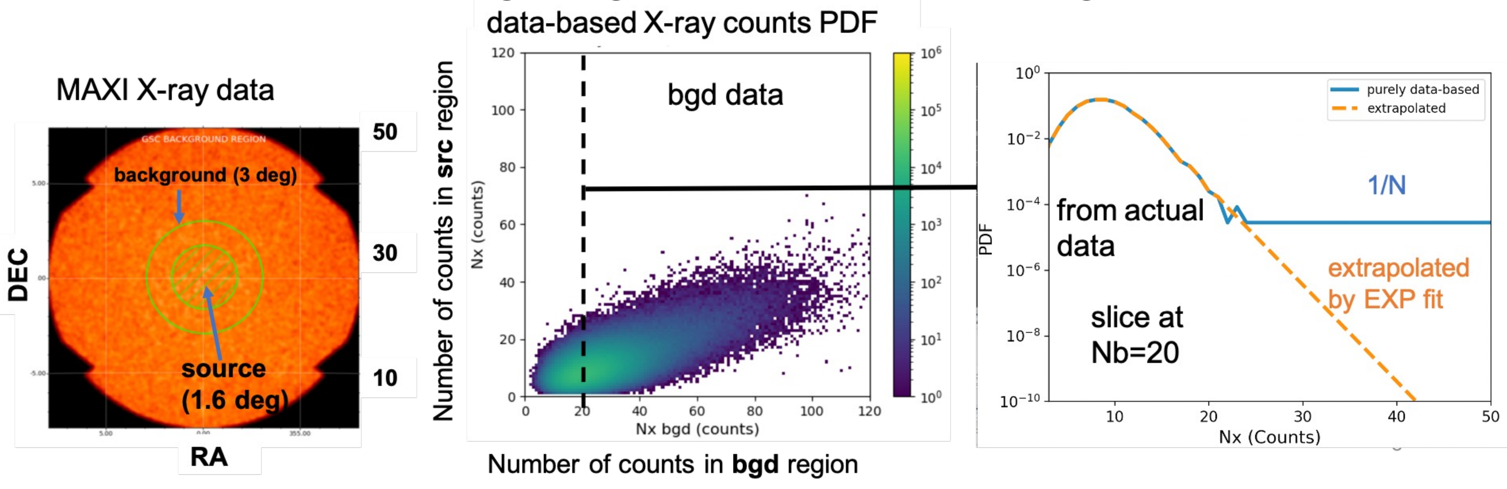

Distance distribution of the transient required to calculate $P_X^{sig}$ in pseudo-signal simulation




$$P_X^{\text{sig}} = \int_0^{z_{\max}} P(z)\, P(N_X \mid \mu_{(L_X)})\, dz \qquad \sum_{n=0}^{N_X} P^{\text{Poisson}}(N_X - n \mid \mu_{(L_X)}) P_{X_{\text{DB}}}^{\text{bgd}}(n)$$

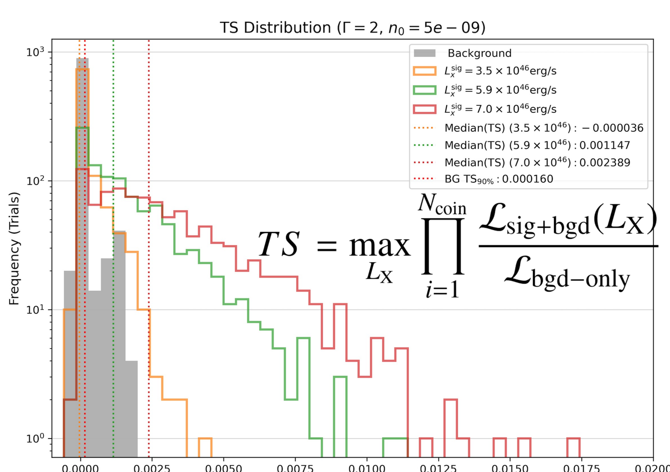
$P_X^{bgd}$ is estimated from MAXI real data every 100 days, considering long-term variations in bgd.




### Procedure of Pseudo experiments

1. Generate pseudo soft X-ray transient sources
   - Calculate the number of sources in each redshift bin based on the assumed transient density and the evolution factor (here assuming SFR).
   - Determine the expected numbers of events detected by IceCube for each redshift bin based on the effective area of IC.
2. Sample atmospheric, diffuse (except the transients) and the transients ν according to the expected energy and angular distribution
3. Distribute background X-ray photons according to the 4000 days MAXI background data
4. Assuming all soft X-ray transients have the same $L_{X\_sig}$. Then, simulate the detected numbers of X-ray photons by MAXI
5. Calculate the TS

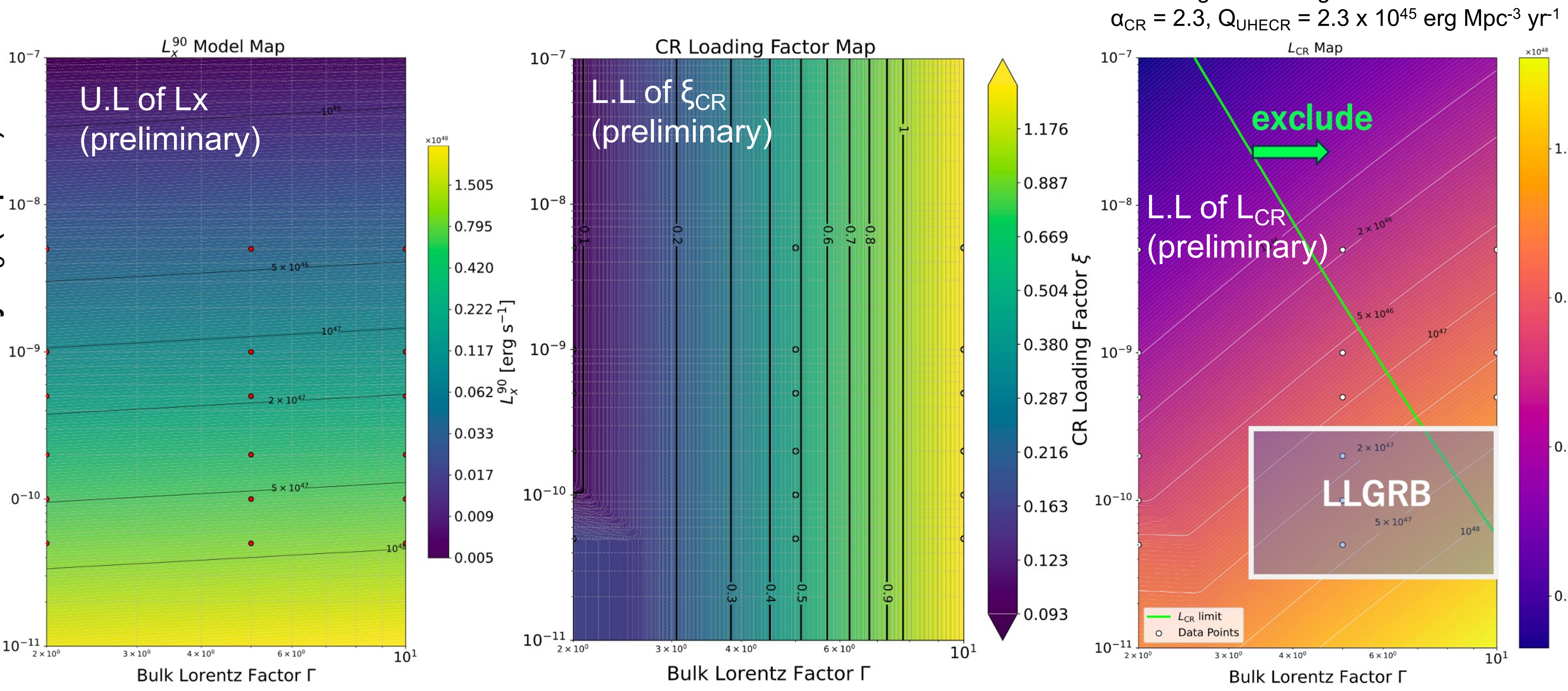
## Results



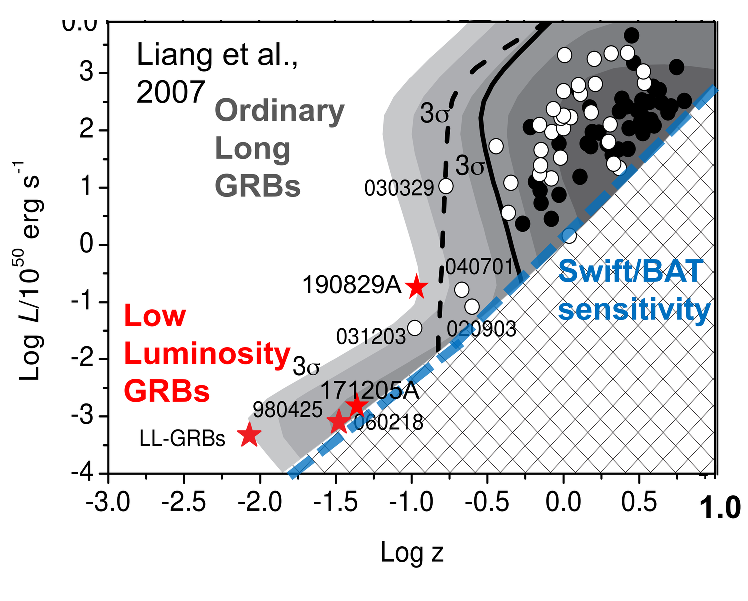

$$TS = \max_{L_X} \prod_{i=1}^{N_{\text{coin}}} \frac{\mathcal{L}_{\text{sig+bgd}}(L_X)}{\mathcal{L}_{\text{bgd-only}}}$$

Define the Lx value where the median of the pseudo-signal simulation distribution exceeds 90% of the bgd scramble's TS distribution as the 90% discovery potential ($Lx^{90}$).

assuming unified origin of UHECR and ν
$\alpha_{CR}$ = 2.3, $Q_{UHECR}$ = 2.3 x $10^{45}$ erg $Mpc^{-3}$ $yr^{-1}$




Calculate $Lx^{90}$ for several $n_0$ and gamma values, modeling within the range $n_0$=$10^{-7}$-$10^{11}$/$Mpc^3$, Γ=2-10 (systematic error approximately 20%).




MAXI is not as sensitive as the current Einstein Probe, but by utilizing its overlap with IC over 10 years, it can constrain the contribution of soft X-ray transients like LLGRBs to the diffuse sources.