Search for High-energy Neutrino Emission from X-ray Binaries with IceCube

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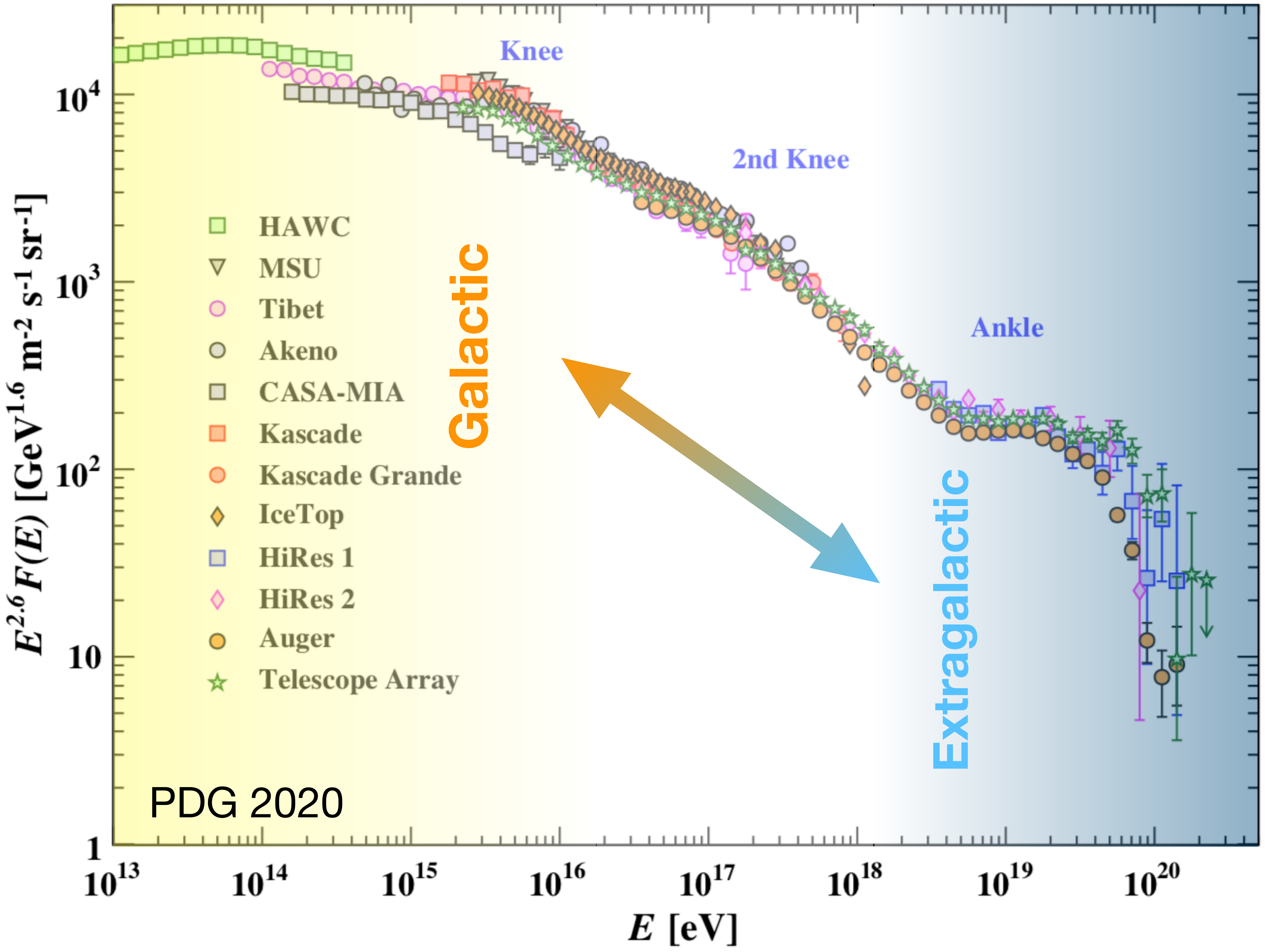
Galactic High-Energy Neutrino Sources

- Galactic cosmic rays reach at least **knee** of the spectrum **(PeV)**, **Guaranteed neutrino flux is expected from the Milky Way**.
- Identification of Galactic neutrino sources can unveil the origin of Galactic cosmic rays and provide smoking-gun for hadronic interactions.

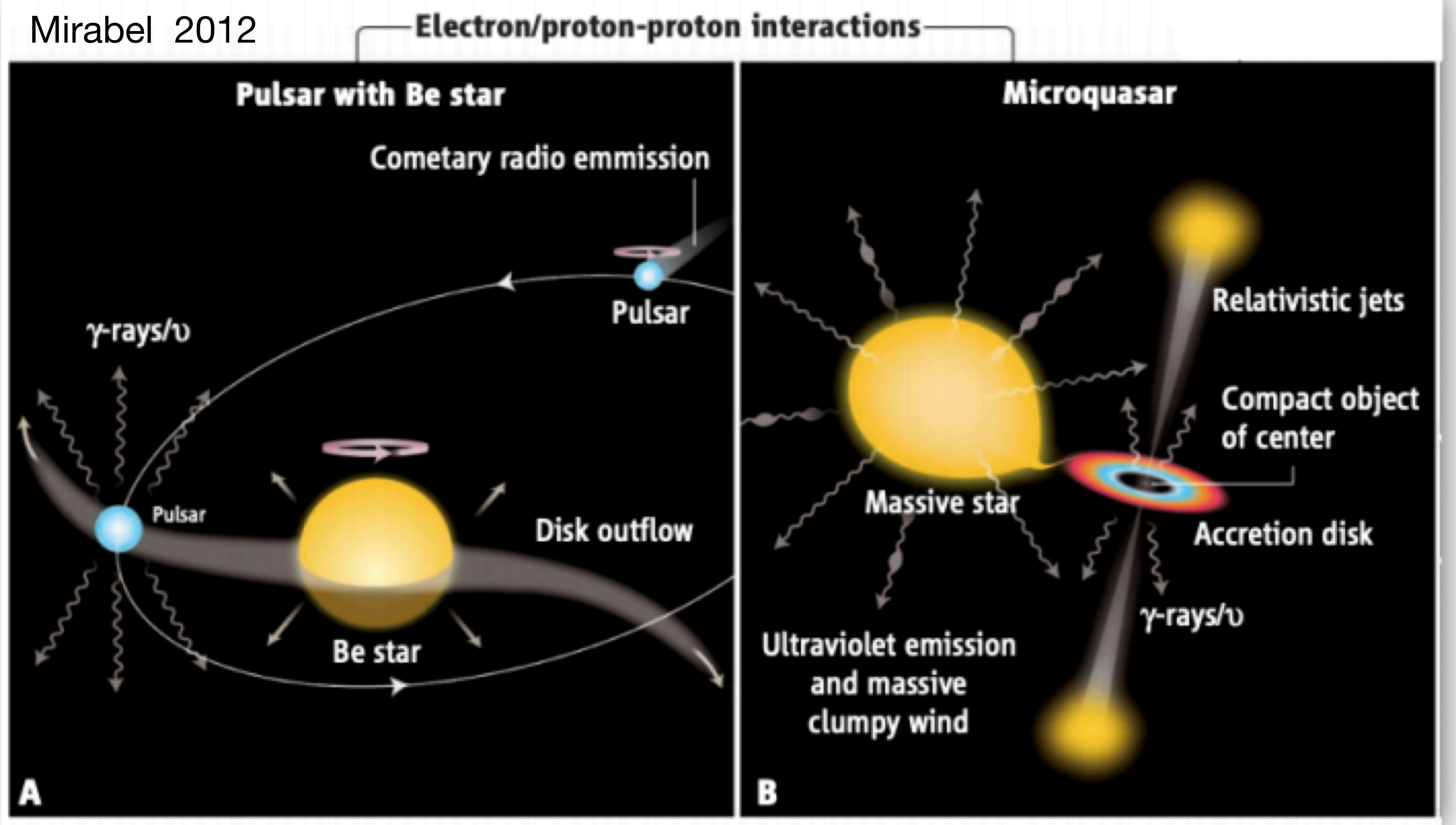


Galactic Candidates

- Point-like: PWNe, SNR, X-ray binaries, unidentified TeV sources…
- Extended Region: Sagittarius A*, Fermi Bubbles, Galactic Halo…
- Diffuse Emission: CR interaction with hydrogen in Galaxy

X-ray Binaries

- Microquasars: similar processes are expected as in quasars. Relativistic jets could be sites of particle acceleration.
- Without collimated beam, cosmic ray acceleration can happen in magnetospheres of a spinning neutron stars.
- Hadronic interactions can happen in the jet with the internal/external radiation, or cloud/wind created by the companion star.
- Detection of TeV gamma rays from some X-ray binaries demonstrated the energy capability.



Mirabel 2012

Neutrinos predictions?

Probing Microquasars with TeV Neutrinos

Amir Levinson[1] & Eli Waxman[2]

Microquasar LS 5039: a TeV gamma-ray emitter and a potential TeV neutrino source[1]

F Aharonian[1], L Anchordoqui[2], D Khangulyan[1] and T Montaruli[3,4]

LS I +61 303 as a potential neutrino source on the light of MAGIC results

Diego F. Torres[1,2] & Francis Halzen[3]

High-Energy Neutrino Emission from Binary X-Ray Sources.

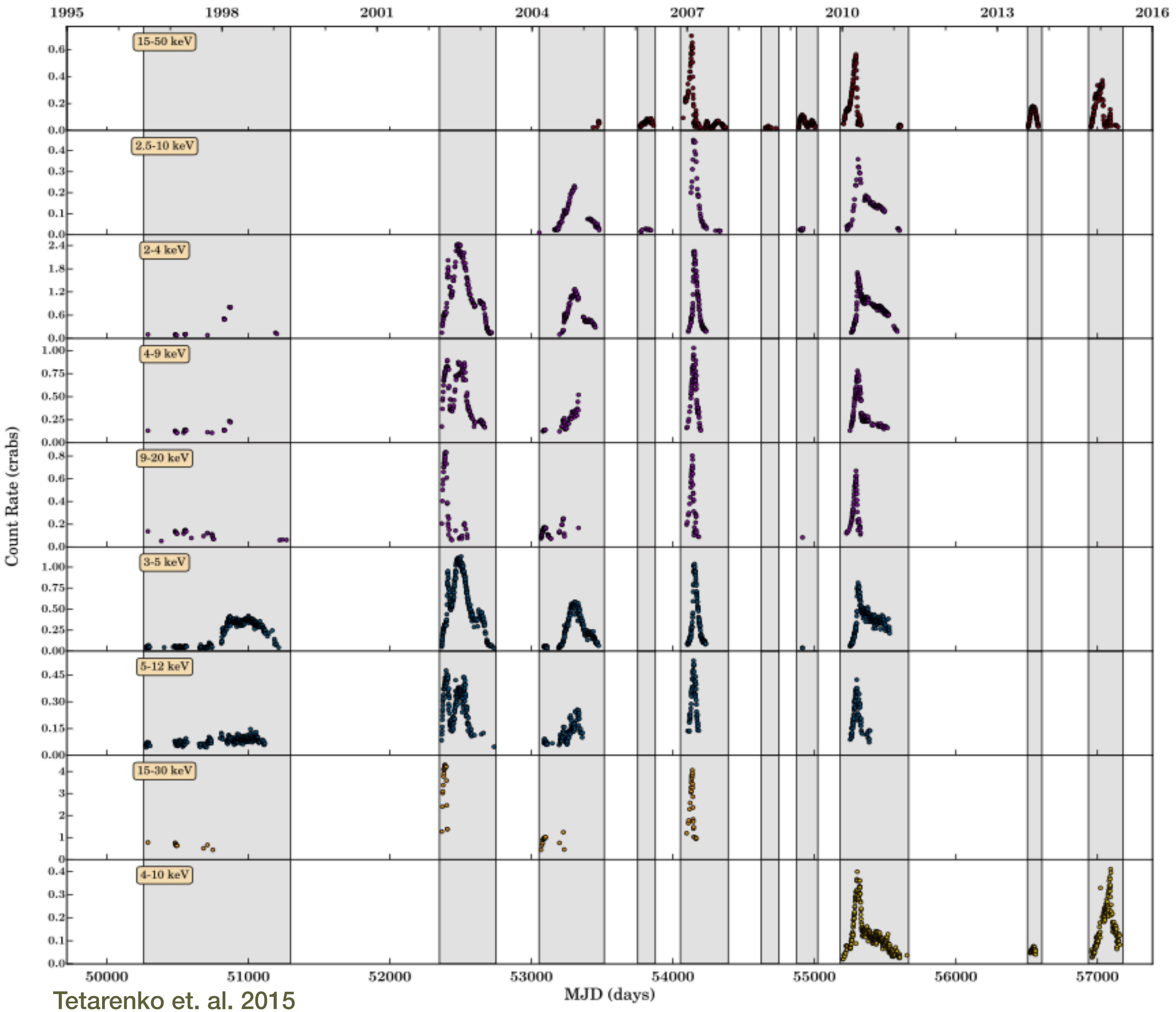
G. Auriemma (*)

HIGH ENERGY NEUTRINOS IN CLOSE BINARY STARS

T.K. Gaisser

...

Neutrinos ~ X-ray



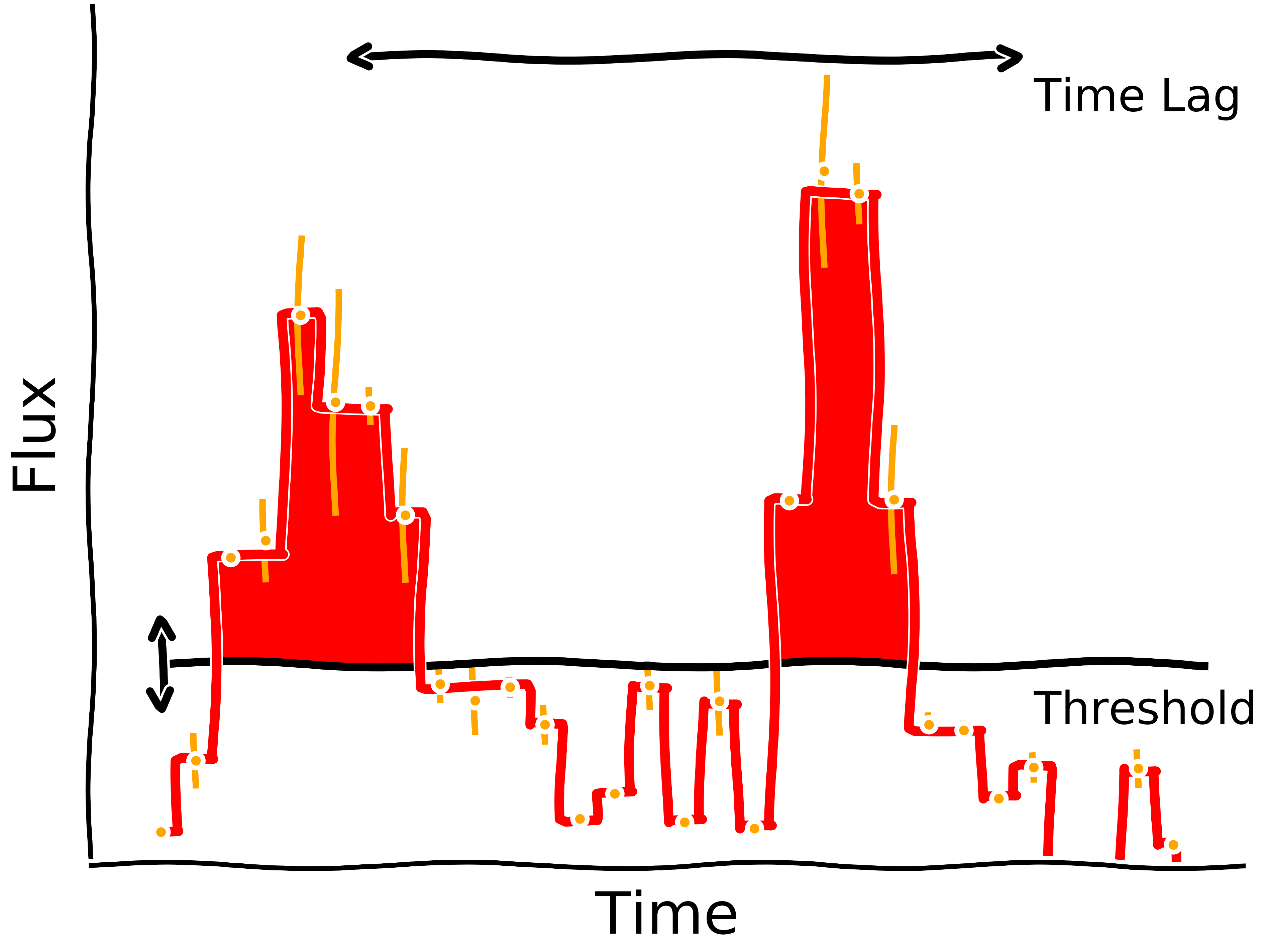
Tetarenko et. al. 2015

Figure 24. Long-term light curve of the transient BHXB GX 339−4. Shaded gray regions span individual outbursts. Colors represent individual instruments: *Swift*/BAT (red), *RXTE*/PCA (purple), *RXTE*/ASM (blue), *RXTE*/HEXTE (orange), and MAXI/GSC (yellow) from top to bottom.

- XRBs are luminous in X-rays.
- We can assume that possible neutrino flaring can be correlated to the X-ray flaring behavior.
- **Time-dependent analysis:**
  - Hard X-ray active sources.
  - Look for correlation between neutrino emission and hard X-ray emission.
- **Time-integrated analysis:**
  - Assume persistent emission
  - 4 notable sources
  - 2 stacked sources lists of microquasars and TeV XRB.

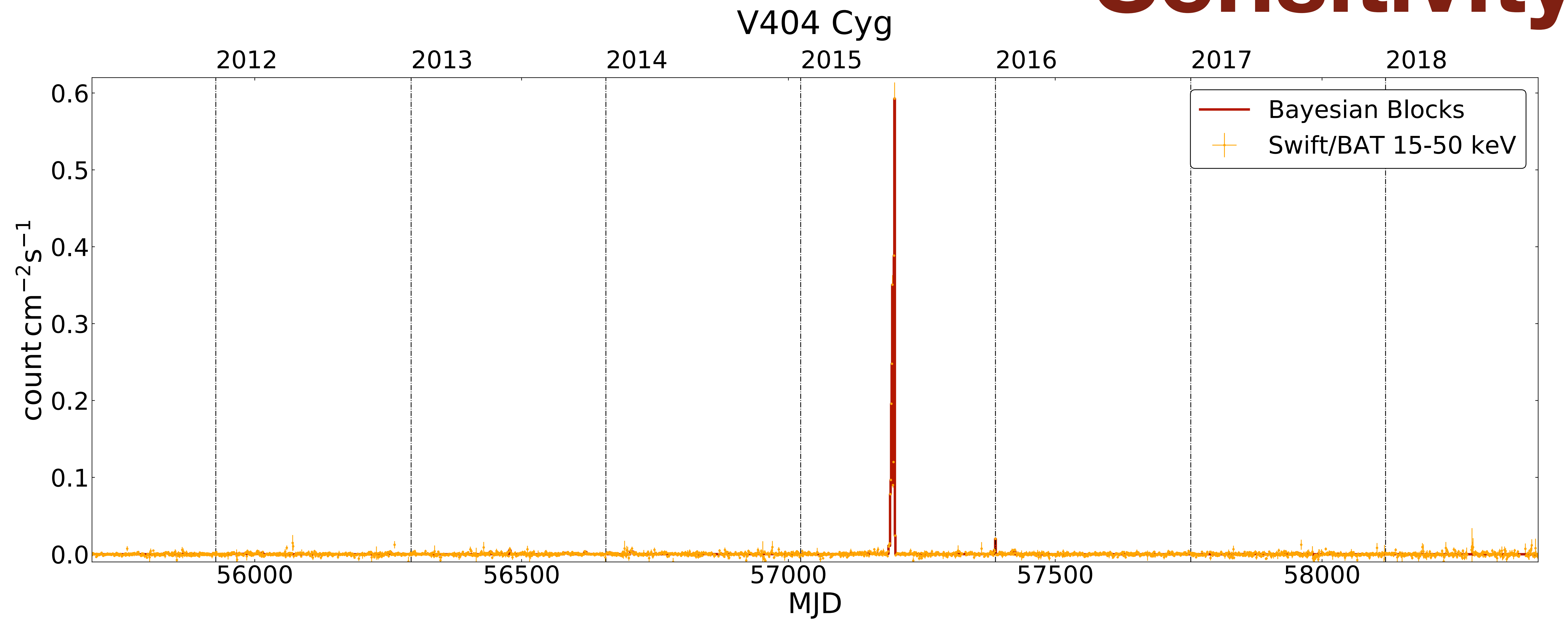
Method

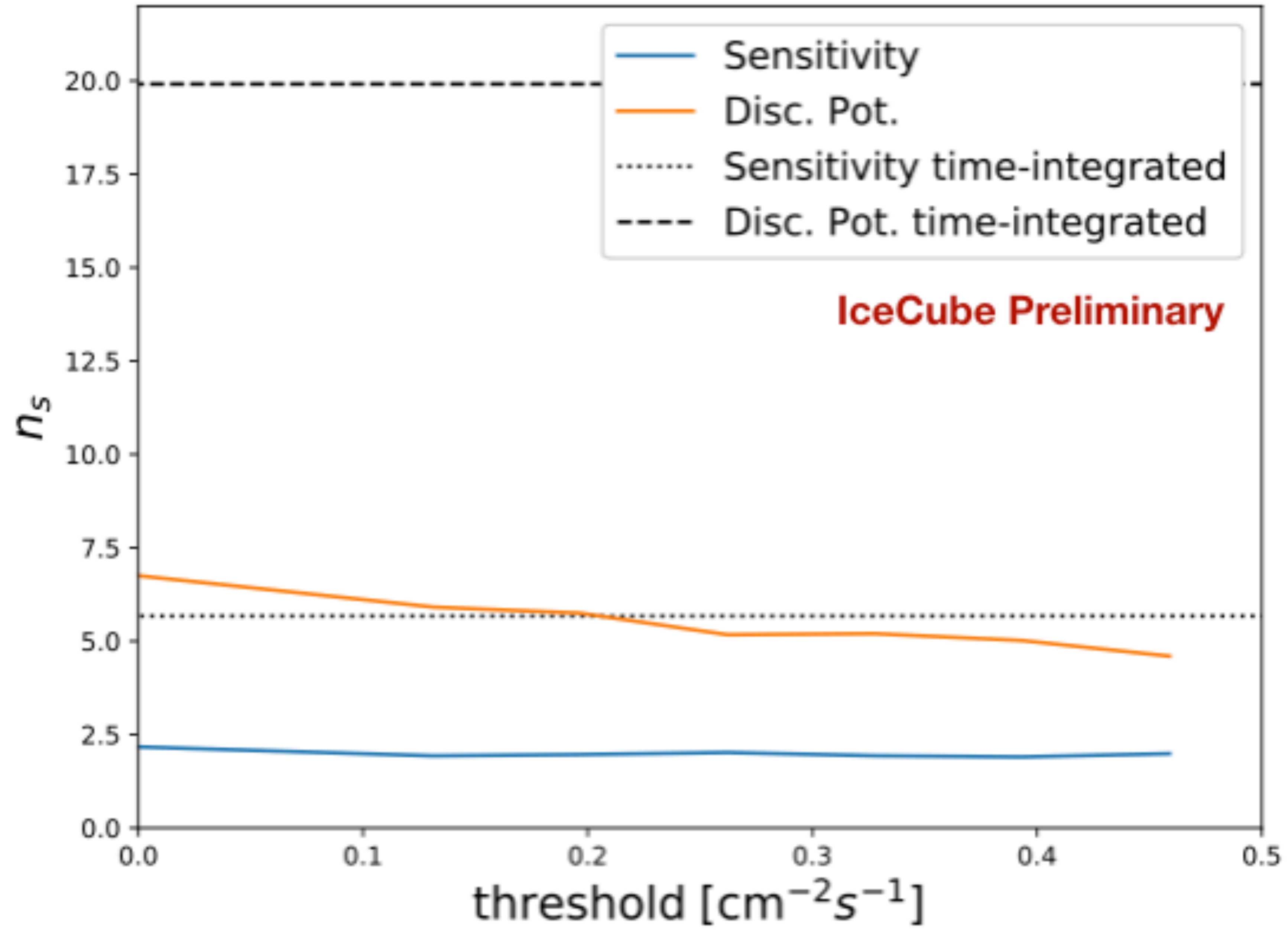
- Unbinned maximum likelihood method.
- Time-dependent search using hard X-ray light curves which serve as template for construction of time PDFs.
- Light curves are from Swift-BAT 15 -50 keV and MAXI 10-20 keV.
- The Bayesian block algorithm is applied to optimize binning of data in order to identify flares in light curves. (Algorithm: *Scargle, J et al. (2012)*)
- Fitting for the signal events, spectral index, time lag, and the threshold

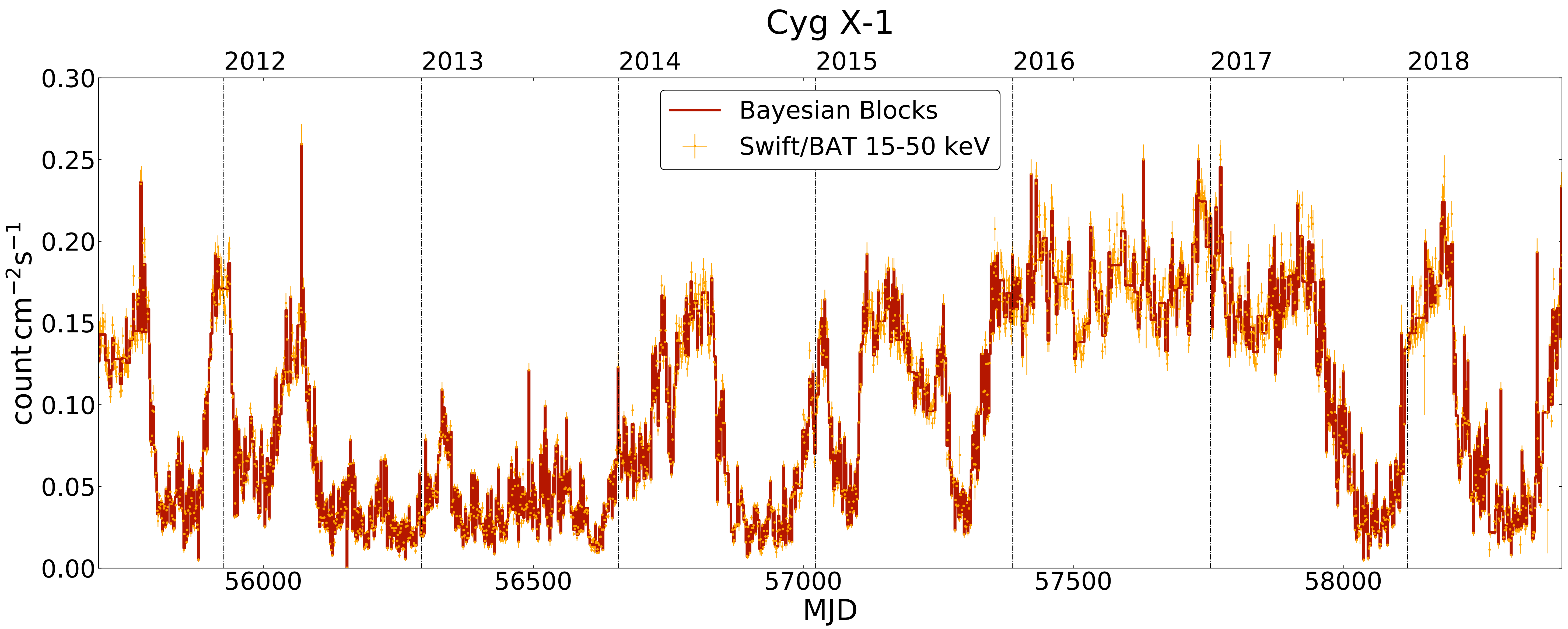


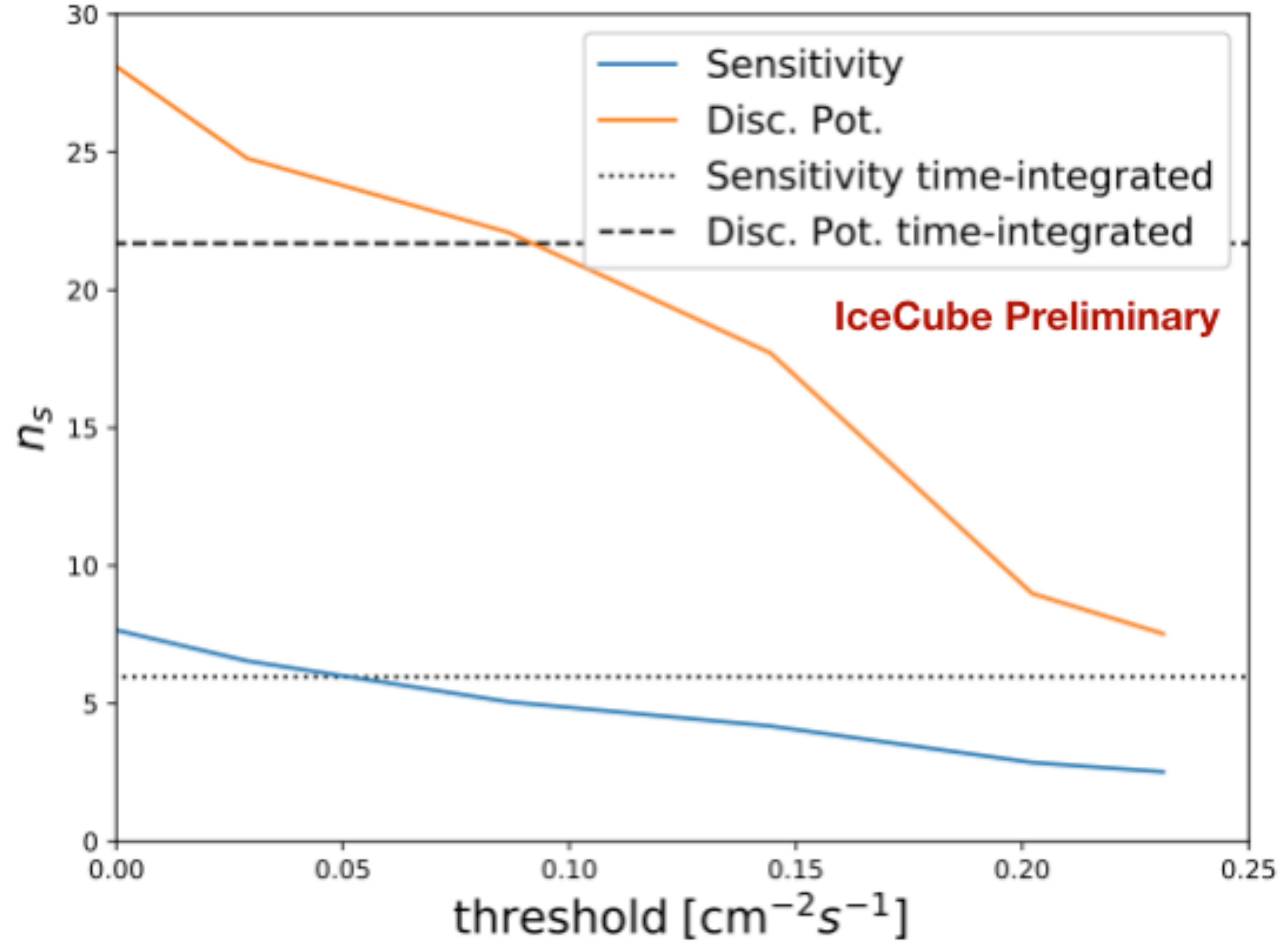
$$TS = -2log\frac{\mathscr{L}(n_s = 0)}{\mathscr{L}(\hat{n}_s, \hat{\gamma}_s, \hat{T}_{lag}, \hat{f}_{th})}$$

Sensitivity

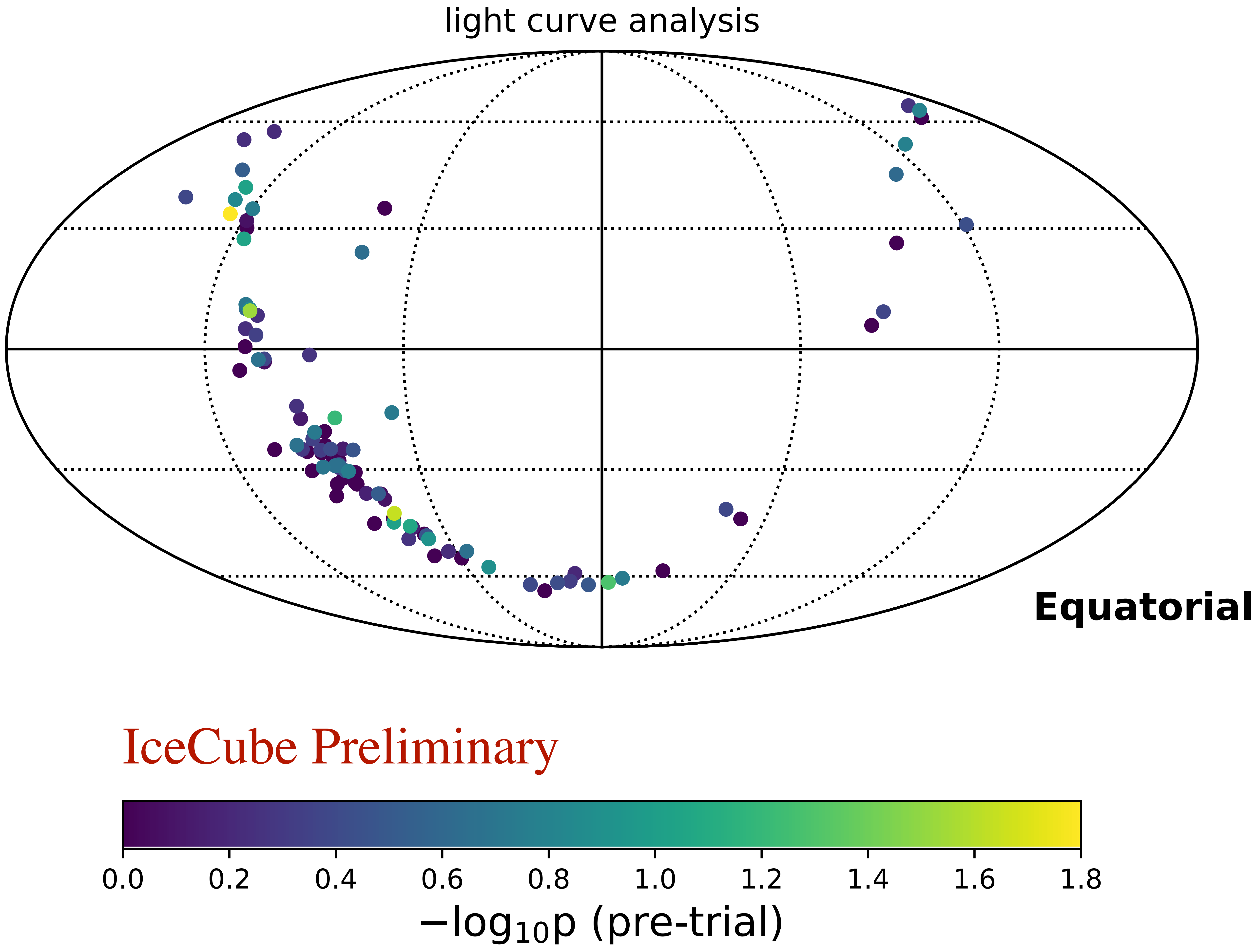






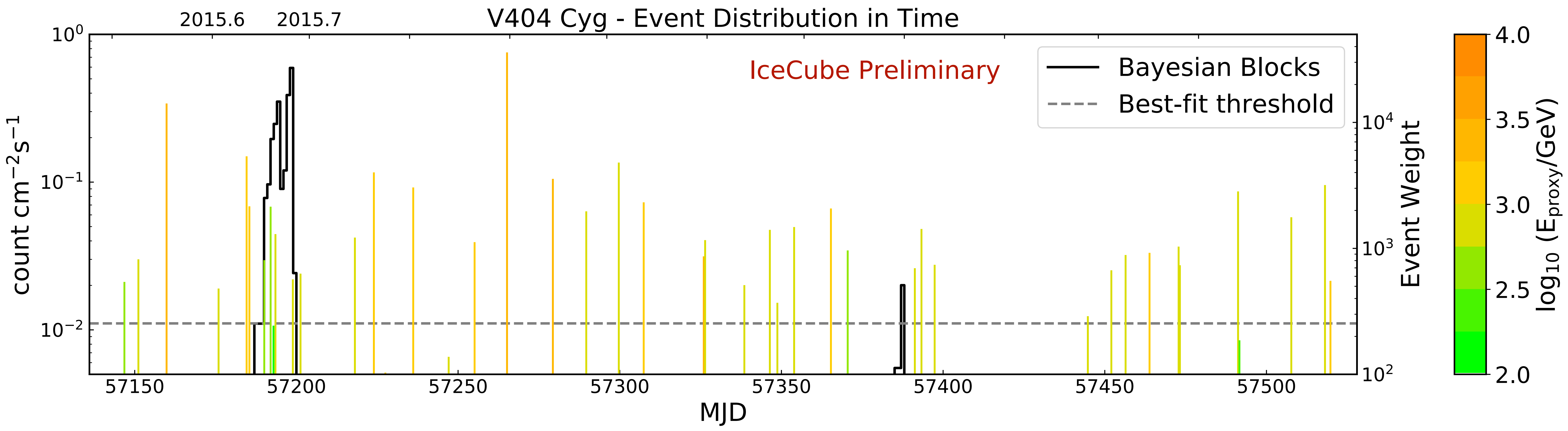


Time-dependent Analysis Results



- 7.5 yr (2011-2018) IceCube muon tracks are used. Livetime ~ 2711 days, ~ 500k events.
- 102 sources selected from high-mass and low-mass X-ray catalogs as active in hard X-ray in the neutrino data taking time are studied.
- No significant signals found.
- The most significant is **V404 Cyg**, a low-mass XRB and microquasar, with a pre-trial **p=0.014** **(post-trial 0.75)**.

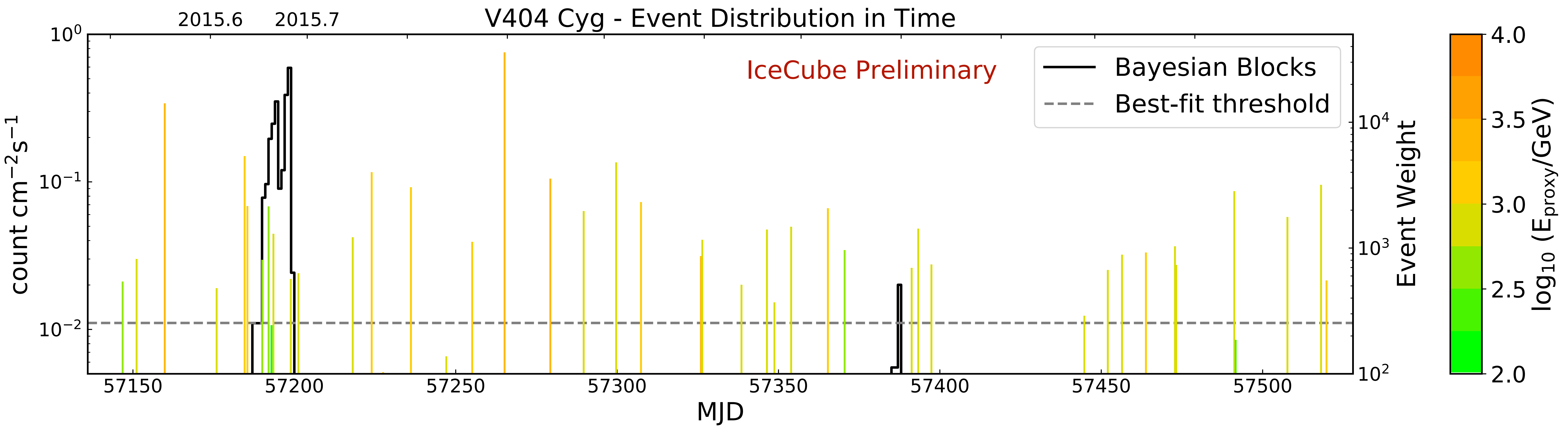
V404 Cyg



- A giant X-ray flare in 2015.
- 5 events within 1.5° in a 11-day window at low energies < 1 TeV.

TS	ns	γ	Threshold	Lag	p-value (post)
8.3	5.4	4.0	0.011	-0.5	0.014(0.75)

V404 Cyg



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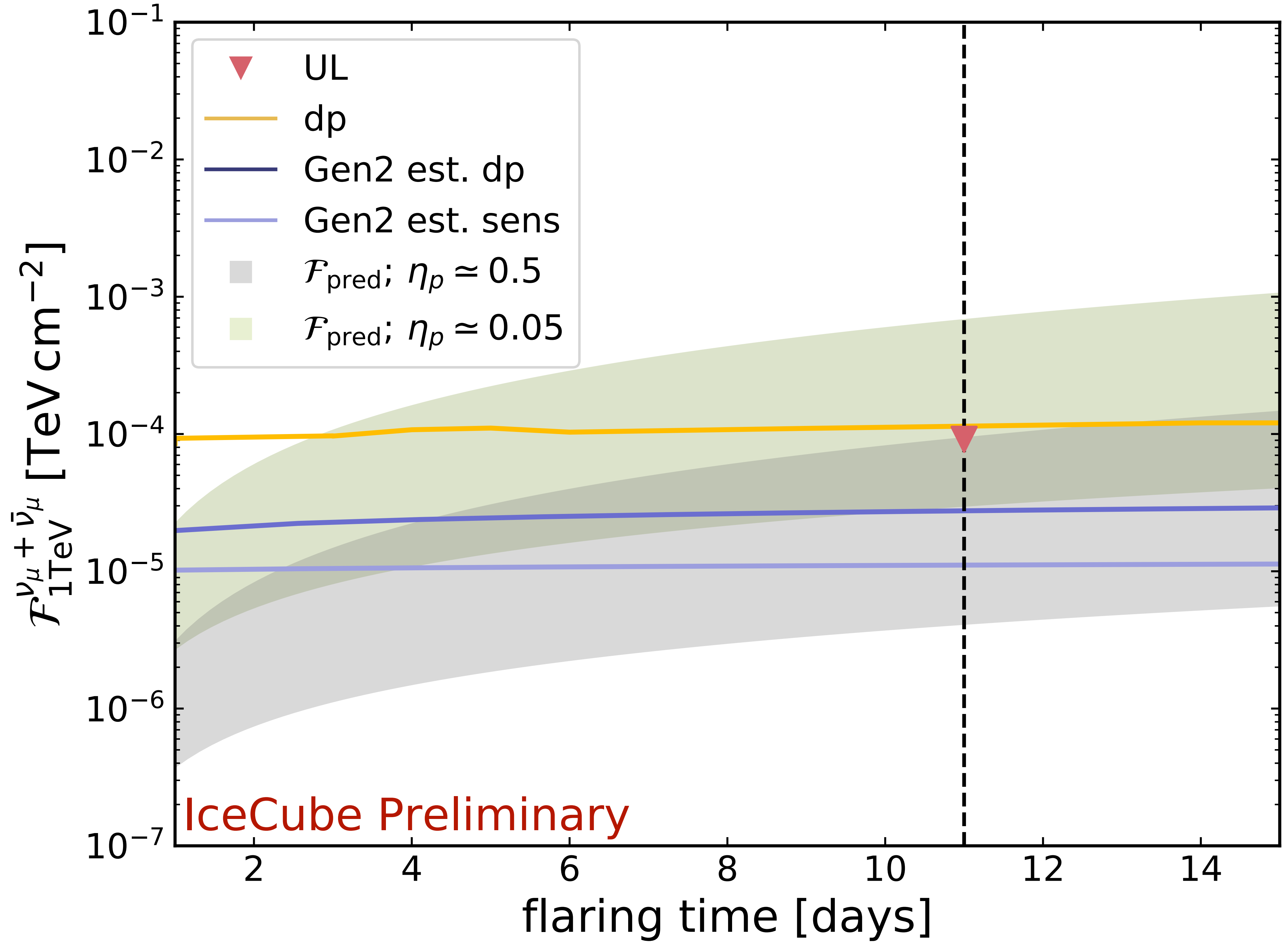


- 90% CL upper limit.
- Estimate sensitivity & 5σ discovery potential in **IceCube-Gen2**.
- Compare with neutrino emission prediction in jet model described in *Levinson & Waxman PRL 2001*, Distefano, C., et al. ApJ (2002): 378.

TS	ns	γ	Threshold	Lag	p-value (post)
8.3	5.4	4.0	0.011	-0.5	0.014(0.75)

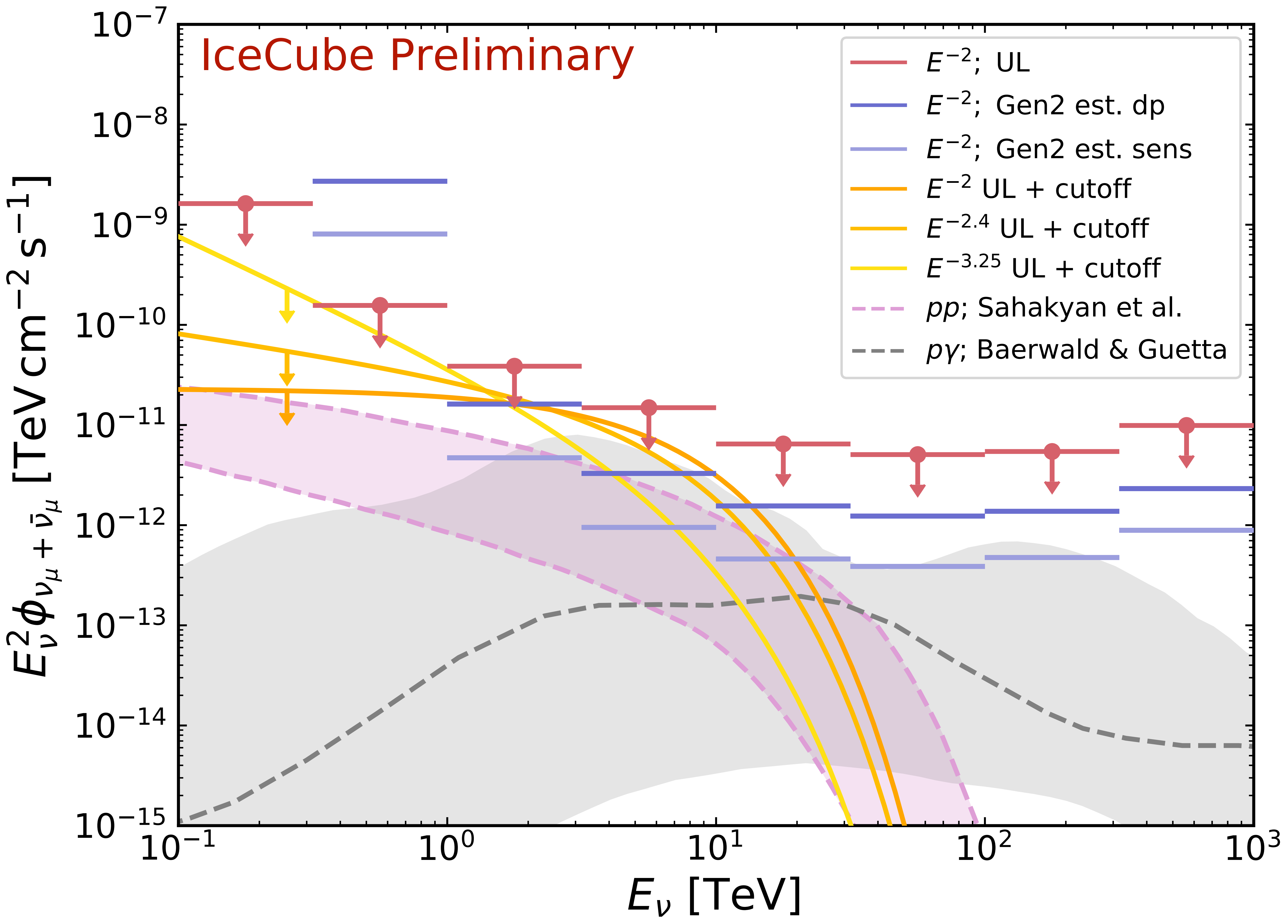
Time-integrated Analysis Results

name	RA [°]	δ [°]	TS	$\hat{n}_s$	$\hat{\gamma}$	p-value (pre-trial)
LSI +61 303	40.13	61.23	0	0	-	1
LS 5039	276.56	-14.85	0.62	5.78	3.62	0.382
SS 433	287.96	4.98	0	0	-	1
Cyg X-3	308.11	40.95	6.80	44.58	3.25	0.009
TeV XRB stacking	-	-	0.06	7.70	3.46	0.587
mqso stacking	-	-	0	0	-	1

- Persistent emission assumption.
- 4 notable single sources, no significant signals found.
- The most significant source is **Cyg X-3**, a high-mass XRB and microquasar, with pre-trial **p-value 0.009** **(post-trial 0.036)**.
- Time-integrated stacking on TeVCat list and microquasars. No significant signal found.

Cyg X-3

TS	ns	γ	p-value (post)
6.8	44.58	3.25	0.009 (0.036)



- 44 events above 1 TeV within 1 degree, highest energy ~ 5 TeV.
- 90% CL upper limits
  - Energy differential
  - Power law + exp cutoff @ 5 TeV
- Estimated sensitivity & 5σ discovery potential in **IceCube-Gen2** with 10 yr exposure.
- Upper limits and sensitivity projection are compared with neutrino flux predictions.

(Sahakyan, Piano, Tavani. ApJ 2013) & (Baerwald & Guetta, ApJ 2013).

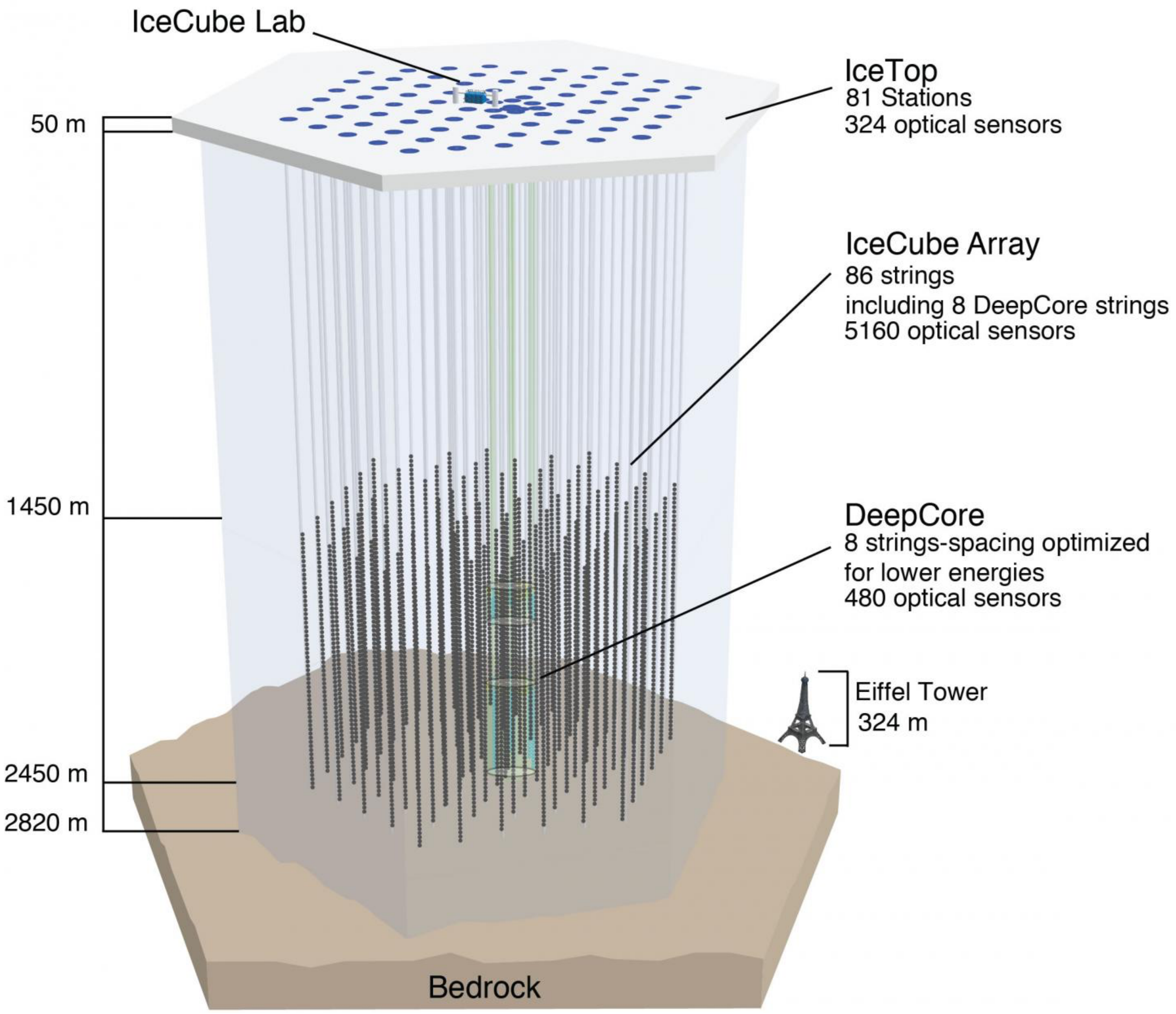
Conclusion

- A study on high-energy neutrino emission from X-ray binaries is conducted by IceCube based on hypotheses of flaring emission and persistent emission.
- No significant signals found and upper limits are set on the neutrino flux from XRB sources studied.
- Two interesting sources V404 Cyg and Cyg X-3 are discussed and the results are compared with neutrino flux predictions.
- IceCube-Gen2 performance is studied for interesting sources, showing detection potential in the future.

Thank you!

Backup Slides

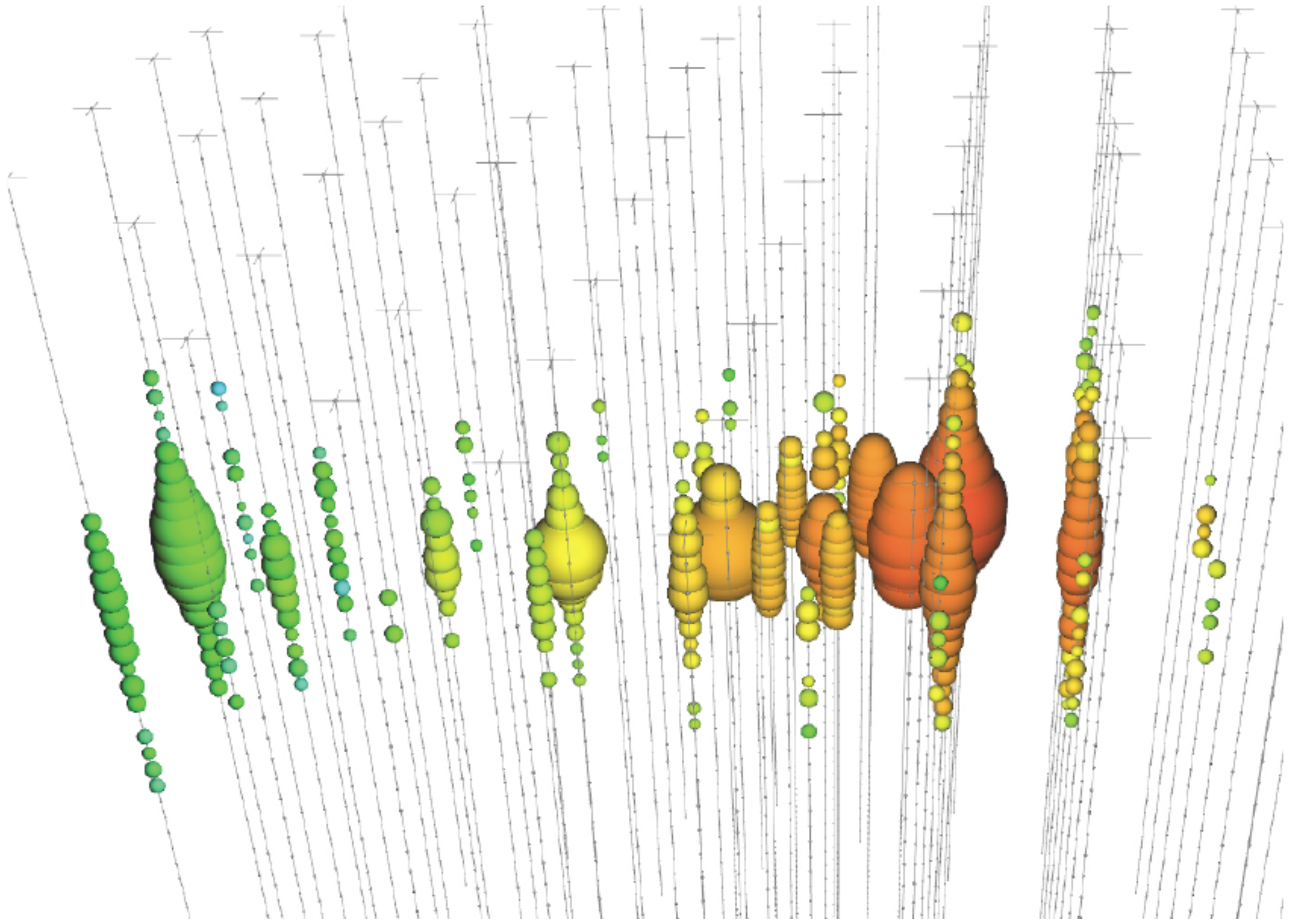
IceCube Neutrino Observatory



Digital Optical Module (DOM)

Event Morphologies

Charged Current ν_μ

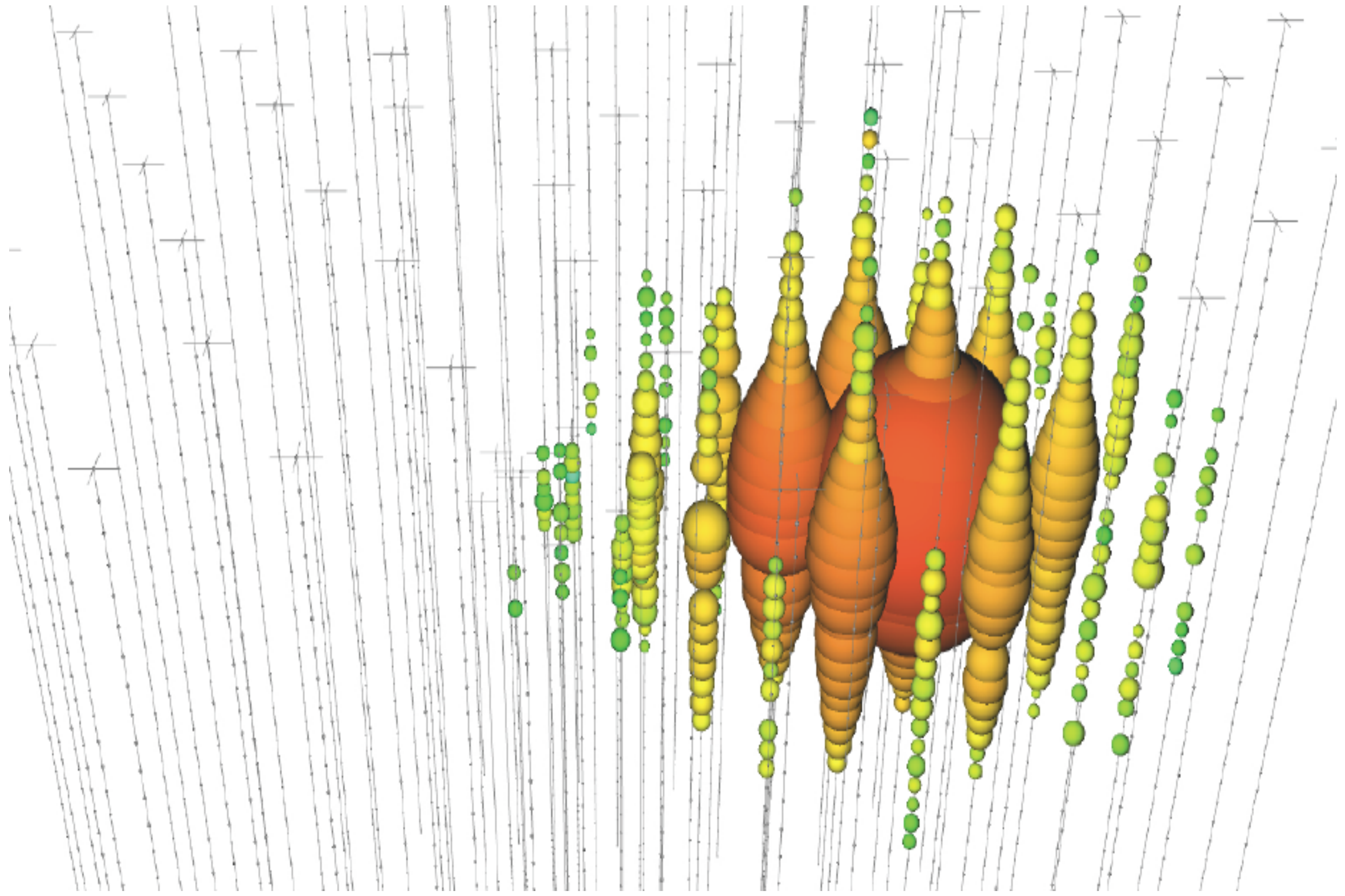


$$\nu_\mu + N \rightarrow \mu + X$$

Track (data)

Angular resolution $< 1^\circ$
Energy resolution ~ 2

Neutral Current / Charged Current ν_e

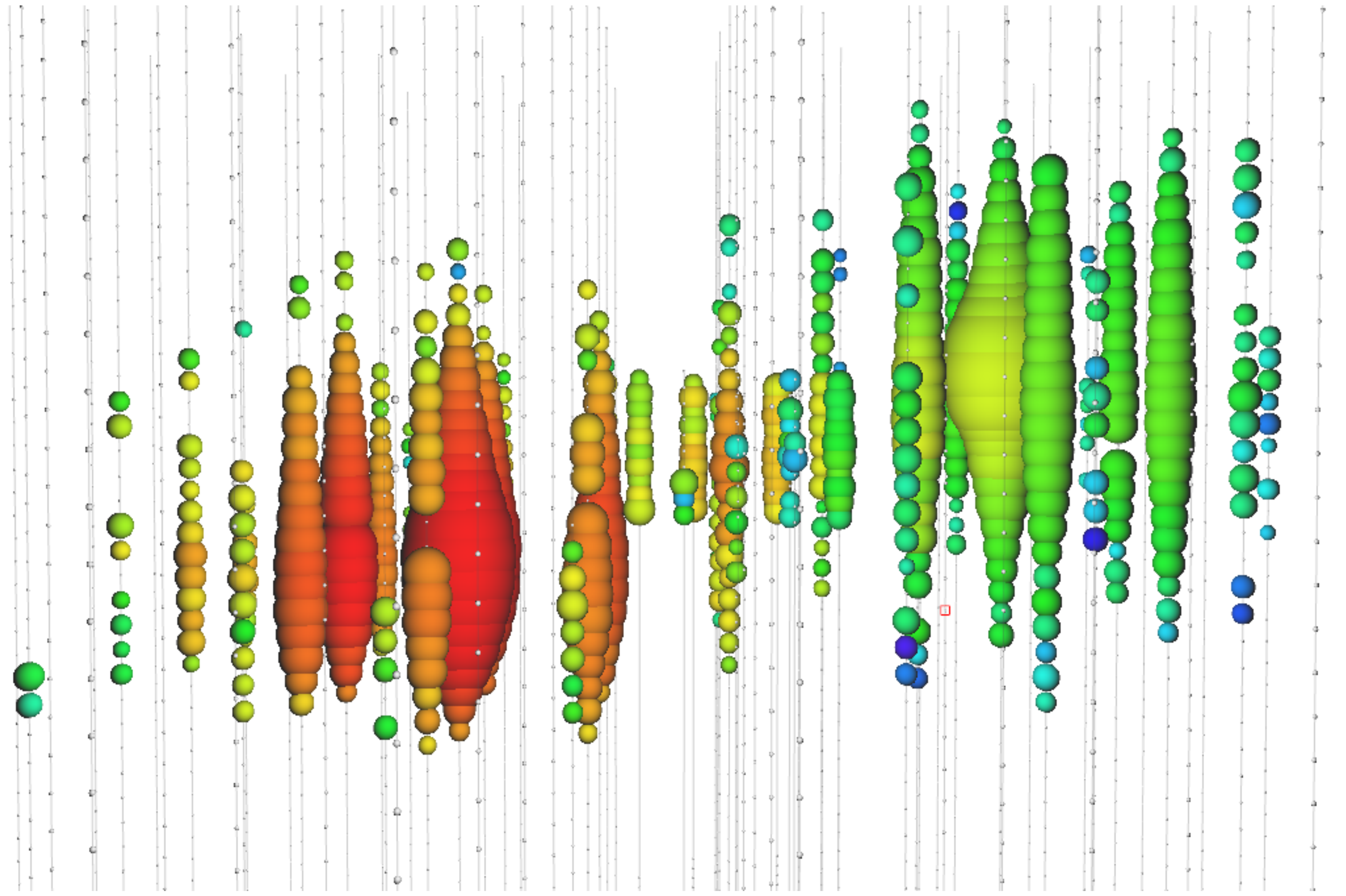


$$\nu_e + N \rightarrow e + X$$
$$\nu_x + N \rightarrow \nu_x + N$$

Cascade (data)

Angular resolution $\sim 10^\circ$
Energy resolution $\sim 15\,\%$

Charged Current ν_τ



$$\nu_\tau + N \rightarrow \tau + X$$

"Double-Bang" (simulation)

first astrophysical ν_τ candidates observation [2011.03561]

Method

$$\mathscr{L} = \prod_{i}^{N} \left[\frac{n_s}{N} \mathcal{S}_i + \left(1 - \frac{n_s}{N}\right) \mathscr{B}_i \right]$$

$$S_i = S^s(x_i, \sigma_i | x_s) \times S^E(E_i | \gamma) \times S^T(t_i | T_{lag}, f_{th})$$

Spatial:
2D Gaussian

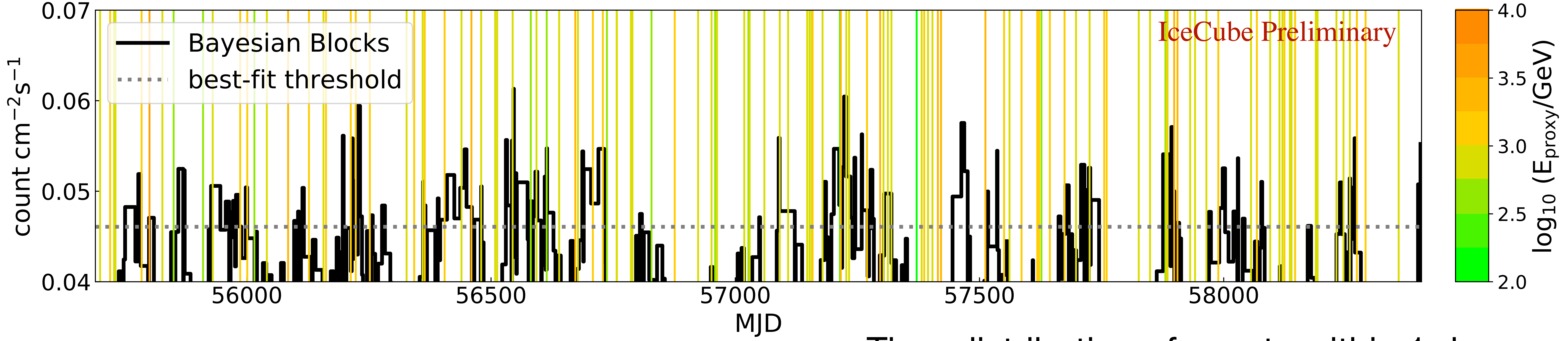
Energy :
Power law

Time:
Normalized blocked X-ray light curve

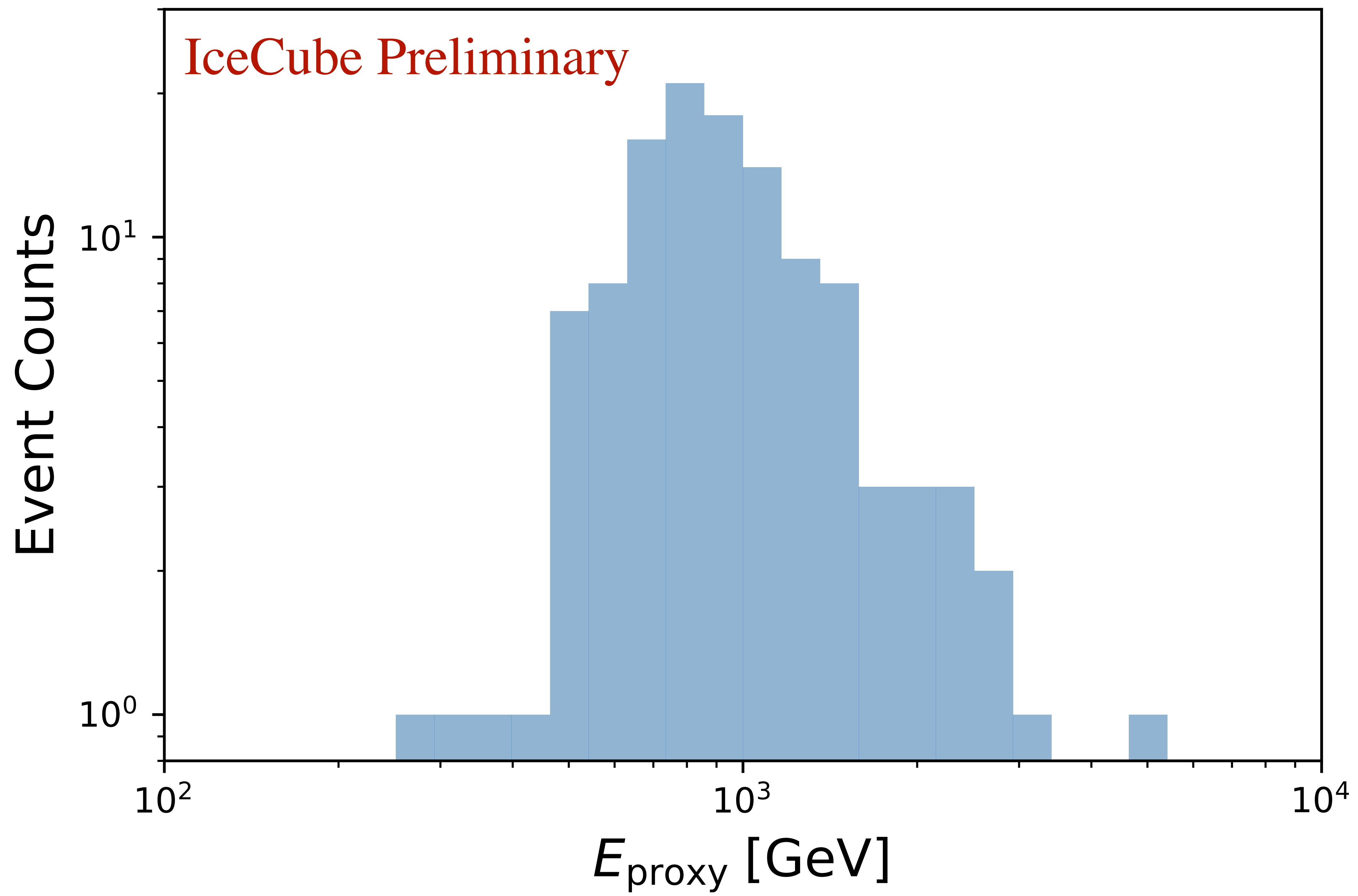
$$S^T(t_i | f_{th}, t_{lag}) = \frac{max\left(0, f(t_i - t_{lag}) - f_{th}\right)}{\int_{T_{min}}^{T_{max}} max\left(0, f(t_i - t_{lag}) - f_{th}\right)\, dt}$$

Background $\mathscr{B}_i$ is constructed from the data itself.

Cyg X-3



Time distribution of events within 1 degree & Bayesian blocks above best-fit threshold.



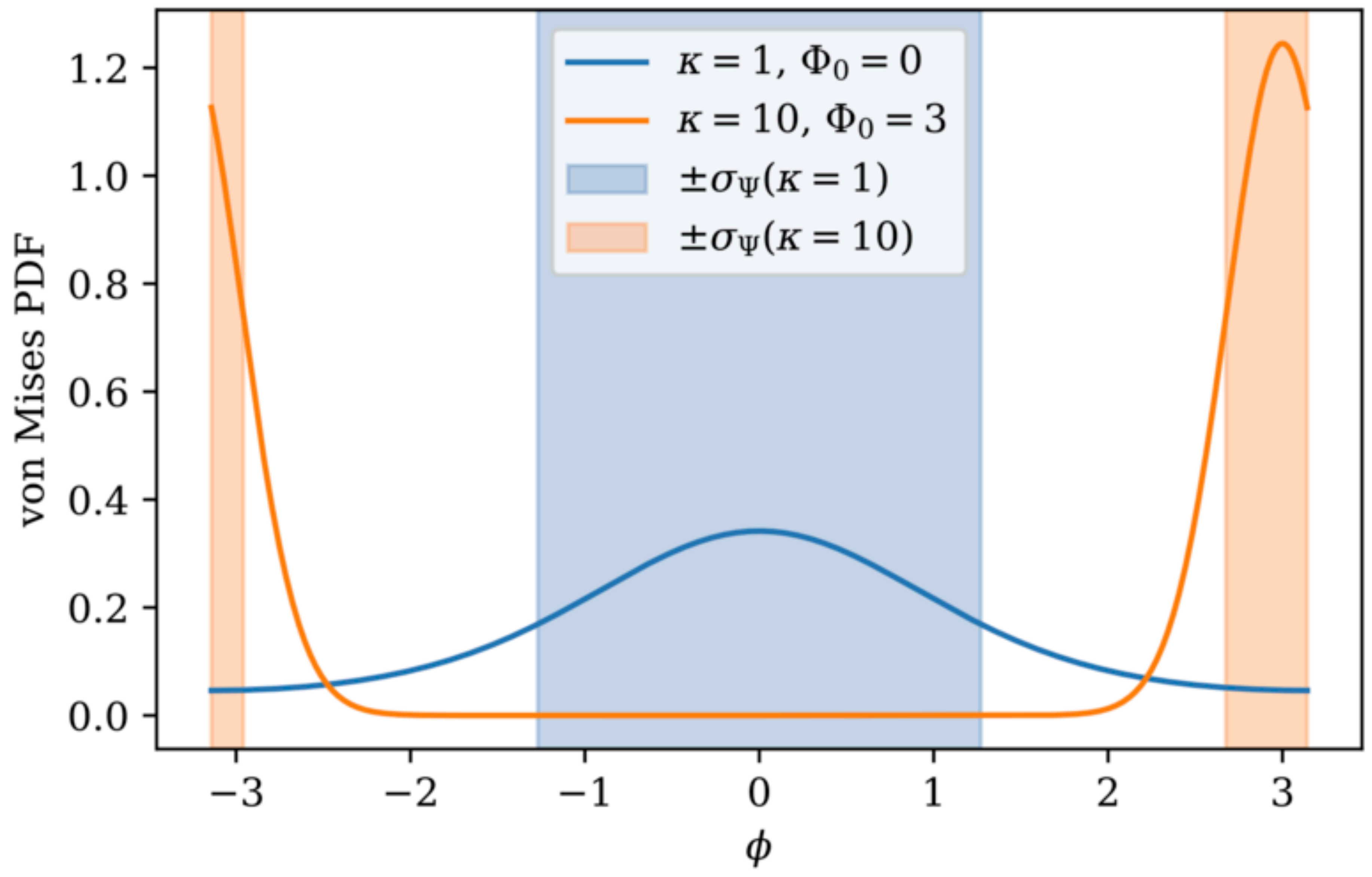
TS	ns	γ	Threshold	Lag	p-value (post)
8.36	21.4	4.0	0.461	0.34	0.09()

- Histogram of events within 1 degree around the source.
- 44 Events within 1 degree of the source with energies 1 TeV - 5 TeV.

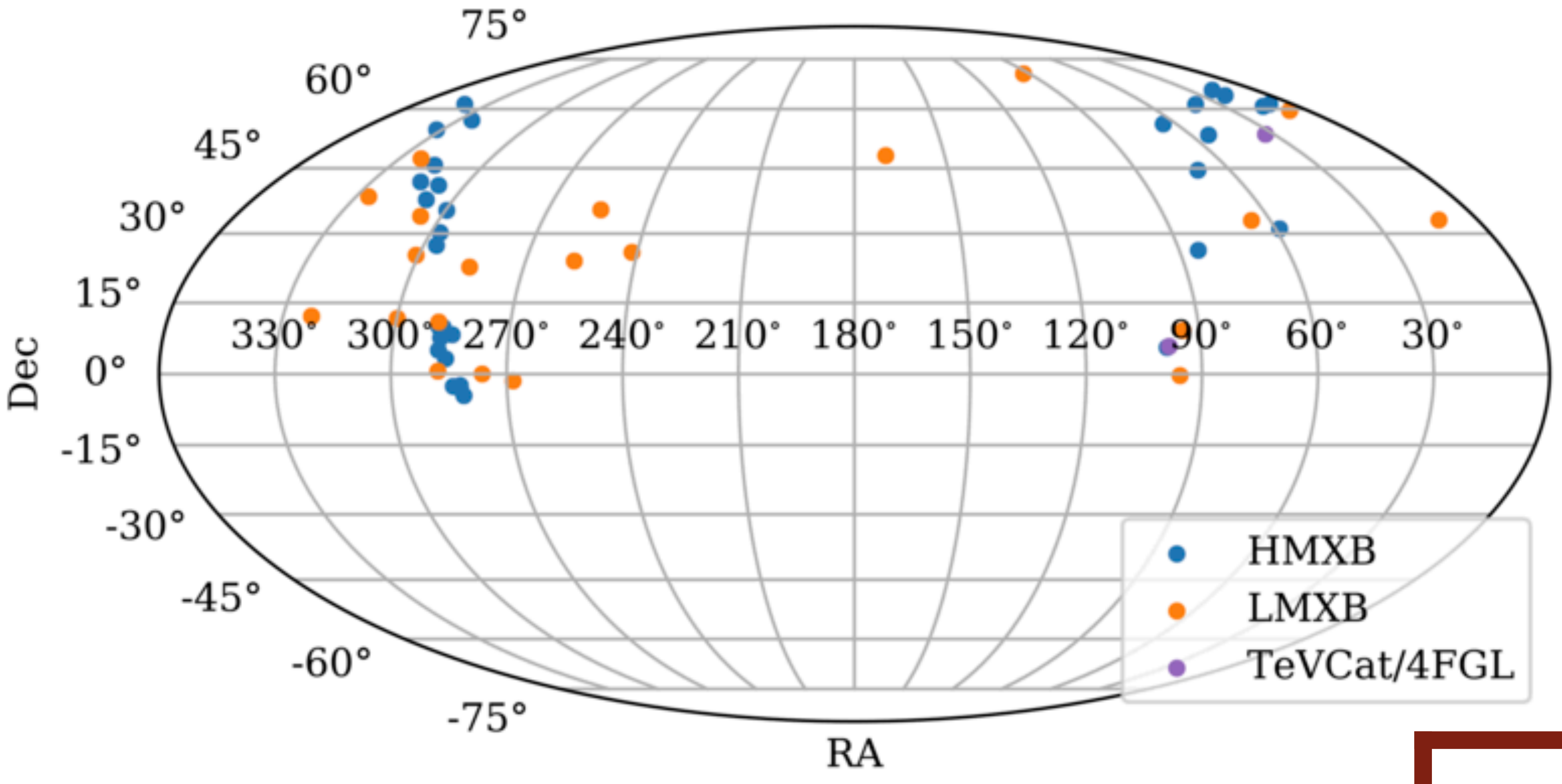
Updated IceCube Periodic Analysis

- An updated periodic search complementary to the flare analysis

$$\mathcal{T}(t_i | \kappa, \Phi_0, P) = \frac{1}{2\pi I_0(\kappa)} \exp\left[\kappa \cos\left(\phi_i\left(t_i | P\right) - \Phi_0\right)\right]$$



- 55 sources in the Northern sky are studied. 30 overlaps with the flare analysis.



- No significant results found. The most significant is V635 Cas, a system of neutron star + Be star.

Name	TS	ns	γ	κ	Φ_0	P	p-value (post)
V635 Cas	4.75	50.5	4.0	0.83	2.58	24.3	0.0052(0.249)

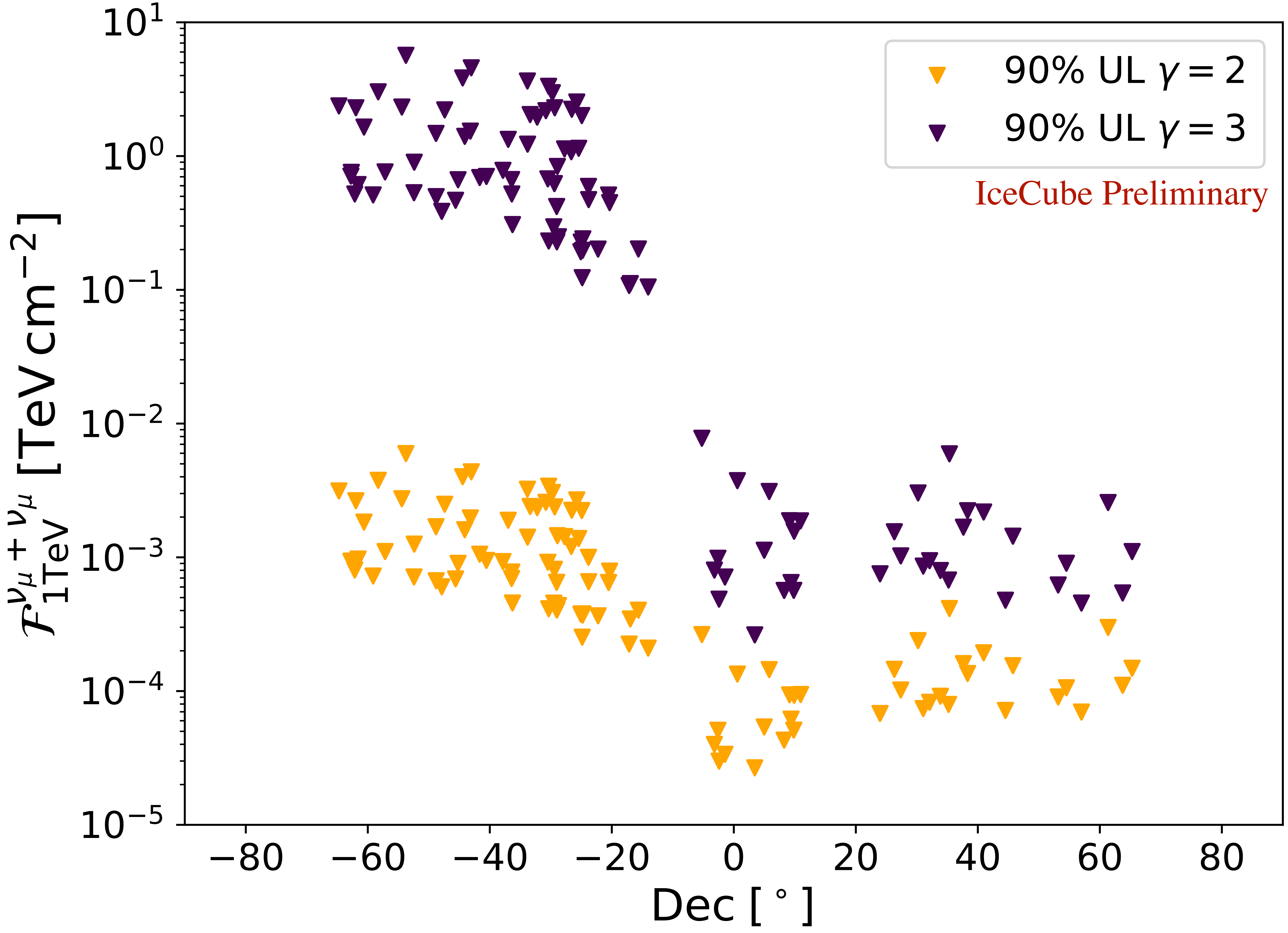
Stacking Source List

Microquasars	Light curve	Periodic
LS I +61 303	X	O
CI Cam	X	O
XTEJ1118+480	X	O
XTEJ1550-564	MAXI	X
4U1630-47	Swift	X
GX 339-4	Swift	X
KS 1731-260	X	X
1E 1740.7-2942	Swift	X
XTE J1748-2829	X	X
GRS 1758-258	Swift	X
V4641 Sgr	MAXI	X
V691 CrA	X	X
LS 5039	X	X
XTE J1859+226	X	O
SS 433	Swift	O
GRS 1915+105	Swift	O
Cyg X-1	Swift	O
Cyg X-3	Swift	O
XTE J1720-318	X	X
Sco X-1	Swift	X

TeVCat	Light curve	Periodic
LS I +61 303	X	O
LMC P3	X	X
HESS J1018-589 A	X	X
HESS J0632+057	MAXI	O
Eta Carinae	X	X
PSR B1259-63	X	X
LS 5039	X	X
HESS J1832-093	X	X
SS 433	Swift	O
PSR J2032+4127	X	X
Vela X-1	Swift	X
Cen X-3	Swift	X
Cyg X-1	Swift	O

- **TeVCat: Binary+XRB**
  13 sources, 8/13 do not have strong hard X-ray emission.
- **Microquasars:**
  21 sources, 9/21 do not have strong hard X-ray emission.
- There are 5 overlaps in these two catalogs.

Upper Limits - Time-dependent



Upper Limits - Time-Integrated