Interpretations
of
IceCube TeV-PeV Neutrinos

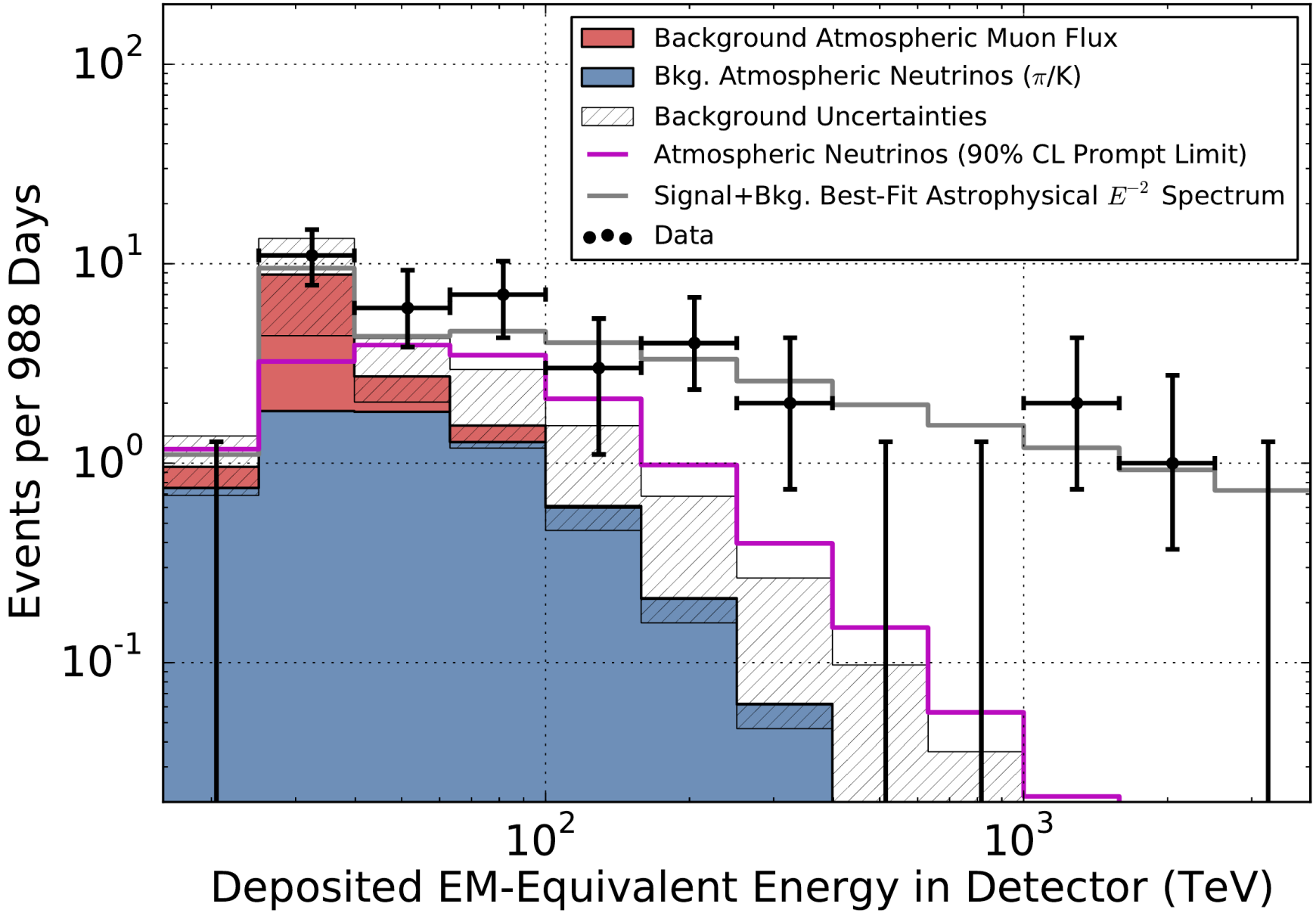
Ran Lu

University of Wisconsin-Madison

1311.5864, 1407.xxxx with Yang Bai, Vernon Barger Jordi Salvado and Andrea Peterson

2014-7-4

IceCube Results



IceCube Collaboration, arXiv:1405.5303

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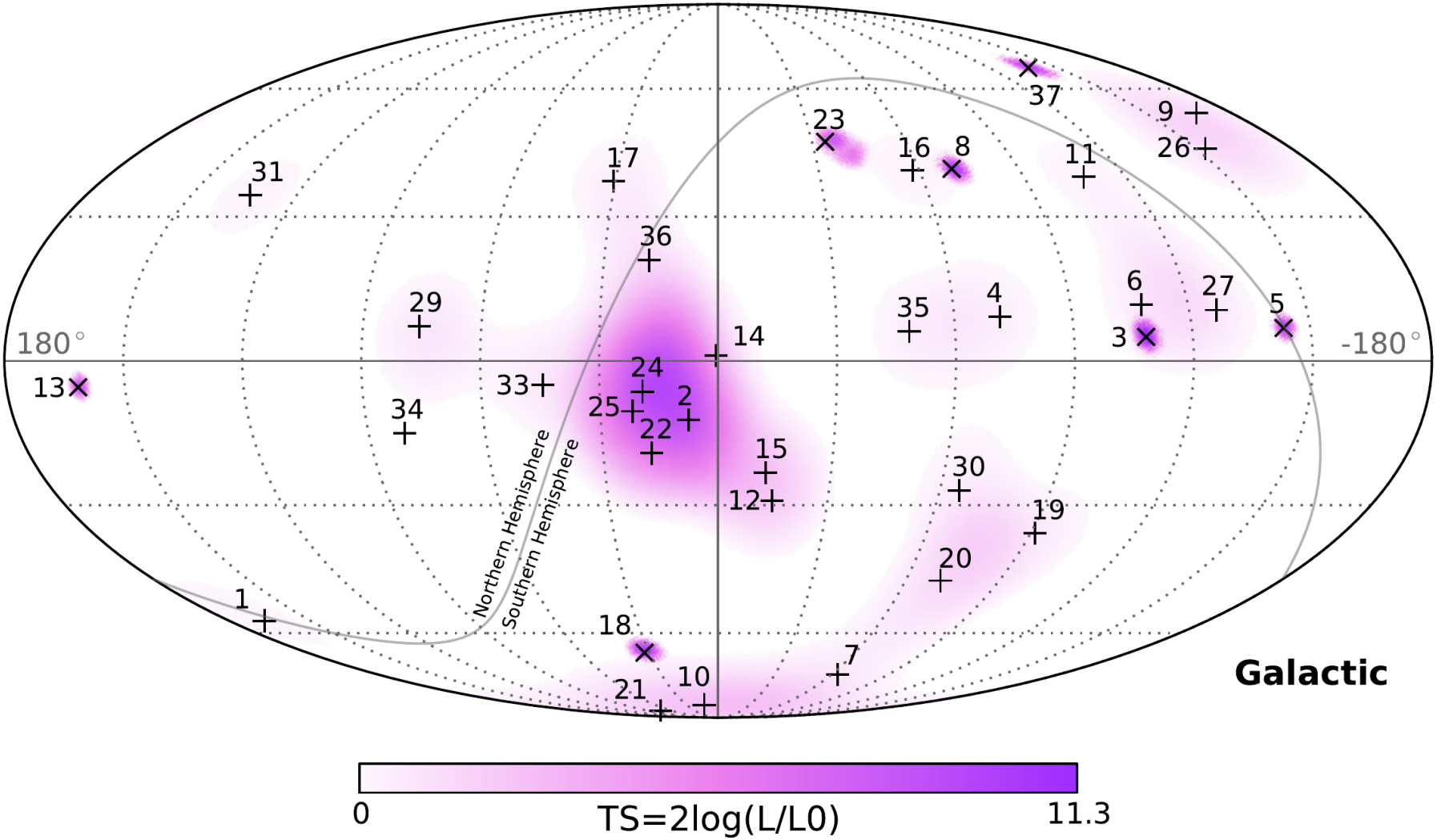
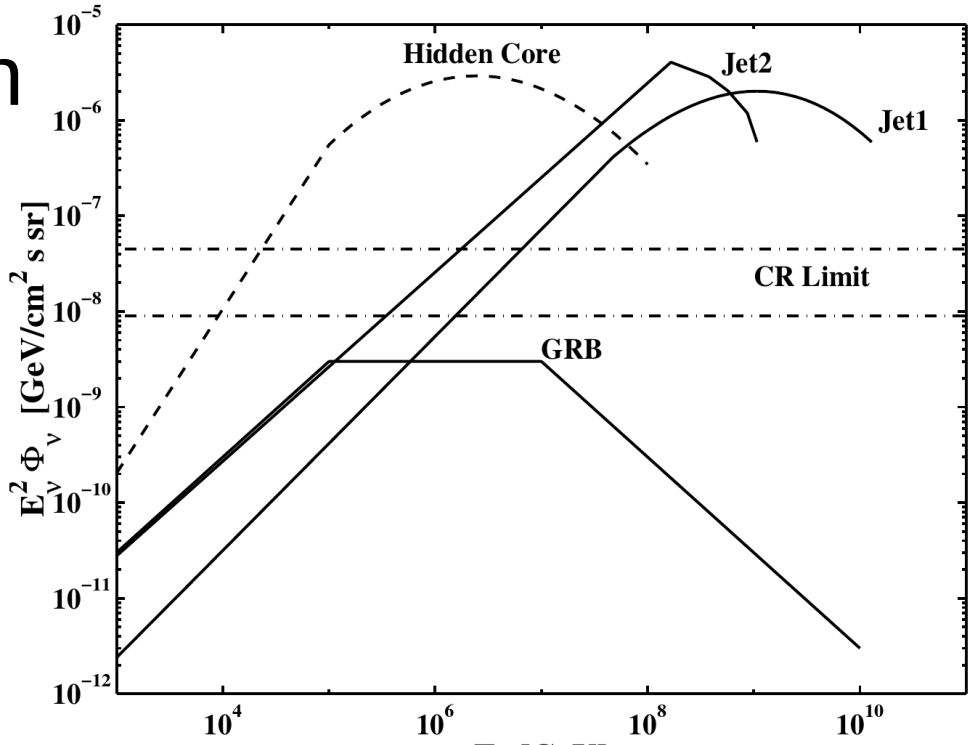


IceCube Collaboration, arXiv:1405.5303

Gamma-ray Burst

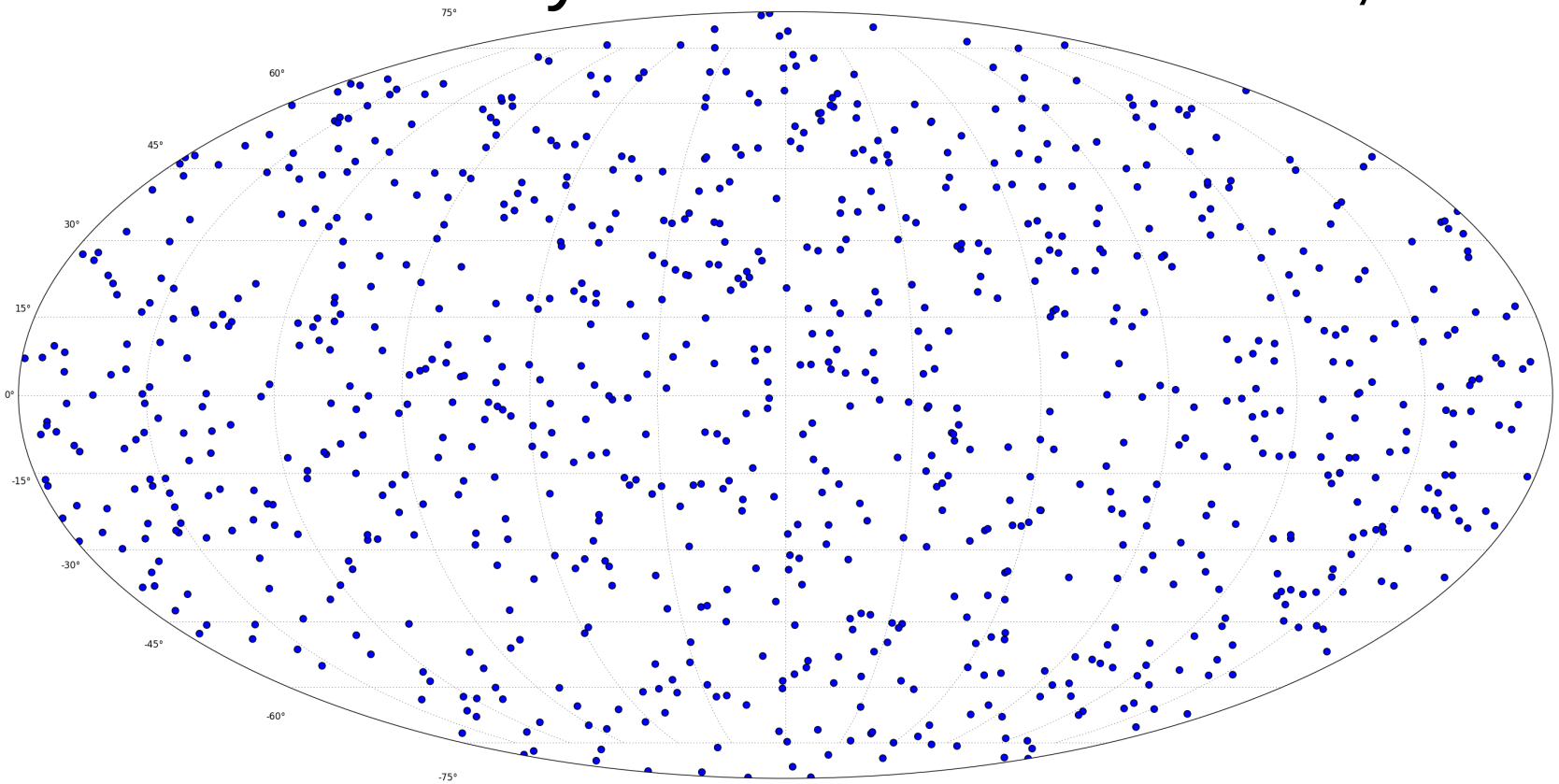
- Fireball Model (Reviewed by Piran, astro-ph/9810256)
- Fermi acceleration, $e, p \sim E^{-2}$
- Synchrotron Radiation, Inverse Compton
- Proton-photon Collision (Waxman, Bahcall astro-ph/9701231)



Gamma-ray Burst and IceCube

K. Murase and K. Ioka, 1306.2274; S. Razzaque, 1307.7596; W. Winter 1307.2793

- ~1000 GRB in 3 years from Fermi GBM, Swift...



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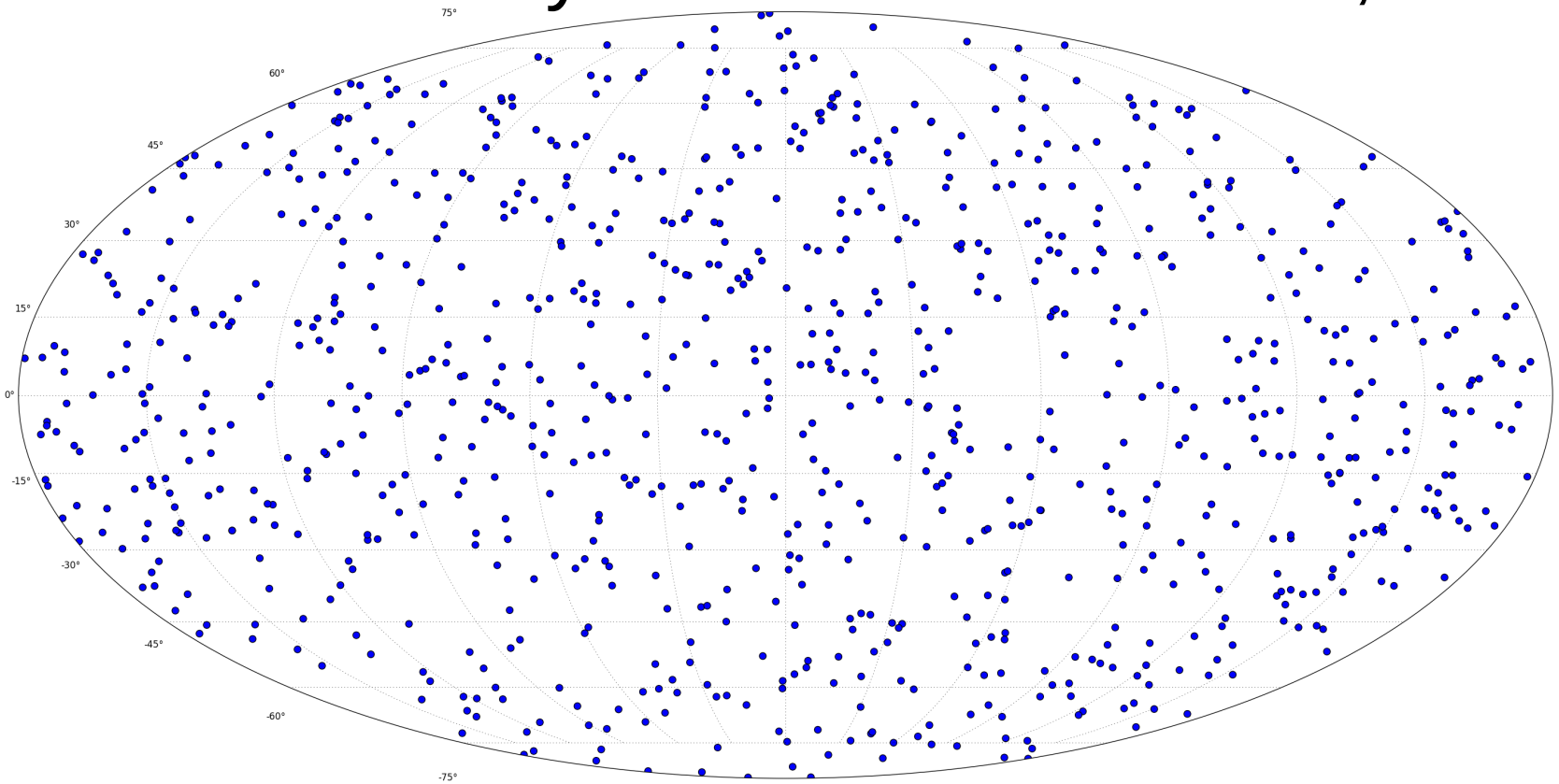

- No coincidence

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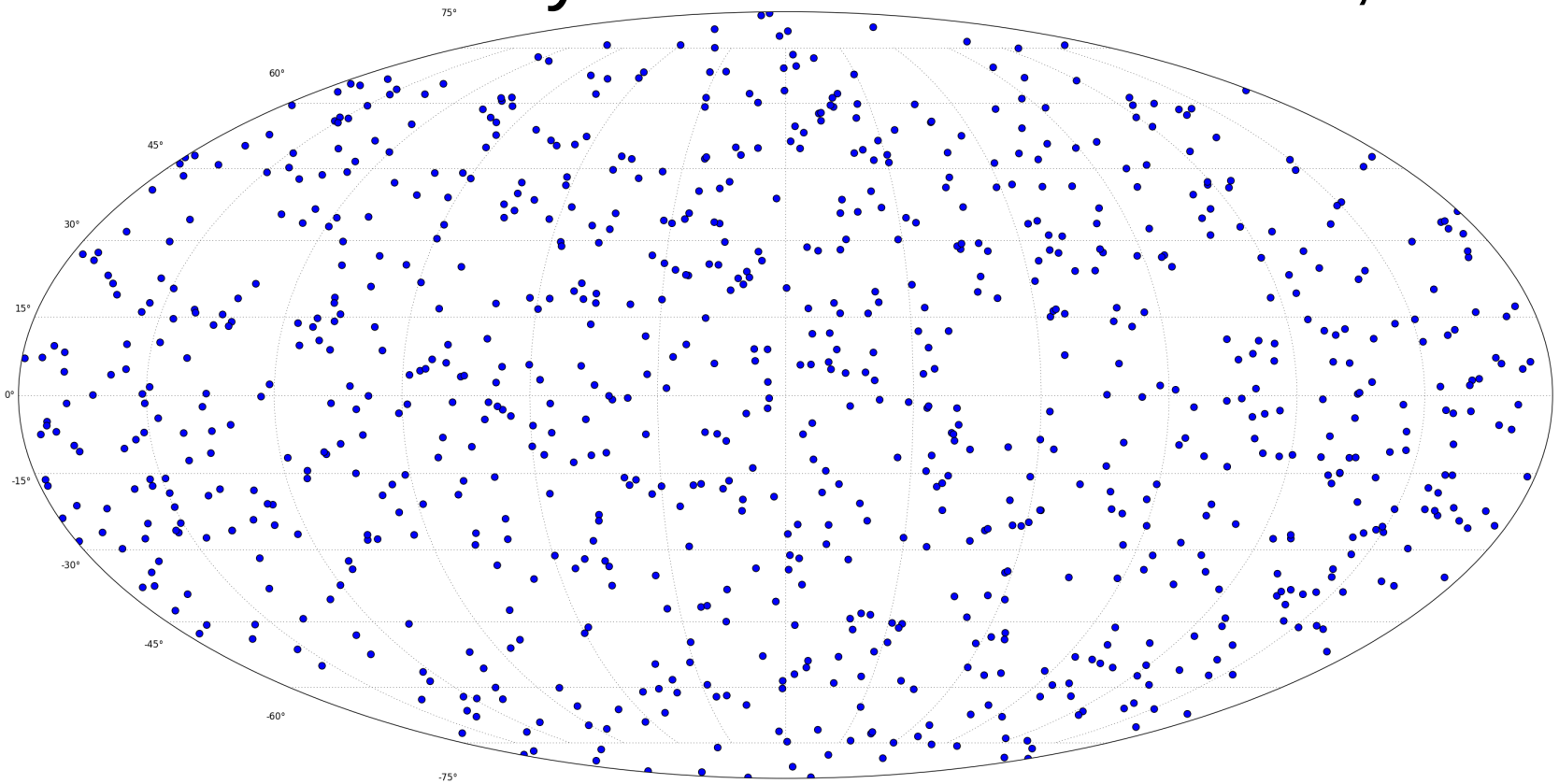

- No coincidence
- Shadow of the earth

Active Galactic Nucleus

O.Kalashev, A.Kusenko, W. Essey, 1303.0300; F.Stecker, 1305.7404; W. Winter 1307.2793

- Seyfert, Blazar, Quazar, BL Lac, FSRQ...
- Super Massive Black Hole
- Fermi acceleration, proton-photon interaction
- No observation near galactic plane

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Starbursting Galaxy

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- Very few candidates (~100)
- NGC 253 (IC Event 10)

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Colliding Galaxies, Supercluster, Leptoquark.....

Decaying Dark Matter

- Why not annihilating?
  - Unitarity Bound on the Cross Section: $\sigma_{total} \sim \frac{16\pi}{m^2 v_{rel}^2}$
  - Event Rate
    - Annihilating Dark Matter ~ ρ^2
    - Decaying Dark Matter ~ ρ
- Galactic Dark Matter
  - Comparing with homogeneous “background”

Yang Bai, RL, Jordi Salvado, 1311.5864

See also:

B. Feldstein A. Kusenko, S. Matsumoto, and T. Yanagida, 1303.7320

A. Esmaili and P. D. Serpico, 1308.1105

Decaying Dark Matter

- Fermionic DM
  - $\chi \rightarrow h + \nu$ $\quad M_\chi = 4\,\mathrm{PeV}, \quad \tau_\chi = 3.5 \times 10^{29}\,\mathrm{s}$
  - $\chi \rightarrow H_L + \nu \rightarrow \tau^+ + \tau^- + \nu$
- Scalar DM
  - $X \rightarrow h + h$ $\quad M_X = 8\,\mathrm{PeV}, \quad \tau_X = 0.9 \times 10^{29}\,\mathrm{s}$
  - $X \rightarrow \tau^+ + \tau^-$ $\quad M_X = 8\,\mathrm{PeV}, \quad \tau_X = 4.6 \times 10^{29}\,\mathrm{s}$

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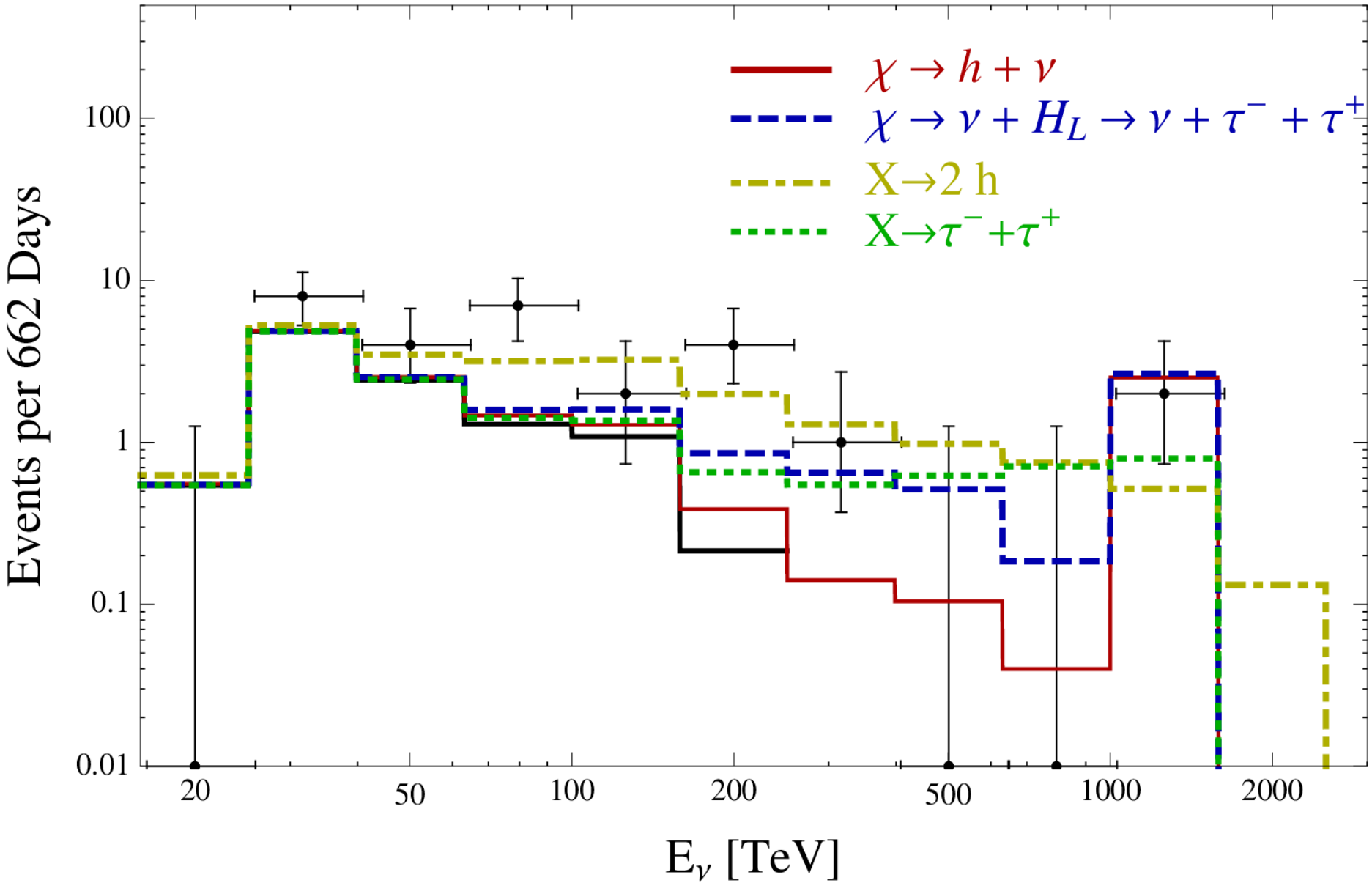
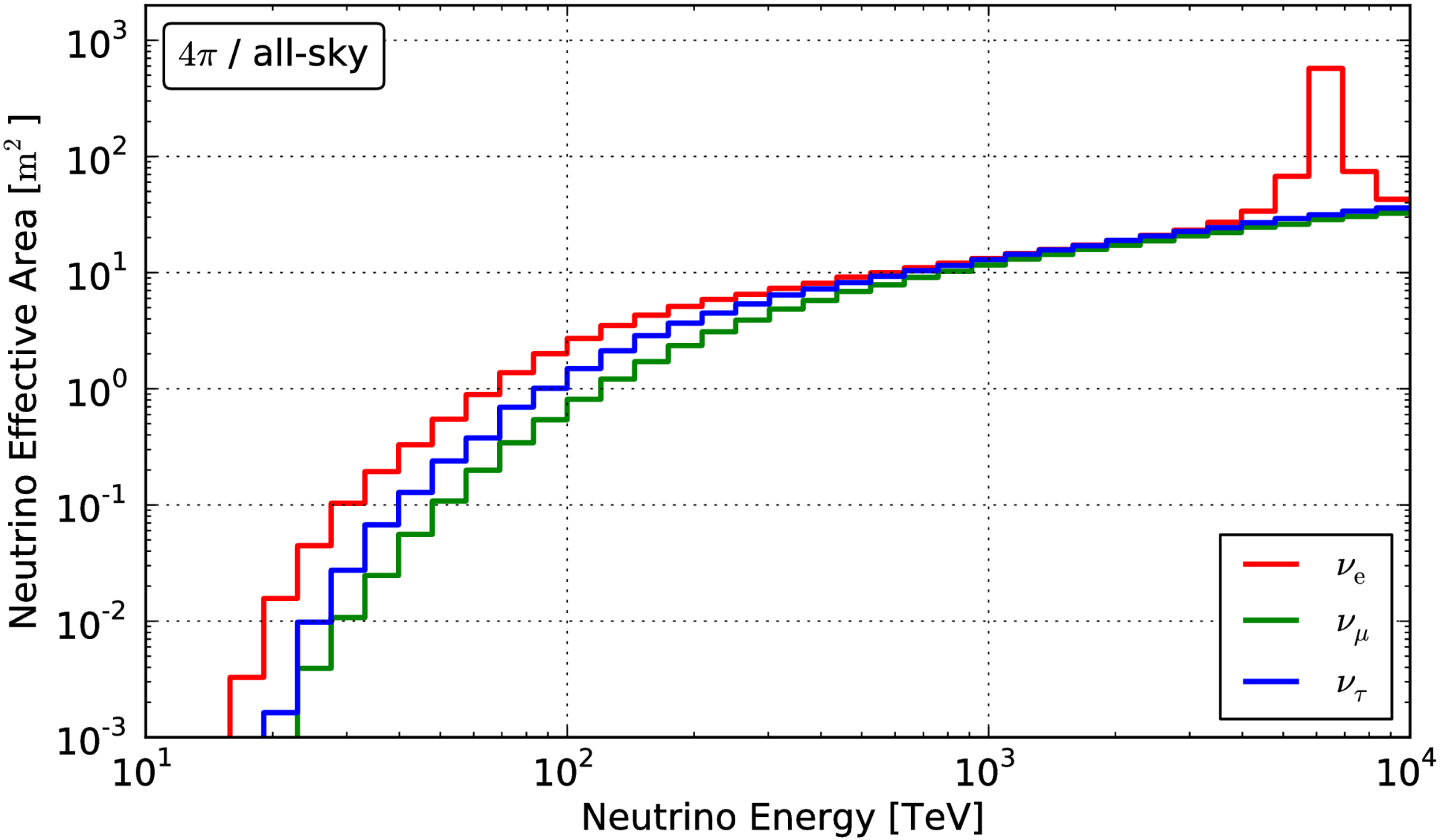
Spectrum

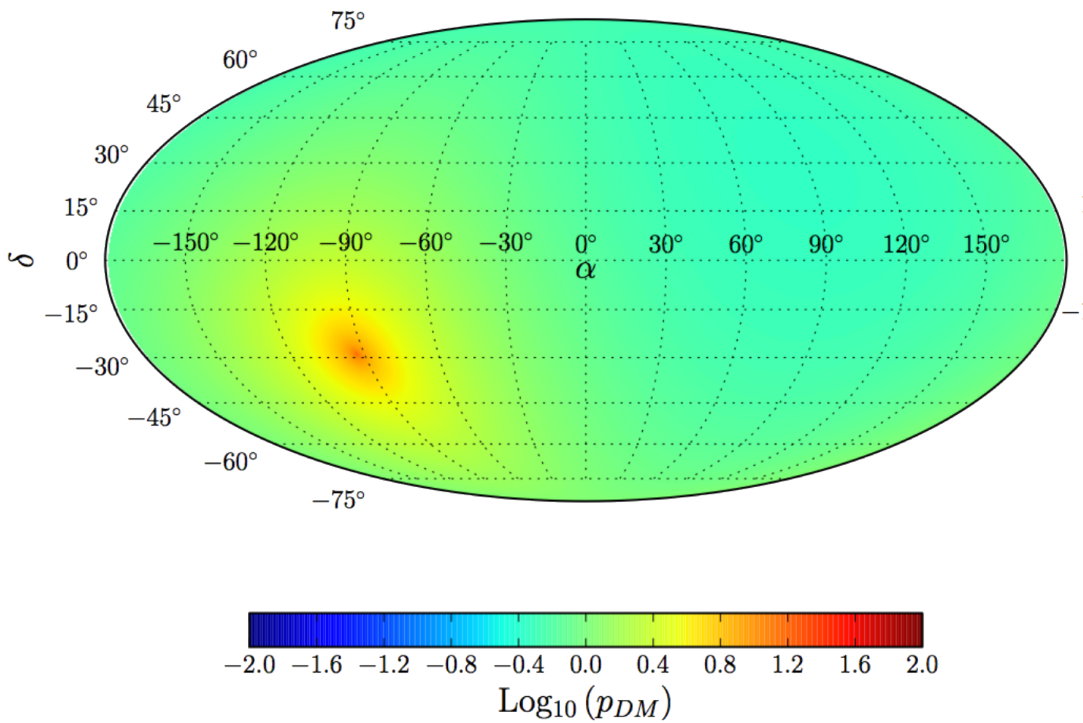

$\chi \to h + \nu$
$\chi \to \nu + H_L \to \nu + \tau^- + \tau^+$
X→2 h
X→τ^-+τ^+
Events per 662 Days
100
10
1
0.1
0.01
20
50
100
200
500
1000
2000
E_ν [TeV]

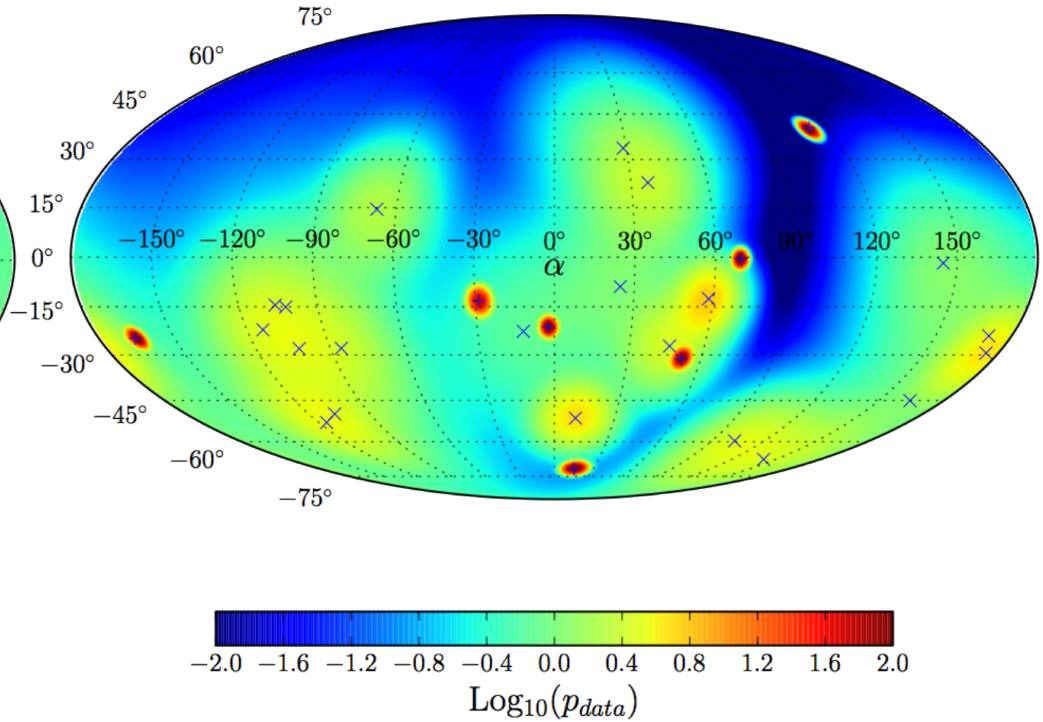
Effective Area



IceCube Collaboration, Science 342, 1242856 (2013)

Geometric Distribution





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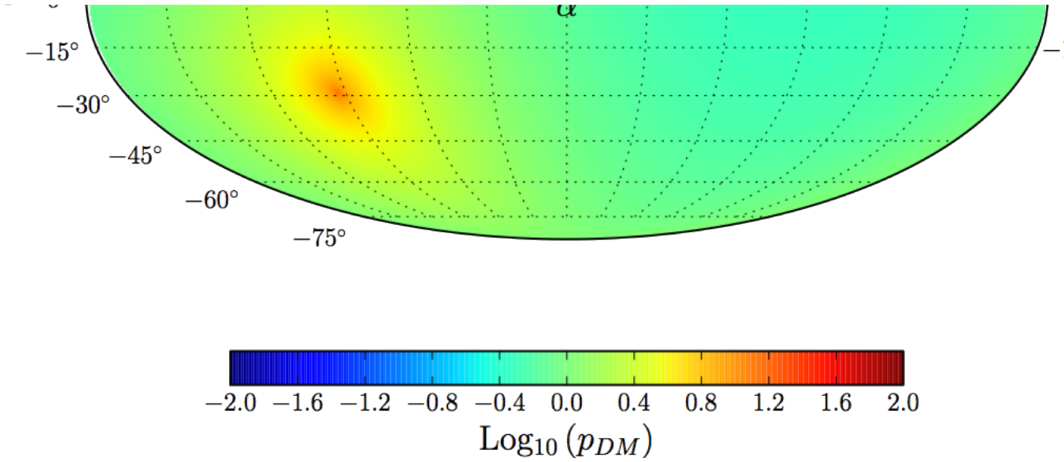
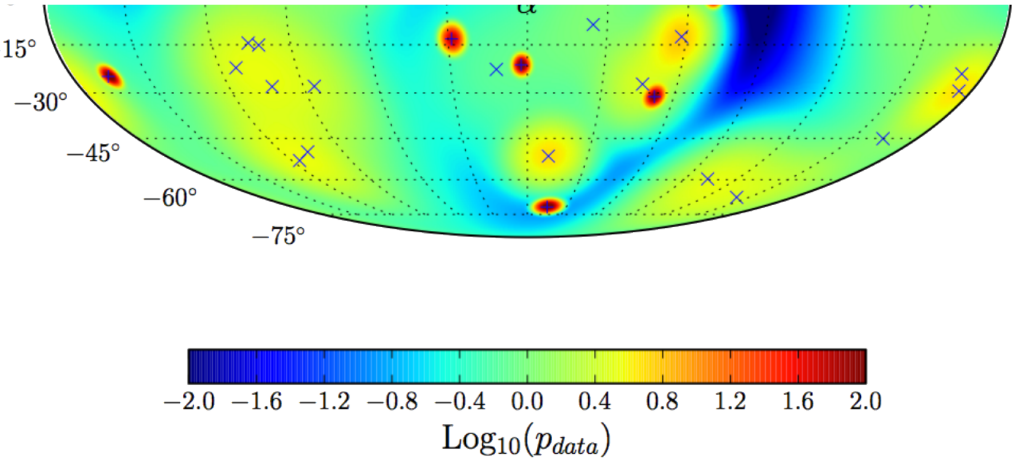




Statistical Tests

- 2D Kolmogorov-Smirnov Test
- Likelihood Ratio Test

Hypotheses

- Dark Matter vs Homogeneous Background
- Dark Matter + Background vs Background
- Dark Matter + Background vs Dark Matter

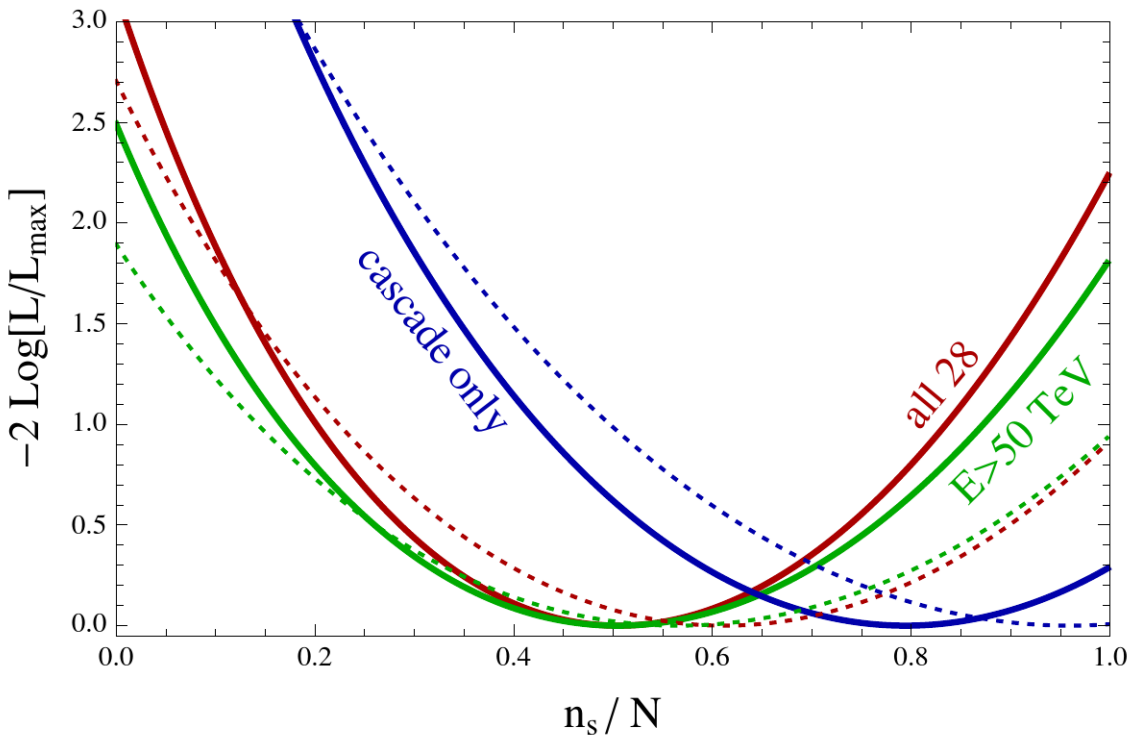
Likelihood Ratio Test

- Likelihood Function

$$L(n_s)=\prod_{i=1}^{N}\left[\frac{n_s}{N}S_i+\left(1-\frac{n_s}{N}B\right)\right];\quad S_i=\int\frac{1}{2\pi\sigma_i^2}e^{\frac{-|x_i-x_s|}{2\sigma_i^2}}\frac{\rho(x_s)}{\rho_0}d^2x_s$$

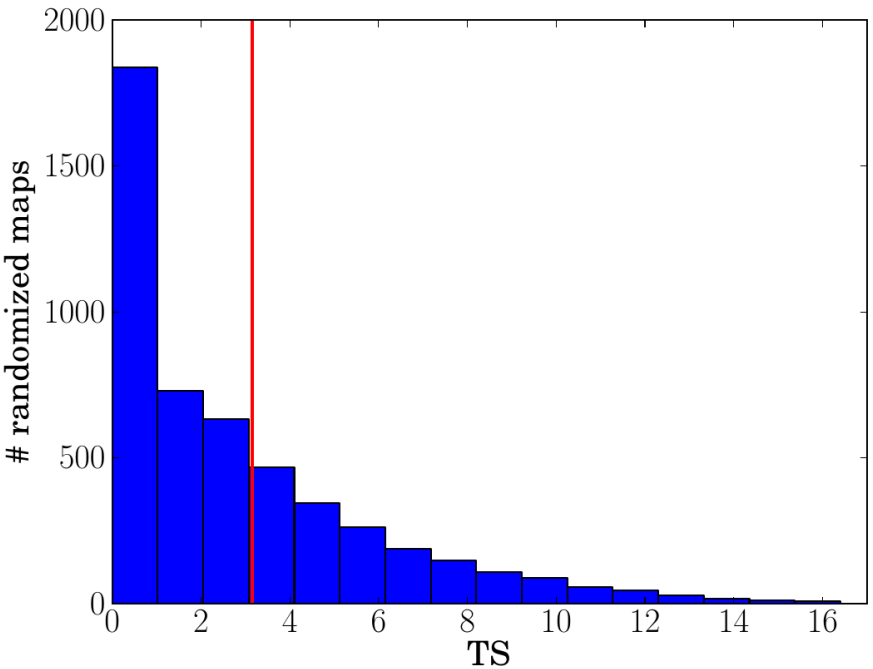
- Test Statistics

$$\mathrm{TS}=\max_{n_s}\left\{2\log\left[\frac{L(n_s)}{L(0)}\right]\right\}$$



P-values

- Probability of obtaining TS as extreme as data
- < 1%: Significant
- >10%: Not signifcant



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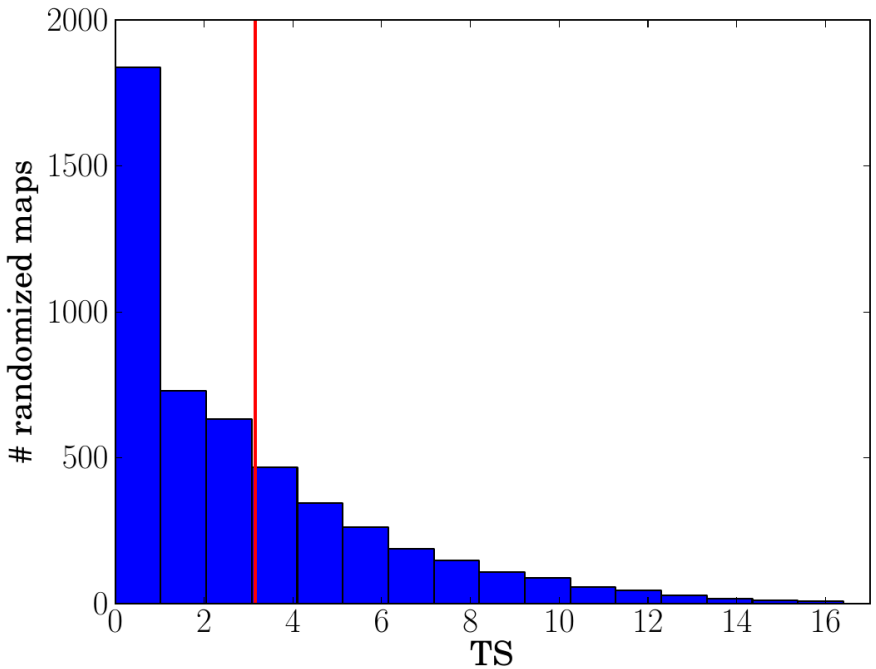
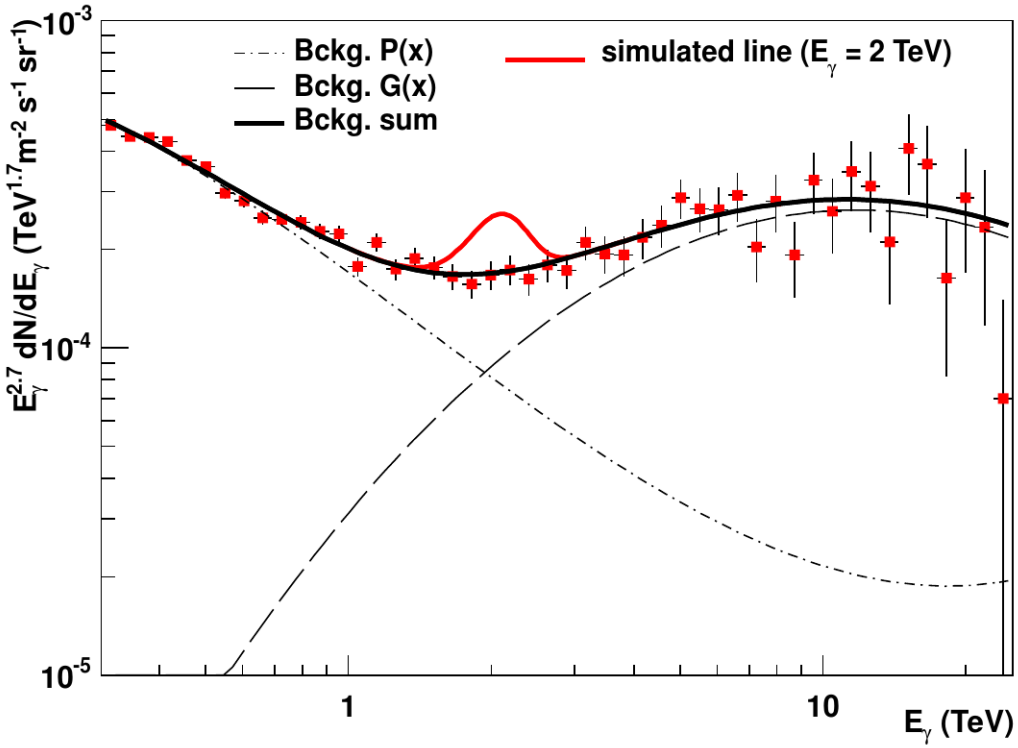


	$\bar{\alpha}=0.17$	$\bar{\alpha}=0.25$
All 28 Events	33.4%	36.0%
18 Events with E ≥ 50 TeV	25.0%	27.2%
21 Cascade Events	15.8%	17.9%

Other Constraints?

- ~~Collider, Direct Detection~~
- Indirect Detection



H.E.S.S. collaboration, astro-ph/0610509

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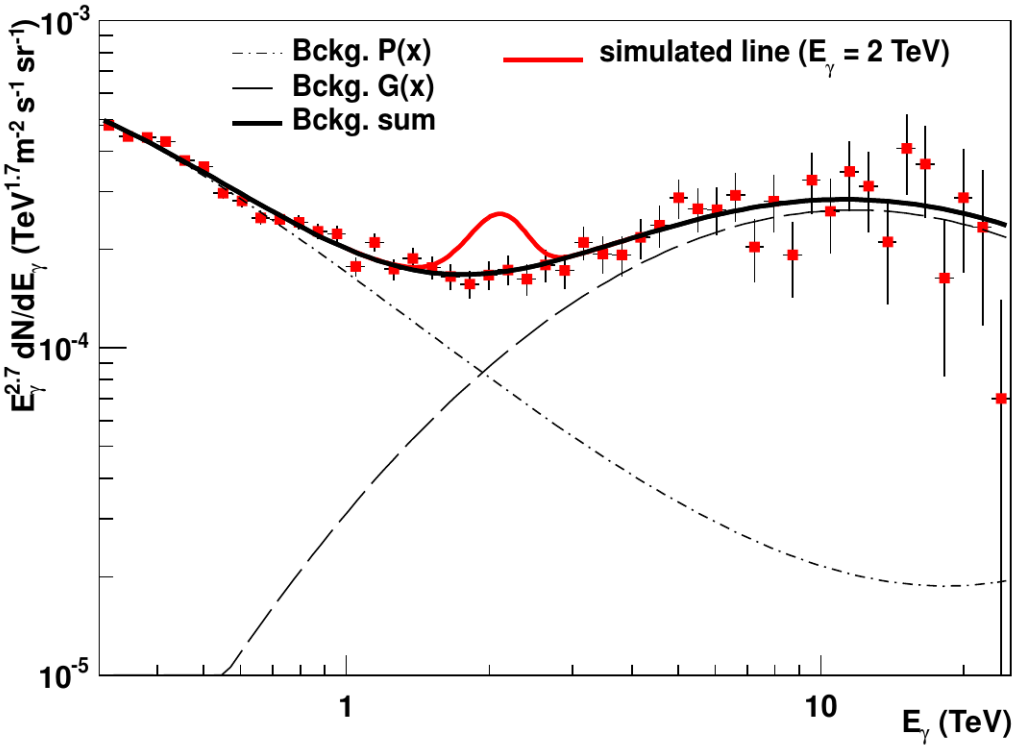

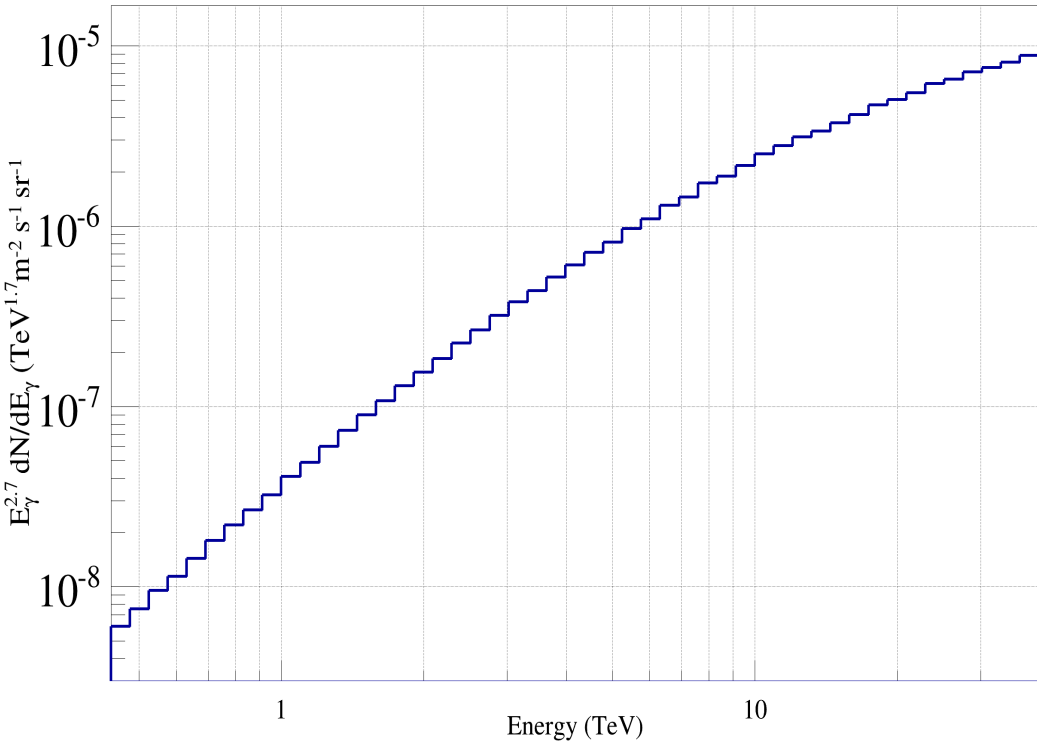

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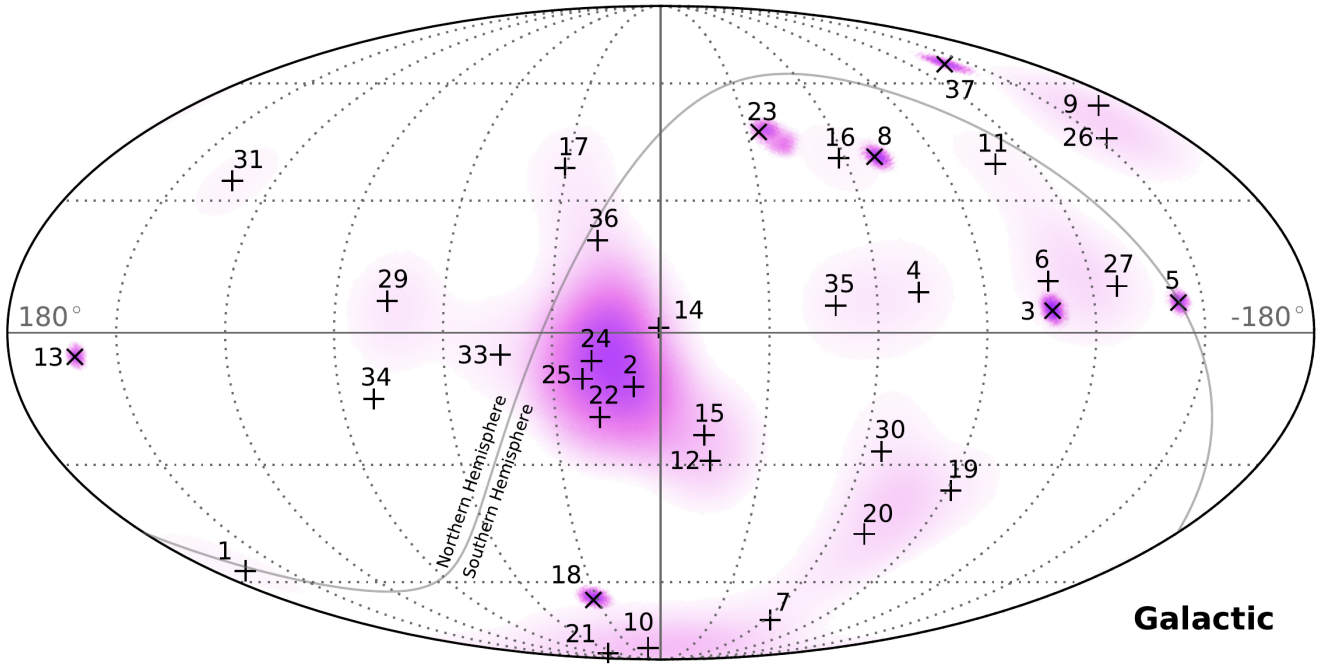
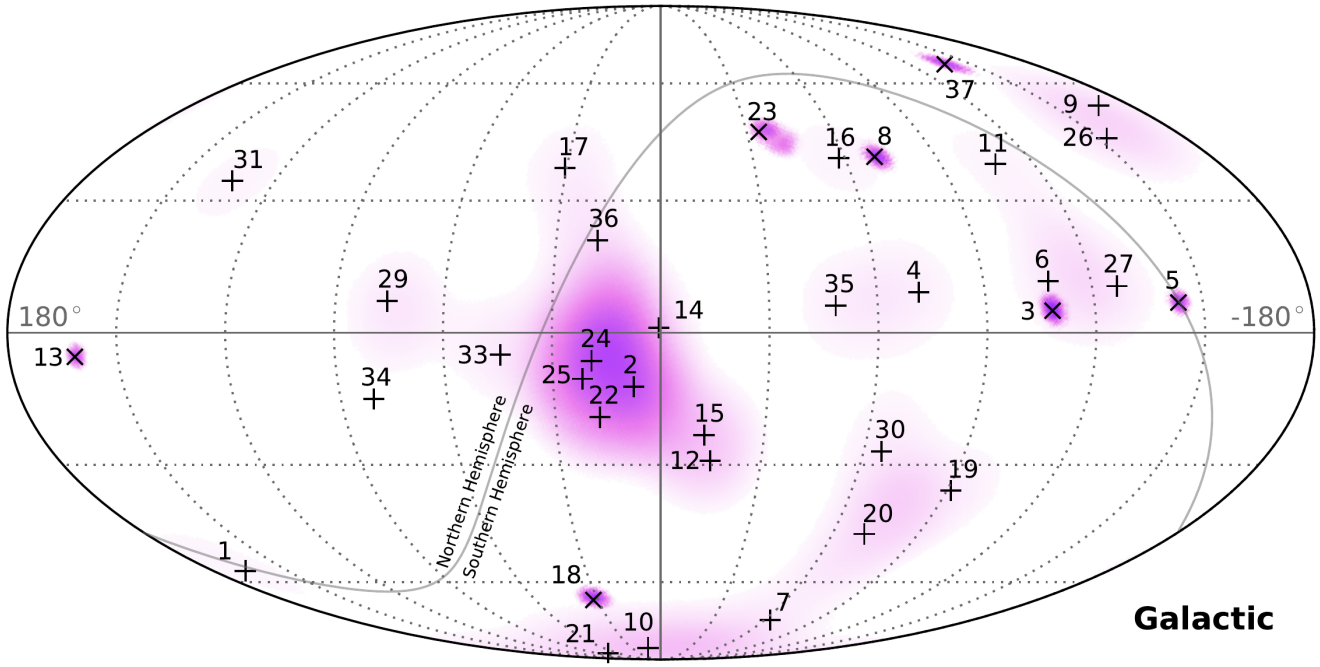
Spatial&Time Correlation

- IceCube Clustering Analysis (1405.5303)
  - Testing time clustering within 11 spatial clustering
  - No significant time clustering



Spatial&Time Correlation

- IceCube Clustering Analysis (1405.5303)
  - Testing time clustering within 11 spatial clustering
  - No significant time clustering
- Other objects with transient activity?

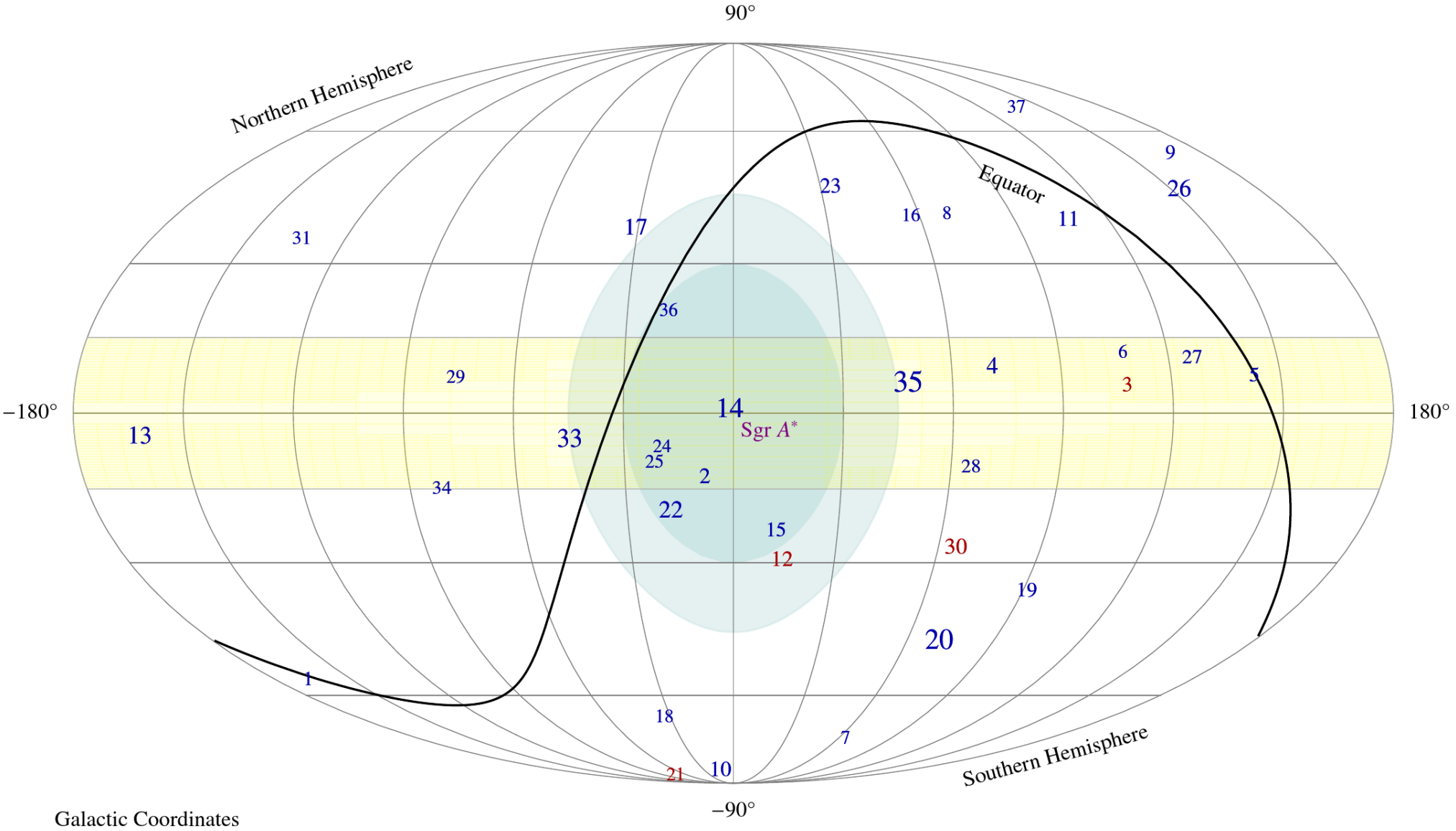


- GRB
- Sgr A*

Sagittarius A*

- Super Massive Black Hole? (10^6 Solar Mass)
- Was an AGN? (Fermi Bubble)
- Multi-wavelength Observation
  - X-Ray (Swift, Chandra)
  - Infrared (Keck II)
  - Submillimeter Radio
- Flare
  - More than 10 times larger flux (X-Ray)

Events around Sgr A*



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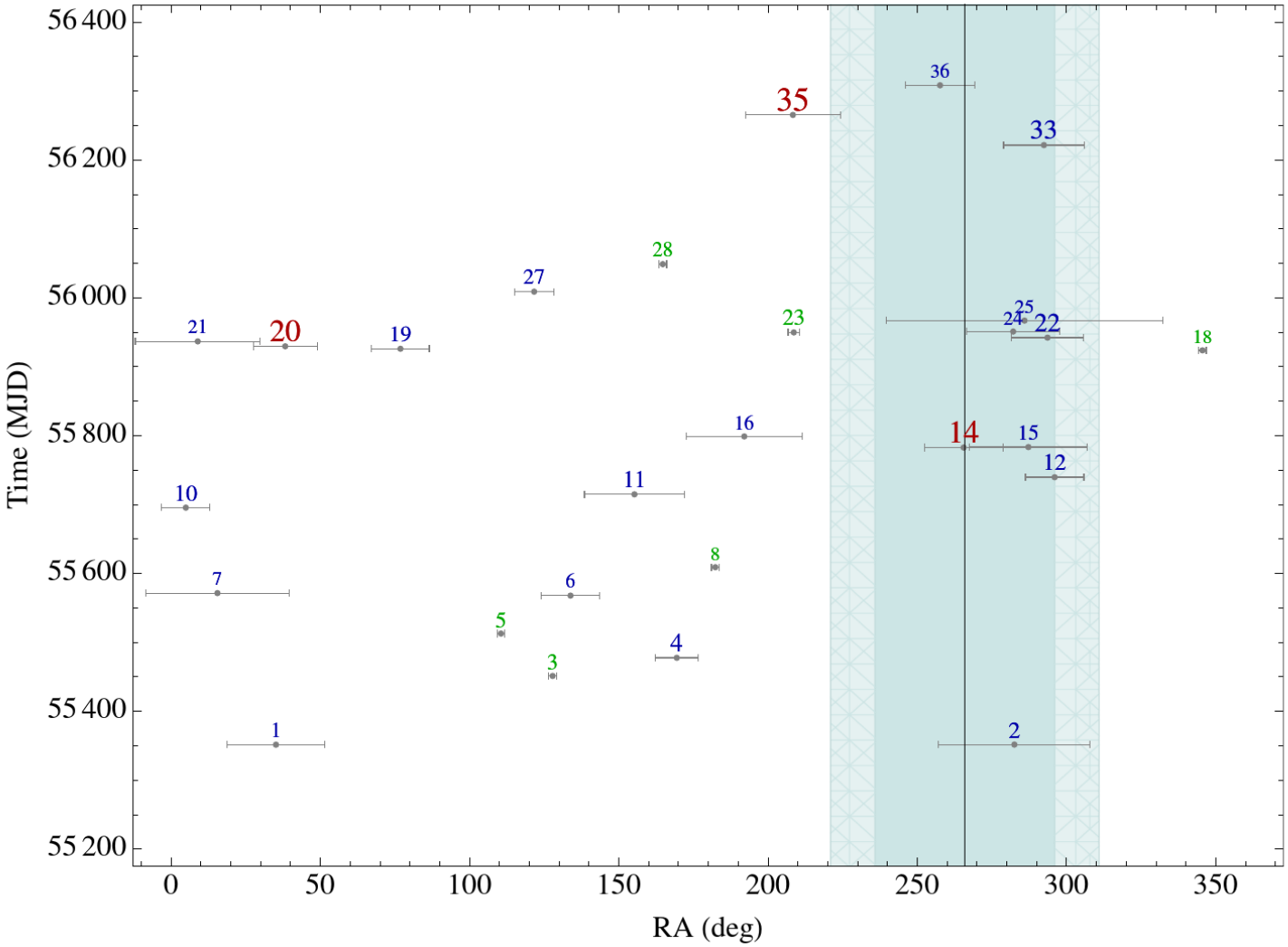

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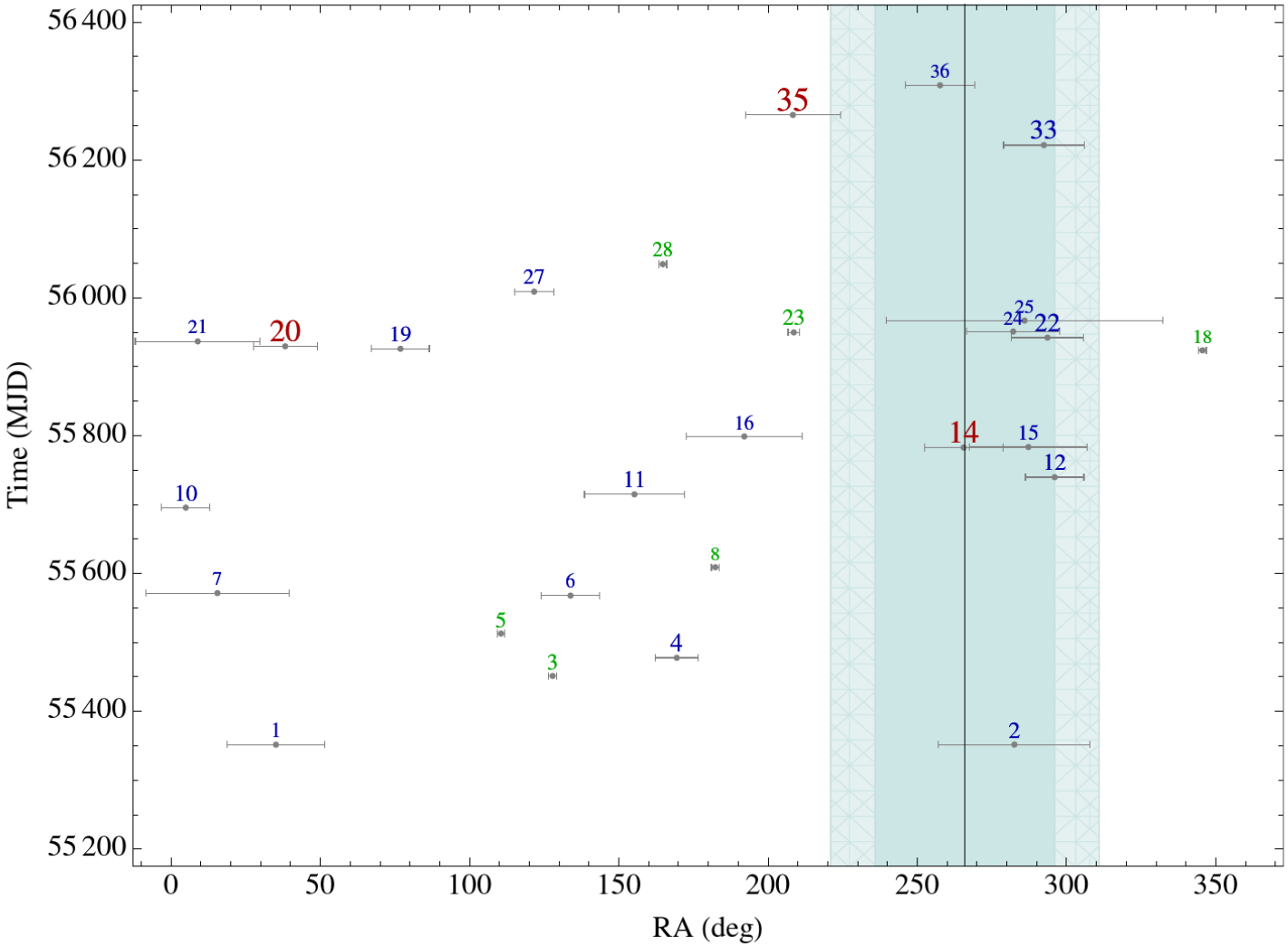
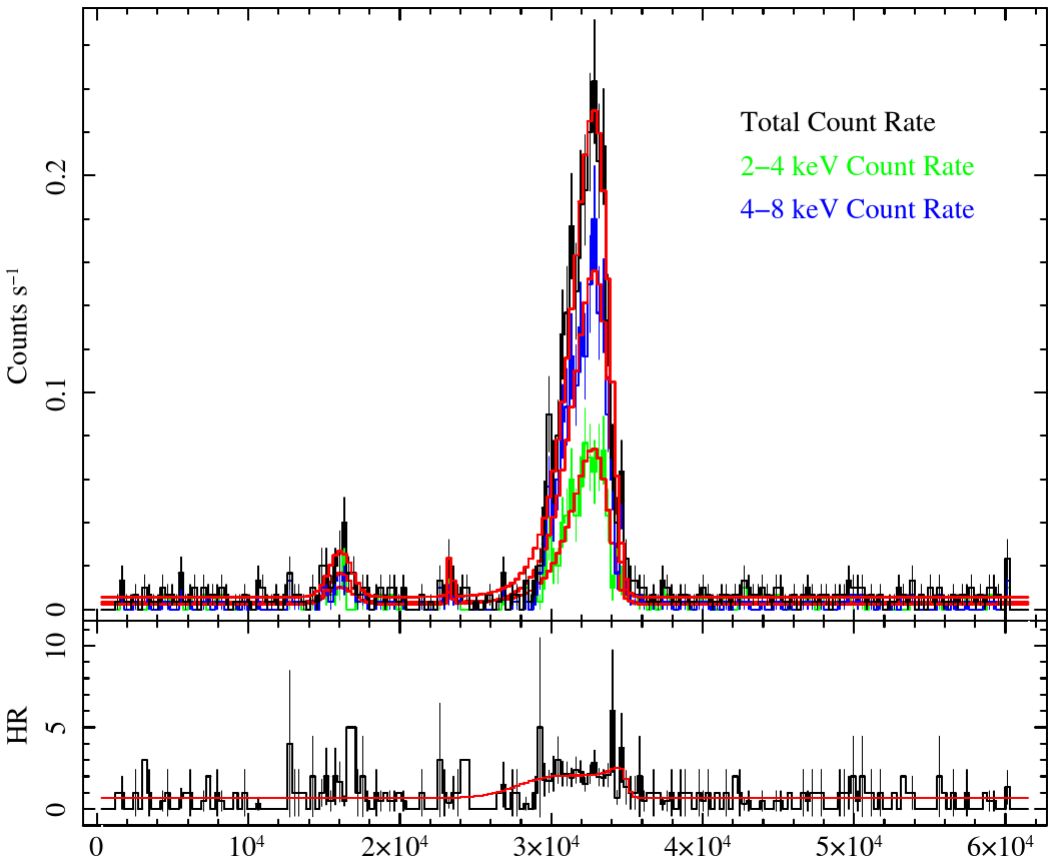


We consider Event 2, 14, 15, 22, 24, 25, 36

“The Brightest Flare”

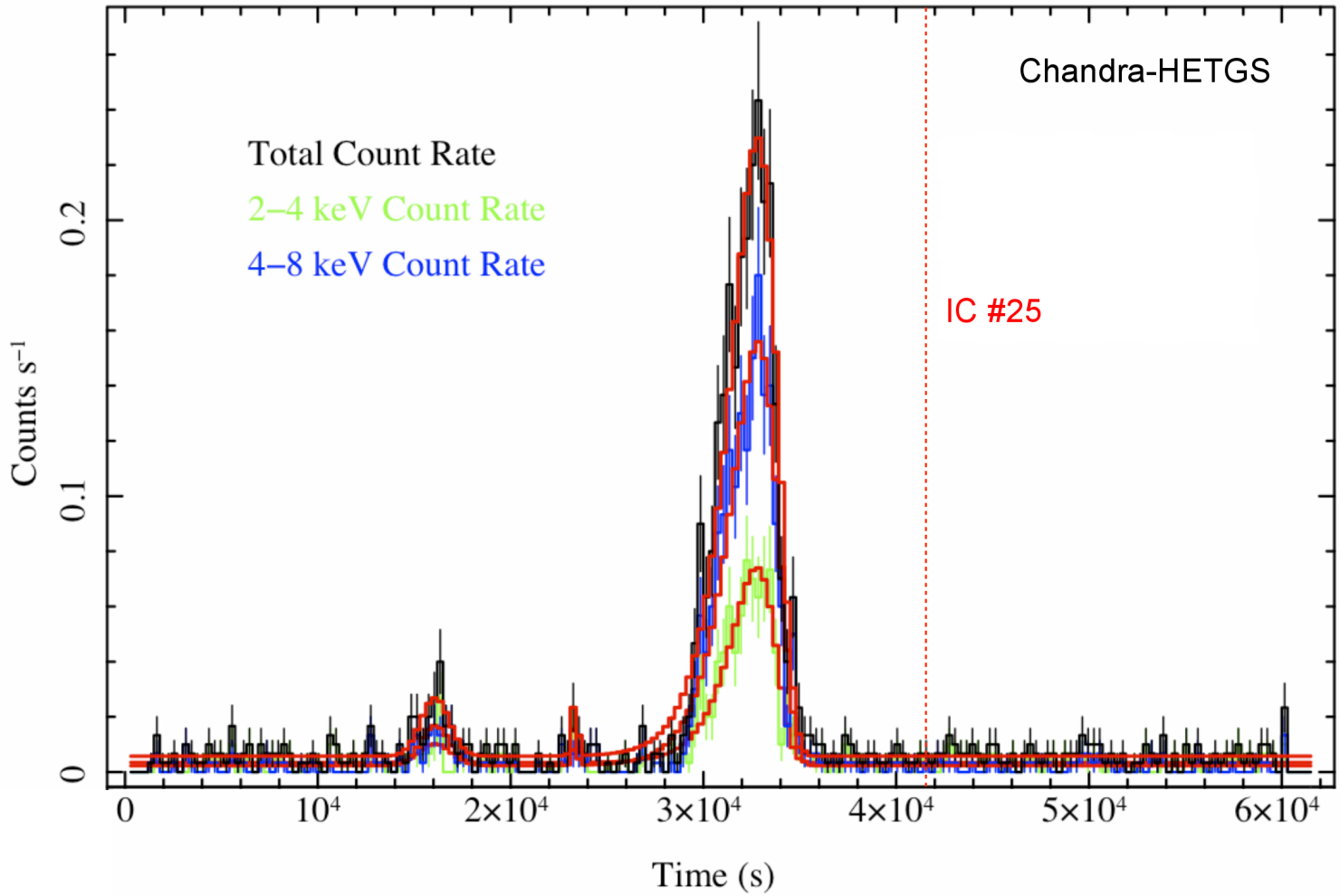


- ~15:10, Feb 9, 2012.
- Duration: ~ 5 ks
- Luminosity:

  $L_x=5\times10^{35}$ erg s^{-1}
- IC 25 after 2.5 hours

M. Nowak et al. 1209.6356

“The Brightest Seen From Sgr A*”



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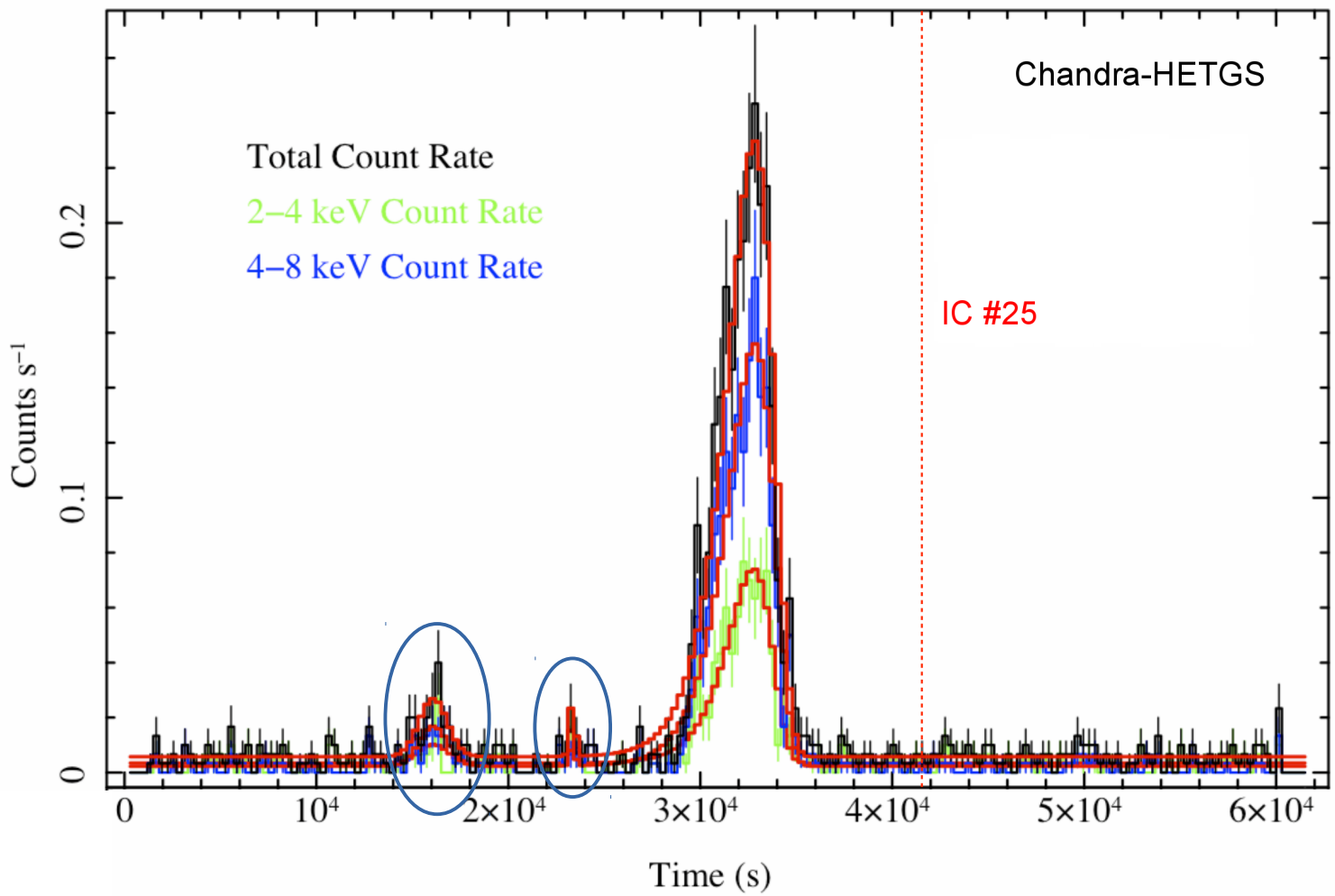
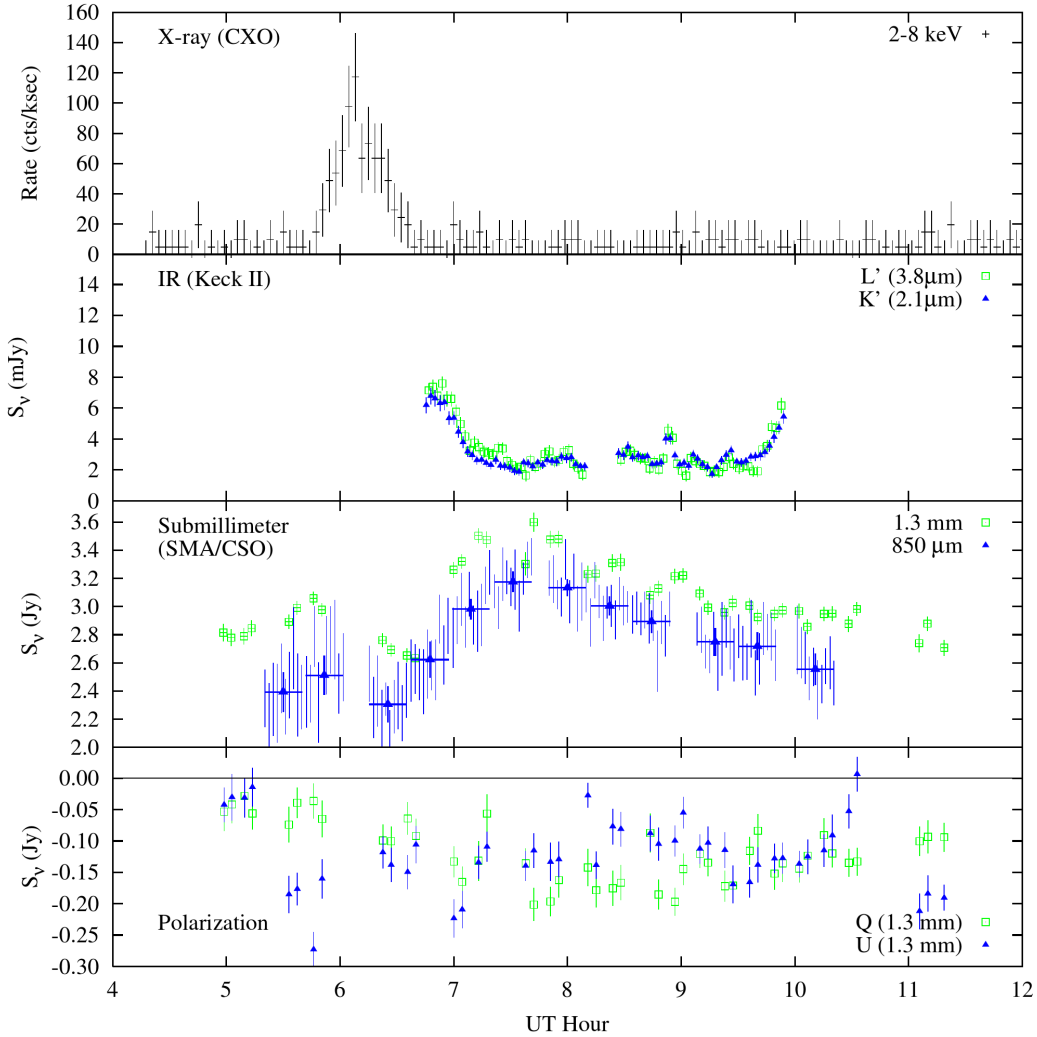


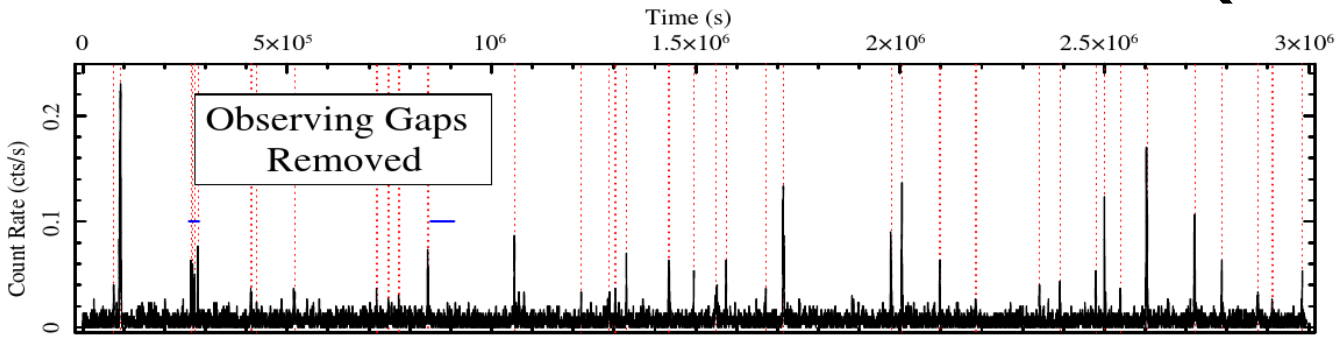
Another Flare at Multi-Wavelengths



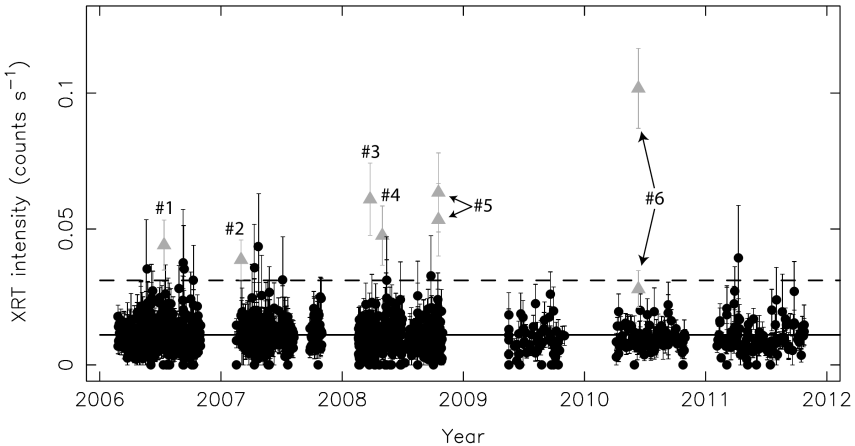
- X-ray Flare: ~ 30 min
- Submillimeter peaked after 1 hour
- Activity could last longer than X-ray flare

D. Marrone et al. 0712.2877

Occurrence Rate of (Bright) Flare



J. Neilsen et al. 1311.6818



N. Degenaar et al. 1210.7237

- Quiescent flux

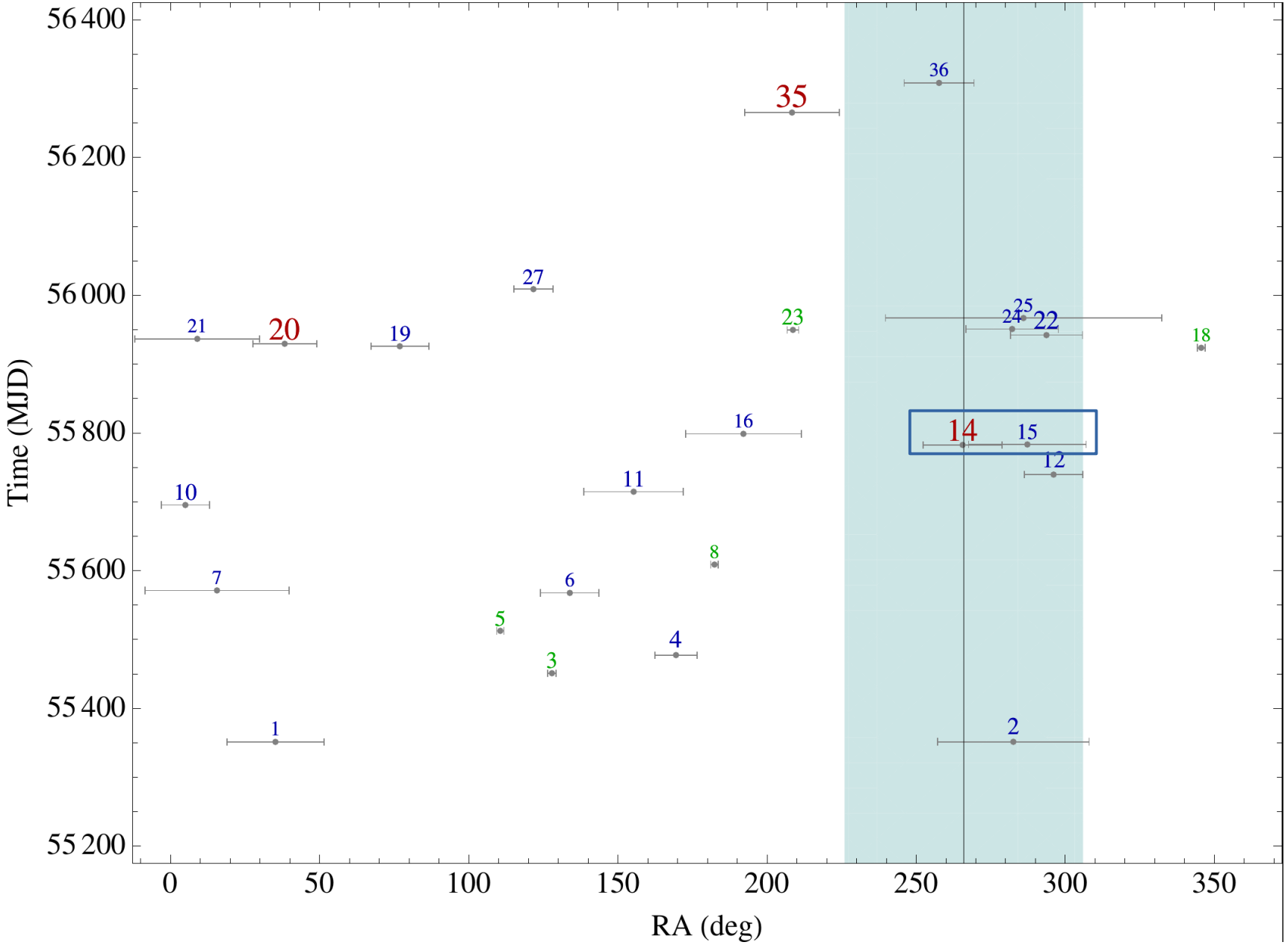
  $L_x \sim 10^{33}$ erg s^{-1}
- $L_x > 10^{34}$ erg s^{-1}: 1 per day
- $L_x > 10^{35}$ erg s^{-1}:0.1-0.2 per day
- $L_x > 5\times10^{35}$ erg s^{-1}:
  - 0.02 per day?

"Brightest Flare" every ~ 50 days

Significance Test

- Active time ~ 12 hours
- Expecting 1 big flare every 50 days.
- Naive estimate: p-value = 1%
- WIP: Neutrino events rate ~ Peak luminosity

Other Neutrino Events



Self-Clustering Test

- Likelihood Function:

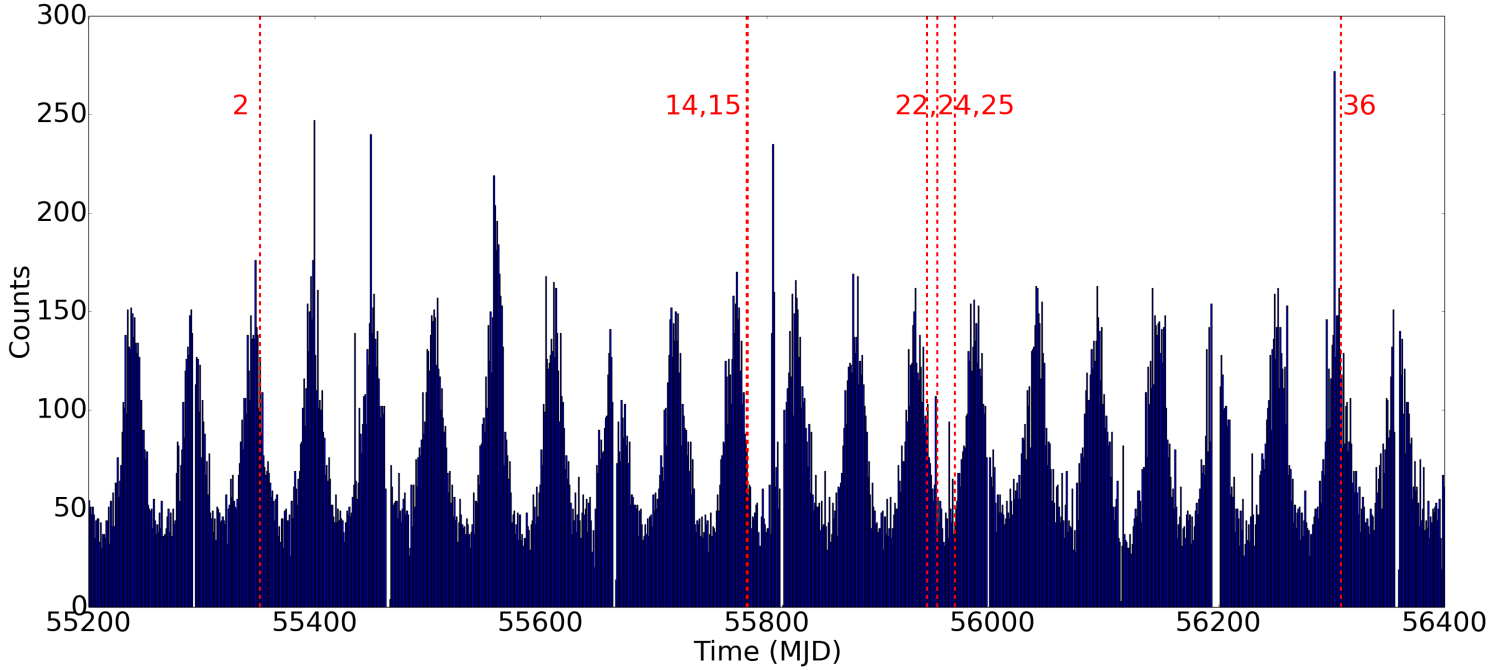
$$L(n_s)=\prod_{i=1}^{N}\left[\frac{n_s}{N}S_i+\left(1-\frac{n_s}{N}B\right)\right];\quad S_i=\frac{\theta(t_{max}-t_i)\theta(t_i-t_{min})}{t_{max}-t_{min}}$$

- Scramble 7 events in 3-year window
- Event 14 and 15: clustering with p-value 1.6%
- Came from a huge flare everyone else missed?

Flares in 2013

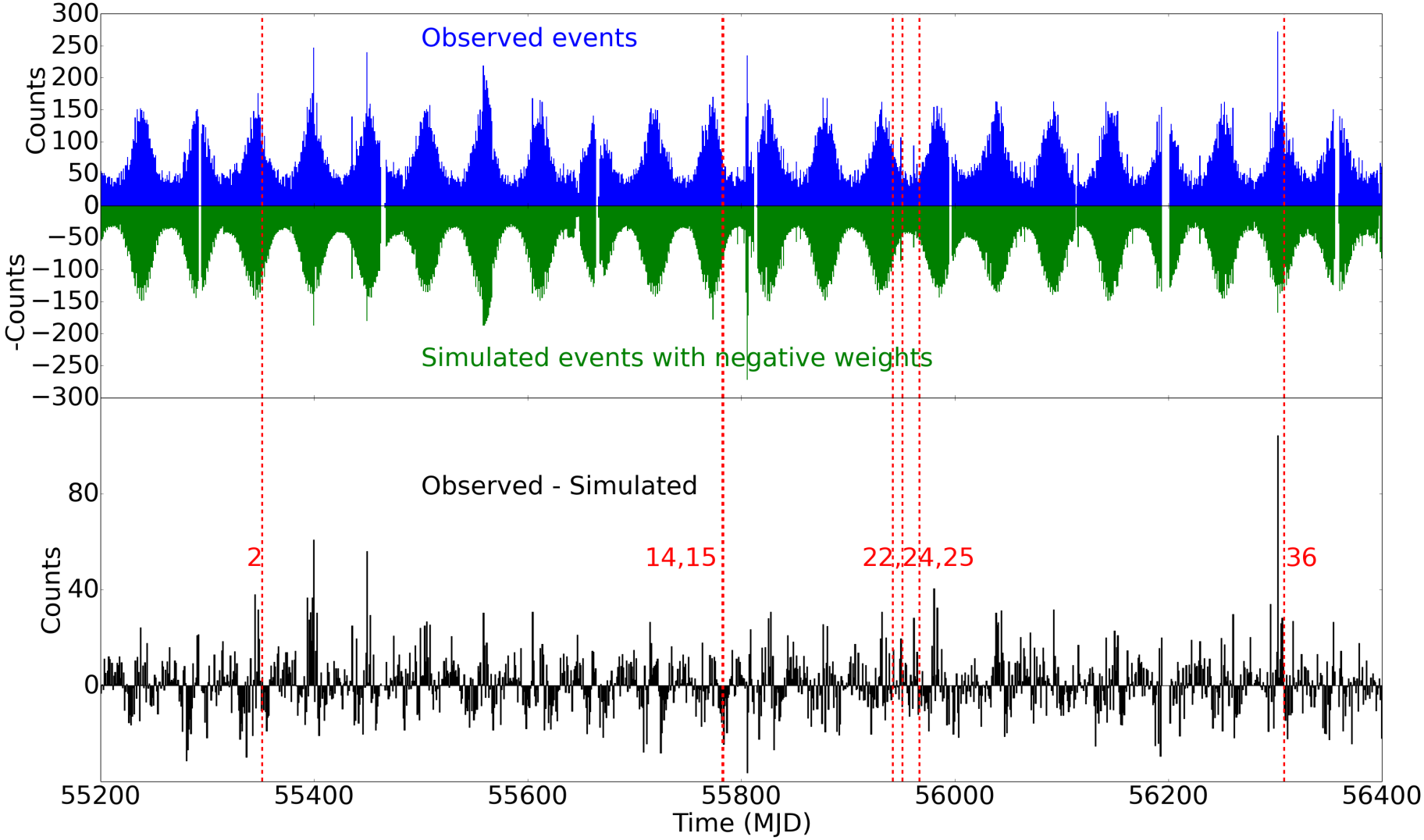
- Observations from Swift and Chandra
- Infrared Flare from Keck (1403.5289)
- Flare from other object near Sgr A* (1405.0267)
- Waiting for IceCube data.

Raw Fermi GC Data



- Simulate events from GC using obssim
- Normalize the total number of events to the observed data
- Check the difference.

Fermi GC Data



Summary

- IceCube: 36 TeV-PeV Events
- Various Interpretations:
  - Astro Objects: GRB, AGN...
  - Detector Effect: Leptoquark
  - Dark Matter
  - ...
- Tempting correlation around Sgr A*