Earth Occultation Monitoring with the Fermi Gamma-ray Burst Monitor
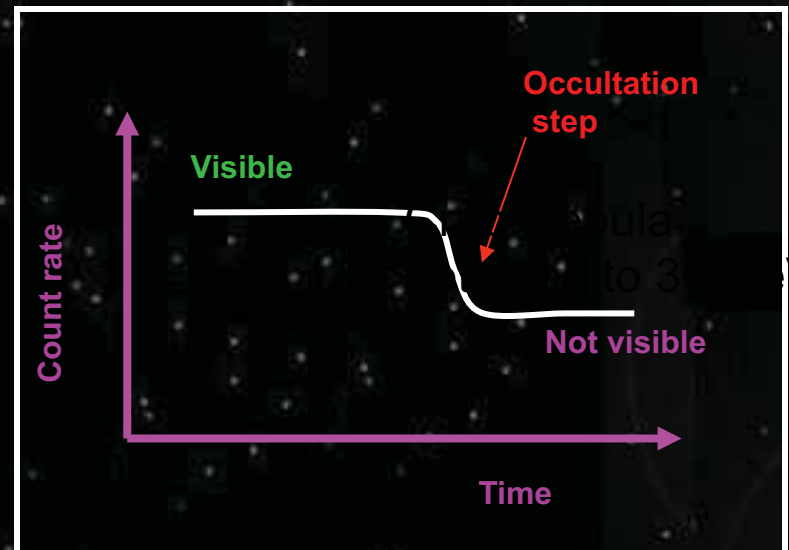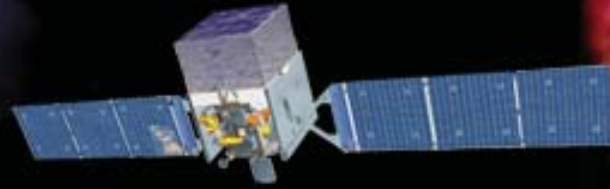

Dr. Colleen A. Wilson-Hodge

NASA/MSFC
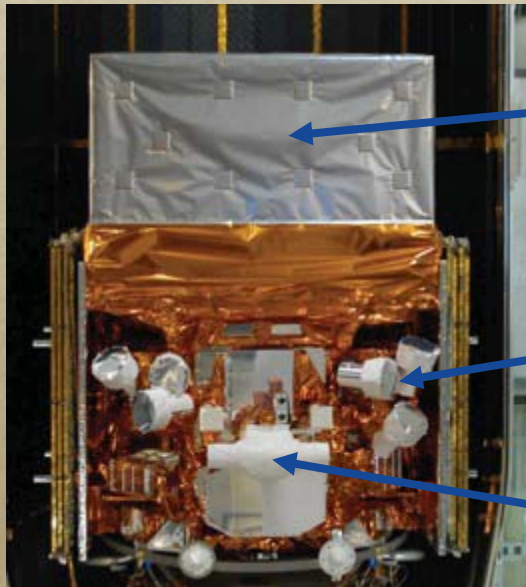
USA

Fermi

Launched June 11, 2008

Large Area Telescope
(LAT)
20 MeV -- 300 GeV

Gamma-ray Burst Monitor

12 NaI detector.
8 keV -- 1000 keV
126 cm^2, 1.27 cm
Triggering, localization, spectroscopy.

2 BGO detector.
200 keV -- 40 MeV
126 cm^2, 12.7 cm
Spectroscopy
Bridges gap between NaI and LAT.

Primary science for GBM is detection of Gamma-ray Bursts

Products

CTIME - 0.512 s time resolution, 8 channels

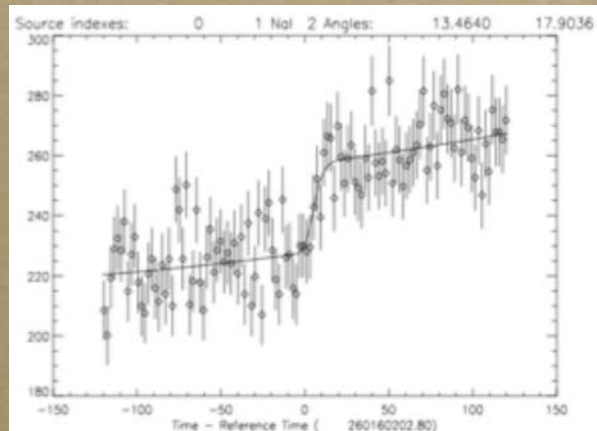CSPEC - 4.096 s time resolution, 128 channels

GBM Earth Occultation Project

PI Colleen Wilson-Hodge

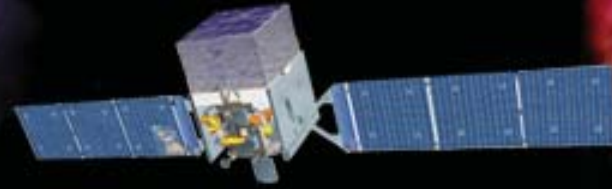## All sky X-ray monitor of known sources from 8 keV - 1000 keV

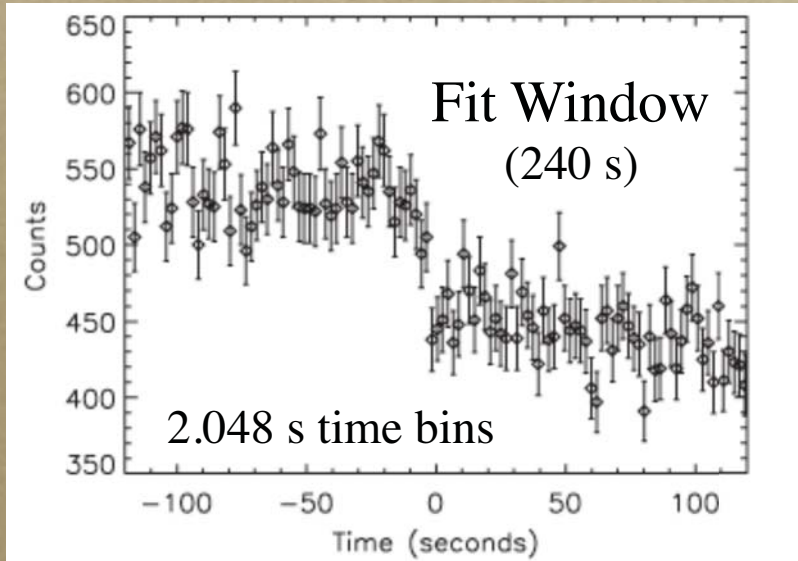
Source Database

Conceptually simple

GBM Earth Occultation Method

In practice....

Fit Window
(240 s)

2.048 s time bins

- Predict occultation times
- Determine detectors viewing source of interest
- Fit to each detector and energy channel
  - Background model
  - Model count rates for each source
    - Detector responses
    - Assumed energy spectrum
    - Atmospheric transmission
- Compute best scale factor for all detectors to estimate fluxes.

Occultation Time

The time where the probability that a 100 keV gamma ray from the source will pass through the atmospheric column is 50%

Atmospheric Transmission function

$$T(E_{\mathrm{ph}}, t) = \exp[-\mu(E_{\mathrm{ph}} A(h(t))]$$
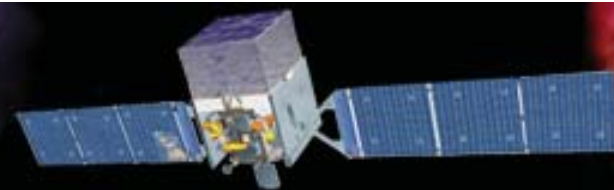
$\mu(E_{\mathrm{ph}})$ — mass attenuation coefficient of gamma rays at photon energy E_{ph} in air

$A(h(t))$ — air mass along the line of sight at a given altitude $h(t)$ based on the U.S. Standard Atmosphere (1976)

Fitting

- Each detector which views the source of interest within 60 degrees of the detector normal is included in the fit

- Observed count rate model for each detector is:

$$r(t, E_{ch}) = b_0(E_{ch}) + b_1(E_{ch}) * (t - t_0) + b_2(E_{ch}) * (t - t_0)^2 + \sum_{i=1}^{n} a_i(E_{ch}) * S_i(t, E_{ch})$$

$b_0(E_{ch}), b_1(E_{ch}), b_2(E_{ch}) =$ Quadratic background coefficients

$a_i(E_{ch}) =$ Fitted scale factors for each source model

$S_i(t, E_{ch}) =$ Source models for source of interest and all other sources included in the fit window

$$S(t, E_{ch}) = R(E_{ph}, E_{ch}, t) \left(T(E_{ph}, t)) * \int_{E_{ph}} f(E_{ph}) dE_{ph} \right)$$

$f(E_{ph}) =$ Assumed source spectrum

$T(E_{ph}, t) =$ Atmospheric transmission

$R(E_{ph}, E_{ch}, t) =$ Time dependent detector response

Flux Measurements

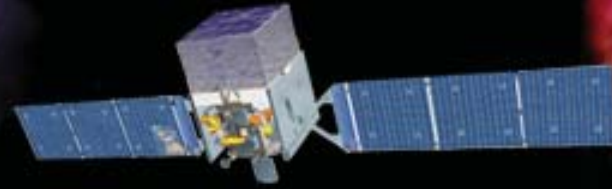Each energy channel and each detector is fitted independently

$$F(E_{ch}) = \bar{a}(E_{ch}) * \int_{E_{ph}} f(E_{ph}) dE_{ph}$$

$\bar{a}(E_{ch}) = $ Weighted mean of scale factors for each detector

Interfering sources in fit window

Each source in the database is identified as:

> 500 mCrabs

> 150 mCrabs

> 50 mCrabs

- Strong - Always include in fit out to 90 degrees
- Moderate - Always include in fit out to 60 degrees
- Weak - Always include in fit out to 40 degrees
- Quiescent - Never include in fit unless it is flaring

Flare database

Public *Swift*/BAT transient monitor data

- 50 mCrabs $\leq$ Source $<$ 150 mCrabs - Weak
- 150 mCrabs $\leq$ Source $<$ 500 mCrabs - Moderate
- Source $\geq$ 500 mCrabs - Strong

If an interfering source meets the criteria for any detector it is included for all detectors

Additional Considerations

Eclipsing sources

10 sources in the catalog are eclipsing

Sun-Solar flare database

- Class M or X flares - Strong
- Class C flares - Moderate
- Class B flares - Weak

Pre-Filtering data

Usually removes class M and X flares as well as SAA entrances and exits

Systematic Effects

- Accuracy of assumed source spectral model
- Heavily tested and researched; -3 power-law
- Large variation in background
- Pre-filtering of data
- Duration of the occultation transition
- High latitude sources; Limited to 20 seconds
- Inaccuracies in the detector response matrices
- Remove steps for all possible solar panel blockages
- Occultation limb geometry
- 52 day precession; Flare database
- Nearby sources
- Exclude steps if bright source is within 8 s of occultation time

Post-Filtering

Occultation steps are removed if:

- The source of interest occults within 8 s of a bright source
- The occultation lasts for longer than 20 s (high latitude sources)
- The space craft is rapidly slewing with a spin rate$> 0.004 \text{ rad s}^{-1}$
- Individual steps are $> 10\sigma$ or $> 3.5\sigma$ from the mean if sources intensities reach 150-500 mCrab or < 150 mCrabs respectively
- The time of the fit window is associated with a solar flare
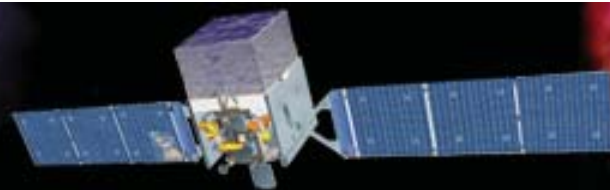
Ghost Source Analysis Systematic Errors
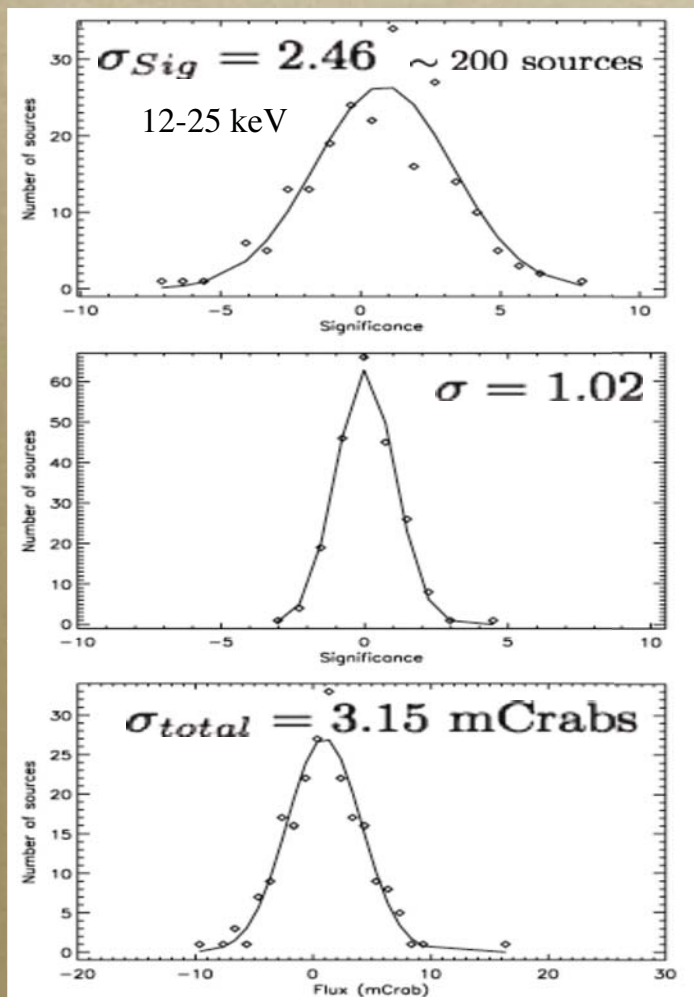
$$k \times \sigma_{total} = \sigma_{stat}$$

$\sigma_{total} = $ Width of flux distribution

$k = 1.0/\sigma_{Sig}$ Scale factor
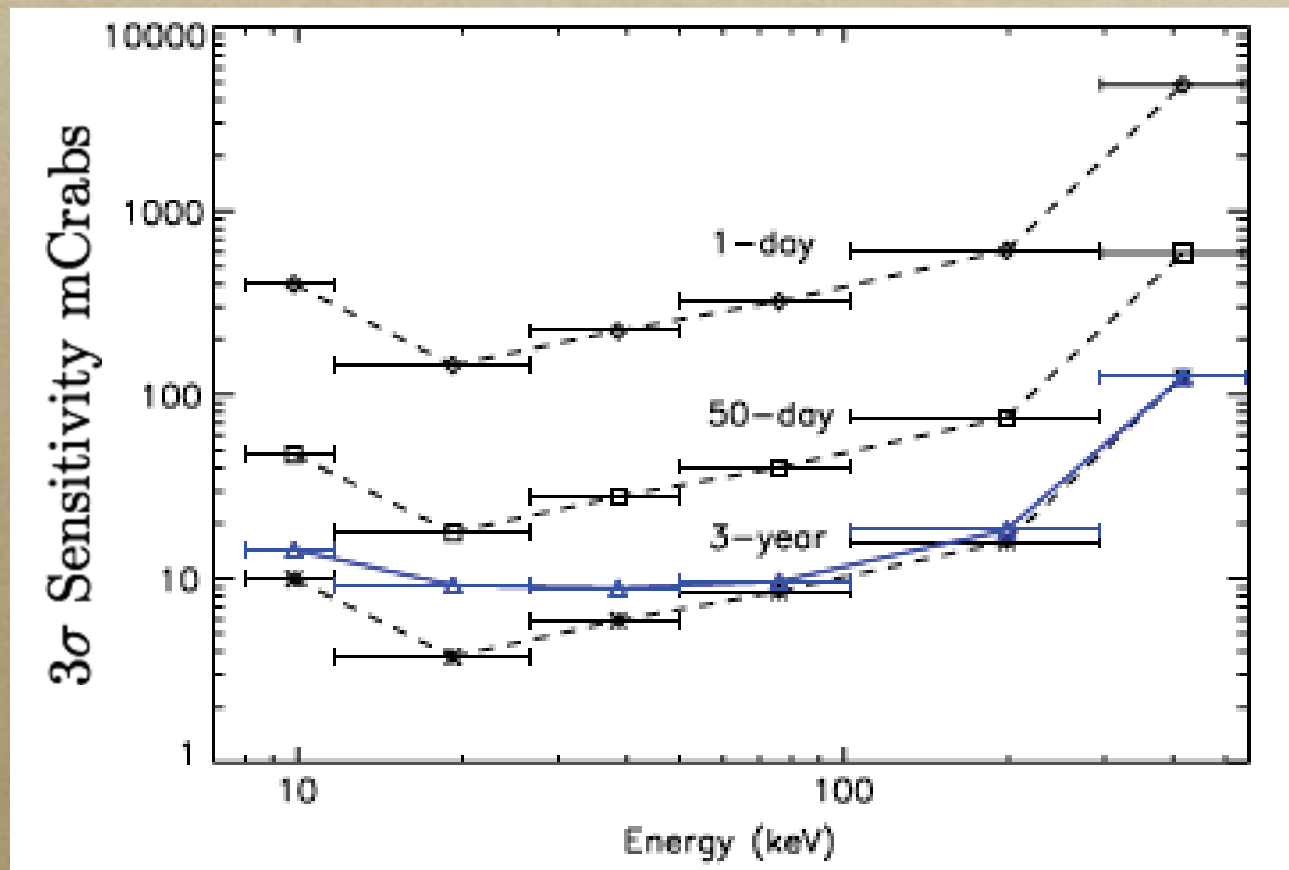
$$\sigma_{sys}^2 = \sigma_{total}^2 - \sigma_{stat}^2$$

Systematic Error Estimates for GBM Earth Occultation Analysis

Energy Band (keV)	Systematic Error (mCrab)
8–12	3.4
12–25	2.8
25–50	2.2
50–100	1.5
100–300	3.1
300–500	3.4

$\sigma_{Sig} = 2.46$ ~ 200 sources

12-25 keV

$\sigma = 1.02$

$\sigma_{total} = 3.15$ mCrabs
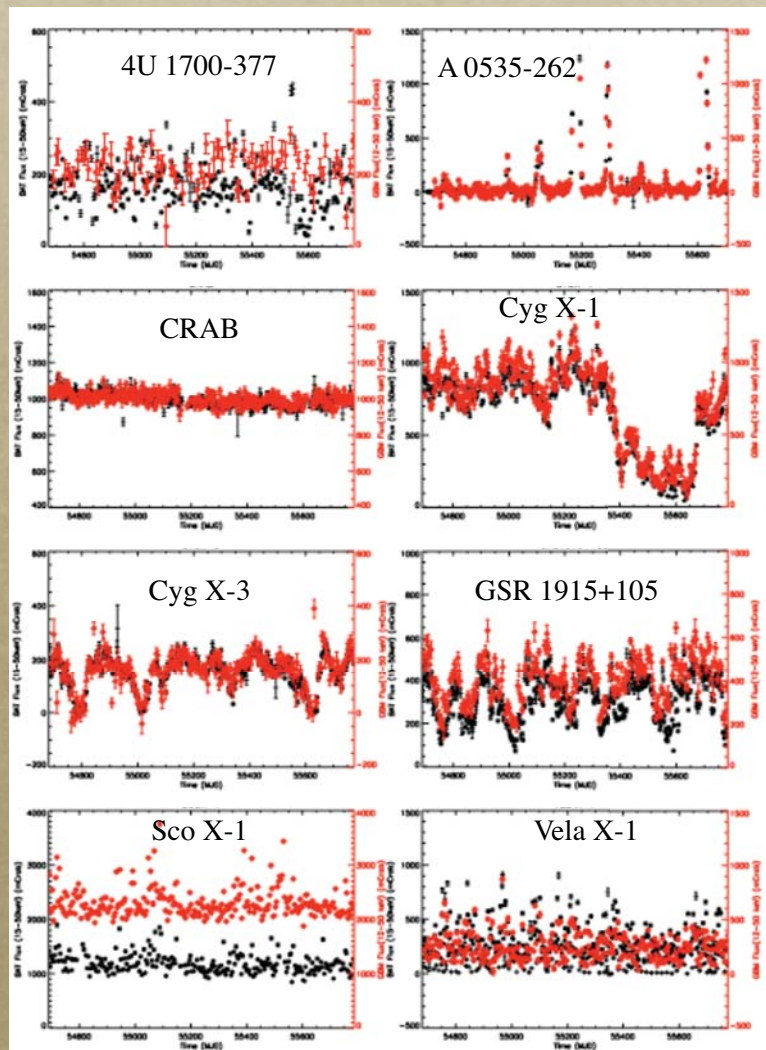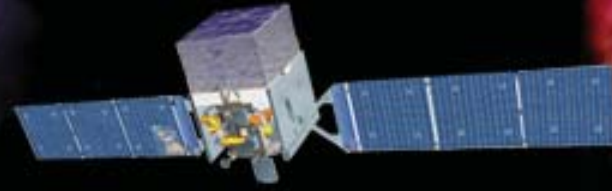
Sensitivity
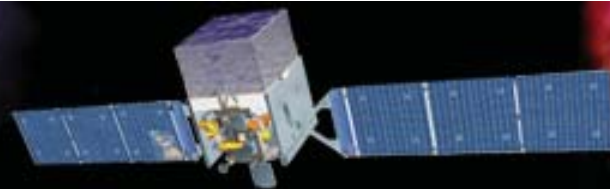
Comparison Between GBM and *Swift*/BAT

GBM 12-50 keV

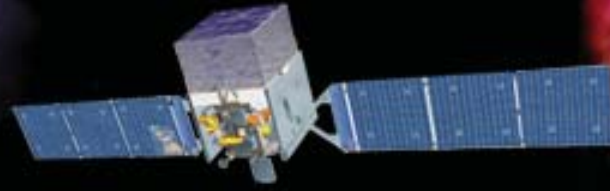Swift/BAT 15-50 keV

2 - 4 day averages

Three Year *Fermi*/GBM Earth Occultation Catalog

- Source Name
- Ra & Dec
- Category (A, B, T, P, N, I)
- 3 Year Average Flux (mCrabs)
  - 12-25 keV
  - 25-50 keV
  - 50-100 keV
  - 100-300 keV
- Significance
  - 12-50 keV
  - 12-300 keV
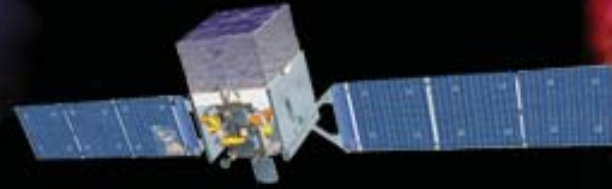- Type

Detection Criteria

- Significance exceeds 5 or 3.5 sigma (Category A and B respectively)
- Detected in the transient search (T) at 5 or 3.5 sigma
- Detected in the orbit folding search at 5 or 3.5 sigma (P)

Non-Detections

- Significance less than 3.5 sigma (Category N)
- Significance is negative (Category I) - only 6 sources

Summary of Results

3 Year Catalog	Current
209 Sources (99 detected-A)	215 Sources (104 detected-A)
40 LMXB/NS	40 LMXB/NS
31 HMXB/NS	34 HMXB/NS
12 BHC	14 BHC
12 AGN	12 AGN
1 Star (Sun)	1 Star (Sun)
1 TDE (SWIFT J164449.3+57345)	1 TDE (SWIFT J164449.3+57345)
1 Pulsar/PWN (Crab)	1 Pulsar/PWN (Crab)
1 Galaxy Cluster (Oph Cluster)	1 Galaxy Cluster (Coma Cluster)
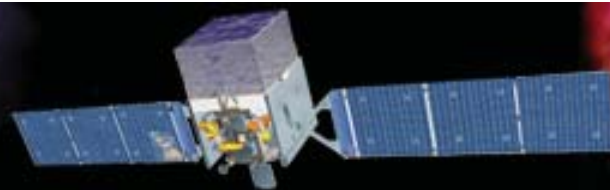
Transients Seen with Earth Occultation
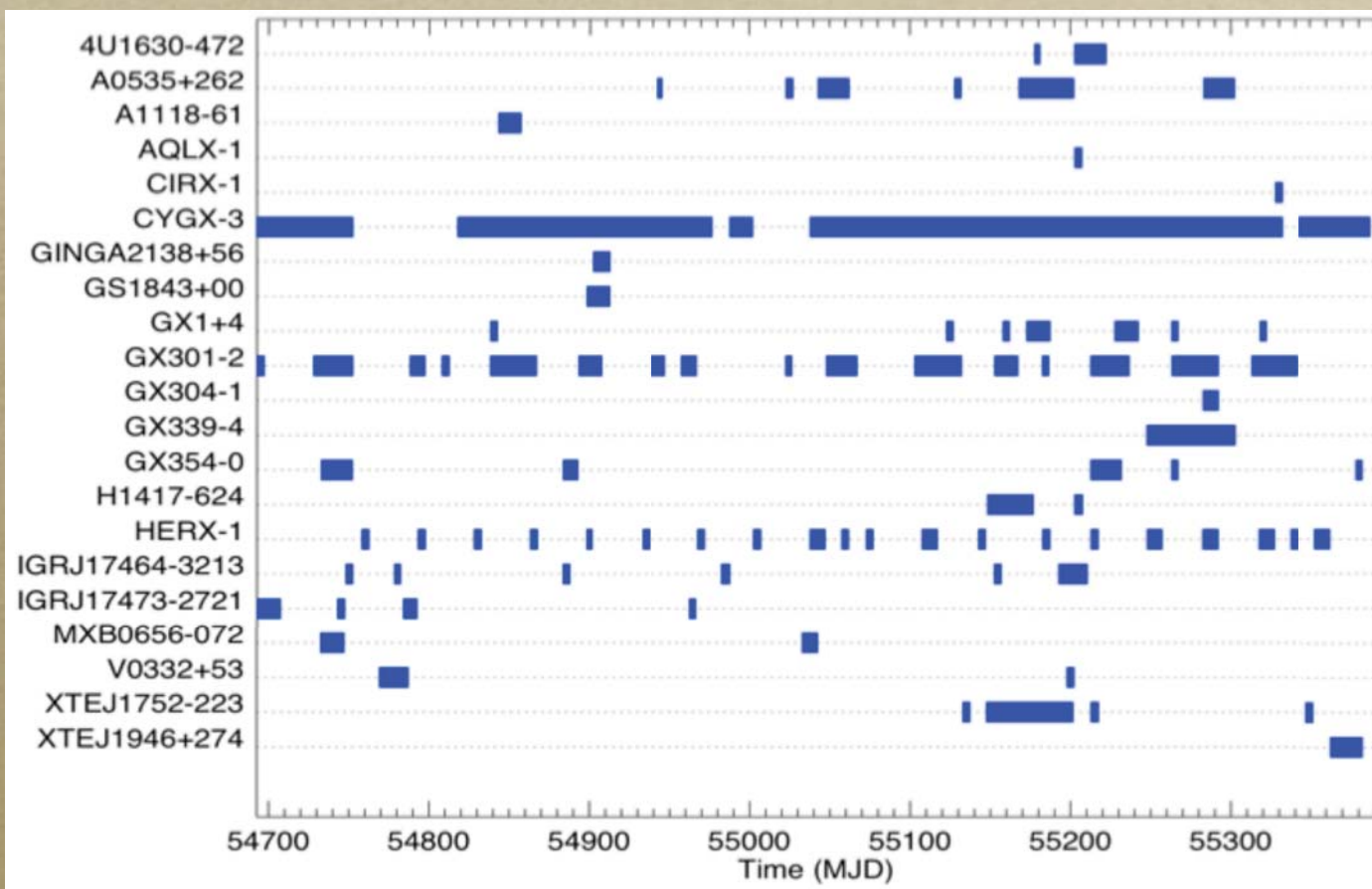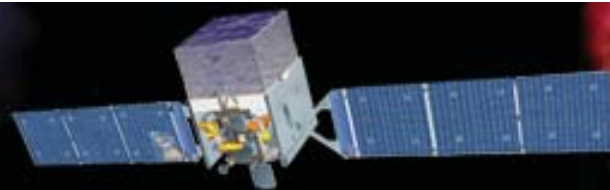
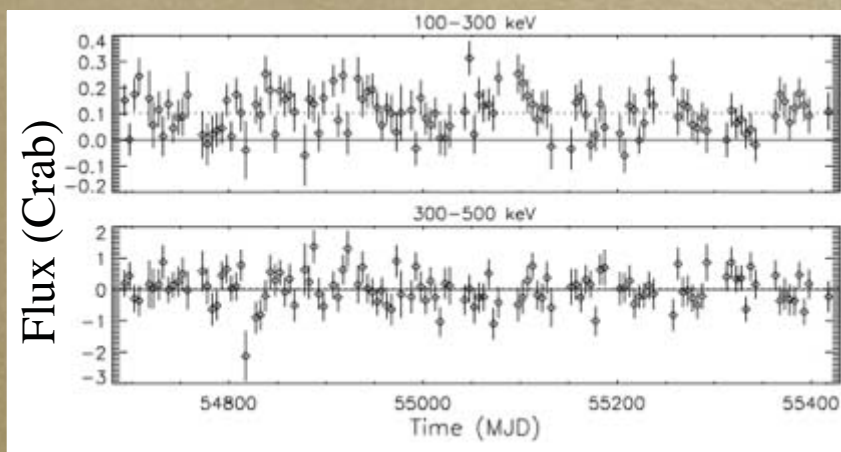# Sources Detected Above 100 and 300 keV
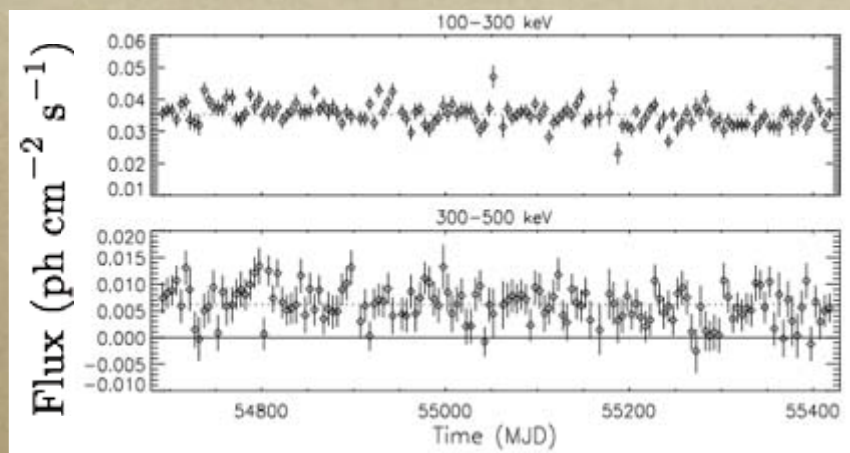
Crab
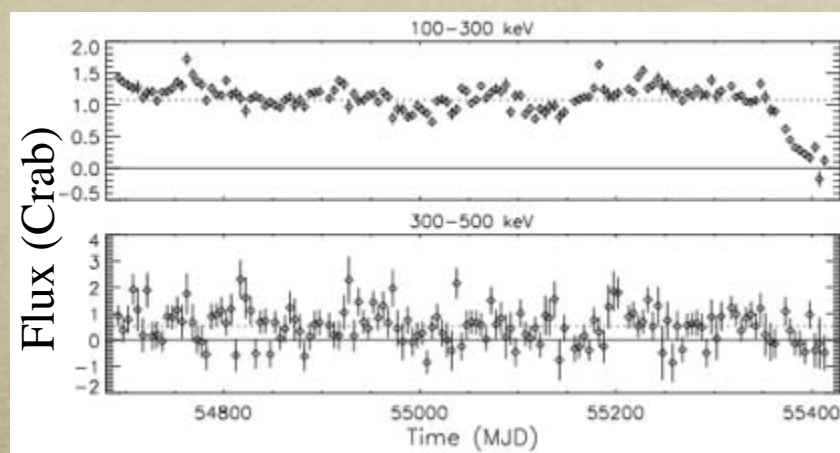
Cygnus X-1

Centaurus A
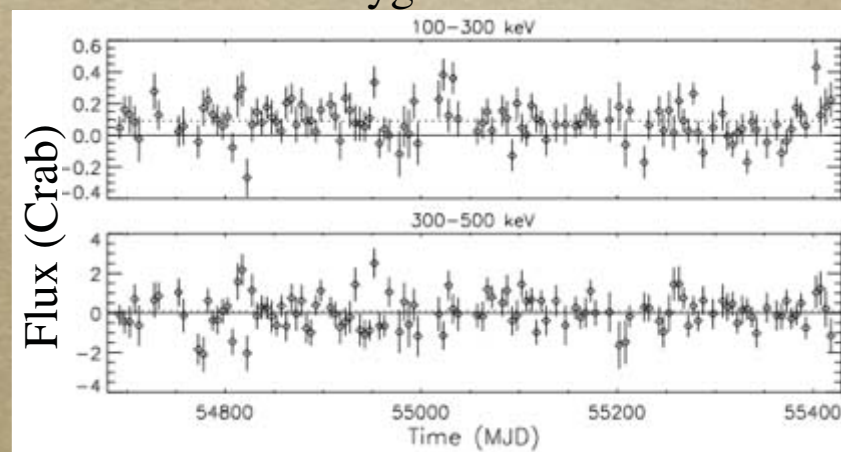
Case et al.

1E 1740-29
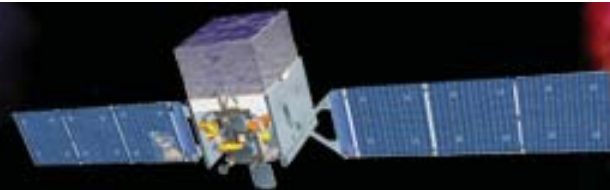
Sources Detected Above 100 and 300 keV
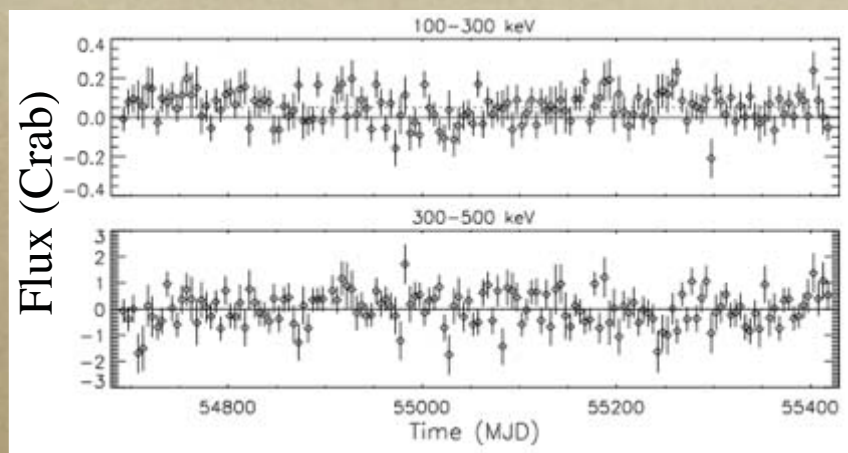
GSR 1915+105
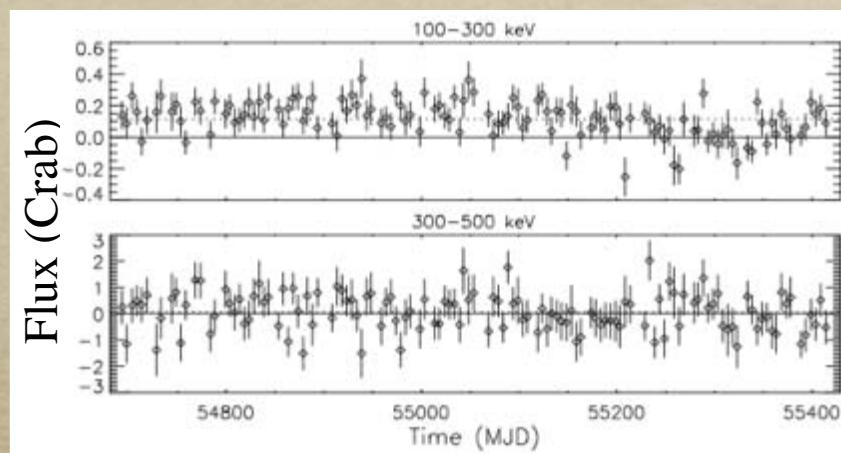
Swift J1753.5-0127
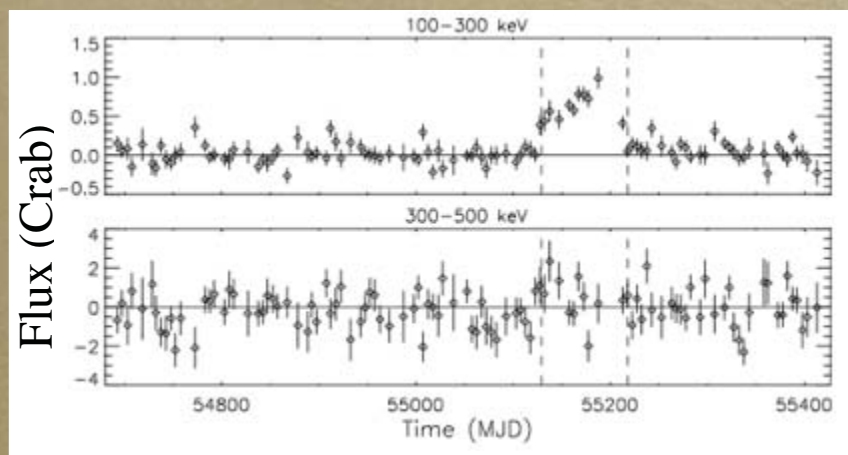
XTE J1752-223
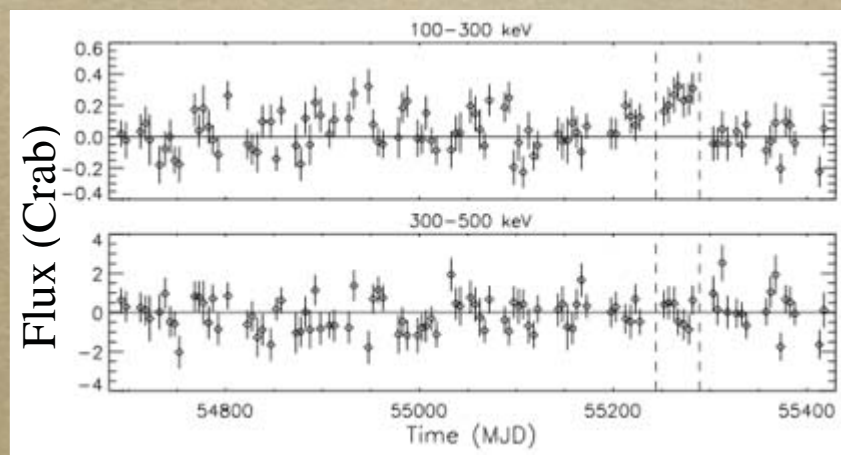
Case et al.

GX 339-4

Crab Flux Decline

C. A. Wilson-Hodge et al.

Crab Spectrum

Average of 69 energy spectra

$6° \times 8°$ Sky bins

$\Gamma_1 = 2.057 \pm 0.009$
$\Gamma_2 = 2.36 \pm 0.05$
Break Energy $= 98 \pm 9$ keV
$\chi_\nu^2 = 1.33$

$\Gamma_1 = 2.04$
$E_B = 62$ keV
$\Gamma_2 = 2.18$

(Jourdain and Roques 2009)

$\Gamma_1 = 2.057 \pm 0.01$
$E_B = 98 \pm 9$ keV
$\Gamma_2 = 2.36 \pm 0.05$

2FGL catalog

James Rodi et al.
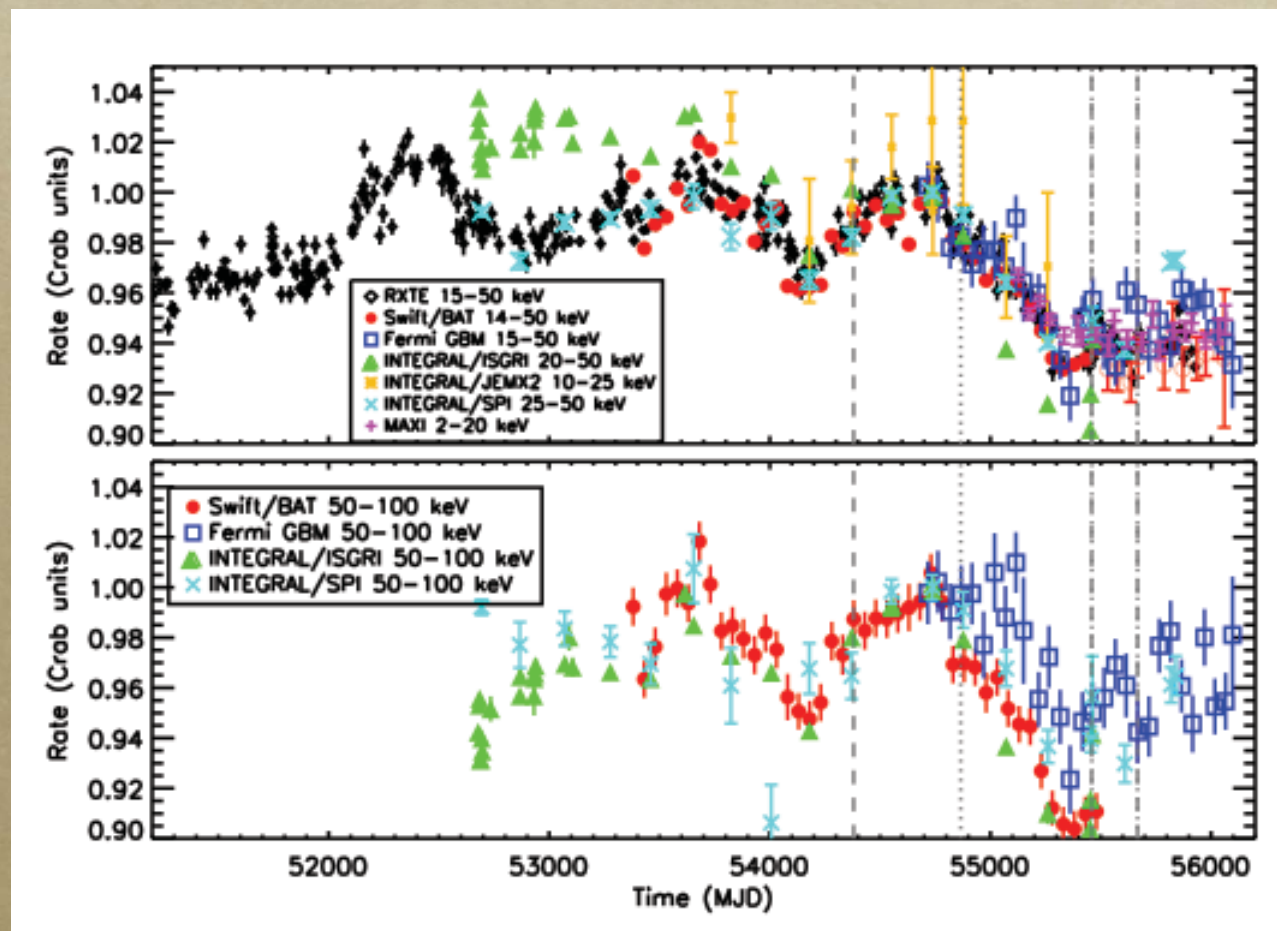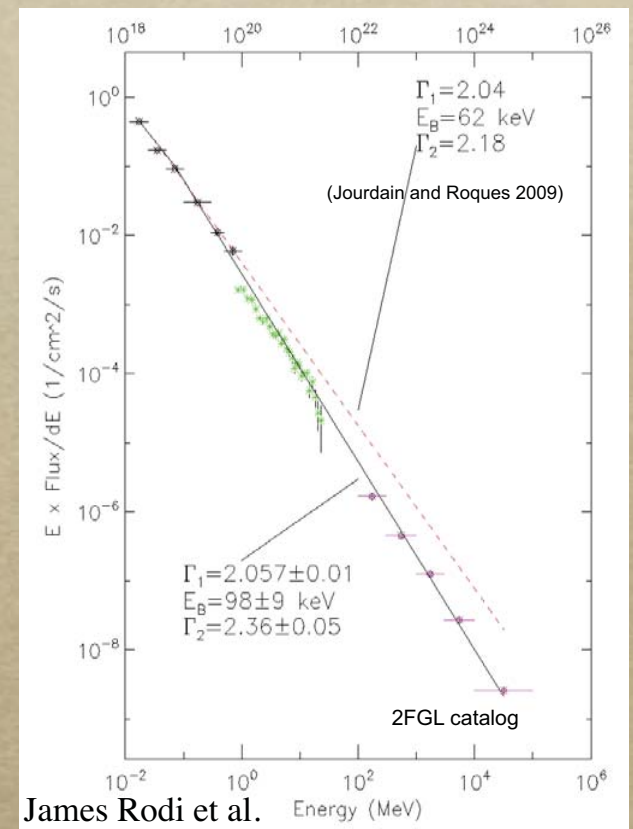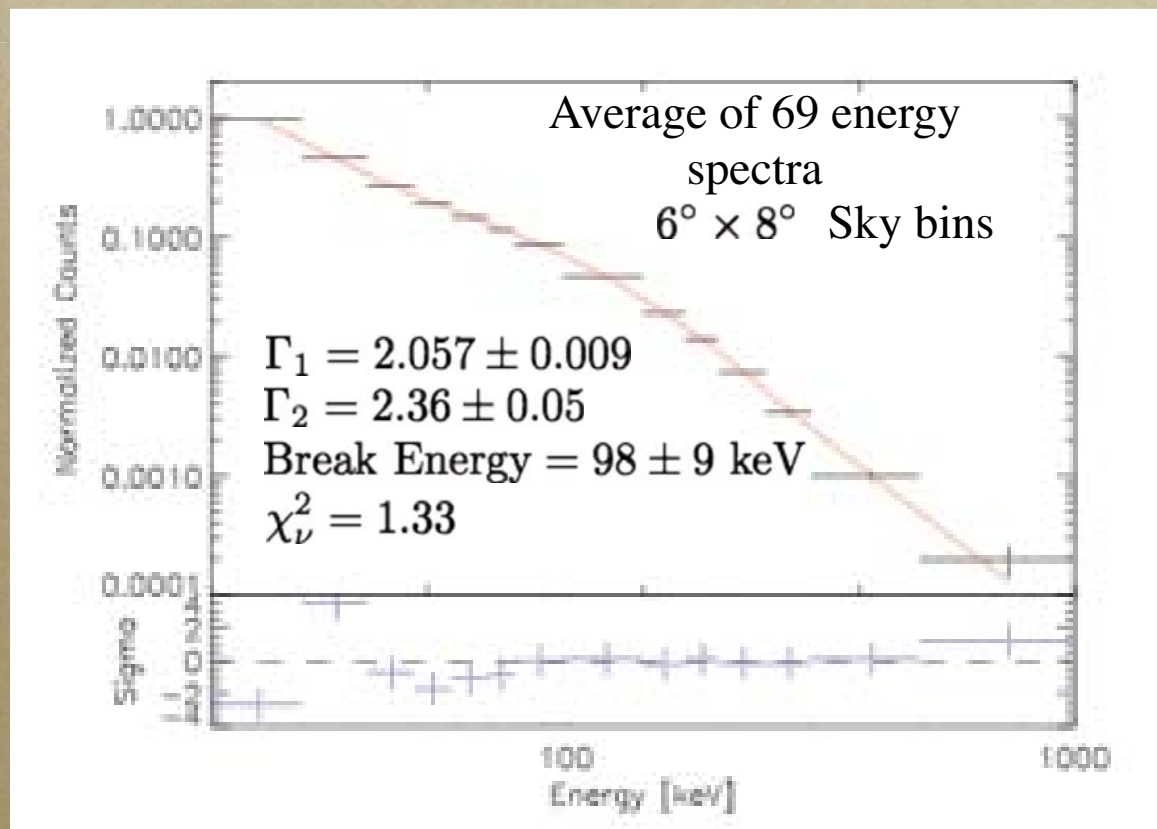
More spectral analysis coming to our web site in the near future
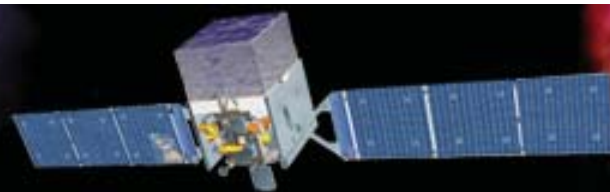
Monitoring of Cygnus X-1 During the 2010-12 State Transitions with the Fermi GBM
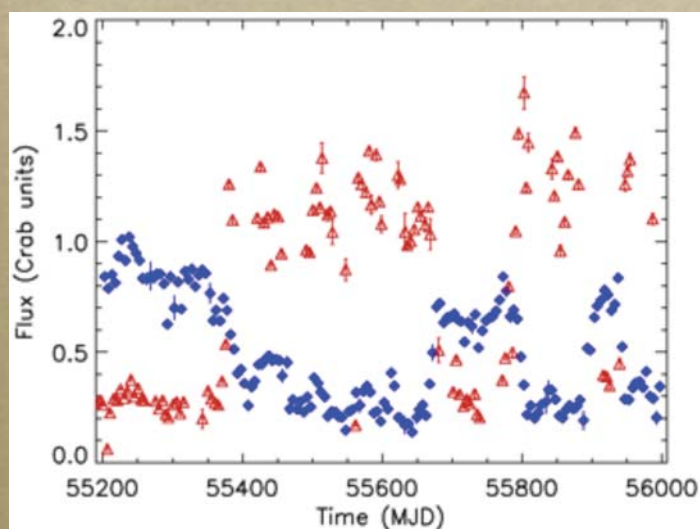
◆ GBM 12-50 keV

▲ MAXI/GSC 2-4 keV

G. L. Case et al.
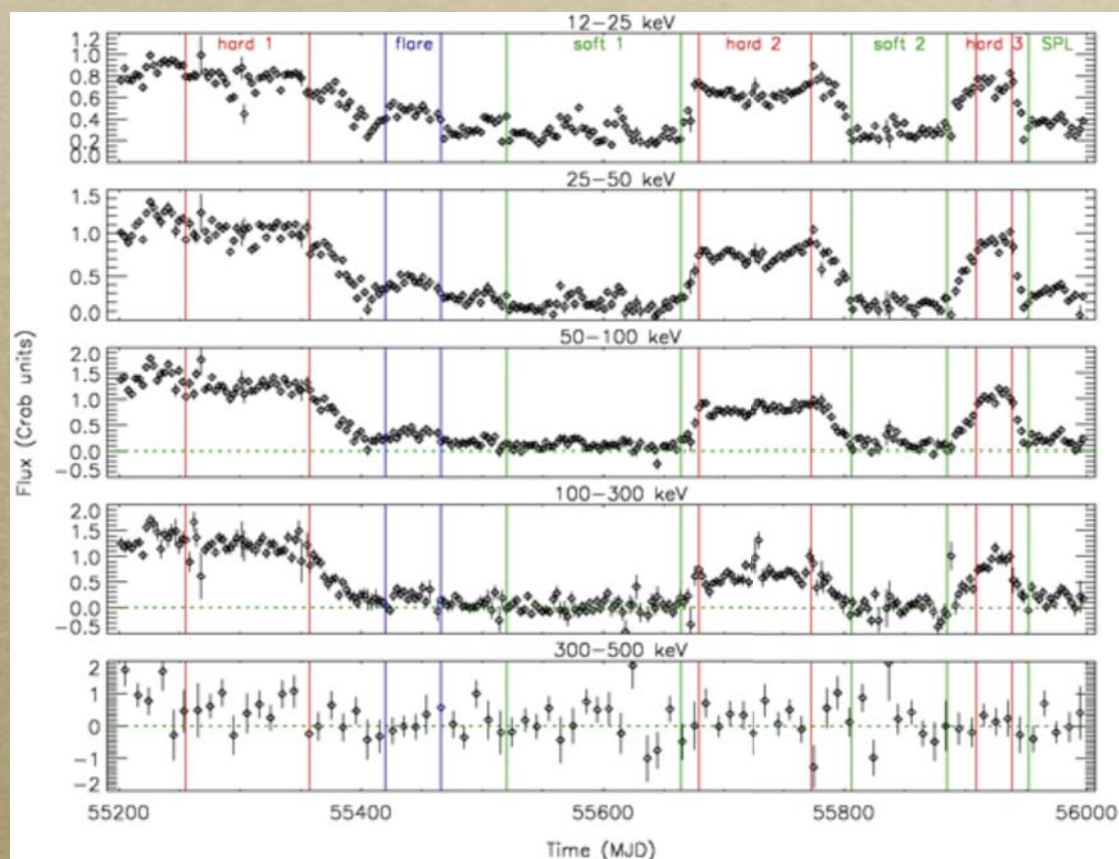
Brief History of X-ray Occultation
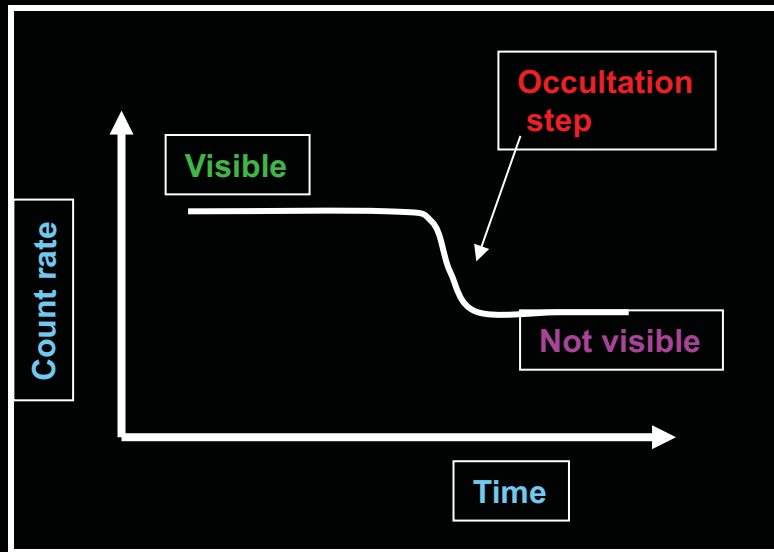
Lunar Occultations

- 1960s and 1970s
  - X-ray extent and structure of Crab Nebula
  - 1977 GX 9+1 located

Earth Occultations

- 1991-2000 monitoring with BATSE
  - EOT at MSFC
  - EBOP at JPL

★ 2008- Earth Occultation measurements with GBM

Occultation Coverage

The diameter of the Earth seen from *Fermi* is ~ 140°, so roughly 30% of the sky is occulted by the Earth at any one time. The precession of the orbit, caused by the oblateness of the Earth means that the entire sky is occulted every ~53 days.

± 26.5°
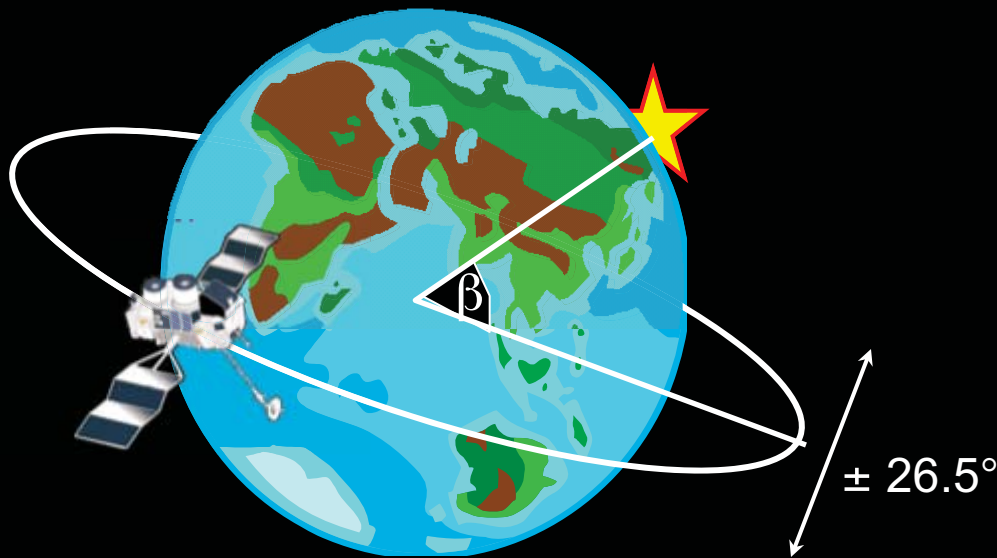
Fermi Orbital Information
- Scans the sky pointing +35° one orbit then slews pointing -35°
- Rolls about z-axis to keep solar panels facing sun

β, the 'elevation angle', is measured at the geo-centre between a source crossing the Earth's limb and the orbital plane.

Imaging with Earth Occultation

- Tomographic method that builds images from projections of Earth's limb (edge) on the sky

- Detectors uncollimated so detector count rate measure of sky brightness

- For detector facing Earth, time derivative of count rate is proportional to line integral of flux along Earth's limb

- During a precession period, elevation angle, $\beta(t)$, changes so flux is measured at different angles w.r.t Earth's limb giving different projection angles

- All available projection angles sampled over course of precession period

Limbs for CRAB on MJD 54690 $\beta° = 16.6$
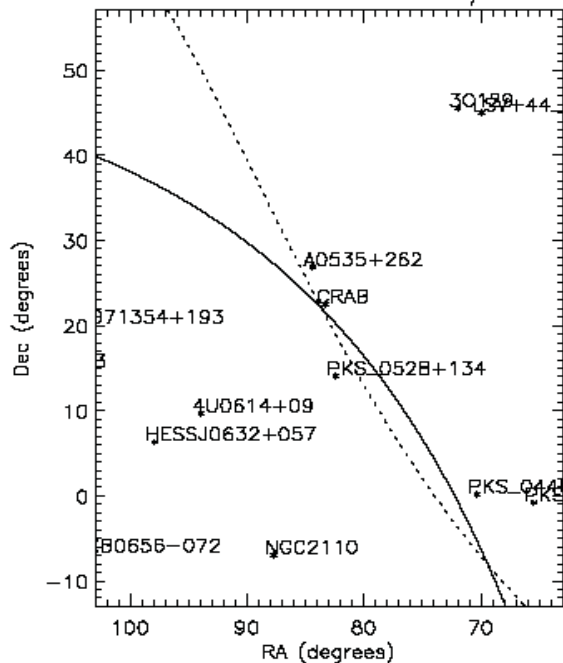
Limbs for CRAB on MJD 54700 $\beta° = 43.1$
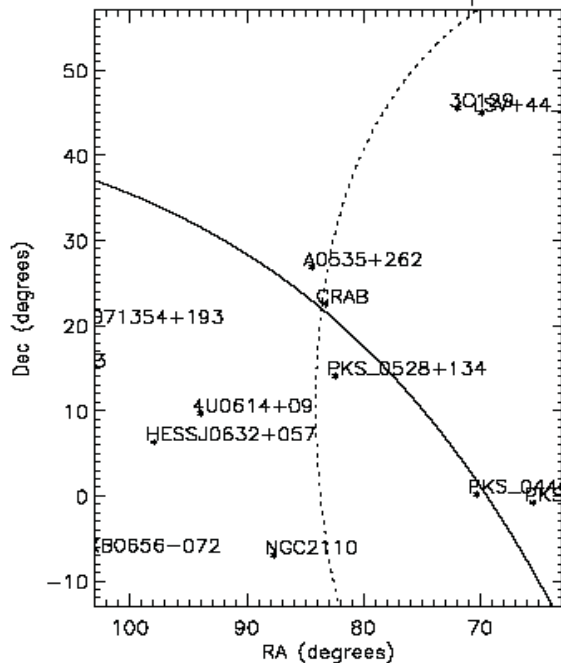
Limbs for CRAB on MJD 54710 $\beta° = 41.0$
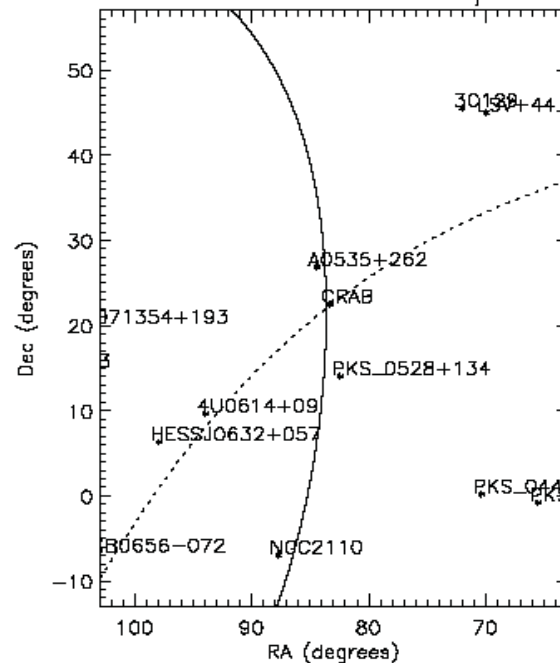
Limbs for CRAB on MJD 54720 $\beta° = 13.7$
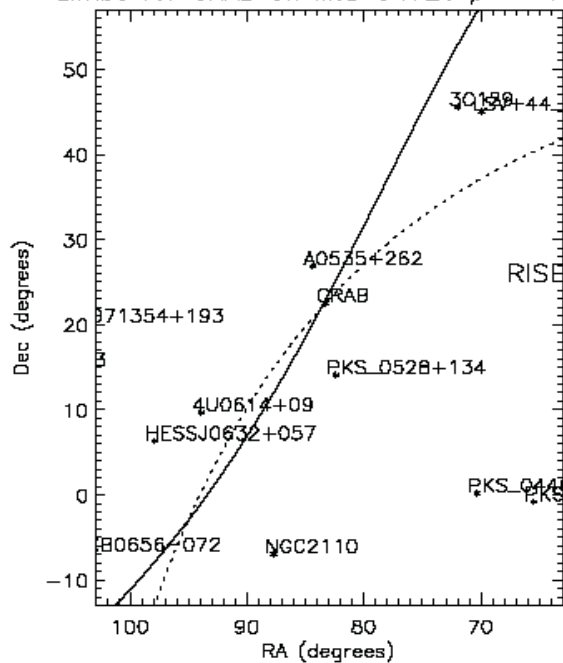
Limbs for CRAB on MJD 54730 $\beta° = -3.3$
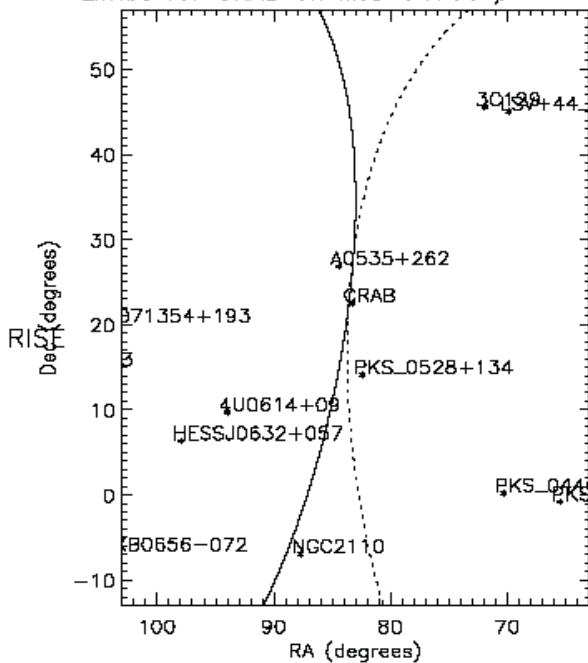
Limbs for CRAB on MJD 54743 $\beta° = 15.5$

Limbs for CRAB on MJD 54690.0 to 54690.0

Occ. Limbs for 3C273 on MJD 54690.0 to 54690.0
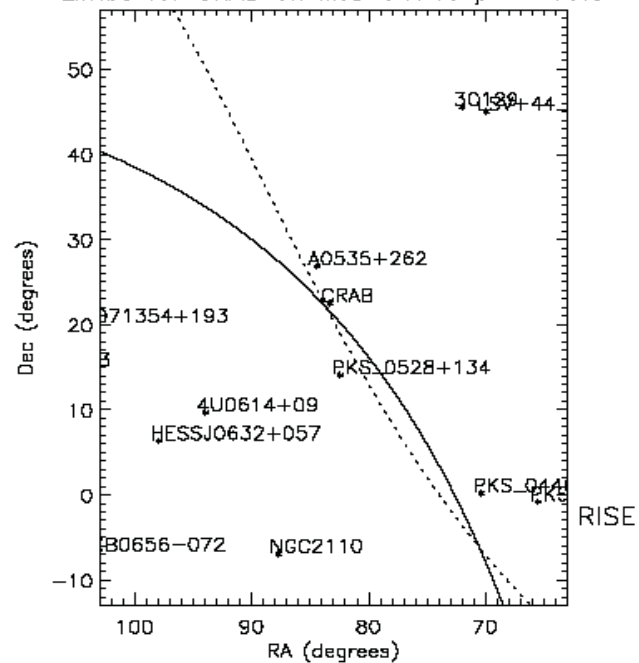
Occ. Limbs for NGC4151 on MJD 54690.0 to 54690.
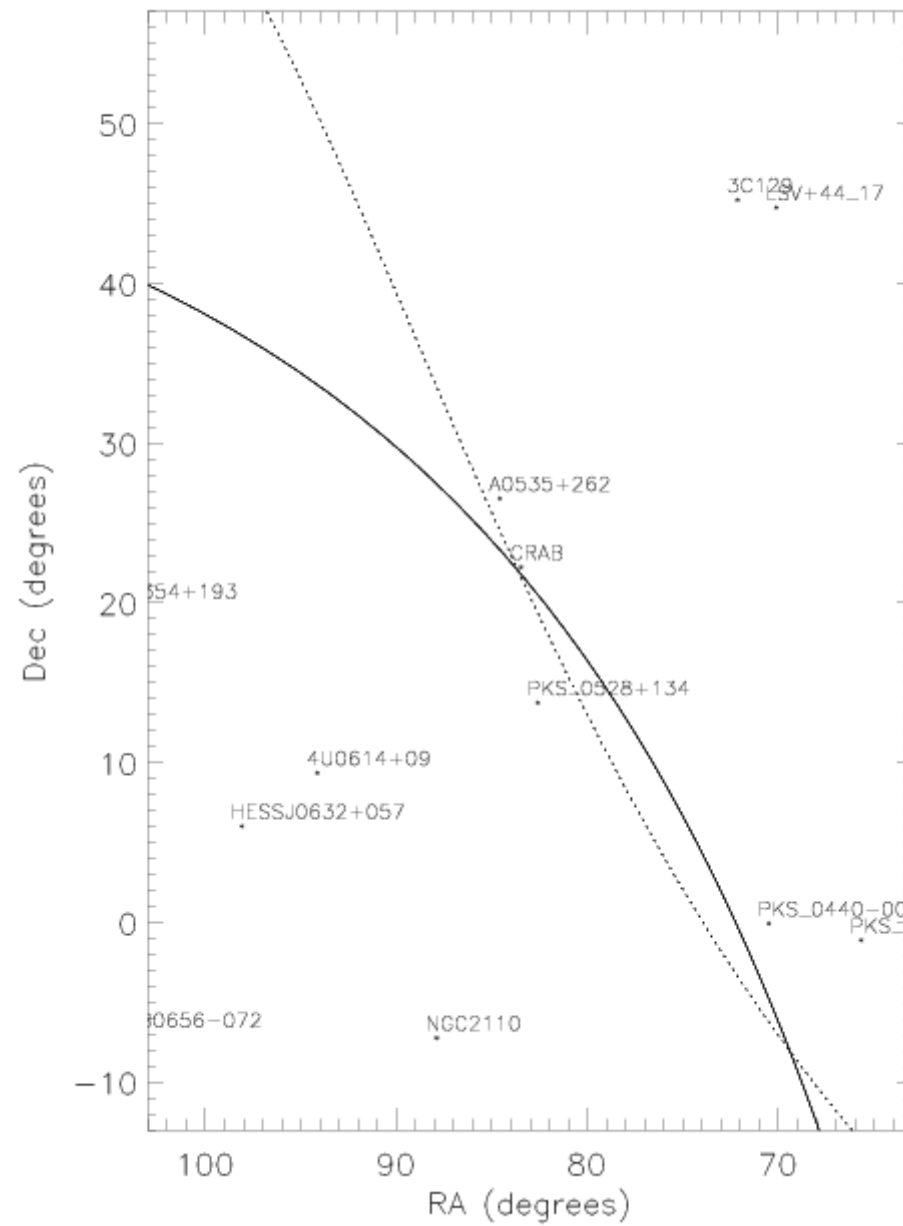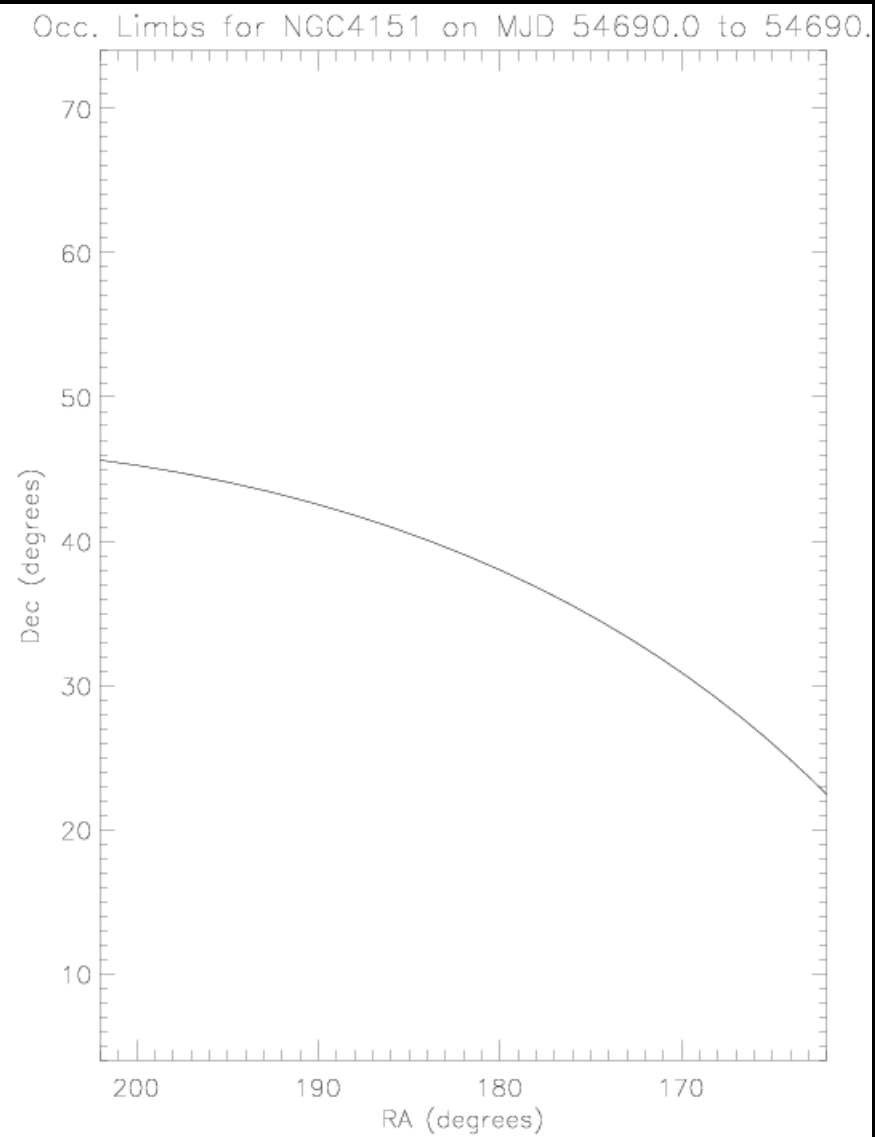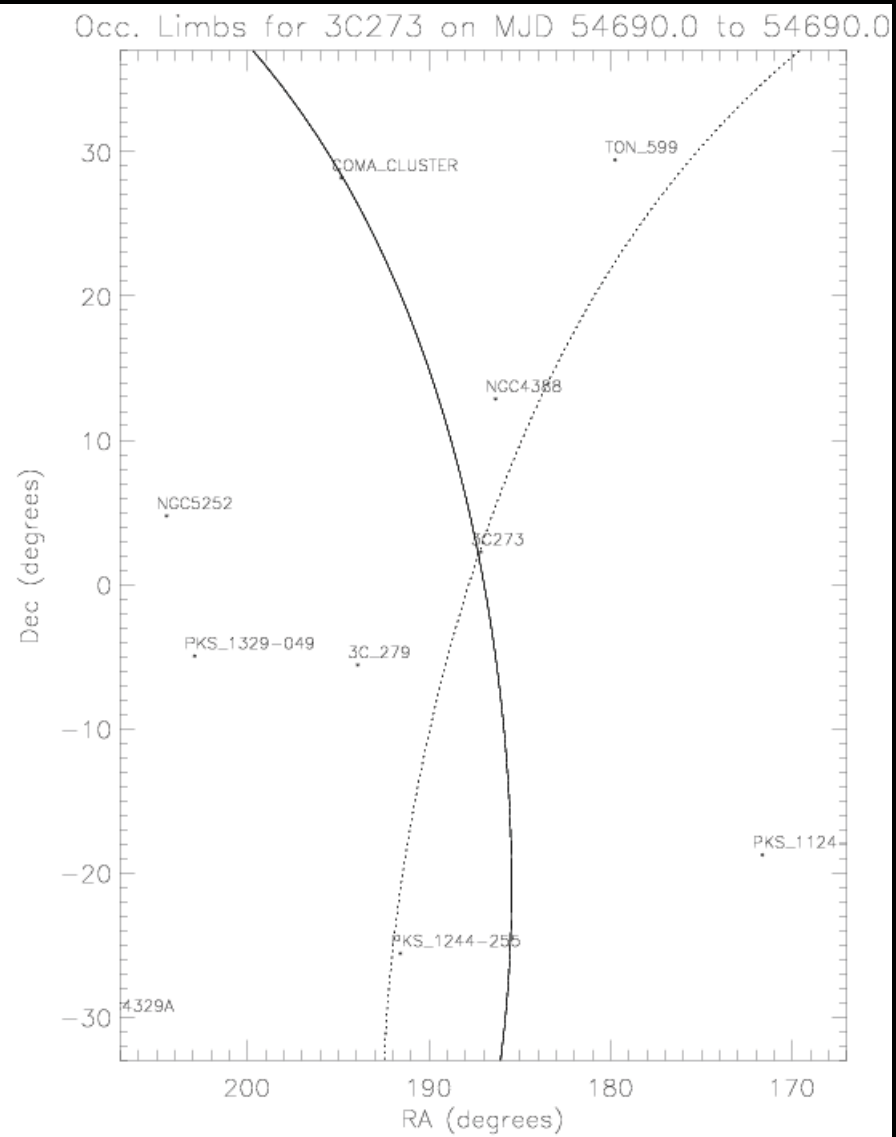
Motivation for Imaging

- Look at high energies to settle discrepancy between EOT vs. EBOP

- Construct complete catalog to reduce a cause of systematic errors
  - Flux from unaccounted-for sources attributed catalog sources
  - Example with 1E 1740-29 and transient GX 1+4 during flare MJD 55708-55774

Energy Band	GX 1+4 Stand. Dev. (σ)	1E 1740-29 with GX 1+4 Stand. Dev. (σ)	1E 1740-29 without GX 1+4 Stand. Dev. (σ)
12-25 keV	21.7	8.6	10.0
25-50 keV	21.1	2.5	7.9
50-100 keV	9.4	3.1	4.5

Imaging with IDEOM

- Grid of virtual sources at 0.25° spacing, ~660,000 sources
- Occ. times predicted
- 4-min window of count-rate data centered on occ. time
- Select detectors view steps < 75°
- Detector response correction to account for angle between source and detector normal and energy efficiency
- Convert rise occ. steps to set steps; rotate about center
- Average together data from all detectors for all windows for a given potential source
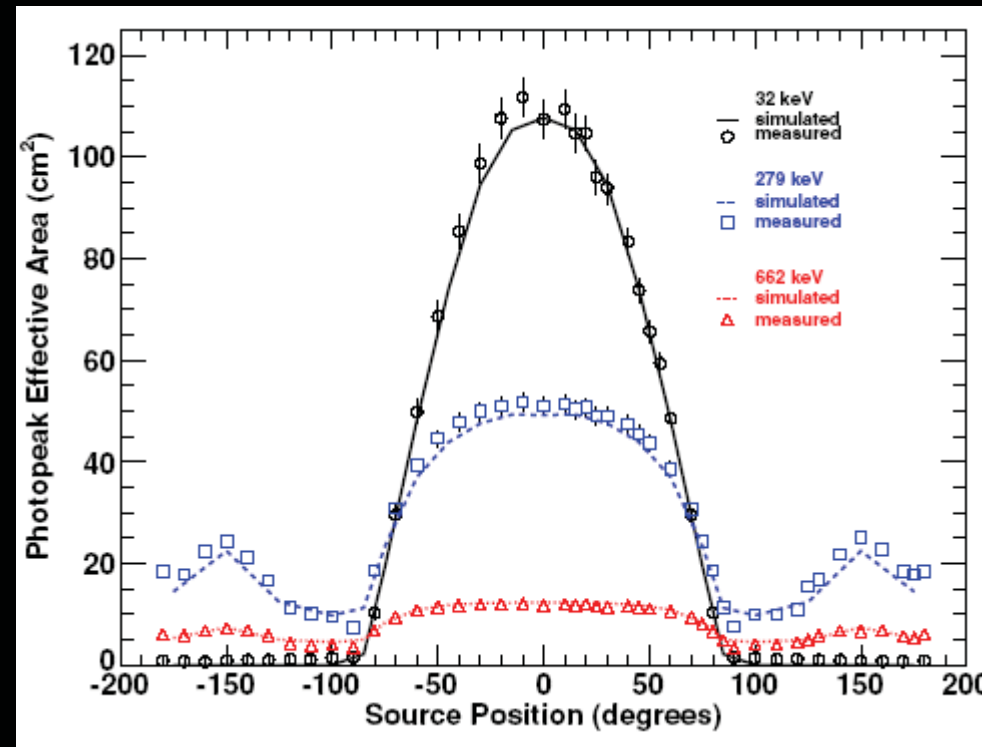
Image: Meegan et al. 2009

Imaging Technique

- Apply differential filter to average window
- f_a = inner boundary = 3
- f_b = outer boundary = 8
- Sums 8 bins of data, skips 6 bins, sums the next 8 bins, and then takes the difference between the 8-bin totals
- Fit polynomial to center region
- Fit a spline function to the side areas for background
- Take the difference between the polynomial and spline at the occultation time

$$o_i = \frac{\sum_{j=i+f_a}^{j=i+f_a+f_b} r_j - \sum_{j=i-f_a}^{j=i-f_a-f_b} r_j}{f_b}$$
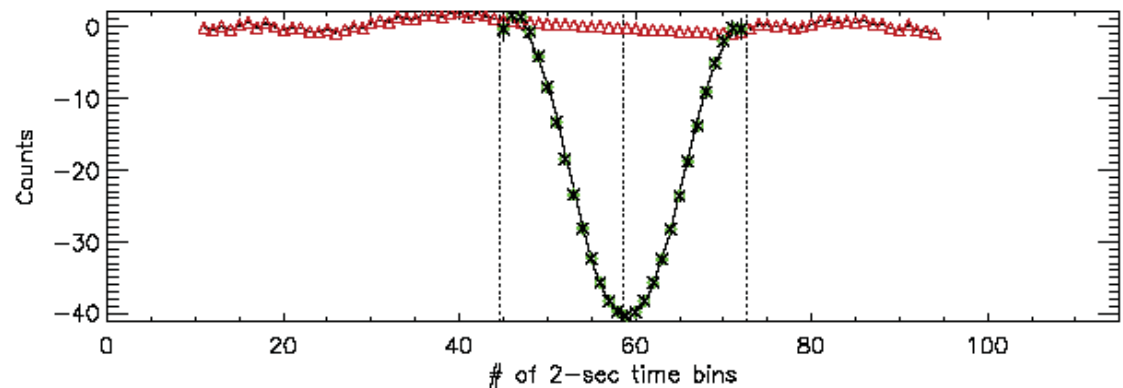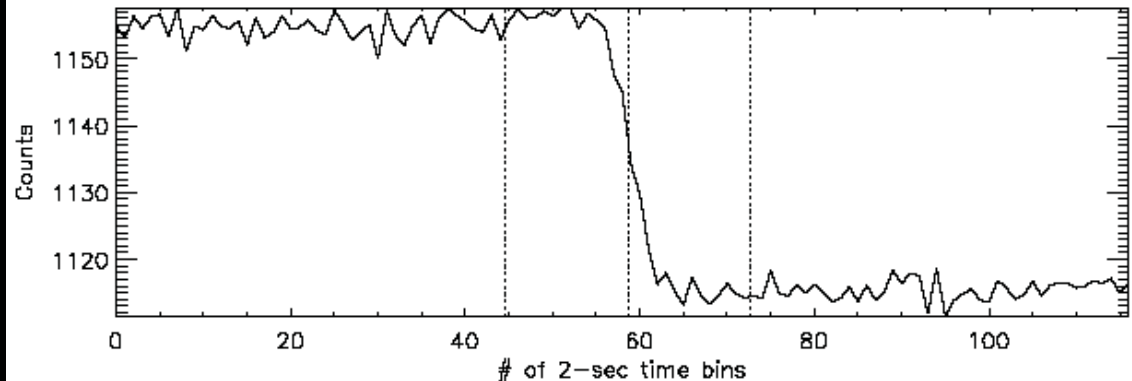
Implementation

- ~660,000 sources
- Parallel machines to process multiple sources at once
- Use LSU HPC Tezpur and LONI Queen Bee machines
- Split catalog into 3 roughly equal sections
- Takes ~6 hours with 80 nodes (320/640 processors) to run 1 catalog for a single energy band

IDEOM Results

- 28 precession periods (~ 4 years) for:
  - 12-50 keV
  - 50-100 keV
  - 100-300 keV
- Single precession period images for 3 energy ranges
- Images summed weighted by number of occ. steps

12-50 keV ~4 Years
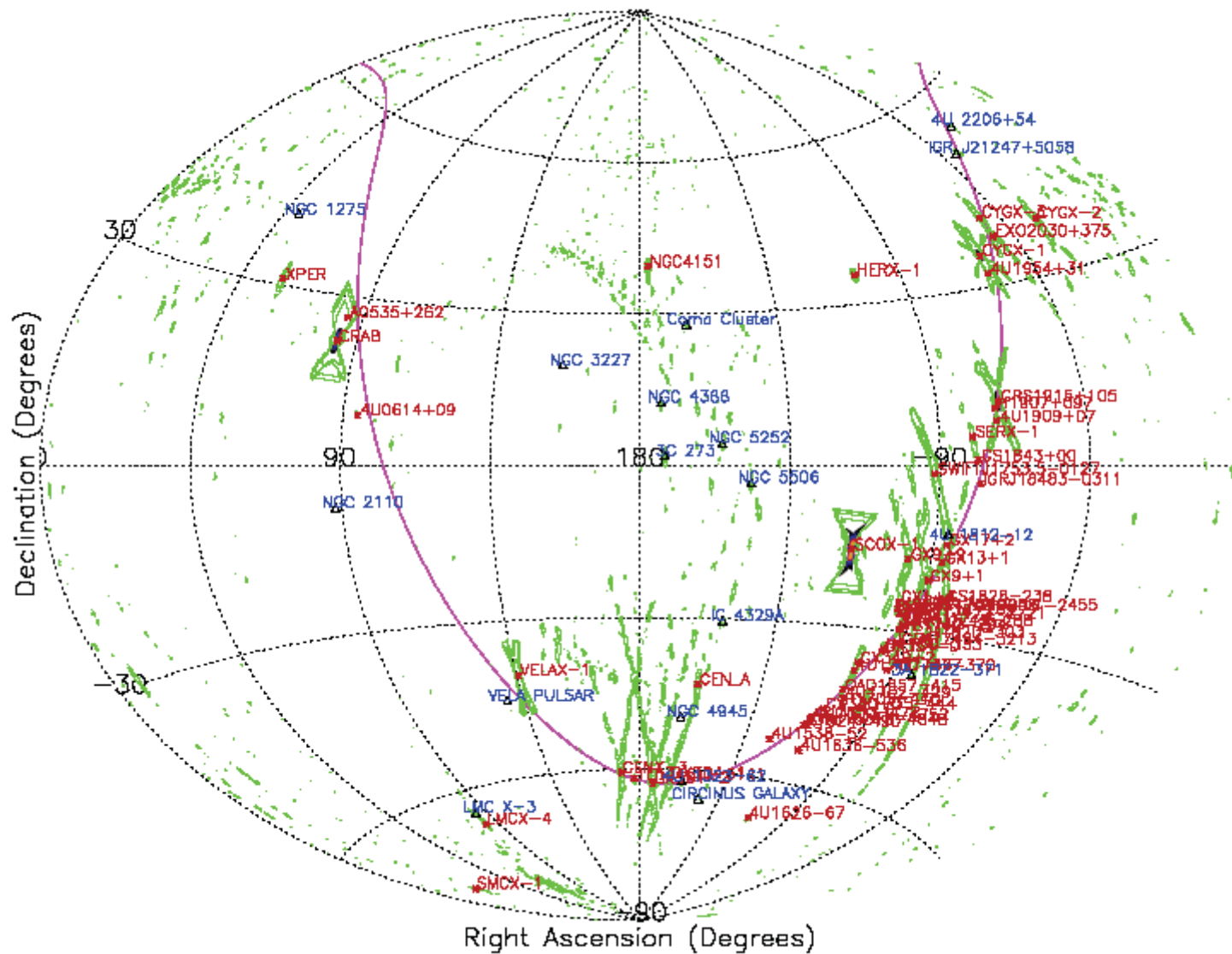
50-100 keV ~4 Years
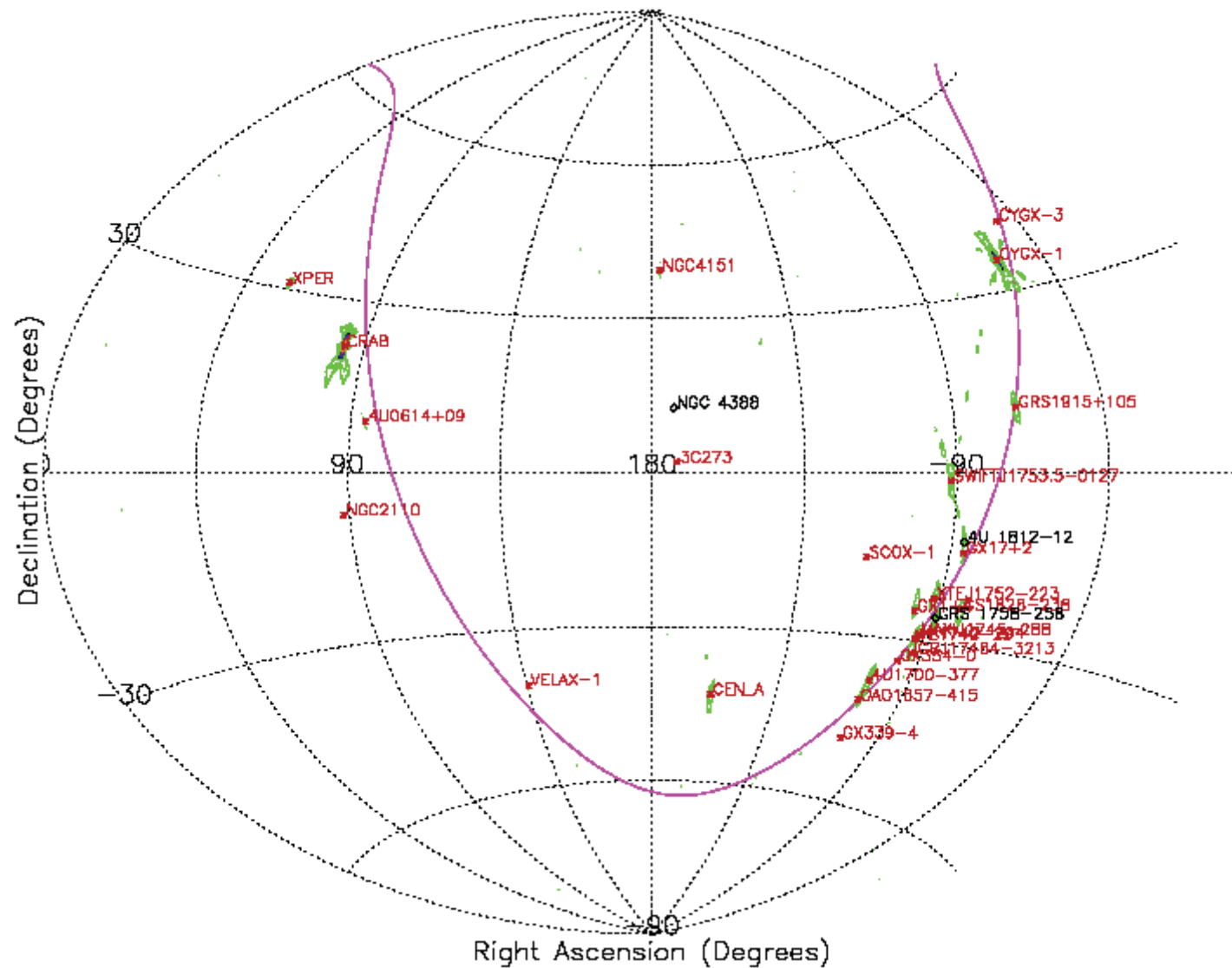
100-300 keV ~4 Years
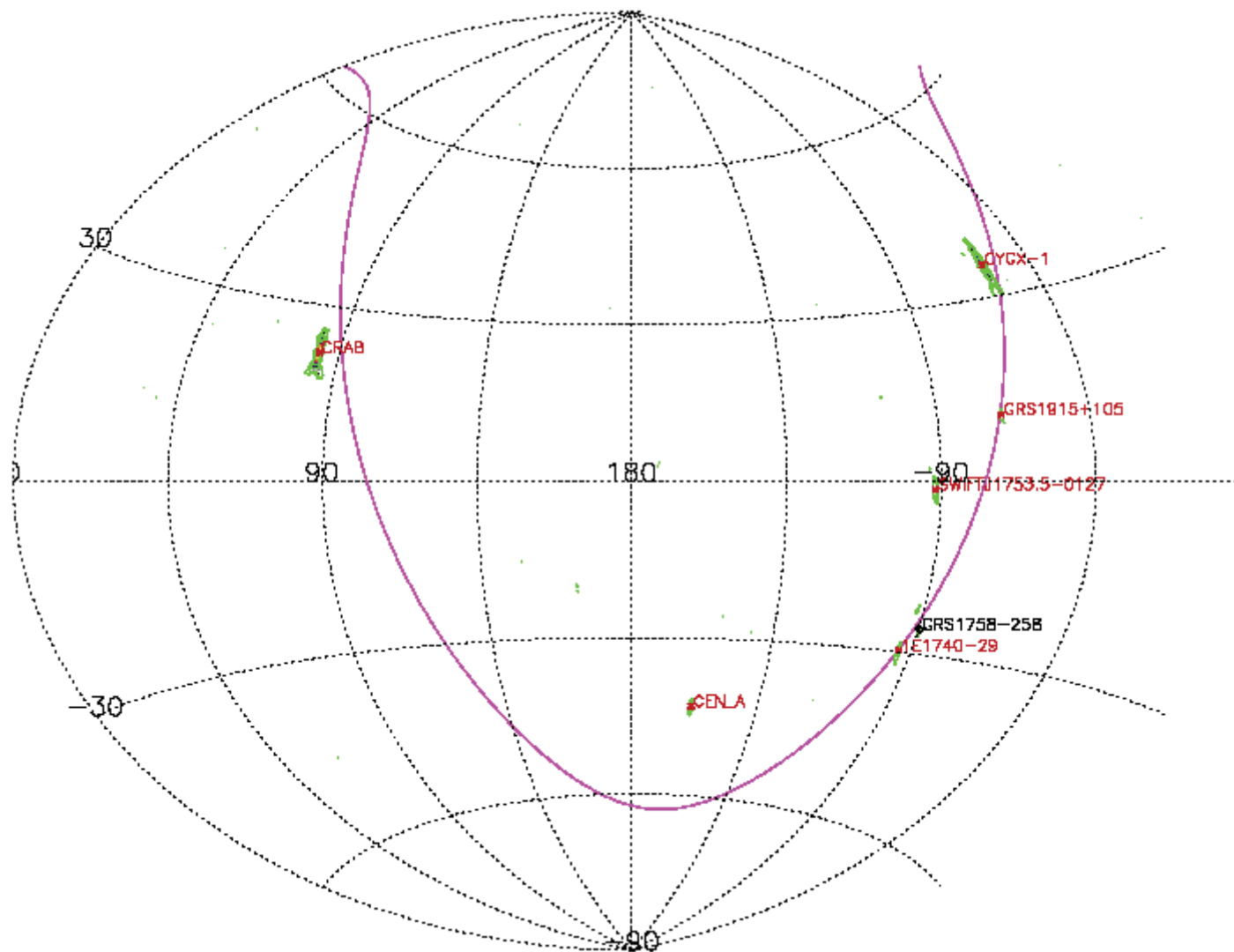
Finding Sources with IDEOM

- Early searches cross-correlated features in images with BAT, *INTEGRAL*, and LAT
  - 16 sources add to catalog this way
- Systematic search
  - For virtual sources $>3.5\sigma$, 5°x 5° regions fit to 2D Gaussian
    - Centroid taken as source position
    - Peak value as source significance
    - Integrated significance from fit Gaussian widths
  - Candidate sources product of peak significance and integrated over stat. error > 10
  - Candidate sources analyzed with EOT

Comparison to GBM Catalog

- 12-50 keV:
  - 67 sources detected by GBM-EOT; 43 by IDEOM
    - 11 blended with brighter
    - 12 no feature
    - 2 with test statistic < 10
    - 1 is A0535+262
  - Sensitivity limit 25 - 50 mCrab
  - Position accuracy ~ 0.4°

Comparison to GBM Catalog

- 50-100 keV:
  - 25 sources detected by GBM-EOT; 23 by IDEOM
    - 2 blended, 3 no feature, 3 IDEOM, but not sig. in GBM
      - GRS 1758-258 and 4U 1812-12 show flux out to 100 keV so consistent with *INTEGRAL*
      - NGC 4388 flux consistent between IDEOM and GBM-EOT
    - Sensitivity limit ~ 22 mCrab
    - Position accuracy ~ 0.47°

Comparison to GBM Catalog

- 100-300 keV:
  - 6 sources by GBM-EOT; 7 by IDEOM
    - 6 GBM-EOT + GRS1758-258
    - Sensitivity ~ 32 – 54 mCrab
    - Position accuracy ~ 0.25°
    - Only GBM sources down to ~20 mCrab
  - No unaccounted-for sources suggests EBOP background model inaccurate

GBM-LAT Sources

- GBM and LAT give energy coverage 10 keV to 300 GeV

- 4 persistent sources detected by GBM and LAT
  - NGC 1275
  - 3C 273
  - Cen A
  - Crab

- Data from GBM, LAT, and COMPTEL

Where do the "hard" photons come from?

- "soft" photons synchrotron emission from AGN jet
- "Hard" photons from
  - Inverse Compton scattering (IC)
    - Synchrotron self-Compton (SSC)
    - External inverse Compton (EC)
  - Proton Induced Cascade (PIC)
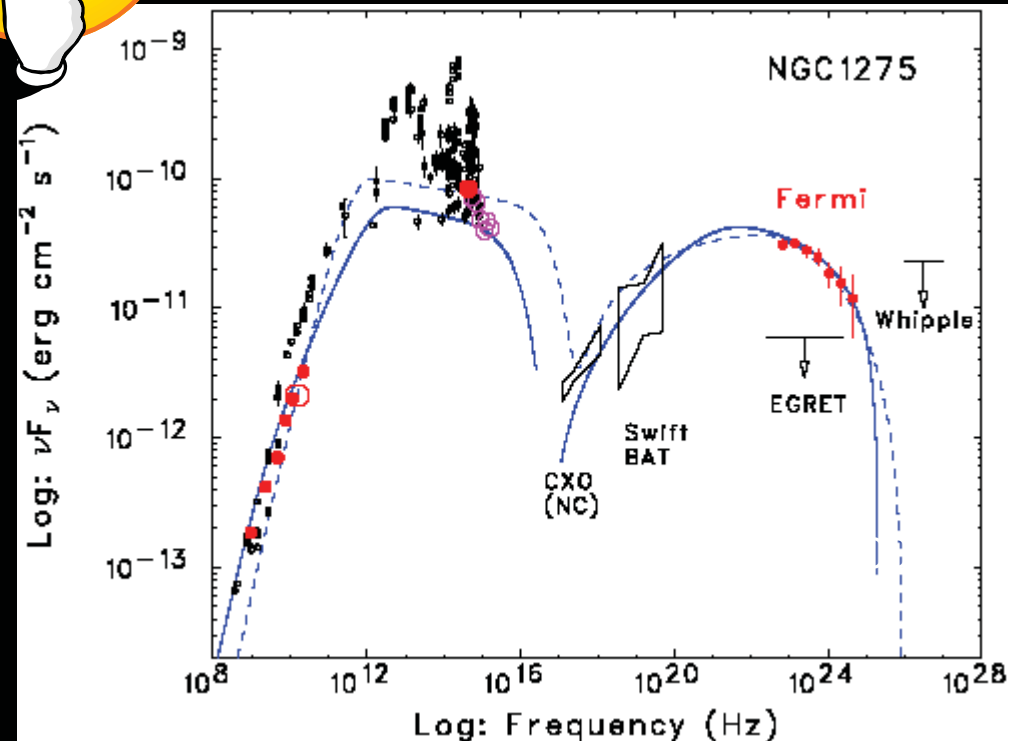
NGC 1275

- Blazar at ~75 Mpc (z=0.017)
- Detected in hard X-rays by *HEAO 1* (1977-1979)
- Not seen by *CGRO* (1991-2000)
- Monthly variations seen by LAT
- Best power-law spectral fit Γ=2.13
- Best fit cut-off power-law Γ=2.07 and E_C=42.2 GeV
- LAT power-law plotted
- Fits GBM data reasonably well
- Flux due to SSC (Abdo et al. 2009)
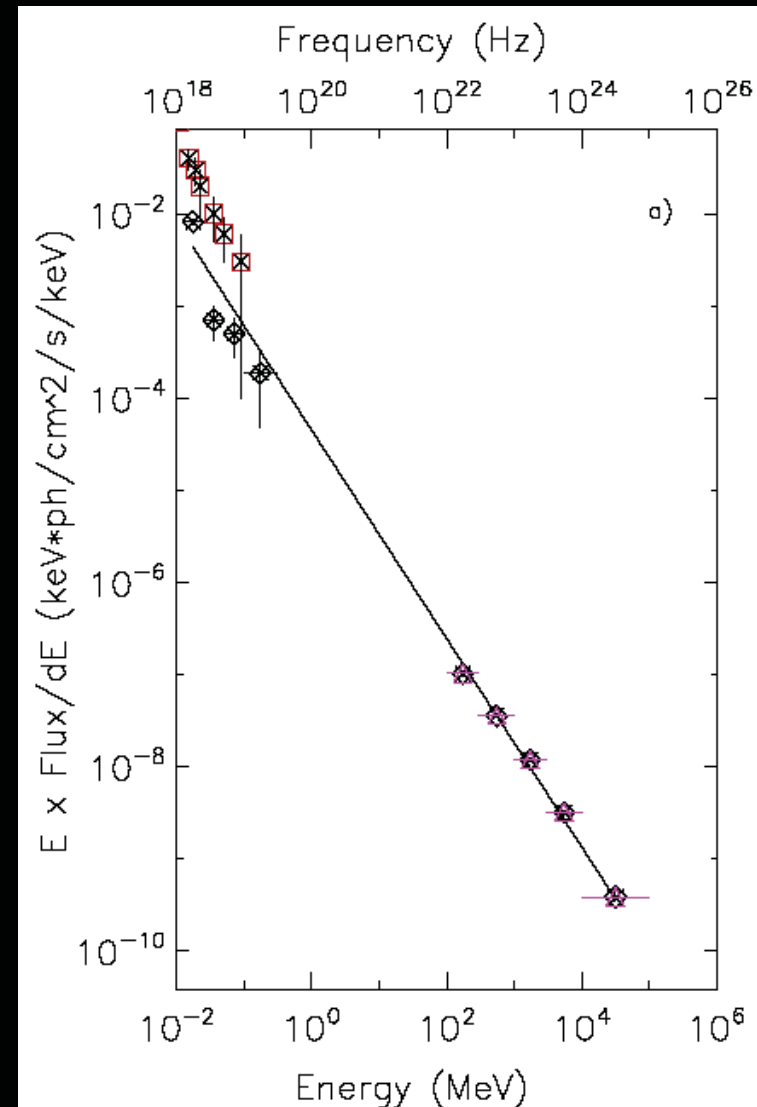
3C 273

- Quasar at ~700 Mpc (z=0.158)
- Spectral hardening >1 MeV
- Von Montigny et al. (1997) fit using SSC, EC, and PIC models
  - Best fit by PIC
  - Fit X-ray/ γ-ray data empirical model

  $$F(E) = N \frac{(E/E_B)^{-\Gamma_1}}{1 + (E/E_B)^{\Gamma_2}}$$

  - Plotted with Γ_1=0.7, Γ_2=0.8 and E_B=2.36 MeV
  - Consistent with data to ~10 GeV
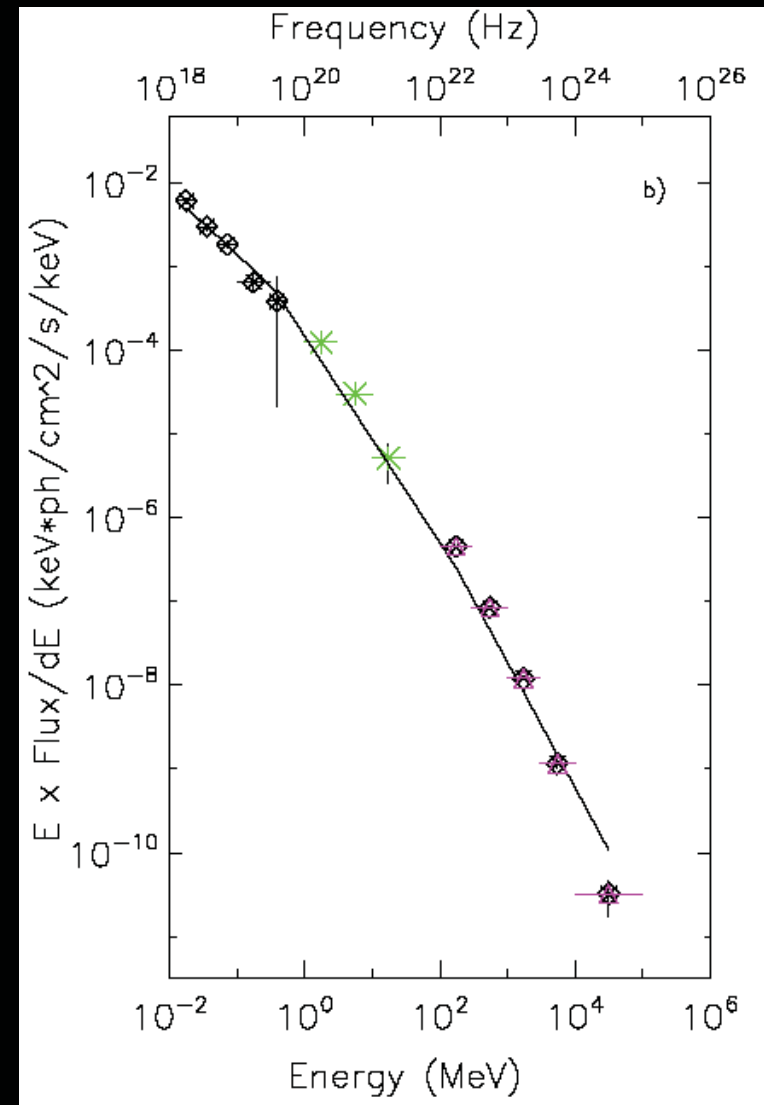
Cen A

- Radio galaxy at ~4 Mpc
- Seen from radio to TeV energies; UHE cosmic rays
- *CGRO* showed spectral variability of increasing break E as source brightens
- LAT fit radio to GeV γ-rays with SSC
- Reynoso et al. (2011) fit radio through TeV with model using e-synch, p-synch, and IC
- Reynoso et al. (2011) overplotted
- Consistent with data out to ~10 GeV
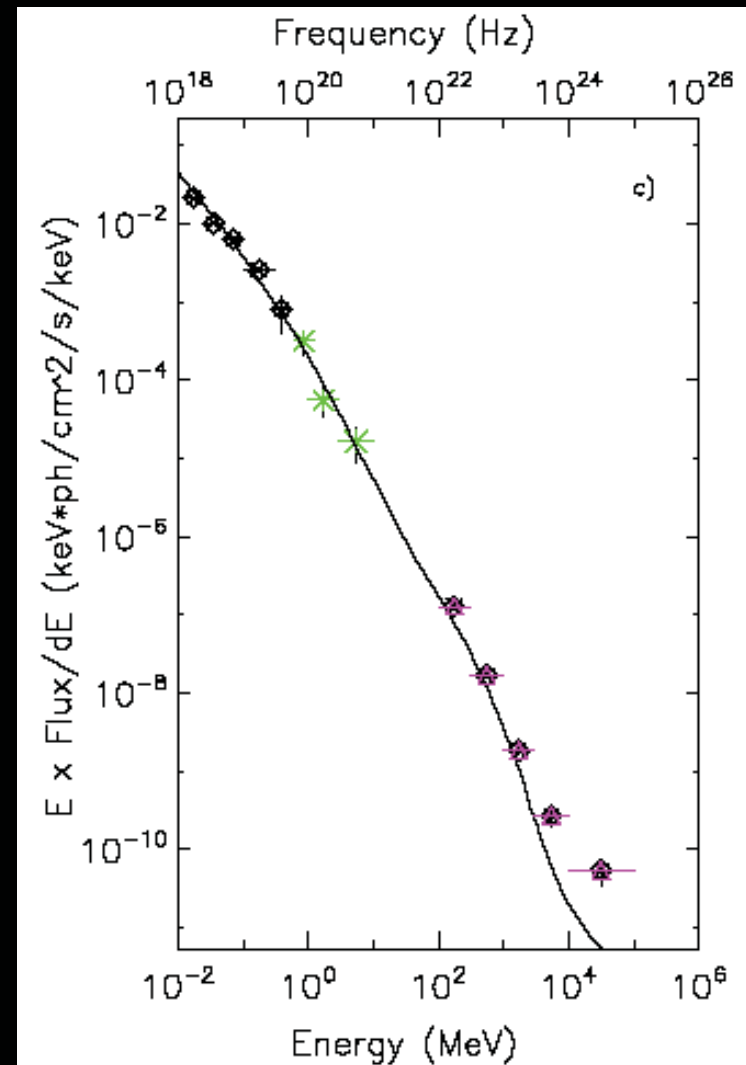
Crab

- Pulsar/PWN at ~2 kpc
- Emission to ~ 100 MeV from synchrotron
- E > 100 MeV from IC, SSC
- Dashed line from *INTEGRAL* with Γ_1=2.07, Γ_2=2.23 and break at 62 keV
- Solid line from GBM with Γ_1=2.06, Γ_2=2.36 and break at 98 keV
- GBM fit in very good agreement with LAT data
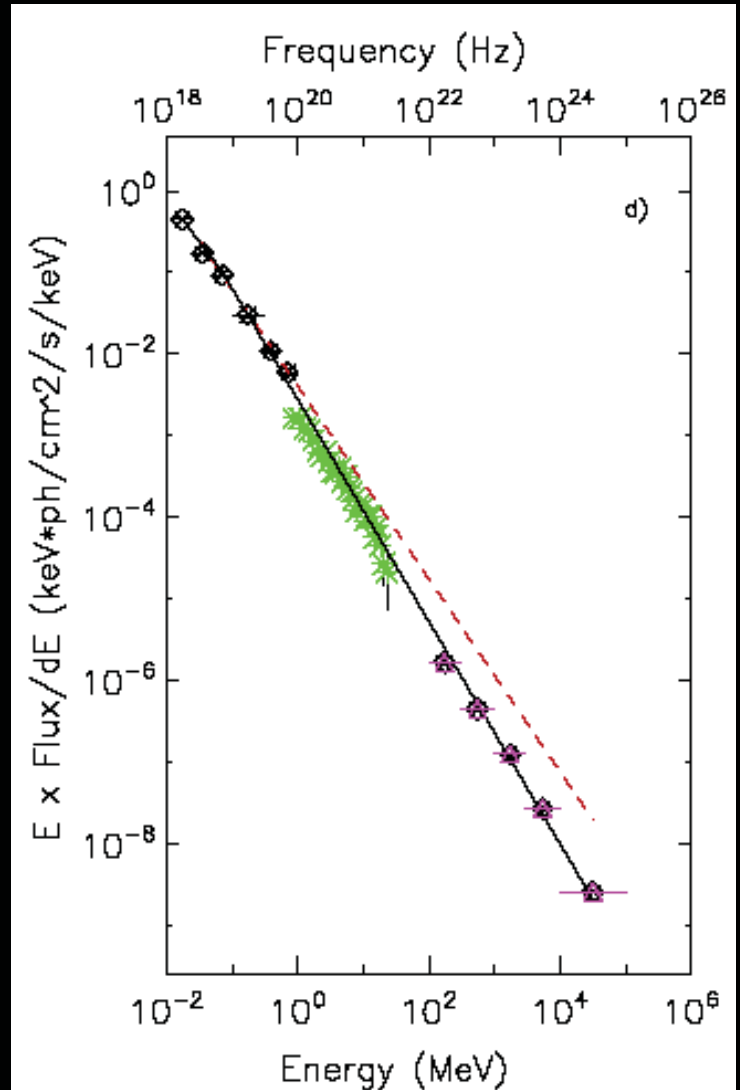
Transient Search

- Wide F.O.V. for frequent monitoring; can observe source during entire flare
- 1-day 3σ sensitivity in 12-25 keV ~150 mCrab
- Use sliding average to increase sensitivity in search
    - 5-day, 9-day, and 19-day binning
- Searched 12-50 keV, 50-100 keV, 100-300 keV, 300-500 keV bands
- Joined consecutive bins >3σ as 1 event
- Events with significance >7σ
- Computed significance above median flux; keeping >6σ

Search Results

- Searched 4 years light curves for all GBM sources
- Detected 168 transient events from 65 sources
  - 7 above 50 keV
  - 1 above 100 keV; XTE J1752-223
- Comparison to GBM flare database
  - Limited to database events at least 5 days
  - 280 events from 44 sources
    - Difference mainly due to periodic sources: SMC X-1, LMC X-4, Her X-1, and EXO 2030+375; > 100 missed detections
    - 72 just from SMC X-1 and LMC X-4; at low declination
  - 10 sources in database not in search; only 1 >6σ (X Per)

GK Per

- GBM flare avg flux ~51 mCrab; one of lowest detected from flare search
- Intermediate polar system
- Cooled mainly by thermal bremsstrahlung radiation
- Spectral blackbody fit give kT_e
- Able to estimate lower limit mass
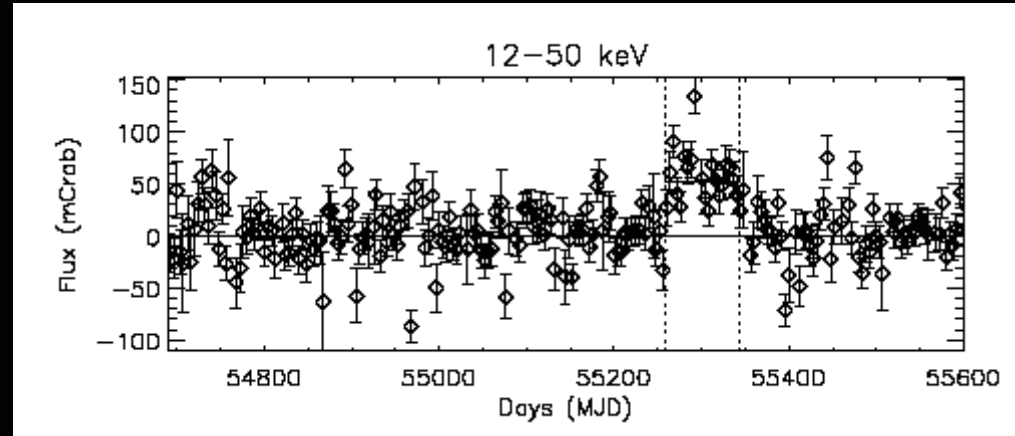
$$kT_e = \frac{3}{8}\frac{GM\mu m_p}{R} = 64\frac{M_1}{R_d},$$

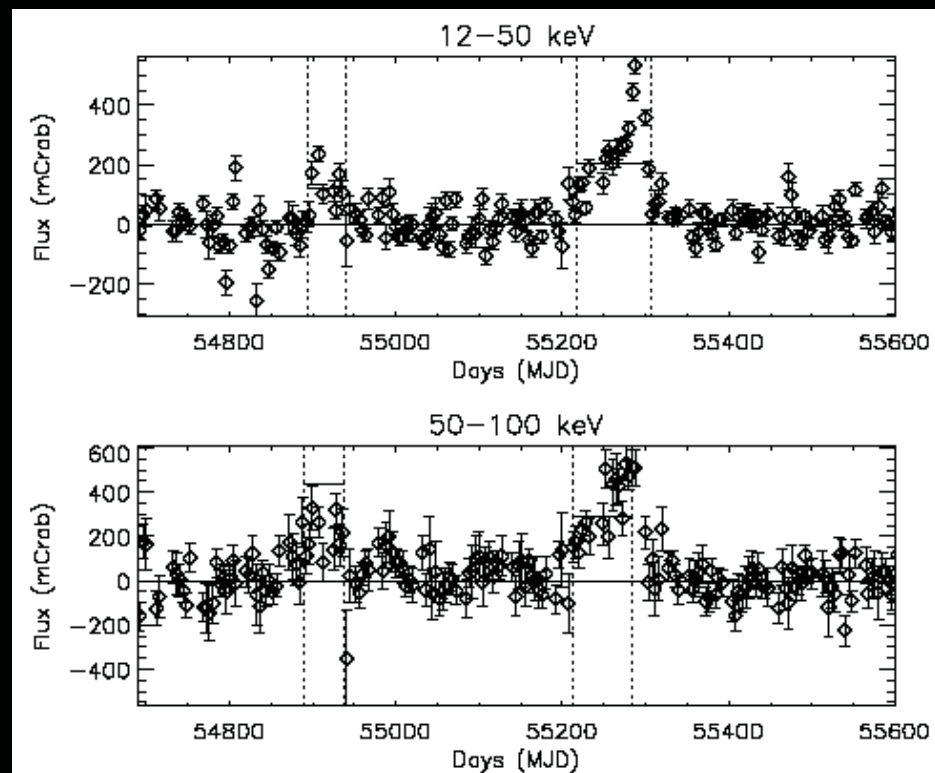$$M_1 = \sqrt{\frac{kT_e}{64}}.$$

GX 339-4

- Historically detected > 100 keV
- Including marginal detection, GBM observations of 2nd flare in good agreement with *INTEGRAL* observations
- In hard spectral state

$$F(E) = NE^{-\Gamma}e^{-E/E_C}$$

- Γ=1.69 and E_C=328 keV
- Emission mostly from IC by soft X-rays from corona
- OR from IC from base of jet
- Jet and corona models diverge > 100 keV

XTE J1752-223

- BHB discovered Oct. 23, 2009
- Due to solar constraints, GBM only instrument to cover duration of hard state
  - *RXTE* missed 2 months
  - INTEGRAL ~ 1 month
- *RXTE* observations shortly after outburst show hard state
  - $\Gamma=1.24$ and $E_C=133$ keV
- No available jet/corona models to compare
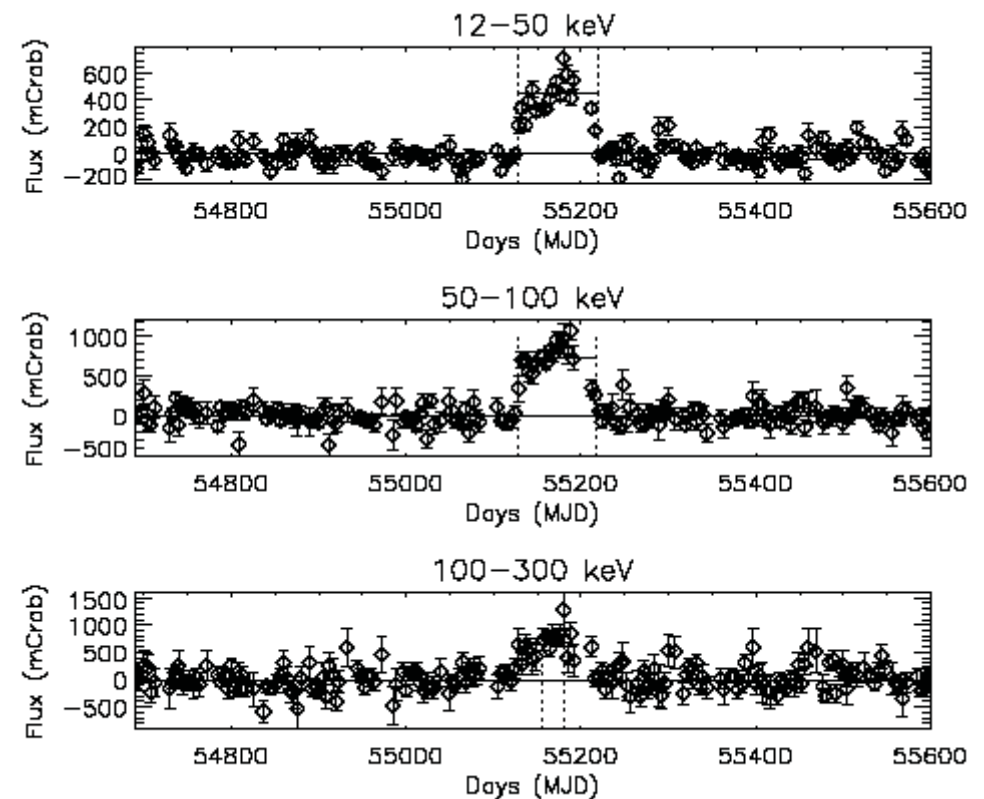
Conclusion

- EOT applied to GBM to monitor in hard X-ray/soft γ-rays
- All-sky imaging with IDEOM for
  - ~4 years of data in 3 energy bands
  - ~45 sources detected
  - 16 added to GBM catalog added by cross-correlating with other catalogs
  - Position accuracy ~0.5°
  - No additional sources detected > 100 keV so likely EBOP background inaccurate
- Spectral analysis of GBM-LAT sources (NGC 1275, 3C 273, Cen A, Crab) show data consistent with models from lit.
- Transient search
  - In 4 years 168 events from 65 sources; 7 >50 keV; 1 > 100 keV (XTE J1752-223)
  - Able to detect flares down to ~ 50 mCrab
  - No solar constraints enable important observations (XTE J1752-223)
  - High energy capability help to distinguish between jet and corona BHB models

Systematic Errors

- Occultation Limb Geometry
  - Occ. time corresponds to arc along Earth's limb
  - If unmodeled source occults at the same time can cause inaccurate fluxes
  - Projection of Earth's limb on sky repeats ~ 53 days creating periodic errors
  - Add newly discovered transients to catalog (BAT/MAXI)
  - Imaging with IDEOM to look for sources
- Nearby Sources
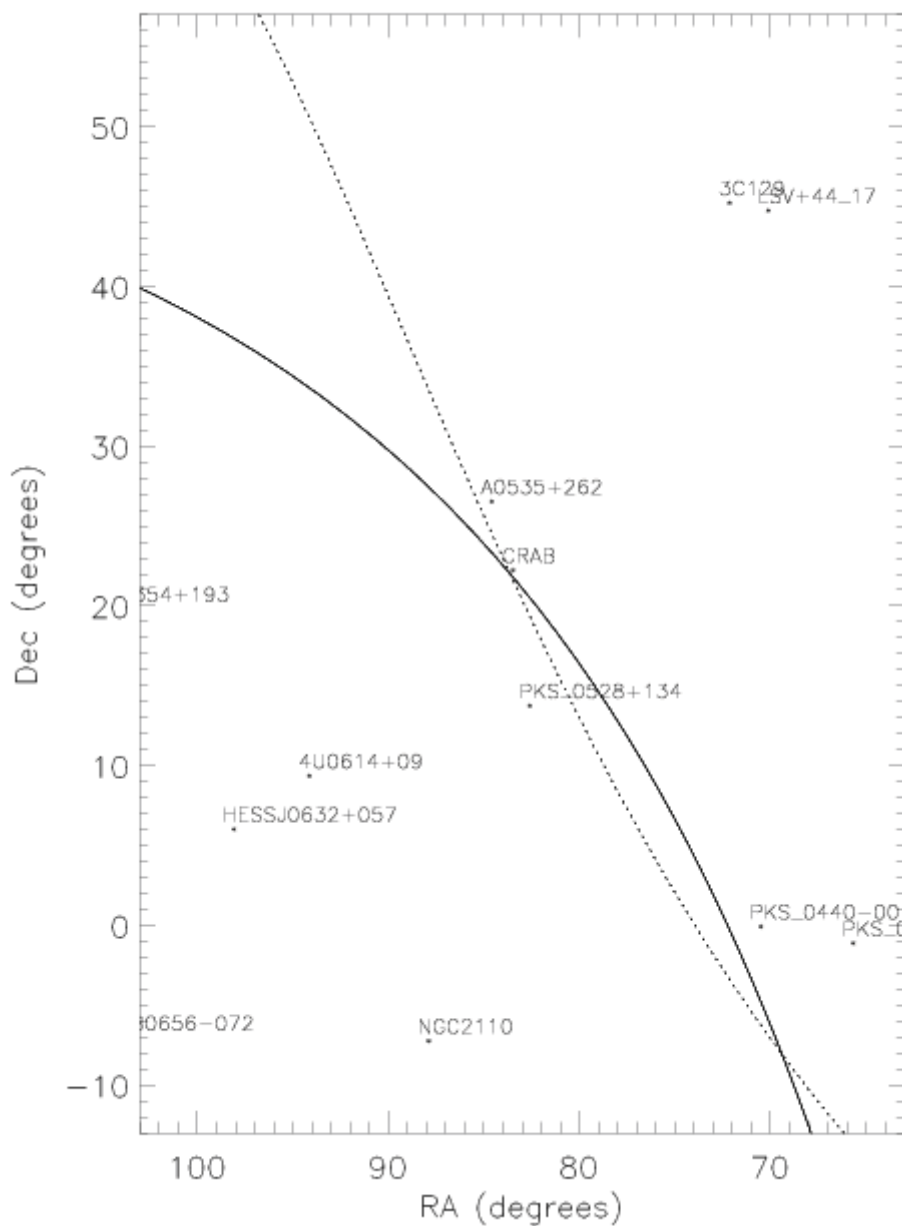 - Unable to properly assign flux when known sources occult within ~8 sec of each other
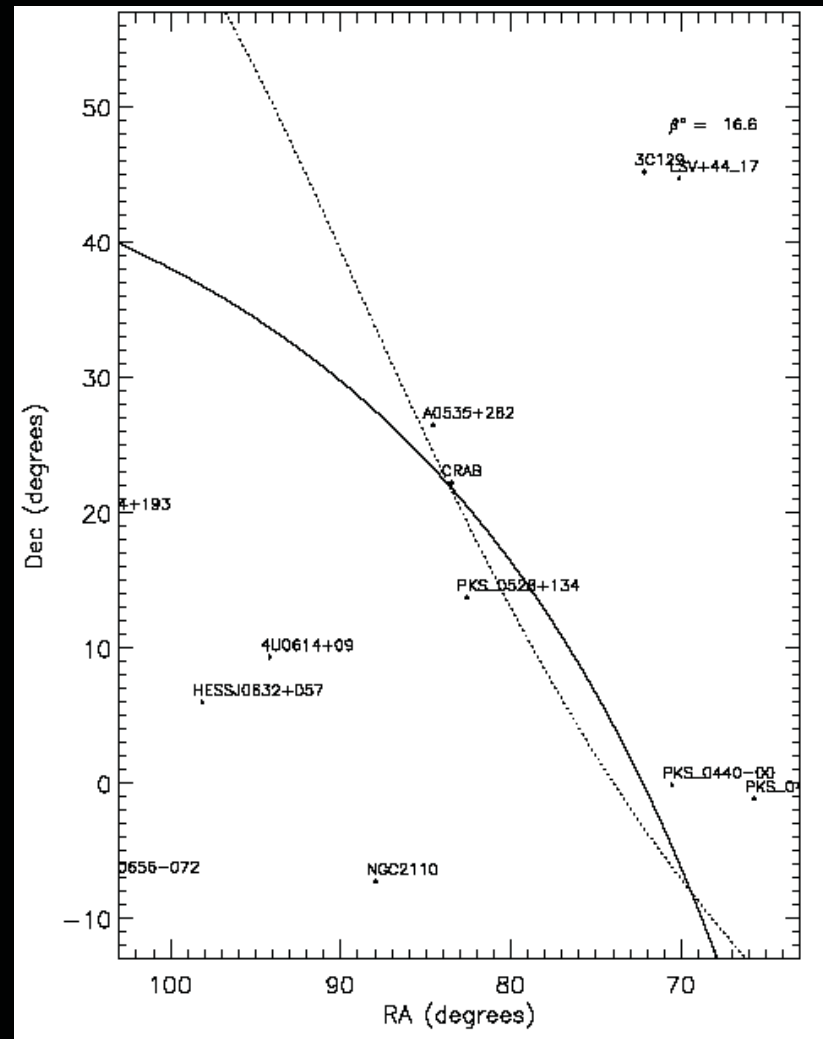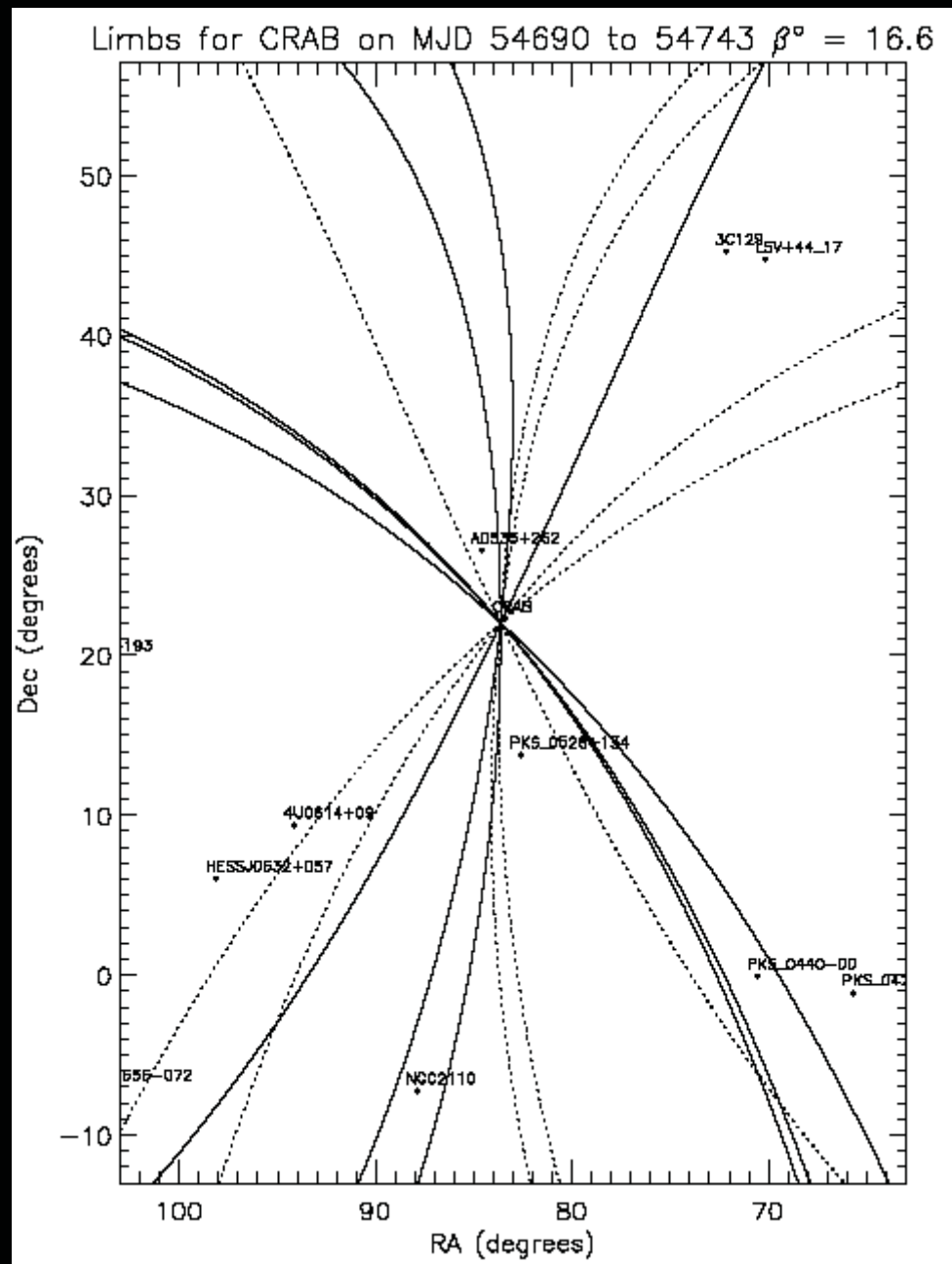
Limbs for CRAB on MJD 54690 to 54743 $\beta^\circ = 16.6$

Limbs for CRAB on MJD 54690 to 54743 β° = 16.6
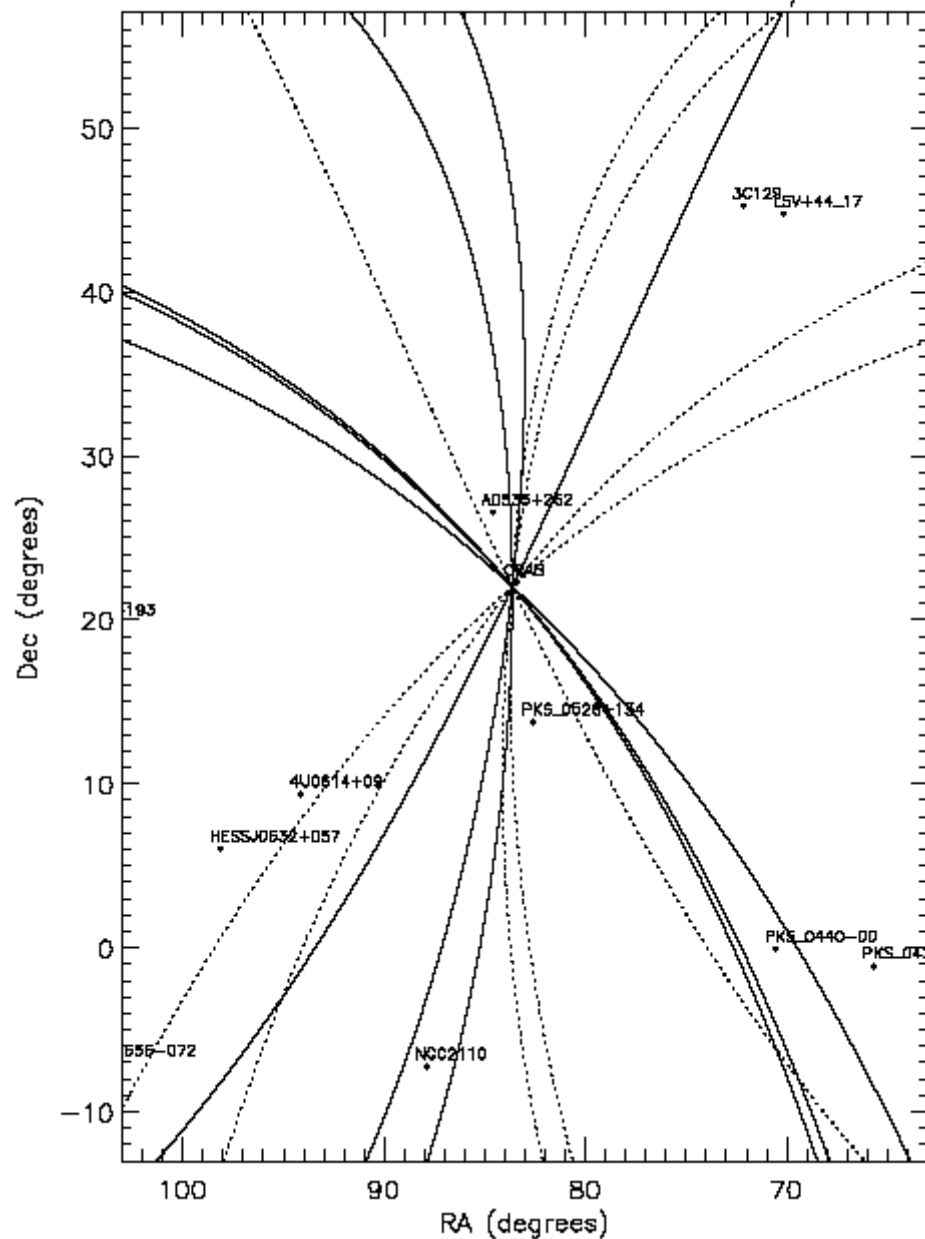
Limbs for CRAB on MJD 54690.0 to 54690.0

Previous Imaging with Earth Occultation

- Occultation transform imaging (Zhang et al. 1993,94,95)
  - Reconstructs projection data using inverse linear Radon transform; used in CT scans and medical tomography
  - Uses Maximum Entropy Method (MEM) to locate sources
  - Able to image 20-300 keV
  - 30° x 30° regions along GP looking for transients
  - Limited to small regions of sky where limb approx. linear
  - Doesn't account for bright sources outside f.o.v

- Likelihood Imaging Method for BATSE Occultation data (LIMBO) (Shaw et al. 2004)
  - Predetermined grid of positions
  - Background subtract data
  - Pass through differential filter
  - Calculate likelihood flux due to a location compared to null result
  - Able to image entire sky, ~ 500 days in 25-160 keV
  - Limited by 2° separation of grid
  - Only single energy range

Fermi
Gamma-ray Burst Monitor

http://heastro.phys.lsu.edu/gbm/