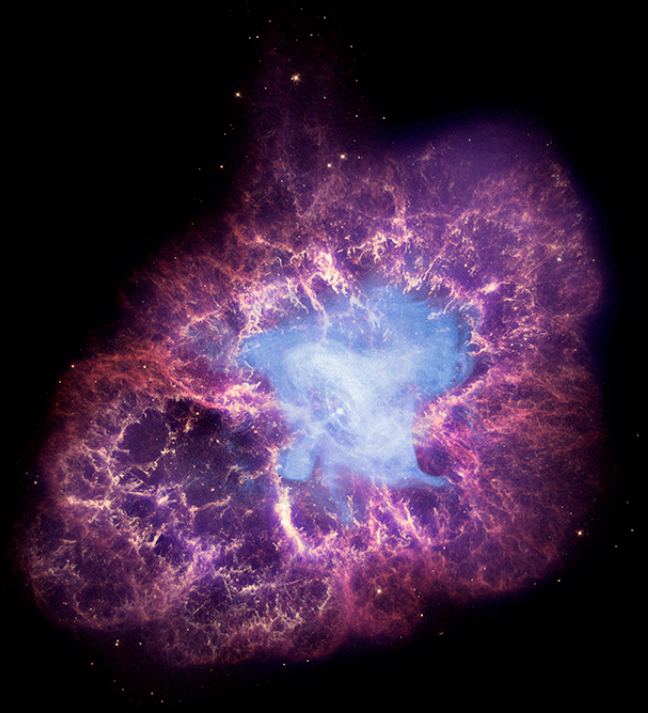
The Crab Nebula - variability and flares from keV to TeV

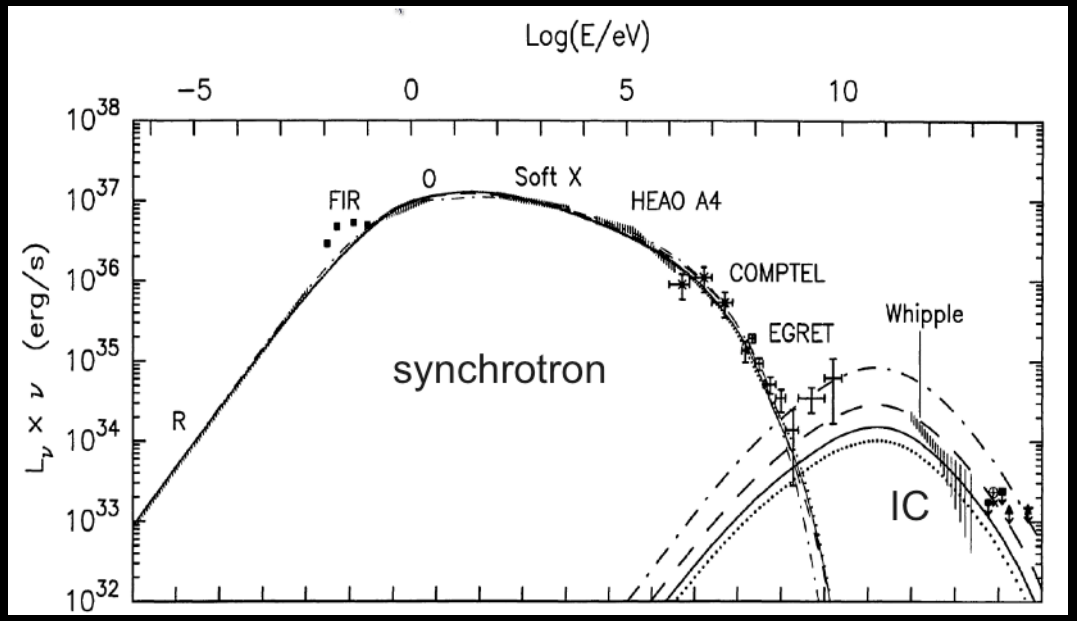
Colleen A. Wilson-Hodge (NASA/MSFC)

Outline

- Introduction
- Year-scale variability of the Crab (8-500 keV)
- Hours to Day-scale high energy flaring from the Crab (>100 MeV)
- Summary & Conclusions

Introduction

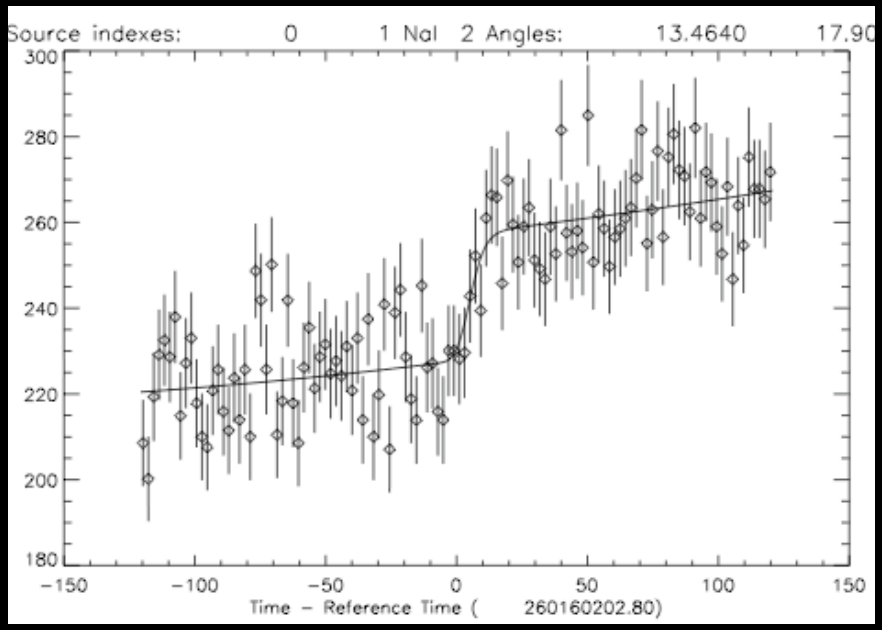




- 1054 AD Supernova at 2 kpc
- Consists of a pulsar, pulsar wind nebula, and a cloud of expanding ejecta
- Energy spectrum: synchrotron & inverse Compton components

GBM Earth Occultation Technique

- Current catalog includes 107 sources, primarily recently active X-ray binaries, the Crab, 5 AGNs, 2 SGRs, and the Sun
- Fluxes for cataloged sources measured by fitting the change in count rate due to Earth occultation
- Source model: assumed spectrum convolved with changing detector response and atmospheric transmission
- 8 energy bands in NaI or BGO detectors
- 6 persistent and 2 transient sources detected above 100 keV; 50+ sources detected <100 keV. (Case et al. 2011, ApJ 729, 105)

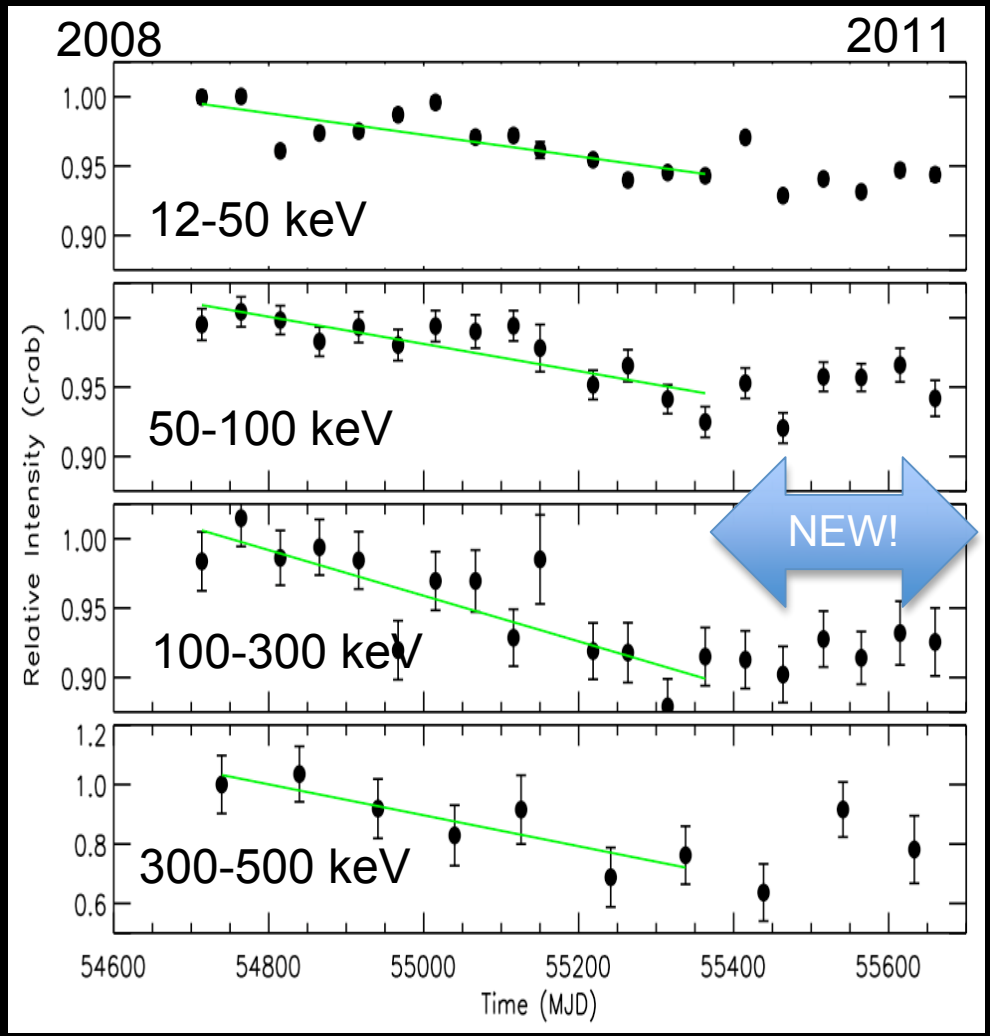


- Over 85% of sky viewed every orbit
- Entire sky viewed every ~26 days
- Sensitivity exceeds CGRO/BATSE below 25 keV and above ~1 MeV
- No solar constraints

See posters #80,82, & 64 by Cherry et al., Case et al., & Rodi et al.

GBM Observations of the Crab Nebula

- 50-day averages
- Nebula + pulsar (~10%)
- Decline in Crab flux (MJD 54690-55390):
  - 5.4 ± 0.4% 12-50 keV
  - 6.6 ± 1.0% 50-100 keV
  - 12 ± 2% 100-300 keV
  - 39 ± 12% 300-500 keV
- No changes in GBM response or calibration
- Flattening since summer 2010

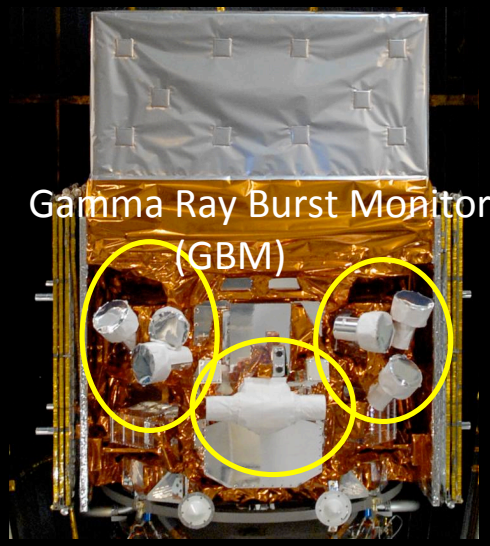


Wilson-Hodge et al. 2011, ApJ, 727, L40

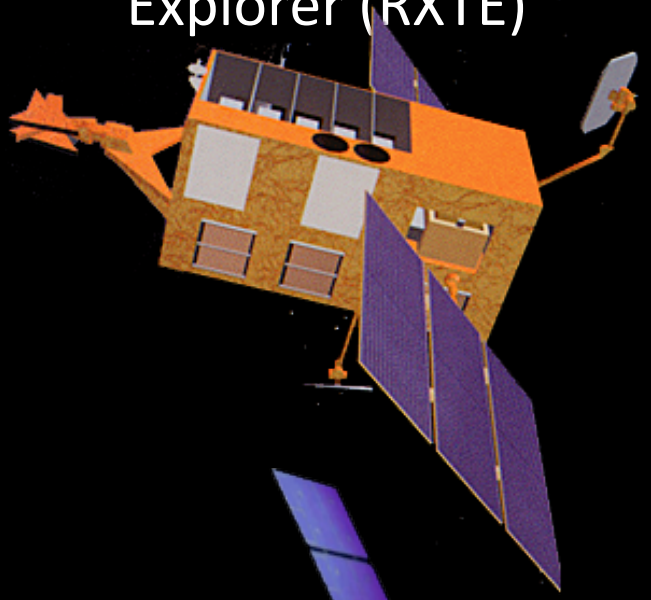
The Satellites

- Good overlap with GBM in time and energy
- GBM
  - 2008 - present
  - 8 keV - 40 MeV
- INTEGRAL
  - 2002 - present
  - JEM-X 3-35 keV
  - IBIS/ISGRI 15keV-10MeV
- RXTE
  - 1995-present
  - PCA 2-60 keV
- Swift
  - 2004-present
  - BAT 15-200 keV

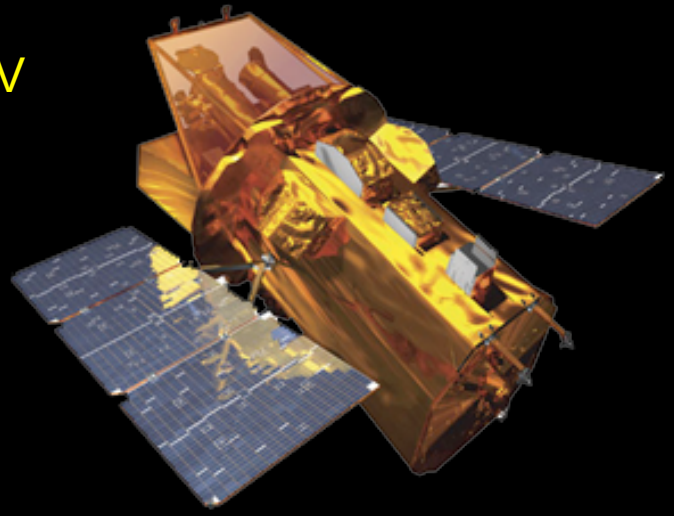
Fermi



Rossi X-ray Timing Explorer (RXTE)



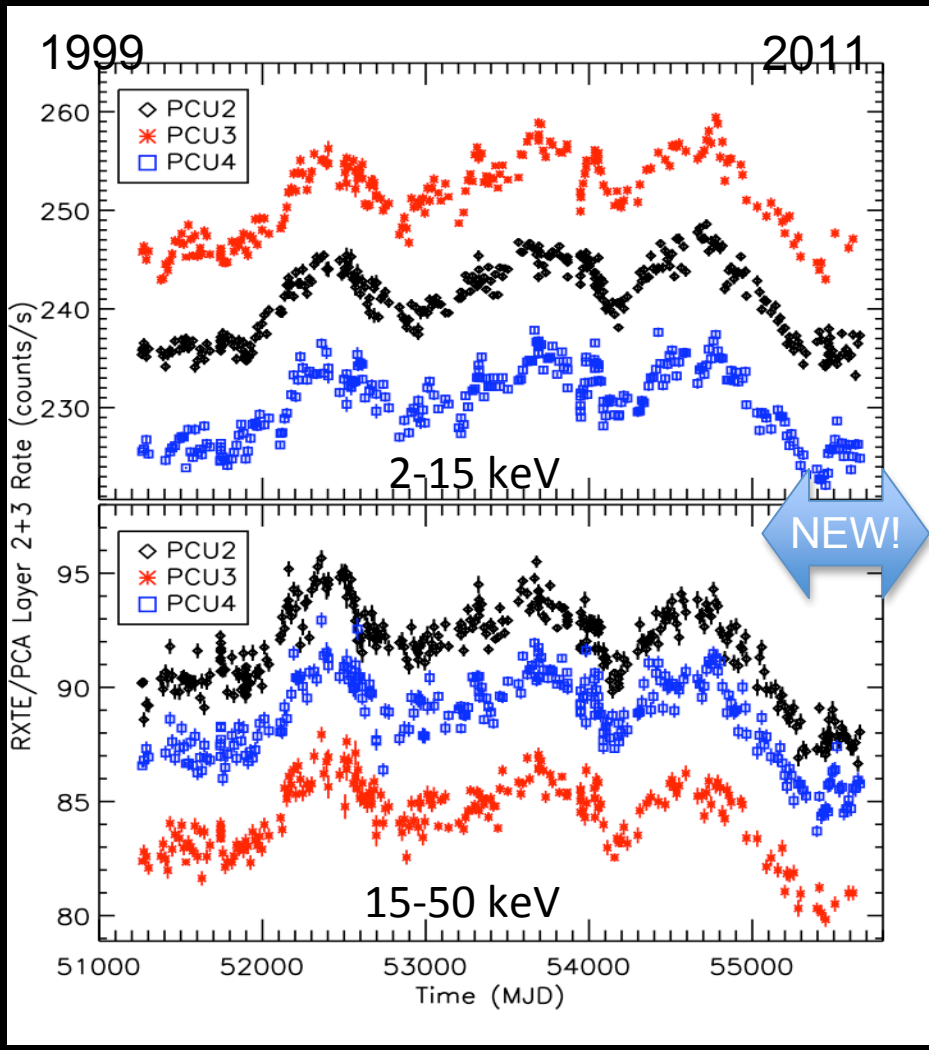
Swift



INTErnational Gamma Ray Astrophysics Laboratory (INTEGRAL)

RXTE PCA Crab Light Curve

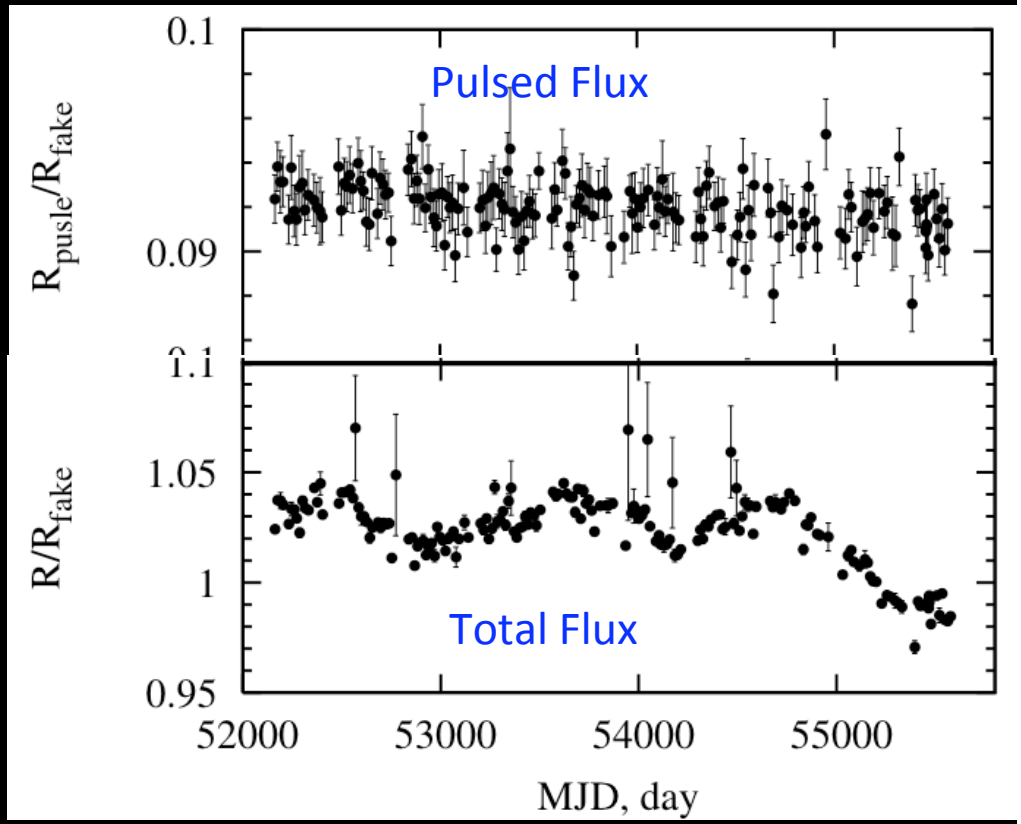
- Standard 2 data
- Layers 2+3
- Background subtracted & dead-time corrected
- Corrected for known time dependence of response
- Variations of
  - 5.1±0.2% (2-15 keV)
  - 6.8±0.3% (15-50 keV)
  - MJD 54690-55435 in all 3 PCUs
- Flattening/increase since summer 2010
- Nebula+pulsar(~10%)



Wilson-Hodge et al. 2011, ApJ, 727, L40

RXTE Crab Pulsed Flux

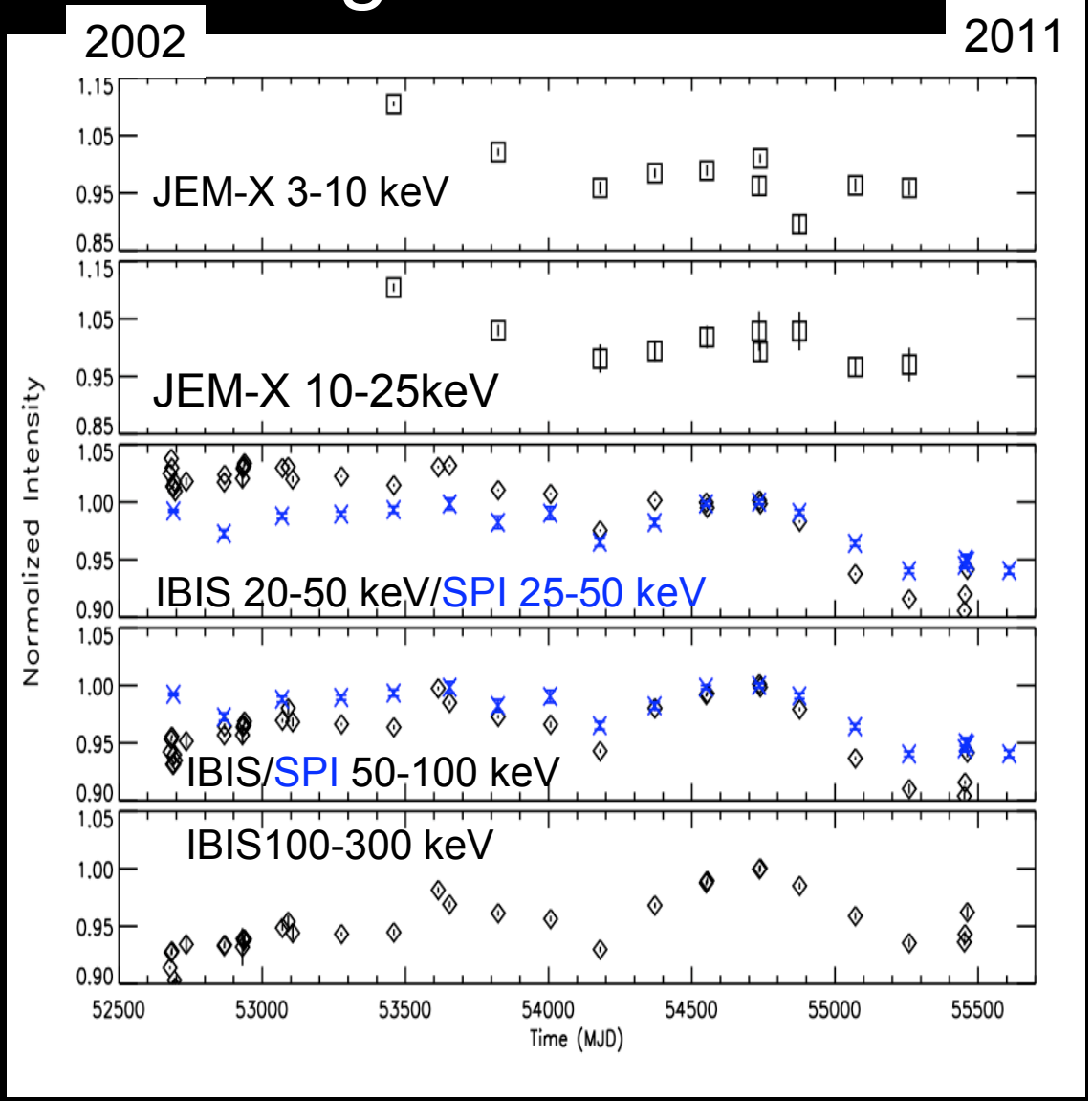
- Event mode data (250μs, 129 channel)
- 3.2-35 keV, all PCU2 layers
- Pulsed flux shows steady decrease at 0.2% per year – consistent with pulsar spin down.
- The larger ~3.5% per year variation is not seen in pulsed emission
- Likely has nebular origin



Wilson-Hodge et al. 2011, ApJ, 727, L40

INTEGRAL Crab Light Curves

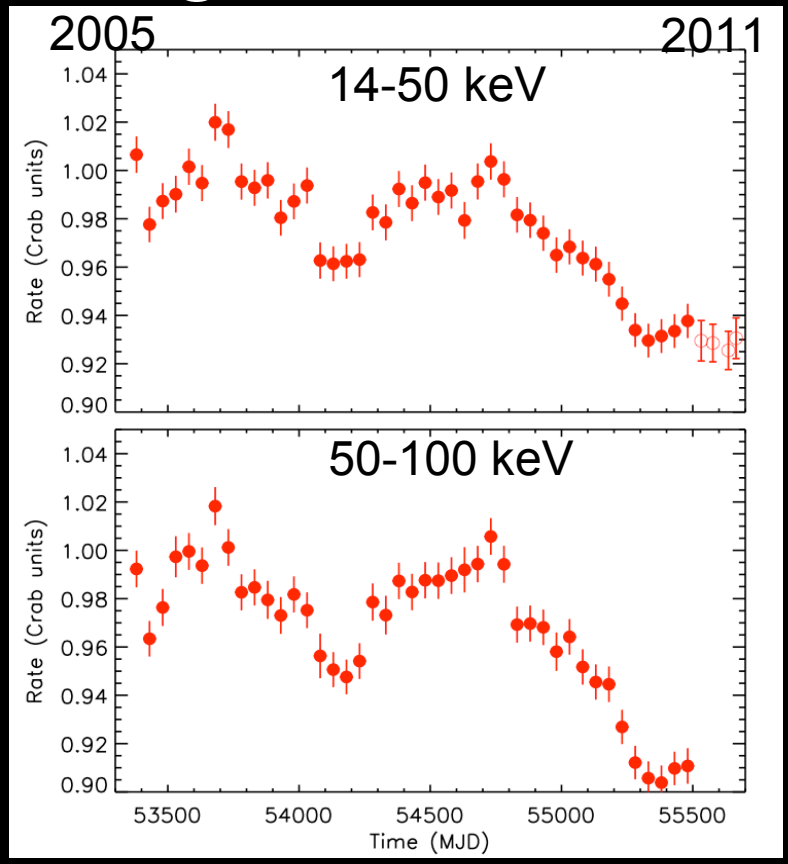
- Publicly available Crab observations
- Produced using OSA 9.0
- Offset <10° (ISGRI); < 3°(JEM-X)
- Corrections based upon constant Crab are omitted.
- ~8% decline is seen in the 20-50 and 50-100 keV bands (MJD 54690-55340)
- Possible upturn after 55340
- Nebula+pulsar(~10%)



Wilson-Hodge et al. 2011, ApJ, 727, L40

Swift BAT Survey: 14-100 keV Crab Light Curves

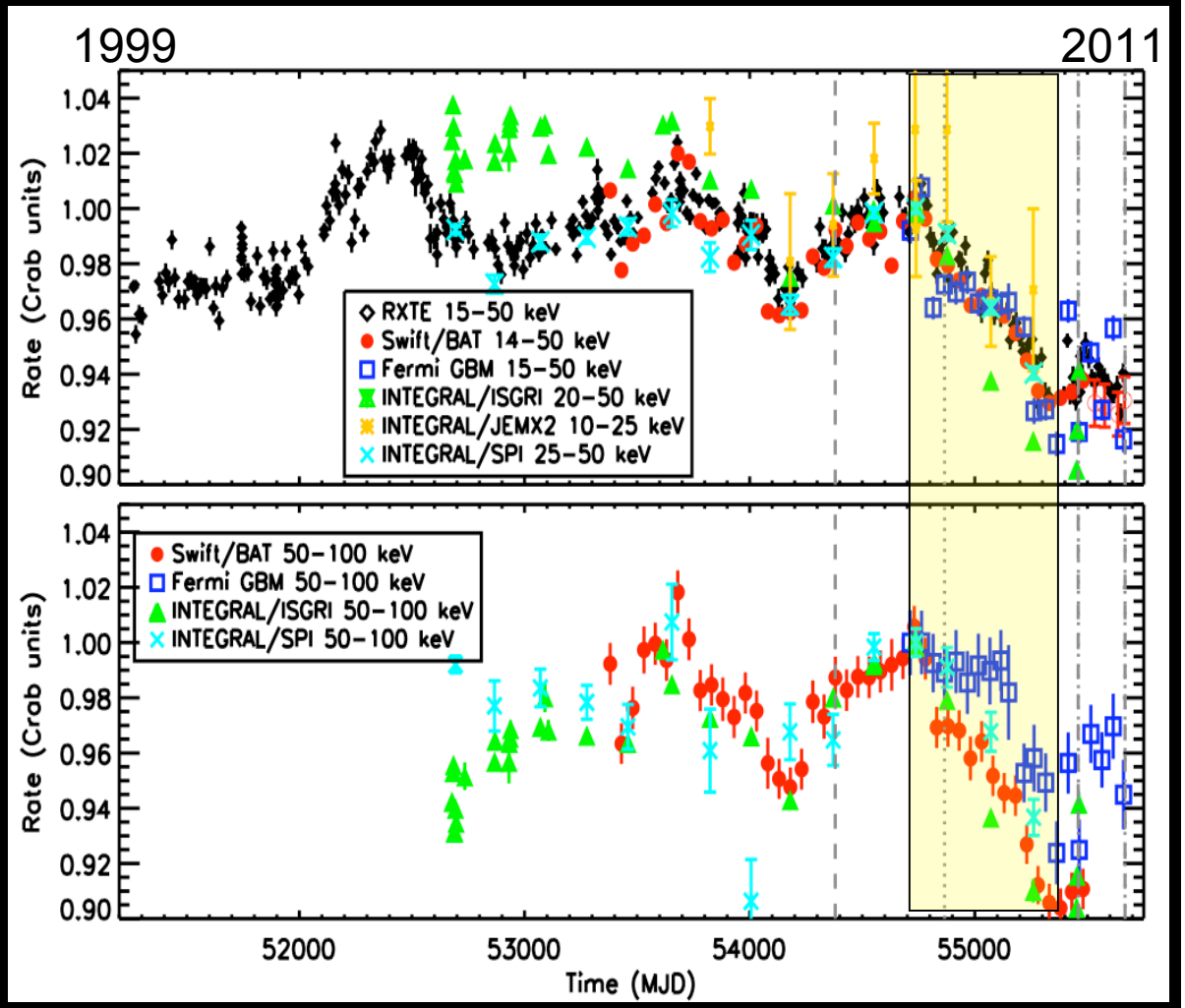
- BAT team extended Survey to Sep 2010
- Transient monitor Sep 2010-Jan 2011
- Points shown are ~50 day averages
- Constructed from single pointing light curves
- Restricted partial coding fractions to >85%
- Included systematic error of 0.75% of the rate
- Nebula + pulsar (10%)



14-50 keV Flux decline of 6.2±0.5% observed during MJD 54690-55340

Comparing Instruments

- Light curves for each instrument are normalized to its average rate from MJD 54690-54790.
- RXTE/PCU2 - Black
- BAT - Red
- IBIS/ISGRI - Green
- JEM X2 - orange
- SPI - Light blue
- GBM - Blue squares
- Instruments on four separate spacecraft show ~7% decline in Crab (nebula+pulsar) flux from summer 2008 to summer 2010.

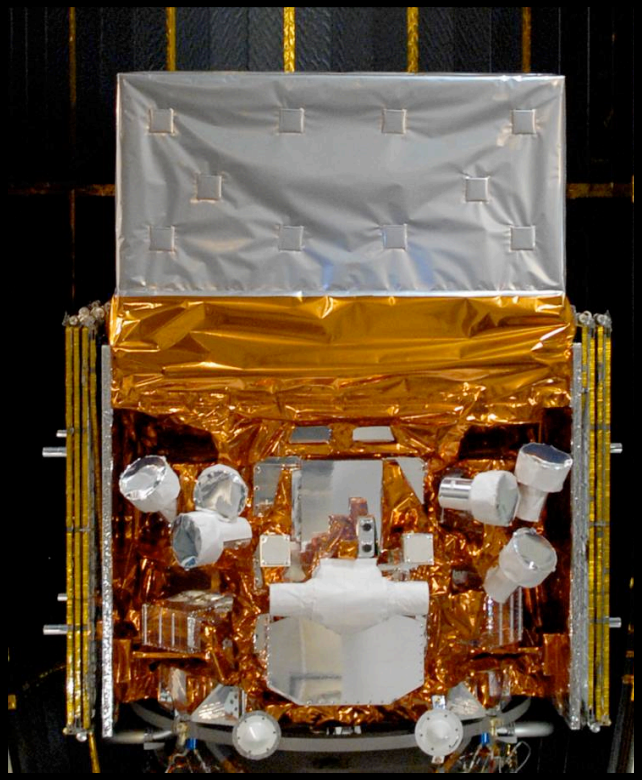


Recent data since summer 2010 suggest the decline has flattened or has begun to recover.

Summary - keV Variability

- The Crab Nebula shows a ~7% (70 mCrab) flux decline (~15-50 keV) from 2008-2010.
  - Decline observed with Fermi/GBM, INTEGRAL/IBIS, JEM-X, & SPI, RXTE/PCA, & Swift/BAT
  - No unexpected decline in pulsed flux, implying nebular origin
- Variations of ~3.5% per year (1999-2008) on a ~3 year timescale in 15-50 keV flux
- Recent data show flattening or possible upturn

High Energy Observations



- Fermi Large Area Telescope (LAT)
- 20 MeV - 300 GeV
- 2.4 steradian field-of-view
- Launched June 11, 2008

Atwood et al. 2009, ApJ, 697, 1102

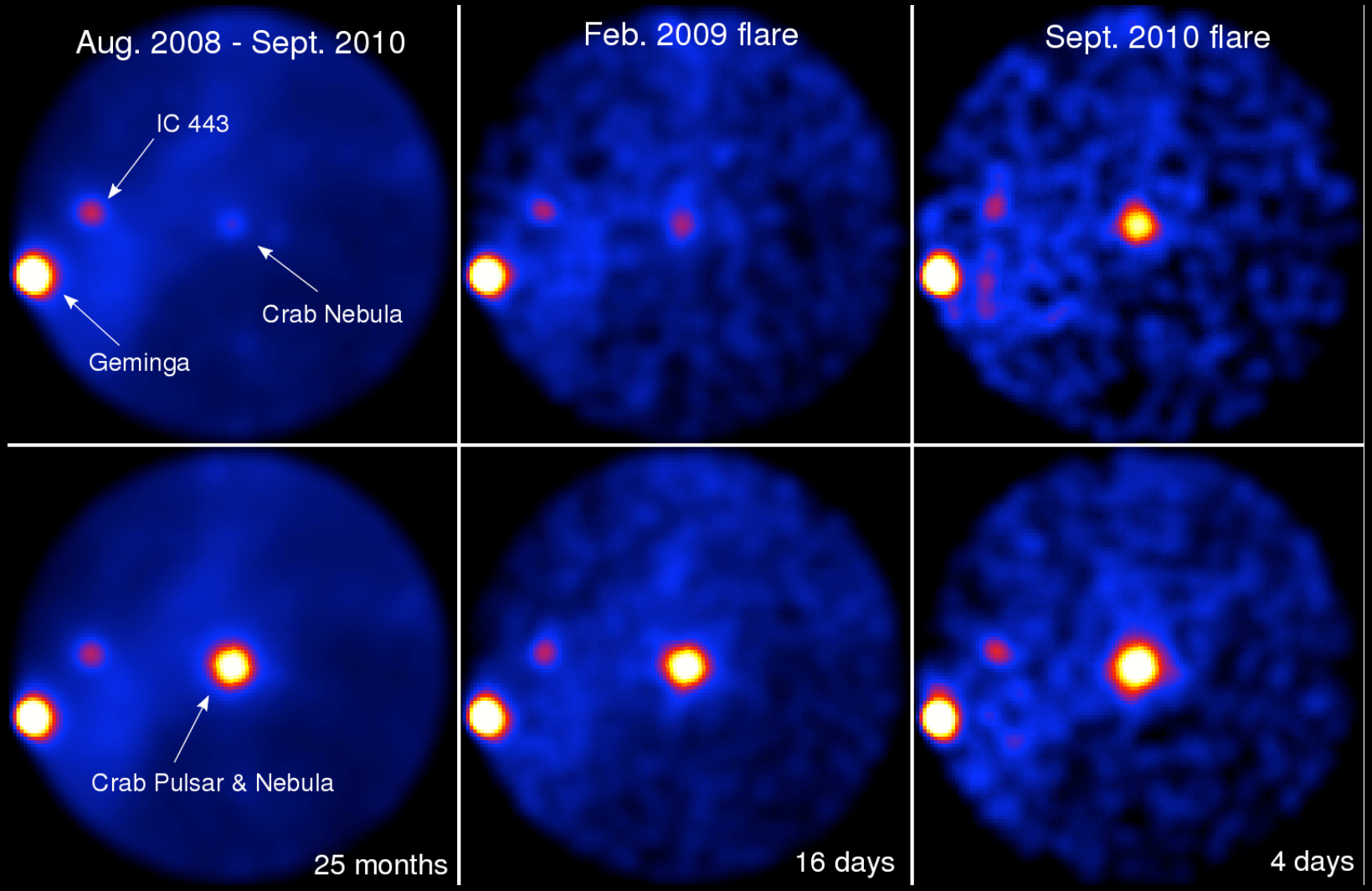
AGILE (ASI)

- AGILE
- 30 MeV - 50 GeV
- 2.5 steradian field-of-view
- About 1/16 of LAT area
- Launched April 23, 2007

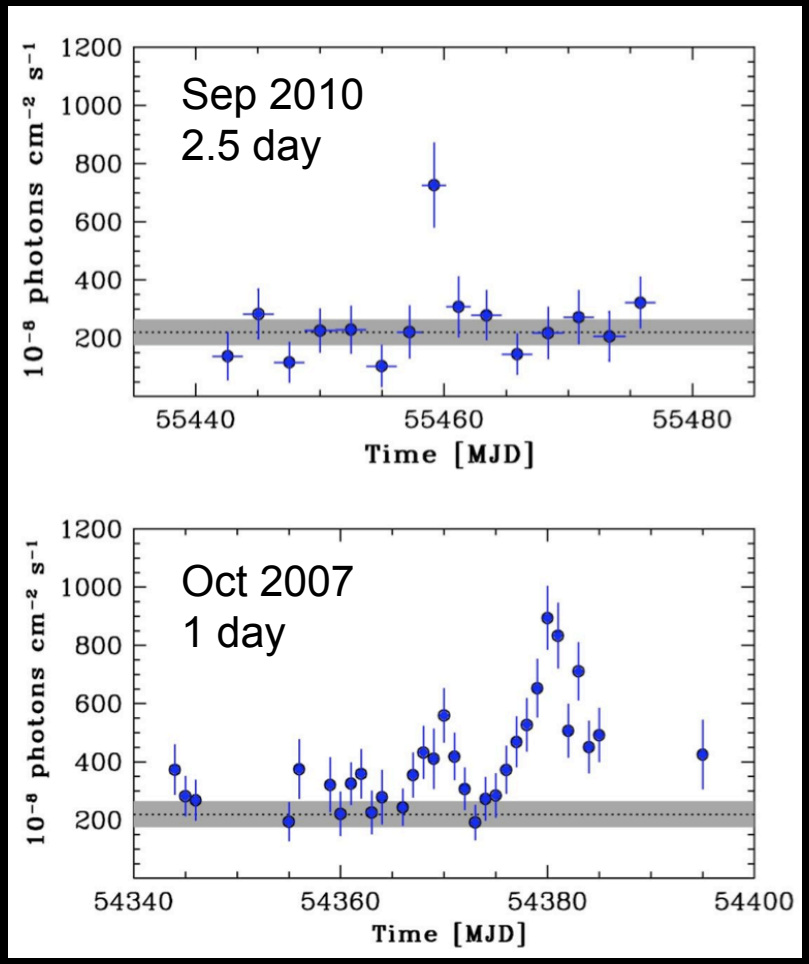
Tavani et al. 2009, A&A, 502, 995

Not from the pulsar!

Top row shows off-pulse phases only.



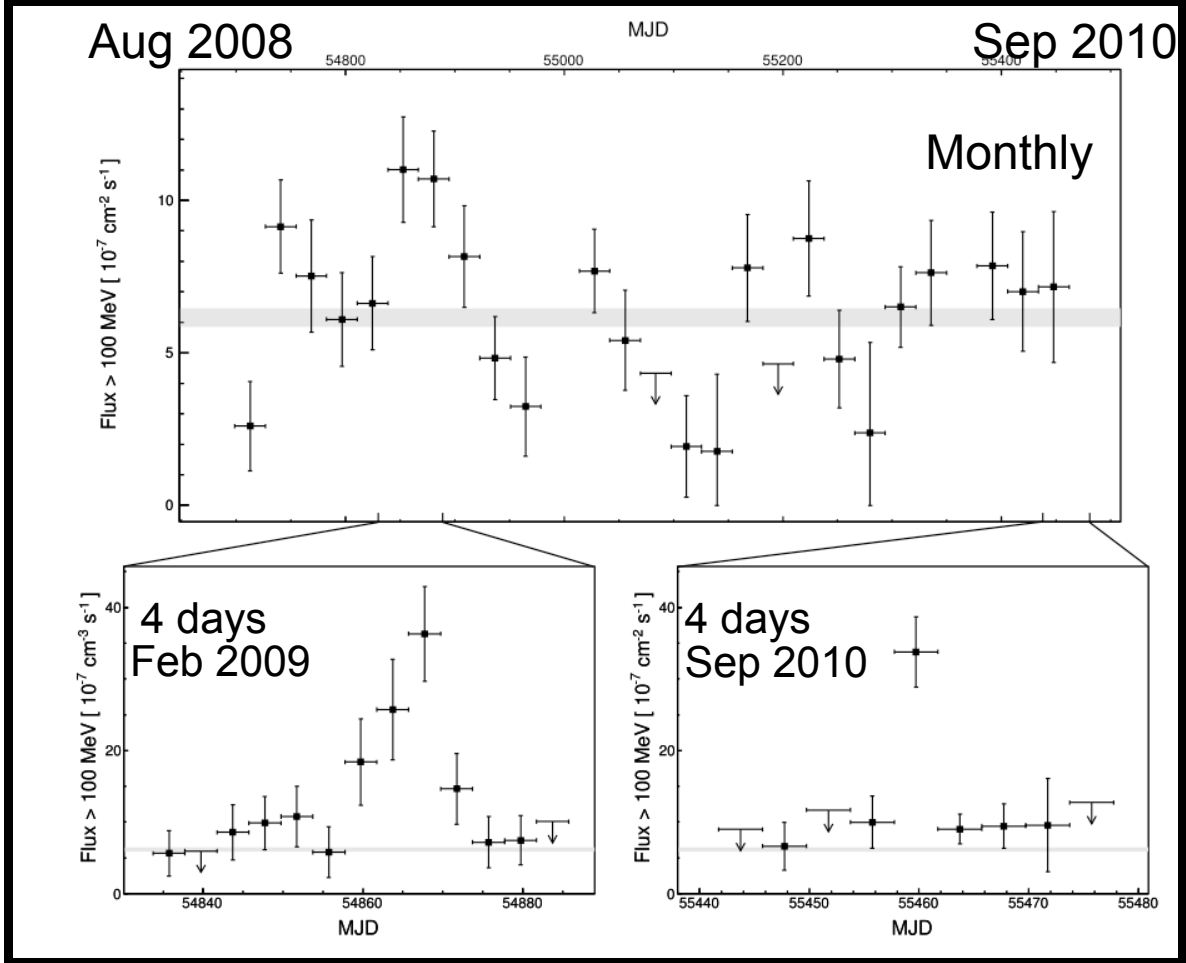
High Energy Crab Flares Observed with AGILE



Tavani et al. 2011, Science, 331, 736
Pulsar + Nebula flux

- September 19-21, 2010
  - Un-pulsed flux increased by factor of ~ 3 (100 MeV-5 GeV)
  - Photon index 2.03±0.18
- October 2007
  - Two week long flare
  - Un-pulsed flux increased by factor of ~3 (100 MeV-5 GeV)
  - Photon index 2.05±0.13
- Typical Crab
  - Flux psr+nebula 2.2×10^{-6} cm^{-2} s^{-1} (100 MeV-5 GeV)
  - Photon index 2.13±0.07
- Poster #150 - Striani et al.

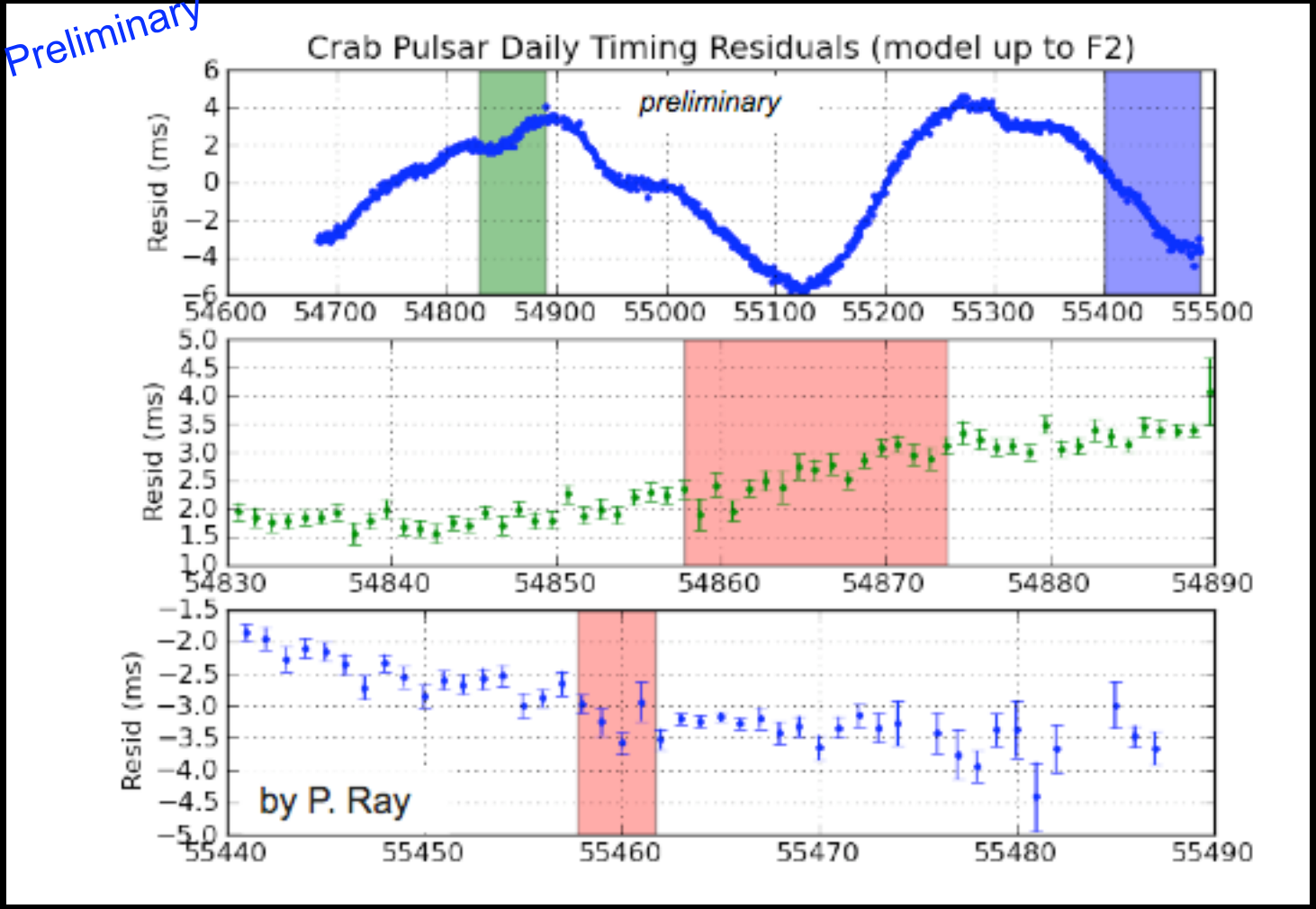
High Energy Crab Flares observed with Fermi LAT



Nebula flux: off-pulse phase only
Abdo et al. 2011, Science, 331, 739

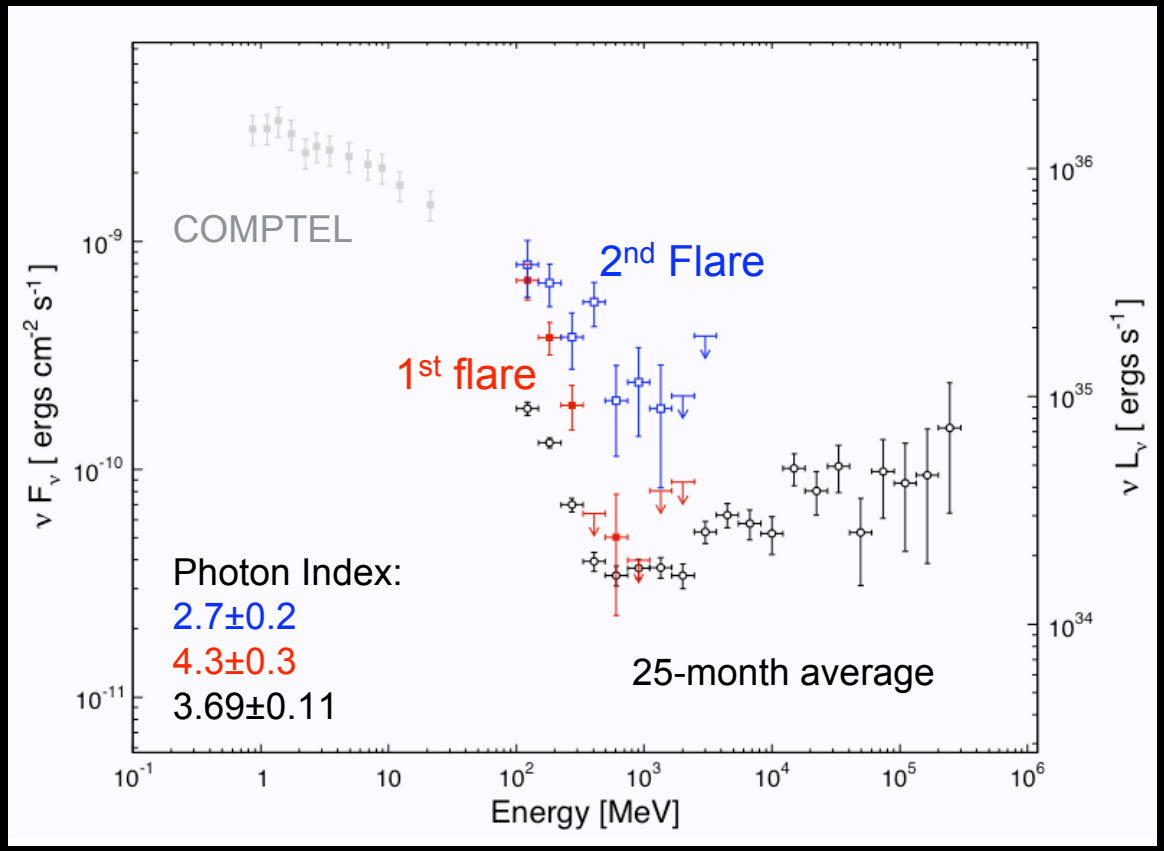
- Monthly variations
- Two flares
  - Flux increase by factor ~4 during ~16 days (26 Jan to 11 Feb, 2009)
  - Flux increase by factor ~6 during ~4 days (18 to 22 Sep 2010)
  - ~12 hr variability in 2010 September flare (Poster #125 Balbo et al.)

Fermi LAT Crab Pulsar Timing



- Nothing unusual during flares in timing residuals
- Pulsar light curve constant to within 5%

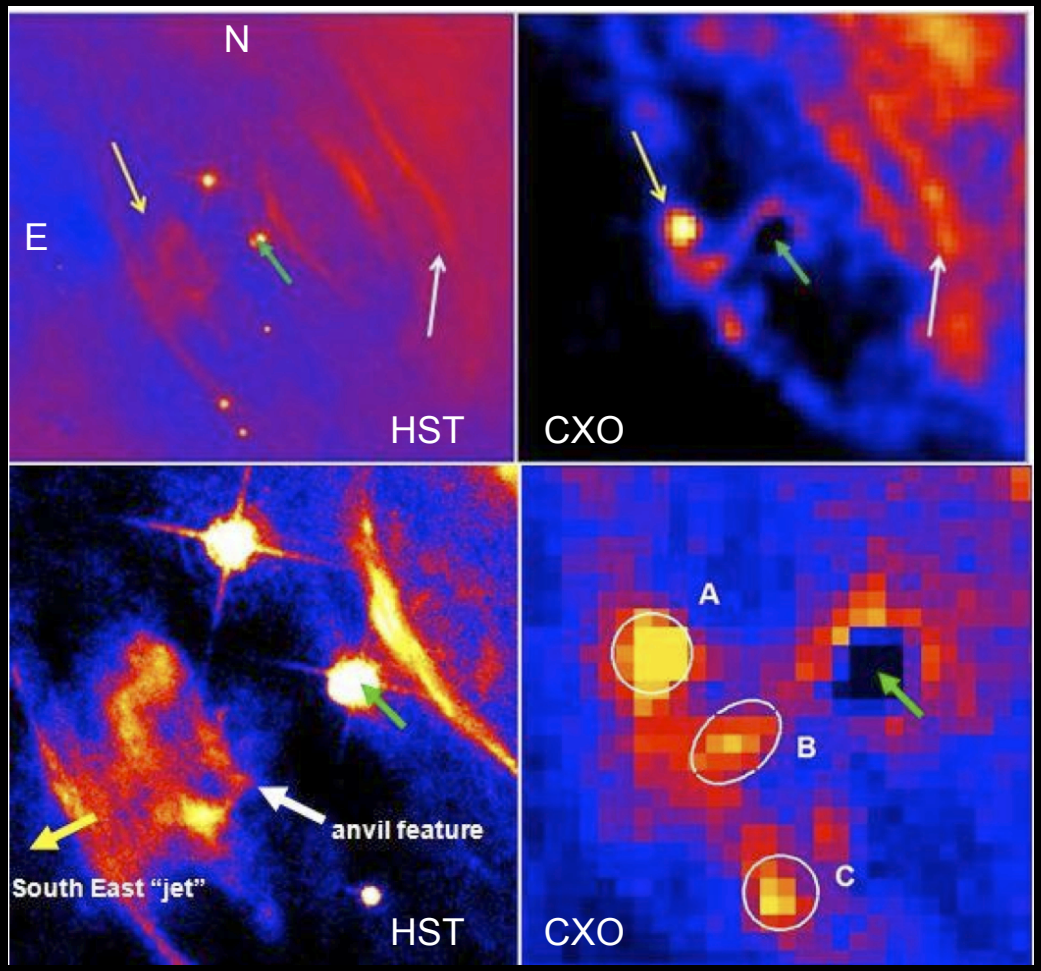
Fermi LAT Spectra for 1st two flares



Abdo et al. 2011, Science, 331, 739

- Second flare has hard spectrum and extends >1 GeV at >3σ
- Energy release small compared to pulsar spin-down ~5×10^{38} erg s^{-1}
- No variation (<5%) IC nebula component

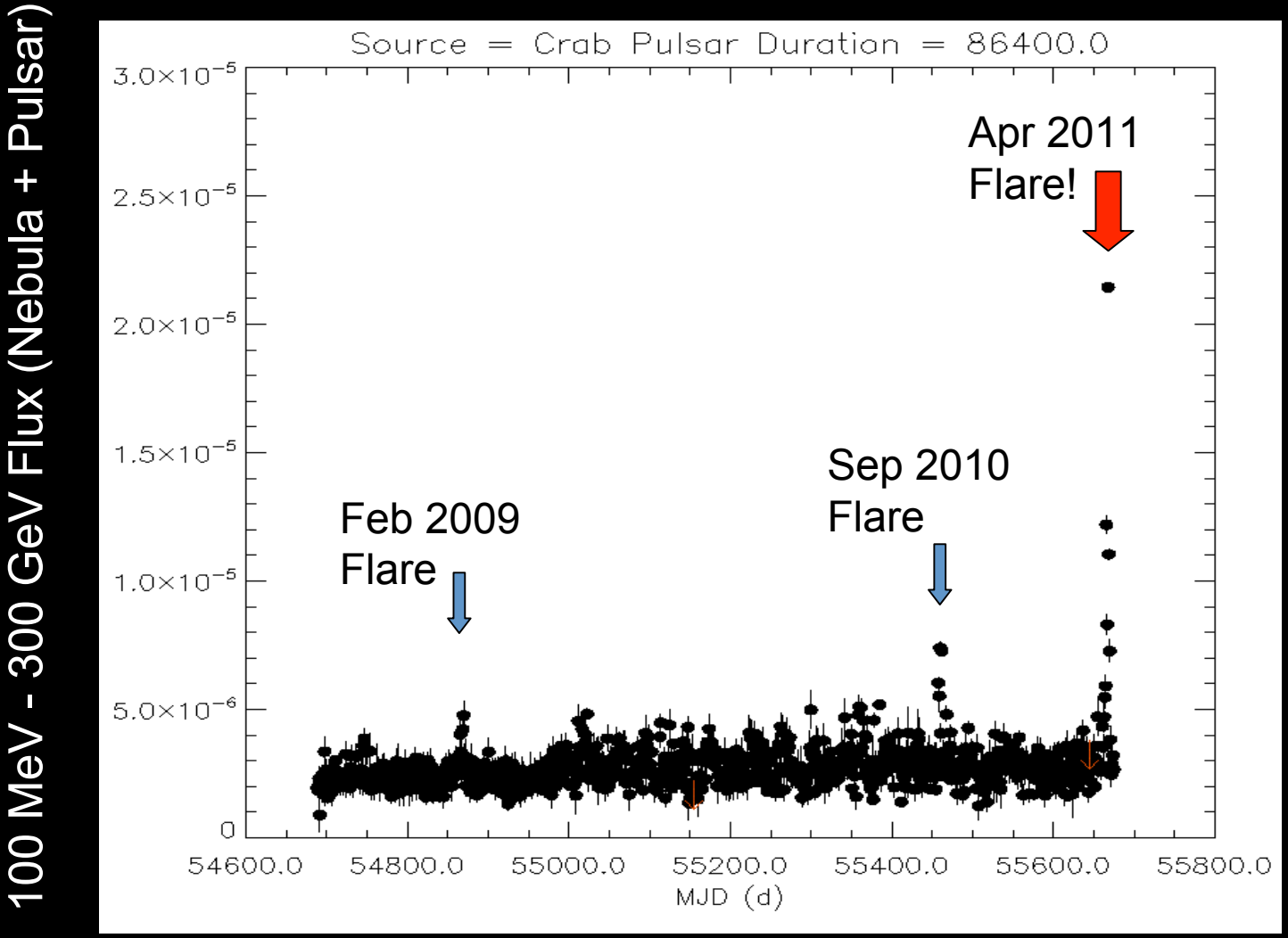
Where are the flares occurring?



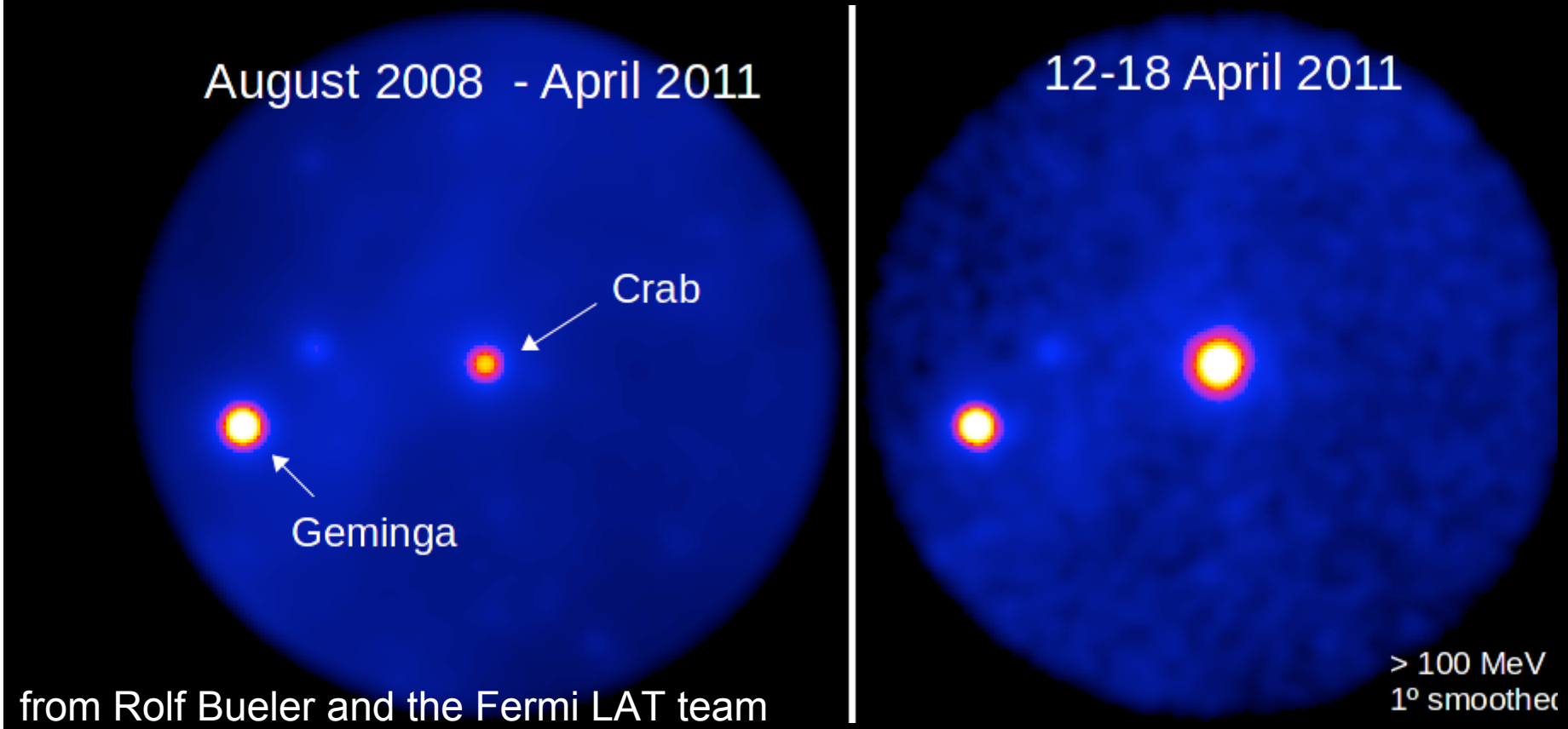
- HST ACS
  - Oct 2, 2010 (3500-11000 Å)
  - 28"×28"
- Chandra ACIS
  - Sep 28, 2010 (0.5-8 keV)
- 4-day flare implies region <1.5"
- April 2011 Flare variability implies <0.04" region !

Tavani et al. 2011, Science, 331, 736

Fermi LAT Daily Crab Light Curve



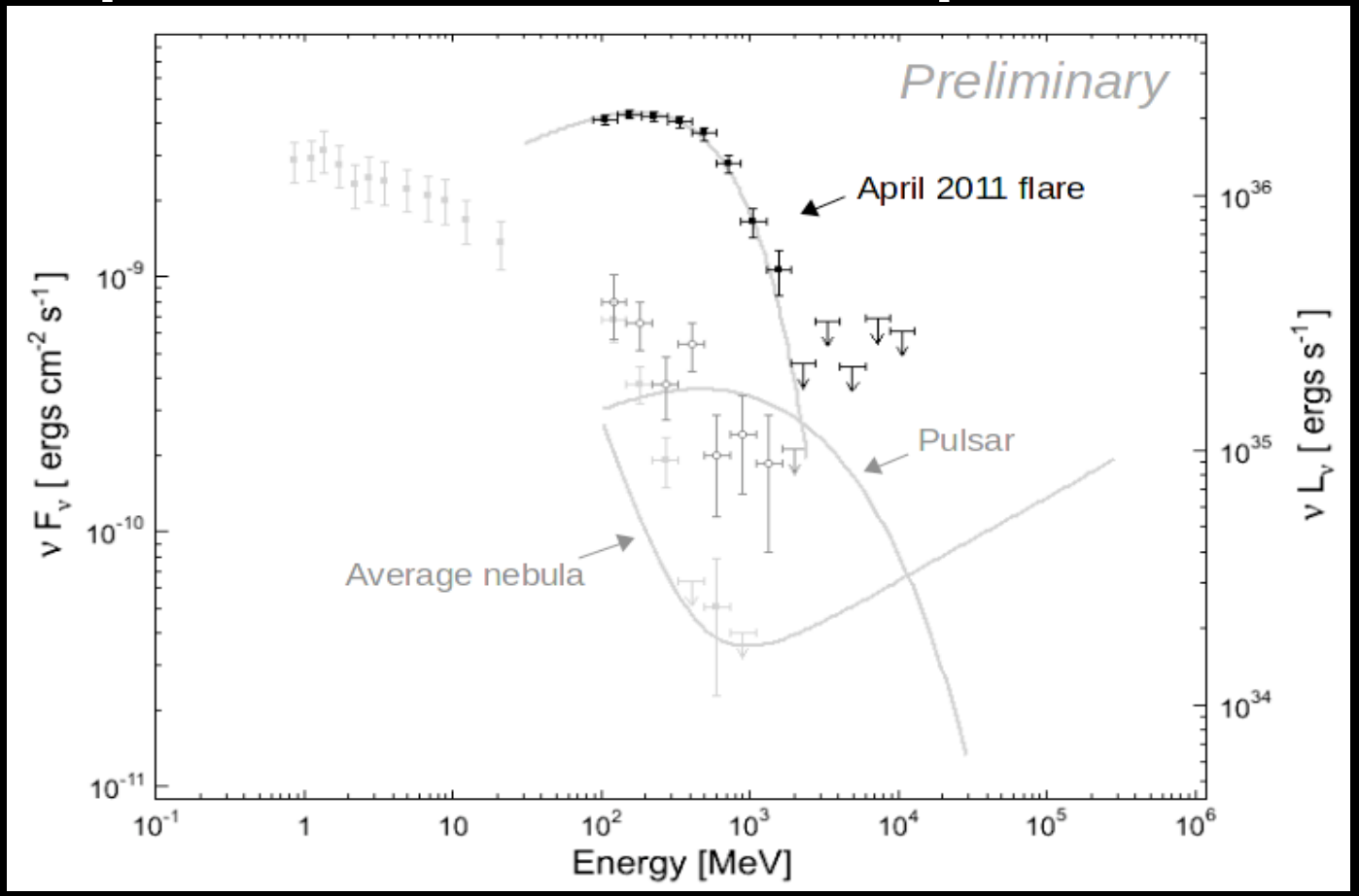
April 2011 Crab Flare



from Rolf Bueler and the Fermi LAT team

- April 2011 Flare is 30 times brighter than the average level!
- Also seen with AGILE

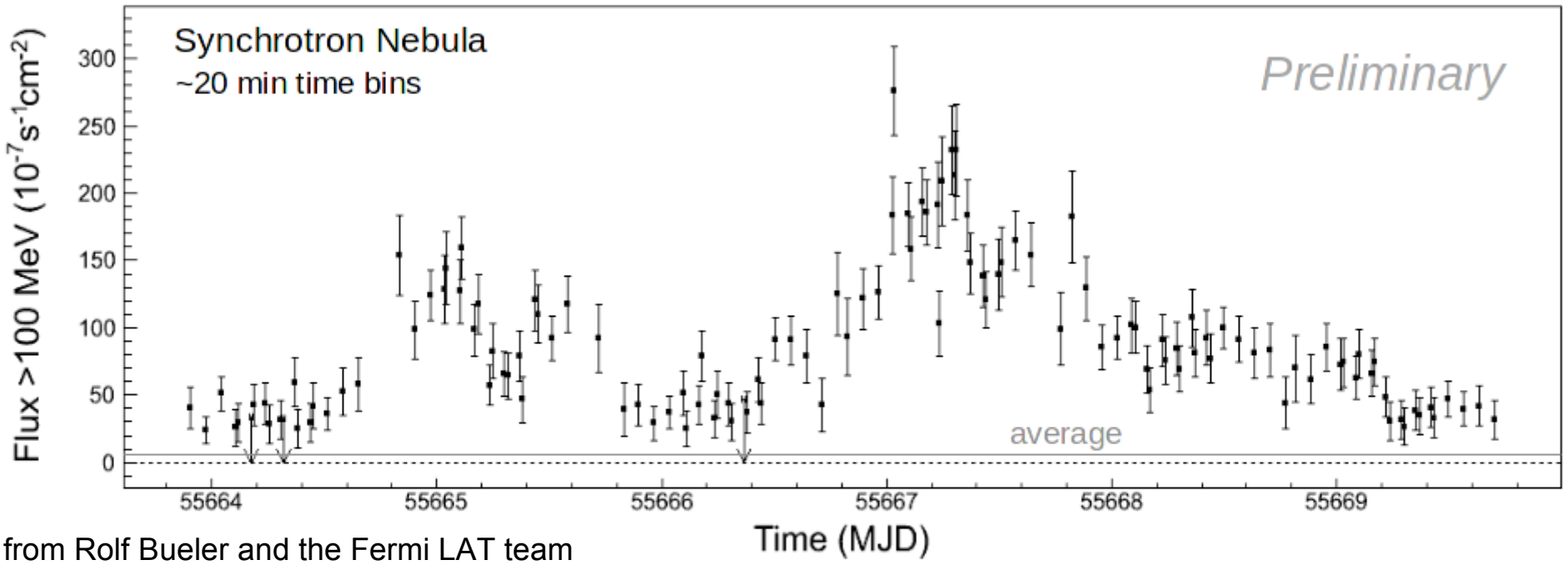
April 2011 Flare Spectrum



(from Rolf Bueler and the Fermi LAT team)

- Flare spectrum: Power law (index 1.6), exponential cut-off at 580 MeV
- Pulsar-like, but no sign of pulsations in flare photons.
- 5 times brighter than previous flare

April 2011 Flare Light Curve



from Rolf Bueler and the Fermi LAT team

- Rapid variability (< 1 hour) --> region size is < 0.04”
- Demonstrates the brightness of the flare and sensitivity of LAT
- No correlated behavior in other wavebands

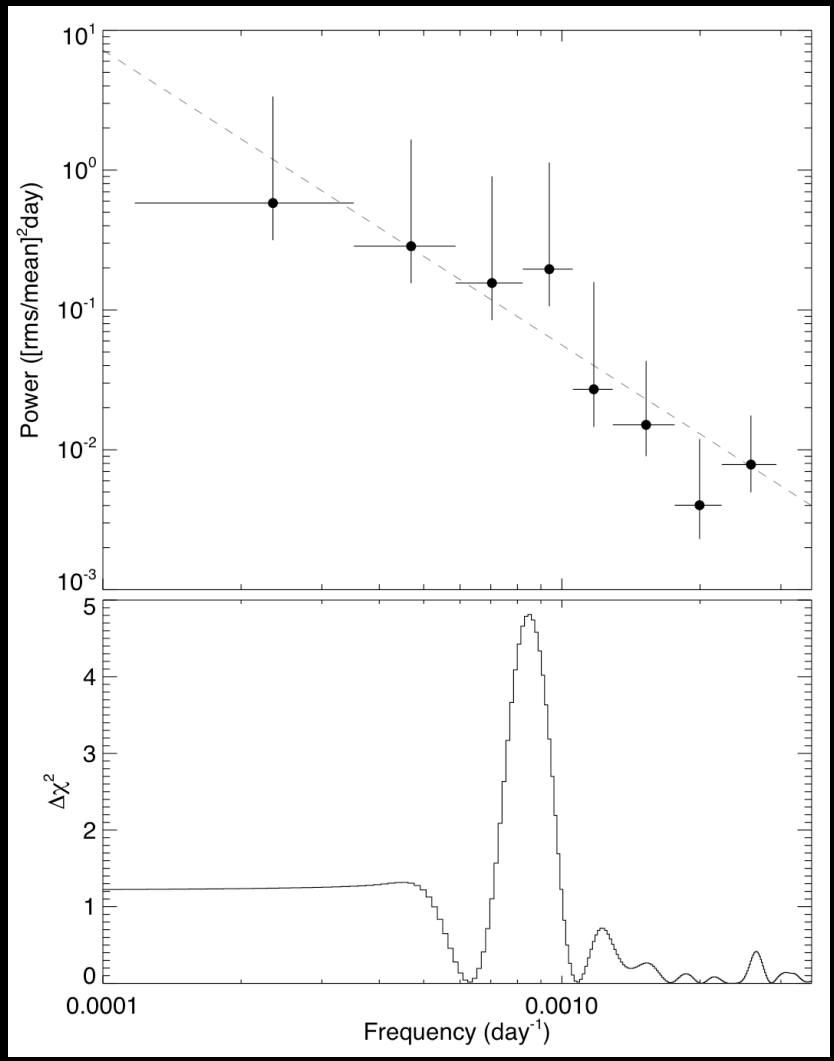
Summary & Conclusions

- The Crab Nebula flux (15-50 keV) shows a ~7% (70 mCrab) decline from 2008-2010.
  - Recent data suggest a flattening or possible increase.
  - Timescales suggest structures comparable to the inner ring in the nebula
- Four High energy (>100 MeV) flares observed from the Crab Nebula
  - Flare emission is synchrotron radiation from a very small region, possibly very close to the pulsar
  - Electrons have ≥ PeV energies for magnetic field 0.2-2 mG
  - April 2011 flare is 30x brighter than average psr+nebula flux
  - April 2011 Rapid variability implies region size <0.04”
  - No correlated behavior in other wavebands
- Relationship between two phenomena unclear.

Backup

RXTE PCA – Search for Periodicity

- PCA light curve has 3 peaks. Is there a periodicity?
- Power spectrum from evenly binned 15-50 keV PCU 2 data (3 bins per year). Power law index 2.1±0.4
- Frequency search – fitted quadratic + sinusoid.
- Highest peak 1176±96 days, only 2σ



April 2011 Flaring!

Date	Peak (pulsar+nebula) Flux (> 100 MeV)	Instrument	Atel
April 9-11, 2011	$(5.7\pm0.7)\times10^{-6}$ cm^{-2} s^{-1}	Fermi LAT	3276
April 12-13, 2011	$(6.5\pm1.5)\times10^{-6}$ cm^{-2} s^{-1}	AGILE	3282
April 14, 2011	$(12.1\pm0.6)\times10^{-6}$ cm^{-2} s^{-1}	Fermi LAT	3284
April 14, 2011	$(19.6\pm3.7)\times10^{-6}$ cm^{-2} s^{-1}	AGILE	3286

- April 14
  - Brightest daily flux observed (to date)
  - Variations on <12 hr timescale
- Chandra – April 12-13 (Tennant et al., Atel #3284)
  - New bright knot 5.7” east of pulsar, not aligned with jet
  - Coincides with initial position of Sep 2010 knot