TeV Observations of Extragalactic Sources

Henric Krawczynski (Washington University in St. Louis), Oct. 2, 2009

Plan of Talk:

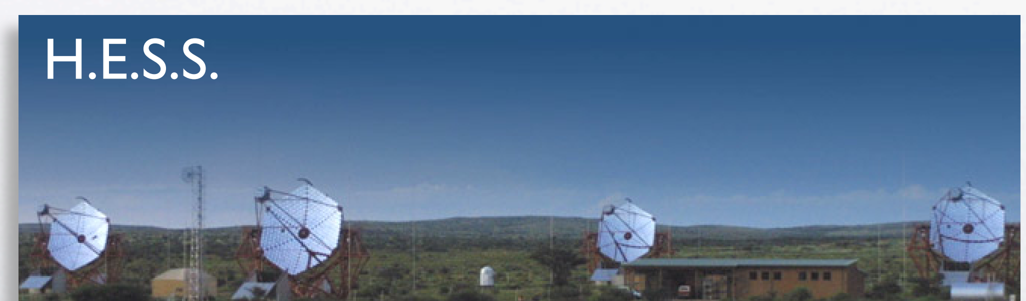
- Status of Experiments
- Key-Results:
  - Radio Galaxies
  - Blazars
  - Starburst Galaxies
- Summary

Status of Experiments

New config.:
09/09

1% Crab
(2×10^{-13} erg cm^{-2} s^{-1}
@ 1 TeV)
in 28 hrs

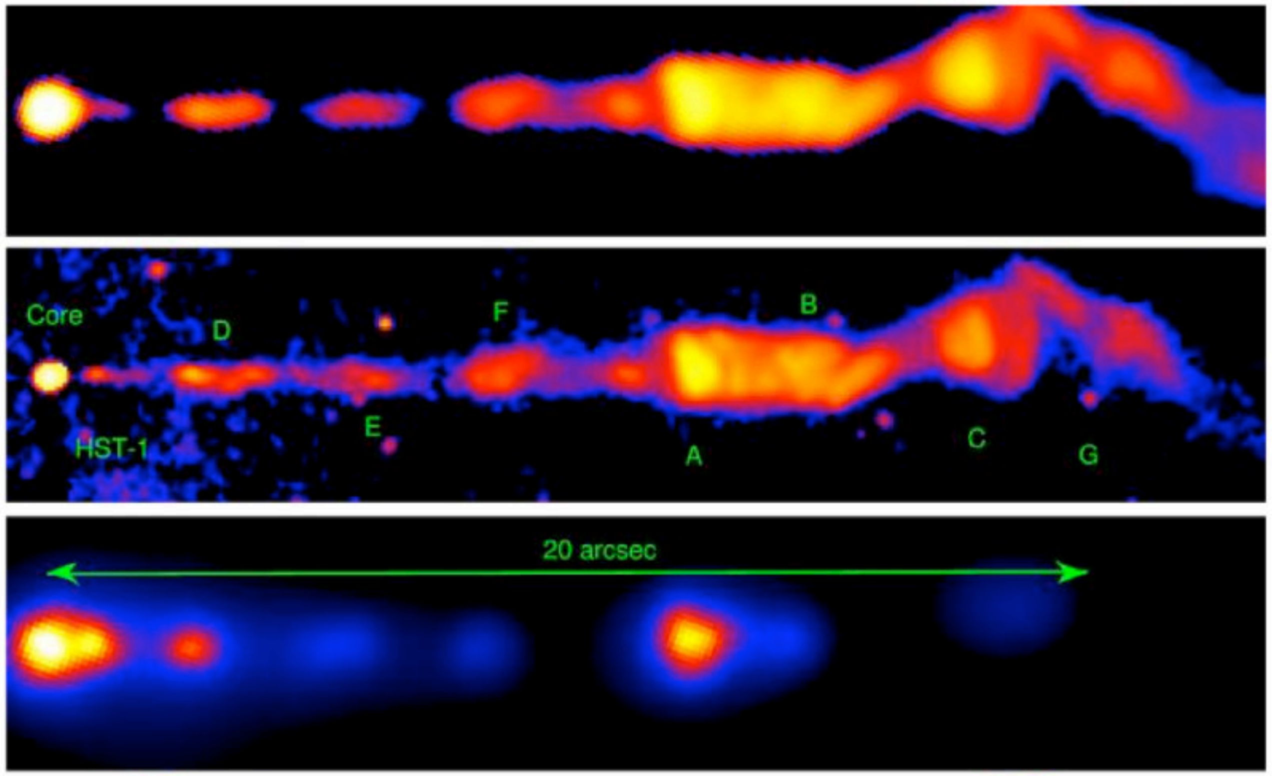
Start of routine stereo operation in 1-2 months.



28 m telescope under construction.

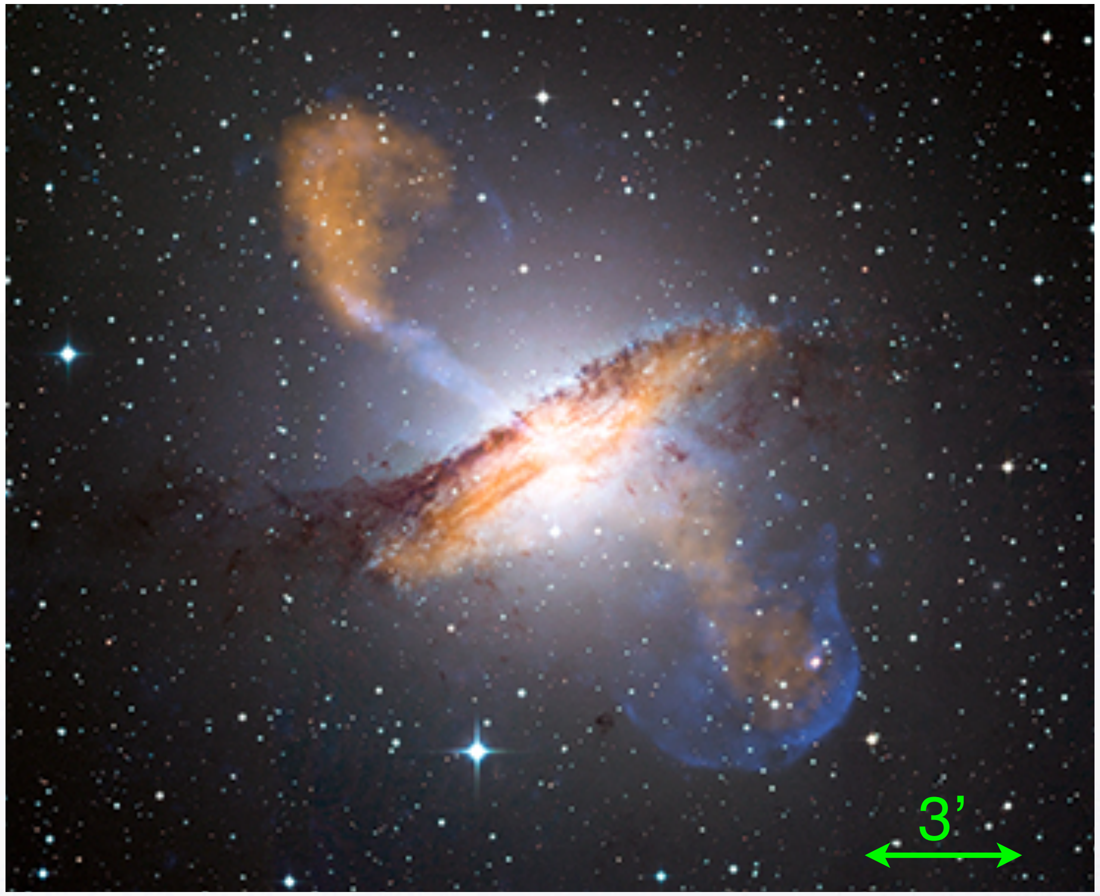
TeV-Bright Radio Galaxies

M87 (R/O/X):



Marshall et al. 2002

Cen A (R+O+X):

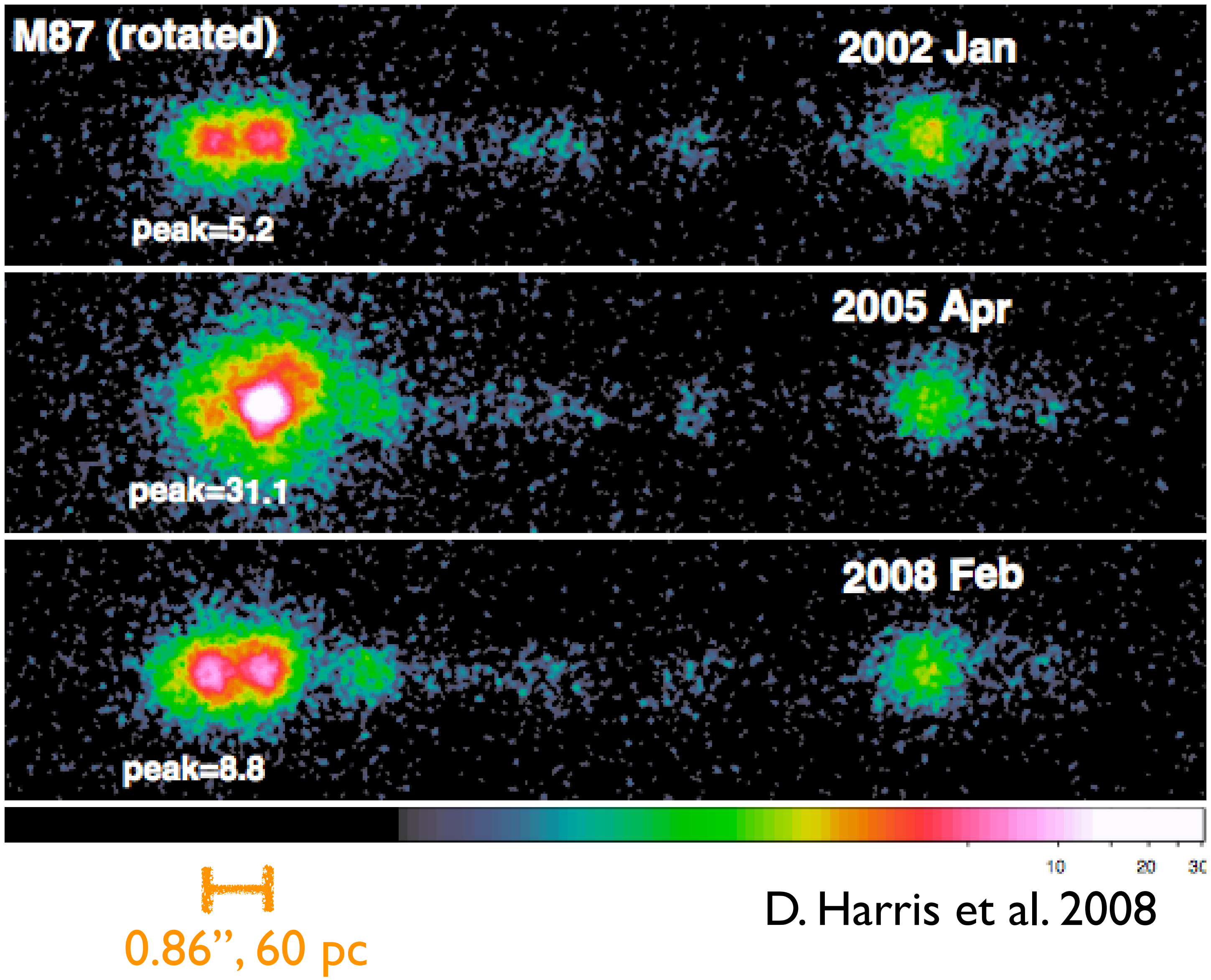


X-ray: NASA/CXC/CfA/R.Kraft et al.; Submillimeter: MPIfR/ESO/APEX/A.Weiss et al.; Optical: ESO/WF

TeV Observations:
HEGRA (2003), HESS (2006), VERITAS (2008), MAGIC (2008)

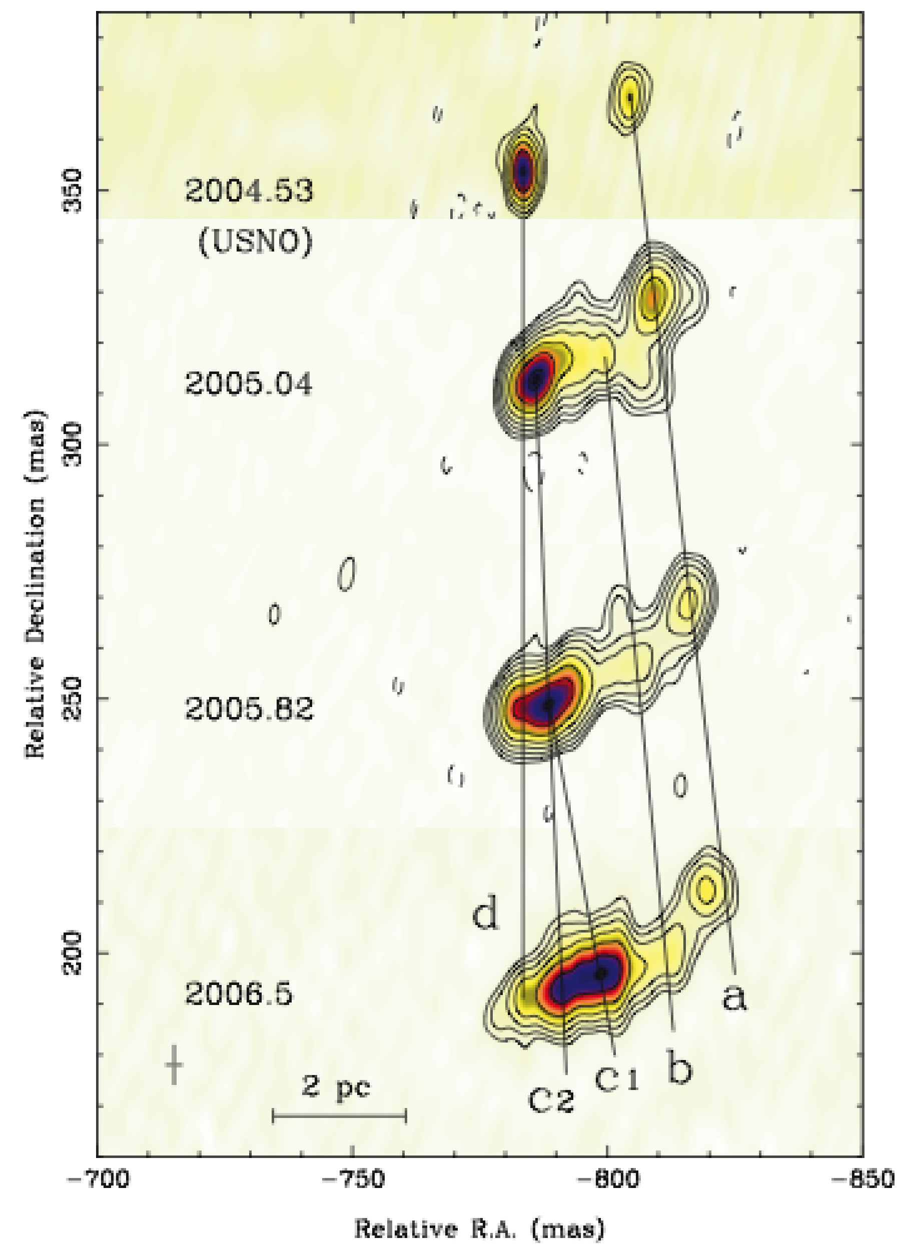
TeV Detection:
Aharonian et al. 2009, ApJ, 695, L40

M87: Chandra Images of HST-1 X-ray Flare



D. Harris et al. 2008

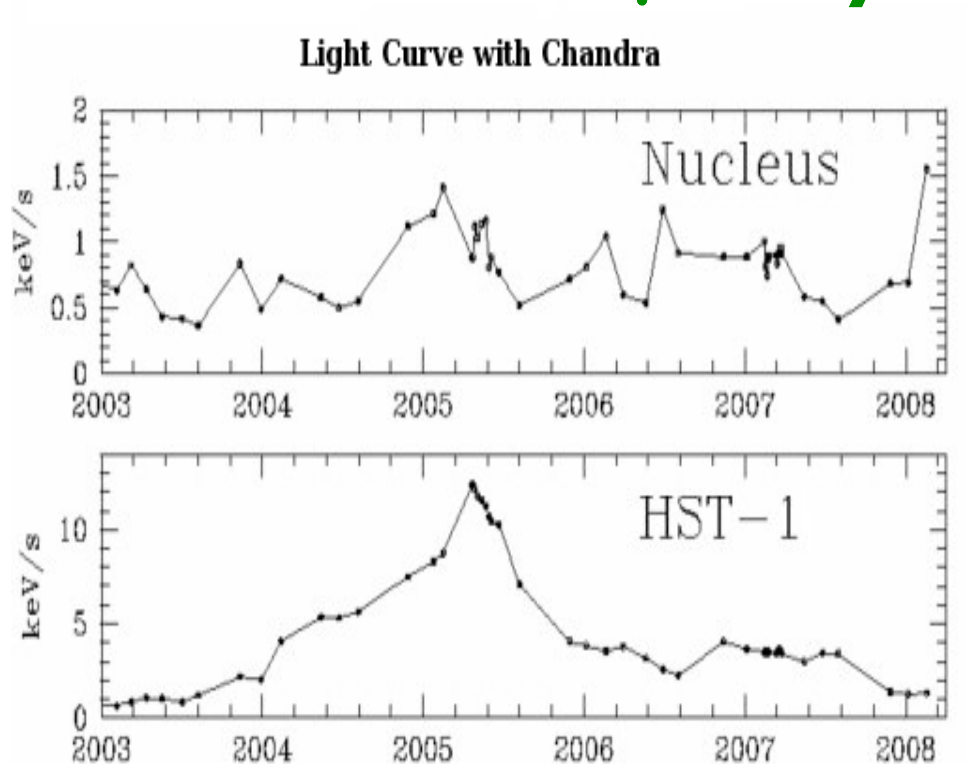
HST-1 VLBA

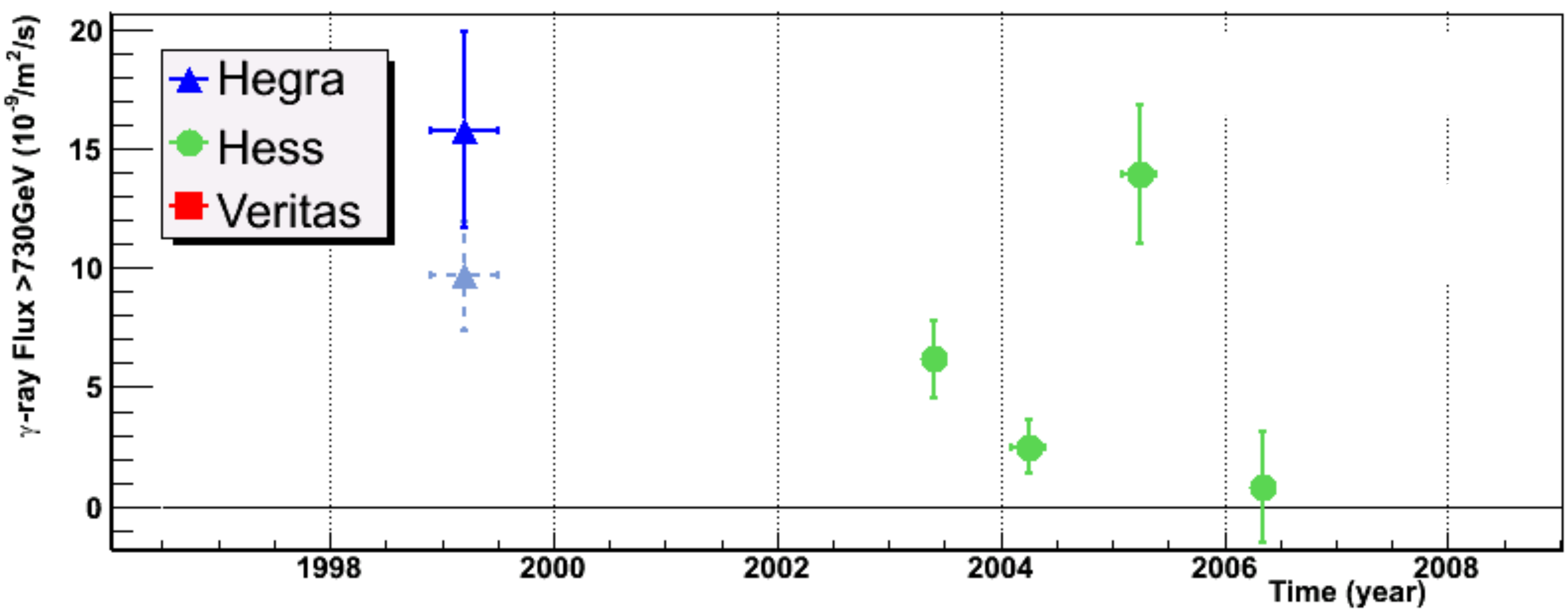


Cheung et al. 2007

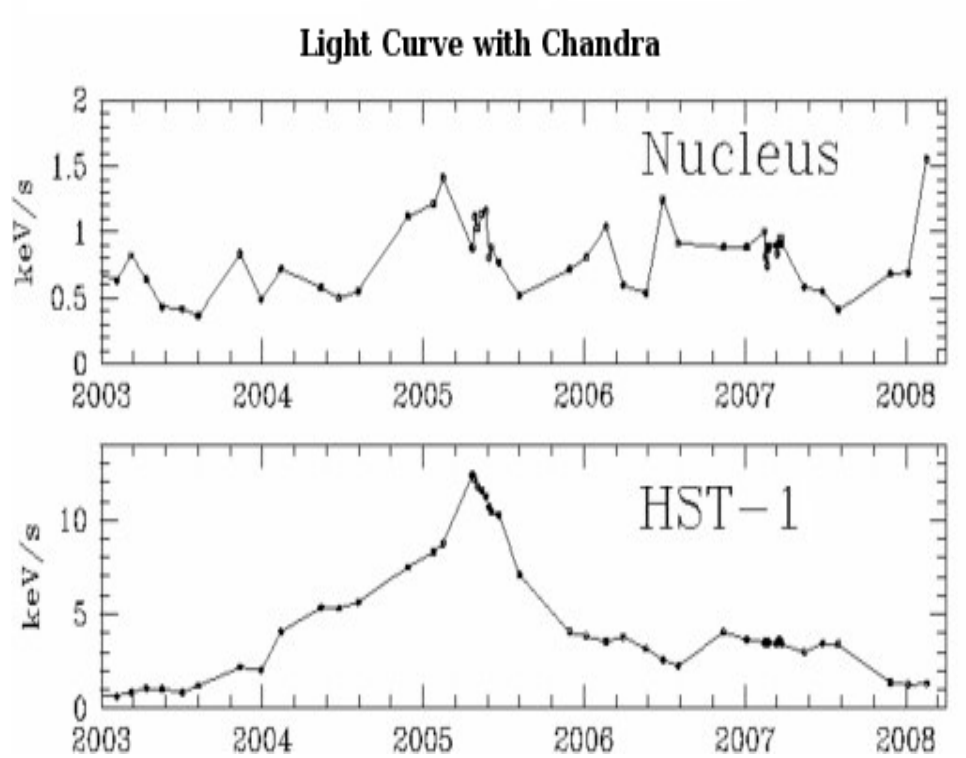
- X-ray flare coincides with brightening of knot HST-1c and emergence of fast knot.

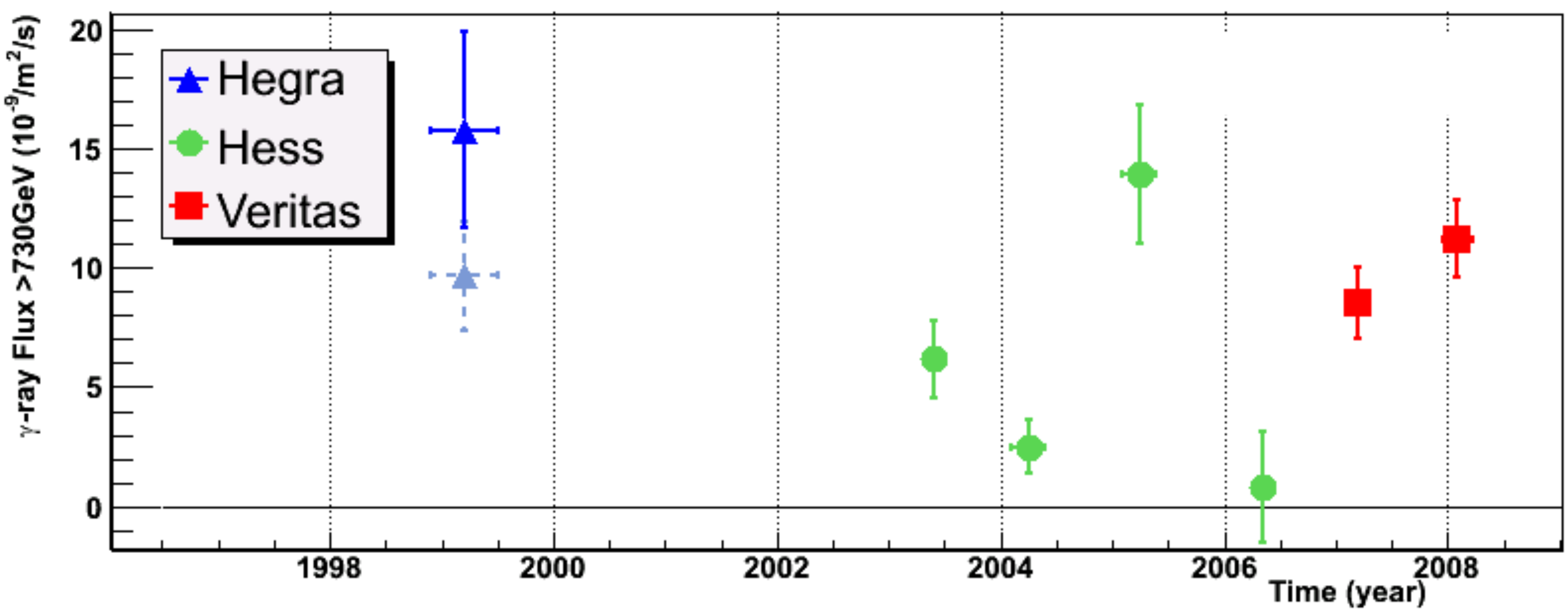
M87 Observations: TeV γ-Rays





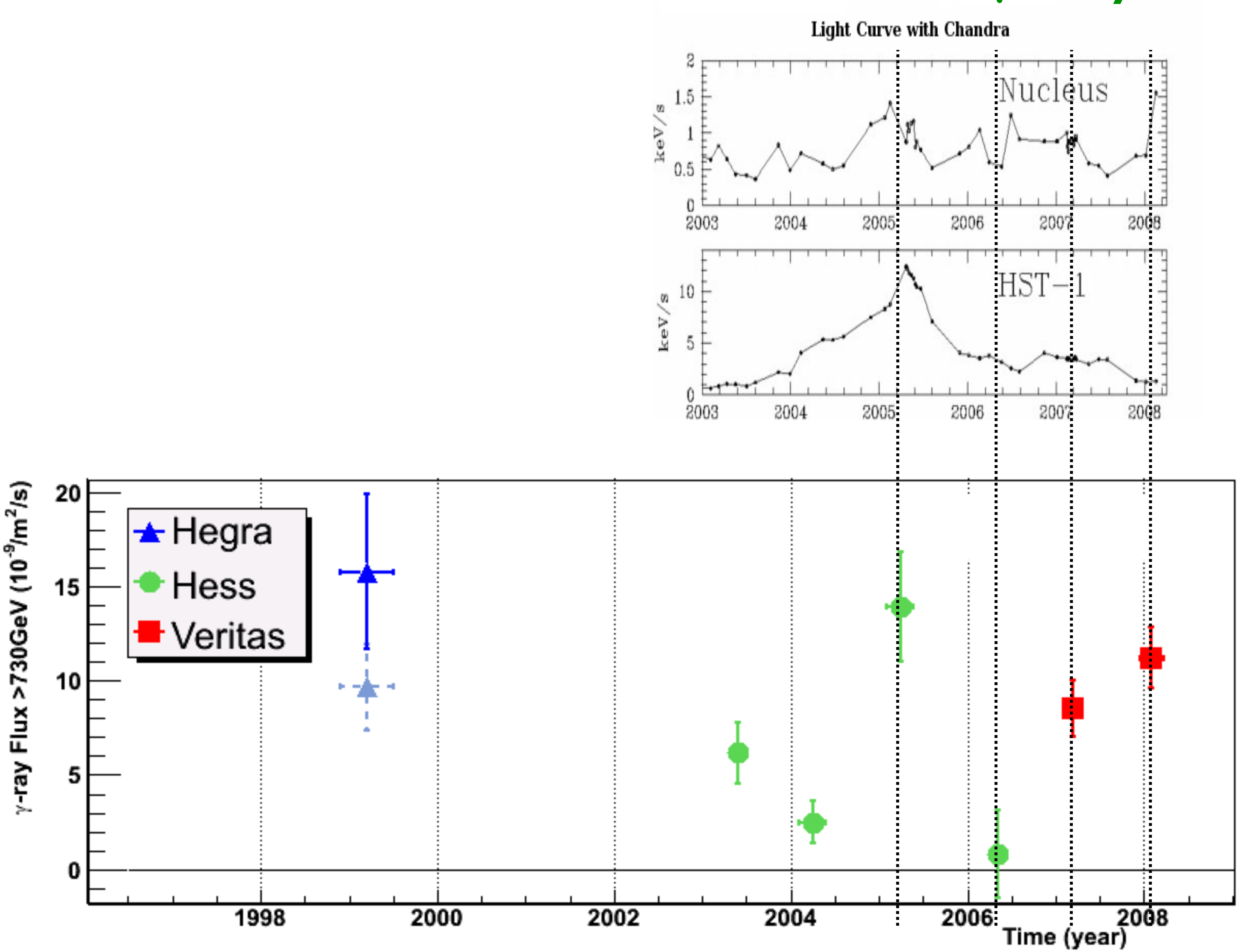
M87 Observations: TeV γ-Rays





Acciari et al. 2008, ApJ, 679, 397

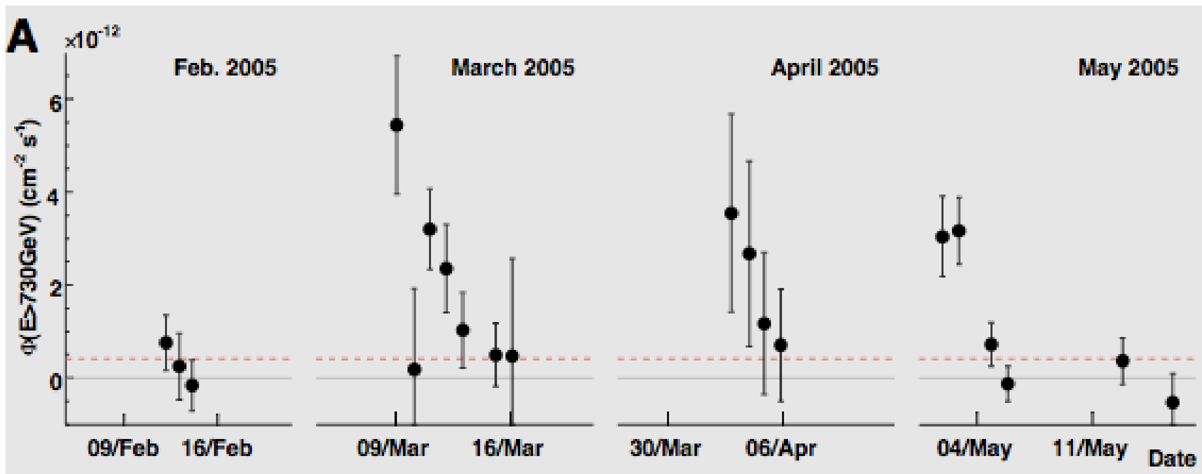
M87 Observations: TeV γ-Rays



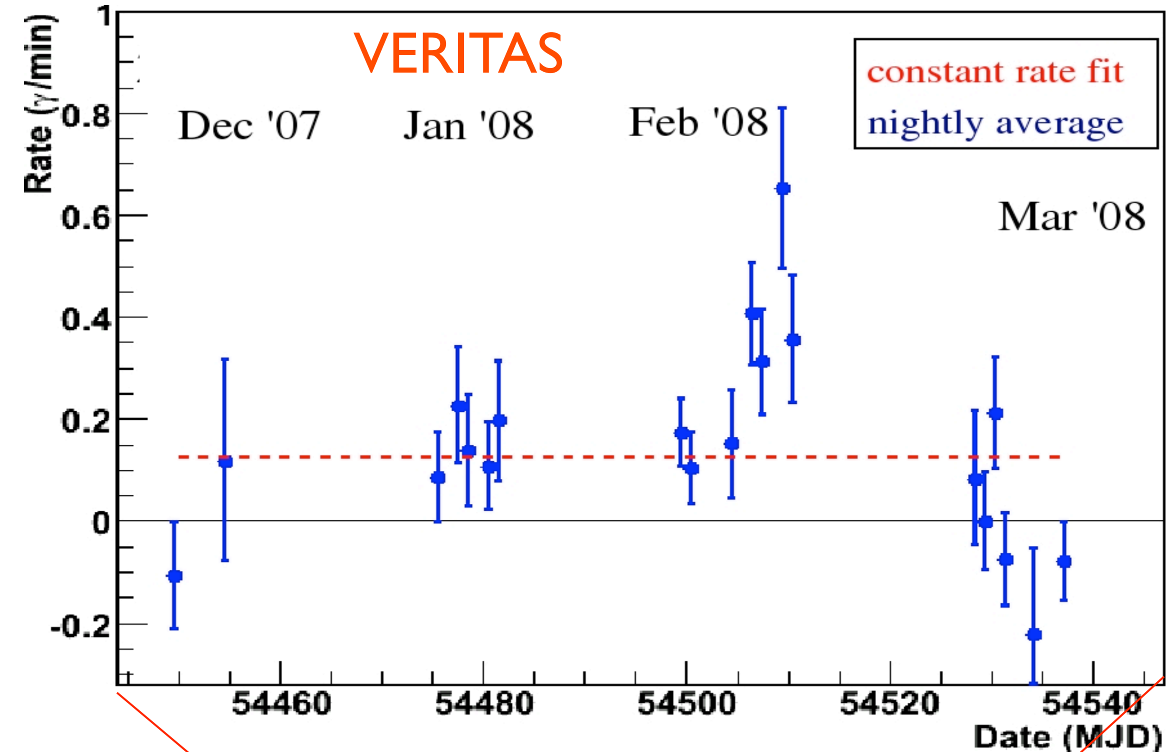
Acciari et al. 2008, ApJ, 679, 397

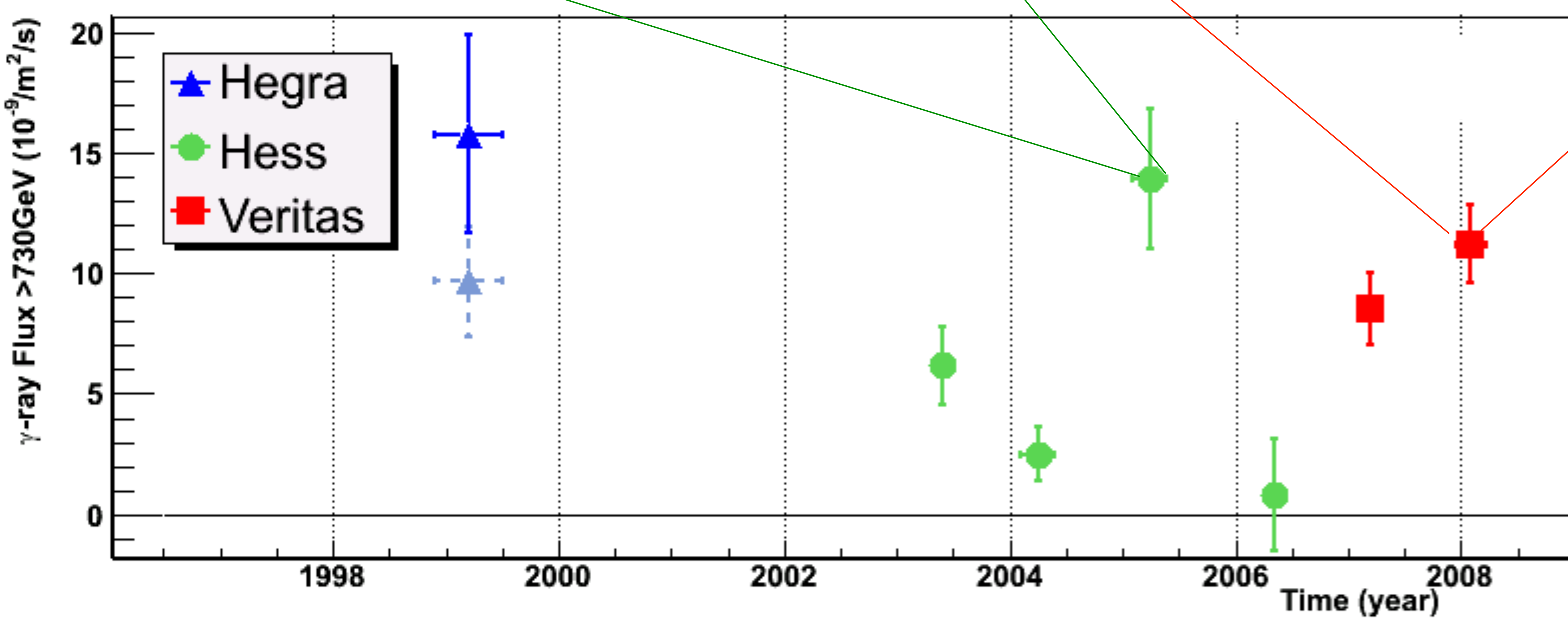
HST-1: no X/TeV 2007 and 2008 data break correlation

M87 Observations: TeV γ-Rays



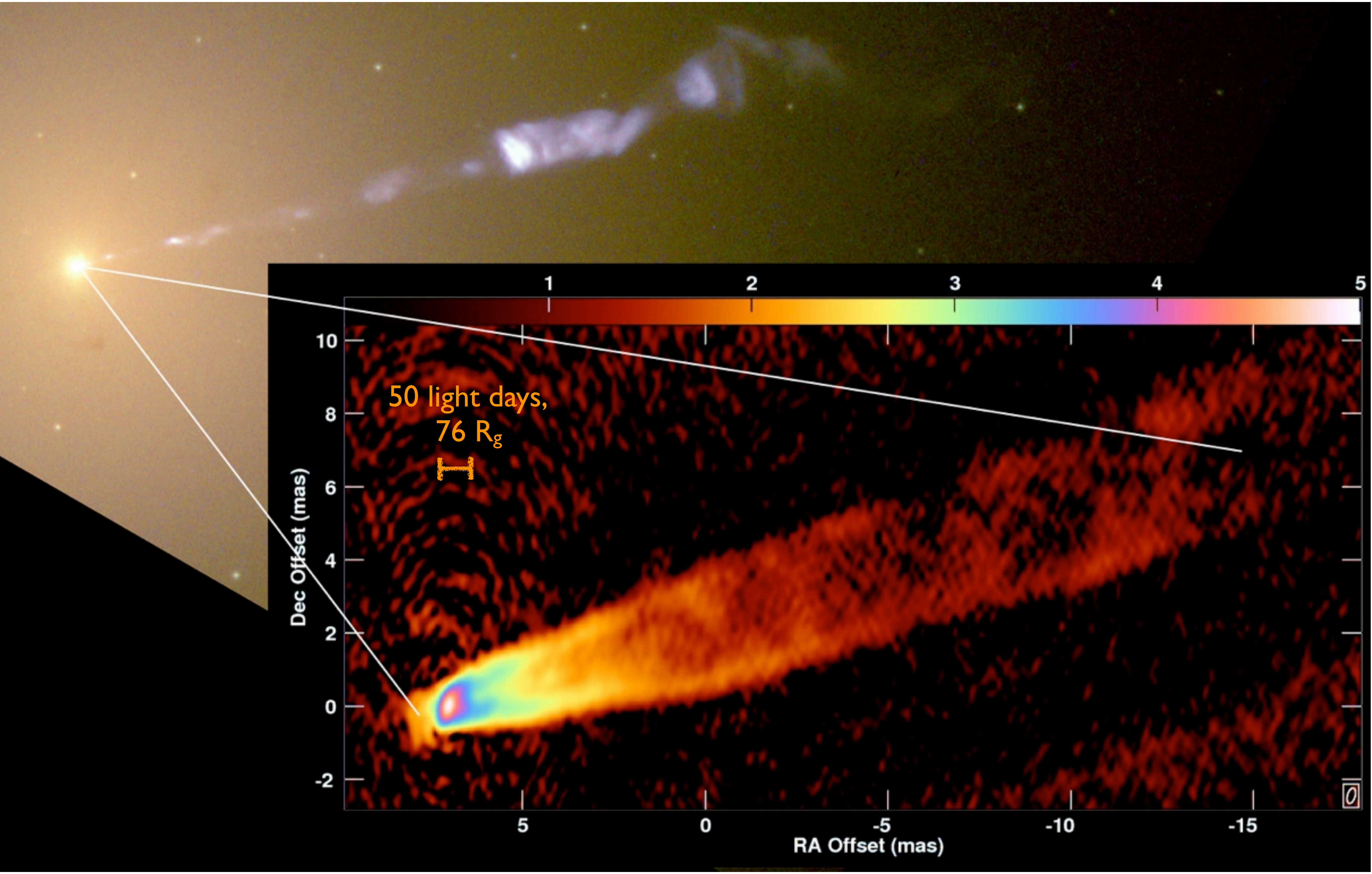
Aharonian et al. 2006



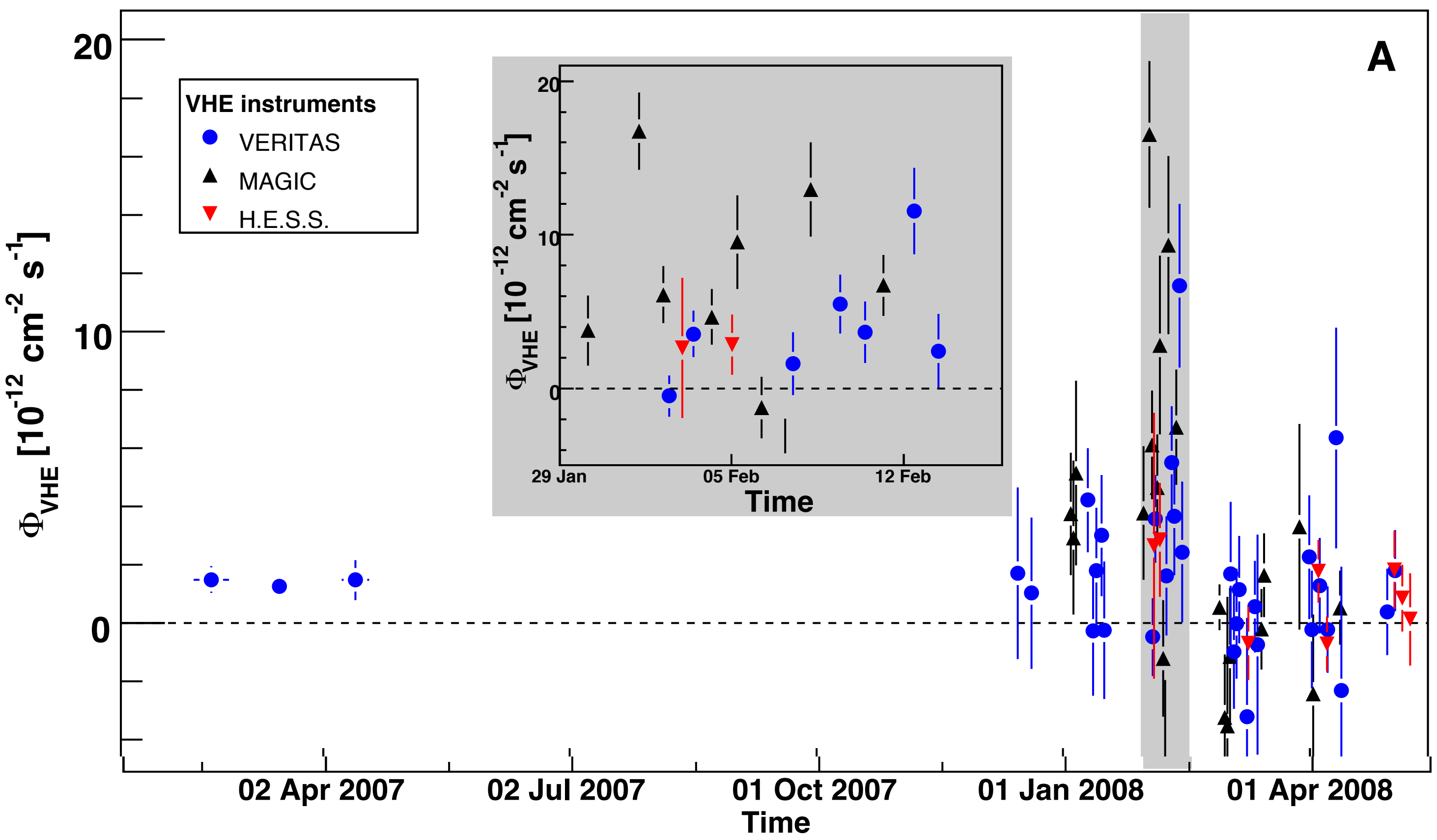


Acciari et al. 2008, ApJ, 679, 397

1-day flares:
$c\,t_{fl} = 3\,R_g$

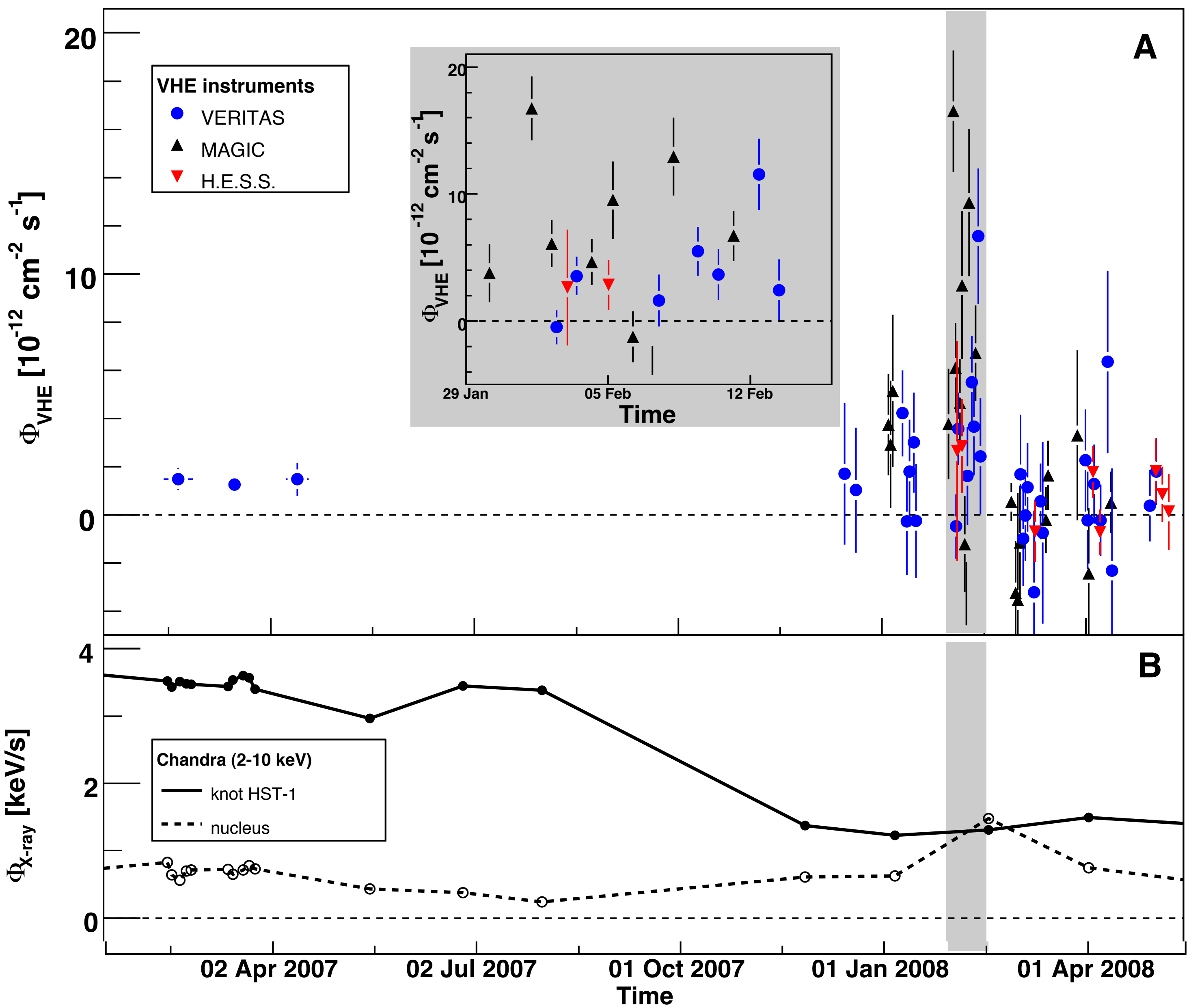


C. Walker et al.



Acciari et al. 2009, Sci, 325, 444

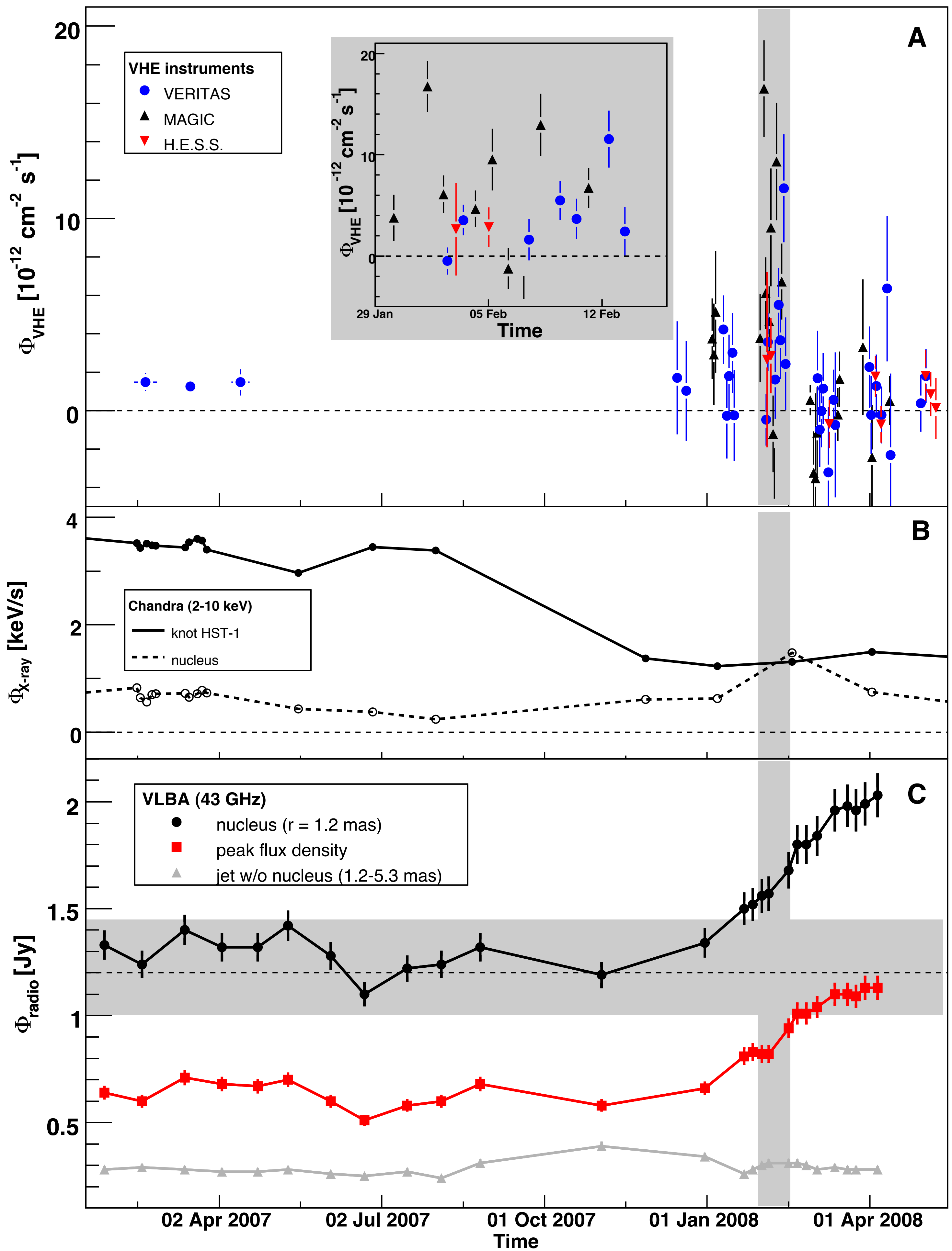
Brightest monitored TeV γ-ray flare



Acciari et al. 2009, Sci, 325, 444

Brightest monitored TeV γ-ray flare

Brightest flare from core detected by Chandra



Acciari et al. 2009, Sci, 325, 444

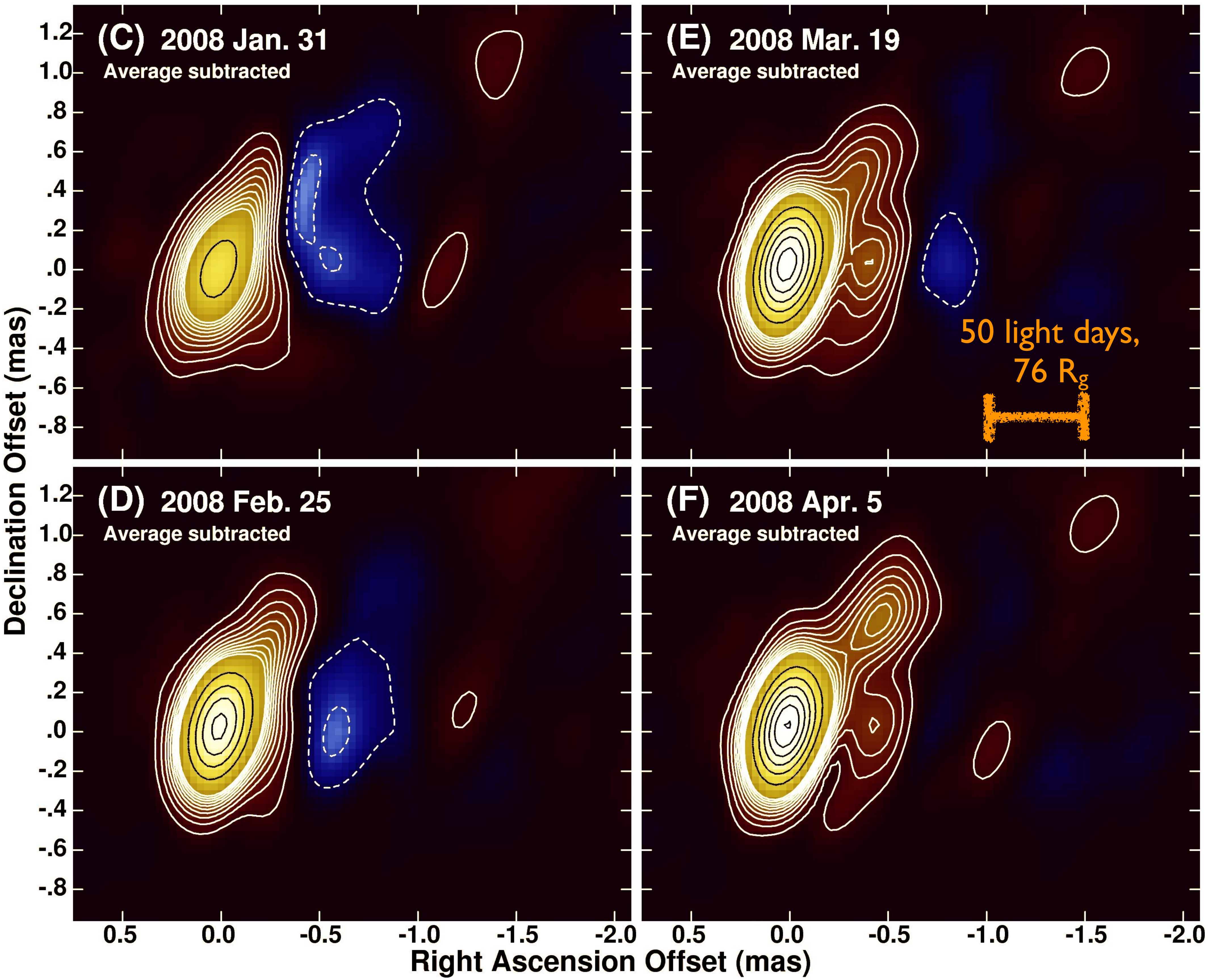
Brightest monitored TeV γ-ray flare

Brightest flare from core detected by Chandra

Brightest radio flare from core detected with VLBA

Evidence for correlated radio/x-ray/γ-ray flare.

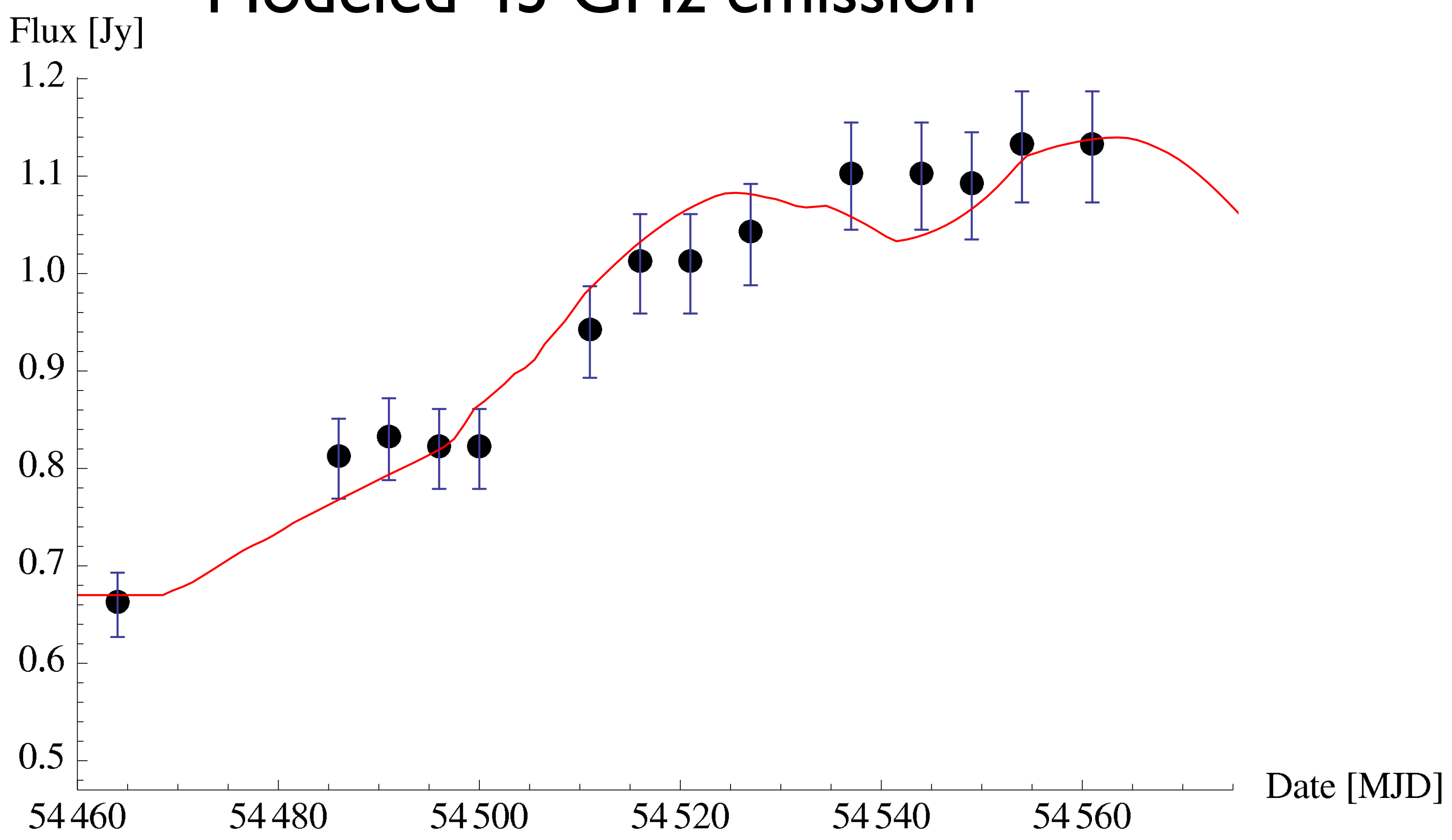
Acciari et al. 2009, Sci, 325, 444



Flare comes from central resolution element 50 $R_g/\sin\theta$!

Modeled 43 GHz emission

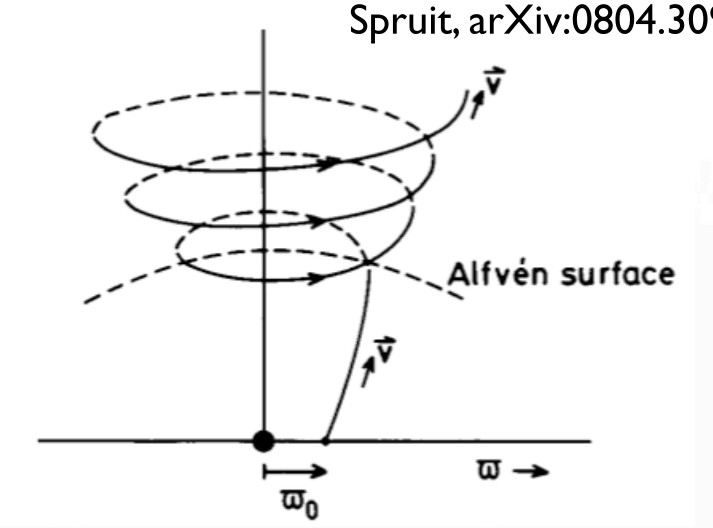
Acciari et al. 2009, Sci, 325, 444



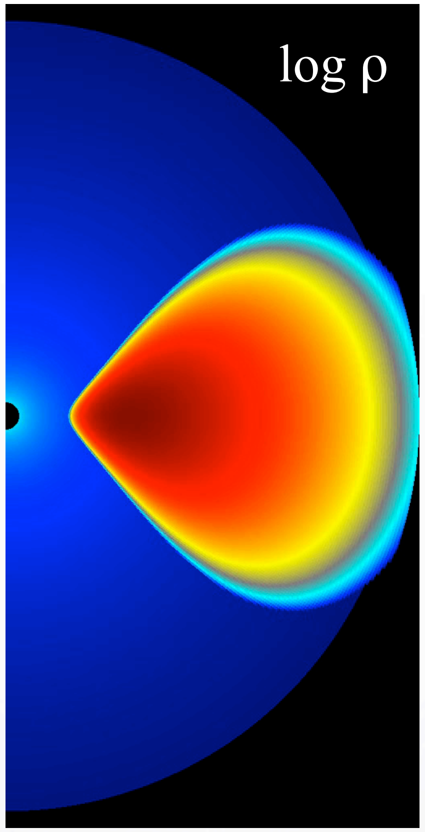
- Use γ-ray light curve as "source function" to inject electron population.
- Electron population cools adiabatically as plasma moves down "hollow cone".
- Account for differences in δ and in light travel time.
- Acceptable model fits for $\alpha=5^\circ$, $\theta=20^\circ$, $\Gamma = 1.01$, $\beta_{jet} = 0.14$, $B = 0.5G$.

Magnetically Driven Jet Formation

Magnetic acceleration and confinement:



Spruit, arXiv:0804.3096



McKinney & Gammie 2004, ApJ, 611, 977.

Analytic calculations:

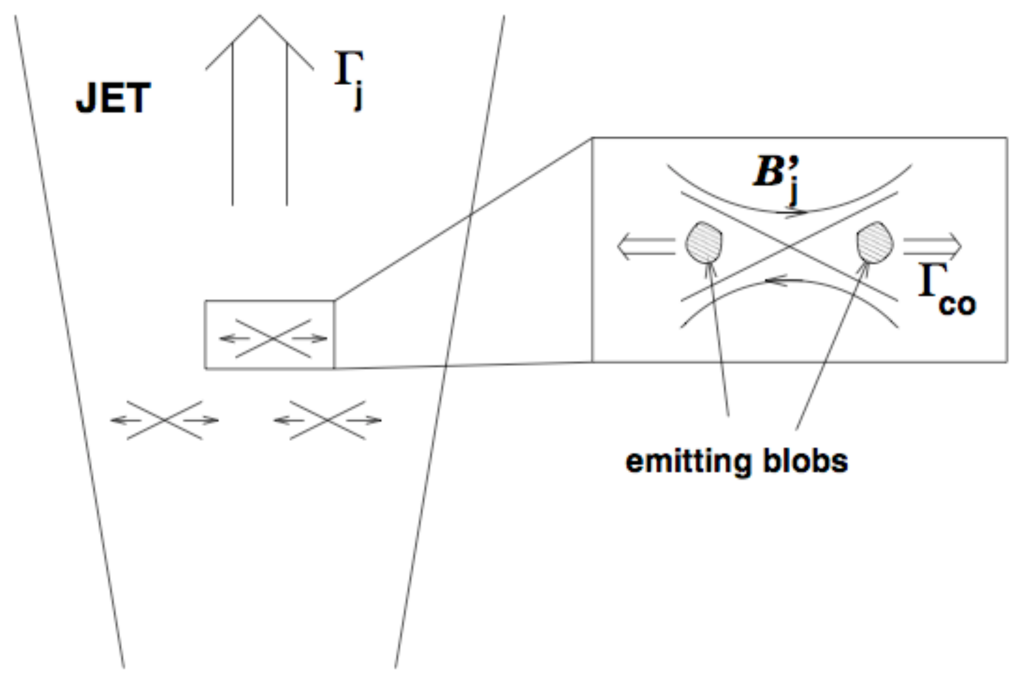
• Bisnovatyi-Kogan and Ruzmaikin 1976, Blandford-Znajek 1977, Blandford & Payne 1982, Li, Chiueh, Begelman 1992)

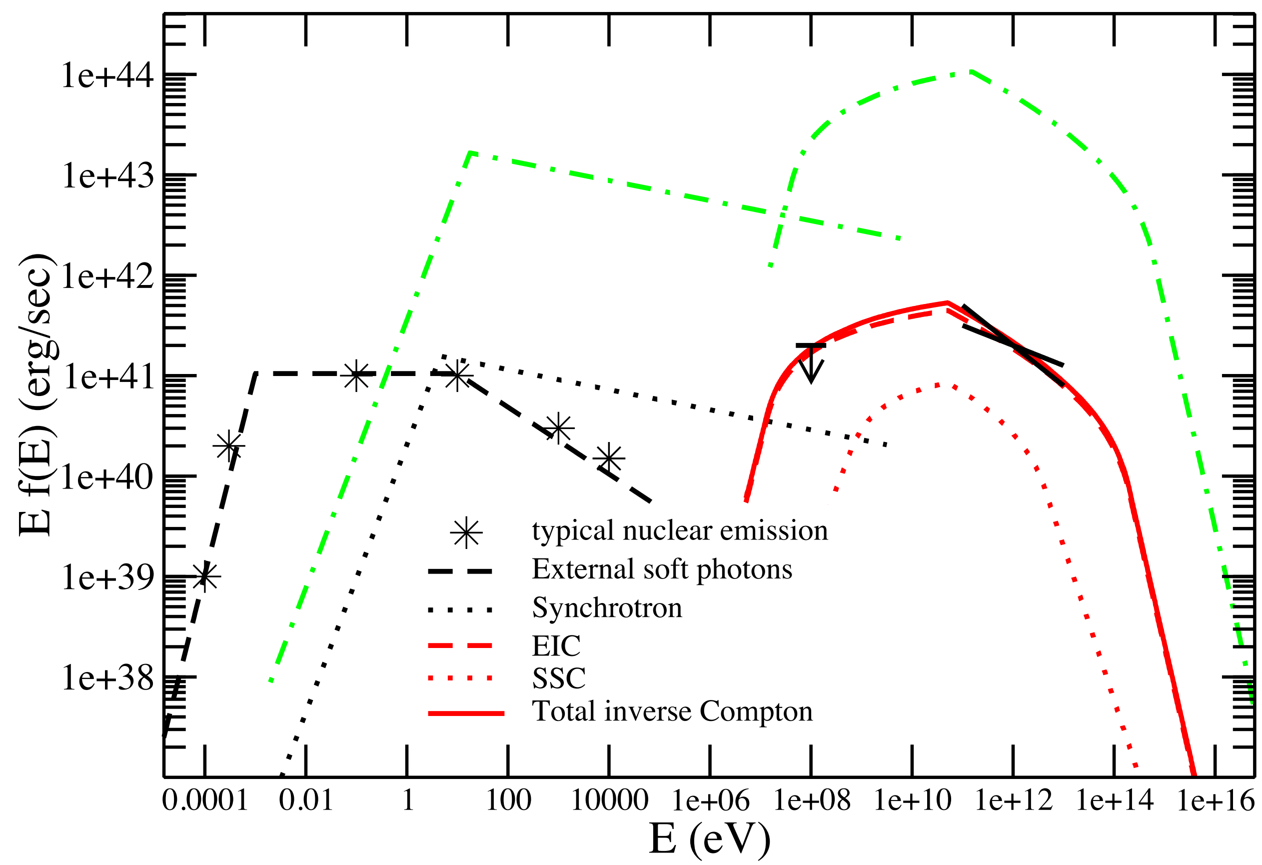
GR-MHD simulations:

• McKinney 2006, Kommissarov 2007, Krolik, Hawley, Hirose, 2007, and others.

Jet accelerates within

$$\frac{50 R_g}{\sin\theta} \sim 150 R_g$$

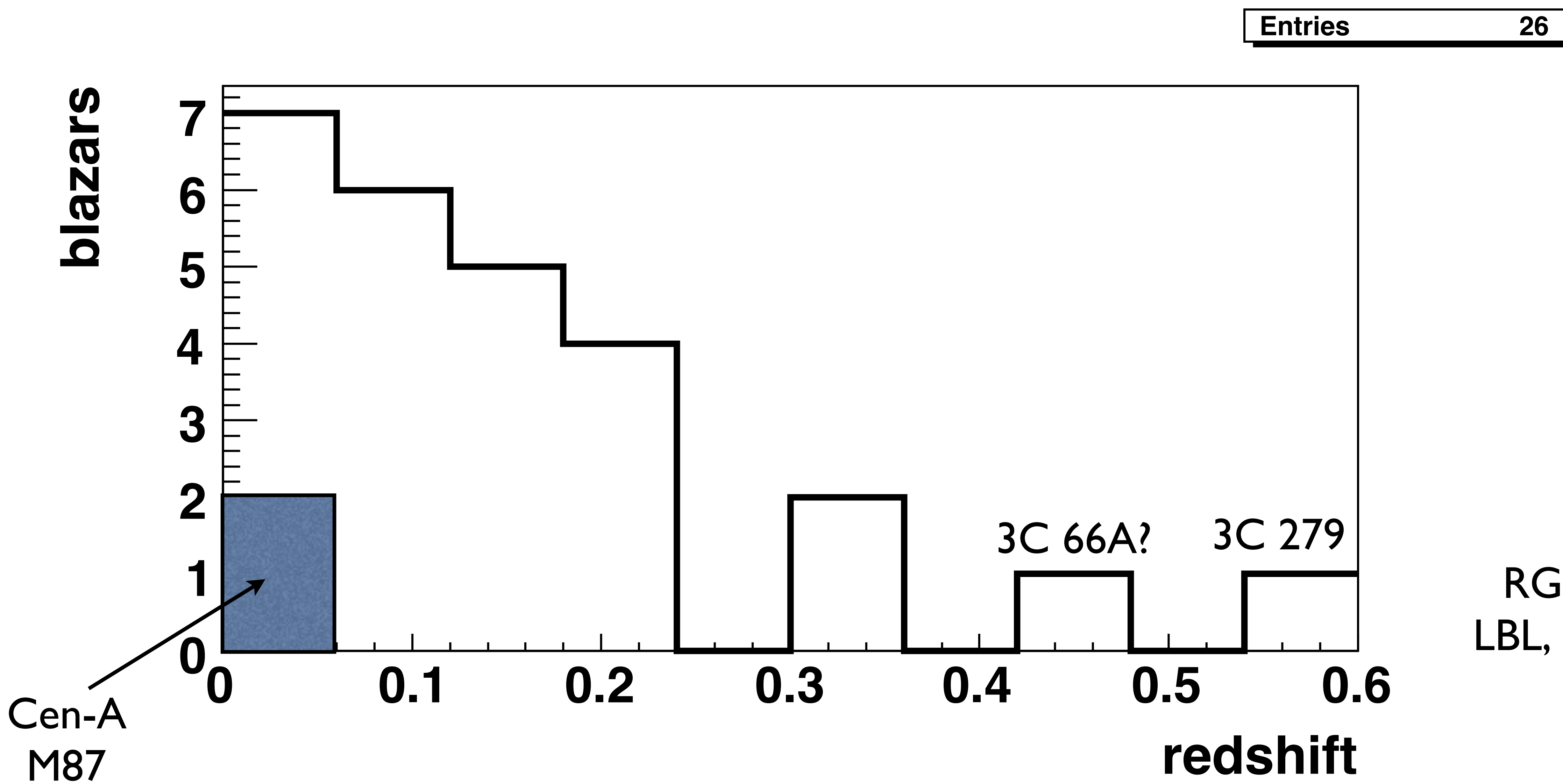




Giannios, Uzdensky, Begelman, 2009, MNRAS, 395, L29, arXiv0907.5005G

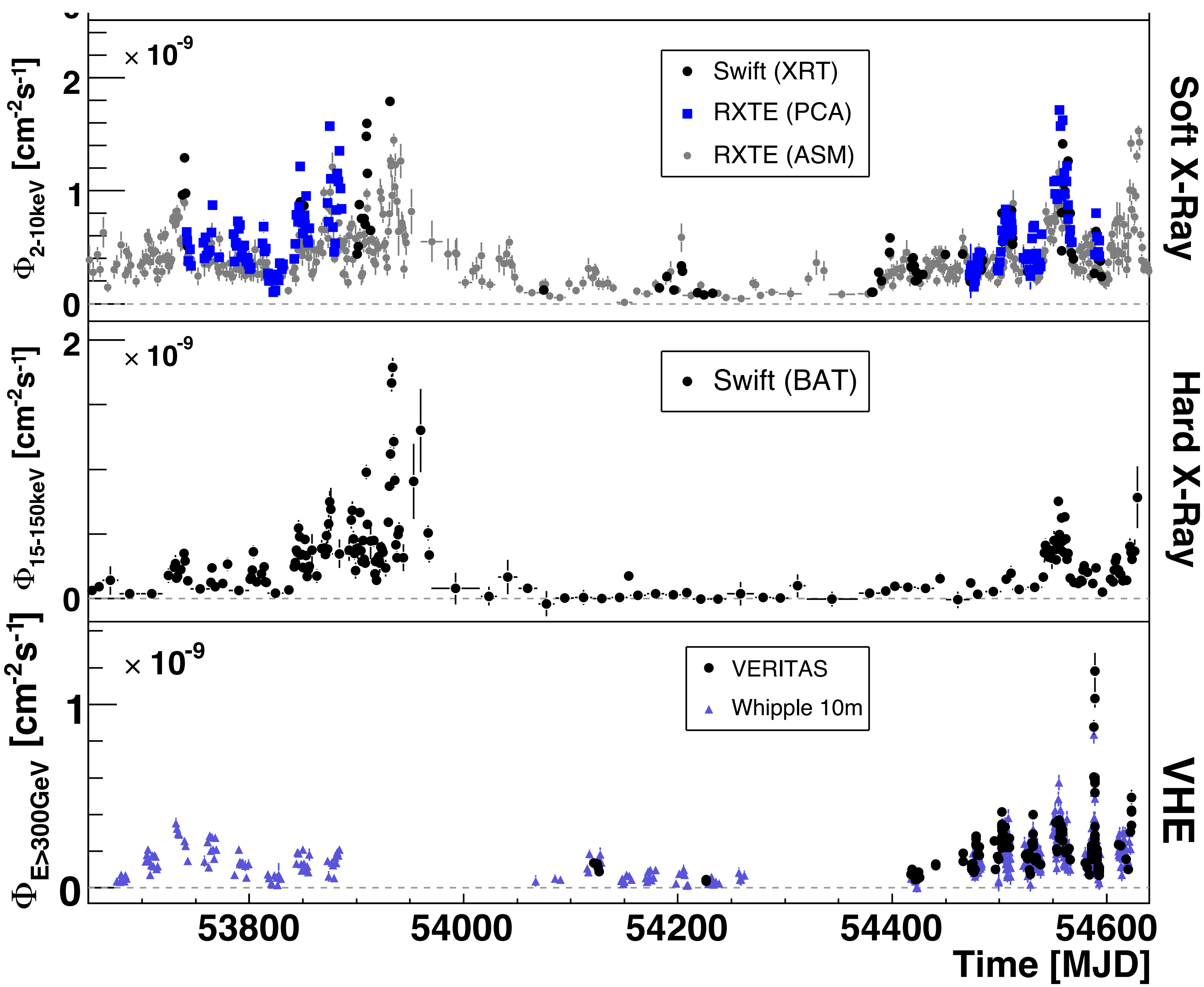
- Relativistic generalization of Petschek-type reconnection (Lyubarsky, 2005):
- Lorentz factor of minijets: $\Gamma_{\rm co} = \sqrt{\sigma}$
- Magnetic energy density in mini-jets: $\sigma_{\rm em} \sim \dfrac{1}{3}$
- Energy per particle before (after) reconnection: $\sigma m_p c^2 \ \left(\sqrt{\sigma} m_p c^2\right)$
- Model explains fast time variability and γ-transparency of jets even though $\delta \sim 1$
- Reconnection: kink instabilities or B-field reversals in BH magnetosphere.

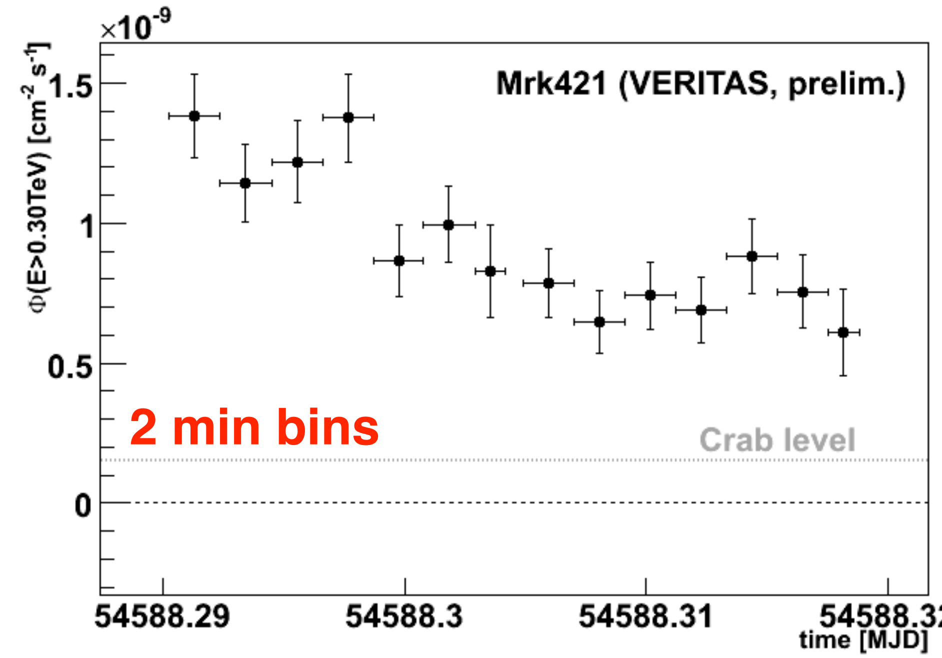
TeV-Bright AGN



RG, FSRQ,
LBL, IBL, HBL,

Whipple/VERITAS Observations of Mrk 421 in 2007 & 2008

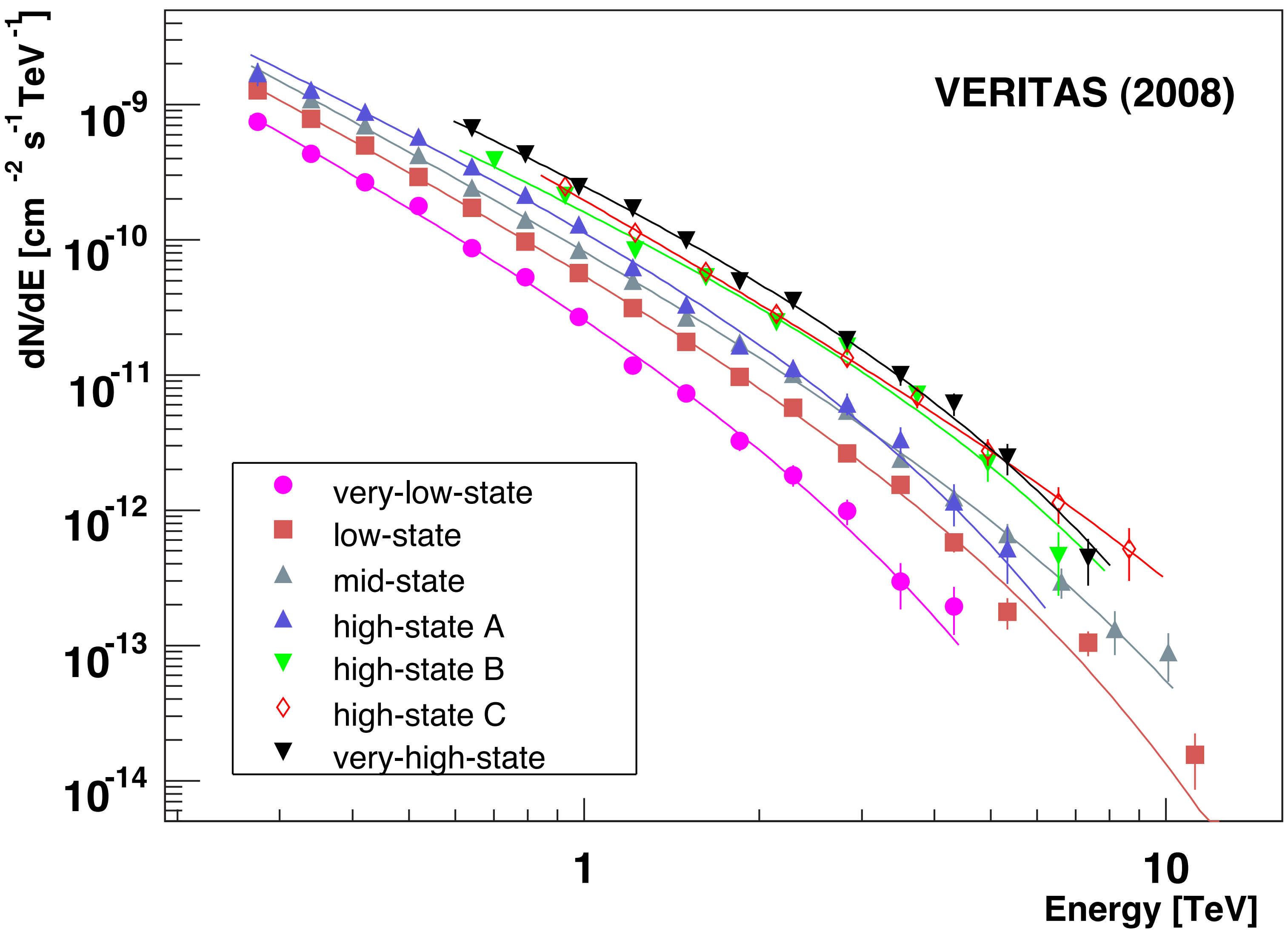


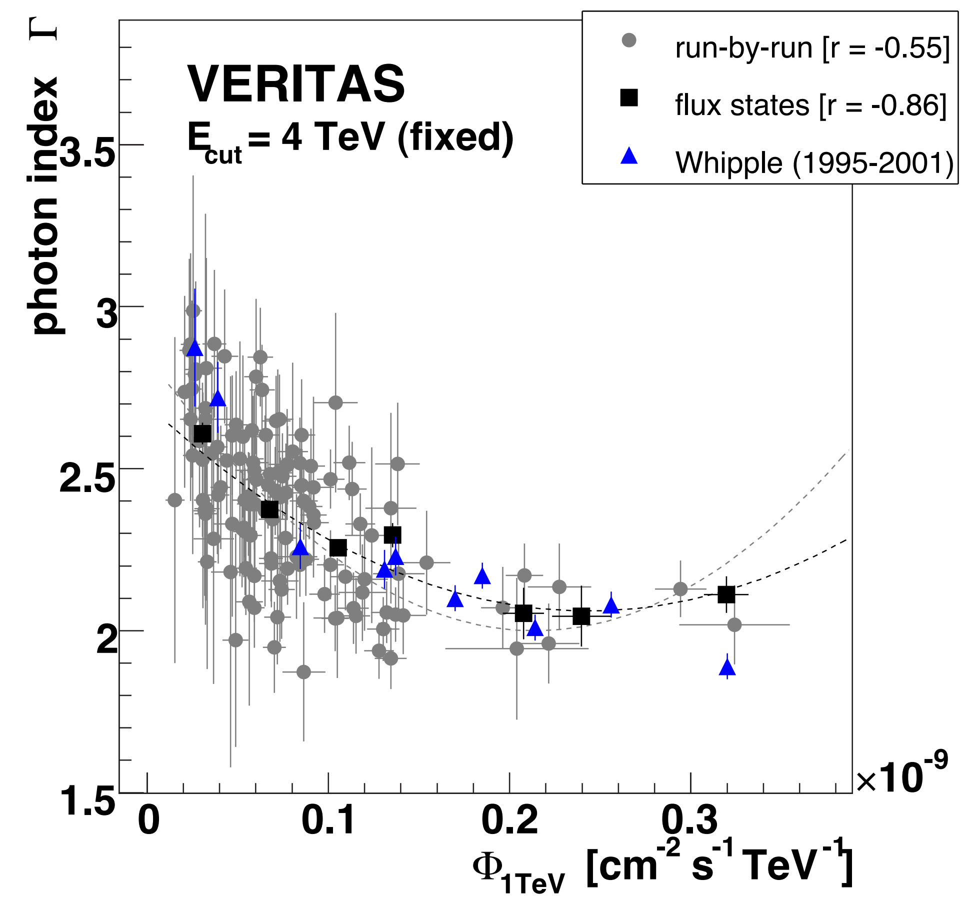


- Rich data set,
- Evidence for X/TeV correlation.

Beilicke, H.K., et al. 2009

Whipple/VERITAS Observations of Mrk 421 in 2007 & 2008

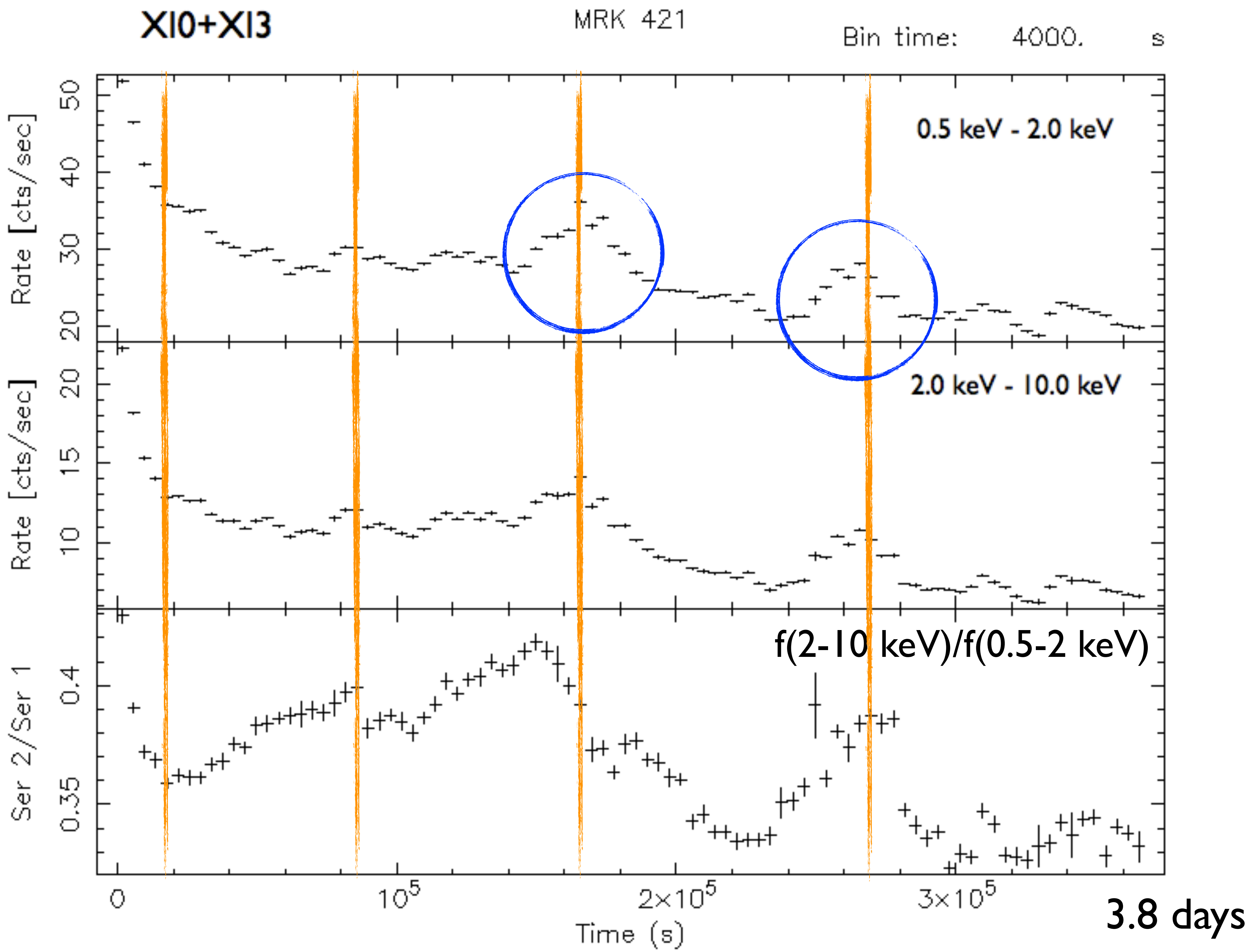




- Spectrum hardens with increasing flux but the trend "saturates".

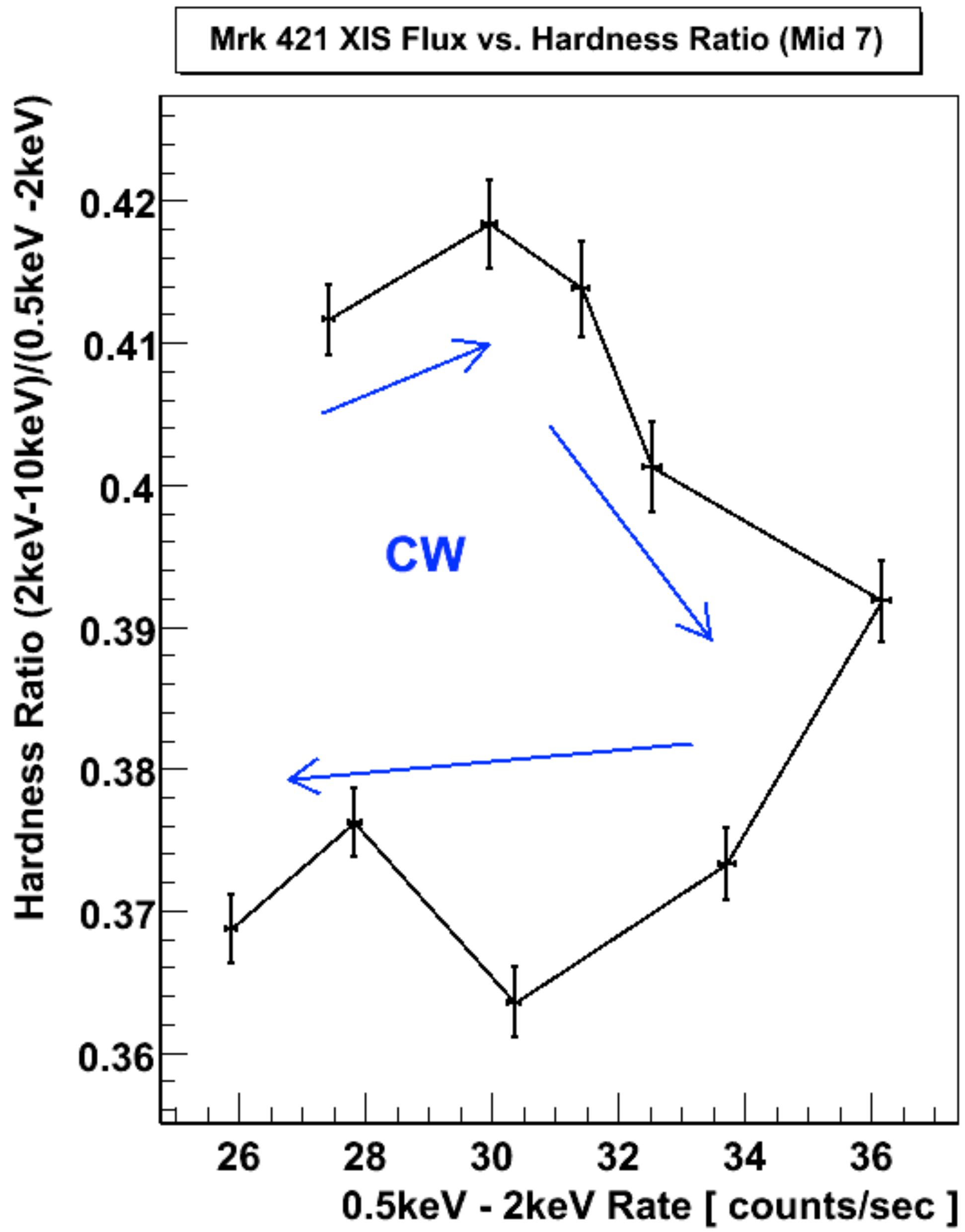
Beilicke, H.K., et al. 2009

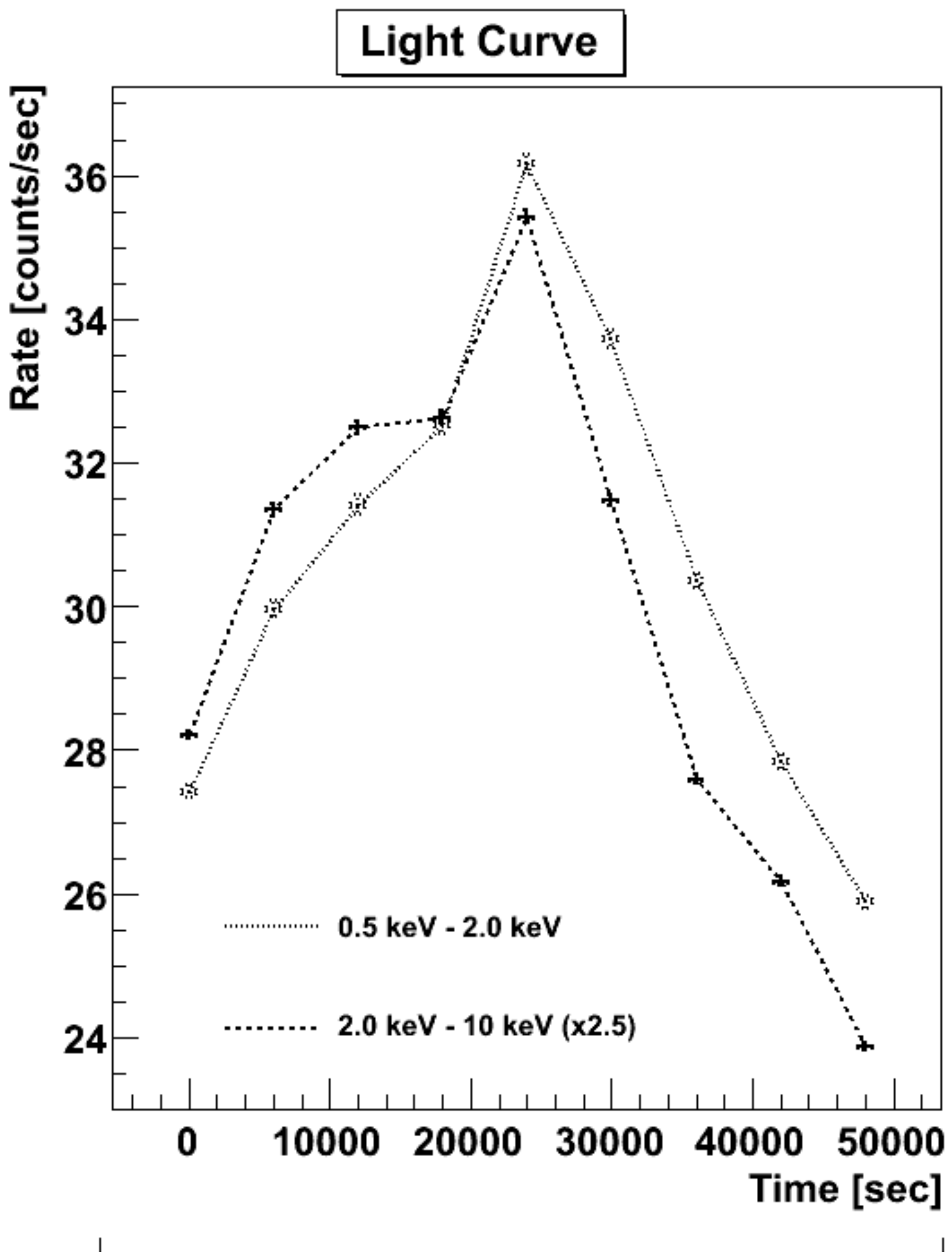
Suzaku Observations of Mrk 421 in May, 2008



Garson, H.K., 2009

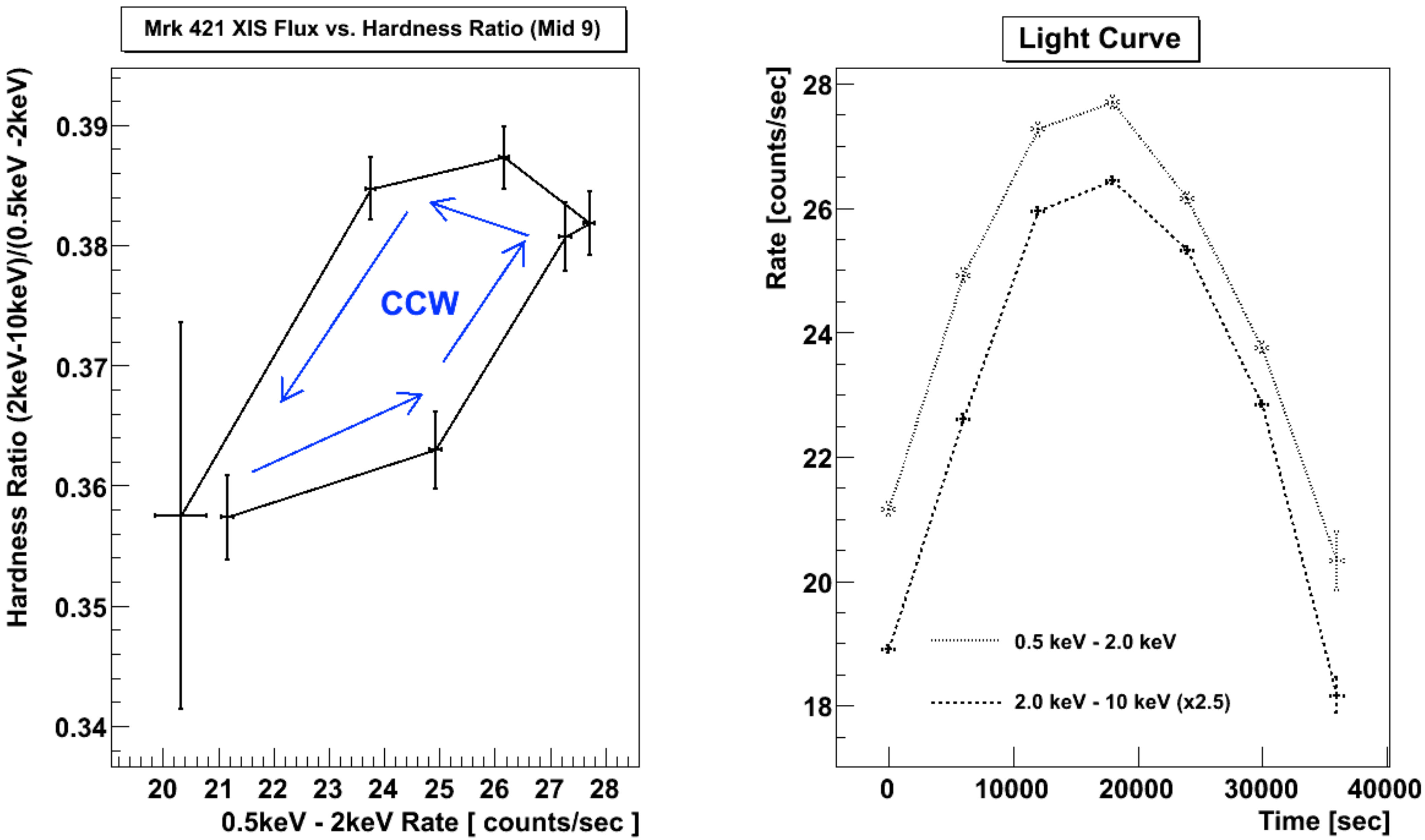
Suzaku Observations of Mrk 421 in May, 2008





Garson, H.K., 2009

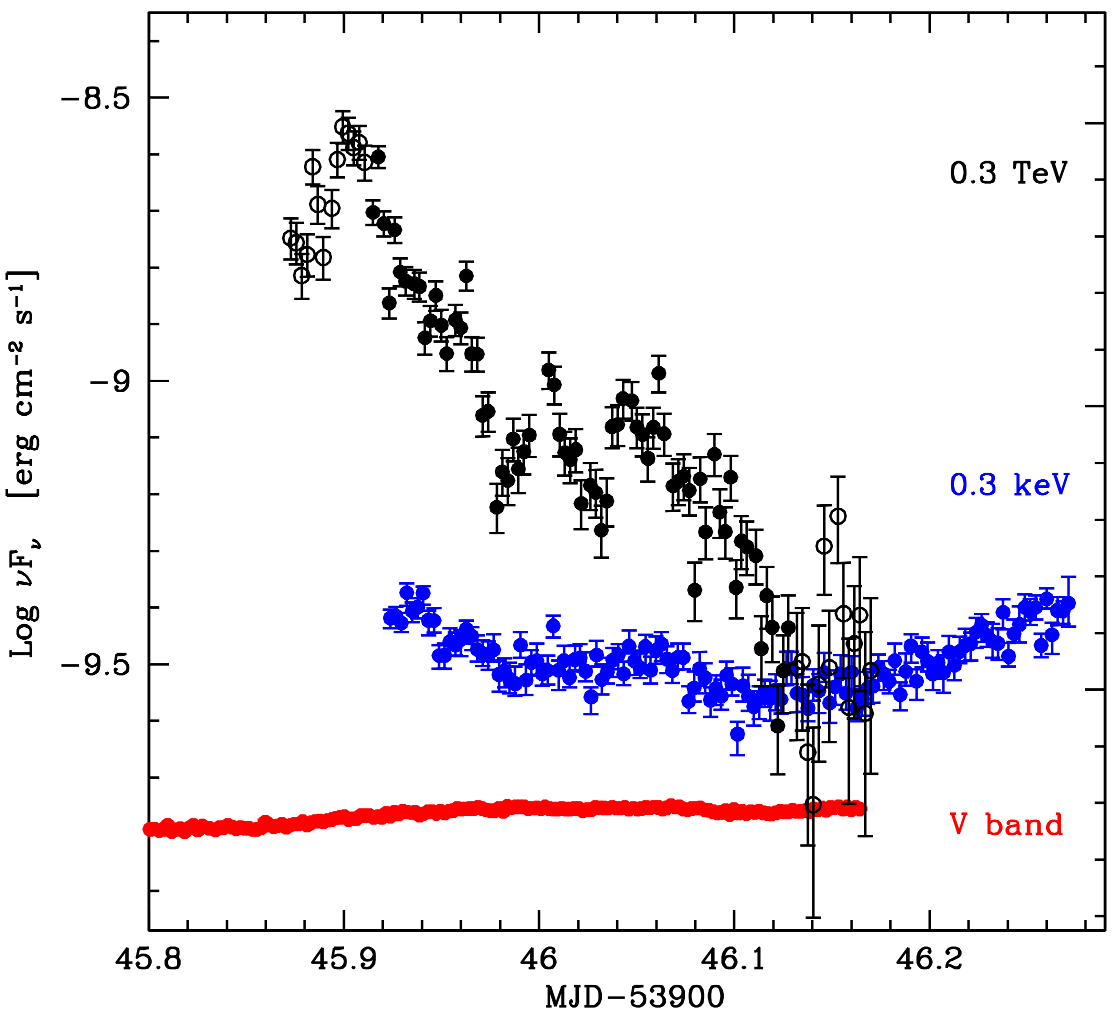
Suzaku Observations of Mrk 421 in May, 2008



Different behavior in different flares...

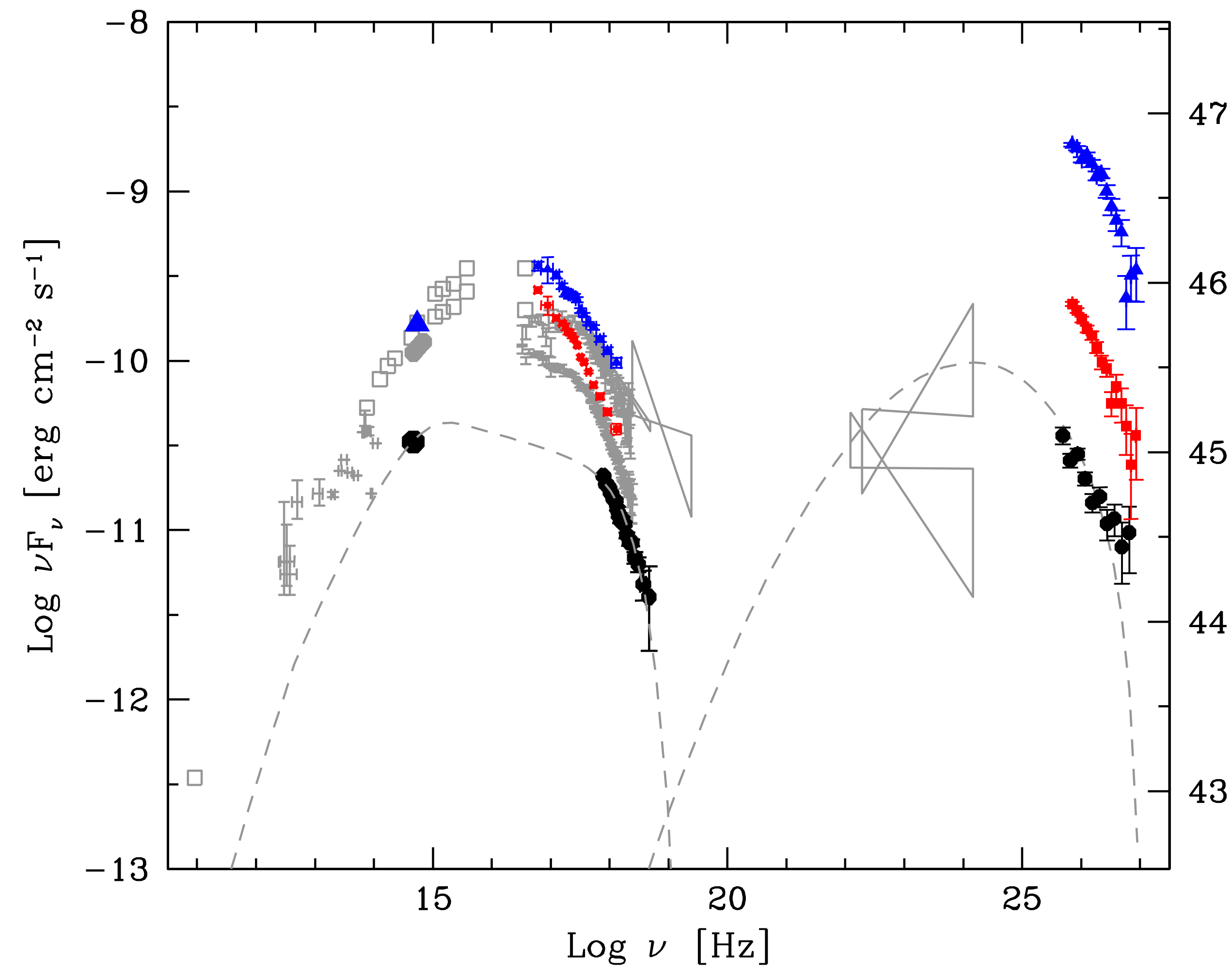
Garson, H.K., 2009

PKS 2155–304 in July 2006



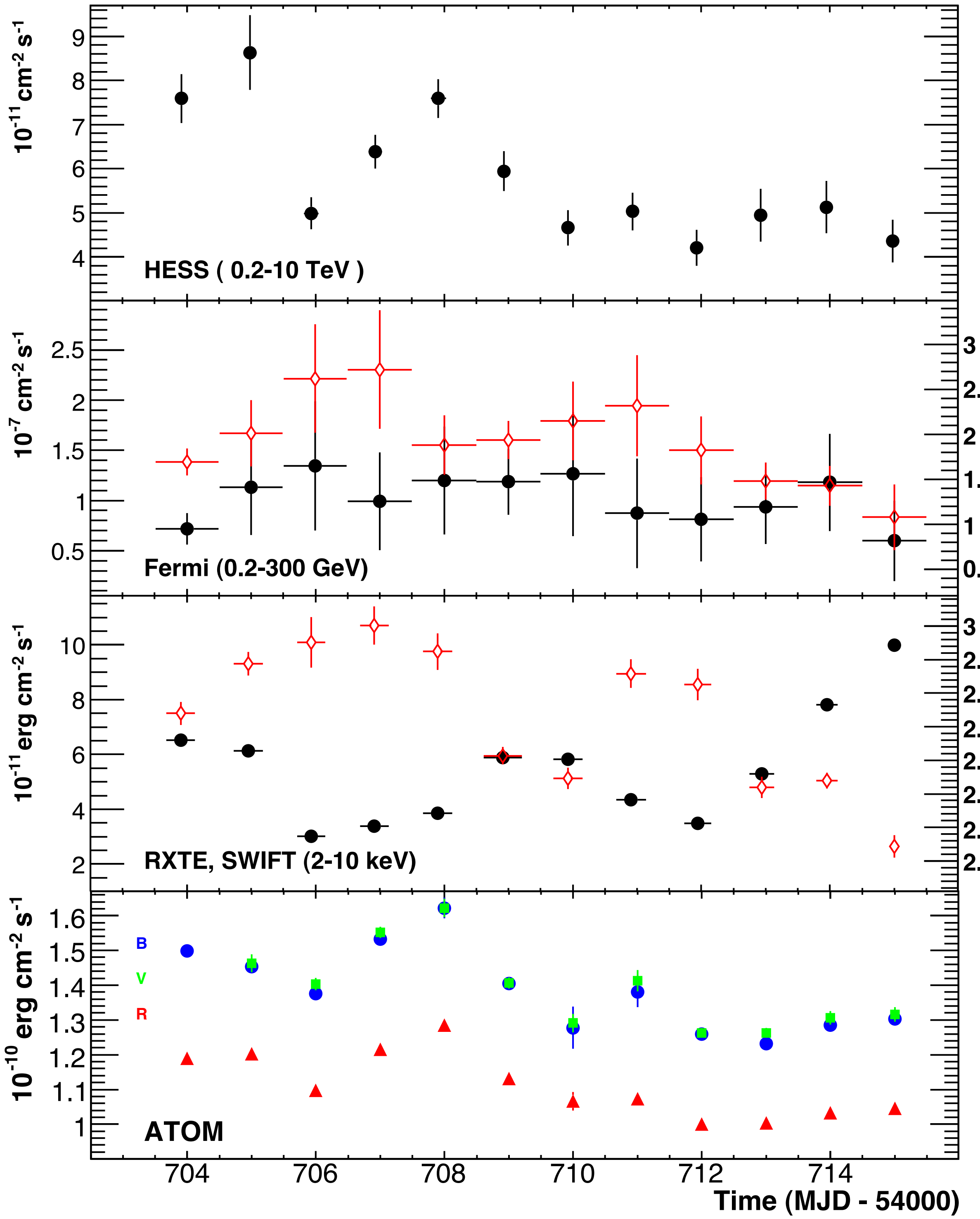
July 29/30, 2006

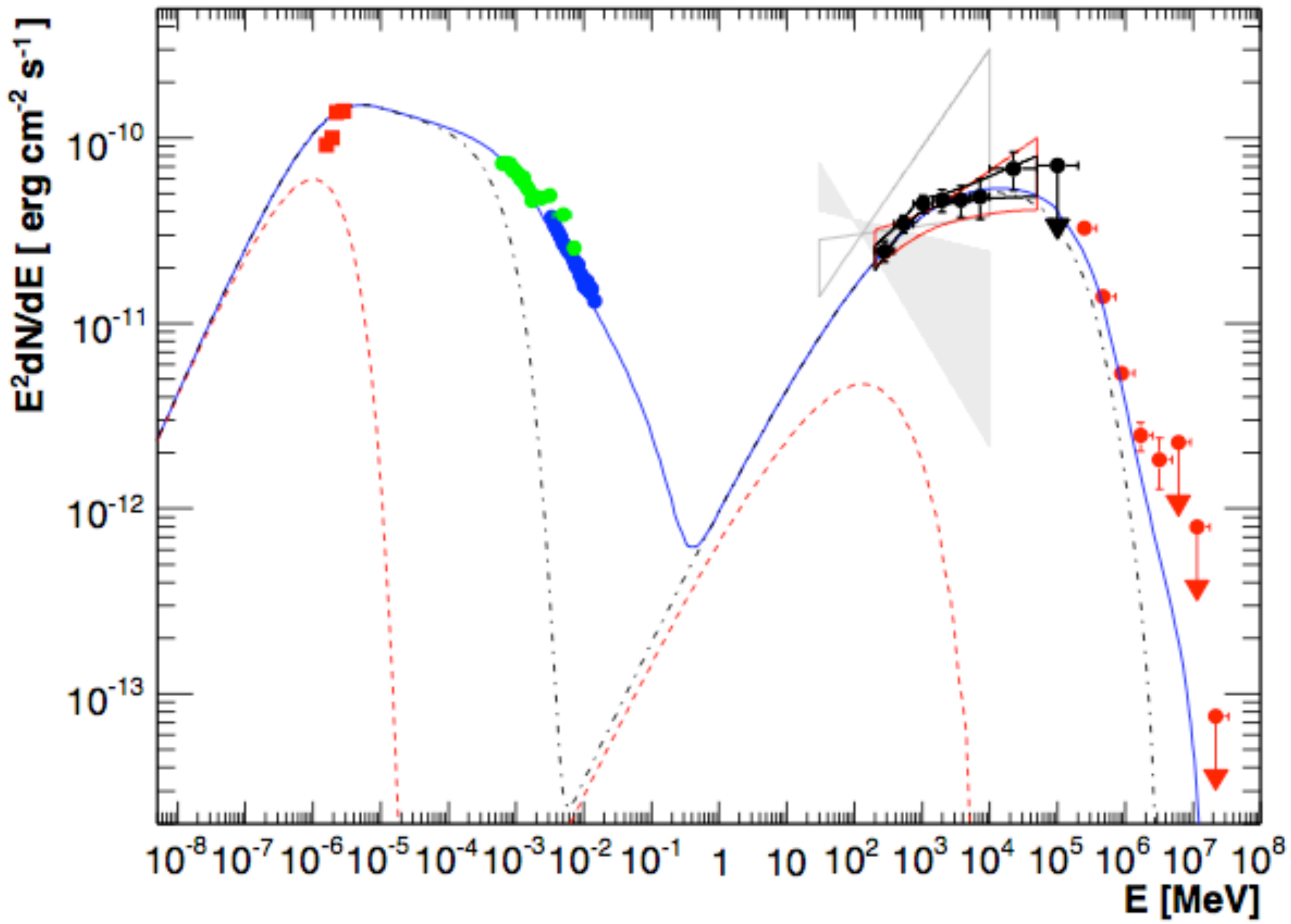
Aharonian et al. 2009



Problems fitting with 1-zone SSC models
⇒ EC models, or 2-zone models.

PKS 2155–304 in August/ September 2008

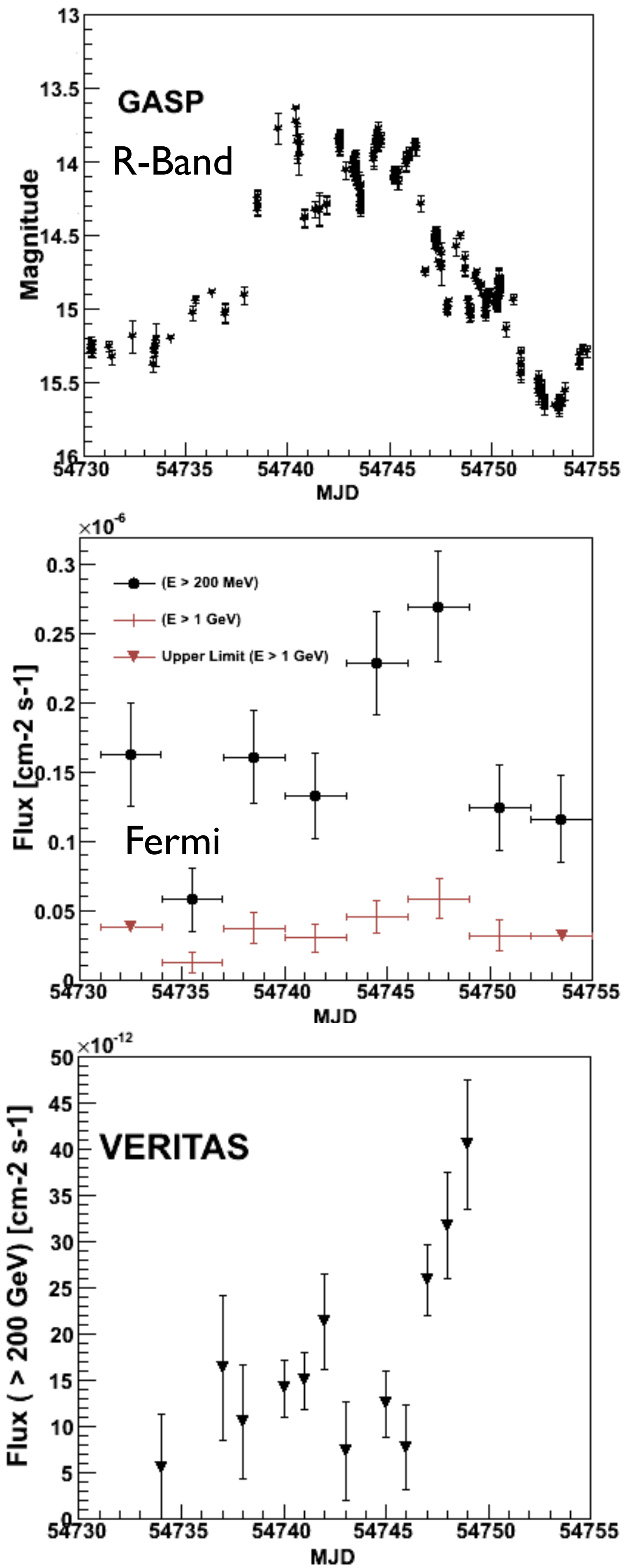




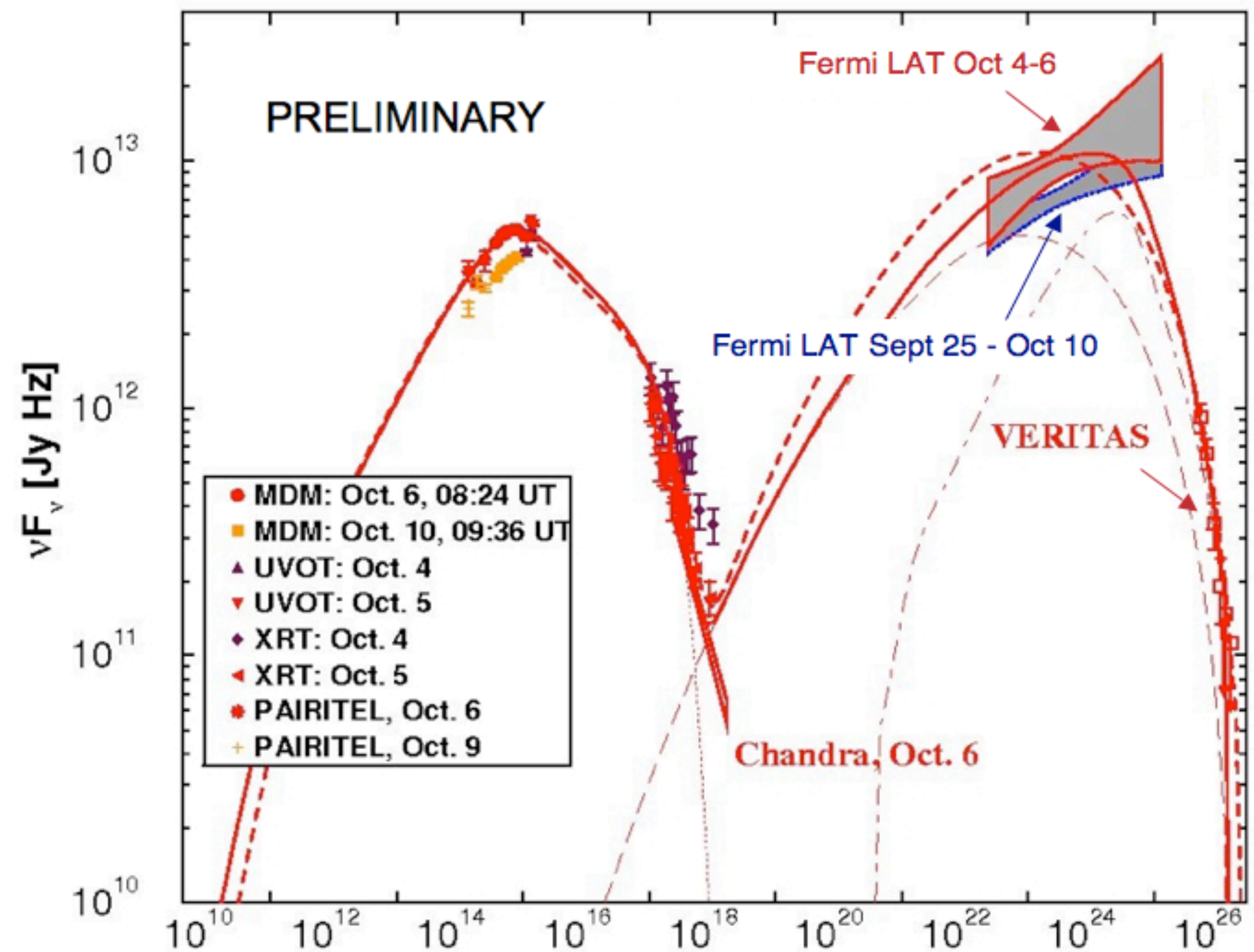
$\gamma_1 = 1.4\times10^4, \gamma_2 = 2.3\times10^5$
$\gamma_{max} = 10^{6.5}$, B= 18mG

L. Gerard for the Fermi LAT team, and the H.E.S.S. Collaboration (2009)

3C 66A (Fermi-VERITAS)



SSC - - EC -



L. Reyes for the Fermi LAT team, and the VERITAS Collaboration (2009)

γ-rays from Starburst Galaxies

- High star formation rate: ~10x Milky Way
- High supernova rate: ~0.1 to ~0.3 / year
- High CR density: ~100x Milky Way
  - Inferred from intense radio-synchrotron emission
- High gas density: ~150 particles / cm^3
- CR hadrons + gas => pions => γ-rays
- CR electrons + ambient photons => γ-rays
- HEGRA & Whipple: VHE flux <10% Crab

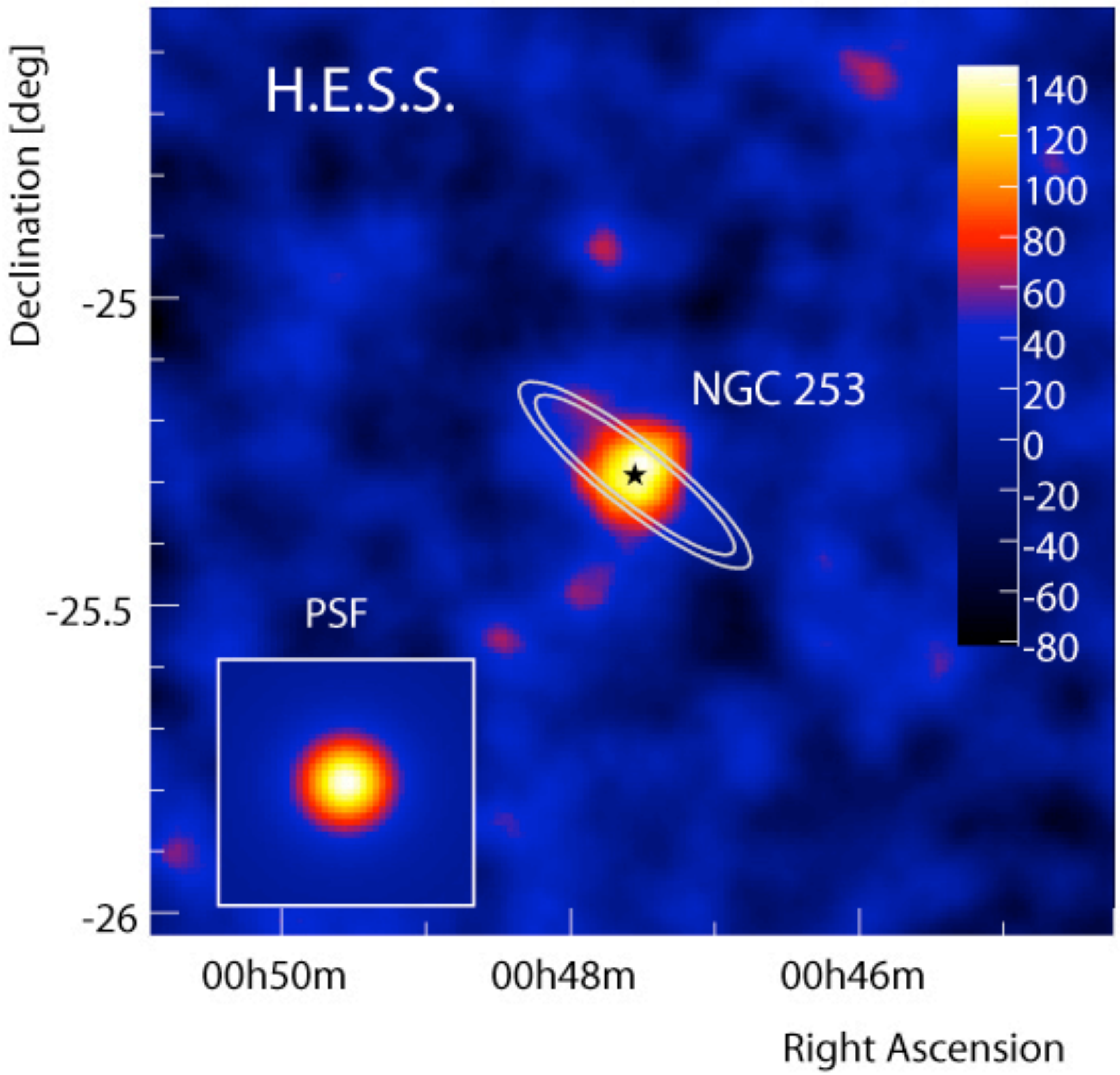
Theoretical predictions:

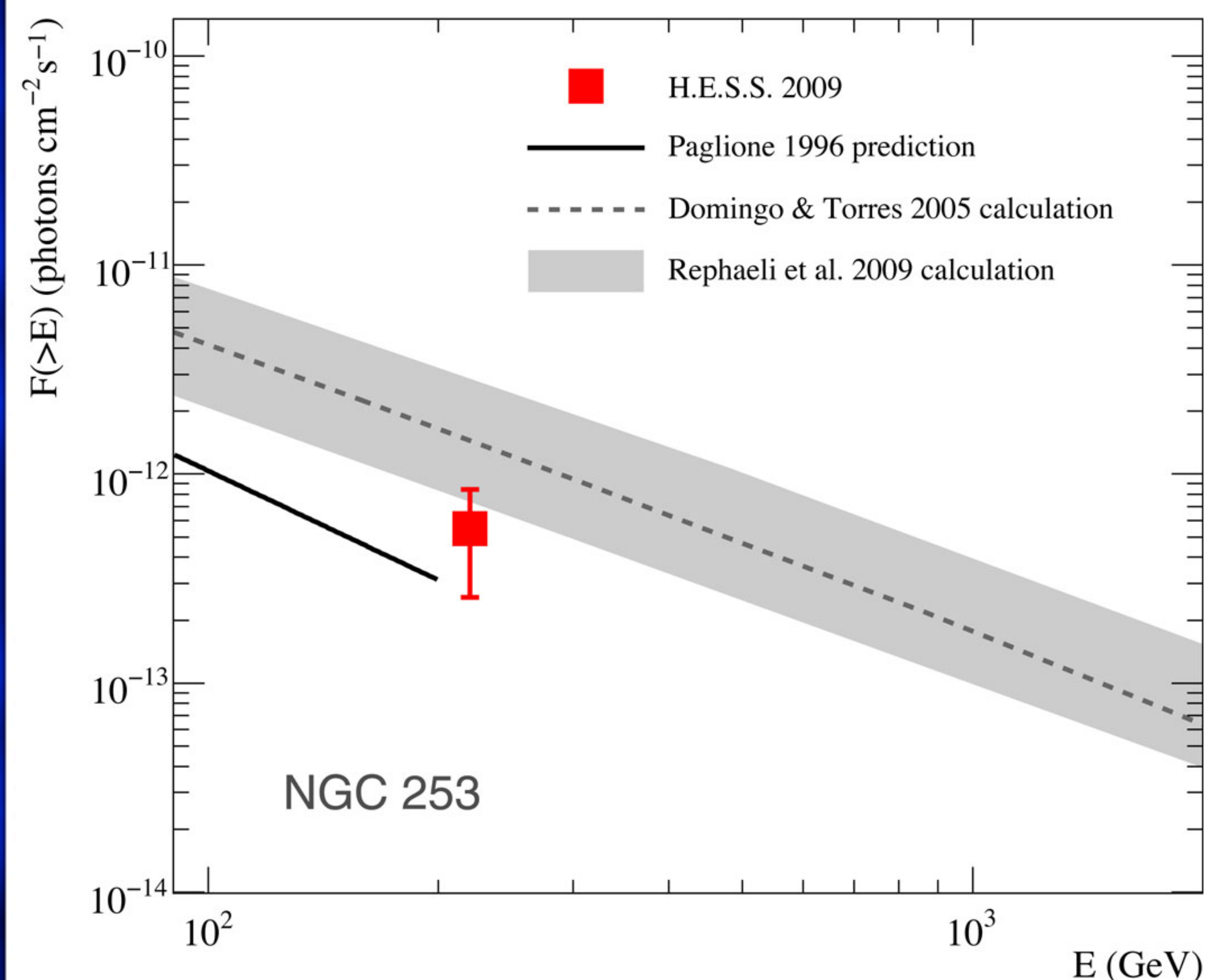
Akyüz 1991, Völk et al. 1996, Pohl 1996, Paglione 1996, Völk 2003, Torres et al. 2004, Zirakashvili & Völk 2005.

γ-rays from Starburst Galaxies

- VERITAS (2007-09): ~137 hrs of M82 observations,
- Standard VERITAS analysis + “hard cuts”:
  - E_{th} ~ 700 GeV; NB: Sensitivity less at θ ~ 39°
- The results are embargoed by the Nature news embargo policy.

γ-rays from Starburst Galaxies!





Acero et al. 2009, science.1178826

Summary - TeV γ-Ray Observations of Extragalactic Objects

- M87:
  - Excellent laboratory: proximity *and* $M_{BH}=6\times10^9\ M_\odot$
    (Cen A: $5.5 \pm 3.0 \times 10^7\ M_\odot$)
  - Evidence that γ-ray emission comes from jet collimation region, $< 50\ R_g / \sin\theta$ from the supermassive Black Hole.
- Blazars:
  - 24 sources, FSRQs, LBLs, IBLs, HBLs.
  - Broadband observations:
    Simple 1-zone SSC models do not work (Mrk 421, 1ES1959+650, PKS 2155–304)
    Flare to flare variations make it difficult to break model degeneracies.
    More exciting Fermi/TeV results soon.
- Starburst galaxies are a new class of VHE γ-ray emitters.