MAGIC Observations of Extragalactic Sources

Spectra, Variability, and Puzzles

Steve Shore for the MAGIC Collaboration

Dip. di Fisica *Enrico Fermi*, Univ. di Pisa and INFN/Pisa

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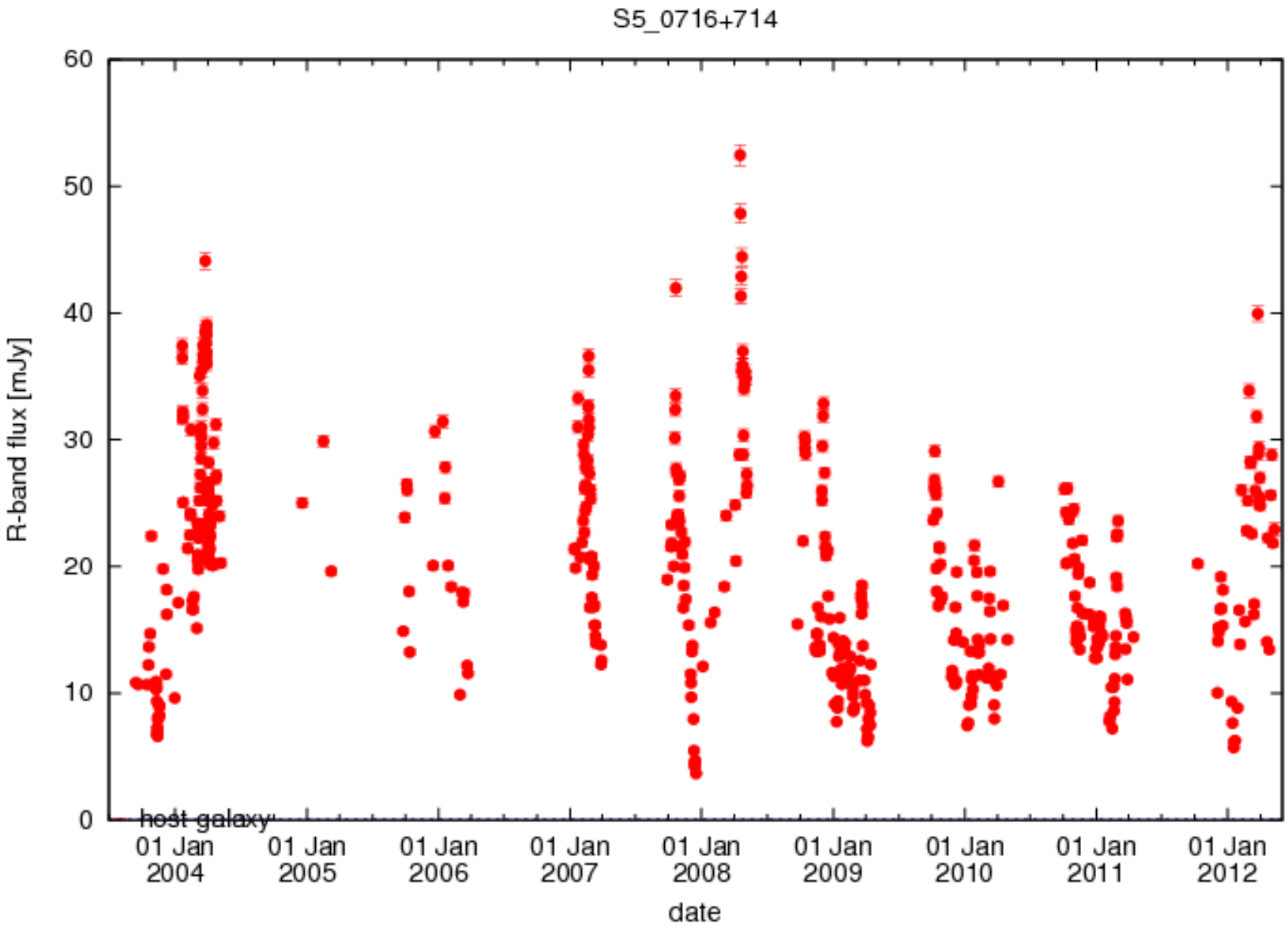
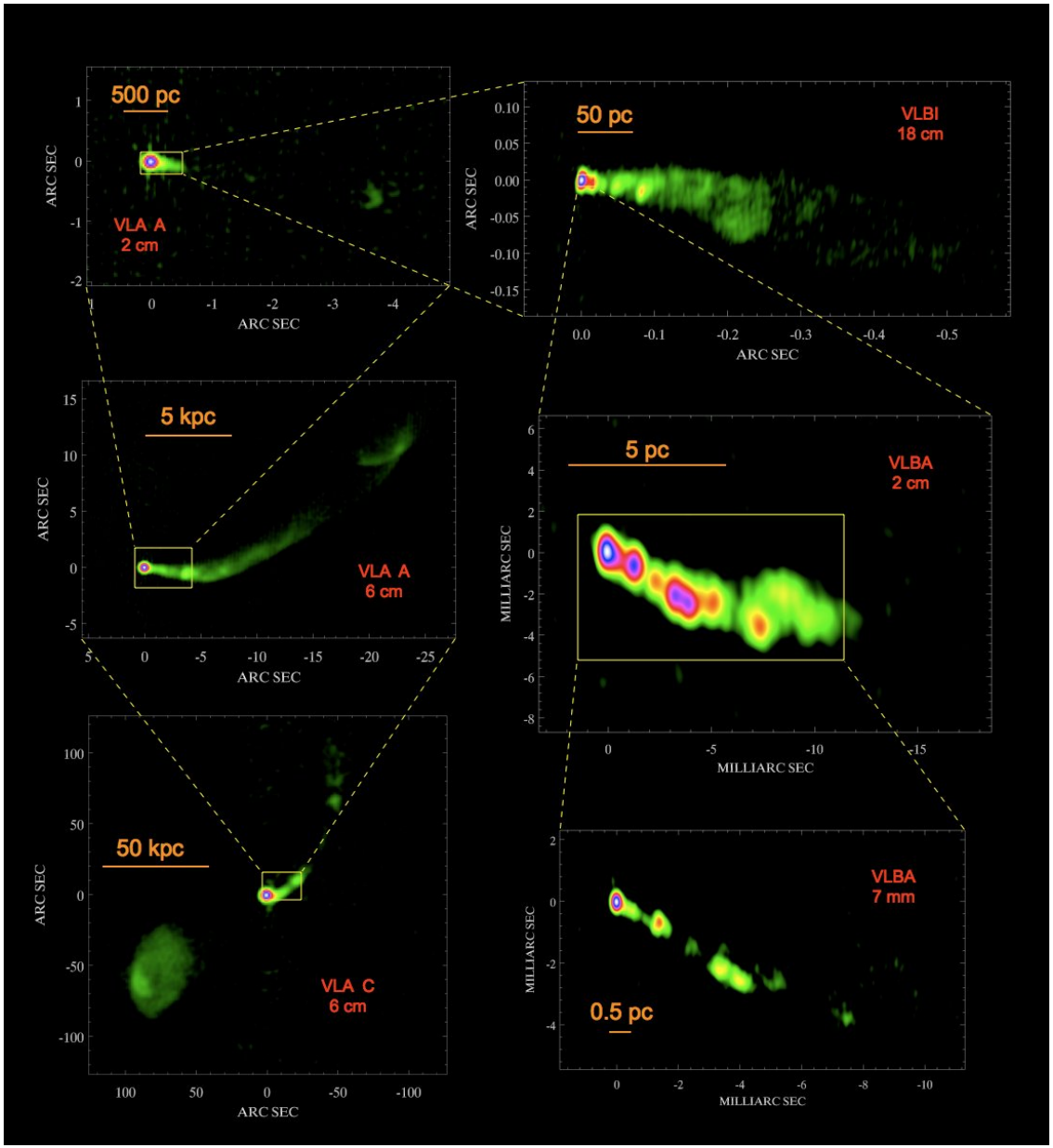
Some vocabulary

- *Blazar* composite class of active galactic nuclei (AGN) comprising the flat spectrum radio galaxies and the BL Lac objects. Highly (e.g. violently!) variable (perhaps better said, they're never not in outburst) with varying contributions of the host galaxy to the photometry and spectrum.
- *Unified model*: depending on the viewing angle to the radio jet, relativistic Doppler boosting factors ($>$ a few, as high as 50) intensifies the jet/galaxy surface brightness ratio.
- *Central engine*: Super Massive Black Holes (SMBH), 0.01-10$GM_{\odot}$, imbedded in a messy nuclear environment, surrounded by an accretion torus and (depending on the type) accompanied by intense massive star formation.

S5 0716+714 optical flux variability

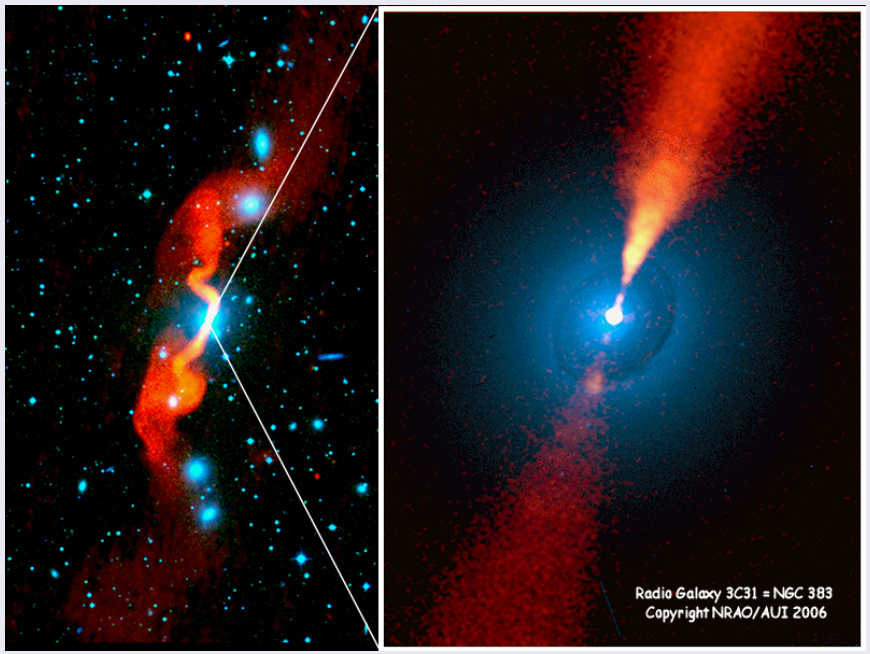


Example of FSRQ: 3C 120 on all scales (Gomez, Walker)

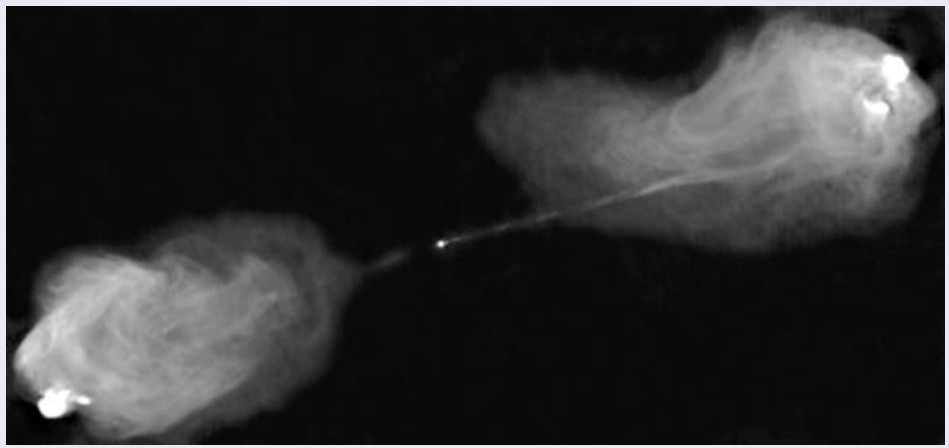


Fanaroff-Riley Classification: FR I and II: The large scale radio structure correlates with the integrated radio luminosity of the lobes and jet; the empirical (still) dividing line (at 178 MHz in the original study) is $\sim 10^{26}$W (sr Hz)$^{-1}$, but this varies with frequency.

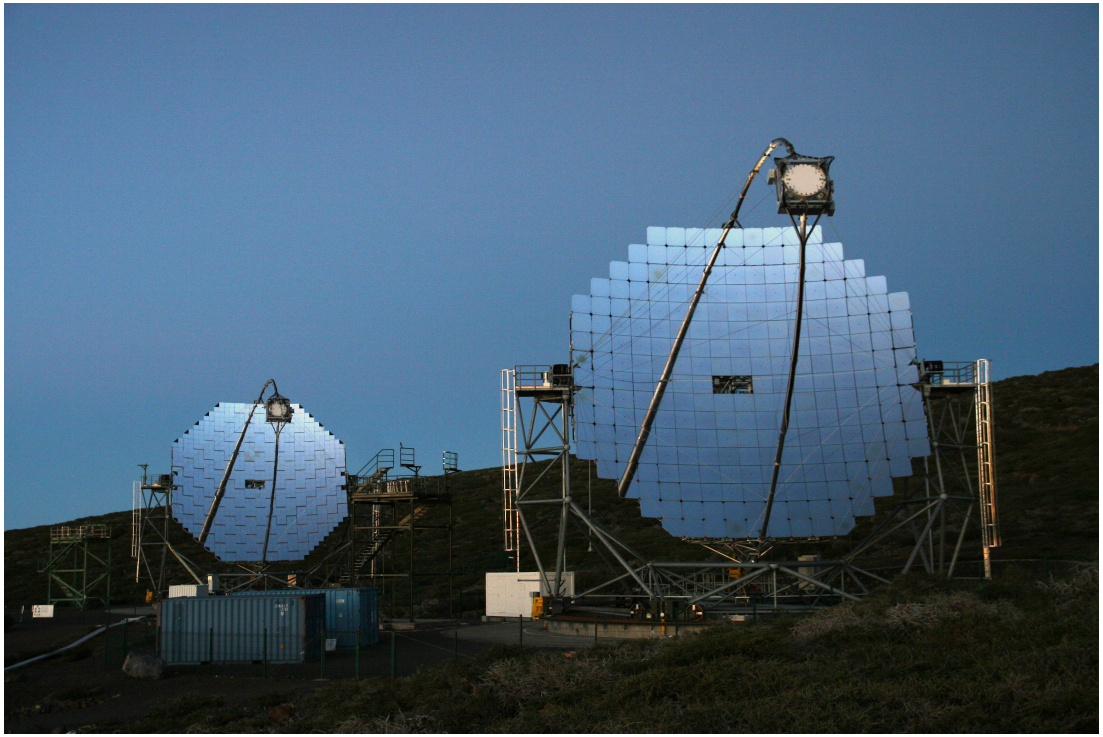
3C 31 FR I (VLA, Bridle)



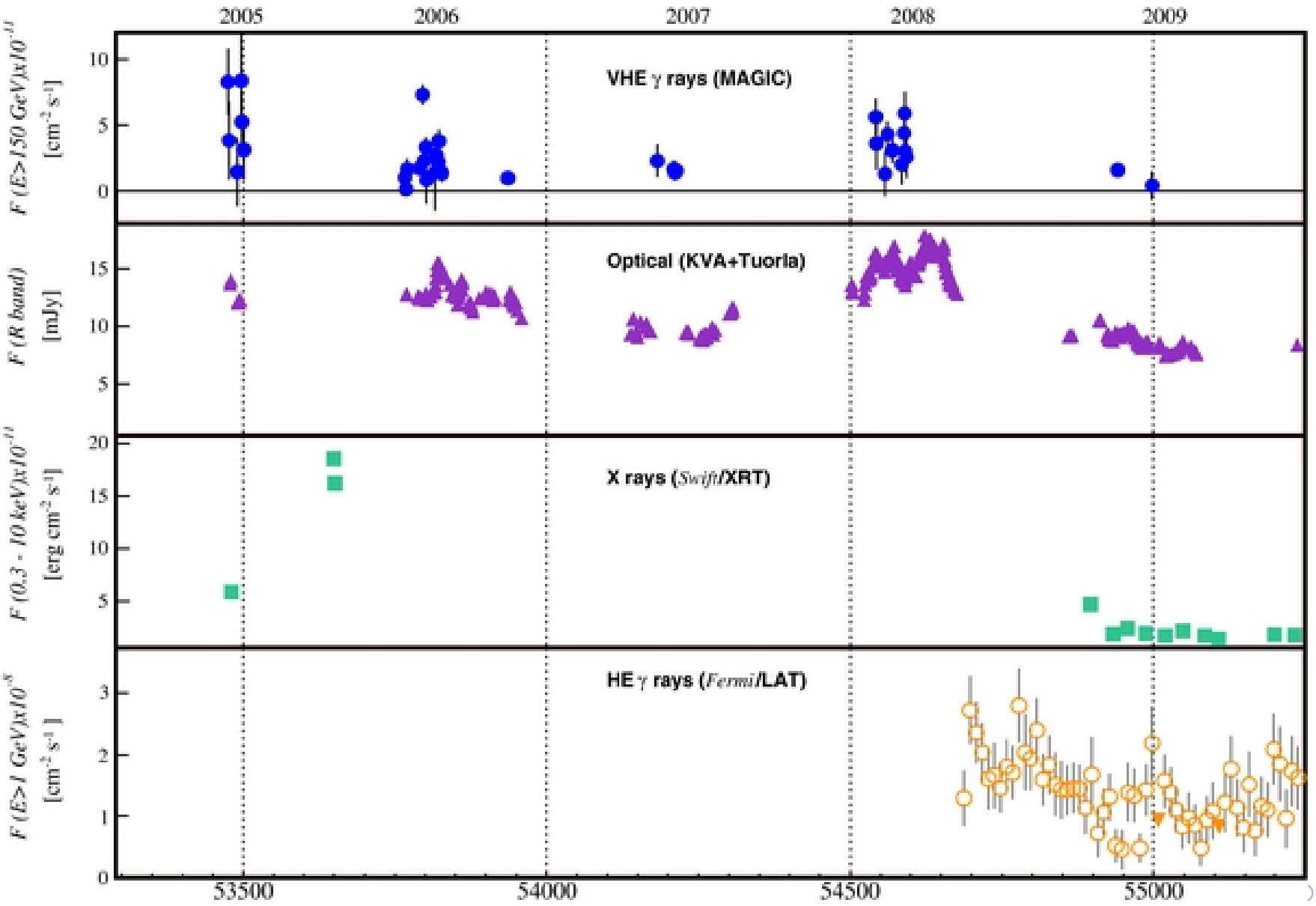
Cyg A FR II (VLA, Carilli et al)

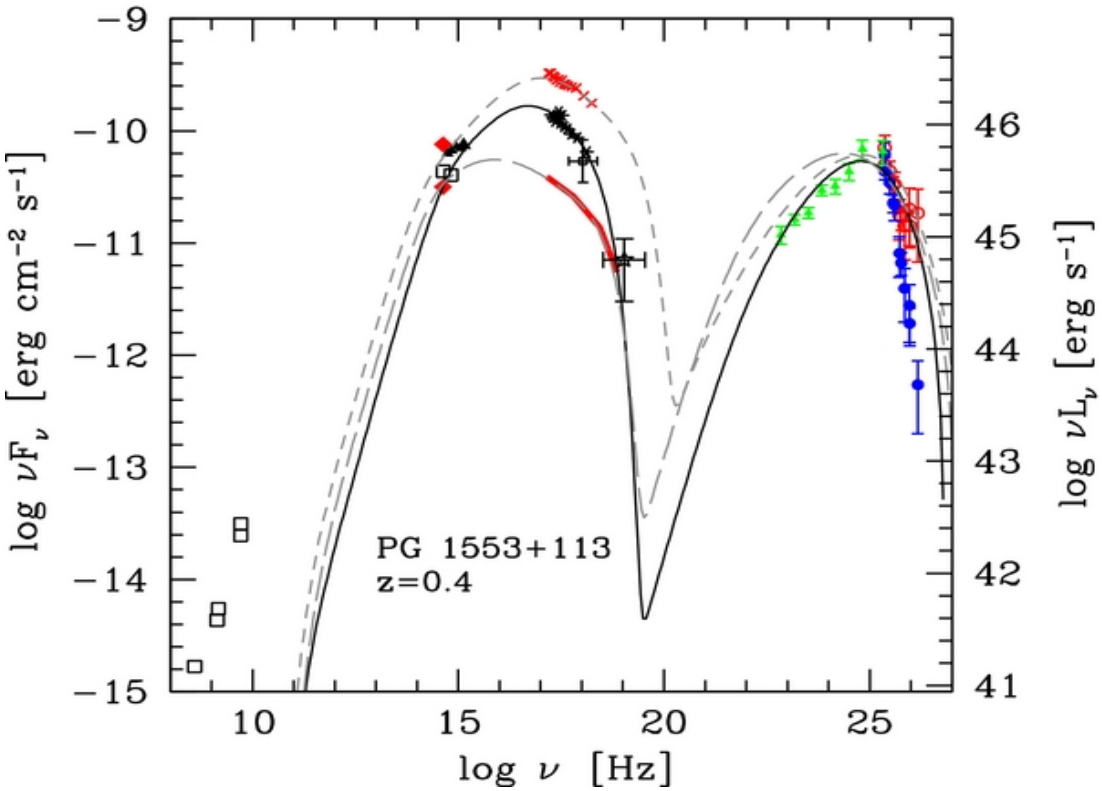


The Major Atmospheric Gamma-ray Imaging Cherenkov Telescopes (MAGIC)


MAGIC (stereo since Fall 2009) is two 17 m IACTs sited on La Palma, 2200 a.s.l. The individual camera FOV diameter of 3.5°, $(psf) \sim 0.1°$ with lower cutoff of 50 GeV in standard trigger mode (currently the lowest) and sensitivity in stereo mode $< 0.8\%$ C.U. above 300 GeV in 50 hrs of observations (e.g. 2012,Astrpart.Phys.,35,435).

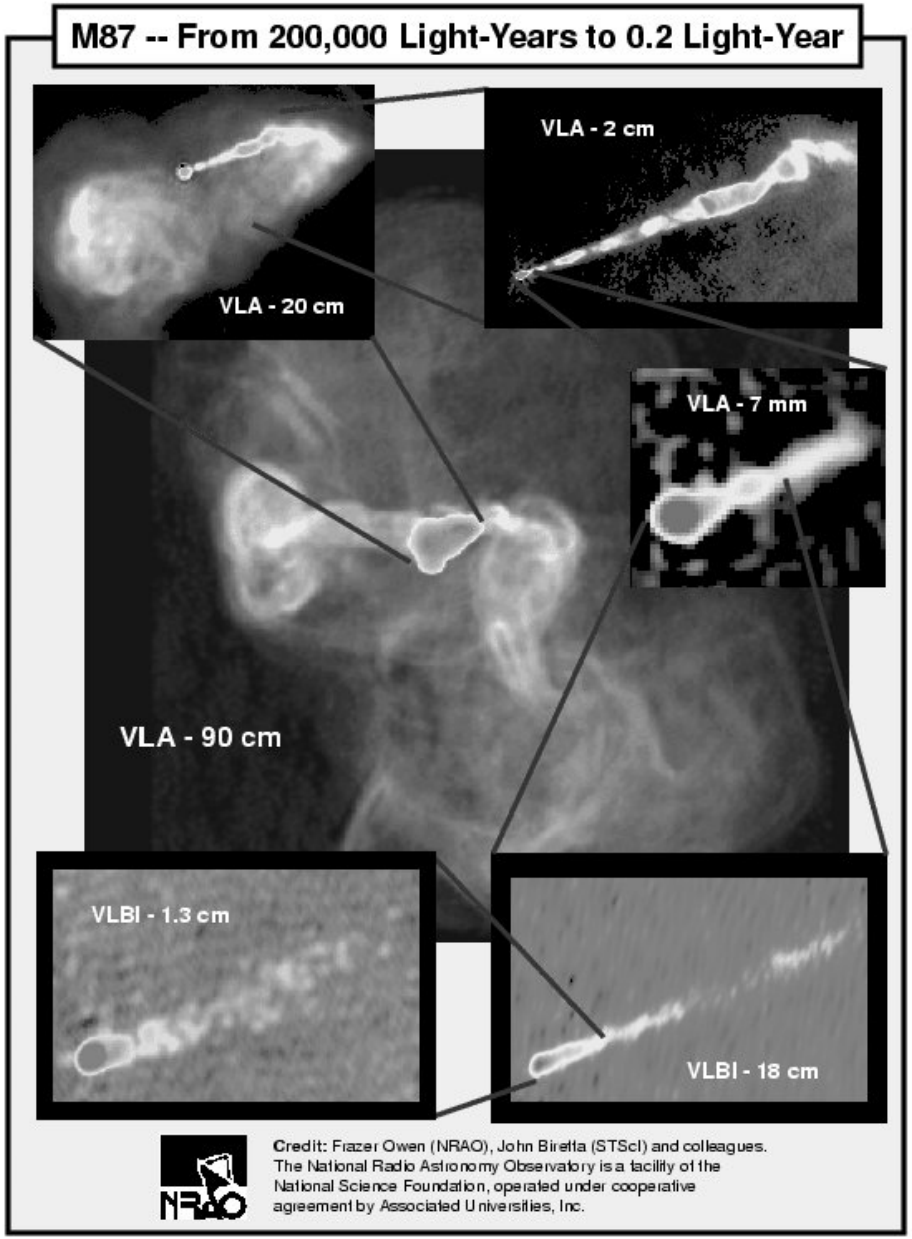
2012, ApJ 2012, 748, 46: PG 1553+113: five years of observations with MAGIC – multiwavelength light curve





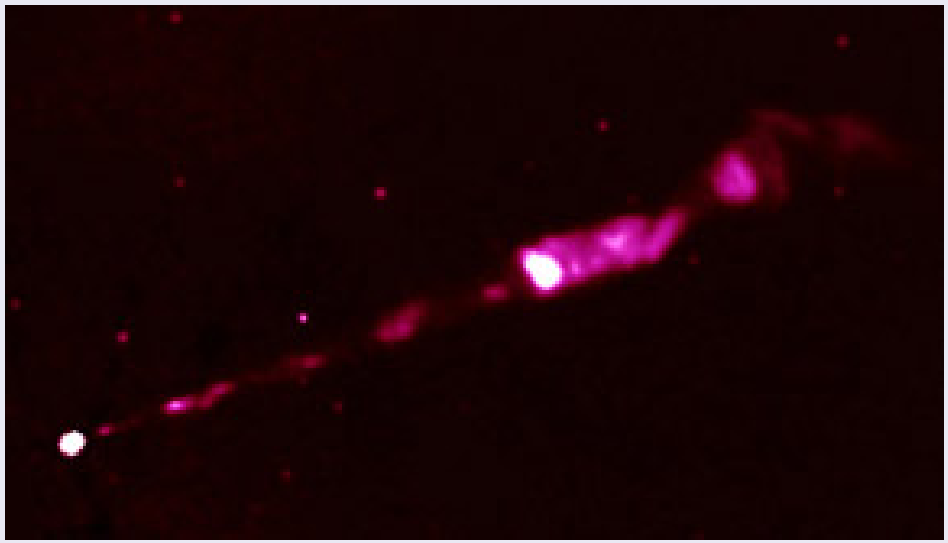
Radio-optical (open black squares). KVA optical minimum and maximum flux 2005-2009 (red dimonds), Swift/UVOT (filled black triangles). Swift/XRT 2005 (high flux, red crosses; intermediate, black asterisks) and *Suzaku* 2006 (continuous red line). Swift/BAT average 14-150 keV flux (black star), average RXTE/ASM flux 2008 Mar. 1- May 31 (small black square), Fermi-LAT spectrum averaged over 200 days (2008 Aug.-2009 Feb.) (green triangles). MAGIC, 2005-2006, 2007-2009 (filled circles) and with EBL correction (red open circles).

M 87 = 3C 274: from marcsec to arcmin, radio

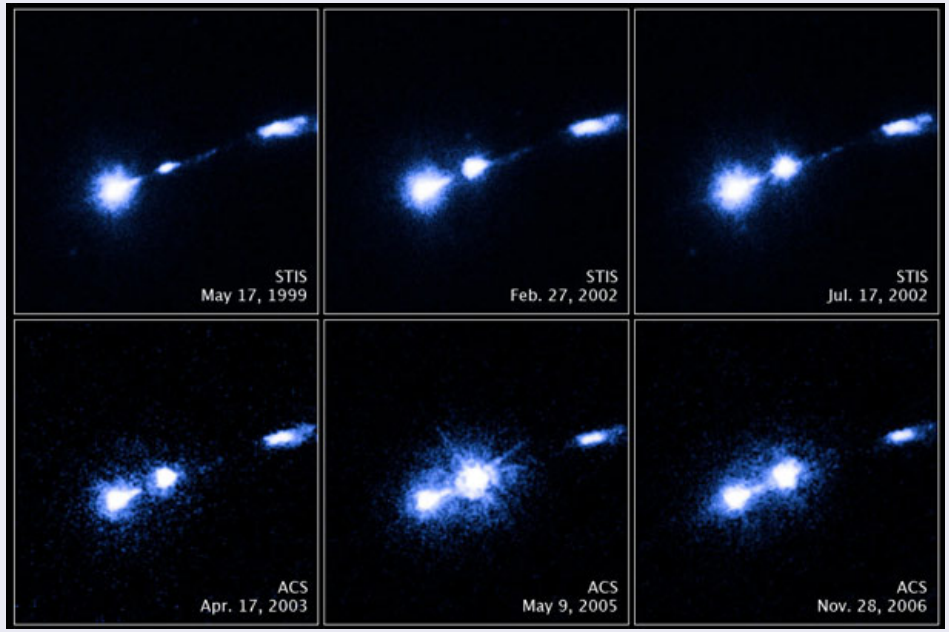


M 87 – the jet from parsec to kpc

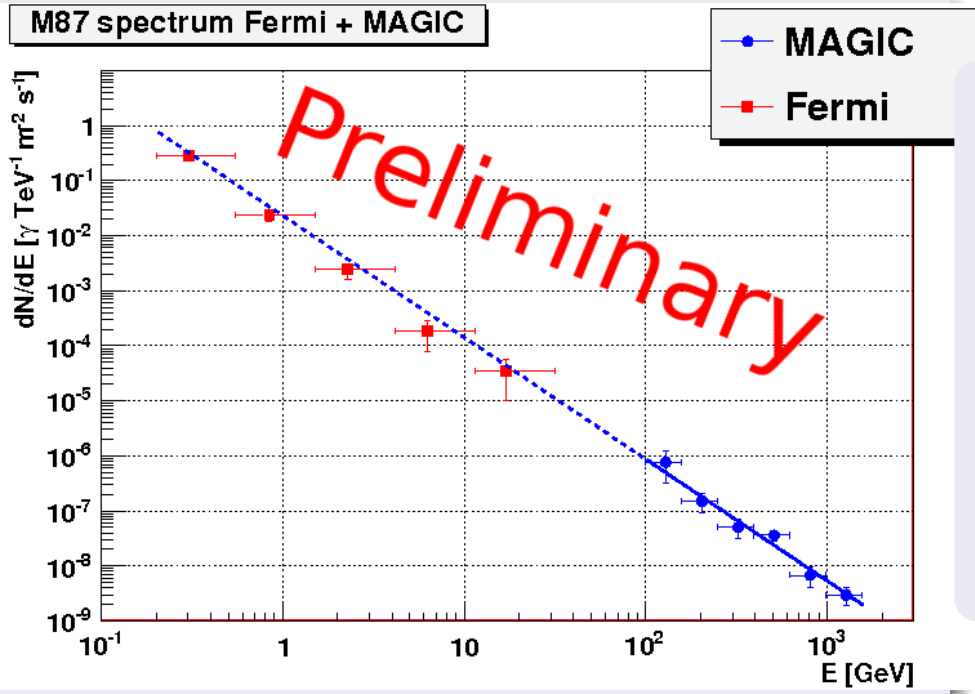
Internal structure, core-spine with shocks



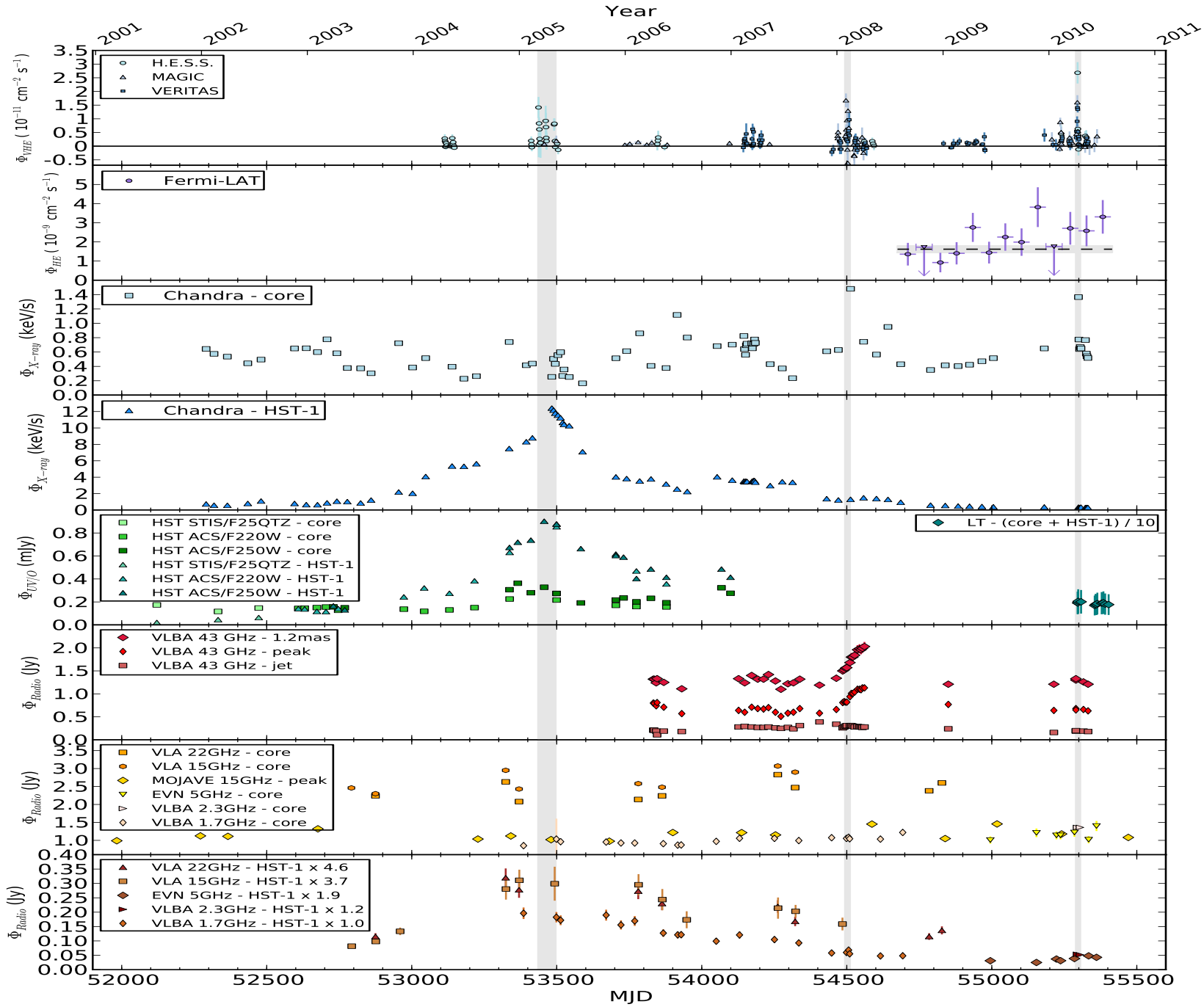
HST: variable UV/optical inner knots



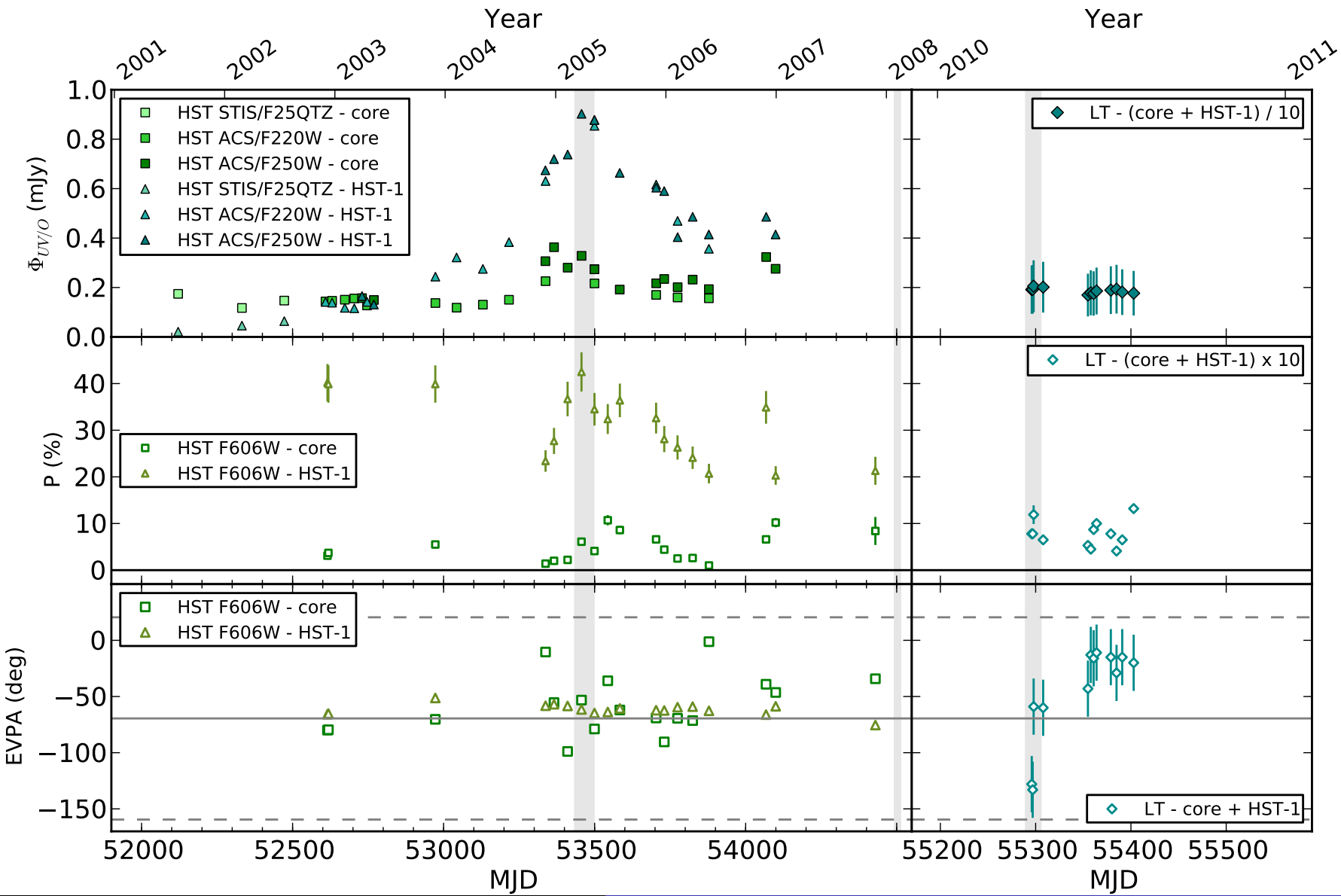
2012, ApJ, 746, id. 151: H.E.S.S., MAGIC, VERITAS – The 2010 very high energy gamma-ray flare 10 years of multi-wavelength observations of M 87



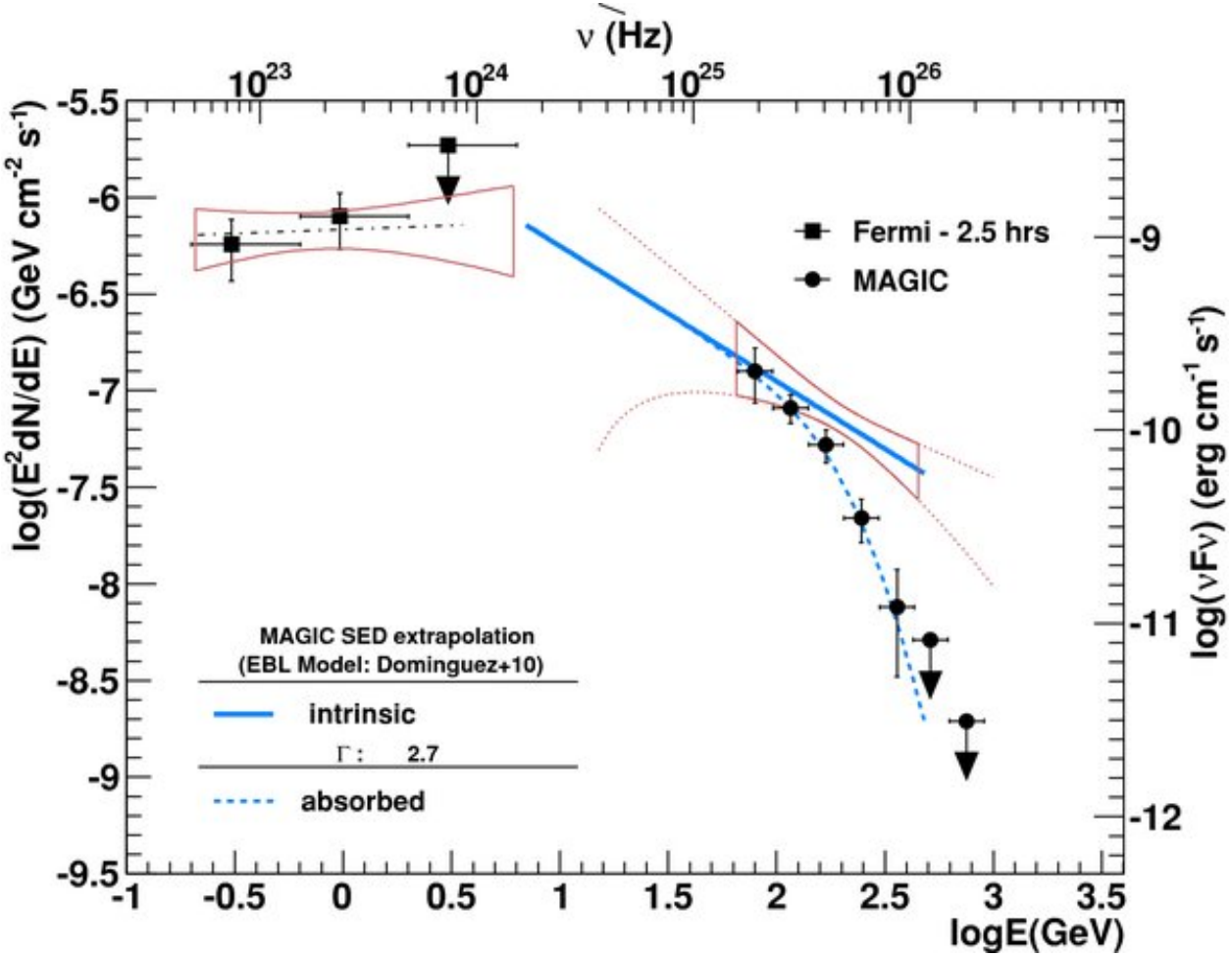
On source, 150 h during 2005 and 2007: MAGIC-I , XR, and Fermi-LAT. No flaring activity , persistent low emission state (confidence level ≈7). A VHE power law with a unique $\Gamma = 2.21 \pm 0.2$ that extrapolates without discernible change into the GeV energy range of the FermiLAT spectrum, four decades.


Year
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
H.E.S.S.
MAGIC
VERITAS
Φ_{VHE} (10^{-11} cm^{-2} s^{-1})
Fermi-LAT
Φ_{HE} (10^{-9} cm^{-2} s^{-1})
Chandra - core
Φ_{X-ray} (keV/s)
Chandra - HST-1
Φ_{X-ray} (keV/s)
HST STIS/F25QTZ - core
HST ACS/F220W - core
HST ACS/F250W - core
HST STIS/F25QTZ - HST-1
HST ACS/F220W - HST-1
HST ACS/F250W - HST-1
LT - (core + HST-1) / 10
$\Phi_{UV/O}$ (mJy)
VLBA 43 GHz - 1.2mas
VLBA 43 GHz - peak
VLBA 43 GHz - jet
Φ_{Radio} (Jy)
VLA 22GHz - core
VLA 15GHz - core
MOJAVE 15GHz - peak
EVN 5GHz - core
VLBA 2.3GHz - core
VLBA 1.7GHz - core
Φ_{Radio} (Jy)
VLA 22GHz - HST-1 x 4.6
VLA 15GHz - HST-1 x 3.7
EVN 5GHz - HST-1 x 1.9
VLBA 2.3GHz - HST-1 x 1.2
VLBA 1.7GHz - HST-1 x 1.0
Φ_{Radio} (Jy)
MJD

Multiwavelength light curve of M87: polarization



PKS 1222+21 = 4C+21.35 – spectrum



Central cD Flat Spectrum radio galaxies (NGC 5128 = Cen A, H.E.S.S.) and NGC 1275 (= Per A)

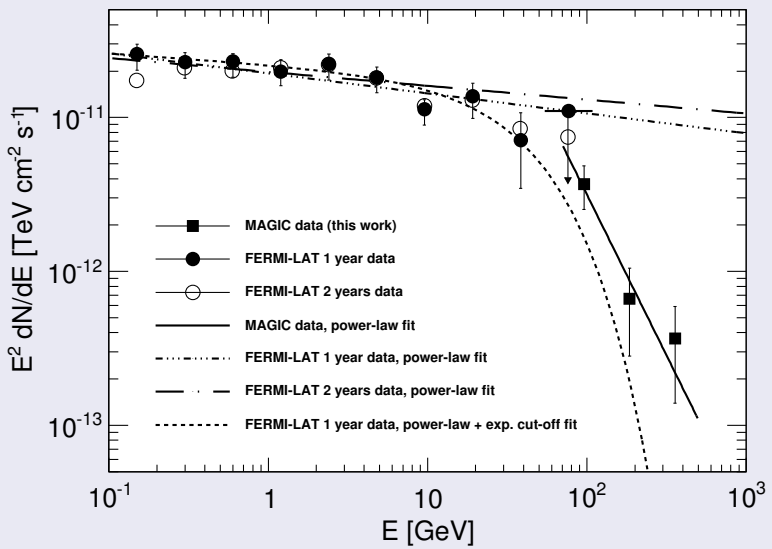
NGC 1275

NGC 5128

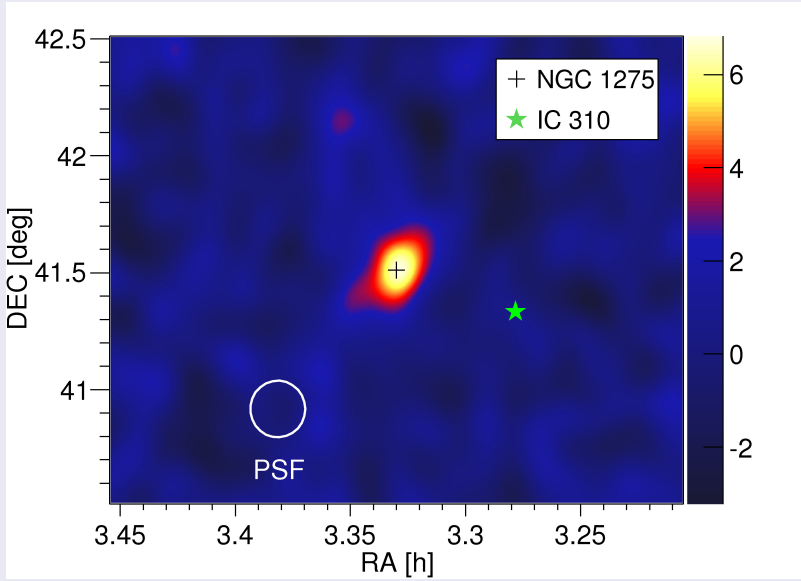
"Local" galaxies thus far detected at VHE (> 100 GeV): NGC 1275 = Per A, M 87 (Aharonian et al., 2003, 2006; Albert et al., 2008a; Acciari et al., 2008), NGC 5128 = Cen A (Aharonian et al., 2009), and IC 310 (Aleksić et al., 2010b).

- NGC 1275: MAGIC (2010-11) – the spectrum 70 GeV and 500 GeV is a single power law, $\Gamma = -4.1 \pm 0.7_{stat} \pm 0.3_{syst}$, *Fermi*–LAT above 100 MeV $\Gamma \simeq -2.1$.
- Broken power law *or* exponential cutoff in the intermediate (10-100 GeV) range tens of GeV in NGC 1275. No evidence (in a few months) of variability above 100 GeV
- In the same field, IC 310 (first detection paper: 2010,A pJ, 723, L207) was *not* detected in late 2010- early 2011, about a factor ~ 3 lower than the mean flux from MAGIC (10/2009-2/2010); there is variation on longer (years) timescale.

NGC 1275: spectrum in 2010-11

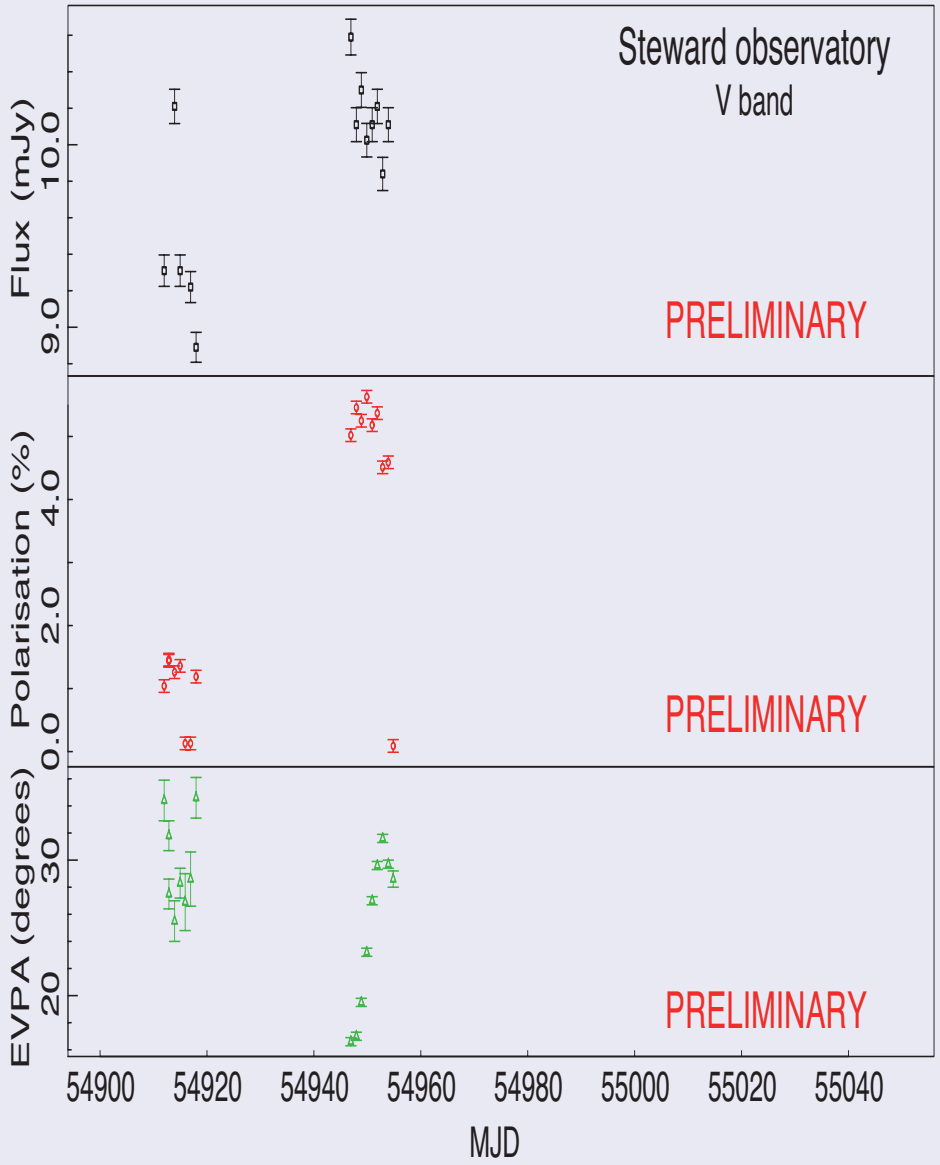


Sky image of Per cluster core

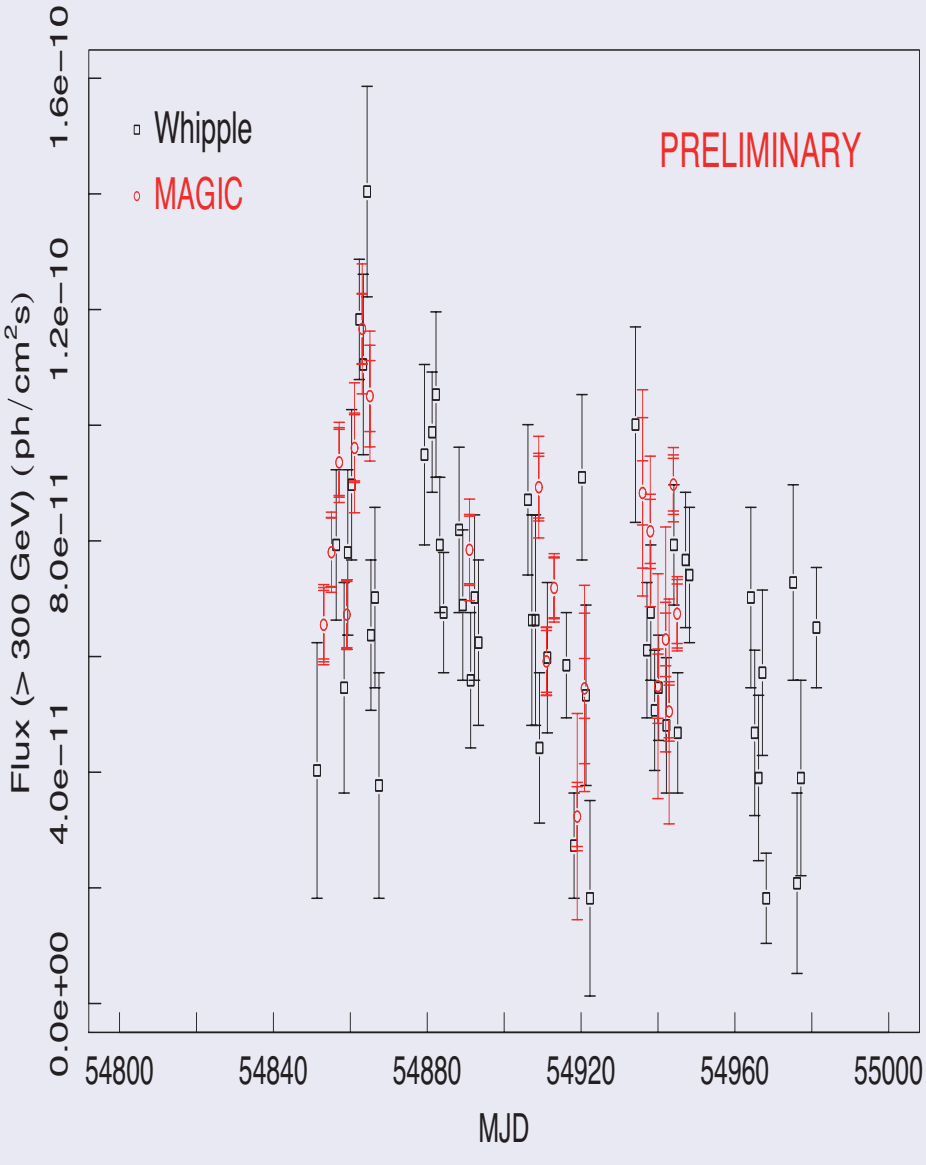


Mkn 501: correlations with magnetic field structure?

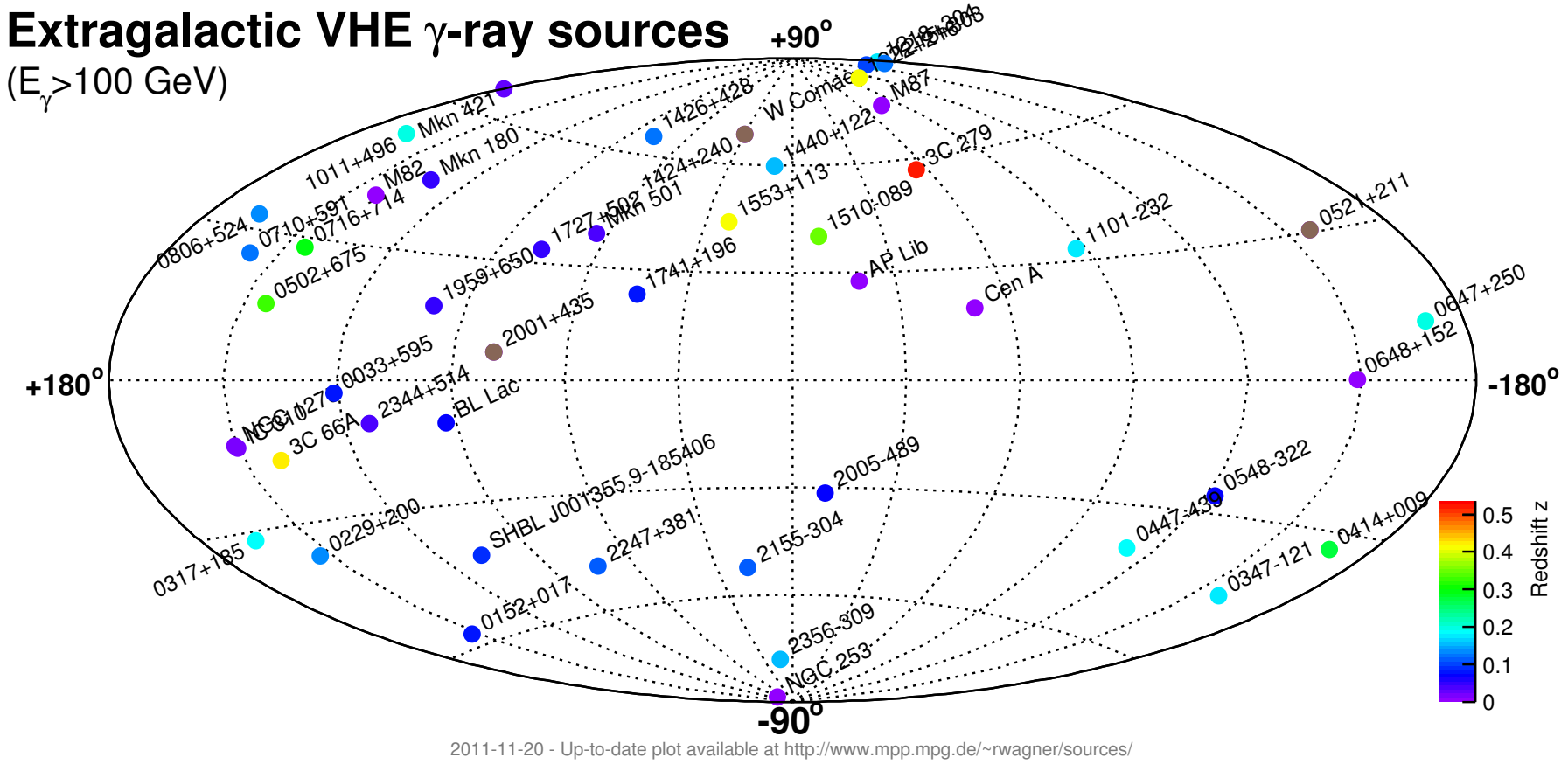
Optical polarimetry during flare



The flaring states. Whipple-MAGIC



The extragalactic sources known to date >100 GeV

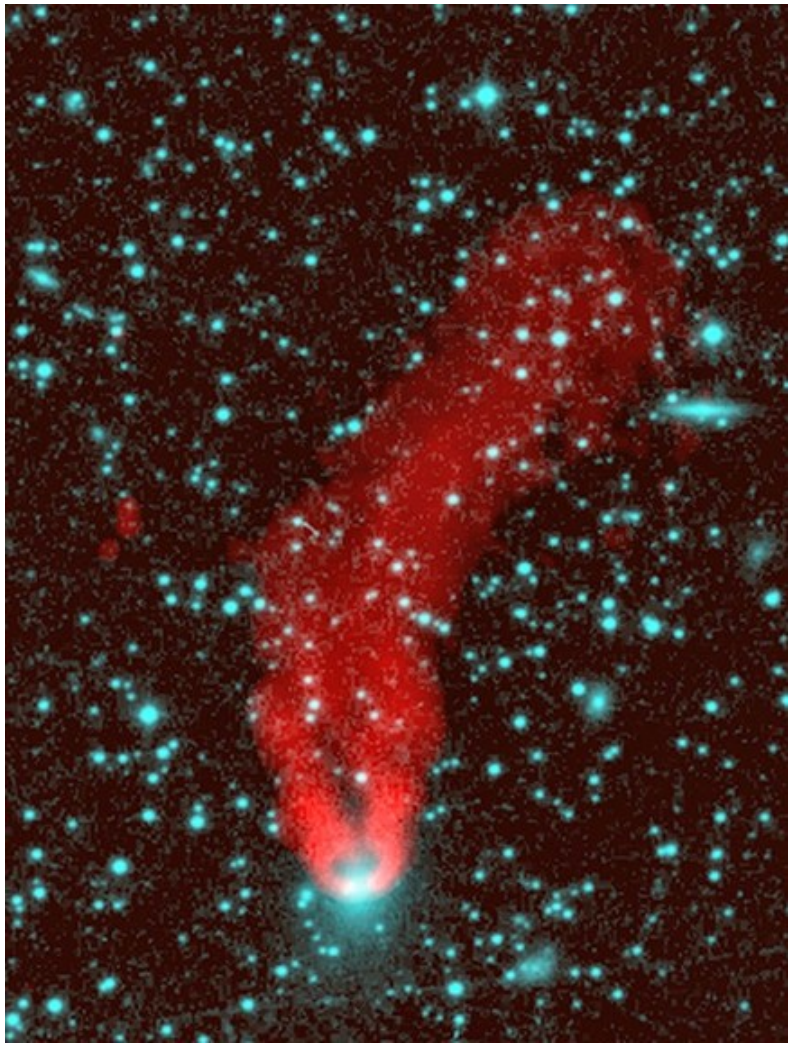


2011-11-20 - Up-to-date plot available at http://www.mpp.mpg.de/~rwagner/sources/

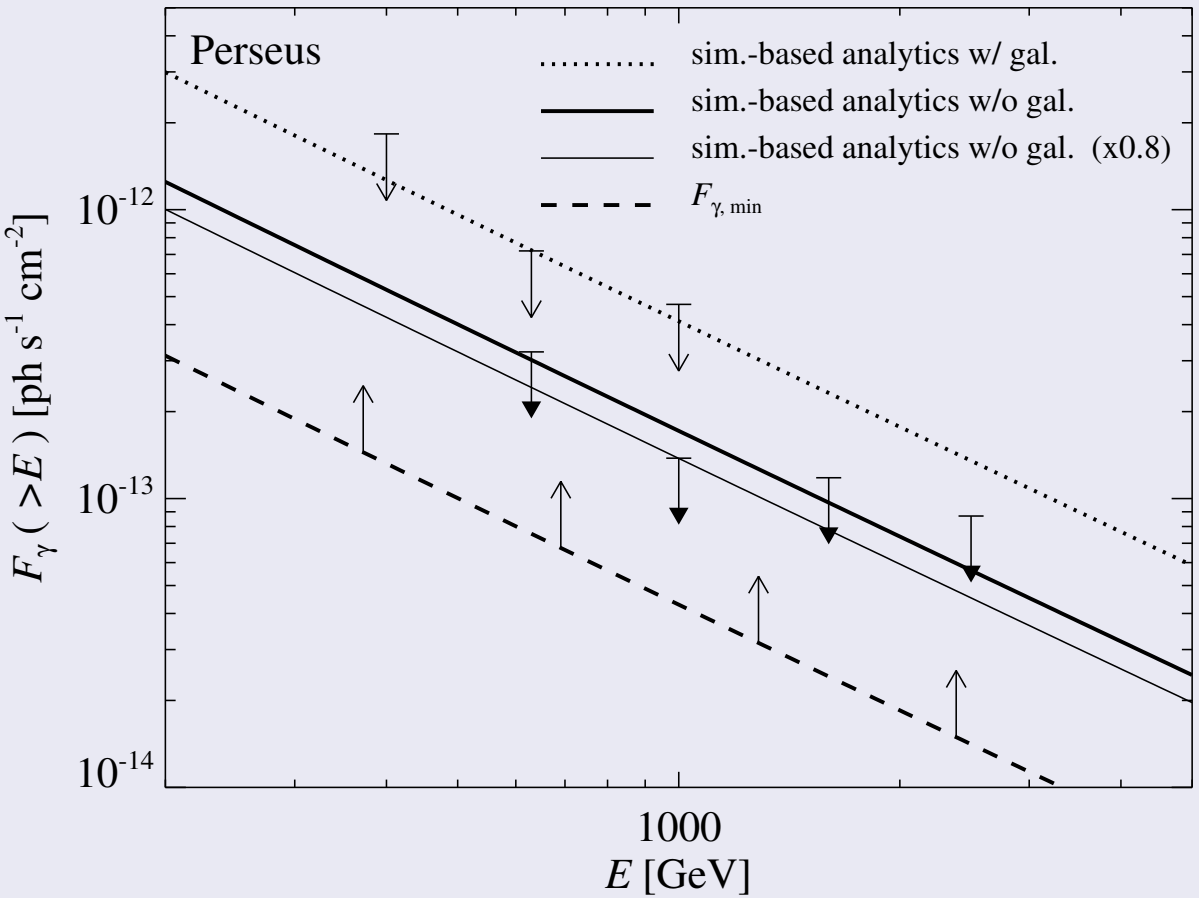
Some summary spectral energy distribution results

- Variable: IC 310, 3C 66A, Mkn 421, Mkn 501, PG 1553+113, NGC 1275
- B3 2247+381 $\Gamma = 3.2 \pm 0.6$ 1Z-SSC with B$\sim$60-80 mG, scales of order 4-8$\times 10^{15}$cm and $\delta \sim 30$
- M87, average $\Gamma \approx 2.3$ extending to 10 TeV (a single power spectrum!)
- 3C 279: during flare $\Gamma = -3.1 \pm 1.1$, poor statistics but reasonable detection >300 GeV
- NGC 1275 (FSRQ): *very* steep spectrum, $\Gamma = 4.1 \pm 0.7_{stat} \pm 0.3_{sys}$; Fermi shows -2.1 to 100 MeV; plausible – cutoff in the several GeV range. Like M87, variable on long (year) timescales but not on shorter with VHE actvity states variable by $\sim 3\times$.
- PKS 1222+21 = 4C+21.35 (FSRQ) $\Gamma = 3.75 \pm 0.27_{stat} \pm 0.2_{sys}$ – 2.7$\pm$0.3 corrected for EBL to 400 GeV
- Mkn 421 $\Gamma \approx 2$ below 1 TeV, rolloff above (steepening); lower cutoff (2010 Jan 14 flare) $\approx$50 GeV
- Mkn 501: VERITAS: $\Gamma = 2.72 \pm 0.15_{stat} \pm 0.1_{stat}$, MAGIC: $2.67 \pm 0.2_{stat} \pm 0.20_{stat}$
- S5 0716+714 $\Gamma = 3.45 \pm 0.54$ above 200 GeV

A galaxy striking a happy medium – NGC 1265 =3C83.1, a head-tail NAT in the Perseus cluster near NGC 1275



2012,A&A,541,A99: Constraining cosmic rays and magnetic fields in the Perseus galaxy cluster with TeV observations by the MAGIC telescopes



Integral flux ULs (2010, grey; 2012, (solid arrows). VHE emission from decaying π^o from CR-ICM interactions: without galaxies (solid line), with galaxies (dotted line). Minimum γ-ray flux estimates for a hadronic Per radio mini-halo (dashed line with minimum flux arrows)

- **Scenario**: During dynamical assembly of galaxy clusters, large scale diffuse shocks should inject CR injection to produce luminous, diffuse γ-ray emission.
- **Result**: At > 630 GeV there is no significant VHE excess. Spatially-averaged P(CR)/P(thermal)≤ 0.02, depending on the emission model for CR emission.
- **Implications**: CR acceleration efficiency at structure formation shocks must be relatively low, not more than 50%, although CRs can diffuse or convect beyond the core. For a generic CR spectrum $\sim E^{-2.2}$ at TeV energies, the central magnetic field should be $\sim$ 4-9 μG, *below field strengths inferred from Faraday rotation measurements in cool cores.*

The Blois model for the central engine?