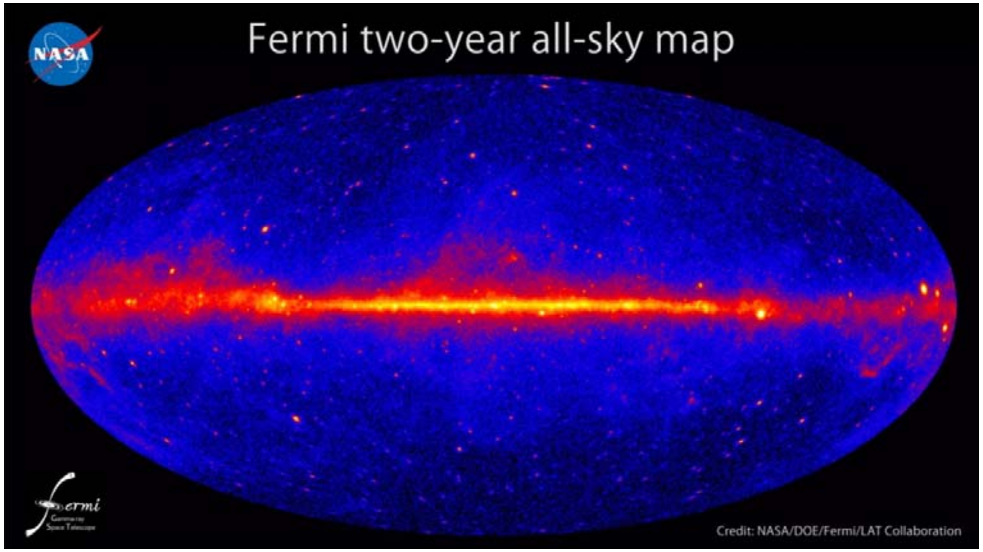


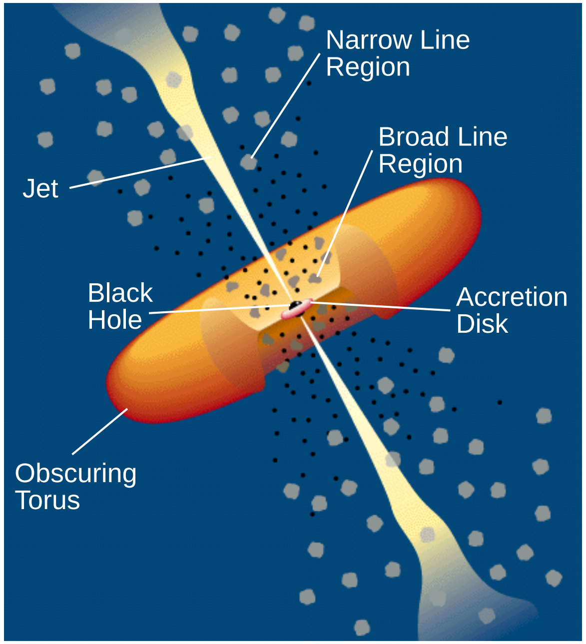
The role of hard X-rays and gamma-rays in understanding of AGN jets

Greg Madejski
SLAC/KIPAC

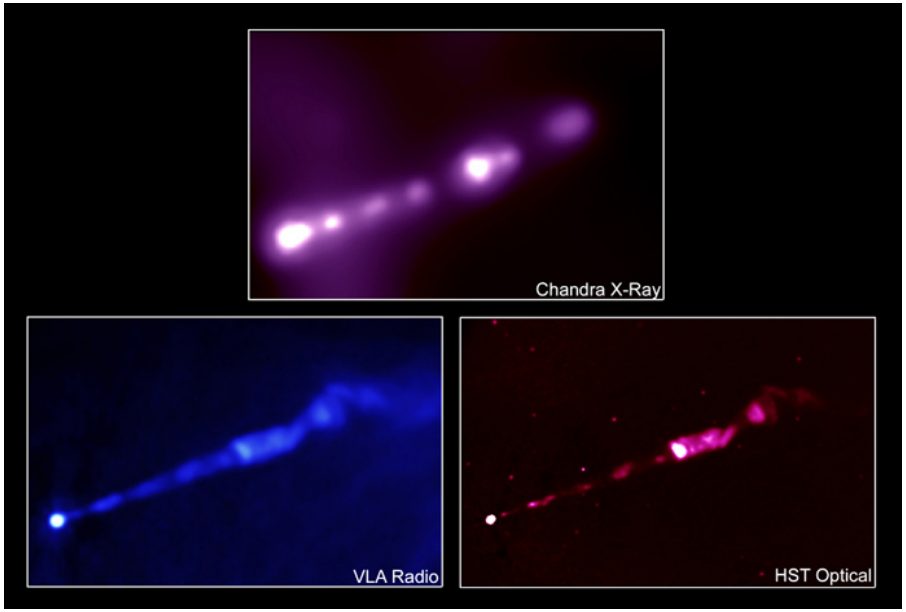
w/ Krzysztof Nalewajko, David Paneque, Mislav Balokovic, Amy Furniss, Meg Urry, Masaaki Hayashida, Marek Sikora, and the members of the Fermi, Veritas, MAGIC, H.E.S.S., & NuSTAR teams

Relativistic jets: why are they interesting?

* AGN = accreting black holes, but only in ~ 10% cases, accretion results in a formation of a relativistic jet (M87 below)
* If the jet points at us, the relativistic Doppler-boosting makes the jet emission appear much brighter, variability more rapid than in the co-moving frame
* There are multiple "handles" on understanding the jet properties, content:
  - broad-band spectroscopy in all bands, variability studies
* They are γ-ray emitters. Need GeV-TeV energy particles to make those γ–rays!



(somewhat overused) schematic of an AGN



Blazar pointing a bit away from our line of sight: radio galaxy M87
Scale: arc seconds, or 100-ish light years

Surveying the whole sky: Fermi Observatory

Large Area Telescope (LAT):

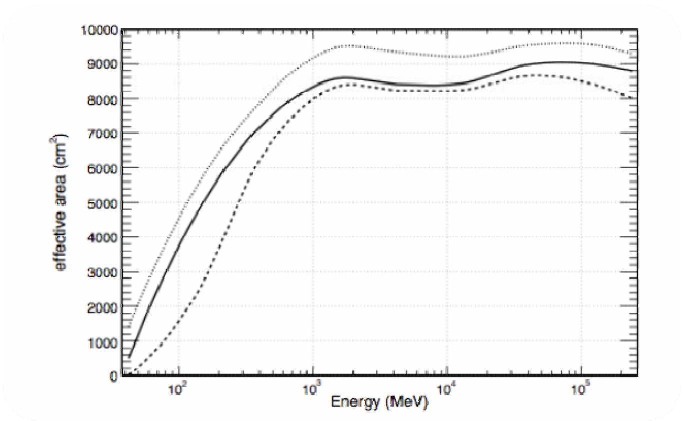
- 20 MeV - >300 GeV
- 2.4 sr FoV (scans entire sky every ~3hrs)

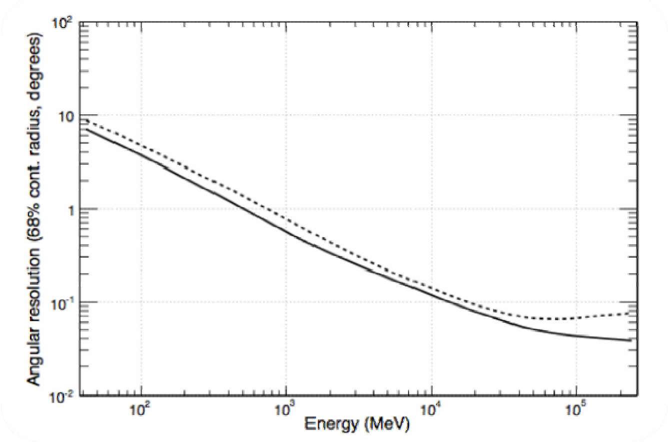
Gamma-ray Burst Monitor (GBM)

- 8 keV - 40 MeV
- views entire unocculted sky

Launched on June 11, 2008 - works perfectly!

Motivated multi-band, multi-messenger monitoring



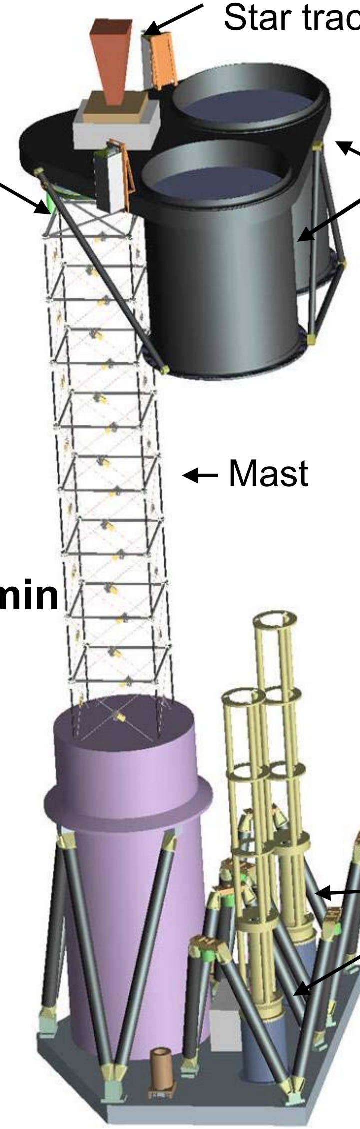


Friends of Fermi: at higher energies…

At the highest energies, one can use the Air Cerenkov technique:
Currently operational MAGIC, HESS-II, and Veritas telescopes
HAWC water-Cerenkov telescope reaches multi-TeV energies (but few AGN)

Another friend of Fermi: Hard X-ray satellite NuSTAR

- Launched in June 2012; led by Caltech
- Two identical co-aligned grazing incidence hard X-ray telescopes:
  - Two multilayer coated segmented glass optics
  - Actively shielded solid state CdZnTe pixel detectors 10 meters away
- Energy bandpass 3 – 80 keV

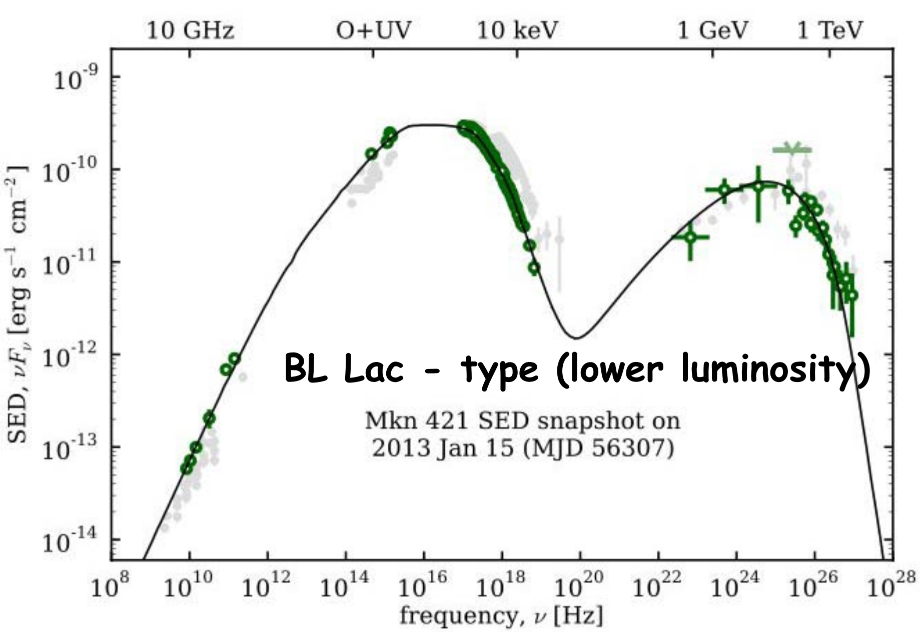


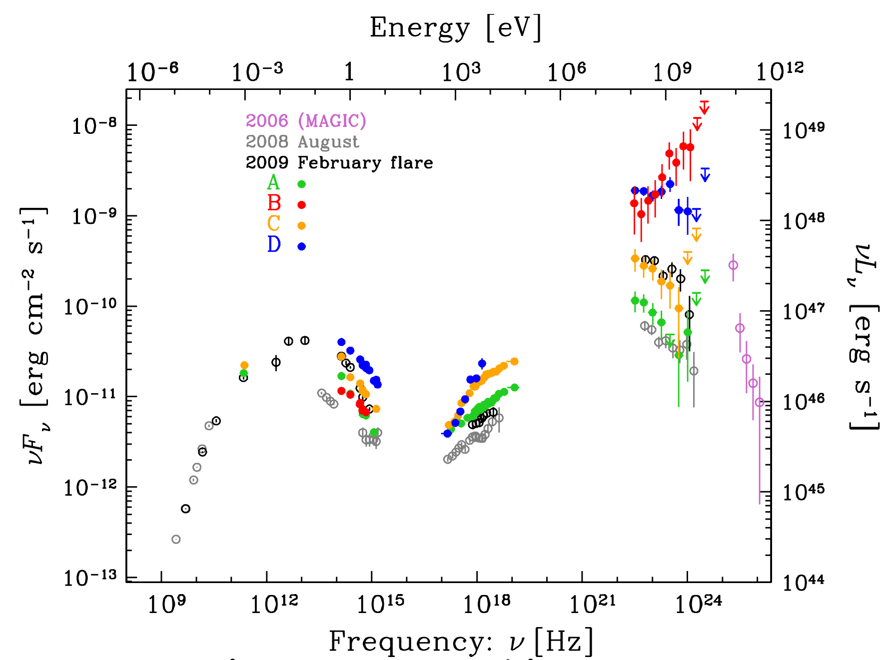
Point spread function: ~ 1 arc min
Energy resolution: ~ 1 keV

But: narrow field of view –
One target at a time

Small dollop of blazar phenomenology

- Blazar spectra show two broad “humps” one peaking in the far IR – to – soft X-rays, another peaking in the MeV – Gev γ-ray range, sometimes extends to the TeV VHE γ-ray regime (2 sub-classes)
- The low-energy hump emission (radio, opt.) – synchrotron emission of <u>plasma consisting of relativistic particles</u> accelerated in the jet
- The high-energy peak - inverse Compton process, by the same electrons that produced the synchrotron hump
- Volume can be estimated from variability time scales
- <u>Questions: location of gamma-ray emission?</u>
- <u>Content of the jet?</u>





Very luminous γ-ray blazar 3C279

Blazars are highly variable! multi-band variability in Fermi days

* Fermi motivates terrific multi-band light curves

* Very important hint: rotation of optical polarization angle, seen in BL Lac (Marscher), but clearly associated with the γ-ray flare in 3C279 (Abdo+ 2010; Hayashida+ 2012): 180° in 20 days

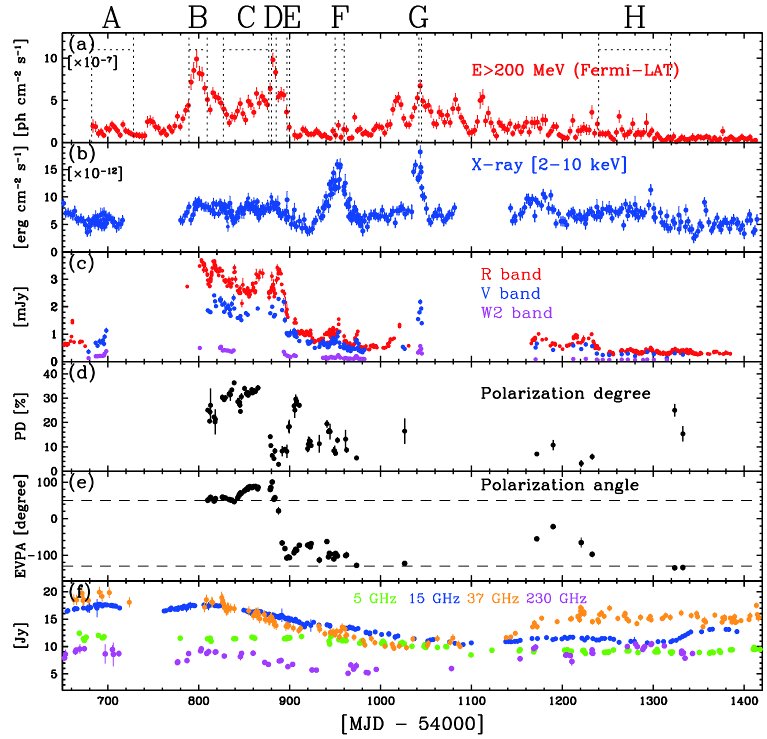
• A clear departure from simple axi-symmetry

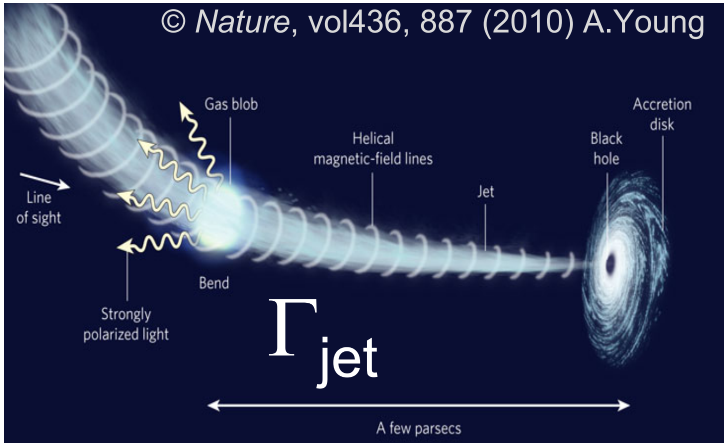
• One possibility is a curved jet: small change of angle – large change of Doppler - boosted flux

• Implies γ-ray emission at a large distance - parsecs from the black hole!

• Consistent with observations of rapid variability at TeV energies (pair production!) – next talk

• Challenge to the jet modelers / theorists – but this is not new: radio hot spots also require efficient transport over 100s of parsecs

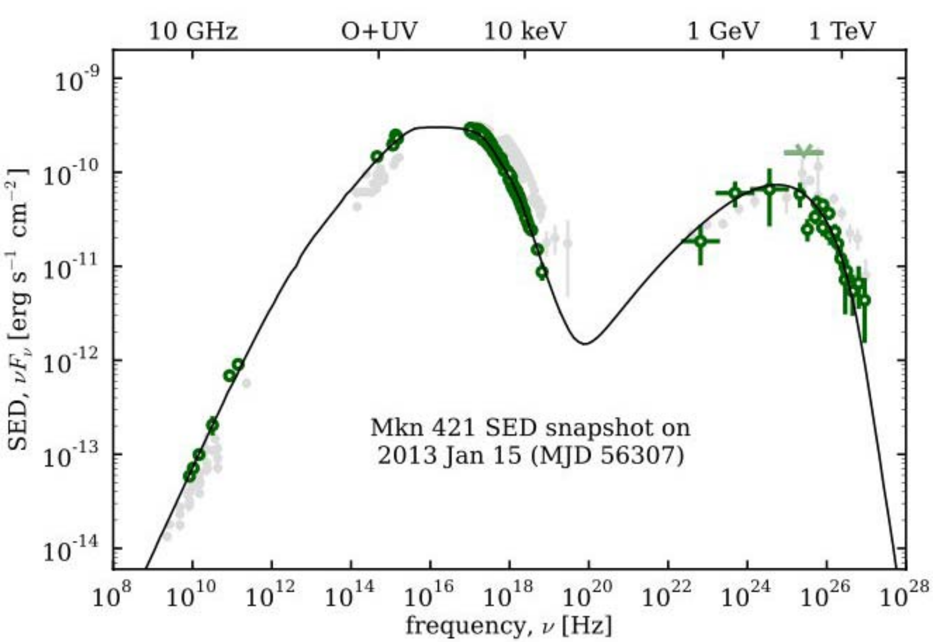


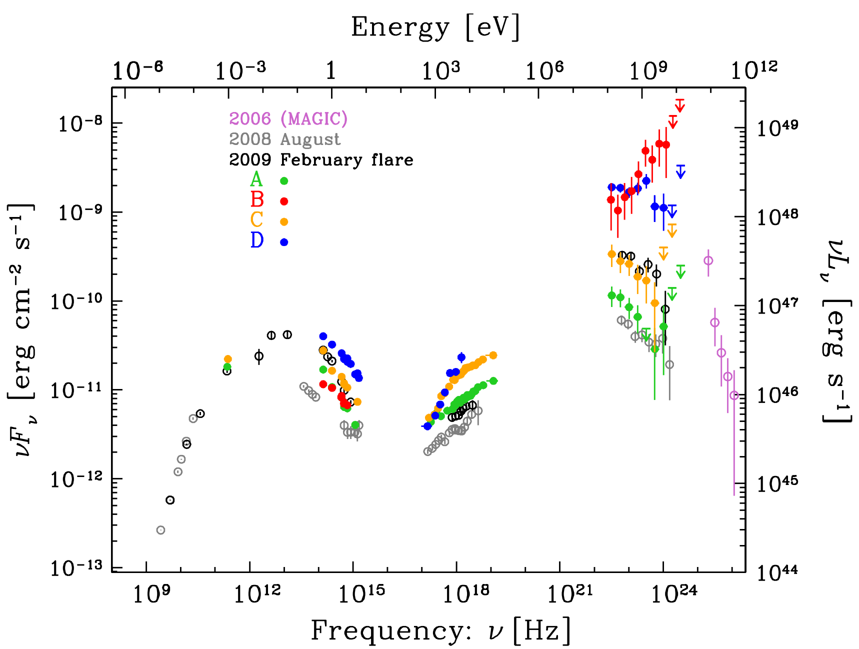


Why are hard X-rays important for blazar studies?

- The hard X-ray band is the intersection of the “tail end” of the synchrotron emission, and the “onset” of the inverse Compton hump
- The “onset” of the inverse Compton peak samples the low-energy particle population in the relativistic plasma - total particle content in the jet (low energy particles are most numerous)

* For the future: X-ray polarization is crucial to verify this picture





Very bright γ-ray blazar 3C279

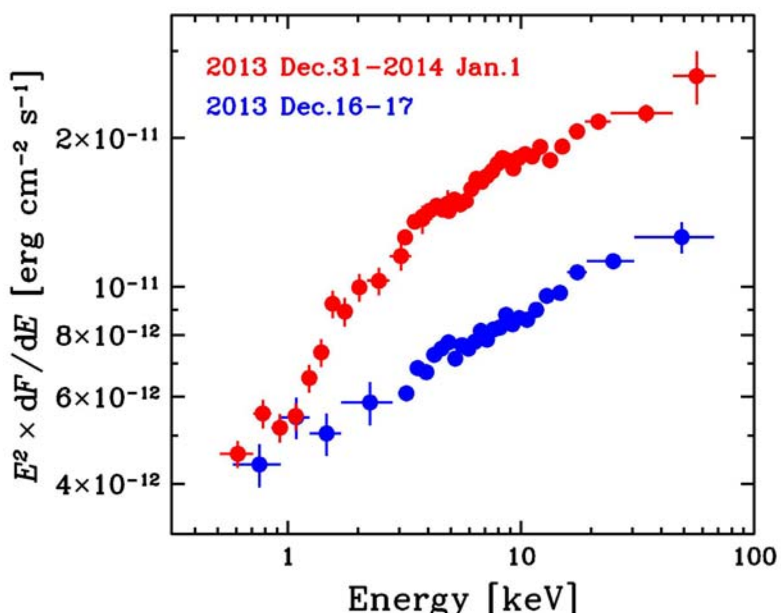
NuSTAR observed ~ 30 blazars

- Blazars were a part of the initial motivation for NuSTAR: to provide a multi-wavelength context to work together with Fermi LAT
- A few were selected for monitoring programs, plus several particularly interesting ones were selected for one or two pointings
- The three famous TeV-emitting objects selected for radio-through-VHE monitoring were Mkn 501, Mkn 421, and PKS 2155-304
- NuSTAR also observed several FSRQs – including high-z objects; implications on formation of black holes in the early Universe
- NuSTAR is poised to observe several more in flaring states

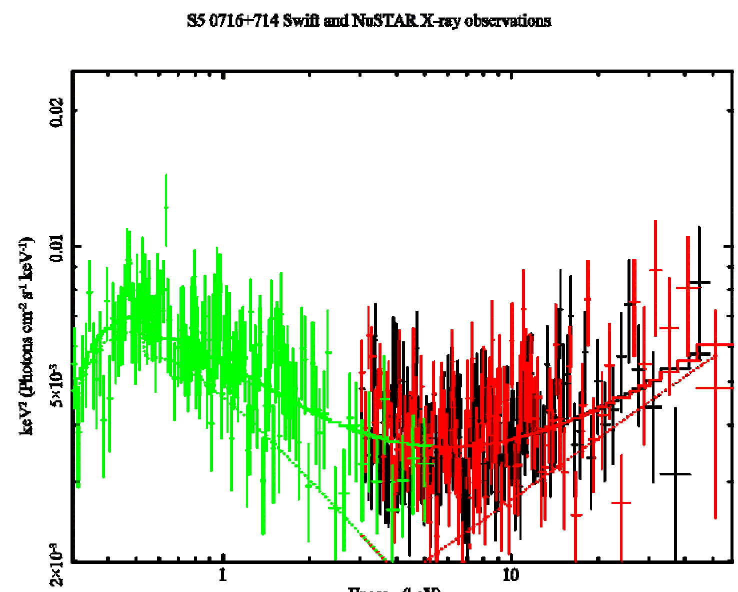
General hard X-ray properties of NuSTAR blazars

- Very "top-level" summary: best results obtained jointly with Swift, XMM-Newton
- NuSTAR measures 3 – 80 keV spectra of FSRQs to be generally quite hard, they are rising in E x F(E), $\Gamma \sim 1.5$, then they often flatten to $\Gamma \sim 2$ (example: 3C279 below)
- HBL-type BL Lac objects generally have soft spectra in the NuSTAR band, falling in the E x F(E), $\Gamma \sim 2.5 - 3$
- In a few cases, one sees the break in the NuSTAR band: example is S5 0716+714

X-ray spectra: 3C279

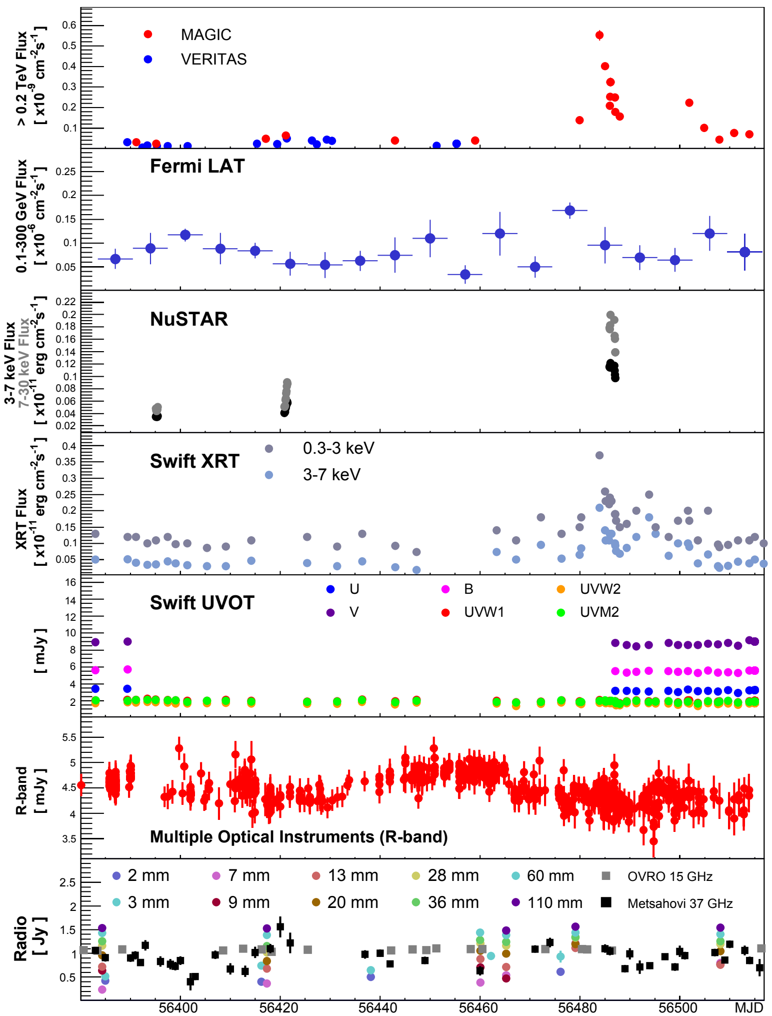


MAGIC – detected blazar S5 0716

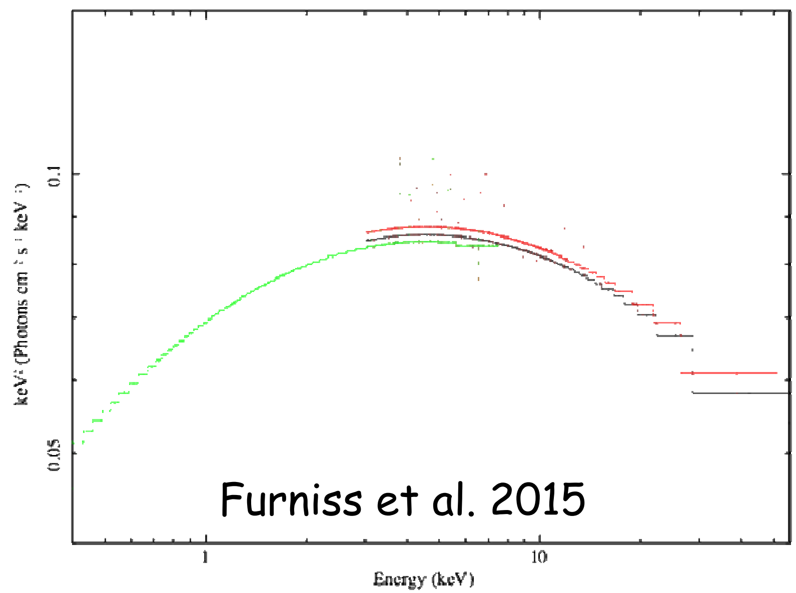


Mkn 501 observed by *NuSTAR*

Campaigns including NuSTAR were conducted generally in the context of MW campaigns…

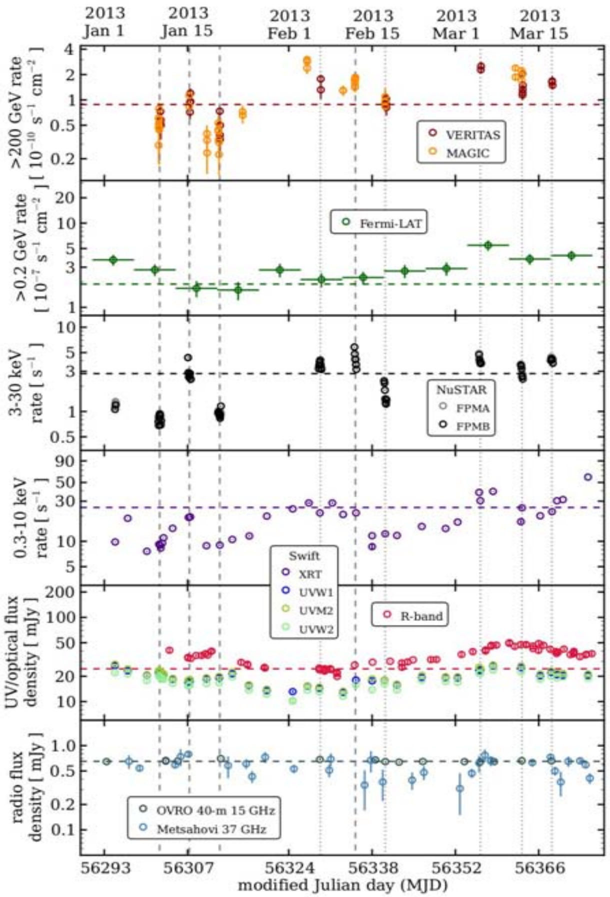


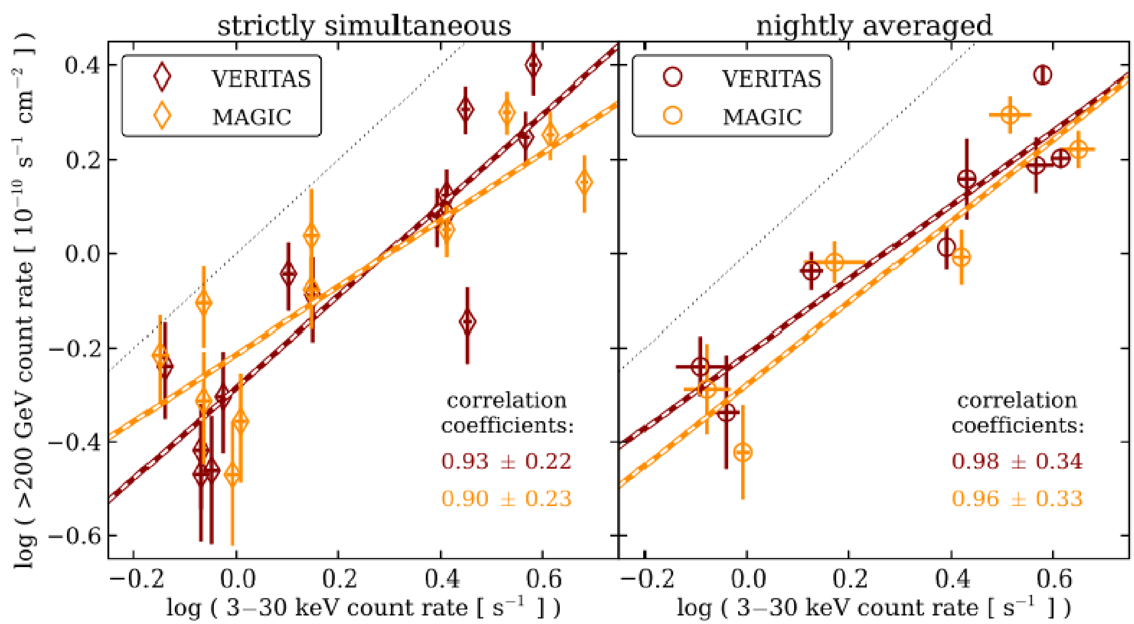
- ***NuSTAR***
- **MAGIC/VERITAS/HESS**
- ***Swift, Fermi***
- **Optical instruments,**
- **OVRO/Metzahovi/f-Gamma**



Example of Swift and NuSTAR data for Mkn 501 (z = 0.03): Able to reconstruct full synchrotron peak with *Swift* XRT simultaneous observations: X-ray spectrum not a simple power law

Mkn 421 (NuSTAR Fermi, optical, VHE γ-rays)





- First results published in Balokovic et al. 2015; source beautifully detected up to 60 keV even in a faint state
- Source is softer when fainter, spectrum generally consistent with a broken power law (Γ_{high} ~ 3), not exponential cutoff – radiating particle distribution does not cut off below $E_{electron}$ ~ a few TeV
- Inferences regarding the particle distribution crucial towards studies of EBL
- The X-ray – TeV analysis suggests indicates “linear” correlation – the scattering is likely in the Klein-Nishina regime

PKS 2155-304 and particle content of the jet

* “One object at a time” approach and study a representative case rather than samples

* Well-known and extensively studied blazar, z = 0.117, one of the first BL Lac – type objects detected in X-rays

* Can be very variable: probably most “notorious” aspect of it is the large amplitude, minute-scale variability seen by H.E.S.S. (Benbow et al., Aharonian+ 2007)

An Exceptional VHE Gamma-Ray Flare of PKS 2155−304 5

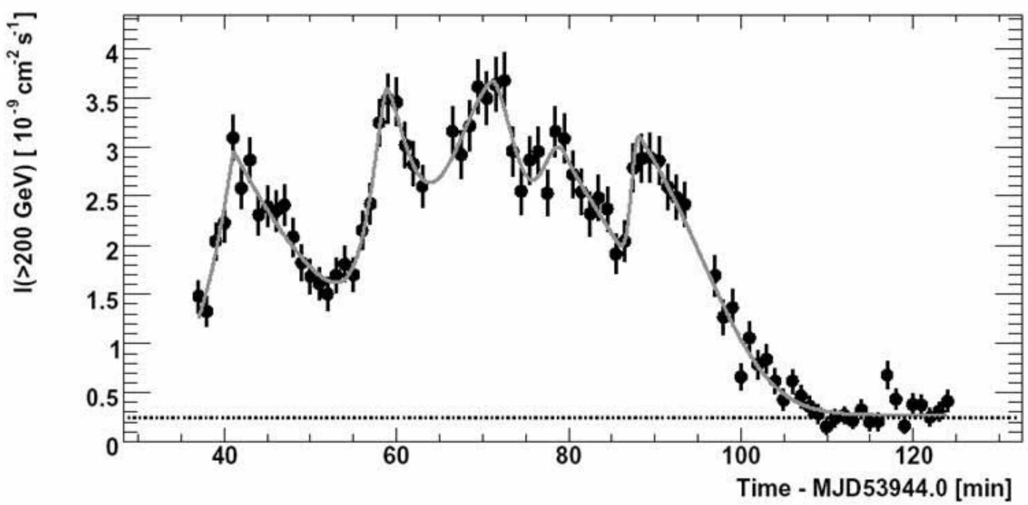


Fig. 1.— The integral flux above 200 GeV observed from PKS 2155−304 on MJD 53944 versus time. The data are binned in 1-minute intervals. The horizontal line represents I(>200 GeV) observed (Aharonian et al. 2006) from the Crab Nebula. The curve is the fit to these data of the superposition of five bursts (see text) and a constant flux.

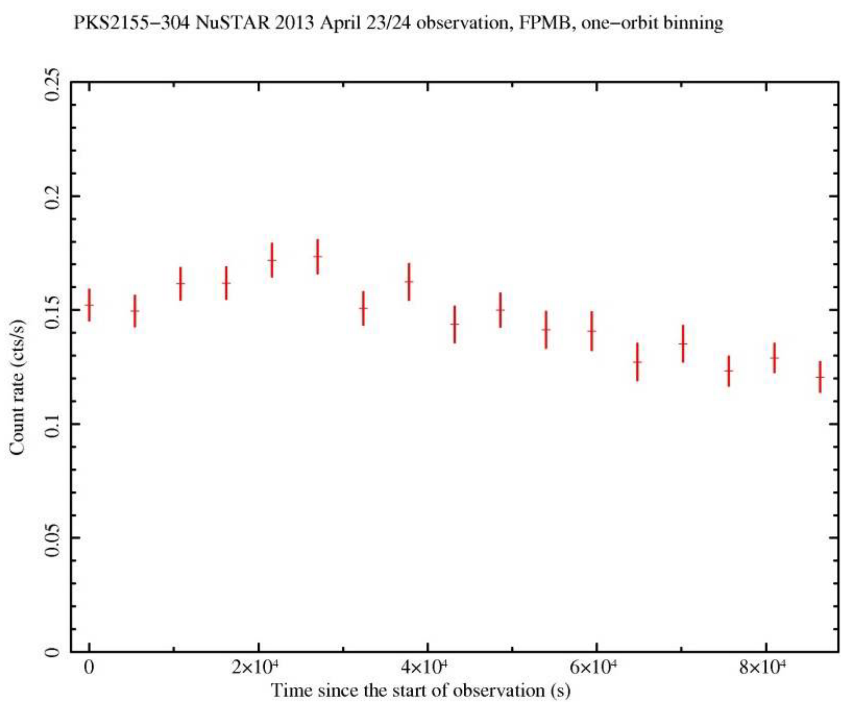
NuSTAR / Fermi observations

* First NuSTAR pointing was done in April 2013 as a part of the cross-calibration with other X-ray missions -> lots of simultaneous X-ray data!

* Object was found in an exceptionally low X-ray state, ~ 10^{-11} erg cm^{-2} s^{-1} (2 – 10 keV), 1/3 of the previously reported "low" state

* NuSTAR collected a day's worth of data (~ 40 ks), shows very little variability,

Fermi analysis straightforward: γ-ray flux during April 2013 is also low, no measurable variability; used +/- 5 days of Fermi data centered on the NuSTAR pointing



NuSTAR and XMM together

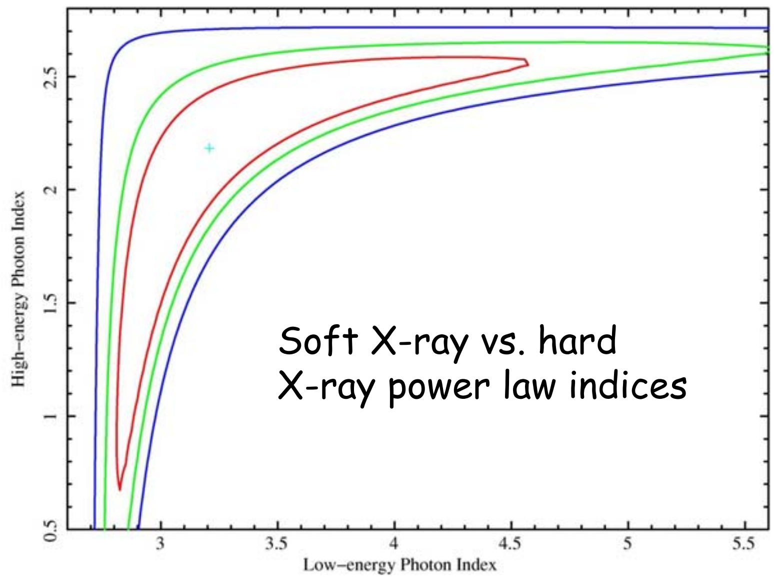
* NuSTAR data alone reveal a “hard tail” - power law indices are 3 & 2

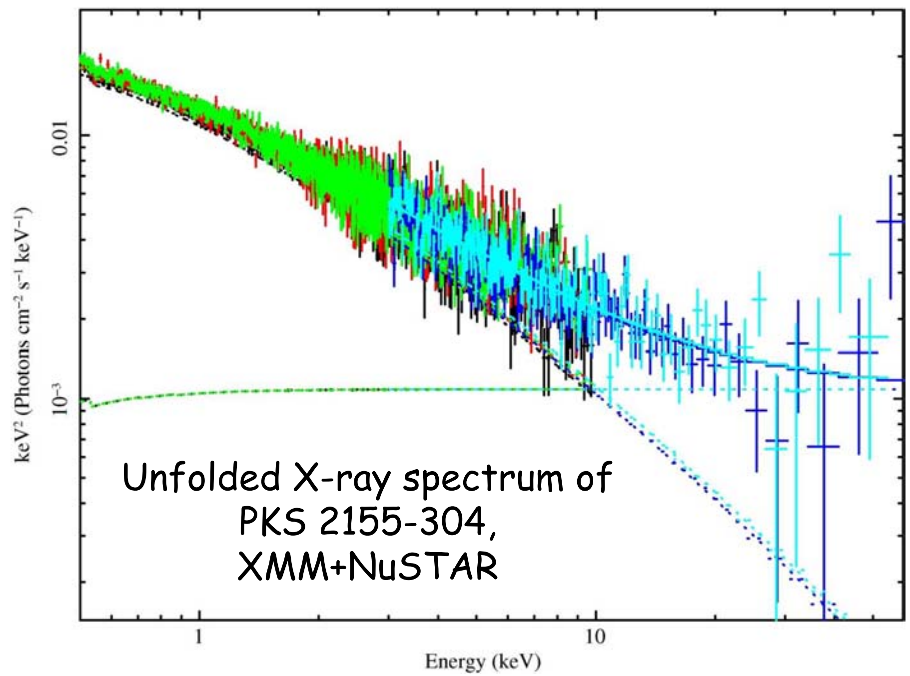
* Adding strictly simultaneous XMM data shows a more complete X-ray picture

- Imposing Galactic column, XMM data alone require a log-parabola model, gradual *steepening* of the spectrum in the 0.5 – 10 keV range

- Joint fit of NuSTAR and XMM implies a log-parabola for the lower E part of the spectrum, + a second, harder power law for the higher E part of the spectrum

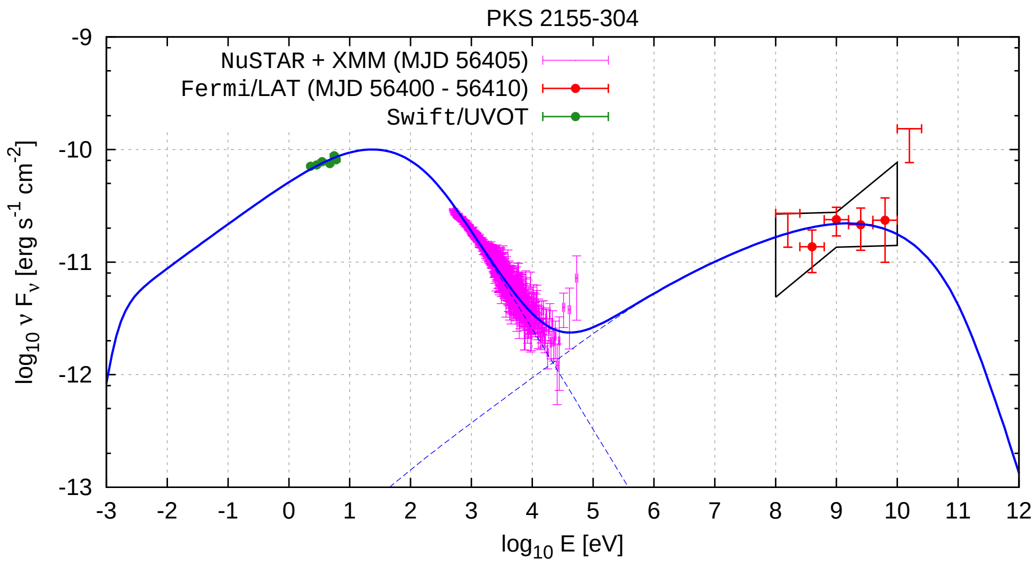
- The 20 – 40 keV flux is ~ 0.8 x 10^{-11} erg/cm^2/s





What does it all mean?
(don't forget about the charge neutrality)

- When we put X-rays together with the Fermi/LAT data, we have a very broad-band picture
- We fit the data with standard synchrotron self-Compton model (Rafal Moderski's "blazar" code, verified via Boettcher / Chiang model)
- The presence of the "hard tail" indicates that the inverse Compton spectrum has to extend to v. low energies!
- But that's where the radiating particles are <u>most numerous</u>!
- Can't be studied in the radio-band synchrotron component (synch. self-absorption), previously unconstrained
- Parameters of the model were calculated using the "standard" $\Gamma_j = 15$, B = 1 G, R = 3 x 10^{15} cm, consistent with all previous modelling
- <u>Important consequence: X-rays definitely should be polarized! (synchrotron process)</u>



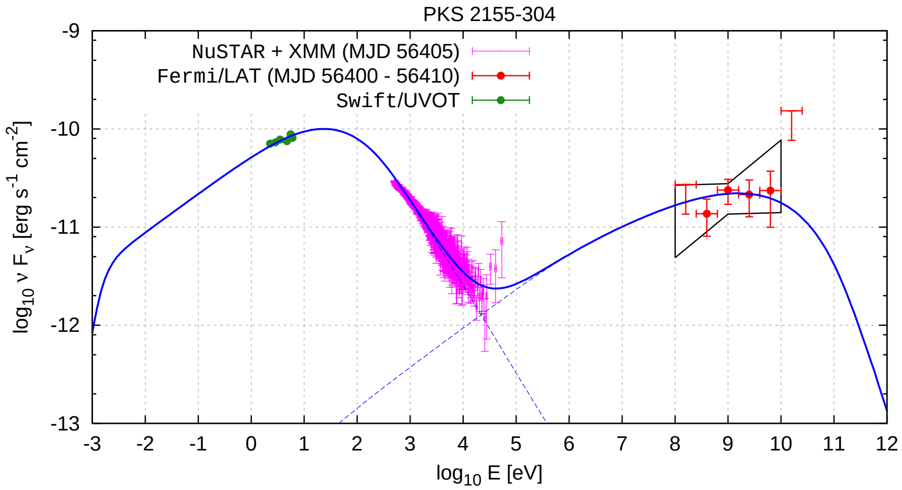
<u>Modelling results:</u>

We find $L_B = 6 \times 10^{42}$ erg/s, $L_e = 3 \times 10^{44}$ erg/s, $L_{rad} = 10^{43}$ erg/s,

Even without protons, the jet is matter-dominated

Need charge neutrality: assuming one proton per electron yields $L_p = 10^{47}$ erg/s. That's a lot!

Jet in PKS 2155-304 is likely pair-dominated!



Modelling results (repeated):

We find $L_B = 6 \times 10^{42}$ erg/s, $L_e = 3 \times 10^{44}$ erg/s, $L_{rad} = 10^{43}$ erg/s,

Even without protons, the jet is matter-dominated

Need charge neutrality: assuming one proton per electron yields $L_p = 10^{47}$ erg/s

CONCLUSIONS FOR THIS ANALYSIS:

$L_p = 10^{47}$ erg/s is huge, totally unrealistic, even with a BH mass of 10^9 M_o, the source would need to accrete at L/L_{edd} ~1

This would imply a radiatively efficient accretion which is not the case for PKS 2155 or any HBLs - no thermal disk emission, no emission lines, low-efficiency accretion

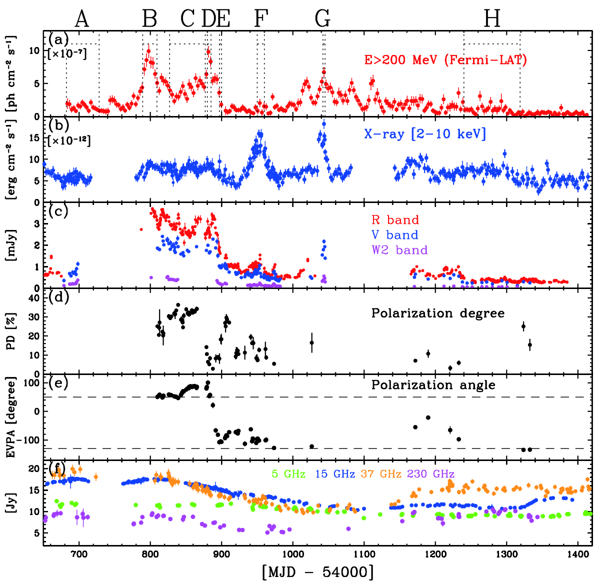
HBL – type blazars are supposed to be advection – dominated accretion sources, not accreting at L/L_{edd} ~1!

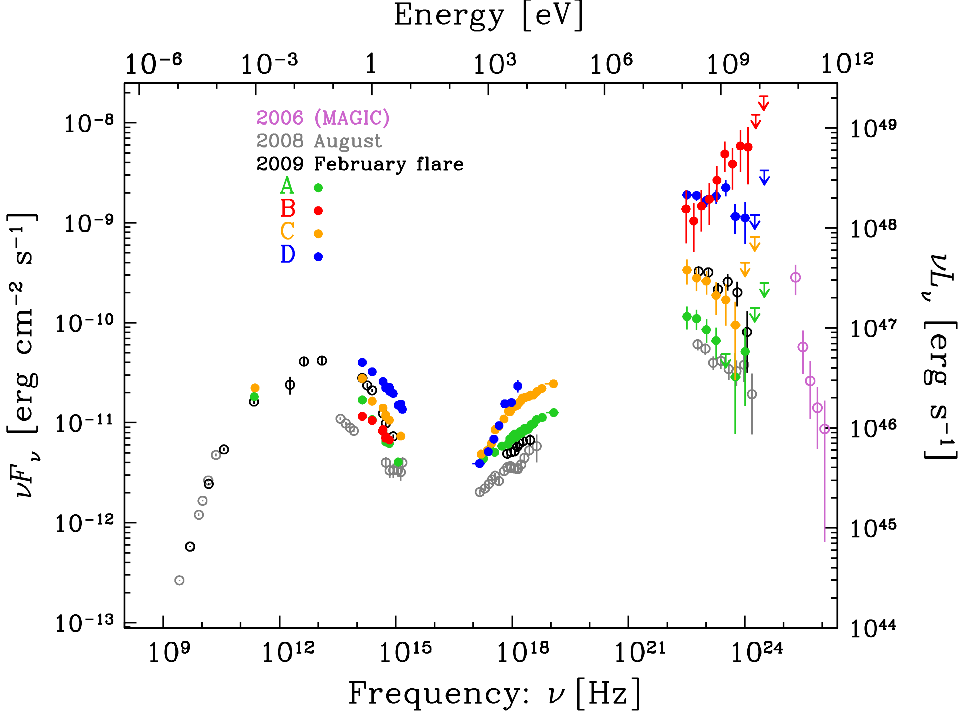
More likely solution: the jet has a substantial pair content (#positrons / #protons ~ at least 50)

Possibly the first direct indication that HBL blazar jets are pair dominated

Conclusion seems robust to changes in Γ_j, B, … (hard to make a x50 error)

Other types of blazars?





High-luminosity FSRQ blazar 3C279

<u>OTHER CLASSES OF BLAZARS? HIGH LUMINOSITY TYPES?</u>

* High-luminosity blazars (Flat-Spectrum Radio Quasars) are different!

• Total power provided by accretion can be very large (signatures of luminous, high accretion-rate accretion disk)

• Their jets <u>cannot be entirely devoid of protons</u>:
If the jet was pure pairs, we'd see the "bulk-Compton" feature ("Sikora bump")
- from inverse Compton emission by the cold electrons in the jet (upscattering circum-nuclear AGN radiation) which has not been detected

* Protons (or alternatively, huge Poynting flux) is needed to provide the jet's kinetic energy

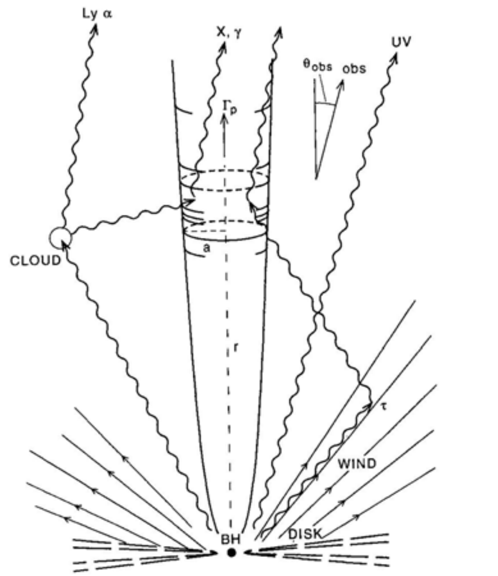


FIG. 2.—Geometry of the source. The radiating region, denoted by short cylinder of dimension a, moves along the jet with pattern Lorentz factor Γ_p. Underlying flow moves with Lorentz factor Γ, which may be different.

Schematic picture of geometry of a blazar jet

Pairs vs. protons in luminous blazars?

<u>Argument goes as follows:</u>

We can estimate the total kinetic power required to be carried by the jet to account for its luminosity for both "pure pair" and "no pair" cases

If we put all this jet kinetic energy into <u>pure pairs</u>, they will Compton-upscatter the Broad Line / accretion disk photon to X-ray energies – this is not seen! - *pure pair jet excluded*

At lease some protons (or huge Poynting flux) needed to carry the kinetic power

Some previous papers assumed no pairs -> requiring one proton per electron implied that the jet power was huge (Ghisellini+ 2014 Nature paper)

G+ 2014 invoked tapping the rotation of the black hole (via "Blandford-Znajek process") to power the jet

They argued that pure positron plasma would be slowed down by Compton rocket, produce the "Sikora bump" (spectral feature in the soft X-rays), which is not detected

But, G+ 2014 didn't consider the intermediate cases…

Another tool – “calorimetry” to rescue!

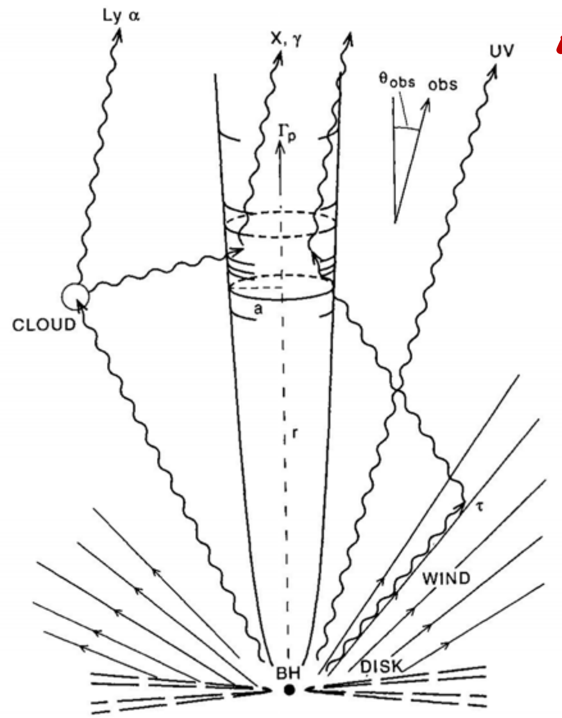
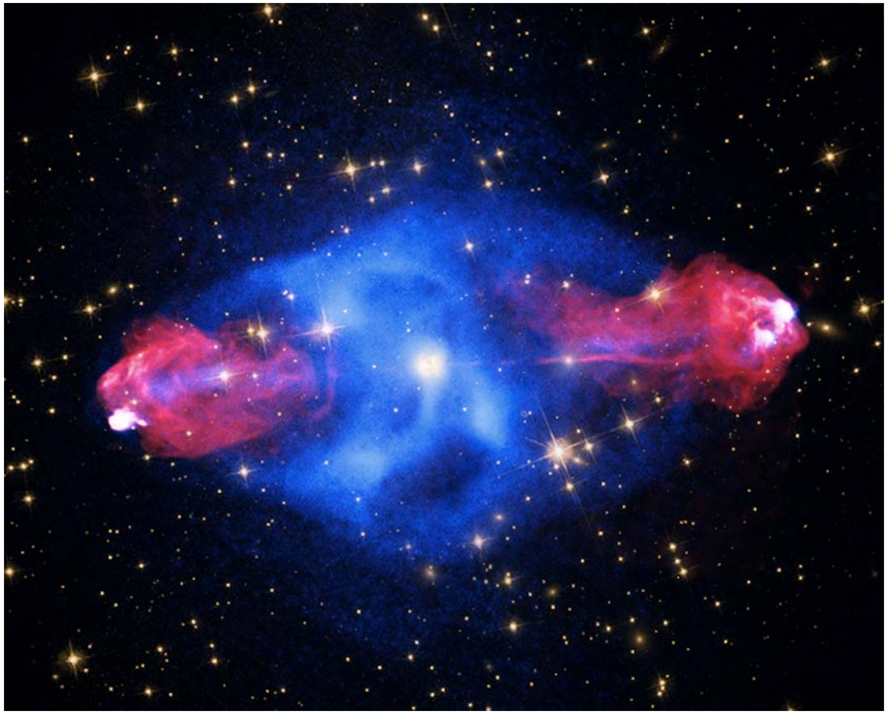


Fig. 2.—Geometry of the source. The radiating region, denoted by short cylinder of dimension a, moves along the jet with pattern Lorentz factor Γ_p. Underlying flow moves with Lorentz factor Γ, which may be different.



Cygnus A radio galaxy:
blazar jet viewed from the side

<u>Hot spots in radio galaxies are a form of a “calorimeter” (beam dump)</u>

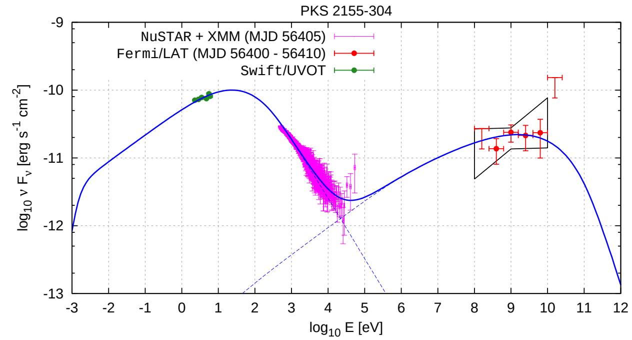
One can estimate the total power of the jet from radio lobes
Those emit isotropically – no issues with Doppler boosting
Estimate of the jet power is now more robust – Pjanka, Zdziarski, Sikora (2016)
infer that total jet power is *lower* than inferred by Ghisellini+

Conclusion: invoking Blanford-Znajek in high-luminosity sources is not required
- but positron-to-proton ratio needs to be ~ 20

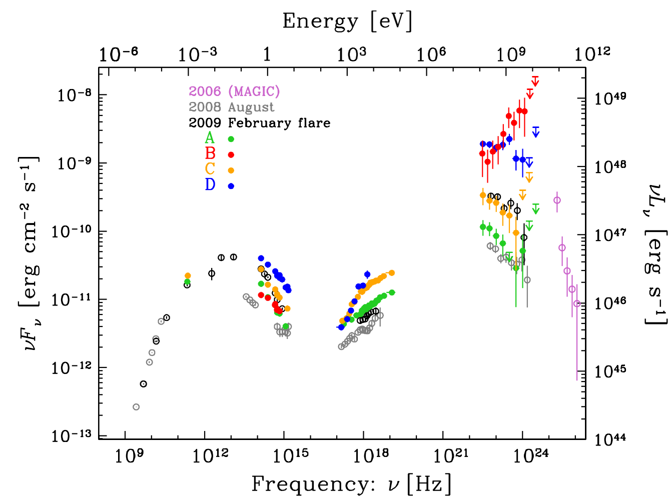
Conclusions

We discussed <u>observations and modelling</u> of 2 types of jet-dominated AGN (blazars)

BL Lac-type blazar: PKS2155-304; "hard X-ray tail" seen in NuSTAR - jet must contain appreciable pairs (e+/P > 20)



In high-luminosity, powerful blazars, there is opposite limit: jet plasma cannot be pure e-/e+ (bulk-Compton limits); BUT, if pure e/P plasma – jet power still excessive…
- e+/P ~ 20 OK, consistent with radio hot spots which provide additional constraints



CHALLENGE TO THEORETICAL EFFORTS: HOW ARE THE PAIRS PRODUCED IN THE JET?

Future X-ray observations will include measurements of X-ray polarization

X-ray / γ-ray polarization <u>predictions</u>: depends on the radiation process

- **synchrotron: strong polarization, probably same angle as optical (X-rays in HBL-type blazars)**
- **inverse Compton: if seed photons unpolarized – probably no polarization (γ-rays in FSRQs)**
- **inverse Compton: if seed photons are polarized – strong polarization, same angle as synchrotron, same swings (X-rays in FSRQs)**