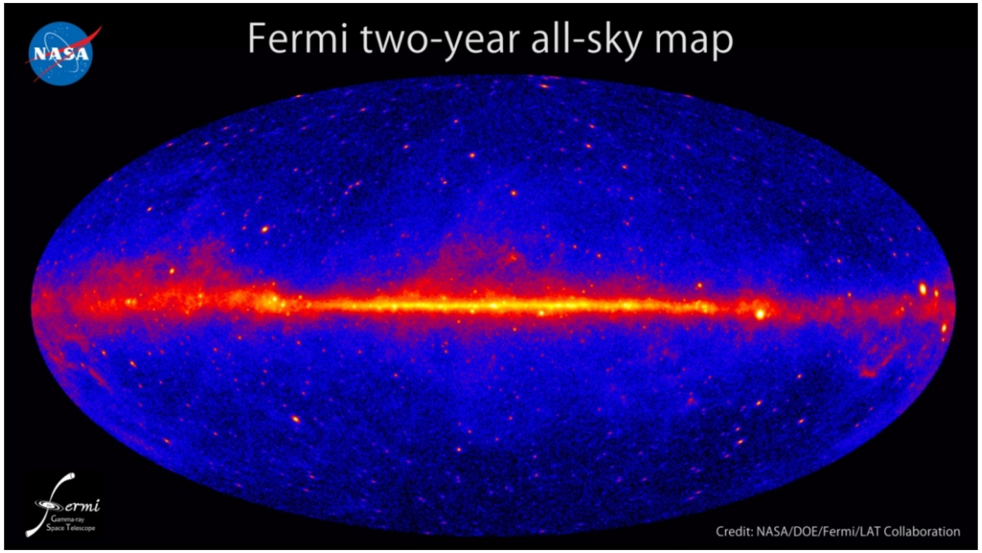


Fermi two-year all-sky map

Credit: NASA/DOE/Fermi/LAT Collaboration

* Content of relativistic jets in blazars and implications on the jet structure
* Future X-ray polarization observations

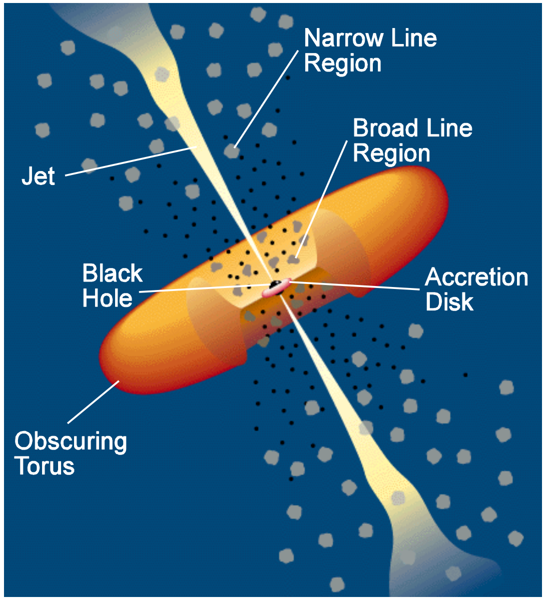
Greg Madejski

SLAC/KIPAC

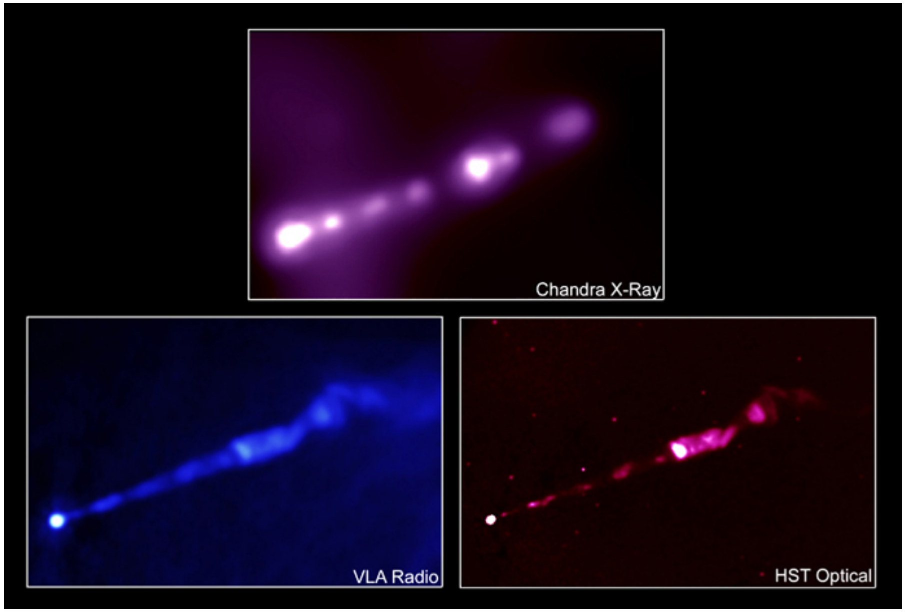
w/ Krzysztof Nalewajko, David Paneque, Mislav Balokovic, Amy Furniss, Meg Urry, Masaaki Hayashida, Marek Sikora, and the members of the Fermi, Veritas, MAGIC, H.E.S.S., & NuSTAR teams

Relativistic jets: why are they interesting?
What do *observations* tell us about their nature?

- Not a question for this audience – we all agree they are interesting!
- There are multiple “handles” on understanding the jet properties, and in particular its content: broad-band spectroscopy in all bands, variability studies

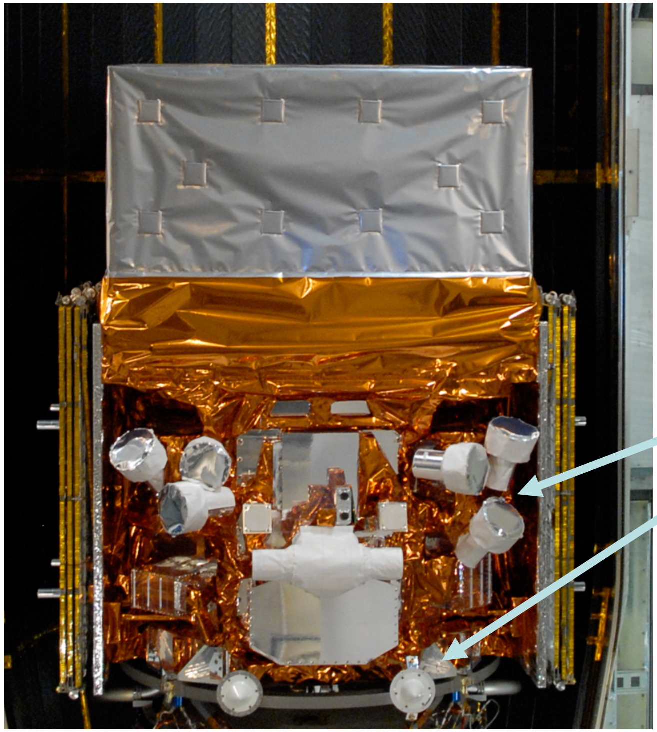


(somewhat overused) schematic of an AGN



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

Important tool for studies of relativistic jets: Fermi Observatory



Large Area Telescope (LAT):

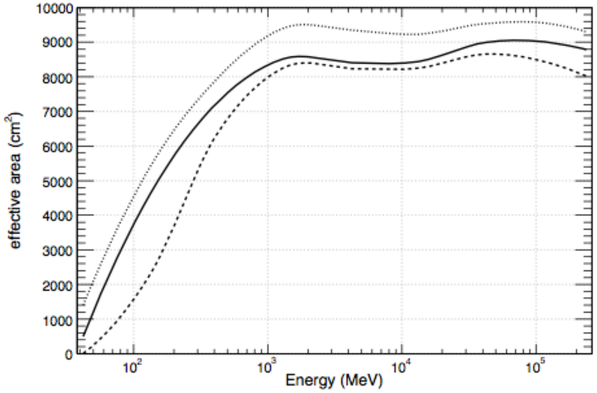
- 20 MeV - >300 GeV
- 2.4 sr FoV (scans entire sky every ~3hrs)

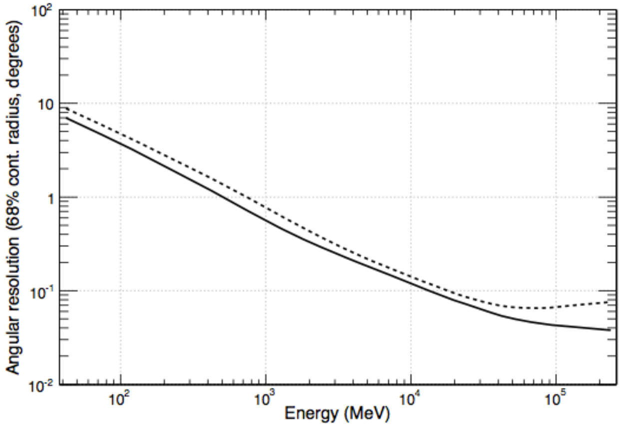
Gamma-ray Burst Monitor (GBM)

- 8 keV - 40 MeV
- views entire unocculted sky

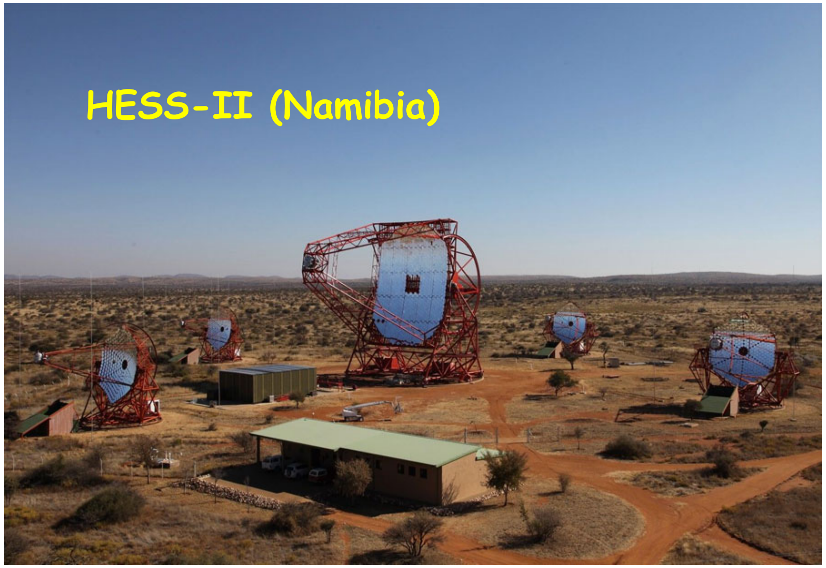
Launched on June 11, 2008 - works perfectly!

Motivated multi-band, multi-messenger monitoring





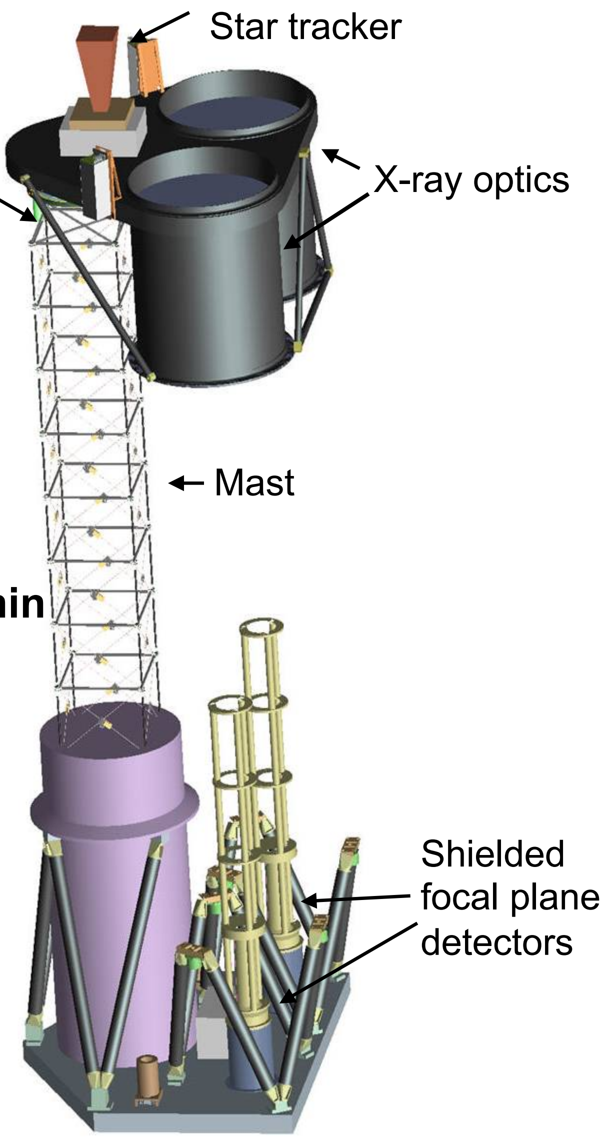
Friends of Fermi: at higher energies…



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)

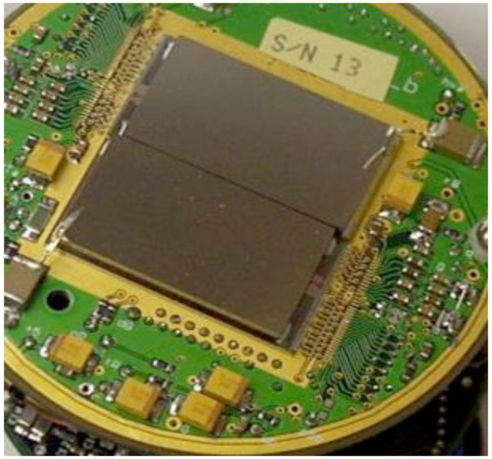
Another friend of Fermi: Hard X-ray satellite NuSTAR

- 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



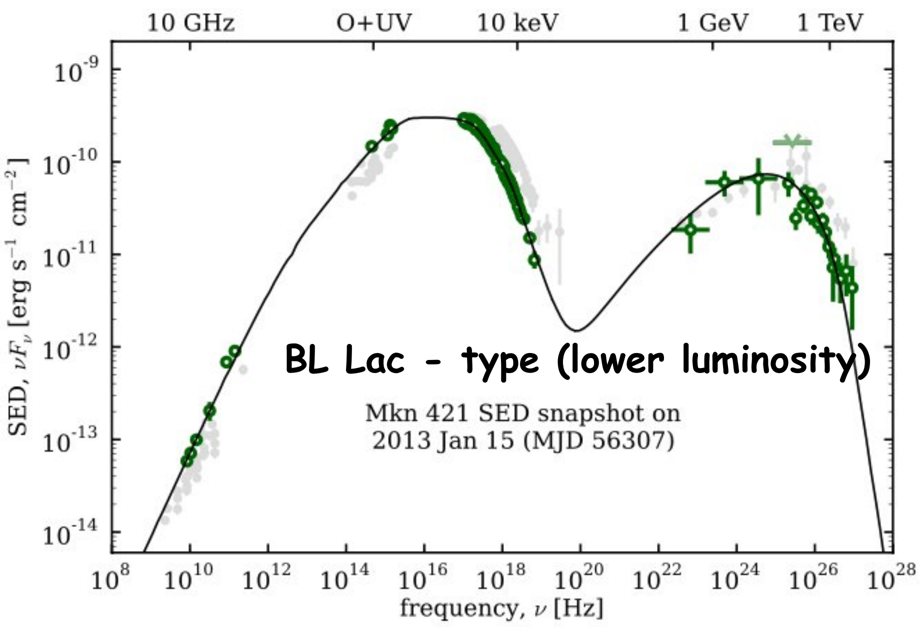
Point spread function: ~ 1 arc min
Energy resolution: ~ 1 keV

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

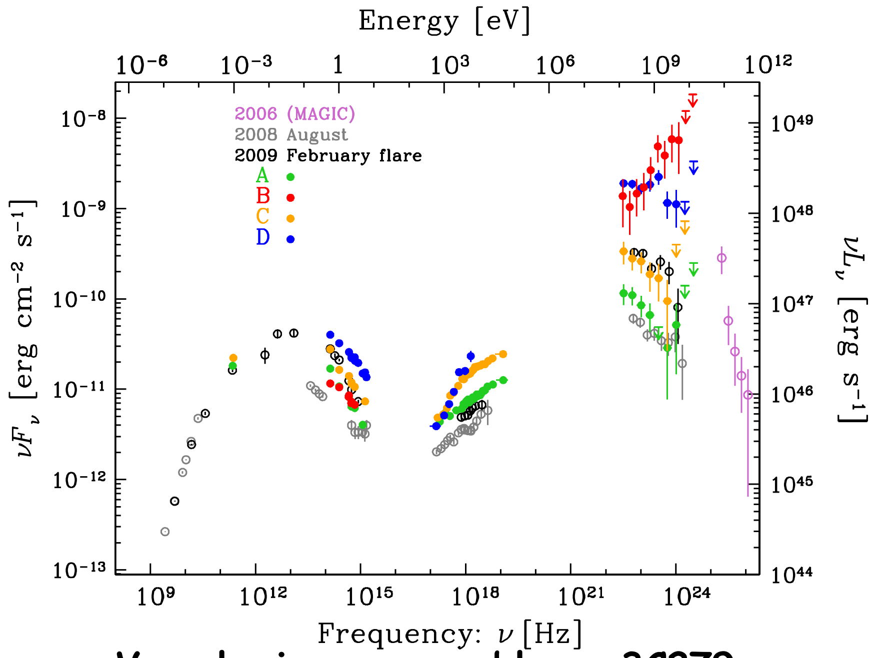


Small dollop of blazar phenomenology

- 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>



BL Lac - type (lower luminosity)



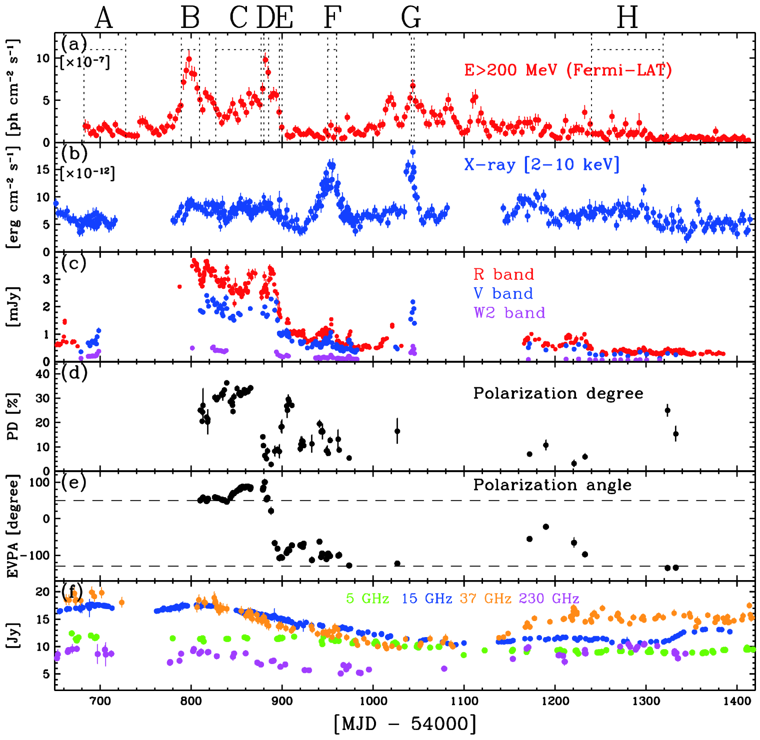
Very luminous γ-ray blazar 3C279

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

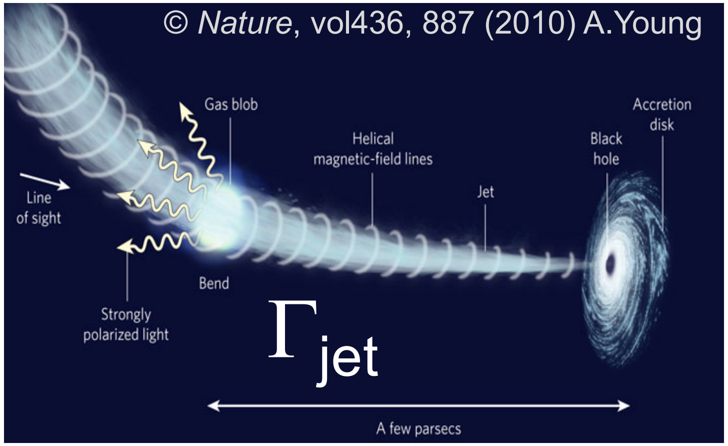
- A clear departure from simple stationary axi-symmetry
- One possibility is a curved jet: small change of angle – large change of Doppler - boosted flux
- Implies γ-ray emission at a large distance - parsecs from the black hole!



•Would imply v. efficient particle acceleration <u>far from the black hole</u> since energy loss time scales of electrons are short

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

* Much progress is being made! --this meeting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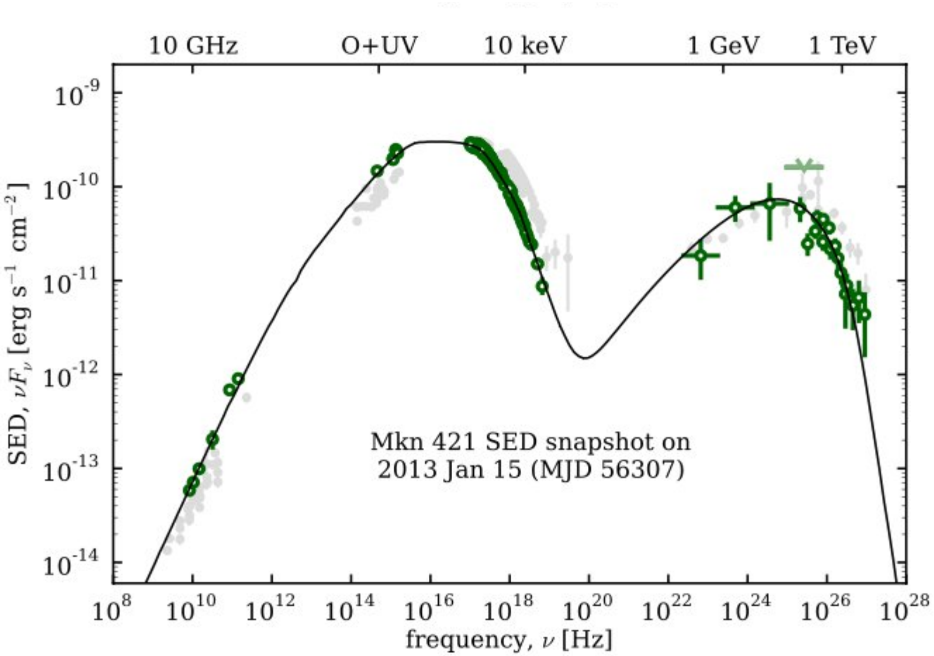
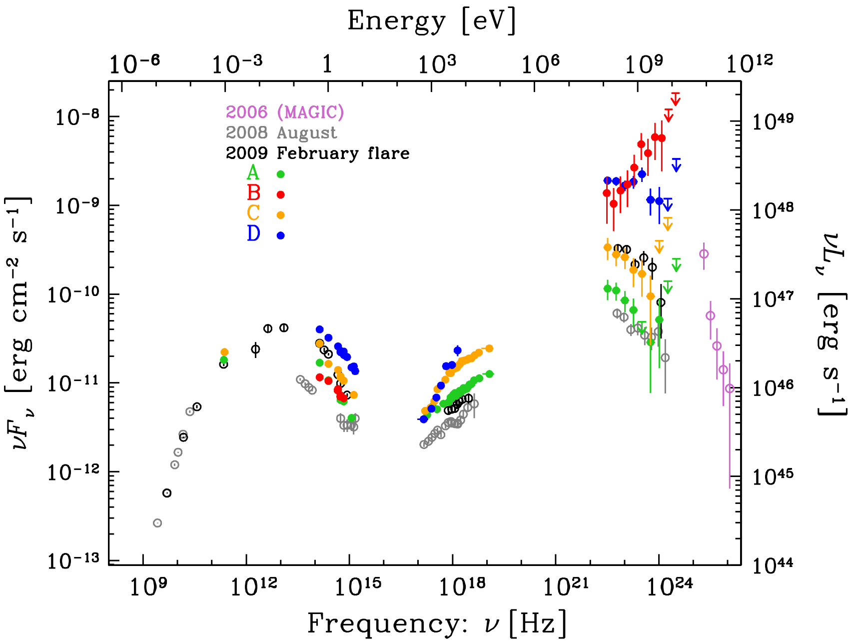
Why are hard X-rays important for blazar studies?

- 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)

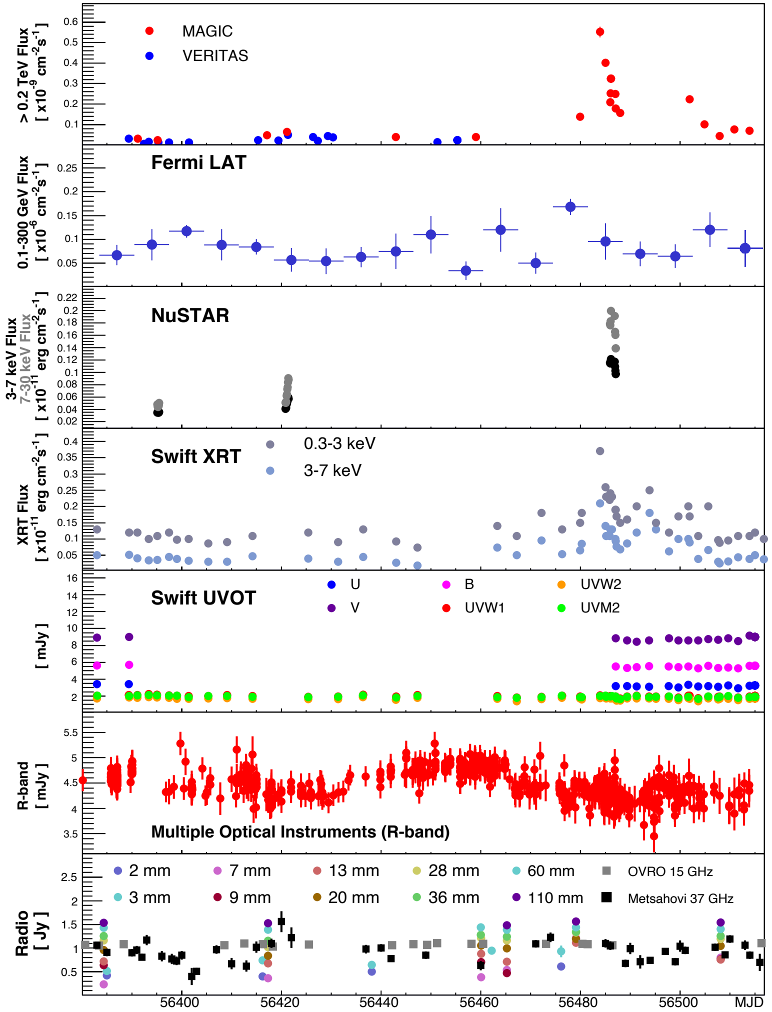




Very bright γ-ray blazar 3C279

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
- NuSTAR also observed several FSRQs at high (z > 3) redshifts; this has implications on formation of very massive ($M \sim 10^9 M_o$) black holes in the early Universe
- The argument goes as follows: for each blazar with jet Lorentz factor Γ_j pointing *at* us there must be ~ Γ_j^2 objects pointing elsewhere
- With $\Gamma_j \sim 10$, this means hundreds!



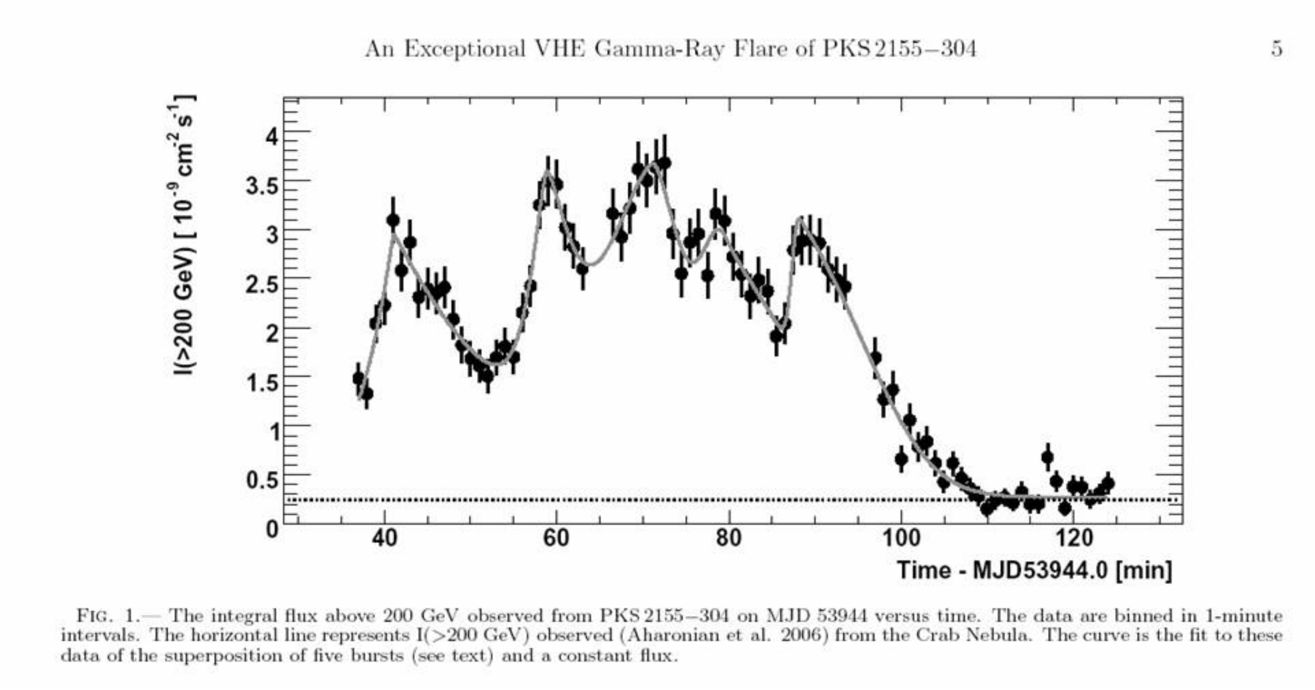
Multi-band campaign for Mkn 501
(Furniss et al. 2015)

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.

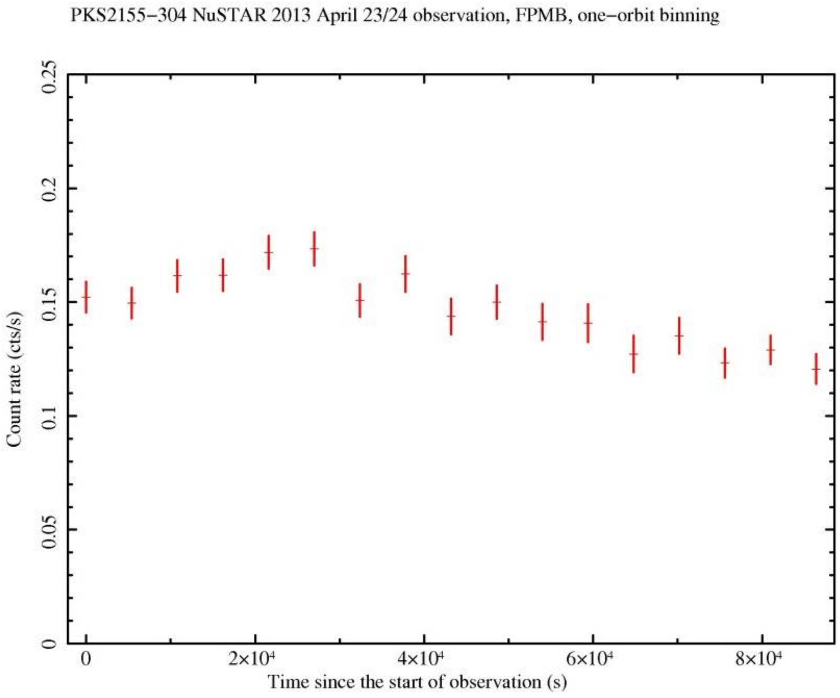
NuSTAR / Fermi observations

* First <u>NuSTAR</u> 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,

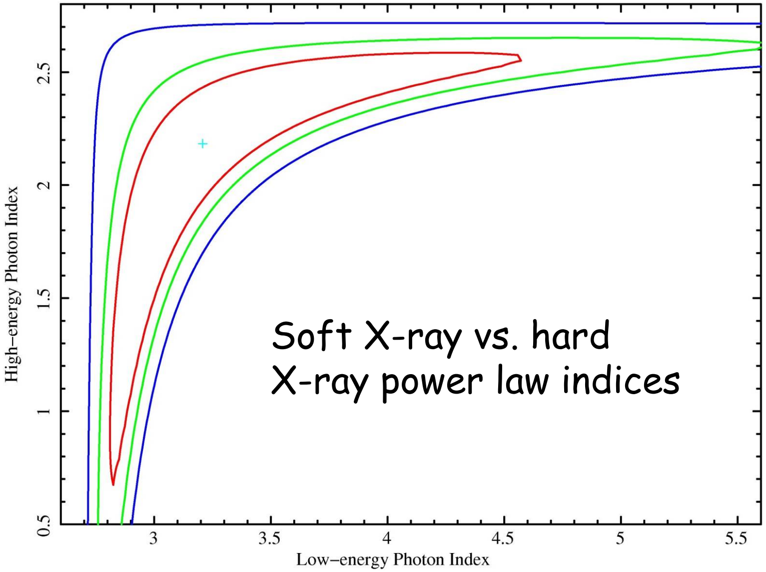
Fermi analysis straightforward: γ-ray flux during April 2013 is also low, no measurable variability; used +/- 5 days of Fermi data centered on the NuSTAR pointing



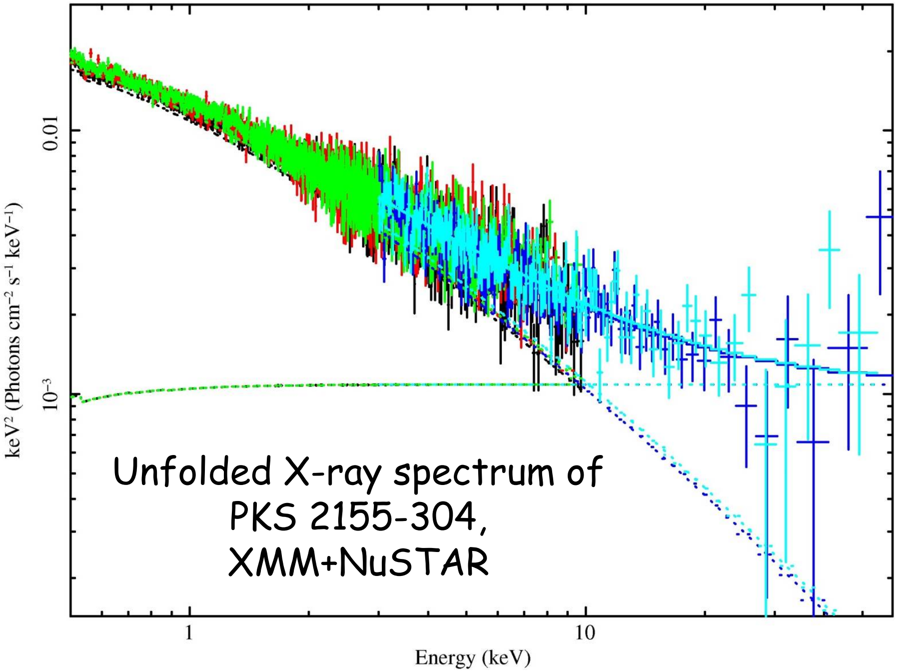
NuSTAR and XMM together

* Considering jointly simultaneous XMM data shows a complete X-ray picture

- 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*
- Presumably this is the “onset” of the inverse Compton component
- The 20 – 40 keV flux is ~ 0.8 x 10^{-11} erg/cm^2/s



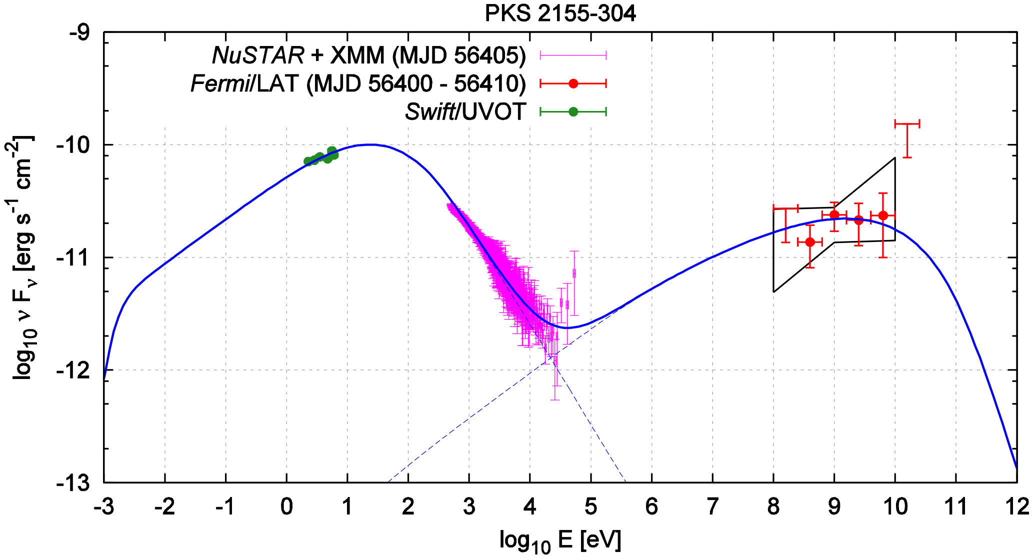
Soft X-ray vs. hard X-ray power law indices



Unfolded X-ray spectrum of PKS 2155-304, XMM+NuSTAR

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 most numerous
- 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
- Important consequence: soft X-rays definitely should be polarized! (synchrotron process)

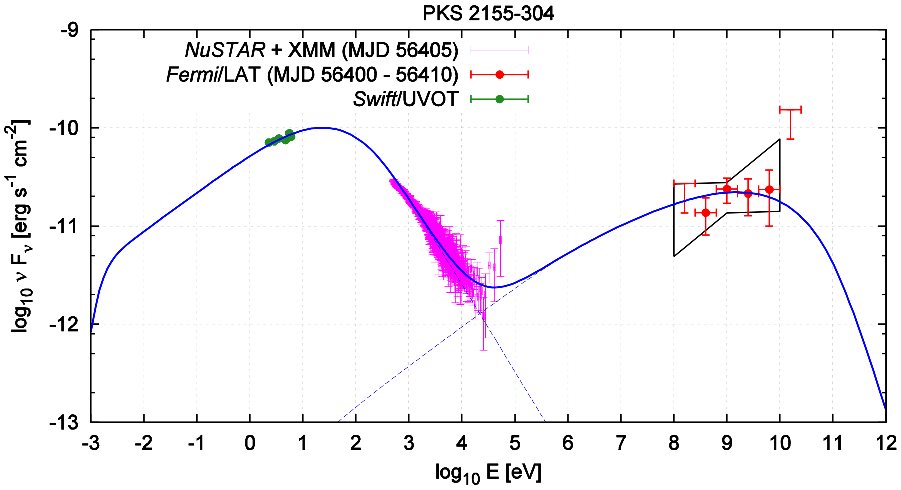


Modelling results:

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!

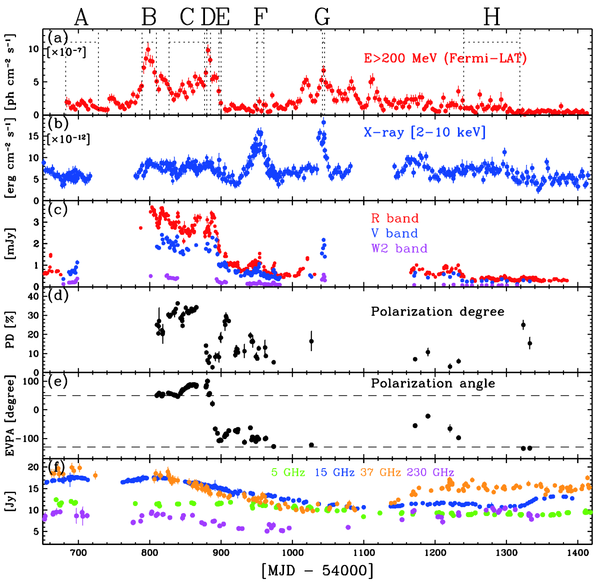
More likely solution: the jet has a substantial pair content (#positrons / #protons ~ at least 50)

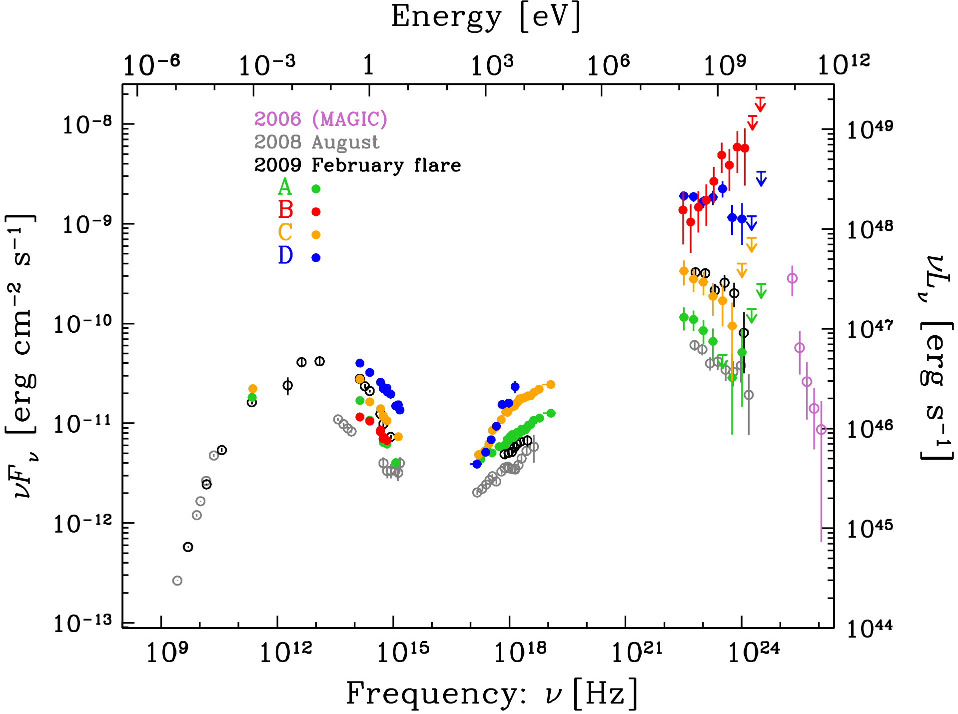
Possibly the 1st direct indication that HBL blazar jets in the blazar zone are pair dominated

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

For more details, see Madejski et al. 2016

Other types of blazars?





High-luminosity FSRQ blazar 3C279

OTHER CLASSES OF BLAZARS? HIGH LUMINOSITY TYPES?

* 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 cannot be entirely devoid of protons:
  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

Pairs vs. protons in luminous blazars?

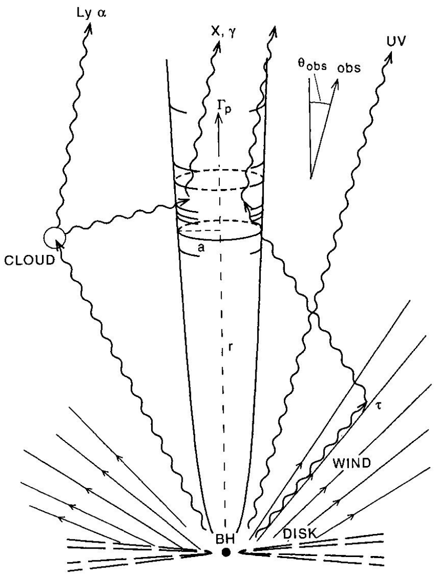


FIG. 2.—Geometry of the source. The radiating region, denoted by short cylinder of dimension a, moves along the jet with pattern Lorentz factor Γ_p. Underlying flow moves with Lorentz factor Γ, which may be different.

Schematic
picture of
geometry
of a blazar
jet

Argument goes as follows:

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

Pure pair jet excluded - at least some protons (or huge Poynting flux) needed to carry the kinetic power

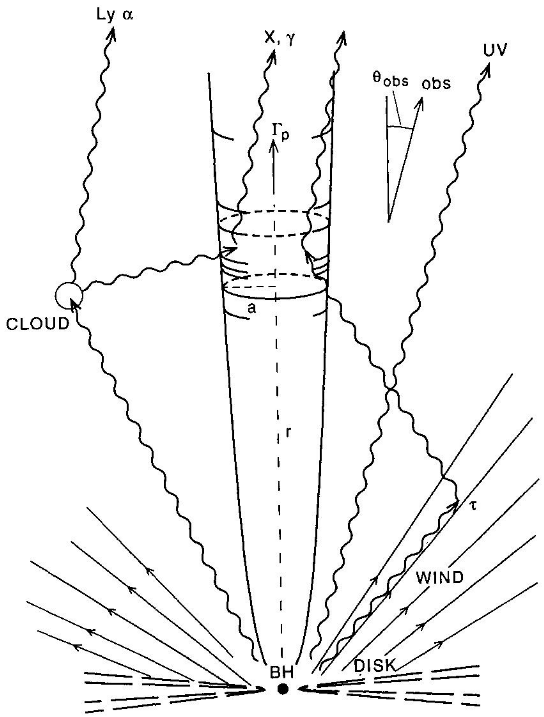
Some previous papers assumed no pairs -> requiring one proton per electron implied that the jet power was huge (Ghisellini+ 2014 Nature paper)

G+ 2014 invoked tapping the rotation of the black hole (via "Blandford-Znajek process") to power the jet but at a level probably too high vis—vis BZ theory

They argued that pure positron plasma would be slowed down by Compton interactions, 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!



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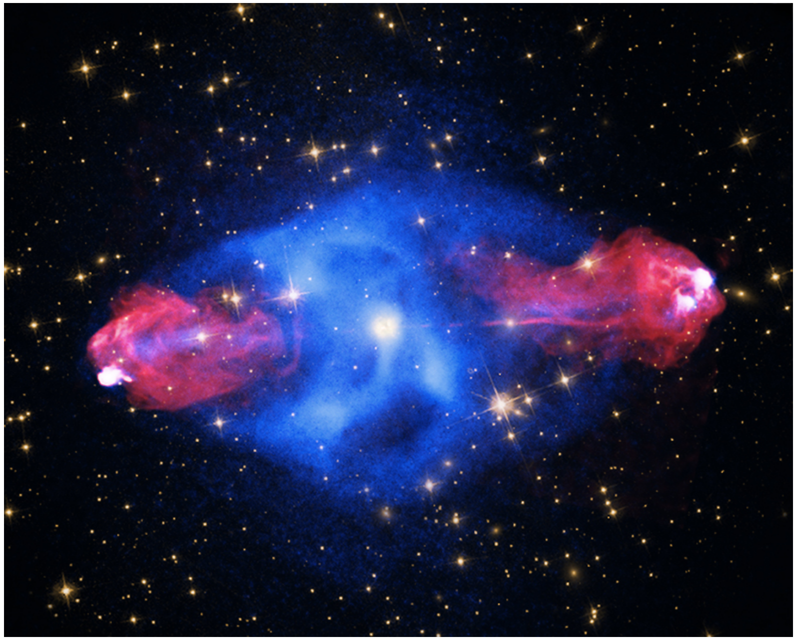


Cygnus A radio galaxy:
blazar jet viewed from the side

<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) consider <u>matched</u> samples of blazars with hot spots, infer that total jet power is much *lower* than inferred by Ghisellini+ from spectral fitting**
- **But, positrons are less massive than protons – invoking those would reduce jet power**

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

What are the predicted polarization signatures for various processes believed to generate radiation in X-ray band?

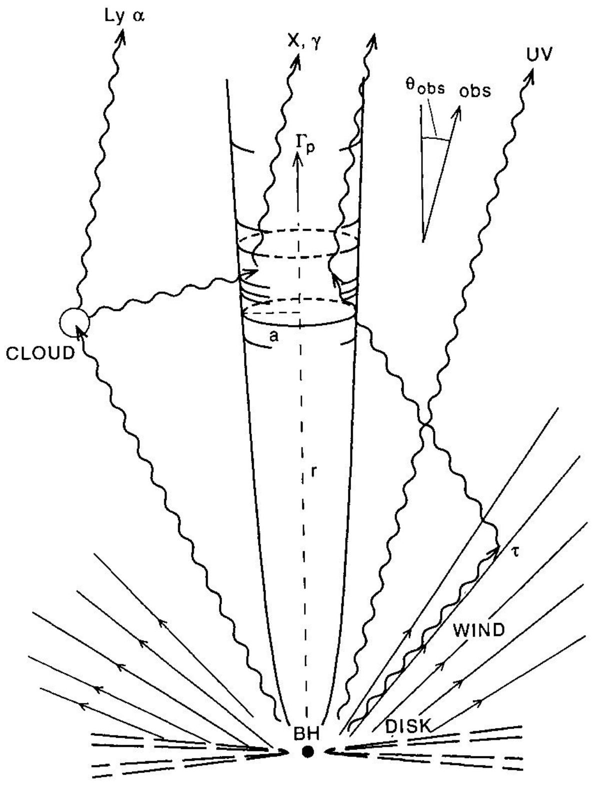


FIG. 2.—Geometry of the source. The radiating region, denoted by short cylinder of dimension a, moves along the jet with pattern Lorentz factor Γ_p. Underlying flow moves with Lorentz factor Γ, which may be different.

The most commonly accepted model for X-ray emission from BL Lac-type blazars (HBLs) is the synchrotron process

This is expected to be highly polarized

If no X-ray polarization is detected, we are back to drawing board…

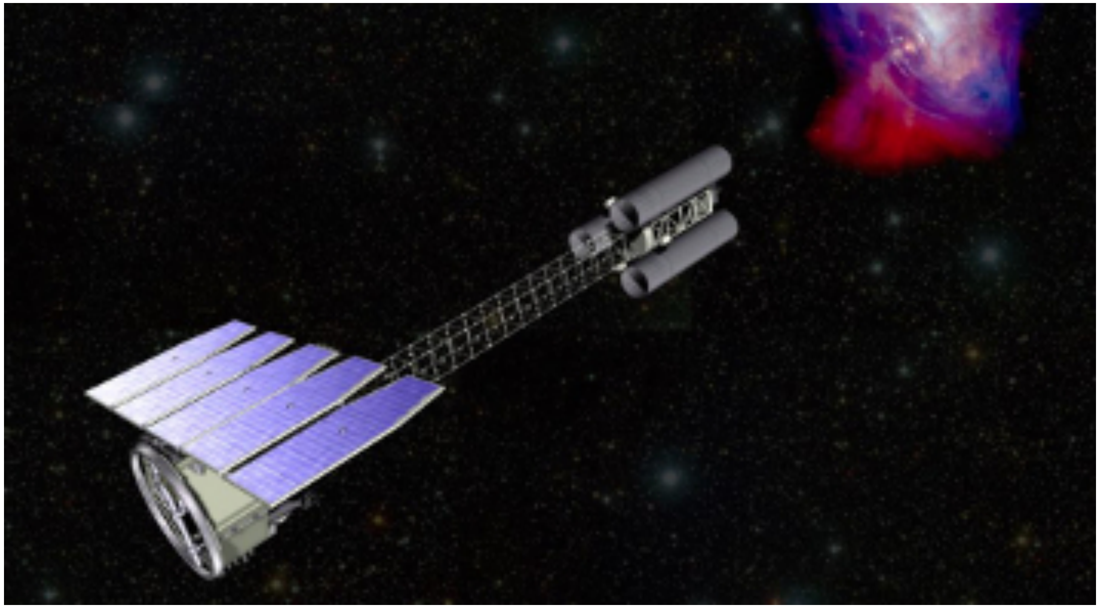
"Standard" picture of hard X-ray emission in luminous, FSRQ blazars is the inverse Compton process

Clear predictive power as to the origin of the "seed" photons

If the "seed" photons are internal to the jet – the so-called "synchrotron self Compton" mechanism, the X-rays should be polarized

If the "seed" photons are external (broad-line region, IR – emitting torus) – "External radiation Compton" – the X-rays should not be polarized

For more extensive discussion, check out Markus Boettcher's talk



Imaging X-ray Polarimetry Explorer (IXPE)

X-ray polarimetry coming soon! - and will include blazar observations

First sensitive X-ray polarimeter is being assembled/tested for launch in November 2021

Three mirrors (NASA's MSFC), three detectors (INFN/Pisa, Italy)

Each mirror has an effective area of ~ 160 cm^2, point spread function ~ 30 arc sec

Field of view ~ 4 arc min x 4 arc min (detector-limited)

The plans are to observe about 10 blazars and radio galaxies during the 1st year

For sensitivity to blazar observations, check out Iannis Liodakis's talk

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)**