

## *Recent advances in phenomenology of blazar jets: jet content*

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with Masaaki Hayashida, Krzysztof Nalewajko, Jim Chiang, Amy Furniss, Marek Sikora, and the Fermi, NuSTAR teams

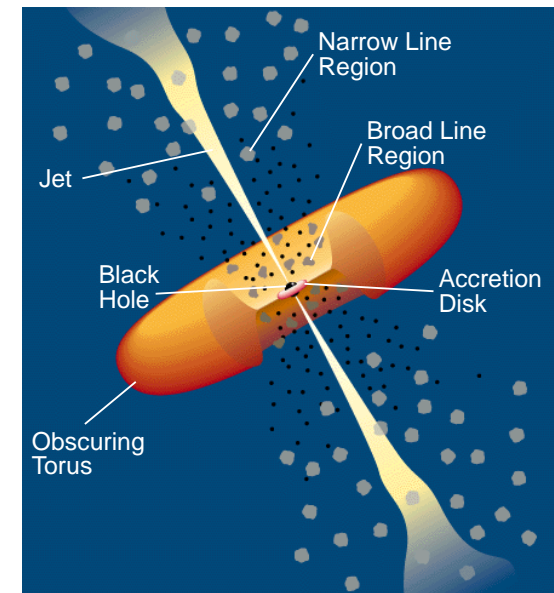
# Fermi and blazars: our attempts to define science goals date back 10 years

- Prior to the launch of Fermi, Anita Reimer, Benoit Lott and myself were charged with defining science goals for Fermi observations of blazars – and the needs for multi-band work
- Excellent opportunity to revisit the questions, and highlight at least some results
- The document (including many science goals) is at Benoit's site:

[ftp://www.cenbg.in2p3.fr/astropart/glast/agn\\_group/AGN\\_Sci\\_goals\\_v\\_Dec13.pdf](ftp://www.cenbg.in2p3.fr/astropart/glast/agn_group/AGN_Sci_goals_v_Dec13.pdf)

Regarding the physics of AGN jets: we considered that studying blazars is like “peeling an onion”:

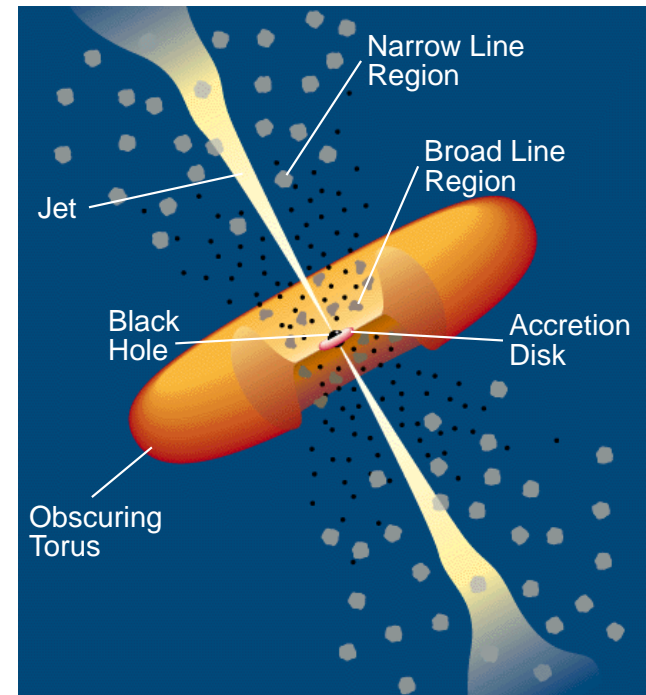
- **First, we study time-resolved multi-band emission,**
- **Next, we infer the emission mechanisms,**
- **This leads to a study of the jet content: population of the radiating particles,**
- \* **Next two steps are: total jet energetics, and the source of its energy**
- **Connection to the accretion process? Jet power from accretion, or rotation of the black hole?**
- **Studies of individual objects, samples – both valuable**
- **This talk focuses on the jet content, touches upon source of the jet power**



(somewhat overused)  
schematic of an AGN

# Active galaxies: brief intro

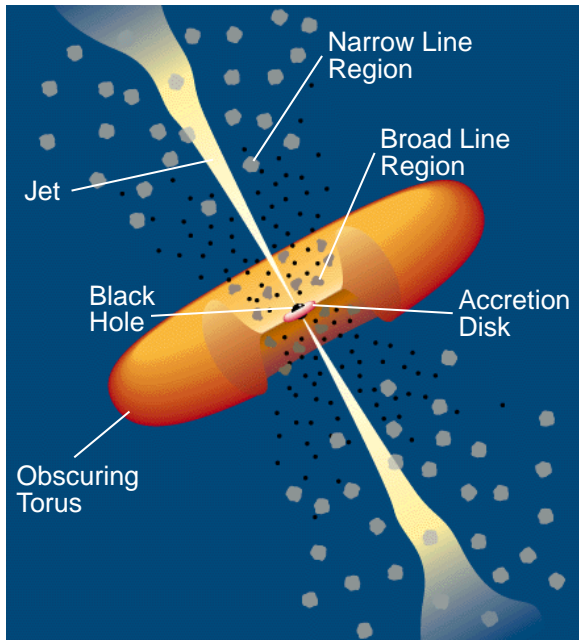
- Many if not most galaxies contain a massive ( $M > 10^6$  Solar masses) black hole
- In the process of their growth, massive black holes accrete material from their vicinity
- Accreting material loses potential energy via heating of an accretion disk -> quasars, Seyfert galaxies
- Accreting material loses angular momentum via some kind of transport (MRI?)
- This results in some form of accretion disk corona, emitting in the X-ray band



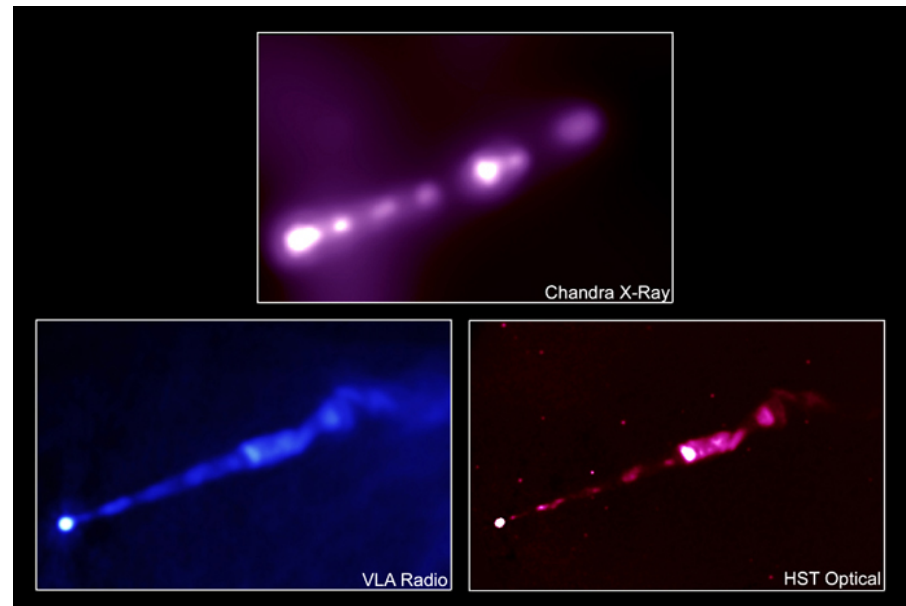
(somewhat overused)  
schematic of an AGN

# Relativistic jets: why are they interesting?

- \* In some ( $\sim 10\%$  ?) 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  $\gamma$ -ray emitters. Need GeV-energy particles to make those  $\gamma$ -rays!



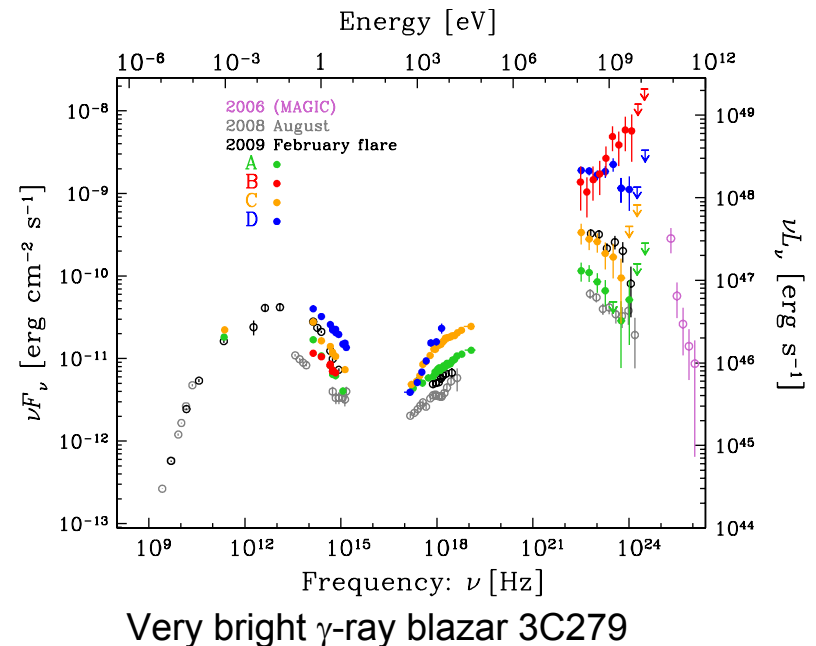
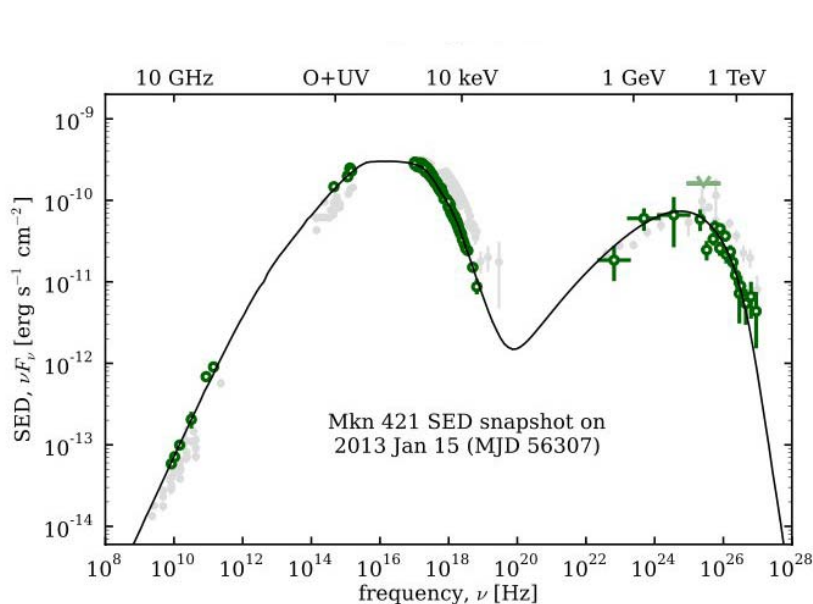
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schematic of an AGN



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

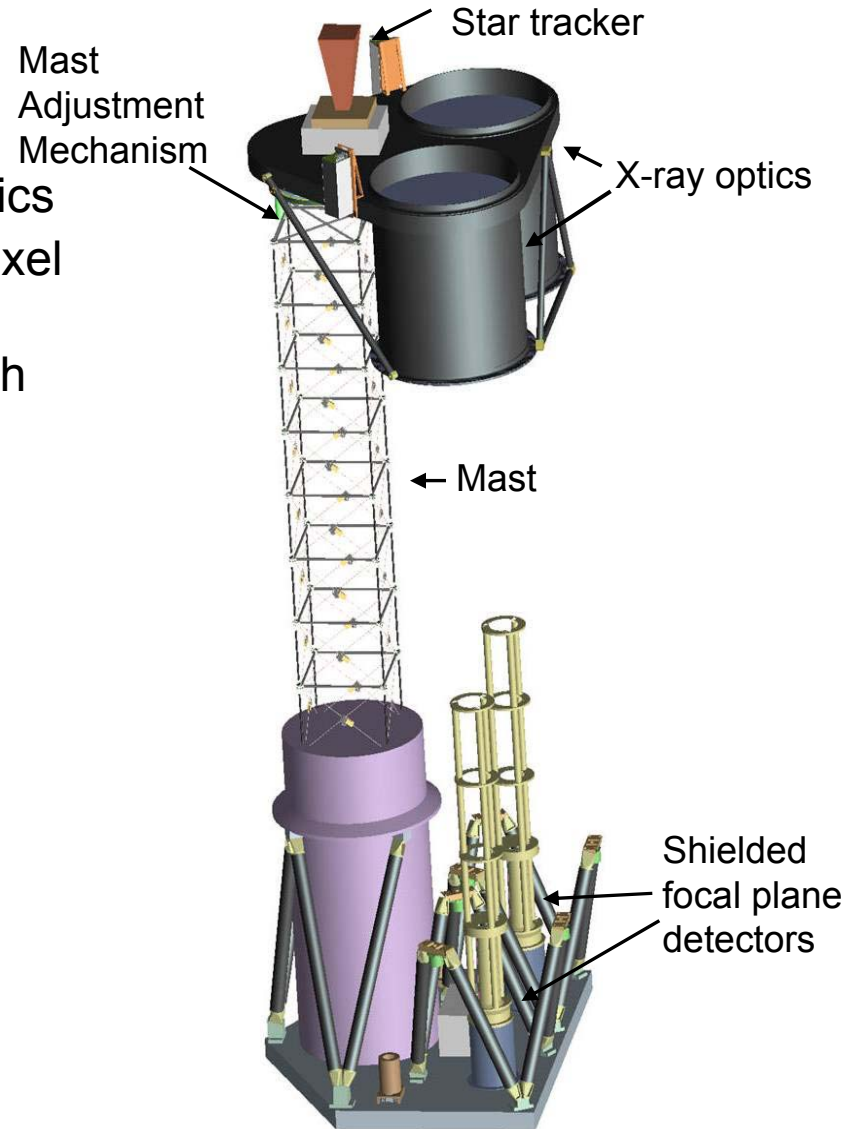
# Small dollop of blazar phenomenology

- Blazars radiate over all accessible spectral bands (15 decades in photon energy)
- Broad-band spectra are remarkably similar to each other but, 2 general “types”
- They consist of two broad “humps” one peaking in the far IR – to – soft X-rays, another peaking in the MeV – GeV  $\gamma$ -ray range, sometimes extends to the TeV VHE  $\gamma$ -ray regime
- The low-energy hump emission (radio, opt.) is polarized, and generally thought to originate via synchrotron emission of plasma consisting of relativistic particles accelerated in the jet
- The high-energy peak is thought to originate via inverse Compton process, by the same electrons that produced the synchrotron hump
- All this takes place in a volume that can be estimated from variability time scales



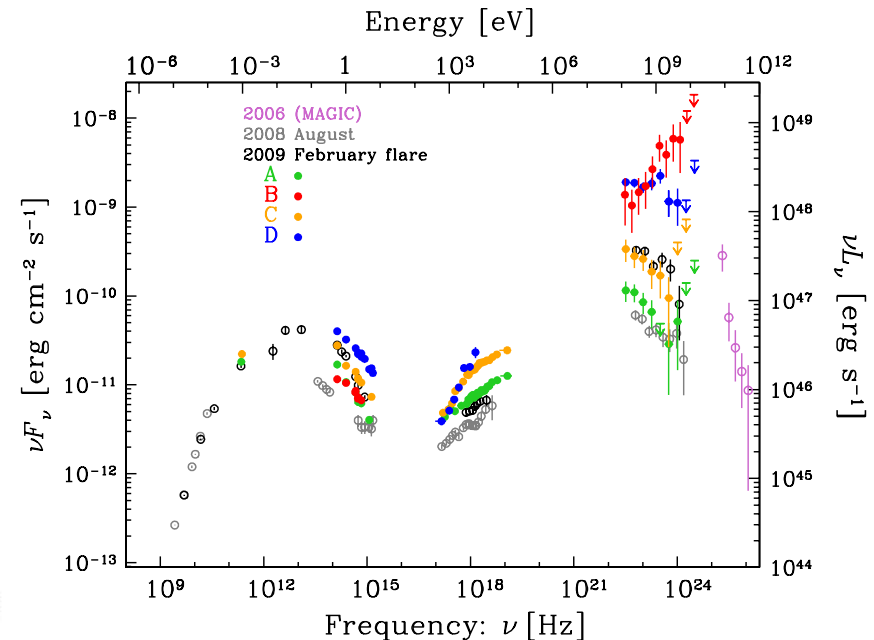
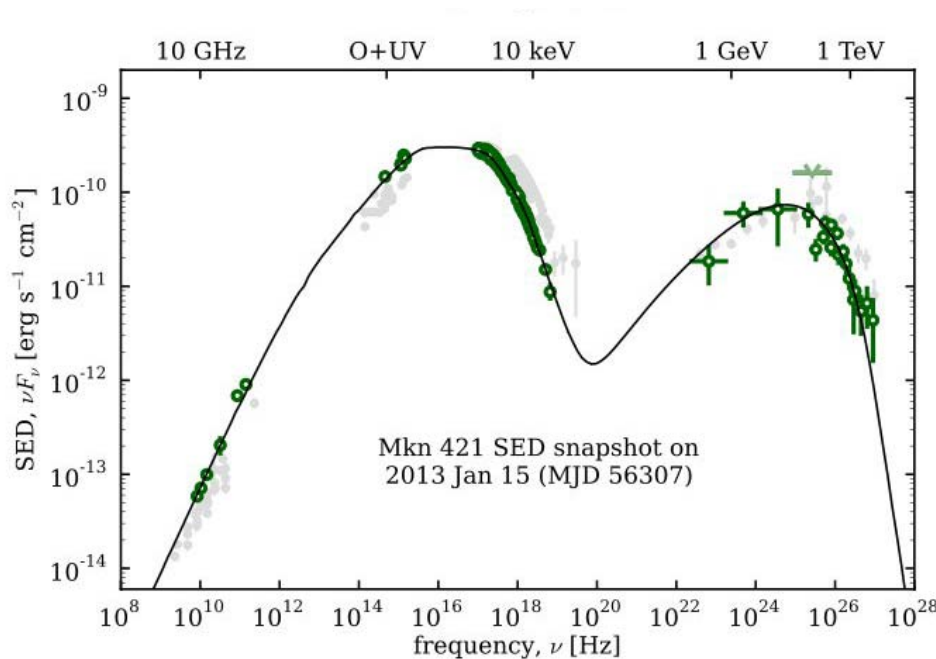
# Friend of Fermi: Hard X-ray satellite NuSTAR

- NASA's Small Explorer mission, launched in June 2012; led by Caltech
- Two identical co-aligned grazing incidence hard X-ray telescopes:
  - Multilayer coated segmented glass optics
  - Actively shielded solid state CdZnTe pixel detectors
- Extendable mast provides 10-m focal length
- Focussing optics, low Earth orbit reduces background!
- Energy bandpass 4 – 80 keV



# 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 “tail” of the synchrotron hump samples the most energetic radiating particles – important for understanding particle acceleration process
- The “onset” of the inverse Compton peak samples the low-energy particle population in the relativistic plasma - important for the total particle content in the jet (low energy particles are most numerous)
- \* For the future: X-ray polarization is crucial to verify this picture



# One example for today: PKS 2155-304

- \* Here, we adopt (for now) “one object at a time” approach and study a representative case
- \* Well-known and extensively studied blazar,  $z = 0.117$ , one of the first BL Lac – type objects detected in X-rays (Schwartz et al. 1979)
- \* Completely featureless optical spectrum, redshift from the host galaxy
- \* Gamma-ray emitter known from the EGRET days; VHE source (Chadwick et al. 1999; Aharonian et al. 2005)
- \* Fermi – LAT observations were reported several years ago (Aharonian et al. 2009)
- \* Can be very variable: probably most “notorious” aspect of it is the large amplitude, minute-scale variability seen by H.E.S.S. (Aharonian et al. 2007)

An Exceptional VHE Gamma-Ray Flare of PKS 2155–304

5

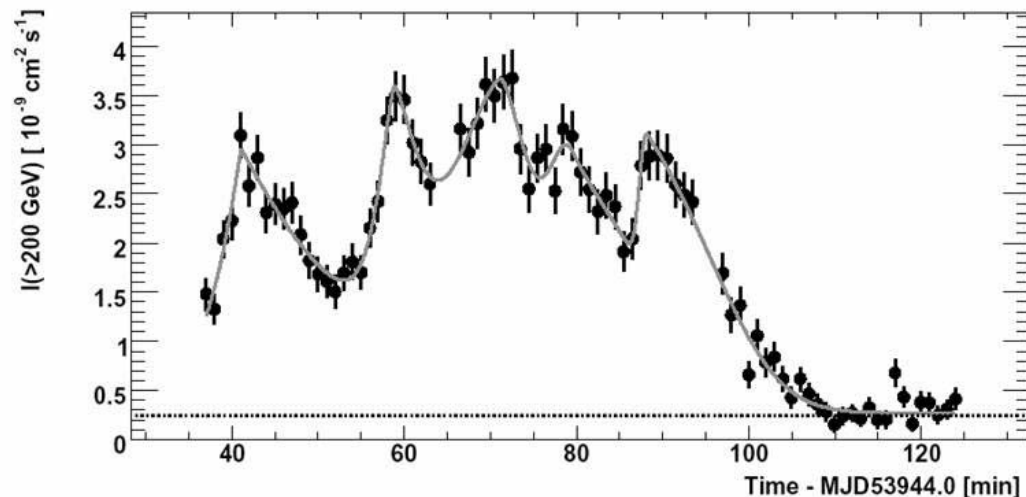
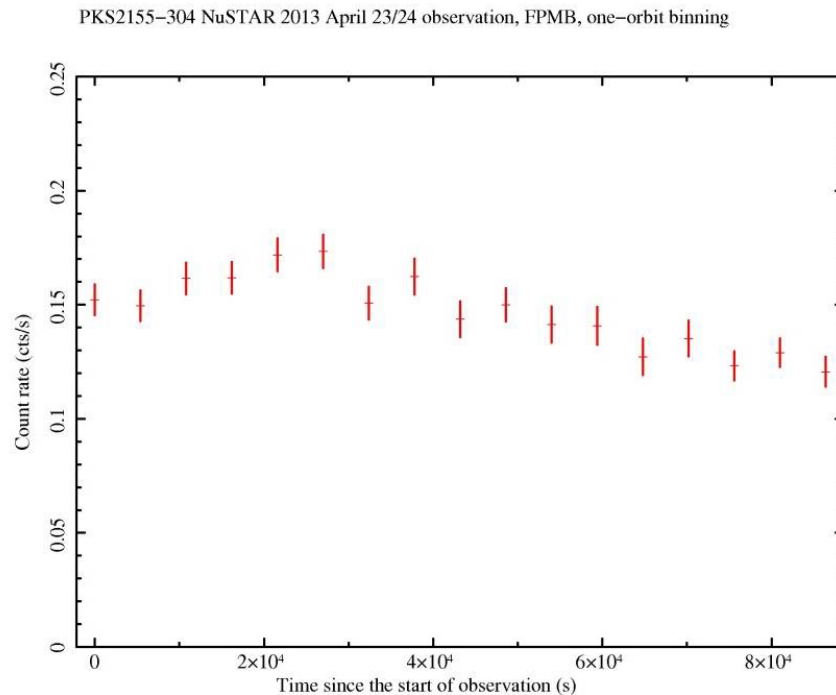


FIG. 1.— The integral flux above 200 GeV observed from PKS 2155–304 on MJD 53944 versus time. The data are binned in 1-minute intervals. The horizontal line represents  $I(>200 \text{ GeV})$  observed (Aharonian et al. 2006) from the Crab Nebula. The curve is the fit to these data of the superposition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



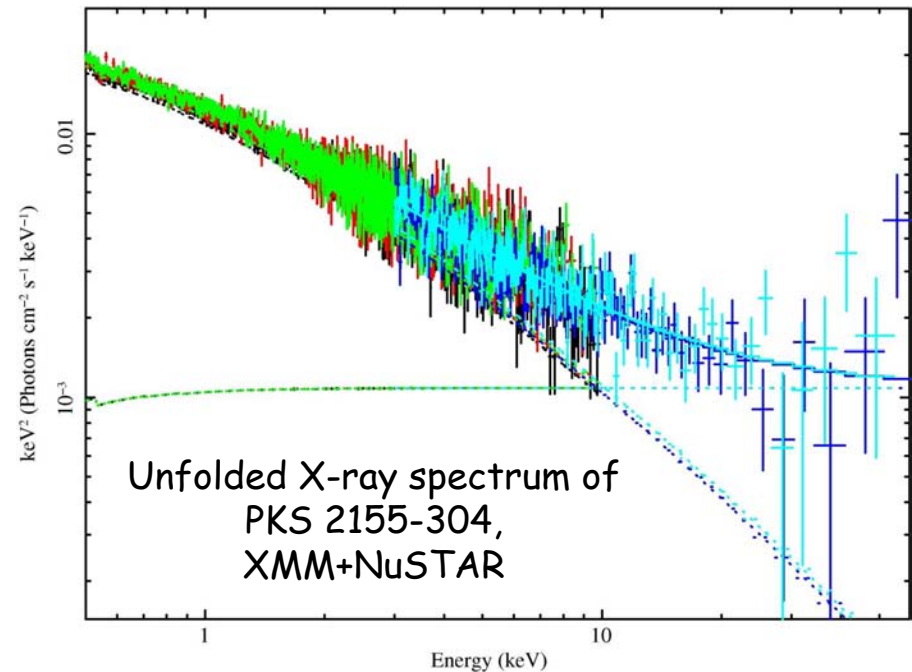
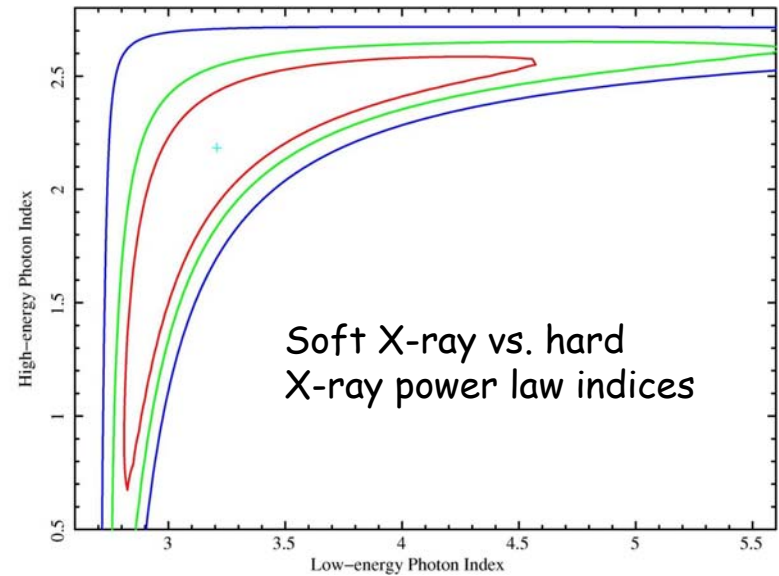
# NuSTAR / Fermi observations

- \* 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,  $\sim 10^{-11}$  erg cm $^{-2}$  s $^{-1}$  (2 – 10 keV), 1/3 of the previously reported “low” state
  - \* NuSTAR collected a day’s worth of data ( $\sim 40$  ks), shows very little variability,
- Fermi analysis straightforward:  $\gamma$ -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



# 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)

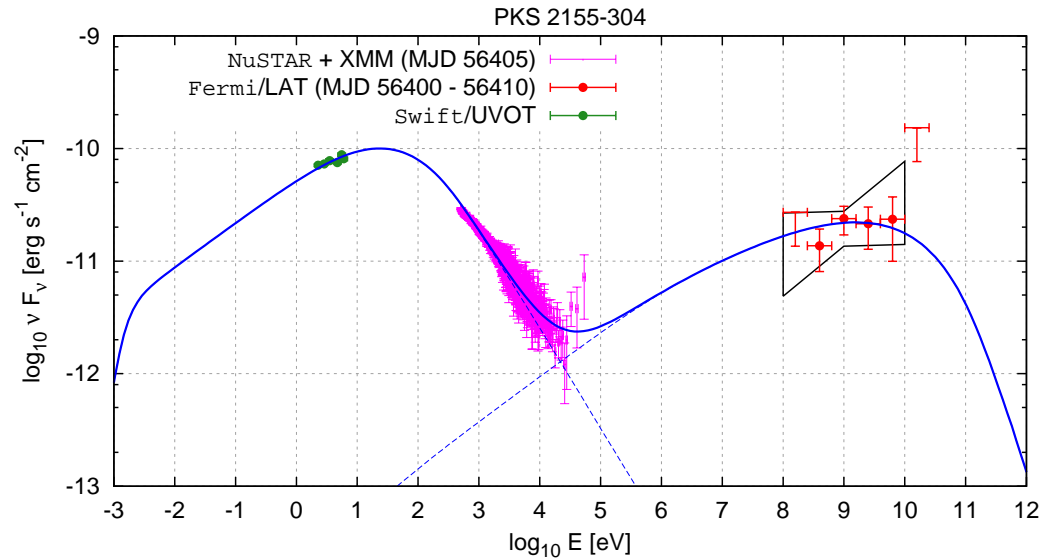
The presence of the "hard tail" indicates that the inverse Compton spectrum has to extend to v. low energies!

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,  $R = 3 \times 10^{15}$  cm, consistent with all previous modelling

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



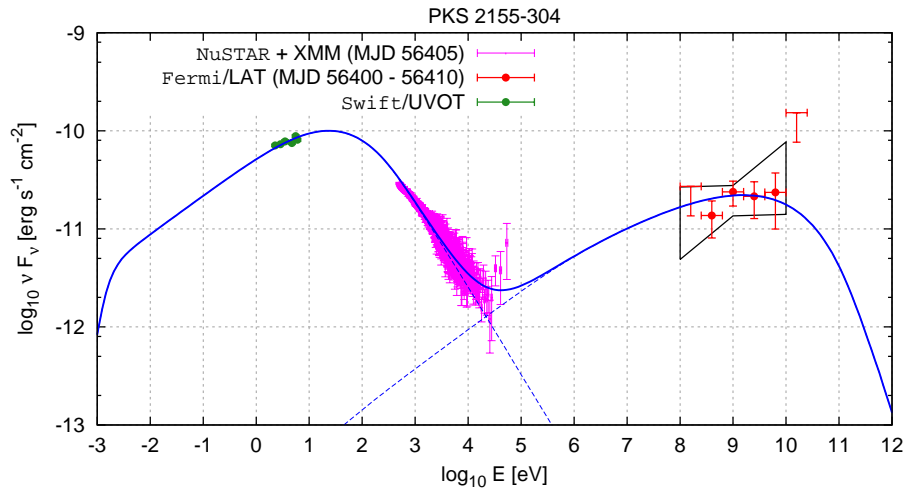
## Modelling results:

We find  $L_B = 6 \times 10^{42}$  erg/s,  $L_e = 3 \times 10^{44}$  erg/s,  
 $L_{\text{rad}} = 10^{43}$  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,  $L_{\text{rad}} = 10^{43}$  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  $10^9 M_\odot$ , the source would need to accrete at  $L/L_{\text{edd}} \sim 1$

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

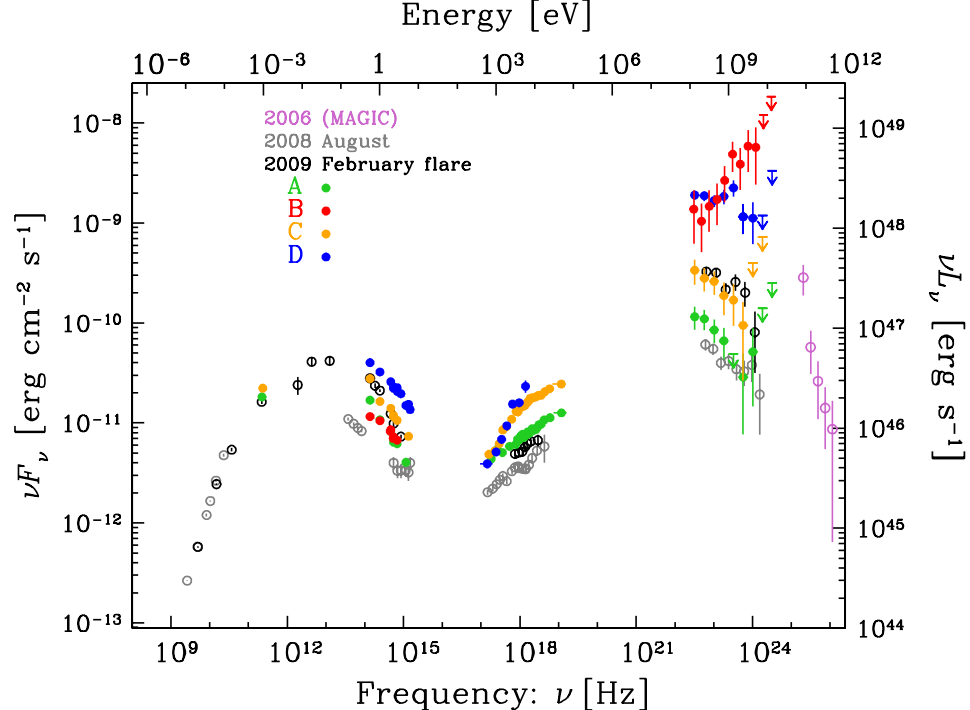
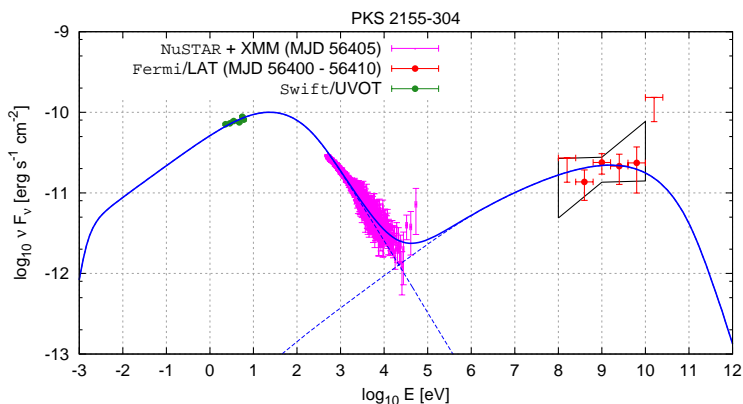
HBL – type blazars are supposed to be advection – dominated accretion sources, not accreting at  $L/L_{\text{edd}} \sim 1$ !

More likely solution: the jet has a substantial pair content ( $\#\text{positrons} / \#\text{protons} \sim$  at least 50)

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

Conclusion seems robust to changes in  $\Gamma_j$ ,  $B$ , ... (hard to make a x50 error)

# 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 are needed to provide the jet's kinetic energy

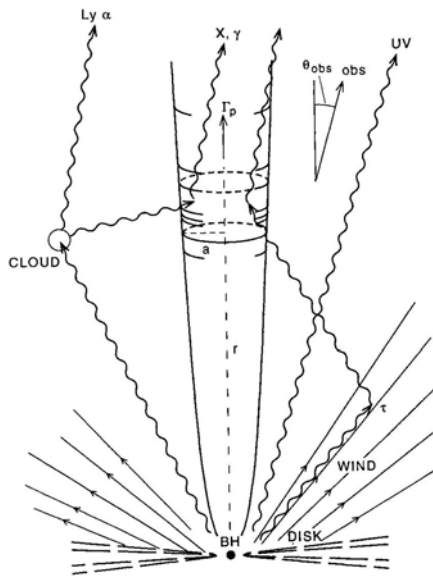


FIG. 2.—Geometry of the source. The radiating region, denoted by short cylinder of dimension  $a$ , moves along the jet with pattern Lorentz factor  $\Gamma_p$ . Underlying flow moves with Lorentz factor  $\Gamma$ , which may be different.

Schematic picture of geometry of a blazar jet

## Pairs vs. protons in luminous blazars?

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**

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

**At least some protons are 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!

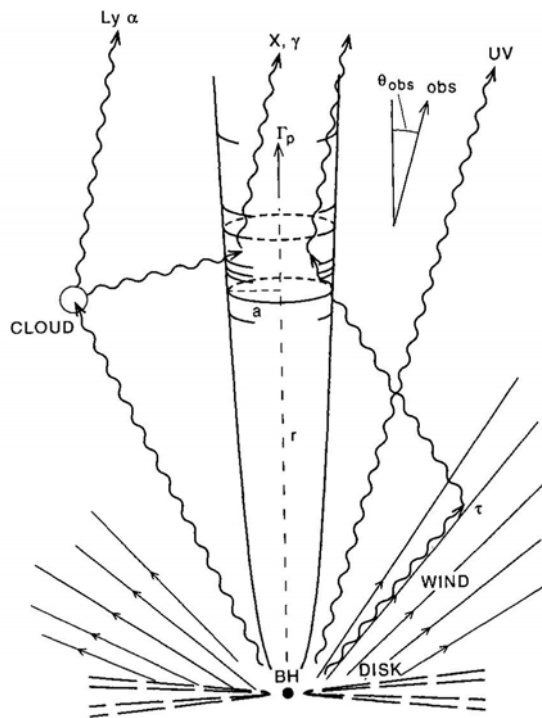
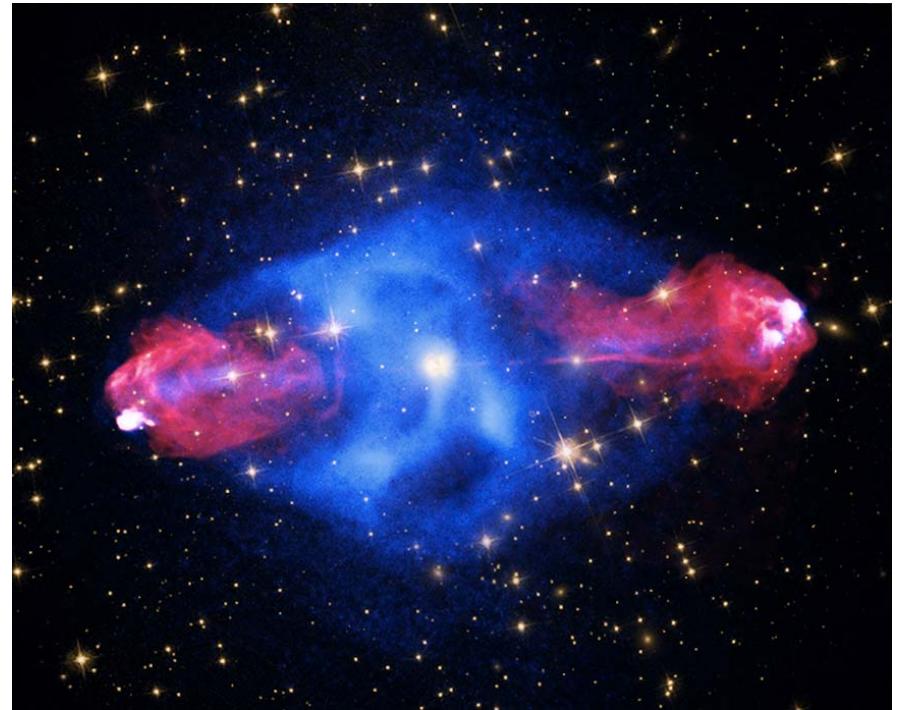


FIG. 2.—Geometry of the source. The radiating region, denoted by short cylinder of dimension  $a$ , moves along the jet with pattern Lorentz factor  $\Gamma_p$ . Underlying flow moves with Lorentz factor  $\Gamma$ , which may be different.



Cygnus A radio galaxy:  
blazar jet viewed from the side

## Hot spots in radio galaxies are a form of a "calorimeter" (beam dump)

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  $\sim 20$

We discussed observations and modelling 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...

- $e^+/P \sim 20$  OK, consistent with radio hot spots which provide additional constraints

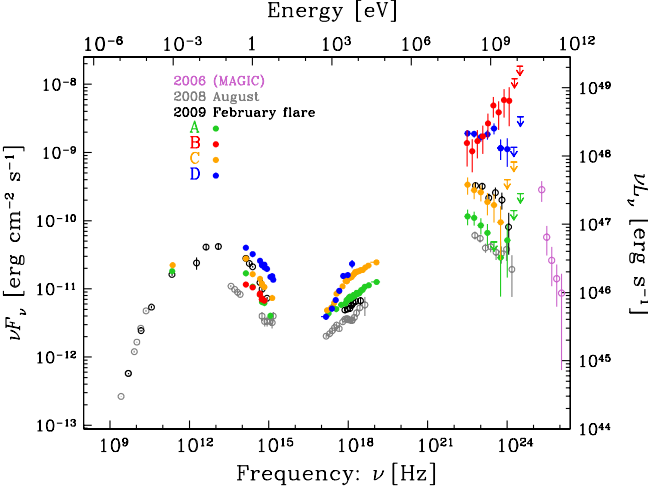
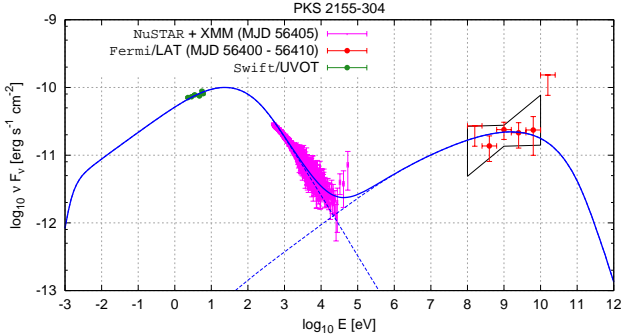
**CHALLENGE TO THEORETICAL EFFORTS: HOW ARE THE PAIRS PRODUCED IN THE JET?**

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

**X-ray /  $\gamma$ -ray polarization predictions:** depends on the radiation process

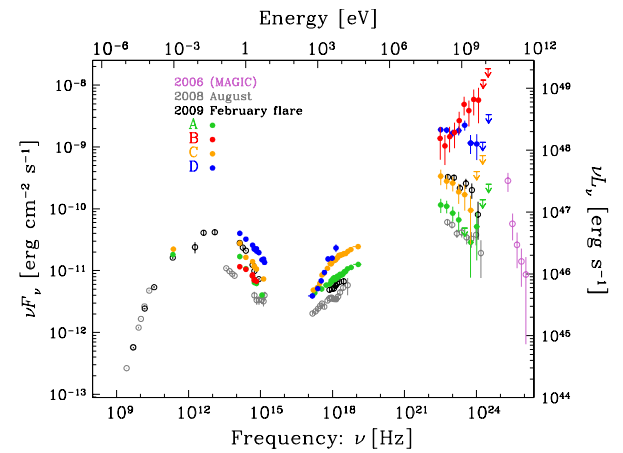
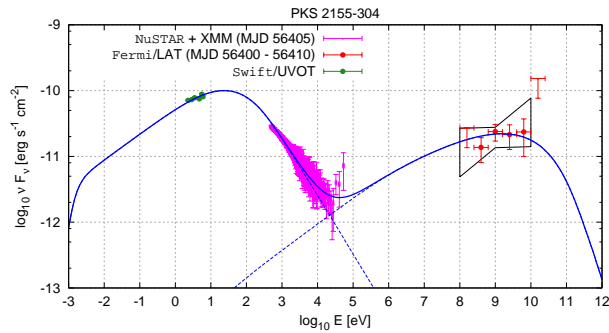
- \* **synchrotron:** strong polarization, probably same angle as optical (X-rays in HBL-type blazars)
- \* **inverse Compton:** if seed photons unpolarized – probably no polarization ( $\gamma$ -rays in FSRQs)
- \* **inverse Compton:** if seed photons are polarized – strong polarization, same angle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

# Conclusions

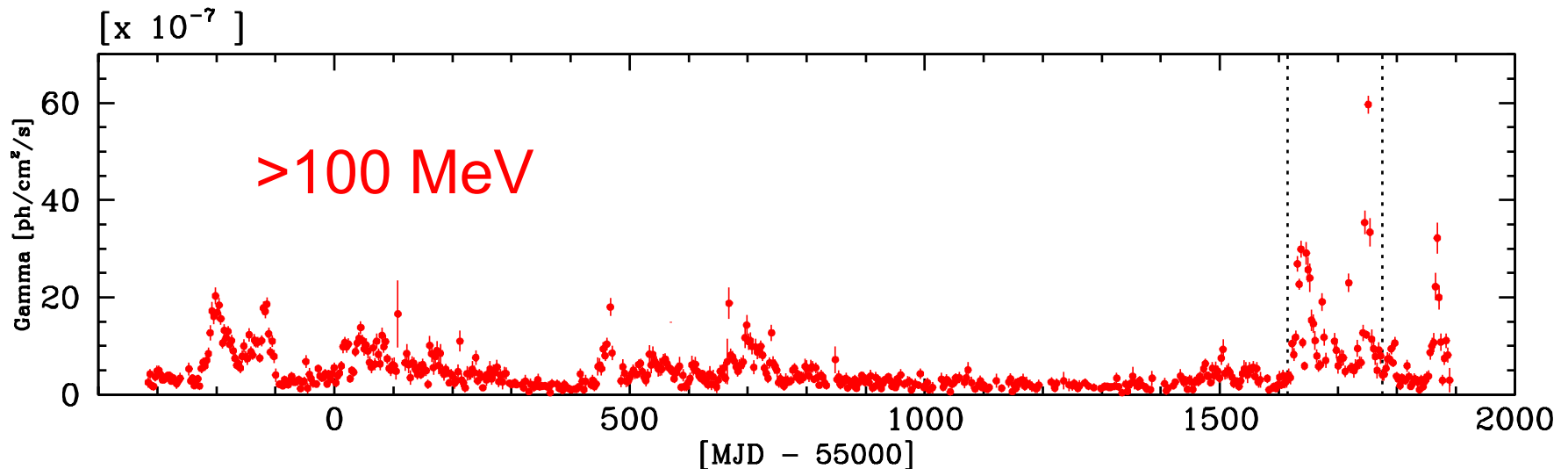




# BACKUP SLIDES: FOCUS ON 3C279



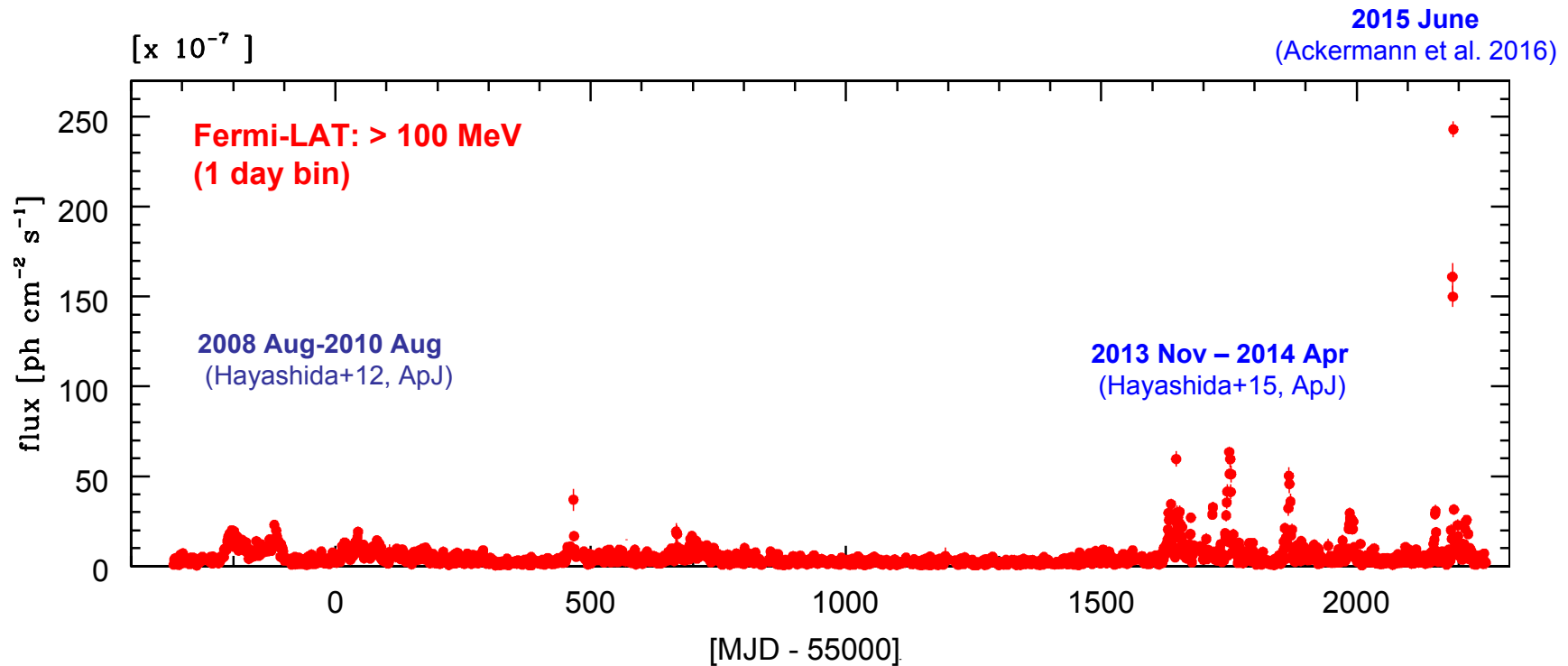
# Switching gears to FSRQs: 3C 279's light curve for 6 years - Aug. '08-Aug'14



- \* FSRQs are very luminous quasars possessing powerful jets
- \* 3C279 is one of the “poster children” of extragalactic  $\gamma$ -ray astronomy
- \*  $z = 0.536$ , BH mass  $\sim (3-8) \times 10^8 M_{\text{solar}}$ ,  $L_d \sim 6 \times 10^{45}$  erg/s
- \* one of the EGRET brightest AGN
- \* the first TeV FSRQ (discovered by MAGIC in 2006)
- Fermi-detected  $\gamma$ -ray flare with polarization change in 2009 – Fantastic result enabled by KANATA!

# You thought we saw the biggest flare in 3C279 in 2014?

7 year Fermi light curve (2008 Aug. – 2015 Aug.)

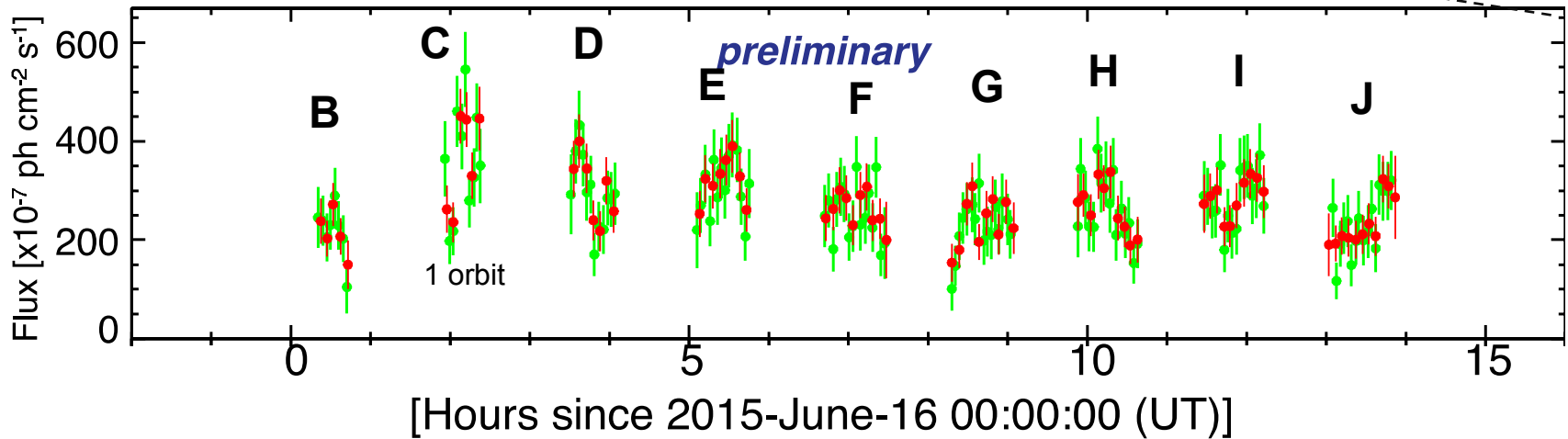
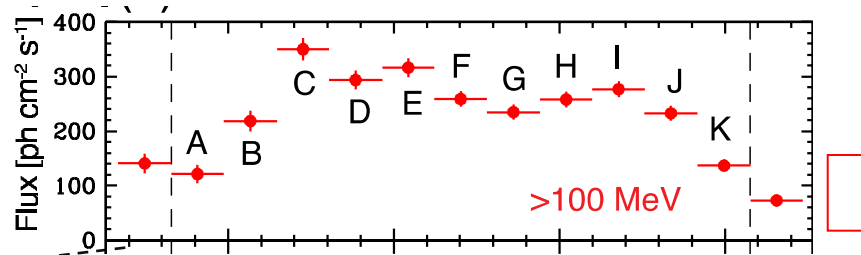


## 1-day average fluxes during 3 large outbursts (at E >100 MeV)

1. 2013 December 20 :  $6.0 \times 10^{-6}$  ph cm<sup>-2</sup> s<sup>-1</sup>
2. 2014 April 03 :  $6.4 \times 10^{-6}$  ph cm<sup>-2</sup> s<sup>-1</sup>
3. 2015 June 16 :  $24.3 \times 10^{-6}$  ph cm<sup>-2</sup> s<sup>-1</sup>

# Short time bin (minutes scale) $\gamma$ -ray light curve

**Red :** 5 minutes bin  
**Green :** 3 minutes bin



**significant variability in orbit C** (and a possible hint in orbit D)

The > 100 MeV flux doubled in less than 10 minutes  
**Possibly the most rapid seen in a FSRQ-type blazar**

# Implications of rapid variability of 3C279

source name	z	src type	$t_{\text{var}}$	energy	Lum.[erg/s]
PKS 2155-304	0.116	BL Lac	~ 2 min	>0.2 TeV	1e47
IC310	0.018	radio gal.	< 4 min	>0.3 TeV	1e44
3C 279	0.536	FSRQ	~ 5 min	>100 MeV	1e49

- to avoid internal absorption ( $E_{\text{max}} \sim 10$  GeV): object must be strongly beamed,
- $\delta > 25$  – model independent
- Broad-band emission is strongly dominated by  $\gamma$ -rays

## The minute scale variability suggests:

*In the context of inverse Compton process producing gamma-rays:*

- An emission region inside BLR, high jet  
Lorentz factor, compact emission region
- Inverse Compton models imply very low magnetization  
(photon energy density dominates)

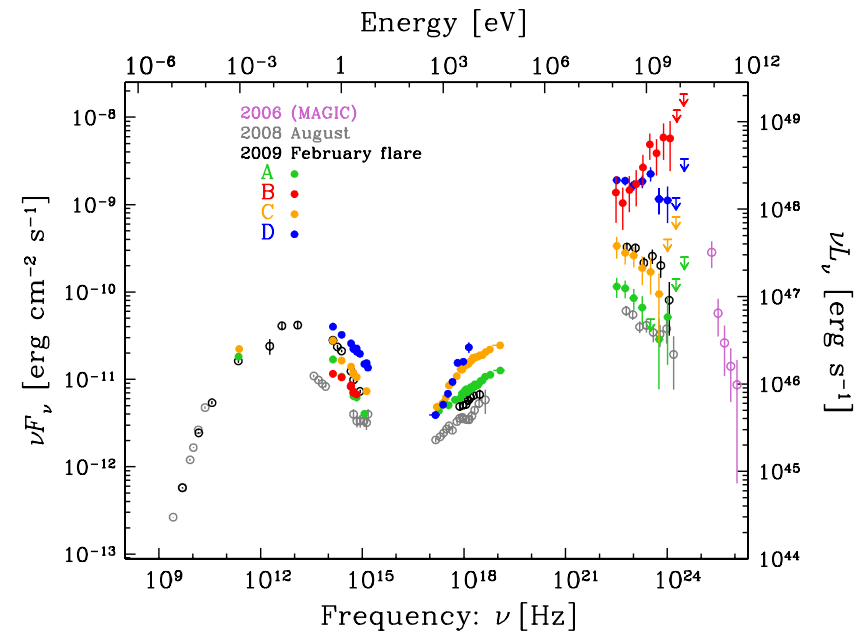
**NEW IDEA:** Perhaps  $\gamma$ -rays are produced by the synchrotron process?

this would require  $B \sim 100$  Gauss,

$\gamma_{\text{el}} \sim 10^6$  – reasonable values

- implications on polarization in the  $\gamma$ -rays

**Multiple processes contributing to  $\gamma$ -ray emission?**



# What are the predicted polarization signatures for various processes believed to generate radiation in X-ray / $\gamma$ -ray bands?

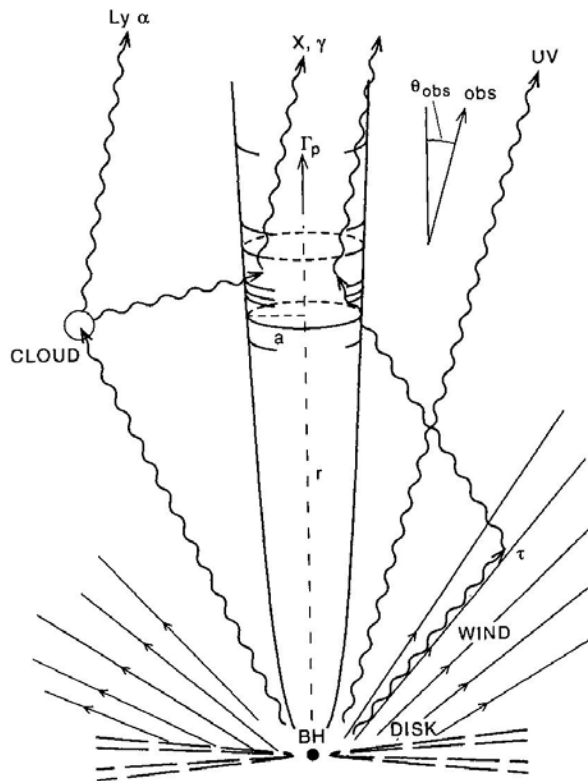


FIG. 2.—Geometry of the source. The radiating region, denoted by short cylinder of dimension  $a$ , moves along the jet with pattern Lorentz factor  $\Gamma_p$ . Underlying flow moves with Lorentz factor  $\Gamma$ , which may be different.

“Standard” picture of hard X-ray and gamma-ray emission in blazars is the inverse Compton process

As mentioned earlier, for BL Lac - type blazars, the “seed” photons are internal to the jet - the so-called “synchrotron self Compton” mechanism

For powerful blazars associated with luminous quasars (FSRQs) - seed photons for gamma-ray inverse Compton scattering are external (broad-line region, IR - emitting torus) - “External radiation Compton”