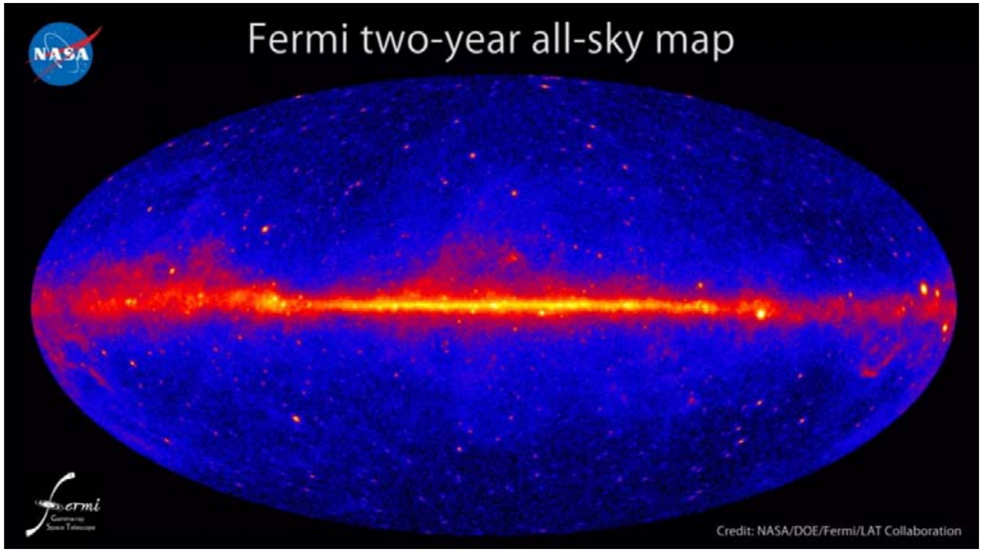
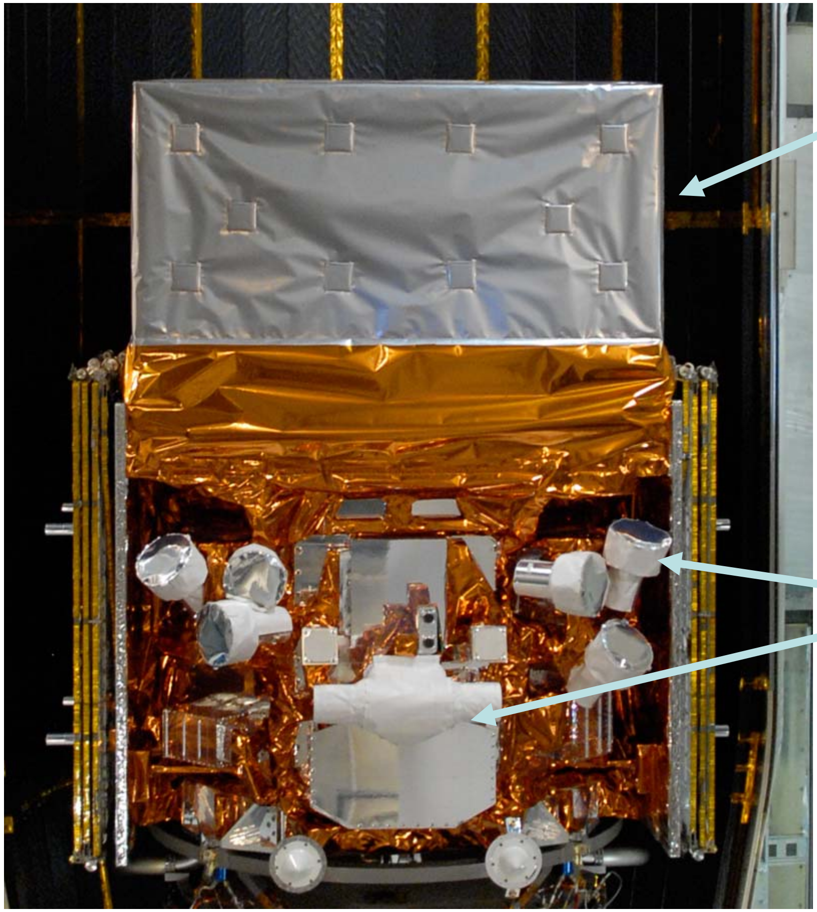


Gamma-ray emission from active galactic nuclei

Greg Madejski
Stanford / SLAC / KIPAC

with Krzysztof Nalewajko, Marek Sikora, Masaaki Hayashida, Mislav Balokovic, Amy Furniss, and the Fermi, NuSTAR teams

Main tool: Fermi Observatory



Large Area Telescope (LAT):

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

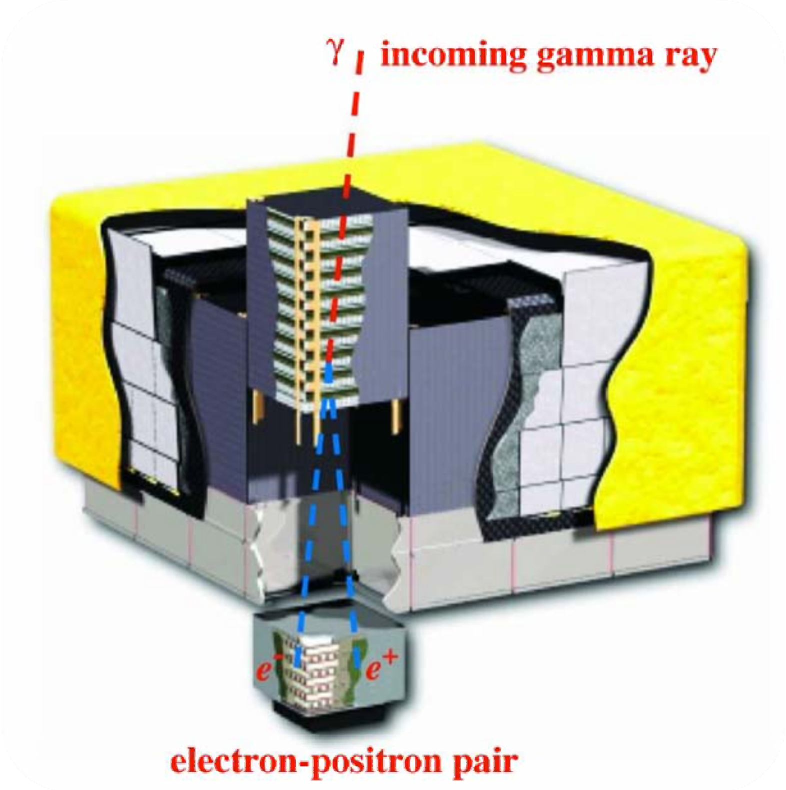
Gamma-ray Burst Monitor (GBM)

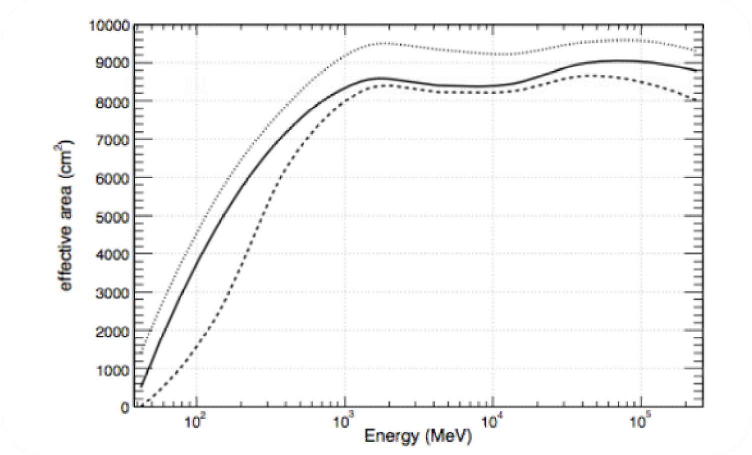
- 8 keV - 40 MeV
- views entire unocculted sky

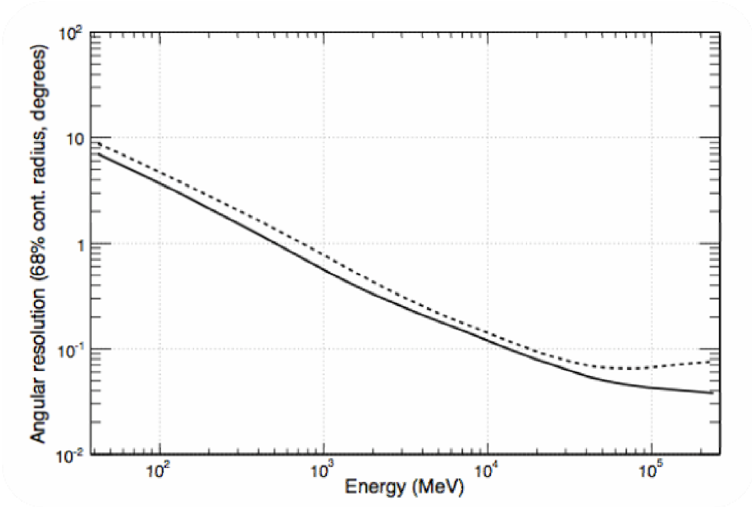
Launched on June 11, 2008 and works perfectly!

Bigger, Sharper, Faster

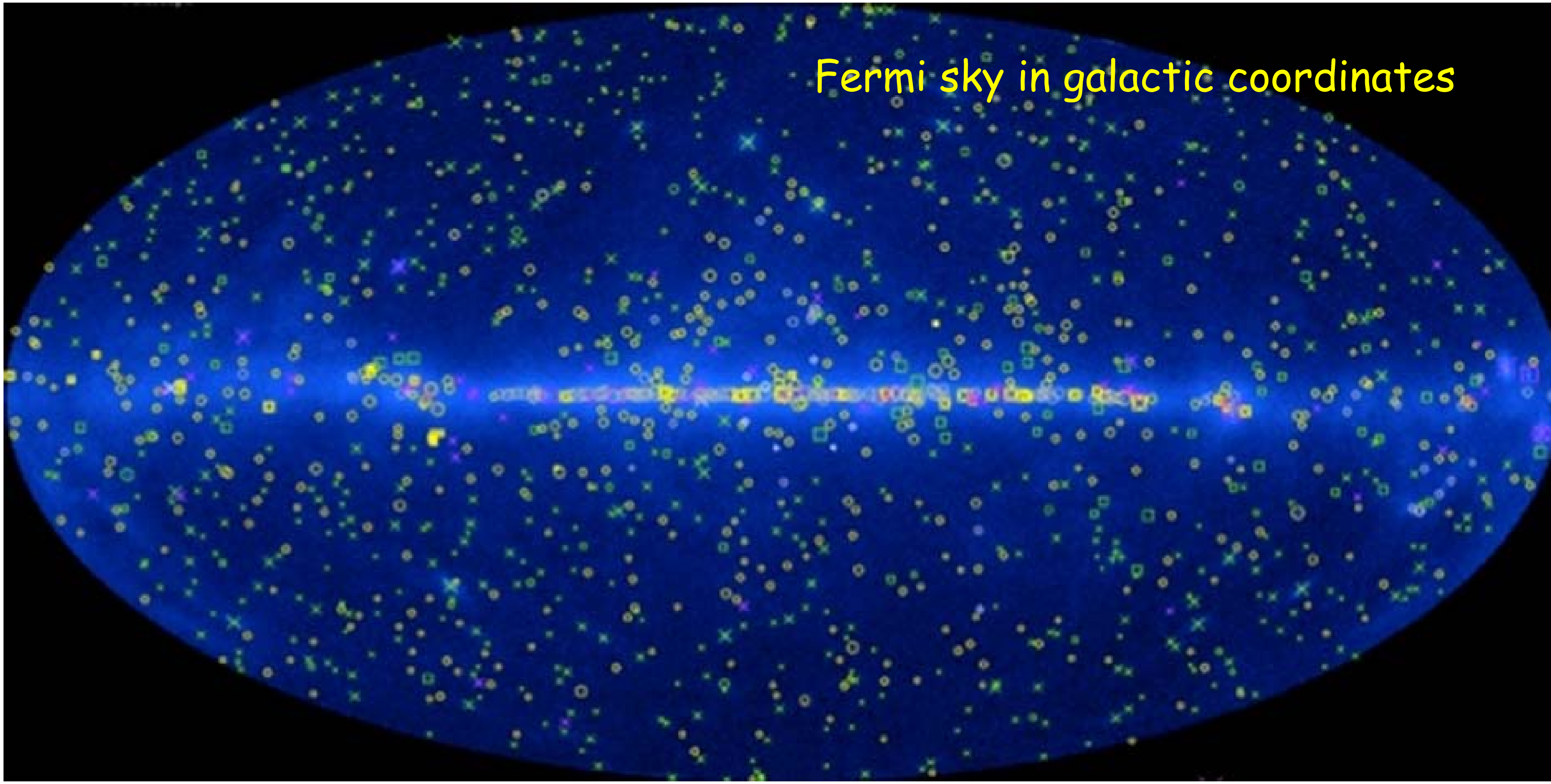
- *Fermi* is a pair conversion telescope with large effective area and good PSF
- It is an all-sky monitor, measuring γ-ray flux from any source every ~ 3 hours







Gamma-ray Sky: Fermi 2FGL Catalog



1800+ γ-ray sources: many source classes, including Active Galaxies, Pulsars, Supernova Remnants, Starburst galaxies, …

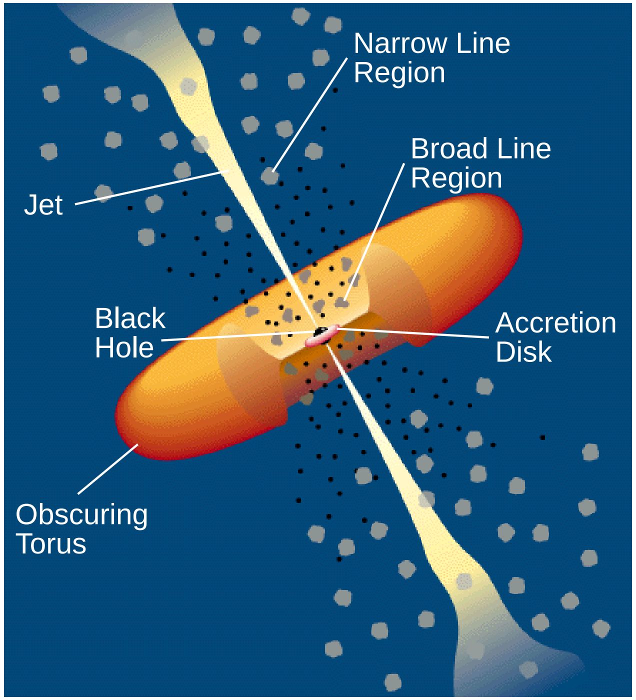
Jet-dominated active galaxies are by far the most prominent

At even 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)

Active galaxies: brief intro

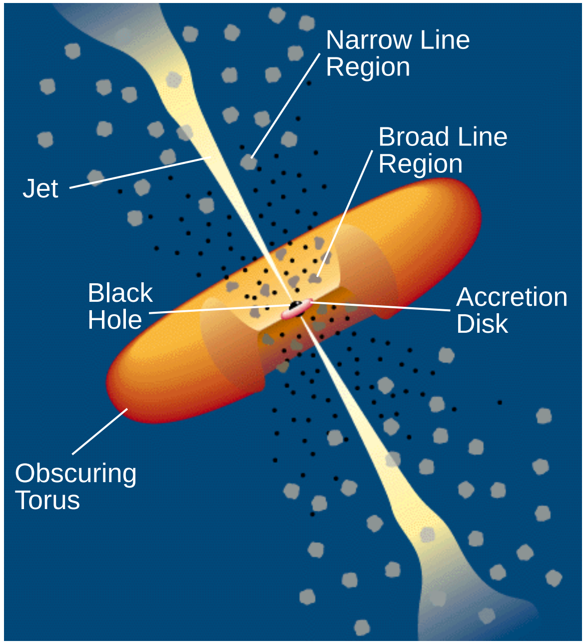
- Many if not most galaxies contain a massive (M > 10^6 Solar masses) black hole
- In the process of their growth, massive back holes accrete material from their vicinity
- Accreting material loses potential energy via heating of an accretion disk -> quasars, Seyfert galaxies
- Accreting material loses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



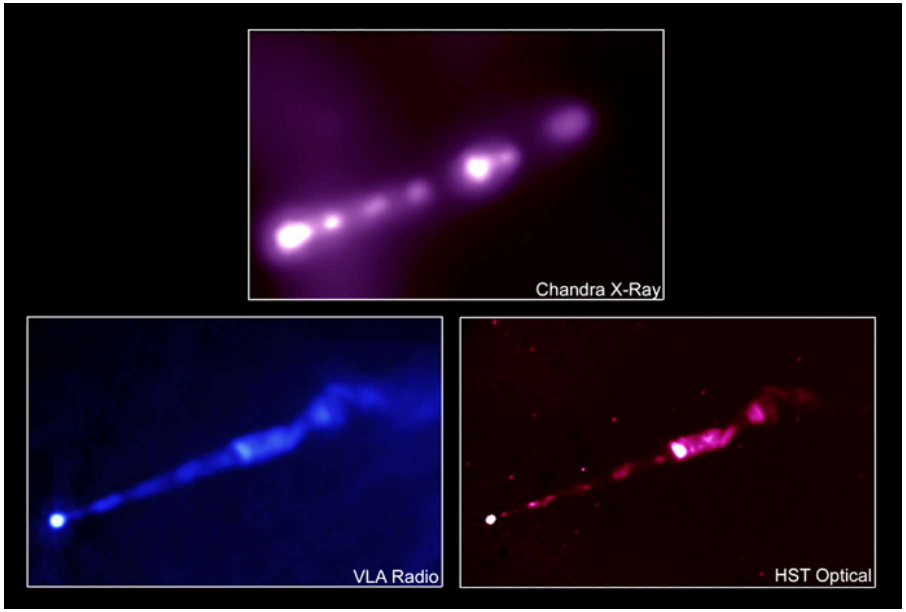
(somewhat overused) schematic of an AGN

Relativistic jets: why are they interesting?

* In some (~ 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-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

Fermi and blazars: the science goals as defined 10 years ago

- Prior to the launch of Fermi we were charged with defining science goals for Fermi observations of active galaxies
  - – and the needs for multi-band work

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,

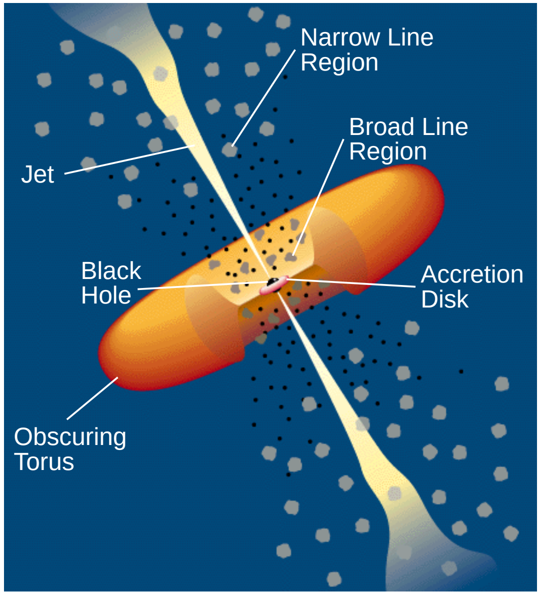
• This leads to a study of the jet content: population of the radiating particles,

*** 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

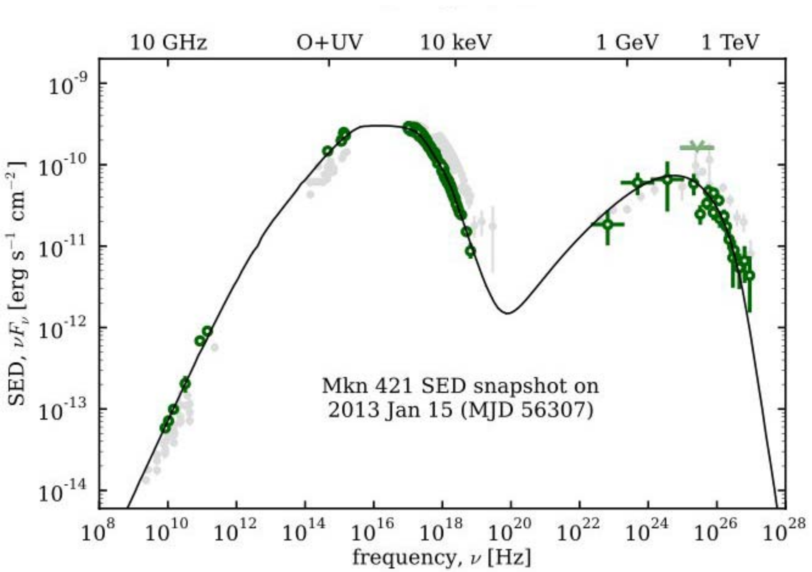
• Here: the jet content, source of the jet power

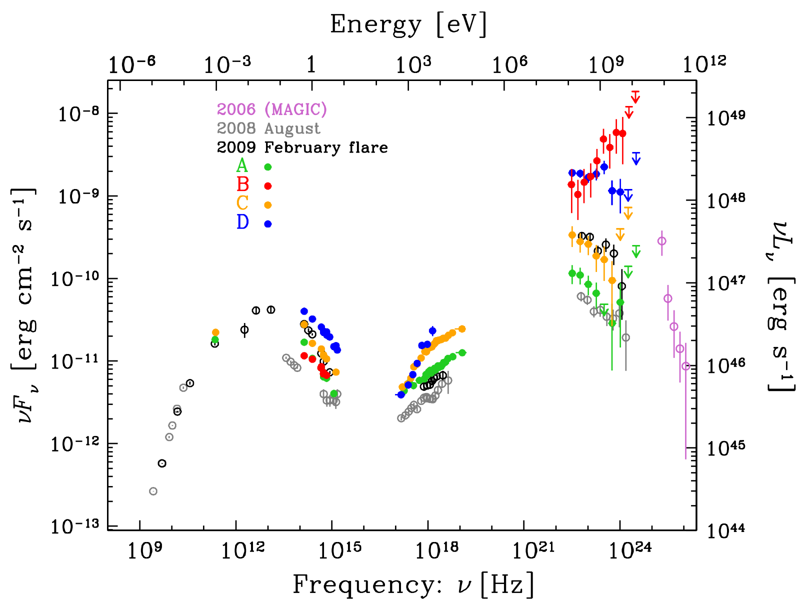


(somewhat overused) schematic of an AGN

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 γ-ray range, sometimes extends to the TeV VHE γ-ray regime
- The low-energy hump emission (radio, opt.) is polarized, 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 (causality arguments)

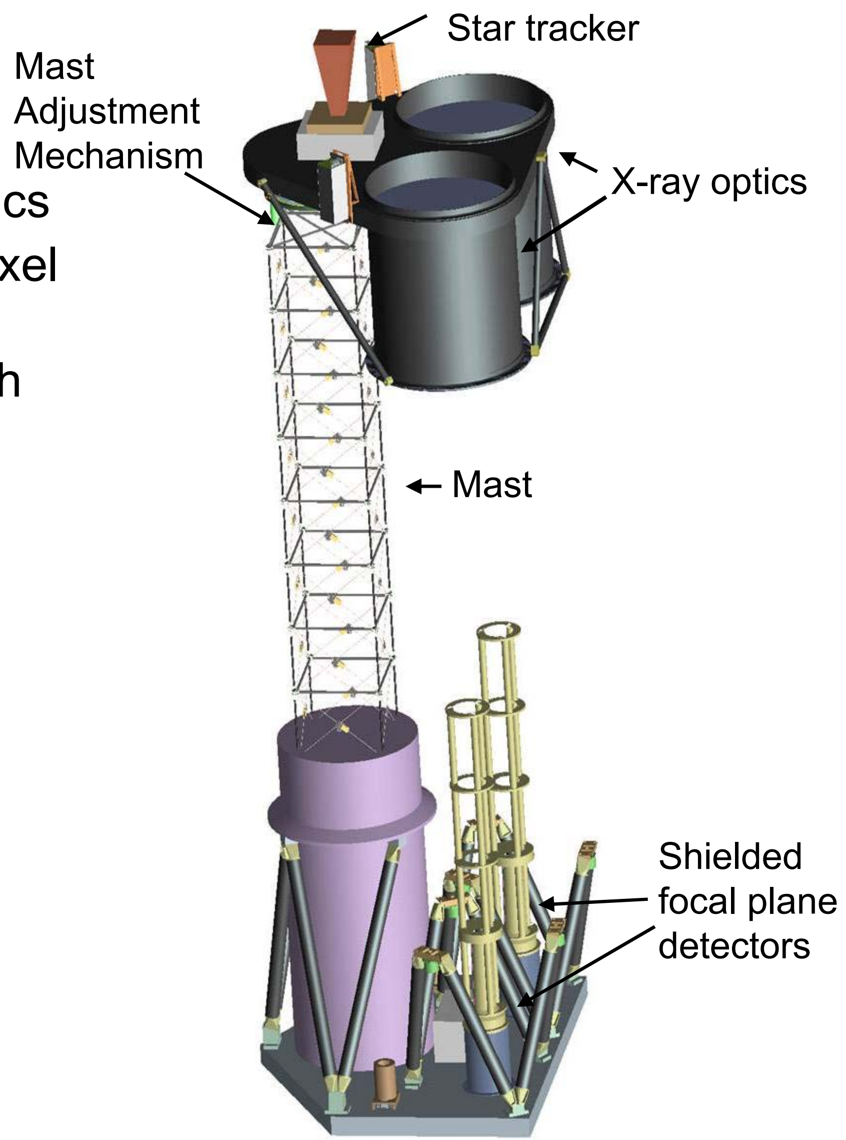




Very bright γ-ray blazar 3C279

Friend of Fermi: Hard X-ray satellite NuSTAR

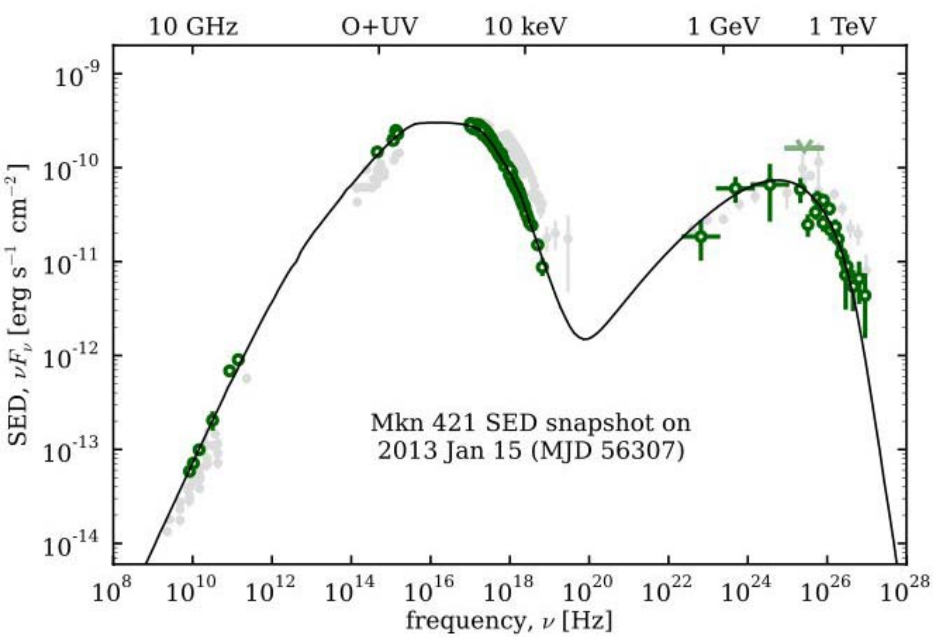
- NASA's Small Explorer mission, launched in June 2012; led by Caltech
- Two identical co-aligned grazing incidence hard X-ray telescopes:
  - Multilayer coated segmented glass optics
  - Actively shielded solid state CdZnTe pixel detectors
- Extendable mast provides 10-m focal length
- Focussing optics,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

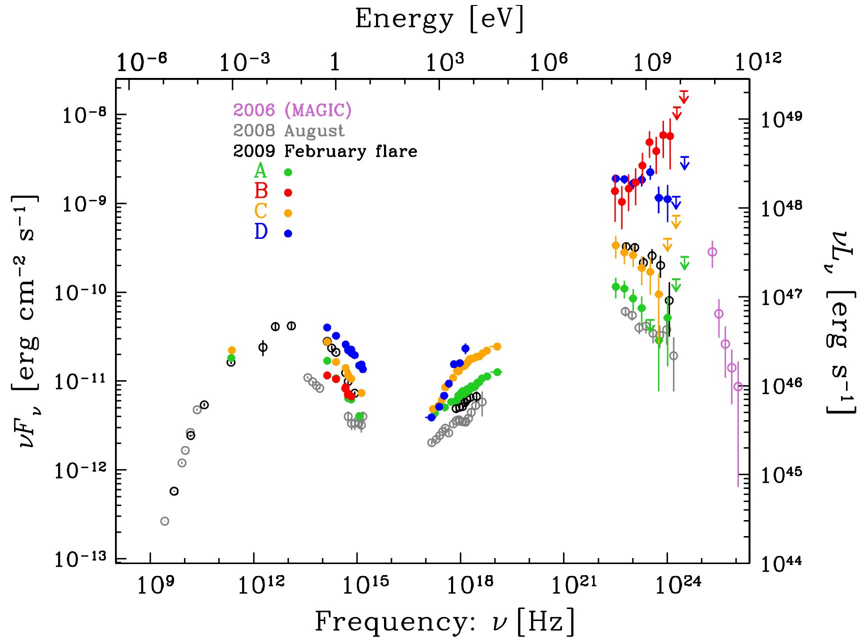


Why are hard X-rays important for blazar studies?

- 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





Very bright γ-ray blazar 3C279

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

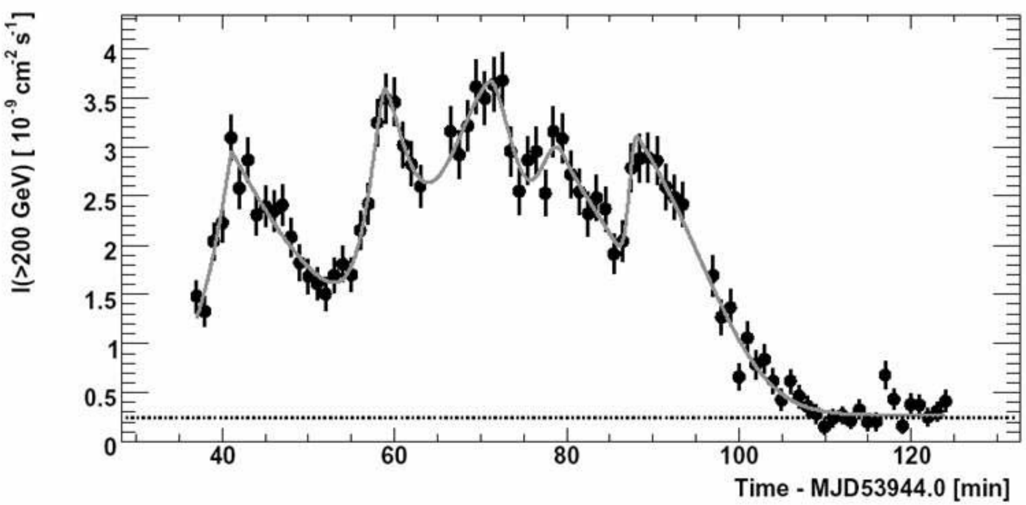


FIG. 1.— The integral flux above 200 GeV observed from PKS 2155−304 on MJD 53944 versus time. The data are binned in 1-minute intervals. The horizontal line represents I(>200 GeV) observed (Aharonian et al. 2006) from the Crab Nebula. The curve is the fit to these data of the superposition of five bursts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

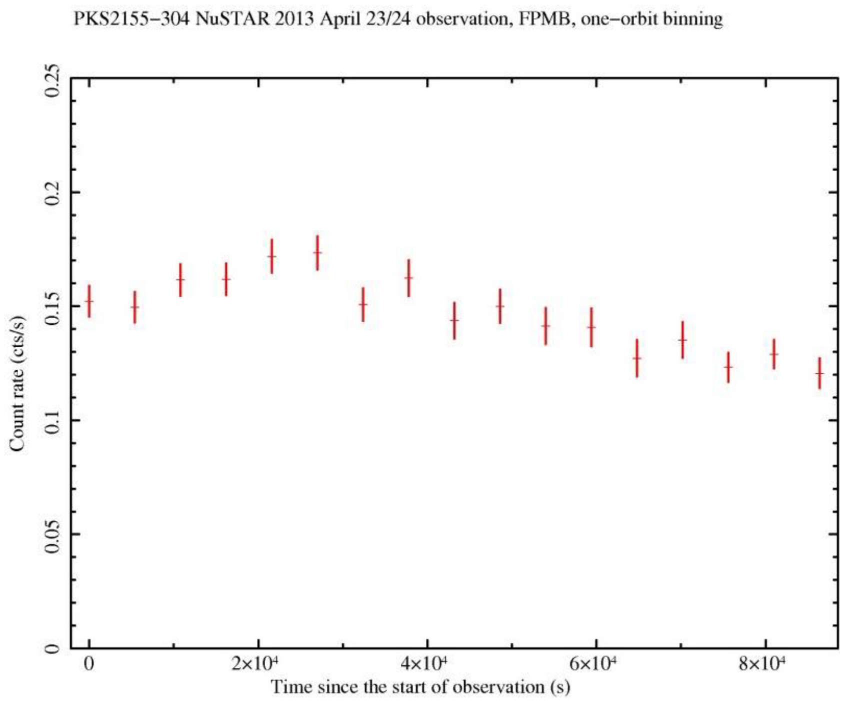
NuSTAR / Fermi observations

* 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, $\sim 10^{-11}$ erg cm^{-2} s^{-1} (2 – 10 keV), 1/3 of the previously reported "low" state

* NuSTAR collected a day's worth of data (~ 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



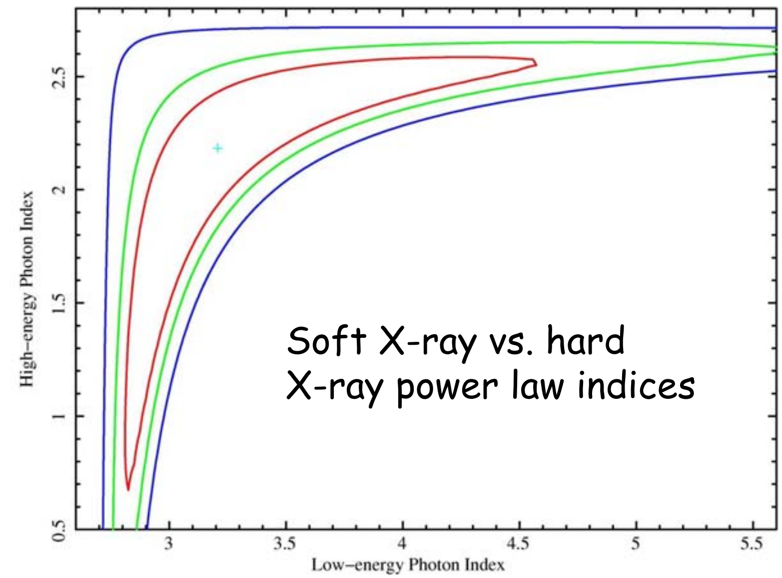
NuSTAR and XMM together

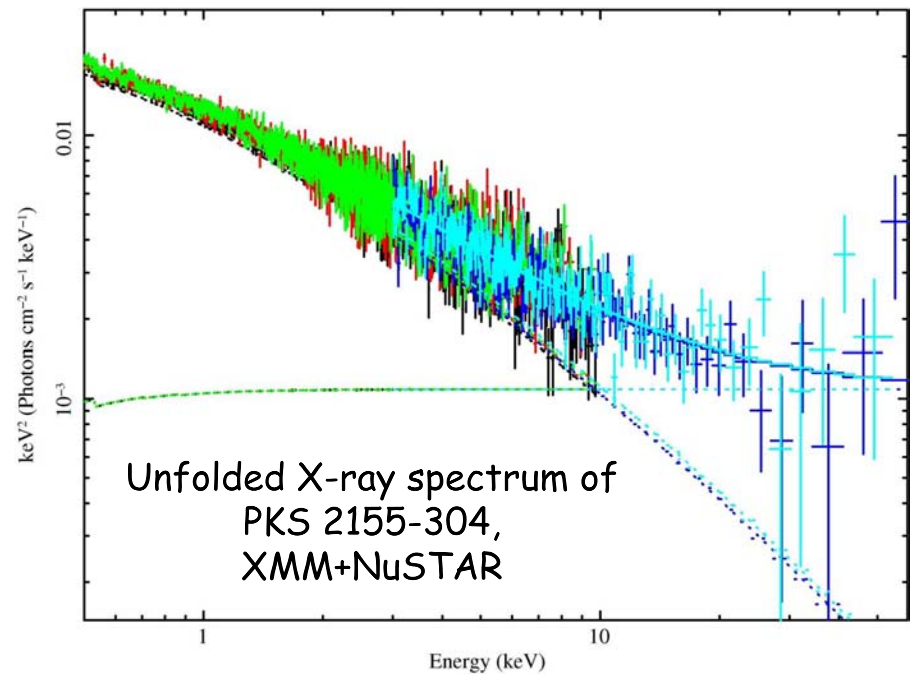
* NuSTAR data alone reveal a “hard tail” – photon power law indices are 3 & 2

* 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

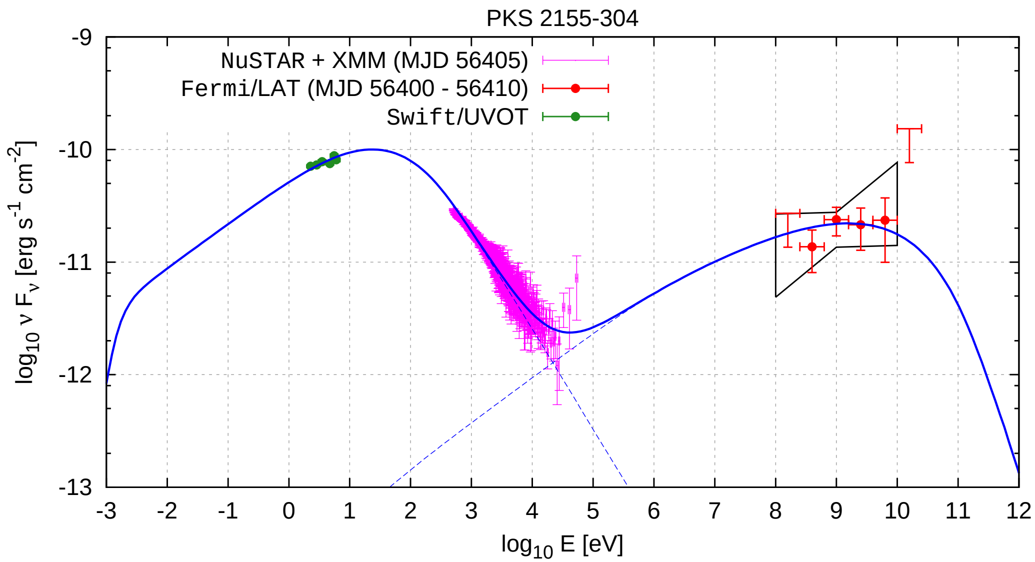
- Joint fit of NuSTAR and XMM implies a log-parabola for the lower E part of the spectrum, + a second, harder power law for the higher E part of the spectrum





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 <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>



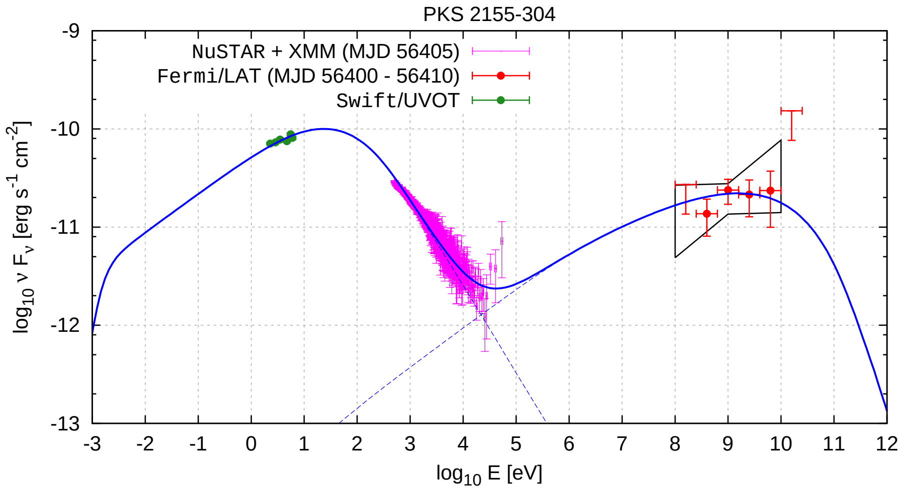
<u>Modelling results:</u>

We find L_B = 6 x 10^{42} erg/s, L_e = 3 x 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 x 10^{42} erg/s, L_e = 3 x 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

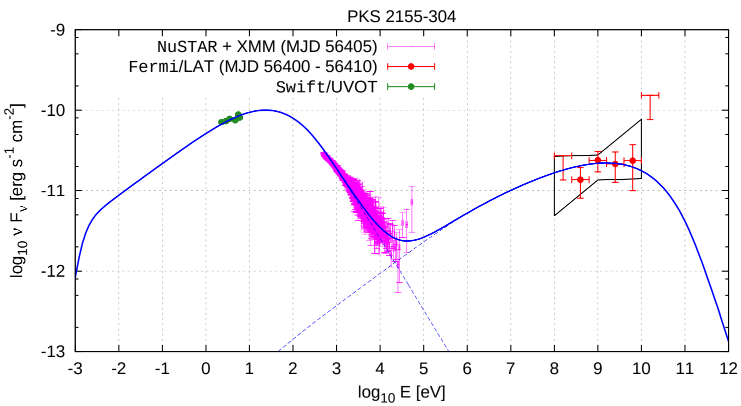
HBL – type blazars are supposed to be advection – dominated accretion sources, not accreting at L/L_{edd} ~1!

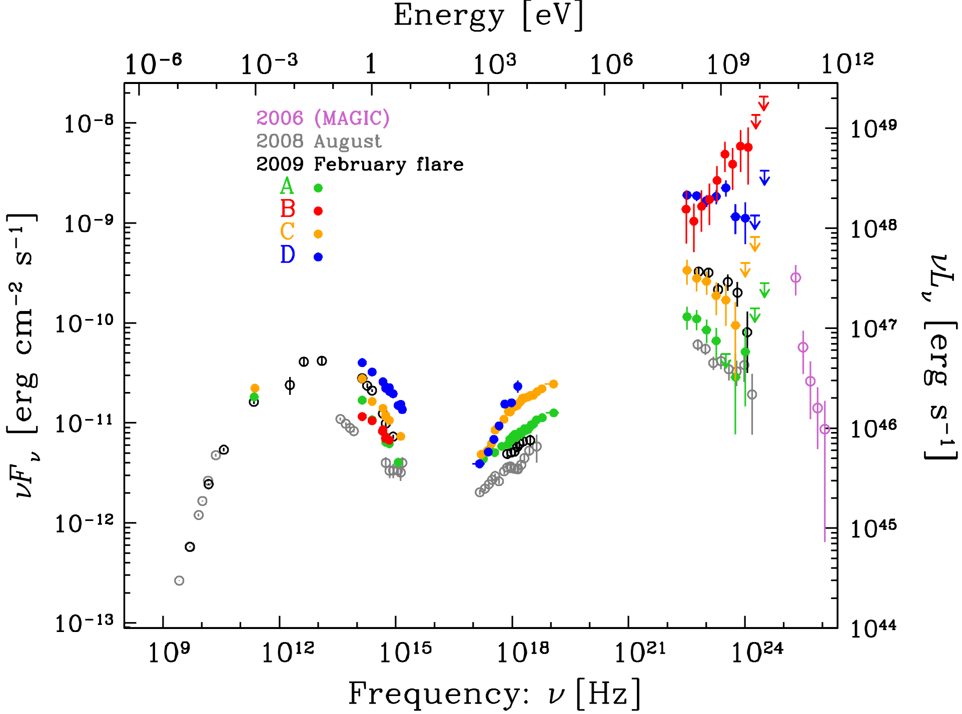
More likely solution: the jet has a substantial pair content (#positrons / #protons ~ at least 50)

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 are needed to provide the jet's kinetic energy

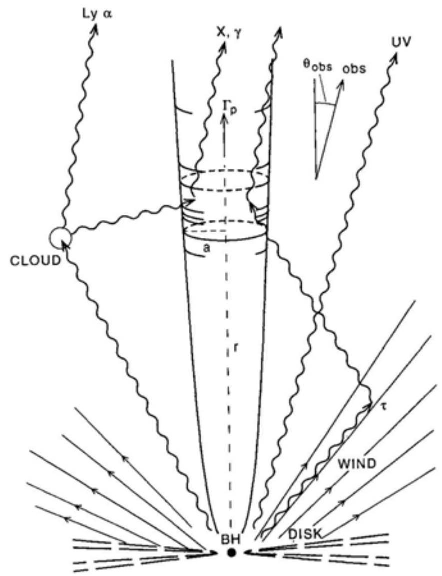


FIG. 2.—Geometry of the source. The radiating region, denoted by short cylinder of dimension a, moves along the jet with pattern Lorentz factor Γ_p. Underlying flow moves with Lorentz factor Γ, which may be different.

Schematic picture of geometry of a blazar jet

Pairs vs. protons in luminous blazars?

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 lease 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… important recent paper by Pjanka et al. 2016

Another tool – "calorimetry" to rescue!

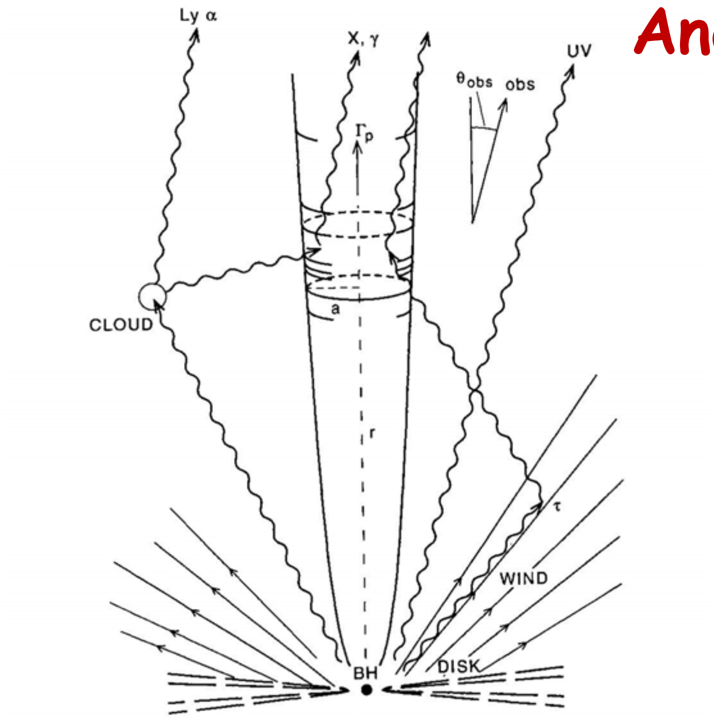
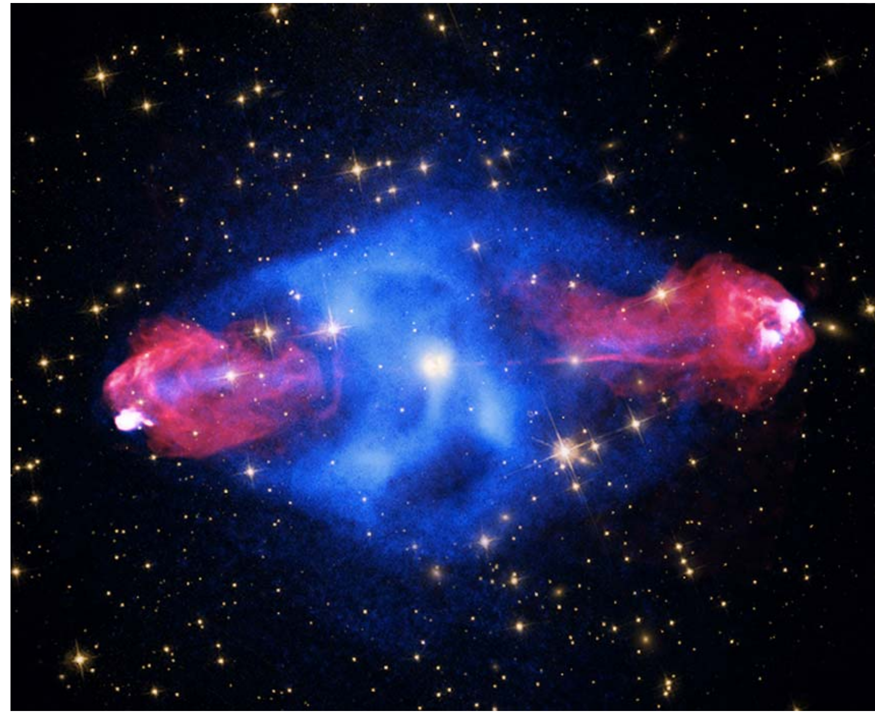


FIG. 2.—Geometry of the source. The radiating region, denoted by short cylinder of dimension a, moves along the jet with pattern Lorentz factor Γ_p. Underlying flow moves with Lorentz factor Γ, which may be different.



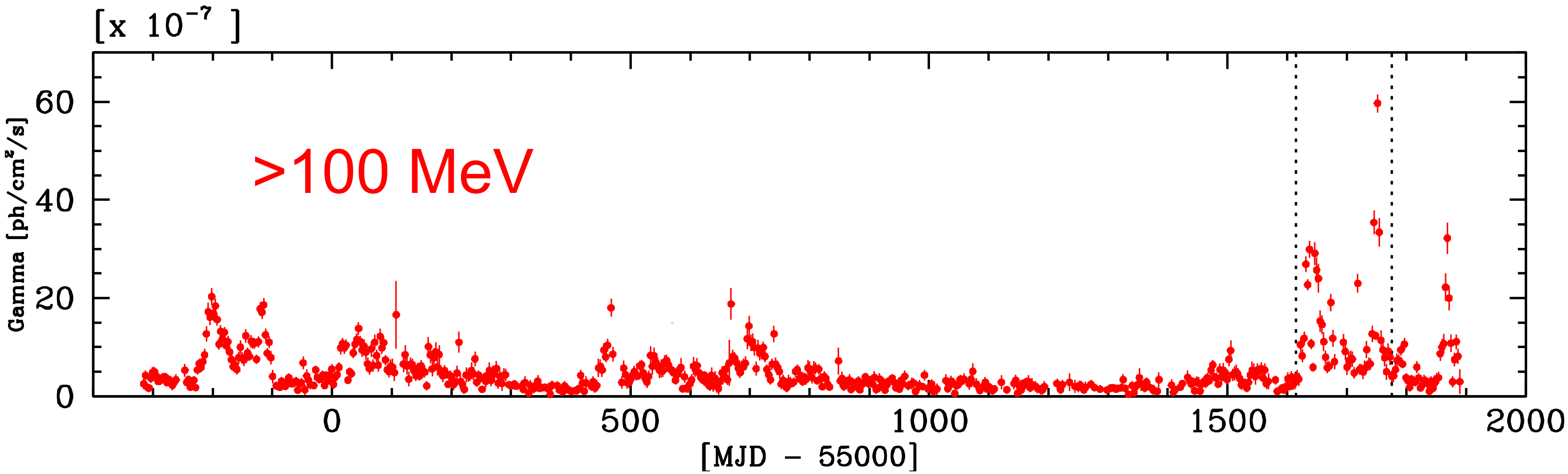
Cygnus A radio galaxy:
blazar jet viewed from the side

<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

Switching gears to luminous blazars: 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 γ-ray astronomy
* z = 0.536, BH mass ~ (3-8) x $10^8 M_{solar}$, L_d ~ 6×10^{45} erg/s
* one of the EGRET brightest AGN
* the first TeV FSRQ (discovered by MAGIC in 2006)
• Fermi-detected γ-ray flare with polarization change in 2009 – fantastic result enabled by KANATA!

Multi-band variability in Fermi days

* Fermi motivates terrific multi-band light curves

• Search for coincidences / delays amongst various bands:
optical and γ-rays closely correlated

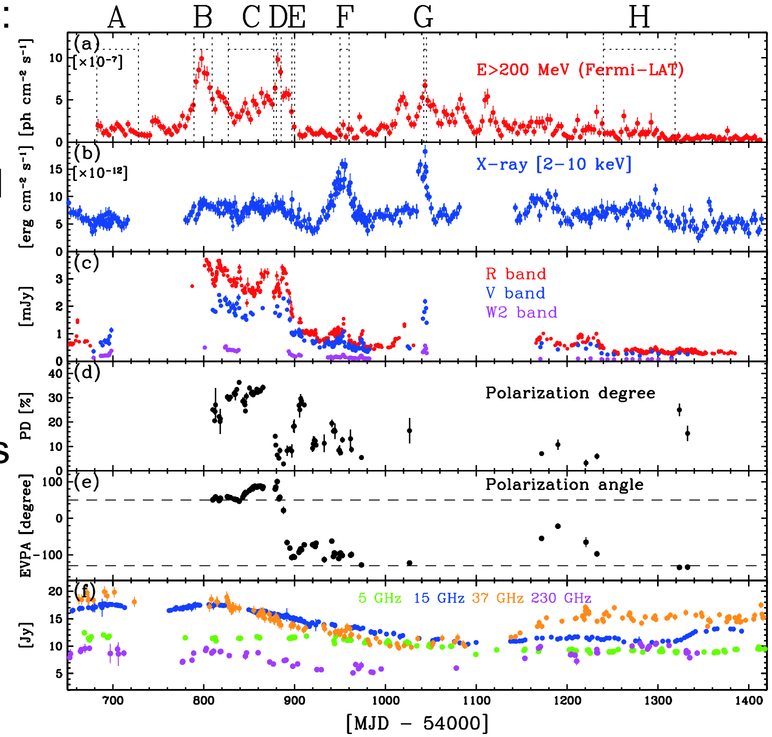
* Very important new hint: rotation of optical polarization angle, seen in BL Lac (Marscher), but clearly associated with the γ-ray flare in 3C279 (Abdo+ 2010; Hayashida+ 2012): 180^{o} in 20 days

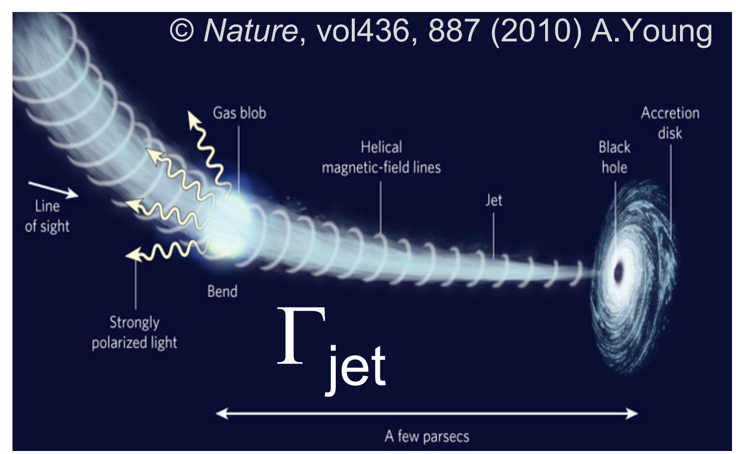
•A clear departure from
simple axi-symmetry – one possibility a curved jet
- a “quivering” jet, presumably unstable, or “jittered” at its base (near the disk) might work as well

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

* Challenge to the jet modelers / theorists

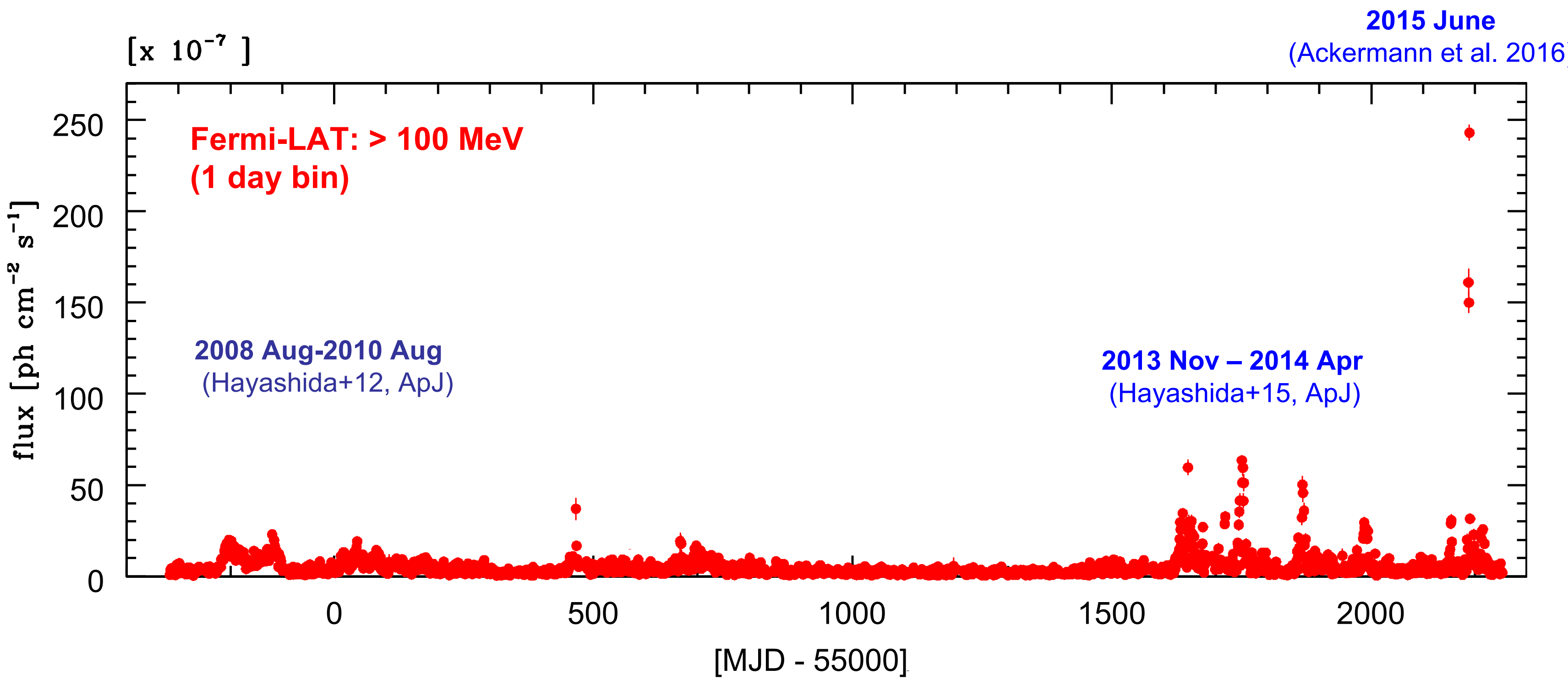
• Opt/γ-ray correlation clear, but
X-rays not clearly correlated with any other band!





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

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

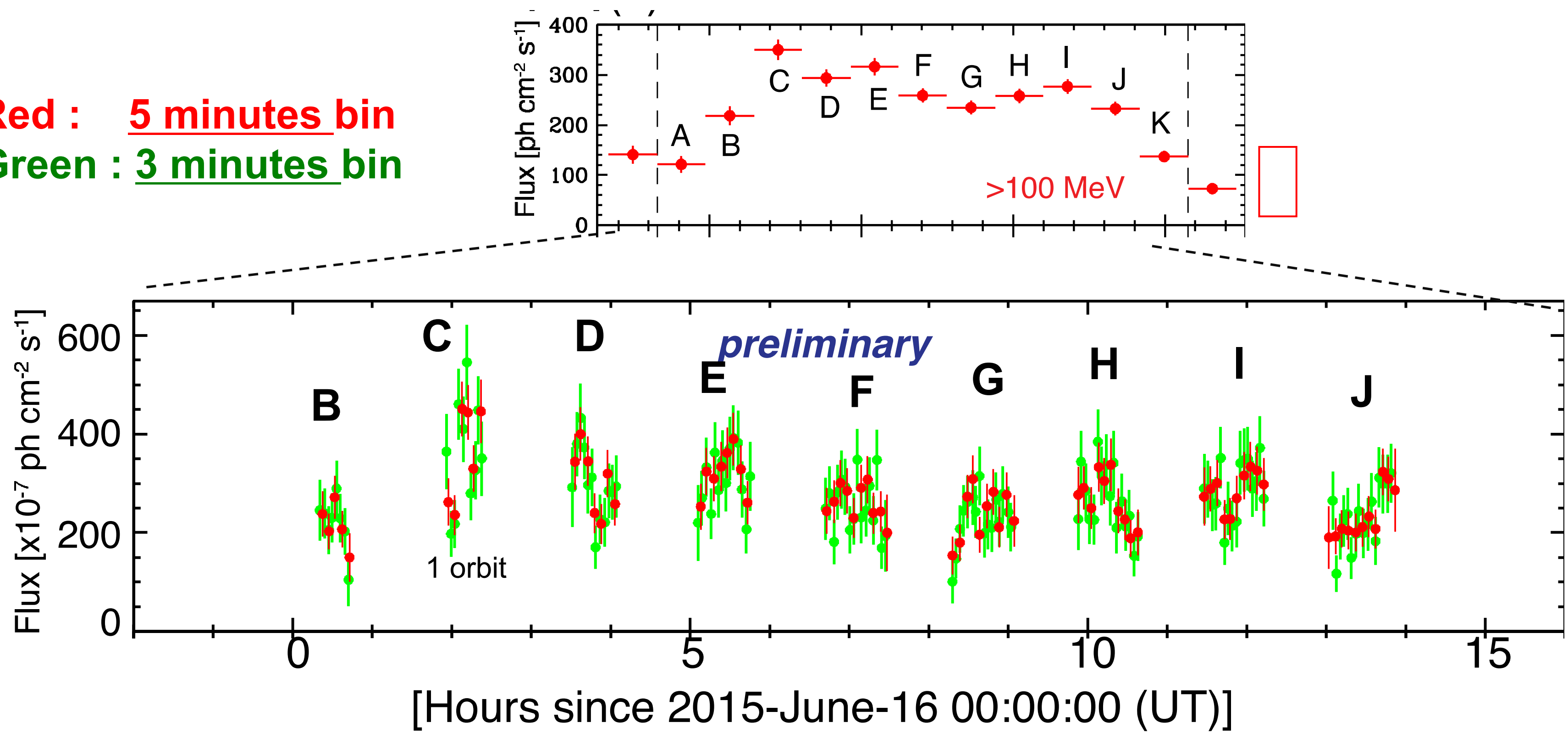


1-day average fluxes during 3 large outbursts (at E >100 MeV)

1. **2013 December 20 : 6.0×10^{-6} ph cm^{-2} s^{-1}**
2. **2014 April 03 : 6.4×10^{-6} ph cm^{-2} s^{-1}**
3. **2015 June 16 : 24.3×10^{-6} ph cm^{-2} s^{-1}**

Short time bin (minutes scale) γ-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_{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_{max} ~10 GeV): object must be strongly beamed,**

□ **δ>25 – model independent**

- **Broad-band emission is strongly dominated by γ-rays**

The minute scale variability suggests:

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

- An emission region inside BLR, high jet Lorenz factor, compact emission region

- Inverse Compton models imply very low magnetization (photon energy density dominates)

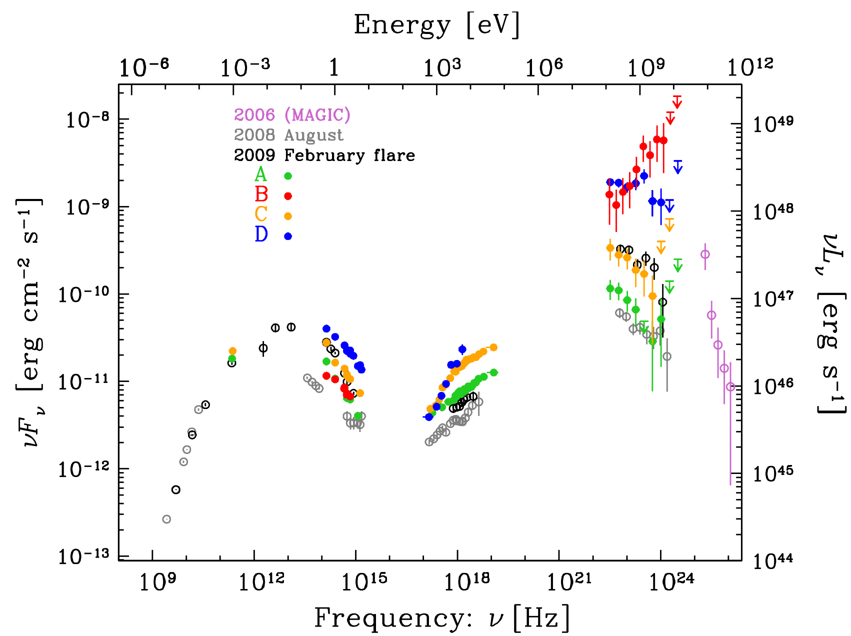
NEW IDEA: Perhaps γ-rays are produced by the synchrotron process?

this would require B ~ 100 Gauss,

γ_{el} ~ 10^6 – reasonable values

- <u>implications on polarization in the γ-rays</u>

Multiple processes contributing to γ-ray emission?



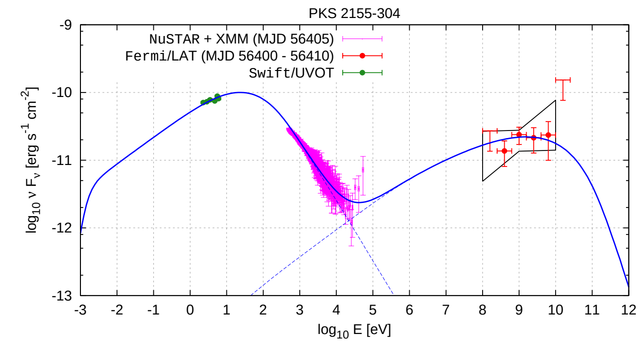
Conclusions

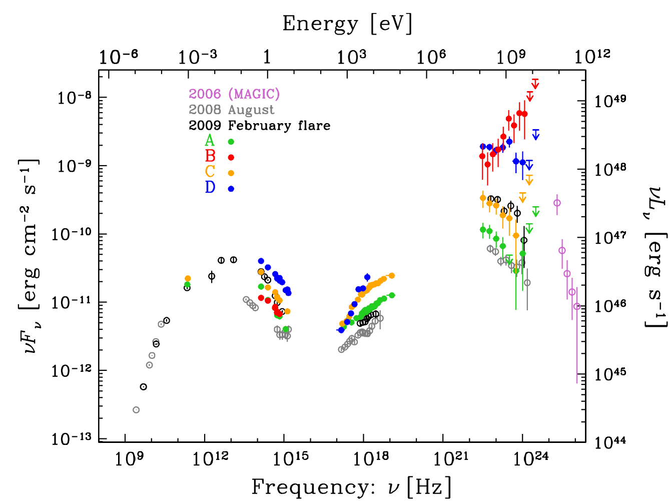
**We discussed <u>observations and modelling</u>
of 2 types of jet-dominated AGN (blazars)**

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

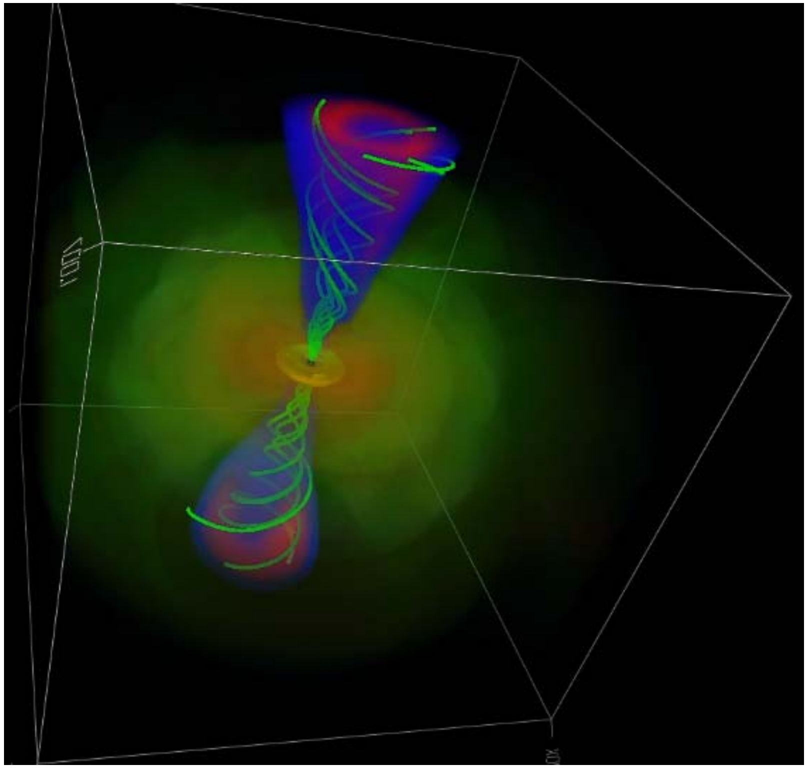
In high-luminosity, powerful blazars, there is opposite limit:
jet plasma cannot be pure e-/e+ (bulk-Compton limits); BUT, if pure electron/proton plasma – jet power still excessive…
- electron / proton ~ 20 OK, consistent with radio hot spots which provide additional constraints

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





Energy transport to the dissipation region



•Accretion releases the gravitational energy very close to the black hole

• Most of the gravitational energy is released within the last 10 R_s (potential goes as 1/R)

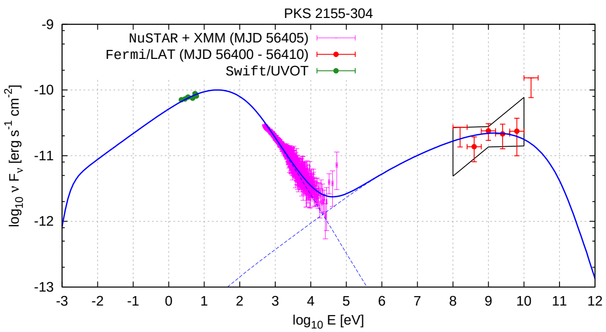
* One of the key questions is:
  Where is the radiation generated – and what is the energy transport to that region?

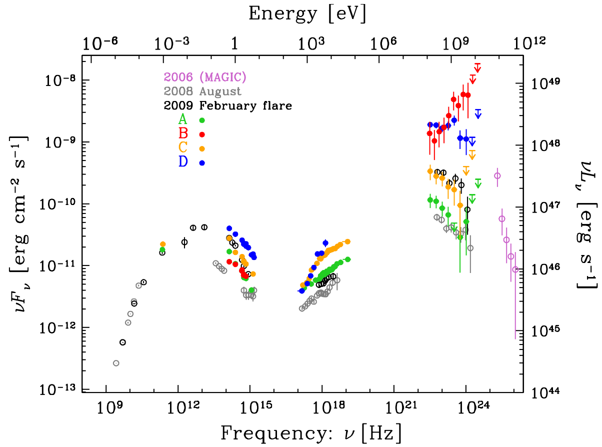
* Evidence seems to be mounting that the radiation is probably not produced very close to the black hole –
  - the transport of energy to the dissipation region must be efficient

* Massive challenge to theory and numerical simulations!

Numerical GRMHD simulations by McKinney and Blandford

BACKUP SLIDES: FOCUS ON 3C279





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

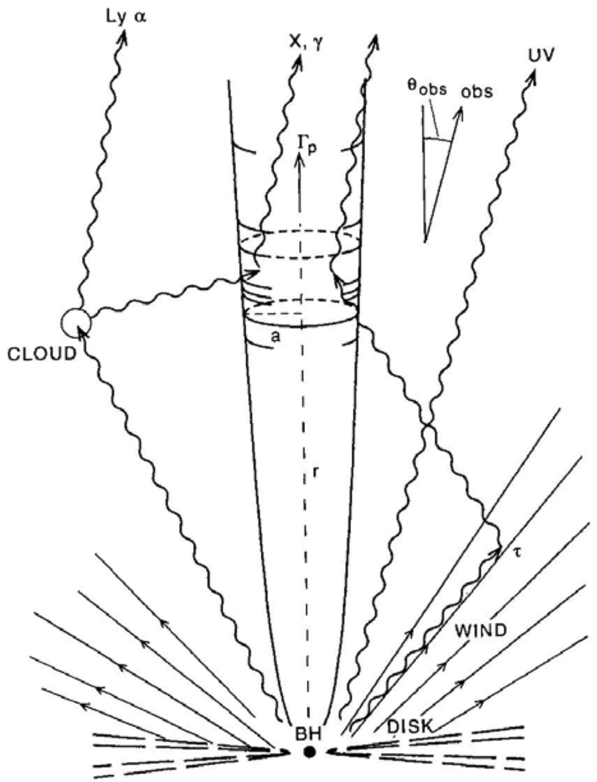


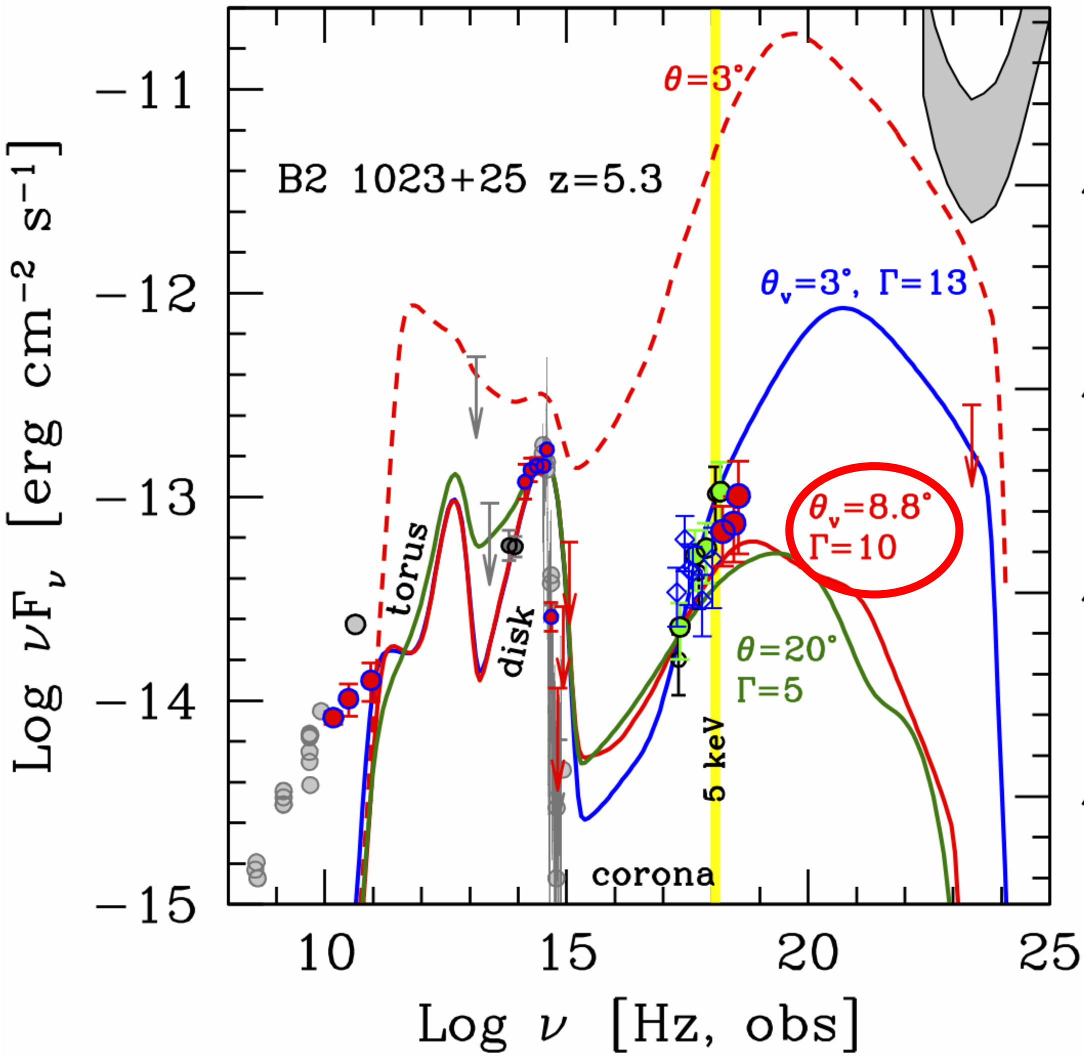
FIG. 2.—Geometry of the source. The radiating region, denoted by short cylinder of dimension a, moves along the jet with pattern Lorentz factor Γ_p. Underlying flow moves with Lorentz factor Γ, which may be different.

"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"

Life at high redshift: blazar B2 1023+25



Quite high redshift! z ~ 5.2

Adding NuSTAR data strongly supports the blazar nature of the object

Clear emission lines, allow an estimate of the isotropic luminosity, BH mass

Synchrotron + IC modelling Implies Γ ~ 10

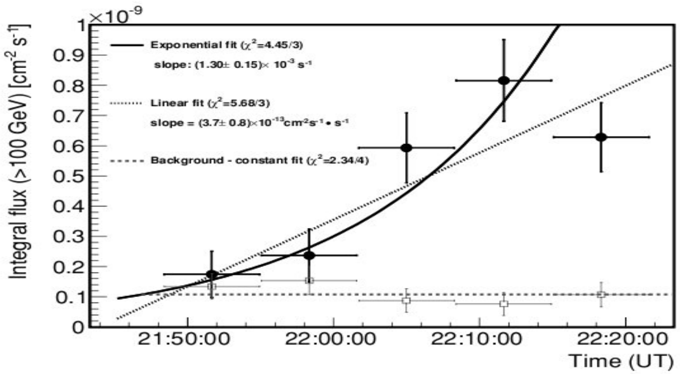
B2 1023+25: implications on growth of supermassive black holes

- The NuSTAR observations confirm that B2 1023+25 is blazar, although with properties somewhat different than expected before: bent, or “wiggling” jet?

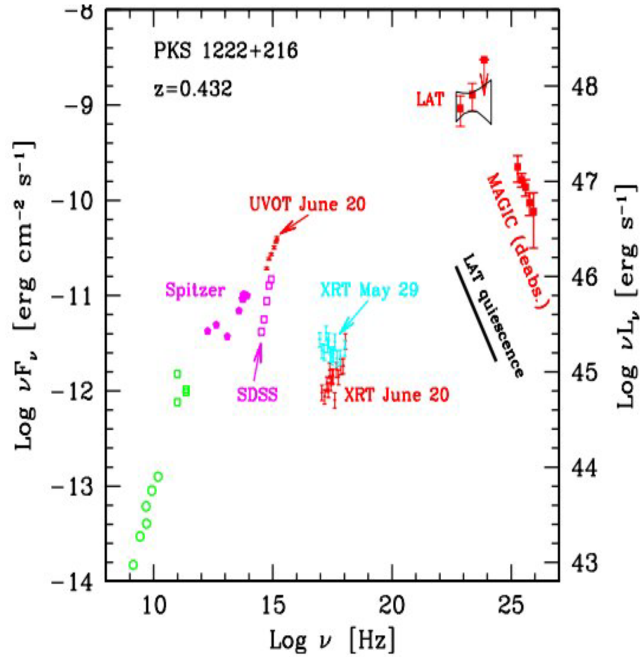
- Strong implications on cosmology (Γ^2 argument)

- ~ hundreds of black holes with mass ~ 10^9 M_o so early on in the history of the Universe – problem for evolution of BH?

γ-ray variability in blazar PKS 1222+216
Fermi, and TeV gamma-rays vary on a short time scale!



(MAGIC Collaboration 2011, ApJ, 730, L8)



Not a NuSTAR target, but…

* Rapid TeV variability presents a severe problem: the target photons providing most TeV opacity are in the optical-UV range (recall E(γ) * E(target) ~ (1 MeV)^2)
- Those are really plentiful from the accretion disk, BEL region, … - certainly in PKS1222, other blazars
- Don't need to invoke co-spatiality from simultaneous variability (BEL light is everywhere!)
- Emission far away (parsecs +) from the BH?

* Yet, rapid variability time scale (less than a day!) -> quite compact dissipation region (light-travel arguments, even including appreciable Doppler factors)

- ***Emerging picture: compact emission region, relatively far away from the BH***
  But… how to accelerate particles so far away? Energy transport?