Extragalactic gamma-ray astronomy: Status and prospects

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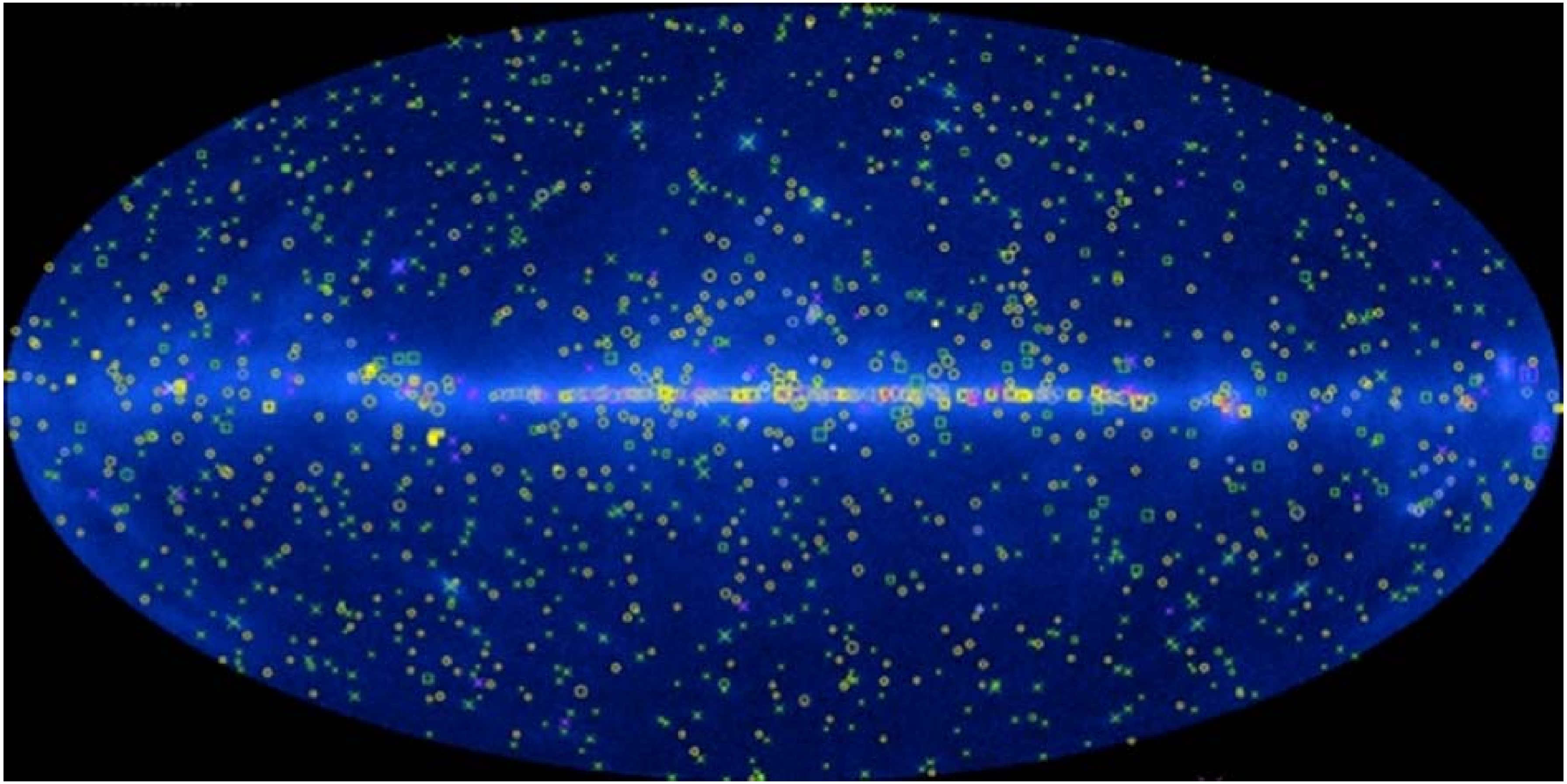
Outline:
Gamma-ray sky and jet-dominated AGN
Overview of Fermi results and taxonomy of blazars
Emission mechanisms
Constraints on the structure of jets
Other classes of extragalactic gamma-ray emitters
Distant TeV emitters and implications on background light
Future observational prospects (HESS II, NuSTAR)

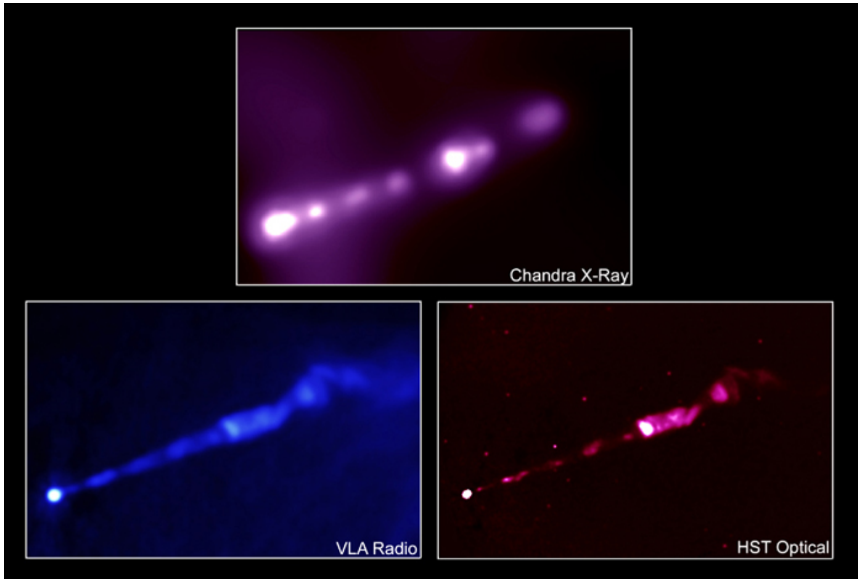
Gamma-ray Sky: 2FGL Catalog



1800+ γ-ray sources: many source classes, including Active Galaxies, Pulsars, Supernova Remnants, Starburst galaxies, … Jet-dominated active galaxies by far the most prominent

Extragalactic relativistic jets

Blazars: active galaxies dominated by the emission of relativistic jets pointing at us



M87 gal

* They are very bright Fermi sources: strongly variable, subject of intense study

* γ-ray emission: is the peak of the observed luminosity -> clues to the source structure

* Variability in *all bands* provides additional crucial information

* The presence of the jet is inferred from rapid variability but also directly imaged in radio, to a lesser extent in optical and X-rays

* Approach to the study is a bit like peeling an onion:
  - start with what you observe over as broad-band as possible
    - infer the radiation processes and the radiation-generating particles,
    - determine the means of their energization,
    - model the structure of the source with a consistent "energy flow"

Jet-dominated active galaxies: Key questions

- What have we learned from observations with Fermi, +other observatories?
- What powers blazars? (accretion, or the accumulated BH spin)?
- What is the energy dissipation mechanism? Where does it operate?
- What observations are not (or poorly) explained?
- What additional observations are needed?
- What are the theoretical challenges?

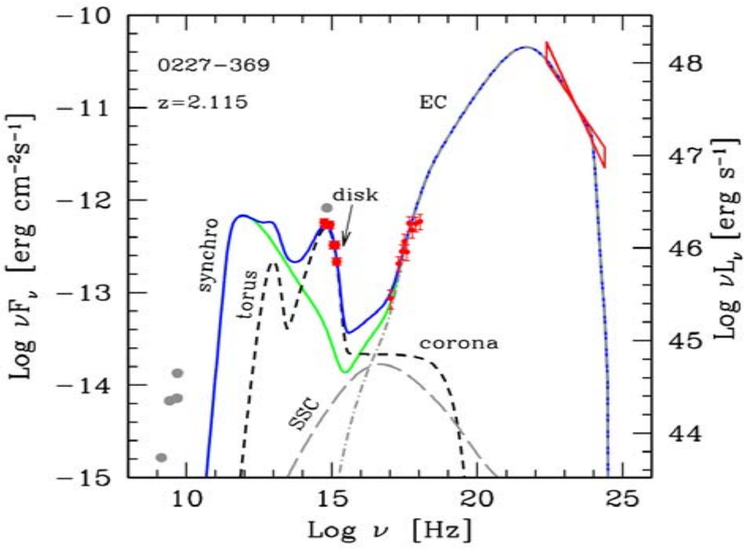
- What do blazar observations tell us about cosmology? Diffuse IR backgrounds? Magnetic fields?

Two avenues for blazar studies

* **Two approaches towards understanding the structure of blazars:**
(1) population studies
(2) detailed, time resolved multi-band studies of a few selected objects

- **Both seem to agree that the best "thumb-nail" picture for all blazars explains the two-peak spectral energy distribution as *synchrotron* process responsible for the l energy peak, *inverse Compton* process responsible for the h energy peak**

* **Lorentz factors of those relativistic jets are ~ 15, perhaps ranging from 10 – 30**



From Ghisellini et al. 2010

What does Fermi see? -spectral diversity

Gamma-ray spectra are quite diverse
(based on the 3-month "LAT Bright AGN Survey" (LBAS): Abdo et al. 2009)

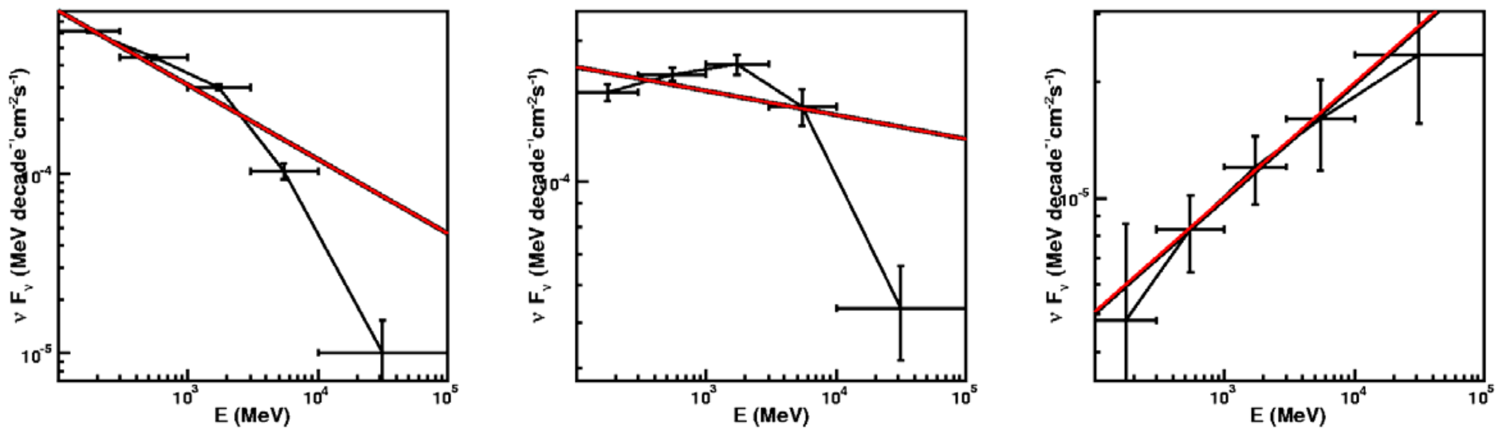


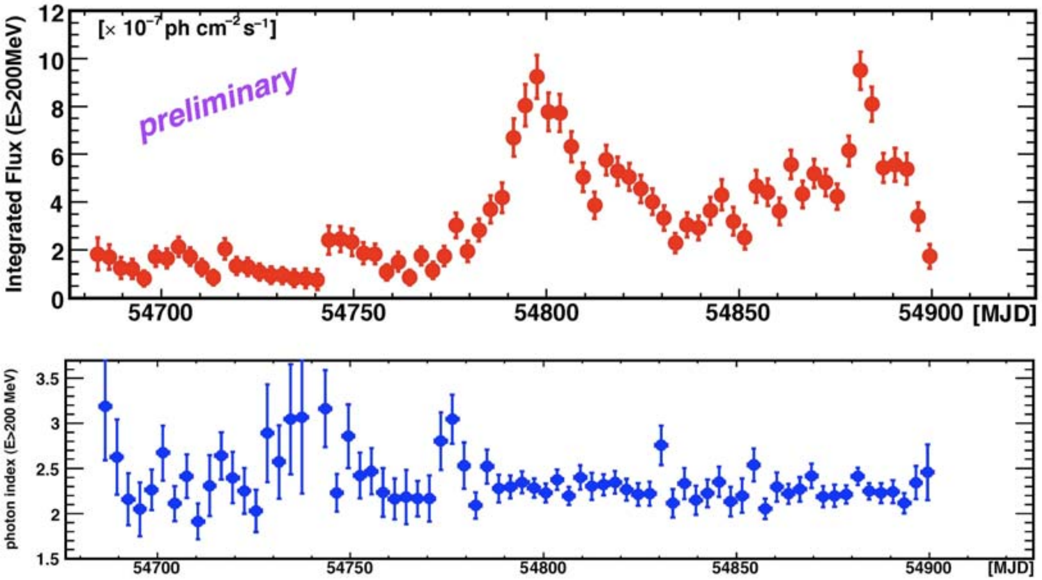
Fig. 10.— Gamma-ray SED of 3 bright blazars calculated in five energy bands, compared with the power law fitted over the whole energy range. Left: 3C454.3 (FSRQ), middle: AO 0235+164 (IBL), right: Mkn 501 (HBL)

<- High luminosity sources **low luminosity sources ->**

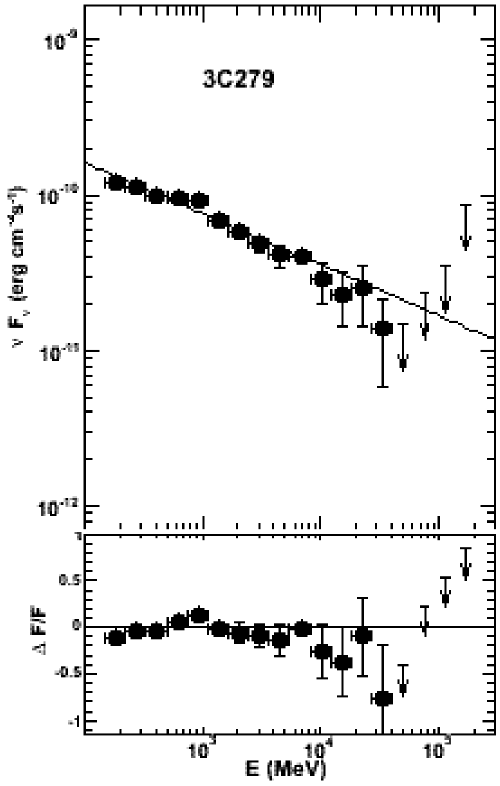
- The spectra are diverse – clear association with blazar sub-class
- This has strong implications on contribution of blazars to the diffuse extragalactic gamma-ray background: still work in progress, but we expect both types would contribute at some level
- Are luminous BL Lacs – LBLs – just objects with preferentially higher Doppler factor -> highest bulk Lorentz factors, quasar-like otherwise? 0235+164 above

Gamma-ray spectral (in)variability

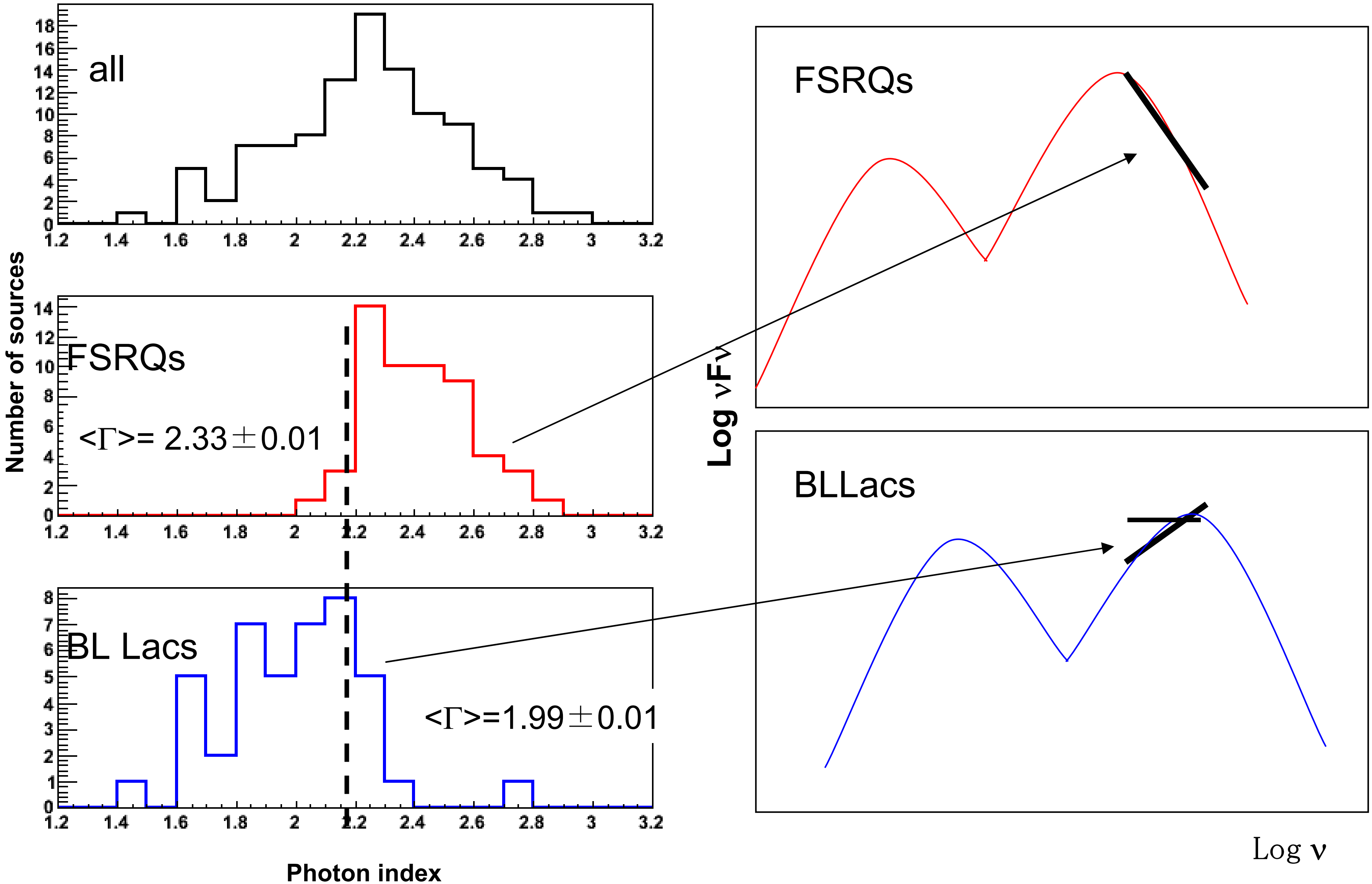
* Simplest way to study spectral variability is to describe them as a power law, plot the time history of index
* Generally, we do not detect significant spectral variability as a function of flux (an example - 3C279 – is shown below)
* If flares were “injection -> cooling” would expect spectral evolution
* Instead – distributed, rapid, nearly instantaneous acceleration throughout the volume of the jet might be more appropriate



Gamma-ray flux and spectrum history of 3C279



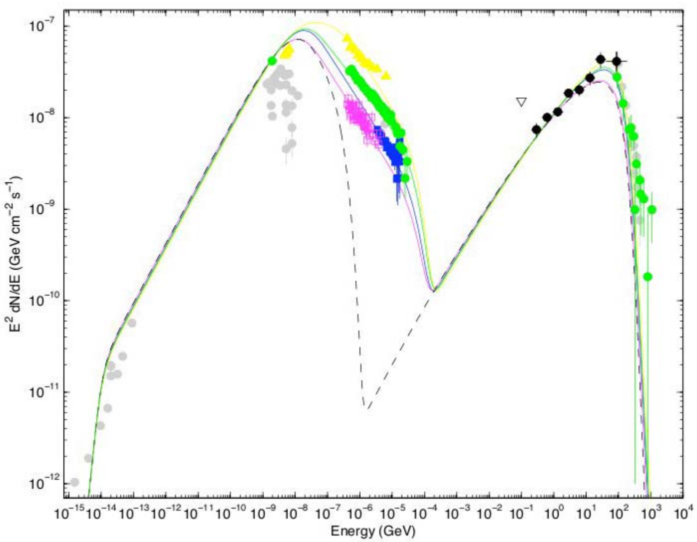
Fermi LAT spectra of blazars in the context of broad-band spectra
Clear spectral diversity!

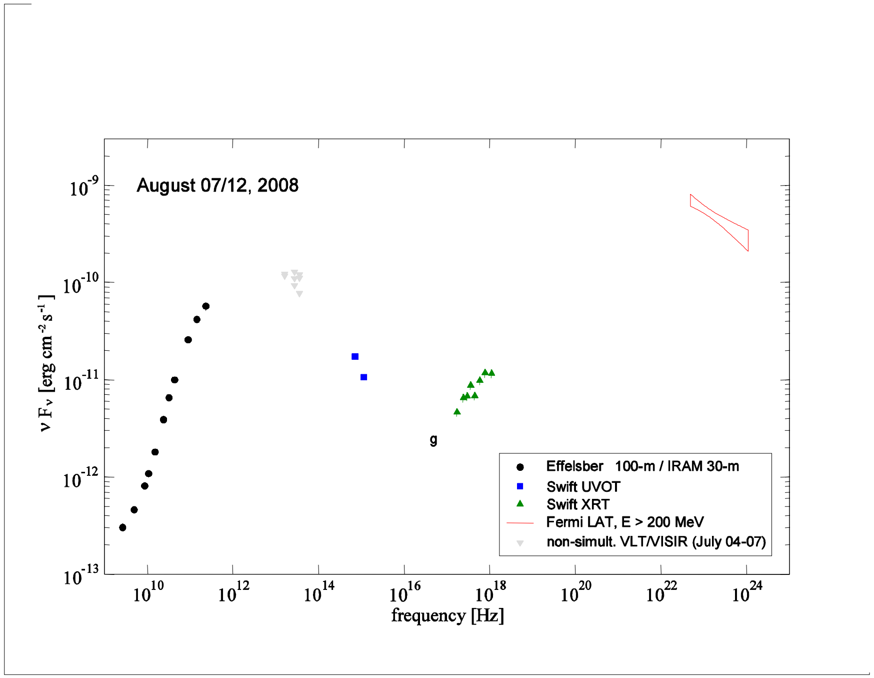


Two kinds of blazars

HBL blazar – BL Lac object 1553 (et al. and Horan 2009, Fermi Coll.)

3C454.3 – blazar that flared recently (Abdo et al 2012)





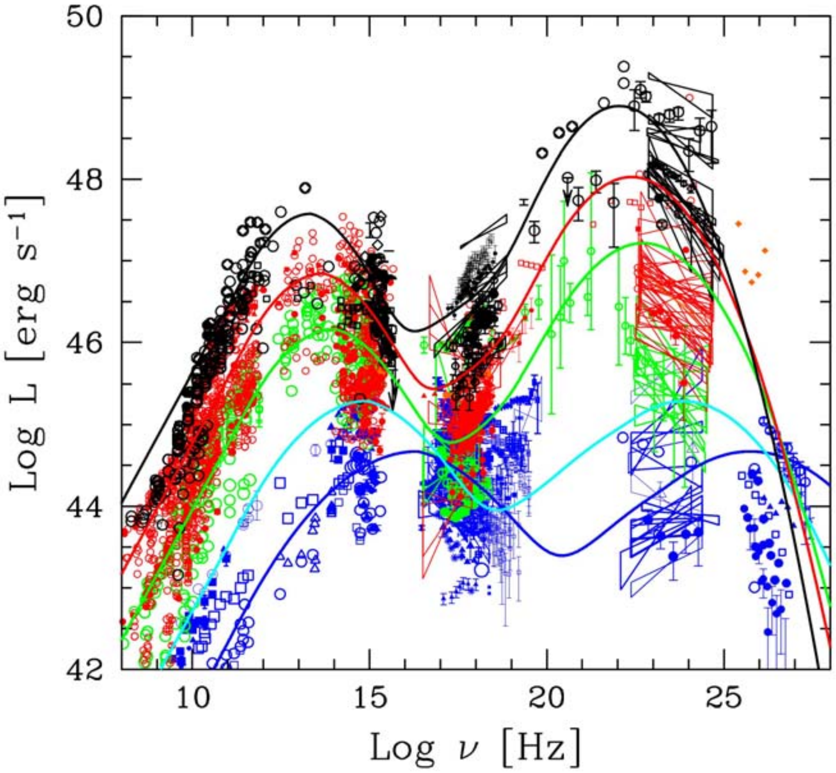
Updated blazar sequence

• Population studies of Fermi sources support the “blazar sequence” (Fossatti, Ghisellini) and expanded recently by Meyer, Fossatti, others

• SEDs of lower luminosity sources have the peaks of the low energy and high-energy components shifted to higher energies than for the high luminosity sources

* The high-luminosity sources seem to have larger Compton dominance, meaning higher F(gamma) / F(optical)

• Robust despite large amplitude variability



Origin of spectral diversity of blazars /modeling /implication on their structure

Electrons producing spectral peaks of HBL blazars have higher energy than those in FSRQ blazars – *Why?*

HBL-type blazars (bright TeV emitters) have different important characteristic properties as compared to quasar-type blazars “FSRQ”:

* HBLs have relatively lower luminosity than FSRQs
* HBLs have relatively high black hole mass: those, estimated for a number of them, are relatively high, ~ 10^9 Solar masses (probably comparable or slightly greater than FSRQs)

  -> lower Eddington luminosity-> lower accretion rate in Edd. units

This trend would imply:

* Luminous, FSRQ blazars have cold, luminous accretion disks
* low-luminosity, HBL-type blazars have hot, advective, undeluminous accretion flows

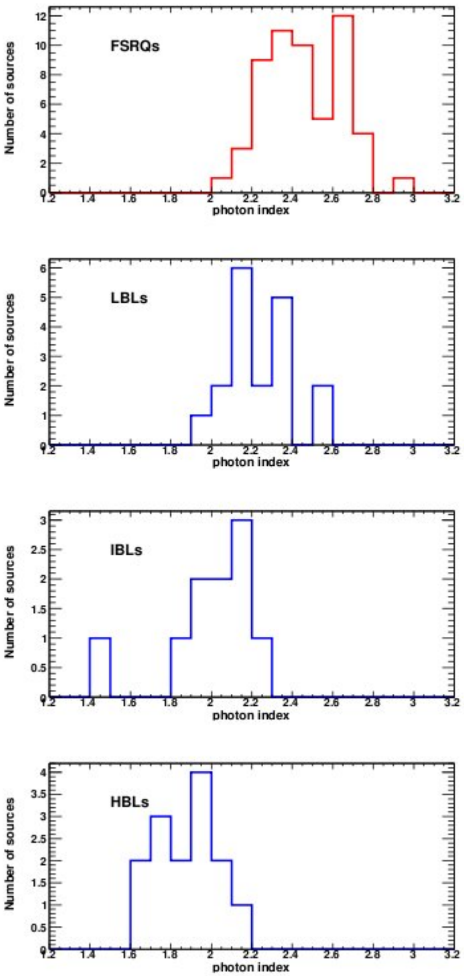
This scenario can explain the difference in electron energies in the two classes of objects – since:

Maximum electron energy is determined by the competition of acceleration and cooling of electrons

* In FSRQs, luminous accretion disk provides ample external photons that are in turn seeds for Compton-upscattering by energetic electrons

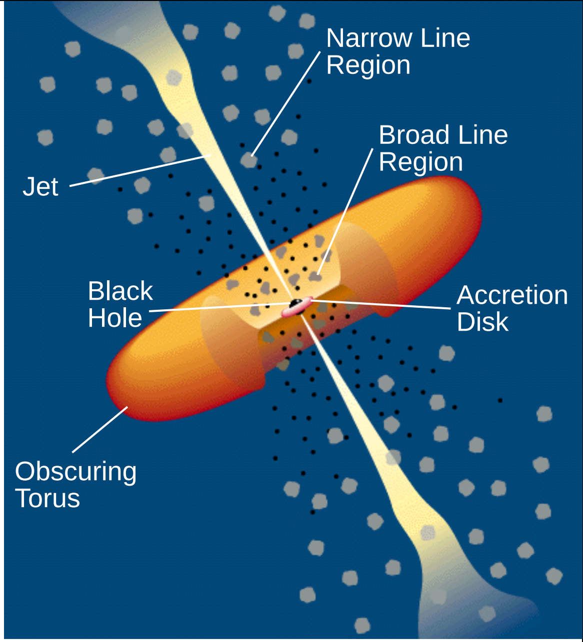
  -> Max electron energy is limited
* In HBL blazars, such external photon field is much weaker

  -> electrons can attain higher energies



Photon index distribution
In early Fermi data

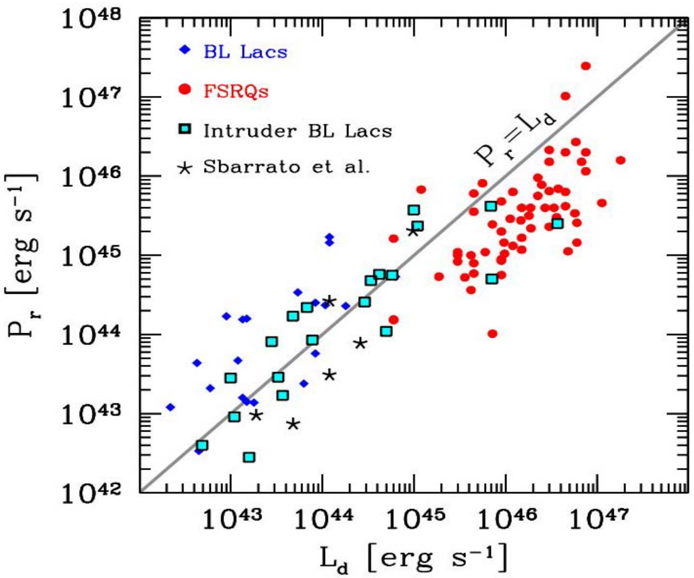
Accretion power vs. jet power



- Blazars are active galaxies with jets, so presumably the original source of power is the accretion of galaxian matter onto a black hole

* The jet power in all scenarios seems comparable to the accretion power (Ghisellini 2010, 2011)

* The energy transfer to the jet must be very efficient and the coupling between the accretion and jet generation must be very tight – unless the additional source of energy is the spin of the black hole and the BH can transfer the energy to jet (Blandford – Znajek process?)



From Ghisellini 2011

Mid-course summary from sample studies: "Standard model" for blazar emission

• Consensus on the radiative processes: leptonic processes are more compelling

• Low-energy peak is synchrotron, high energy peak inverse Compton

• No Paradigm shift – IC still most compelling for HE peak

• Internal shocks unlikely – inefficient (Tanihata et al., many later papers), to explain light curves, "shells" must have very different Lorentz factors

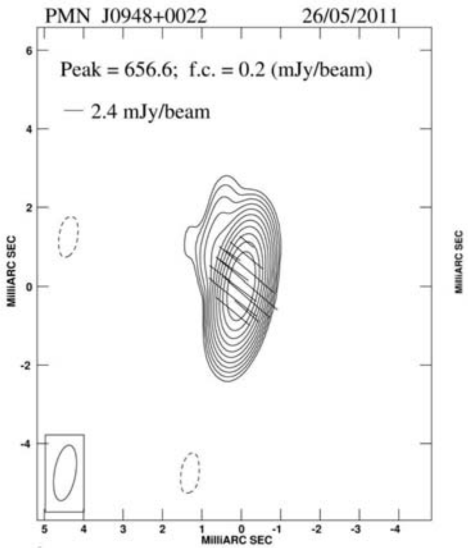
• Neutrons probably not important – where would they come from?

• Hadronic processes problematic (extreme energies required)

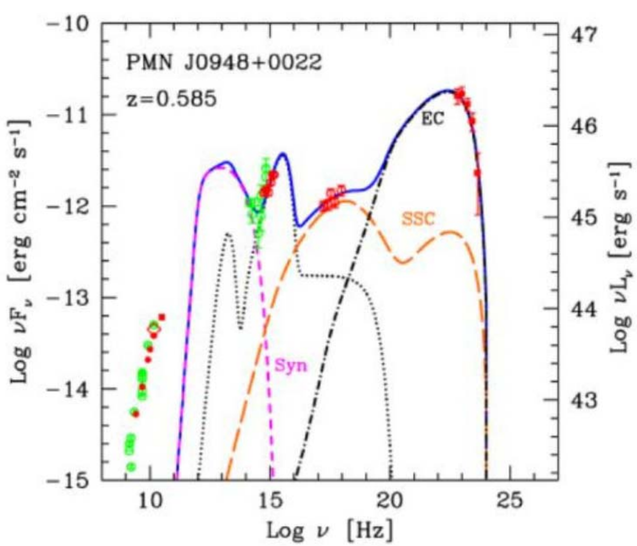
New Fermi result: AGN jets are also present in spirals – case for NLSy1

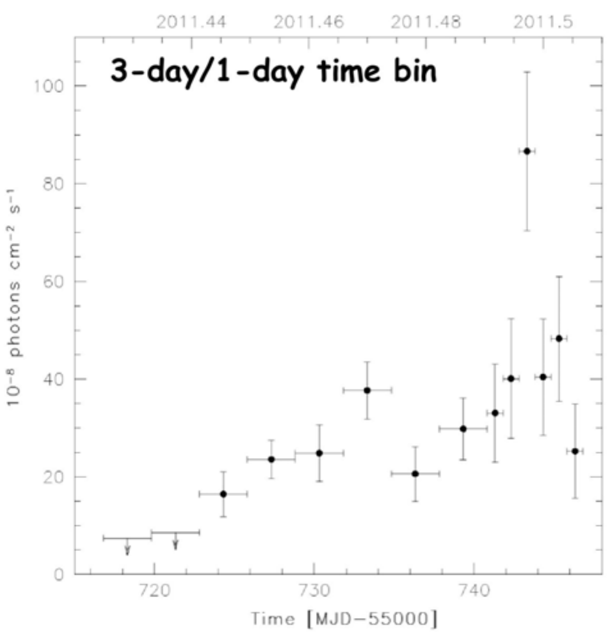
- Not only in ellipticals! – example of PMN 0948, about ~ 10 or so known
- Presence of radio jet is still required – no radio-quiet gamma-ray emitters

PMN J0948+0022



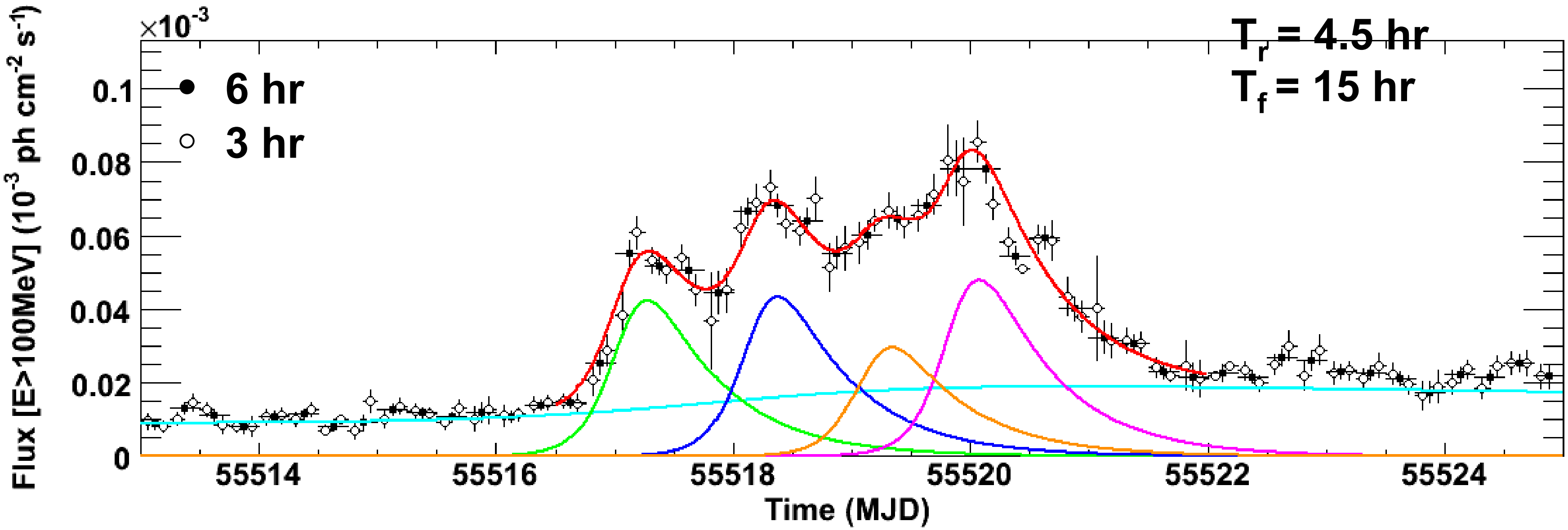
D'Ammando+2013c





D'Ammando et al. 2012, MNRAS, 426, 317

Fermi breaks records - the extreme case: 3C454.3 and its high-resolution light curve (work of Benoit Lott)



- 3-hr peak: F_{100}= (85 $\pm$ 5) x 10^{-6} ph cm^{-2} s^{-1}
- most luminous AGN yet observed, isotropic L_γ = (2.1 $\pm$ 0.2) x10^{50} erg s^{-1}
- 4x flux increase in ~12 hr: ~ 6 hr doubling time

•dL/dt ~ 10^{46} erg s^{-2} largest ever measured for a blazar (dwarfs PKS2155-304, Mrk 501…)

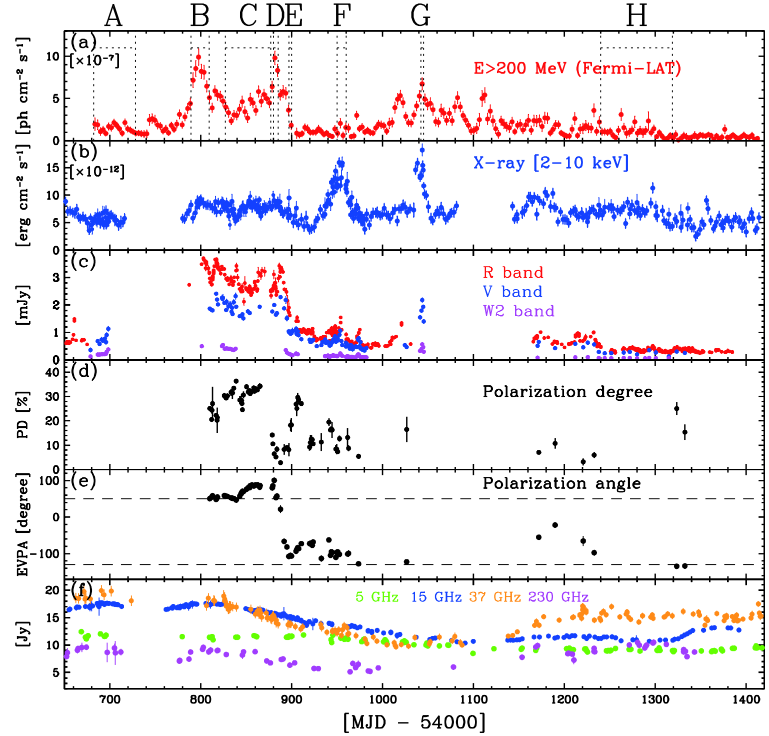
Single source studies: Multi-band variability of 3C279 in Fermi days

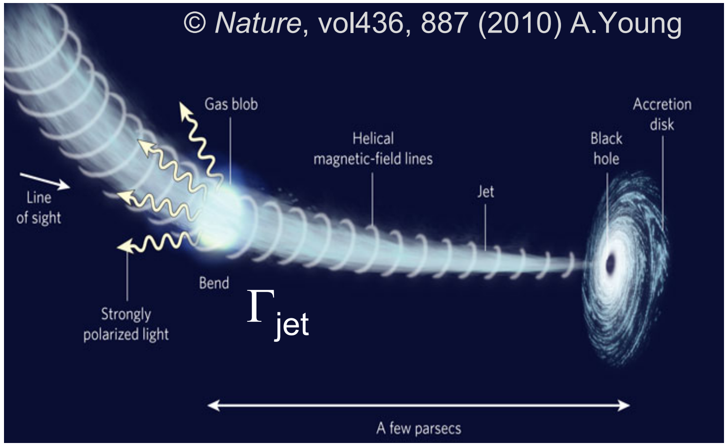
* Fermi motivates terrific multi-band light curves

• Search for coincidences / delays amongst various bands: optical and γ-rays closely correlated; X-rays – less so

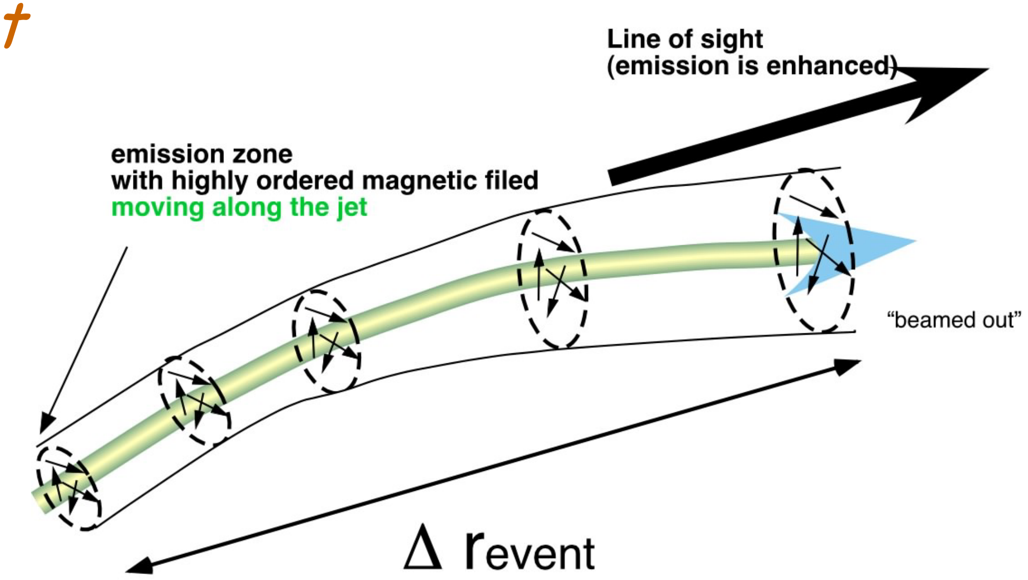
•Very important new hint: rotation of optical polarization angle, seen in BL Lac (Marscher), but clearly associated with the γ-ray flare (Abdo+ 2010; Hayashida+ 2012): 180° in 20 days

•Rotation of polarization angle: 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





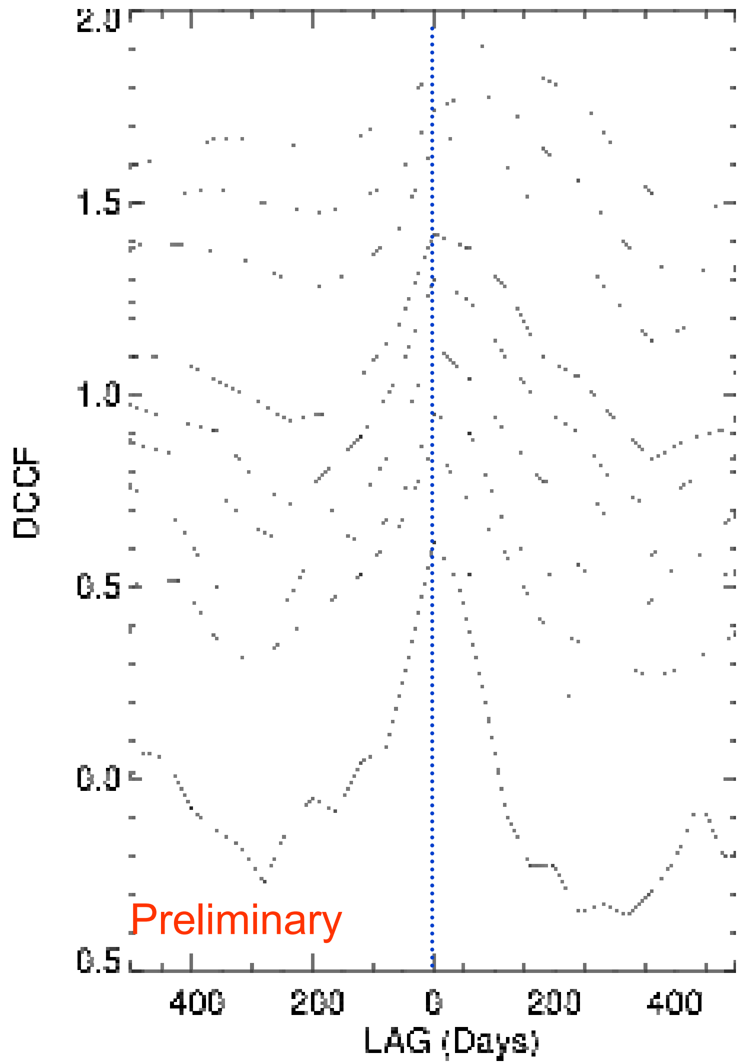
Location of dissipation of jet energy into photons



- Simplest model: bending jet, emission relatively far from the BH, taking place over the distance $\Delta r_{event} \sim \Gamma^2 * c * \Delta t$ – yet the dissipation region must be compact (synchrotron self-absorption)

- Somewhat unsatisfying on the energetics grounds: how to carry significant part of the accretion power so far (10^5 R_s !) from the BH before it is converted to radiation? Poynting flux?

Gamma - radio correlation



F-GAMMA sub-mm to cm band radio

11 cm

0.8 mm

Radio lagging: Lags close to 0 at mm/sub-mm bands & increasing towards lower frequencies

Positive delay: gamma-rays from inside / upstream of “mm-core”

Delay origin: opacity/synchrotron self- absorption

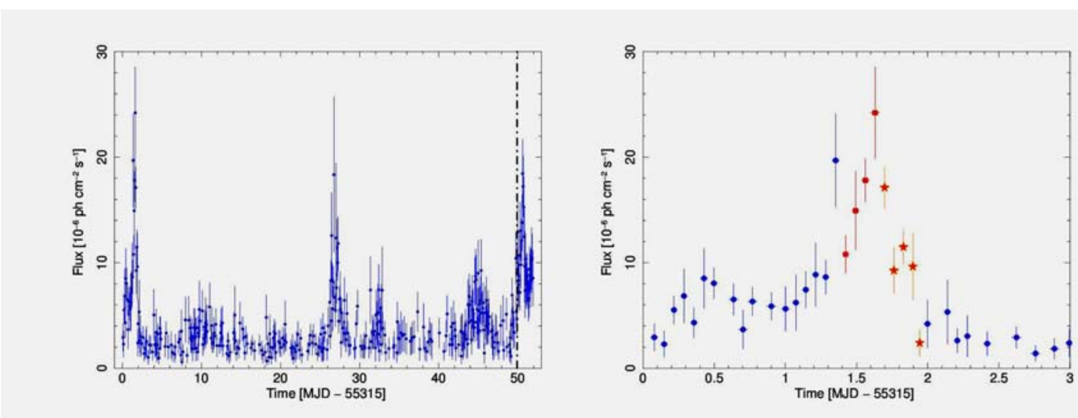
Work of Lars Fuhrmann, Stefan Larsson

γ-ray variability w/Fermi, TeV observatories (MAGIC)

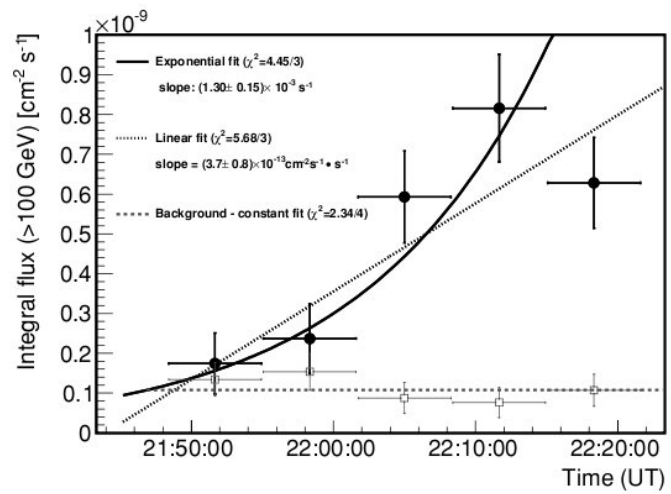
* Much better sampling in the Fermi days, together with observations in other bands seem to support this “distant” picture

• A remarkable and very important observations are those joint with Fermi in the TeV regime: the luminous blazar PKS 1222+216 (z=0.43) was detected by MAGIC – and the flux appeared rapidly variable!

* Excellent area for HESS-II studies



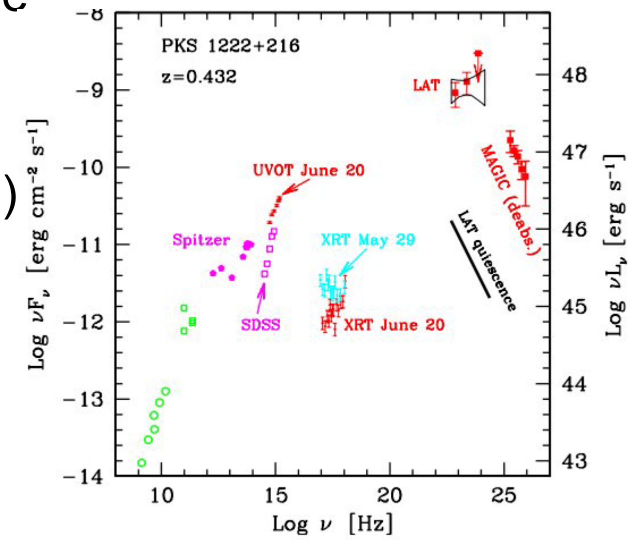
Fermi time series (Tavecchio et al. 2011)



(MAGIC Collaboration 2011, ApJ, 730, L8)

γ-ray variability in blazar PKS 1222+216

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 cospatiality 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?

Energy transport to the dissipation region

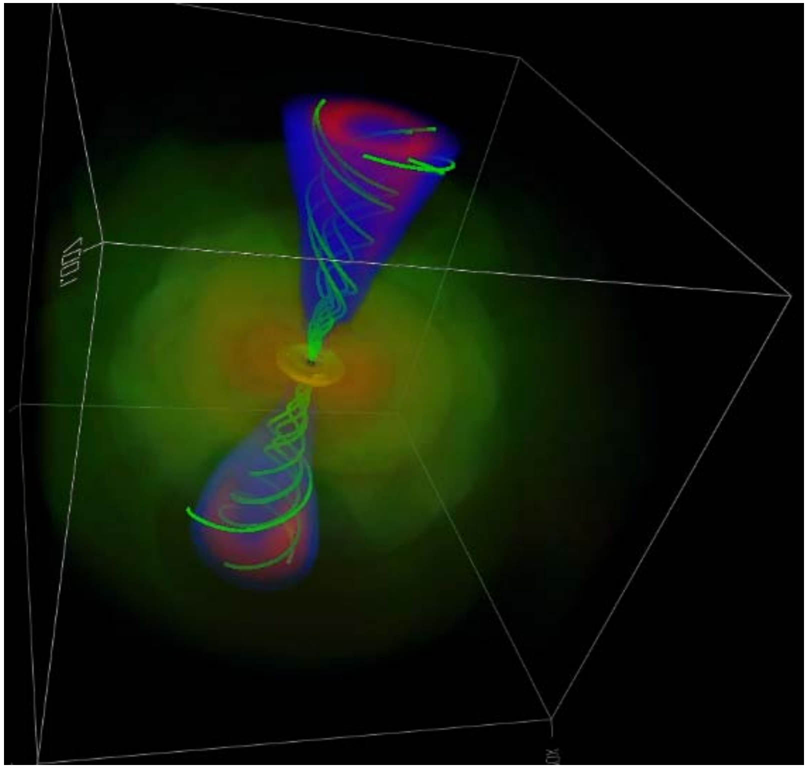
- **Accretion releases the gravitational energy very close to the black hole**

- **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

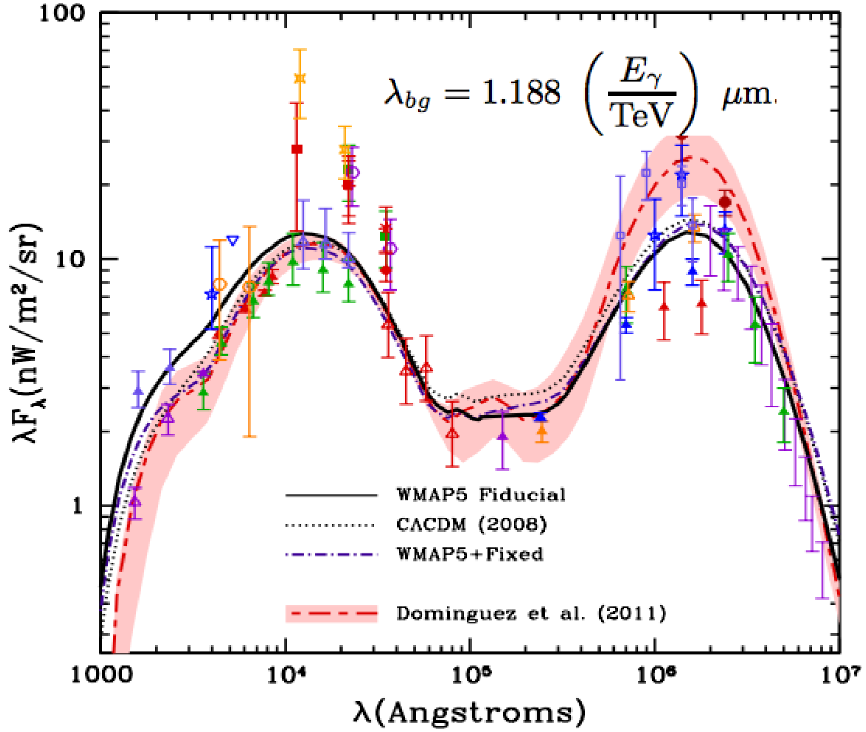
*** Massive challenge to theory and numerical simulations!**

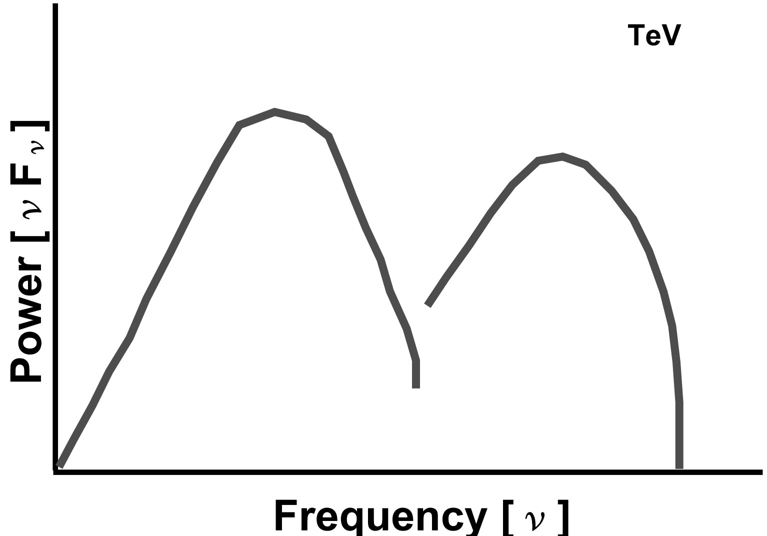


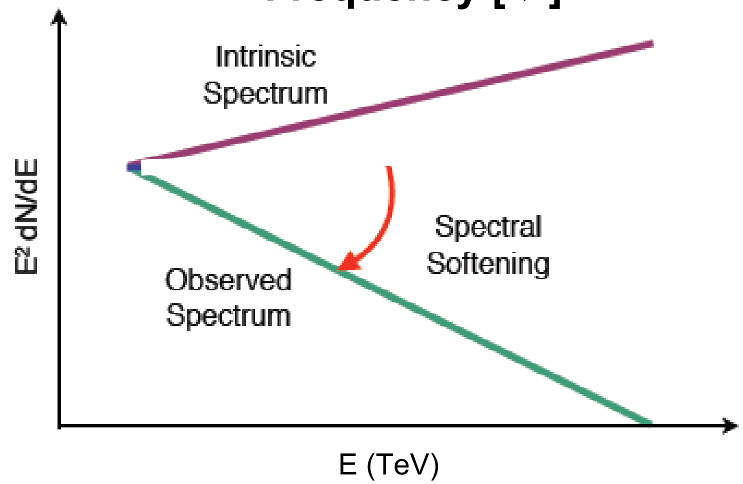
Numerical GRMHD simulations by McKinney and Blandford

TeV-Emitting Blazars and the Extragalactic Background Light

- TeV photons interact with EBL
- EBL is the sum of all emitted and reprocessed starlight
- Interaction absorbs TeV flux
- Limits distance to which TeV emitters can be detected

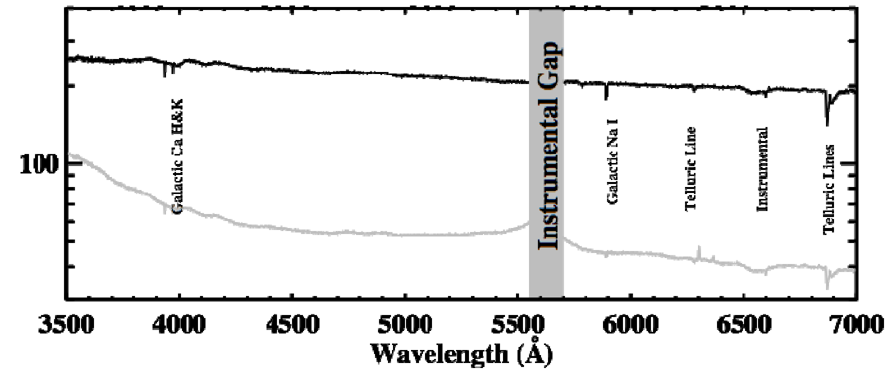






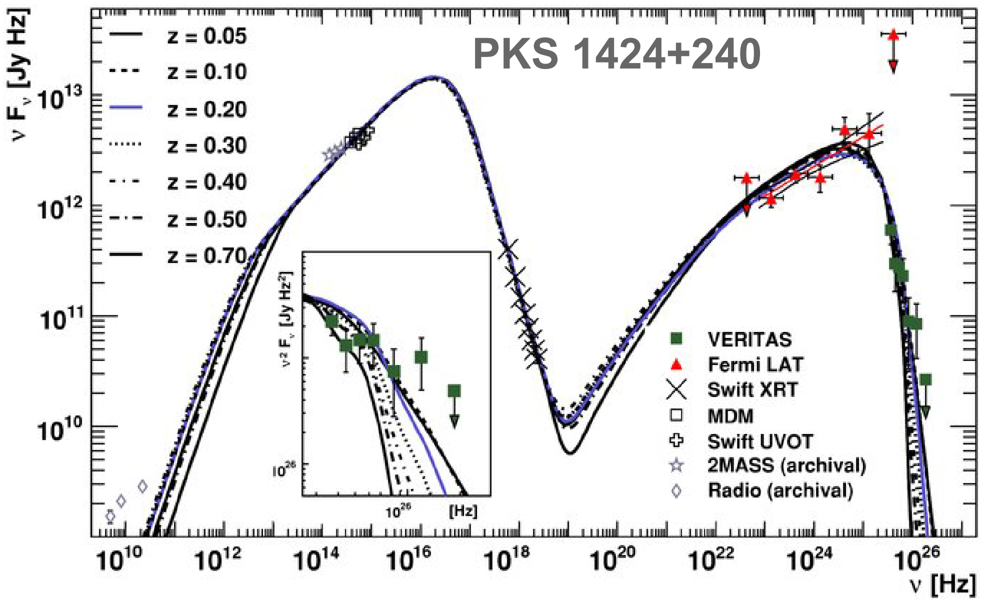
$$F_{obs} = F_{int} e^{-\tau(z,E)}$$

Using blazars for cosmology: measuring distances

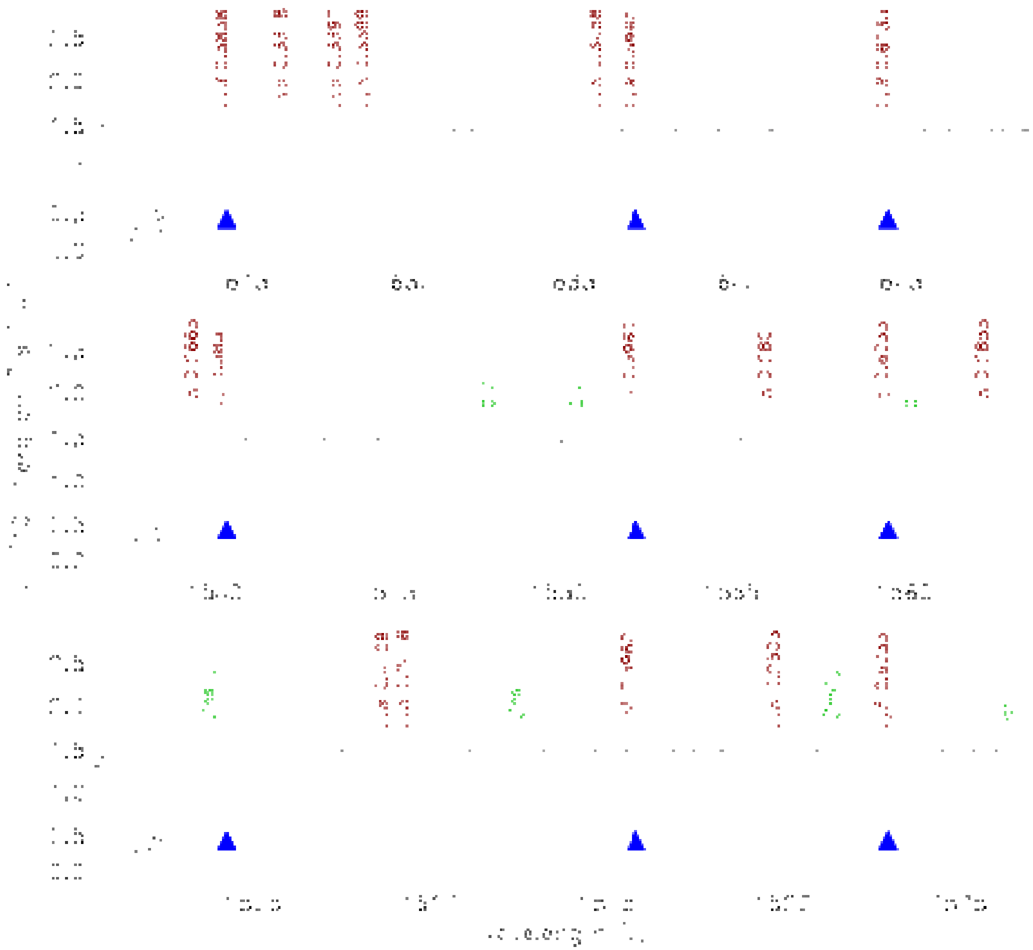


Blazar distance is critical for blazar emission and cosmological studies

But… BL Lac objects show very weak or no host galaxy emission/absorption lines



Recent success: Redshift Lower Limit of PKS 1424+240 from Far UV Observations with Hubble ST Cosmic Origins Spectrograph (COS)

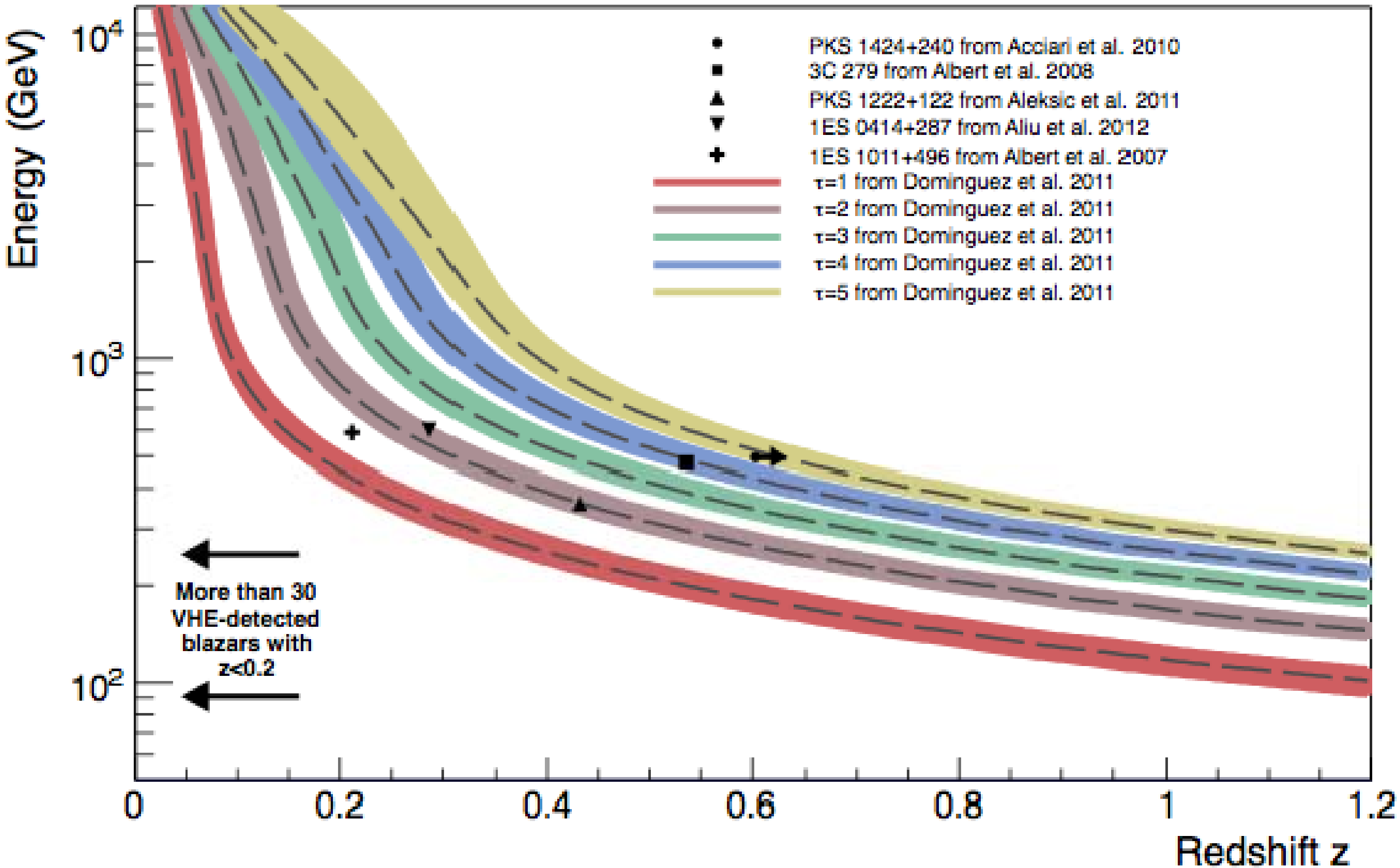


Observations of PKS 1424+240 on April 19, 2012 show higher-order Lyman absorption at z=0.6035

(Furniss et al. 2013, ApJ Letters 768, 31)

PKS 1424+240 and the Gamma-ray Horizon

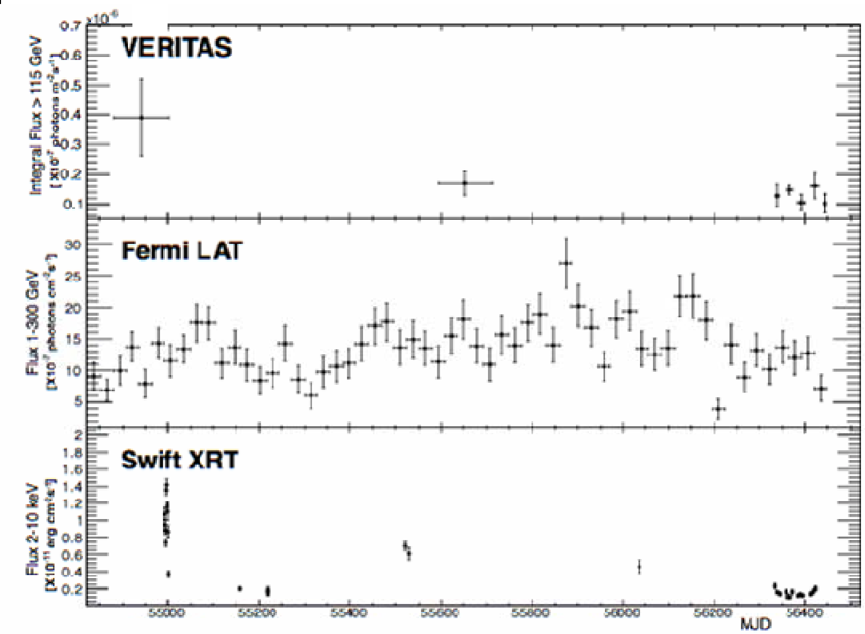
$$F_{obs} = F_{int} \times e^{-\tau}$$

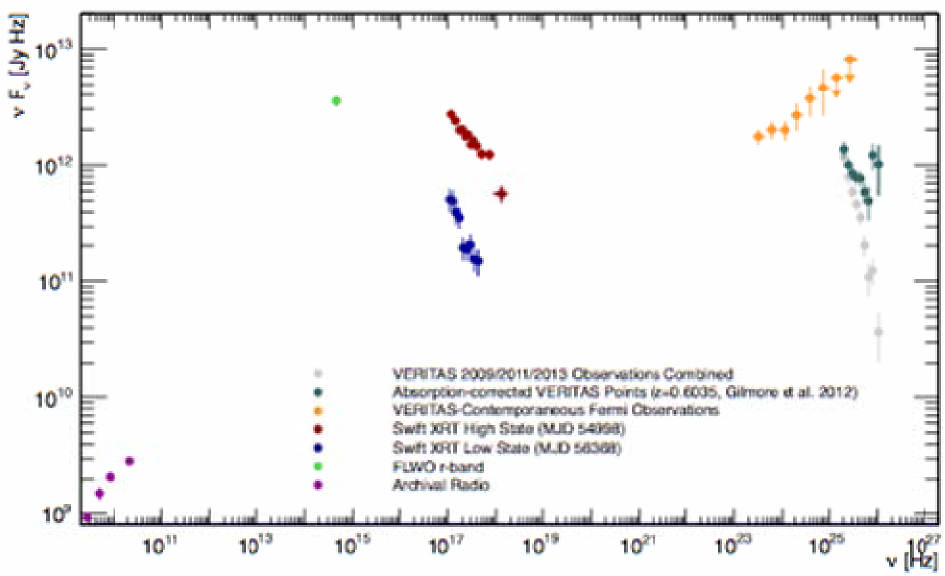


Furniss et al. 2013

High Energy Light Curve and broad-band spectrum for PKS 1424: modelling is in progress

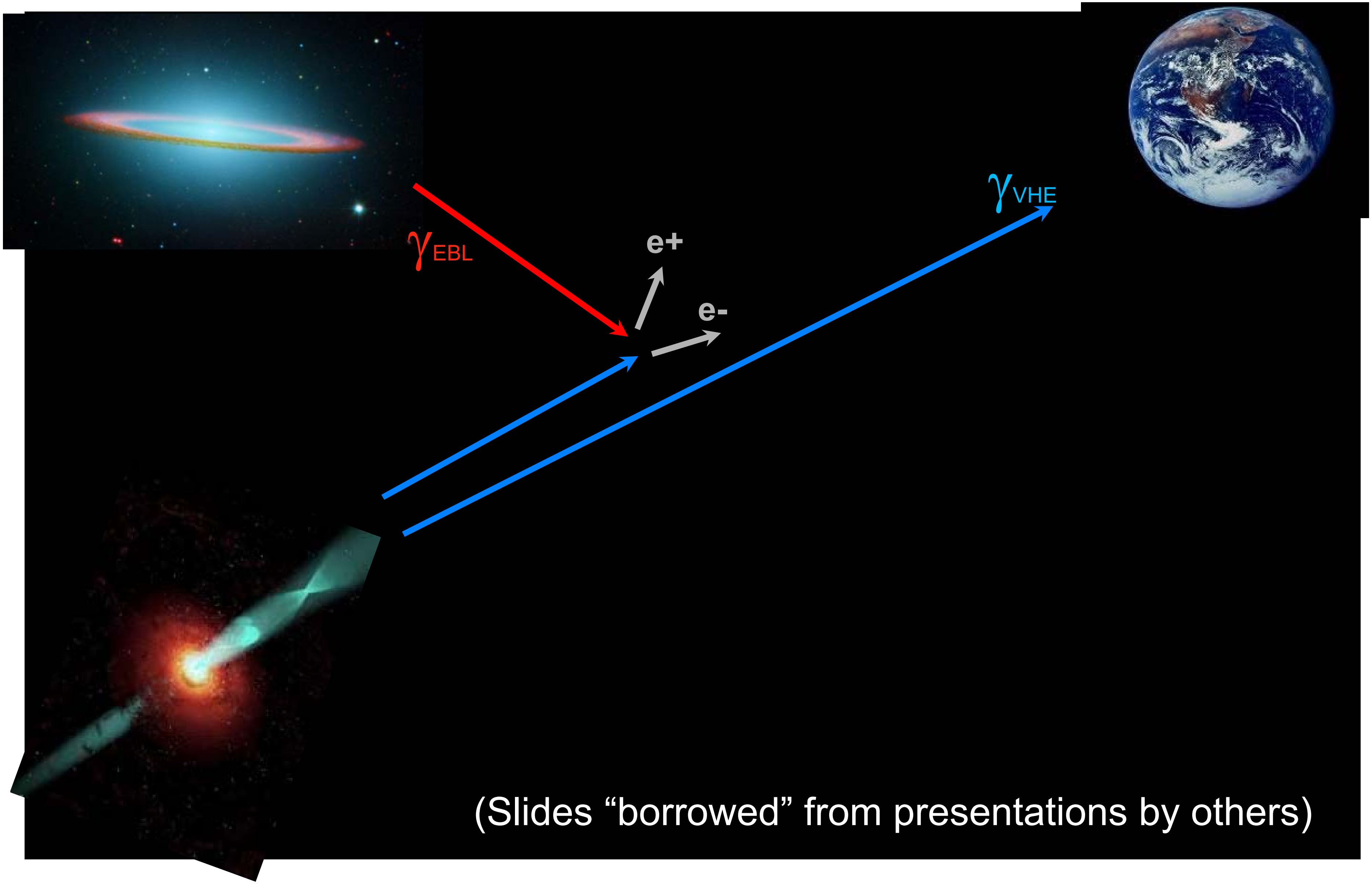
Preliminary



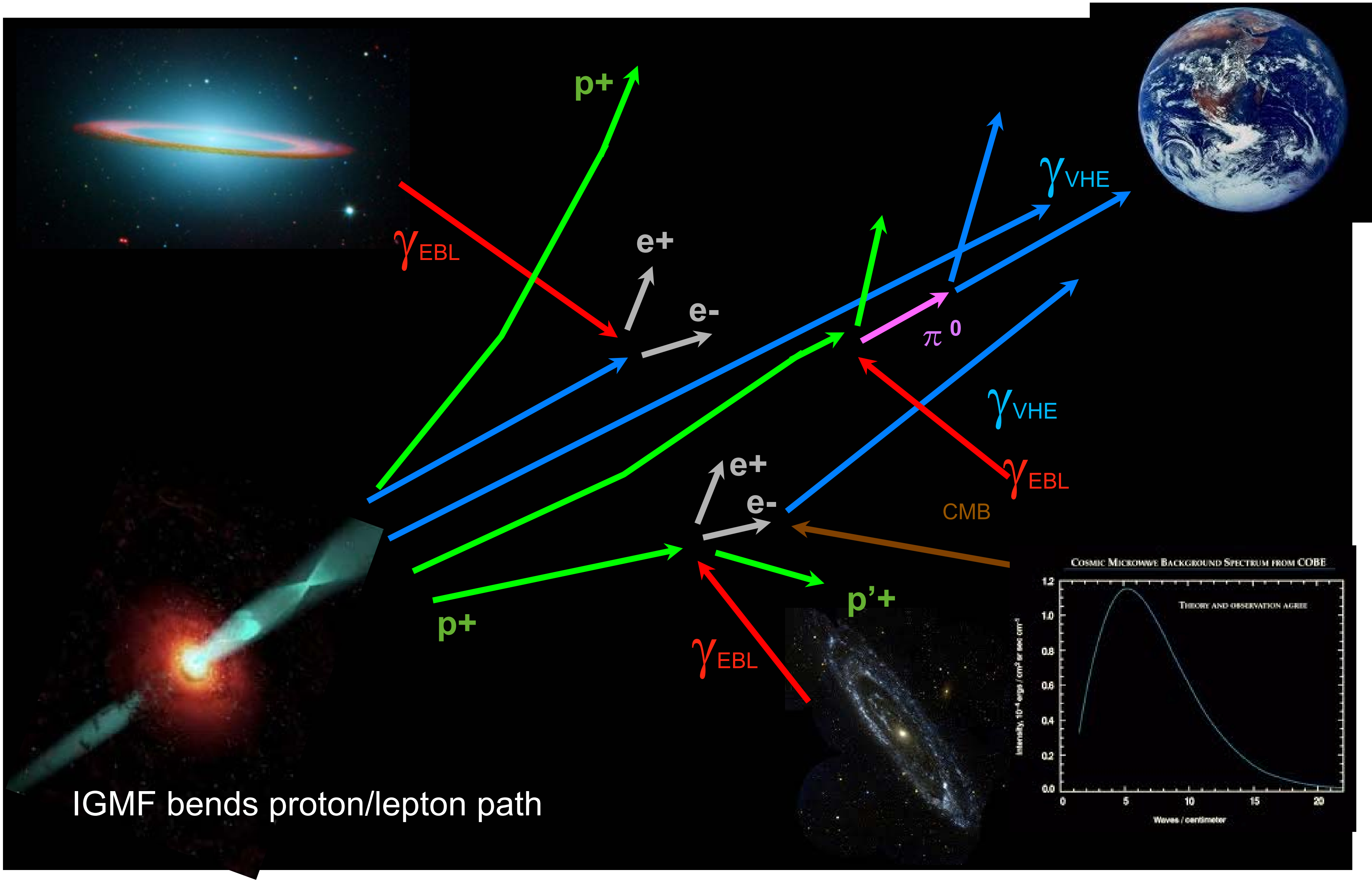


Furniss et al. 2013

Commonly Applied Picture of Intrinsic VHE photons interacting with the EBL might be insufficient… (other talks)

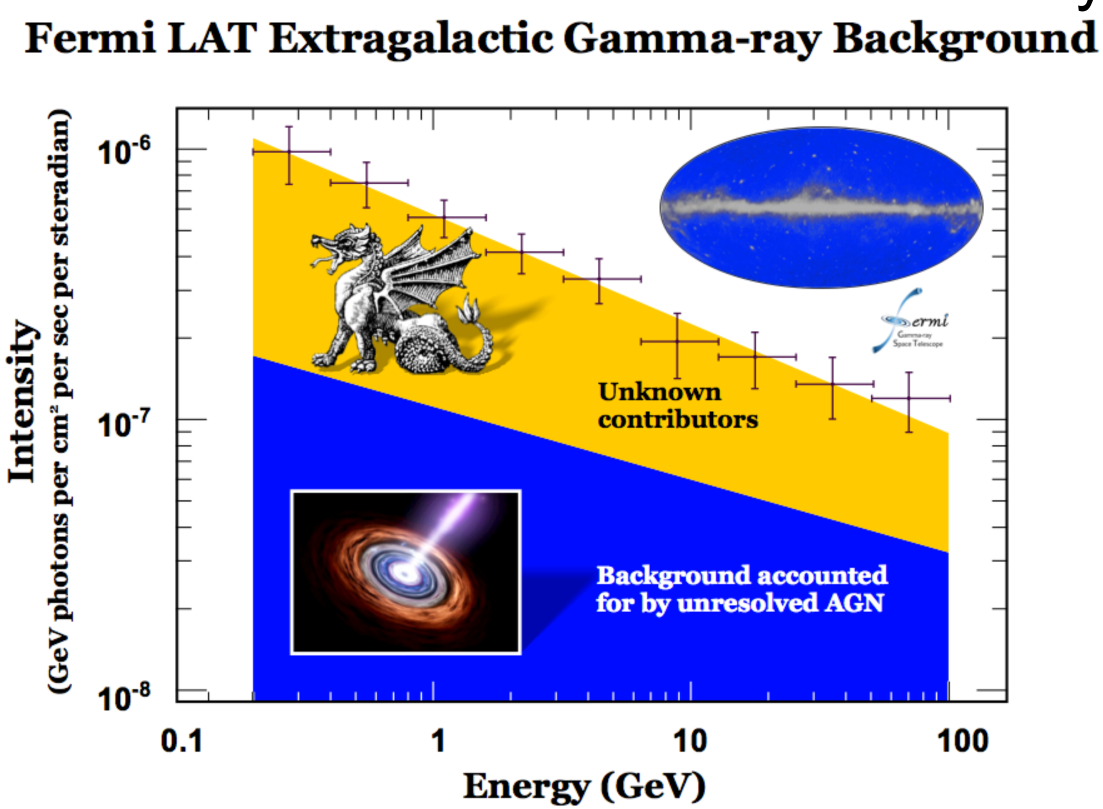


Cosmic-ray Contribution? Cascades? “Pair Halos”?



Sources contributing to the isotropic γ-ray background

A few years ago, we thought that probably the main contributors are individual AGN jets – but that's still no more than ~ ½ … and it's not the whole story



Marco Ajello's and Marcus Ackermann's work

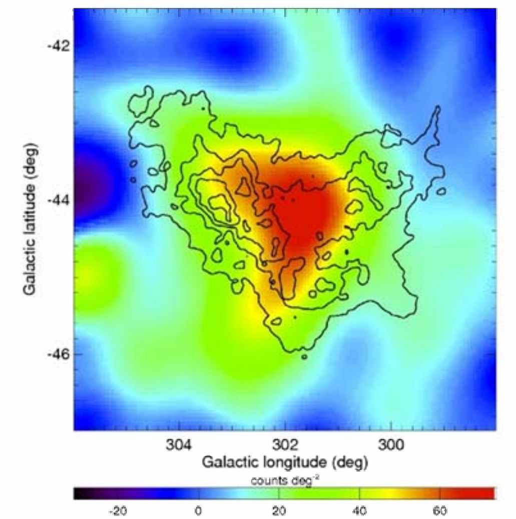
Sources contributing to the isotropic γ-ray backgnd

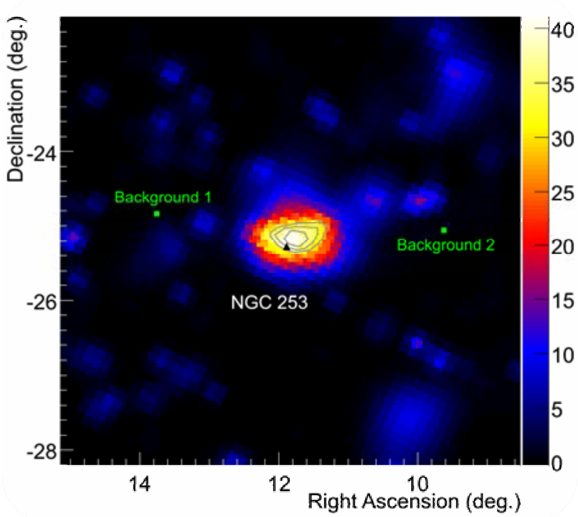
One recent example for new sources: discovered that ordinary galaxies produce copious γ-rays resulting from proton-proton interaction (M82, NGC253)

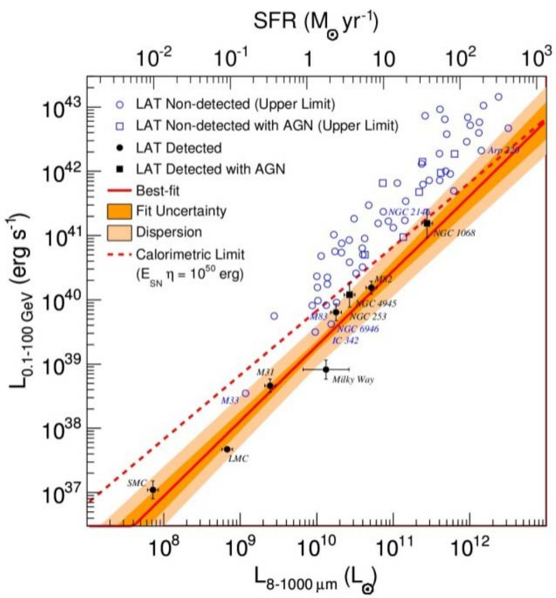
Protons are presumably accelerated in young supernova remnants – closely associated with vigorous star formation

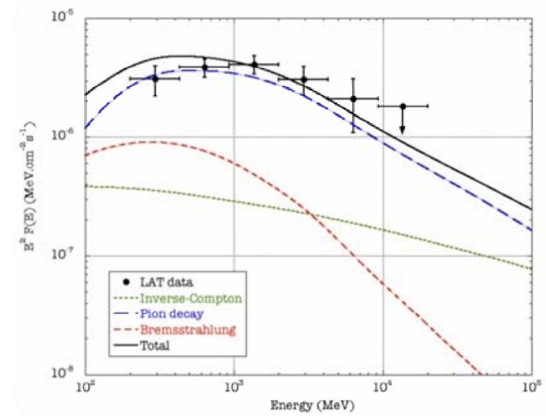
Such star-forming galaxies are important contributors

(Ackermann, …, Bechtol, … 2012)









Gamma-ray image and spectrum of the Small Magellanic Cloud


New an interesting example:
Circinus galaxy
Work by Masaaki Hayashida, Lukasz Stawarz, Keith Bechtol, GM

Circinus Galaxy

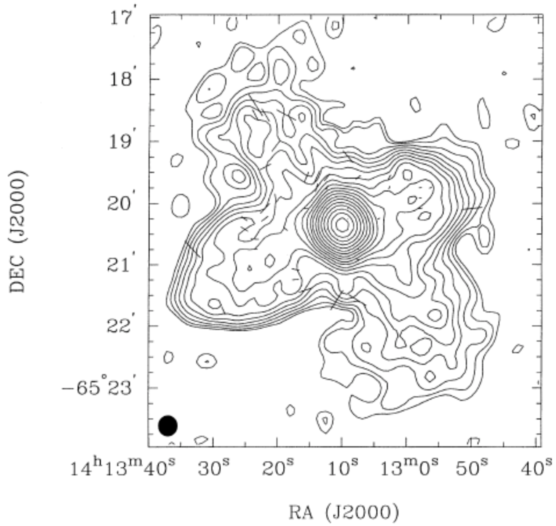
(RA, Dec: J2000) = (14h13m09.95s, -65d20m21.2s)

Distance: 4.2 Mpc (Tully et al. 2009)

H_2O maser emission $(1.7 \pm 0.3) \times 10^6 M_{sun}$ (Greenhill et al. 2003), also known as a starburst galaxy and Seyfert 2 type AGN.

large radio lobes are observed (e.g., M. Elmouttie et al. 1998)

Radio 1.4 GHz (ATCA) Map



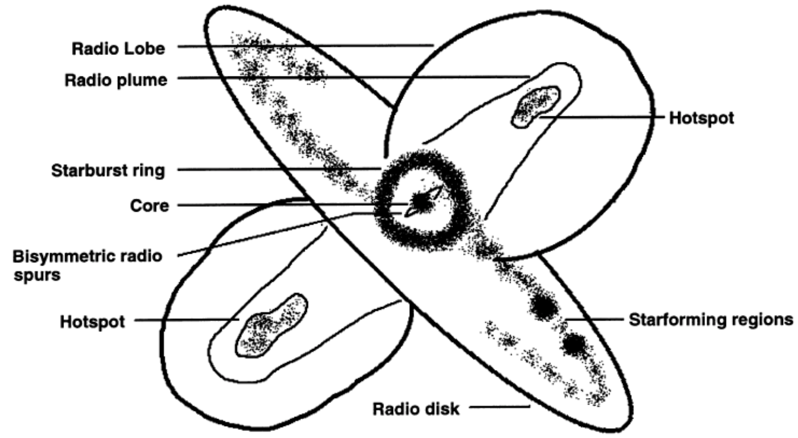
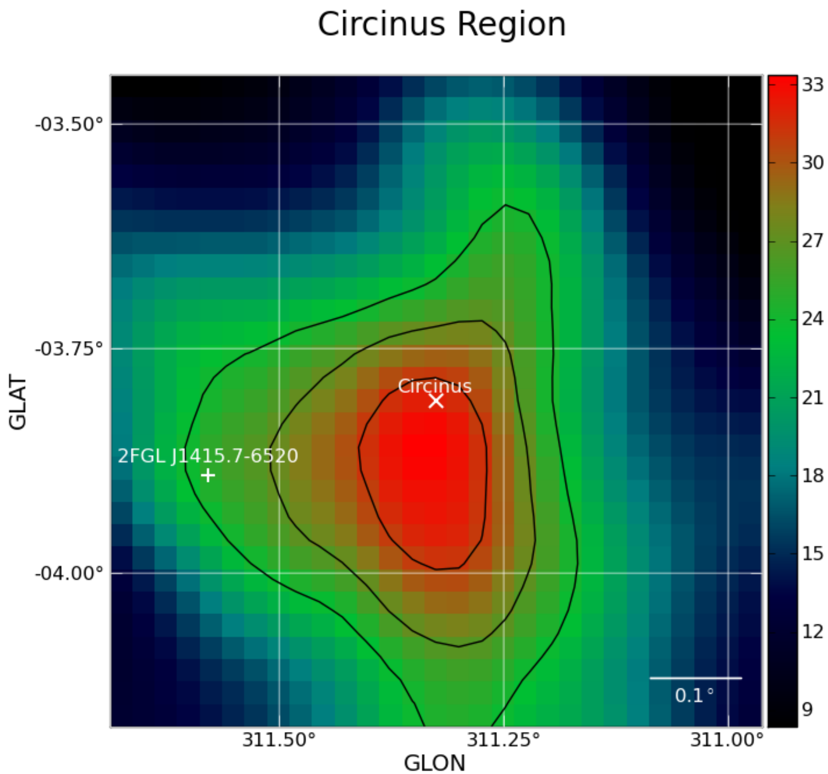


Figure 13. The proposed geometry for the radio continuum structures in Circinus. The figure is not to scale.

But, ***not included*** in the radio-quiet Seyfert paper (close to galactic plane: b=-3.8°) nor starburst paper (not covered by the HCN survey).

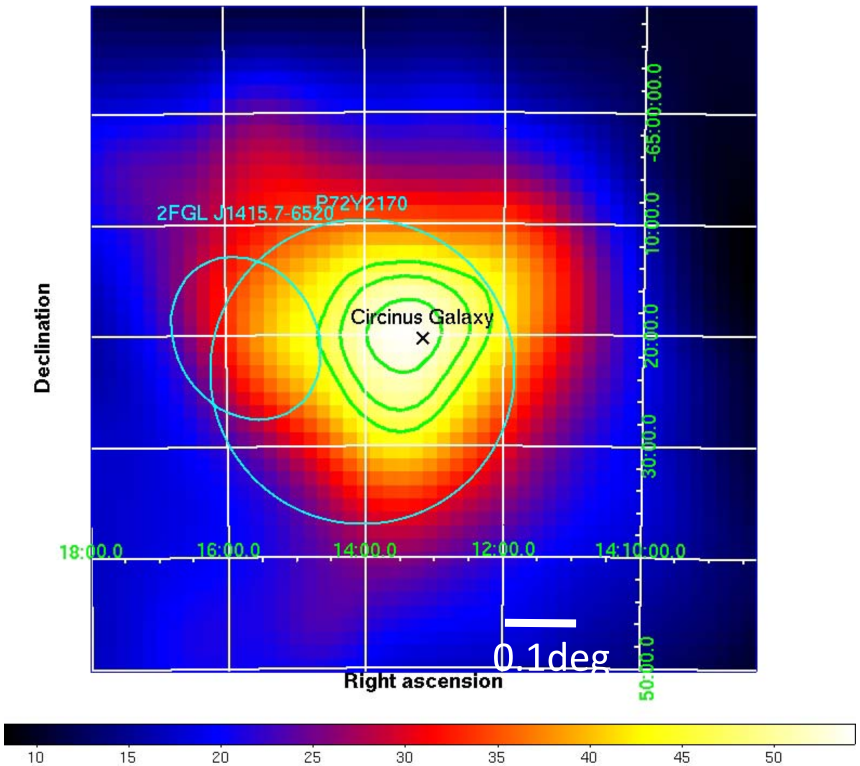
Circinus Galaxy with Fermi: TS map (> 100 MeV)

3-year data (Keith)



*Galactic coordinate

3.5-year data (Masaaki)

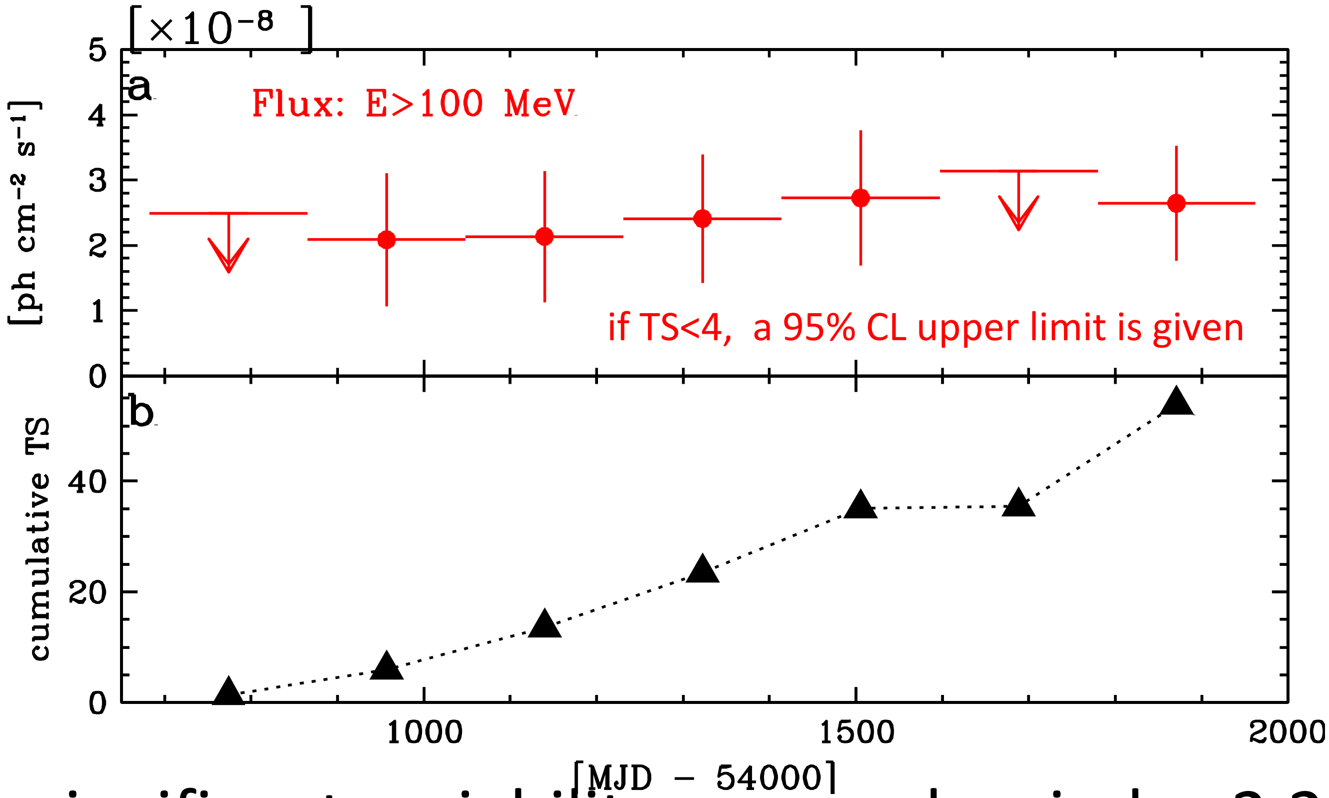


* Equatorial (J2000.0) coordinate

Two independent confirmations the positional coincidence of the γ-ray excess with the source

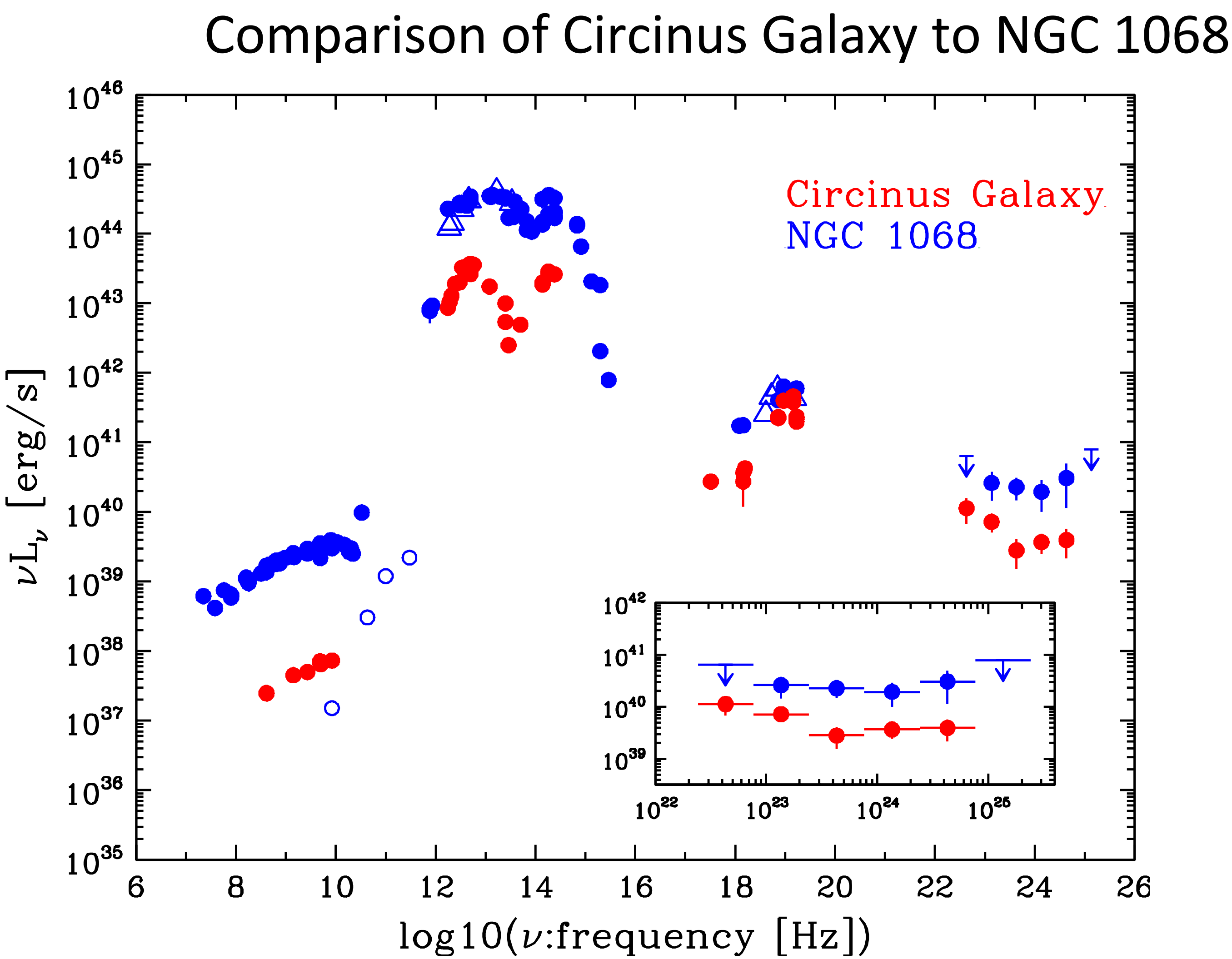
Light curve (6-month bin, E>100 MeV)

Fluxes were estimated with a fixed photon index at 2.25 (3.5-year value)

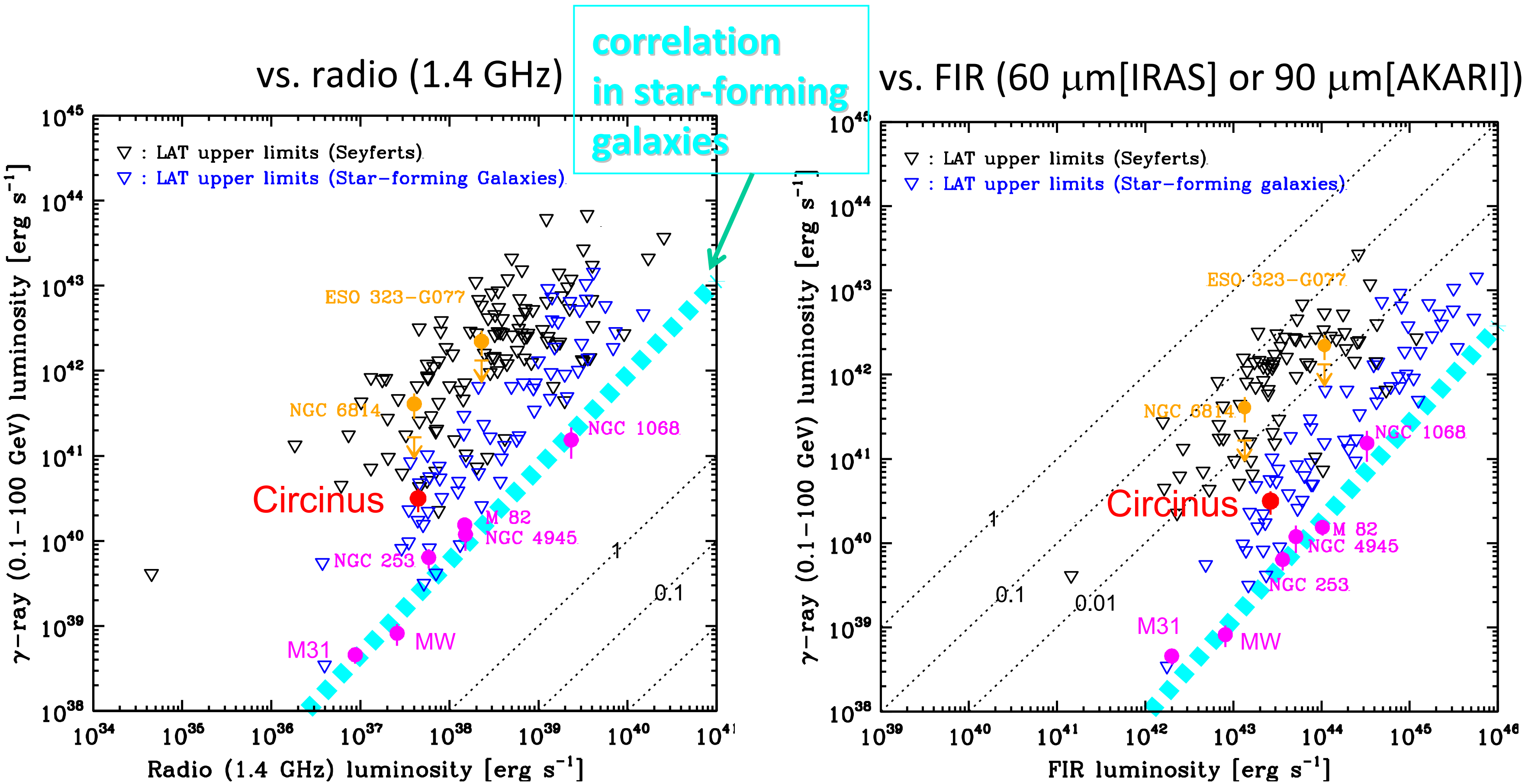


- No significant variability; power law index 2.25+/-0.13
- The TS of the γ-ray excess at the source position is constantly increasing; flux ~ 2 x 10^{-8} photons/cm^2/s

Broad-band spectral energy distribution



Multi-wavelength comparisons (including Seyferts and star-forming galaxies)



The source seems to have a higher γ-ray luminosity compared to the $L\gamma$-L_{radio} or $L\gamma$-L_{FIR} relations (cyan lines) in the star-forming galaxies.

Summarizing Circinus:

* Positional coincidence of the γ-ray excess indicates that Circinus galaxy is a γ-ray source

- The source seems over -luminous in the γ-ray band compared to other γ-ray detected star-forming galaxies
- Is the gamma-ray emission due to starburst activity? AGN? radio lobe?
- AGN unlikely (no other jet-less AGN shows nuclear gamma-ray emission)
- Analysis of possible inverse Compton emission from the radio – emitting lobes implies the IC emission to be way too weak (~ x10)
- Still an open question – starburst origin not ruled out, since there might be additional, significantly extended IR and radio emission beyond that measured in surveys
- Paper was just accepted by ApJ

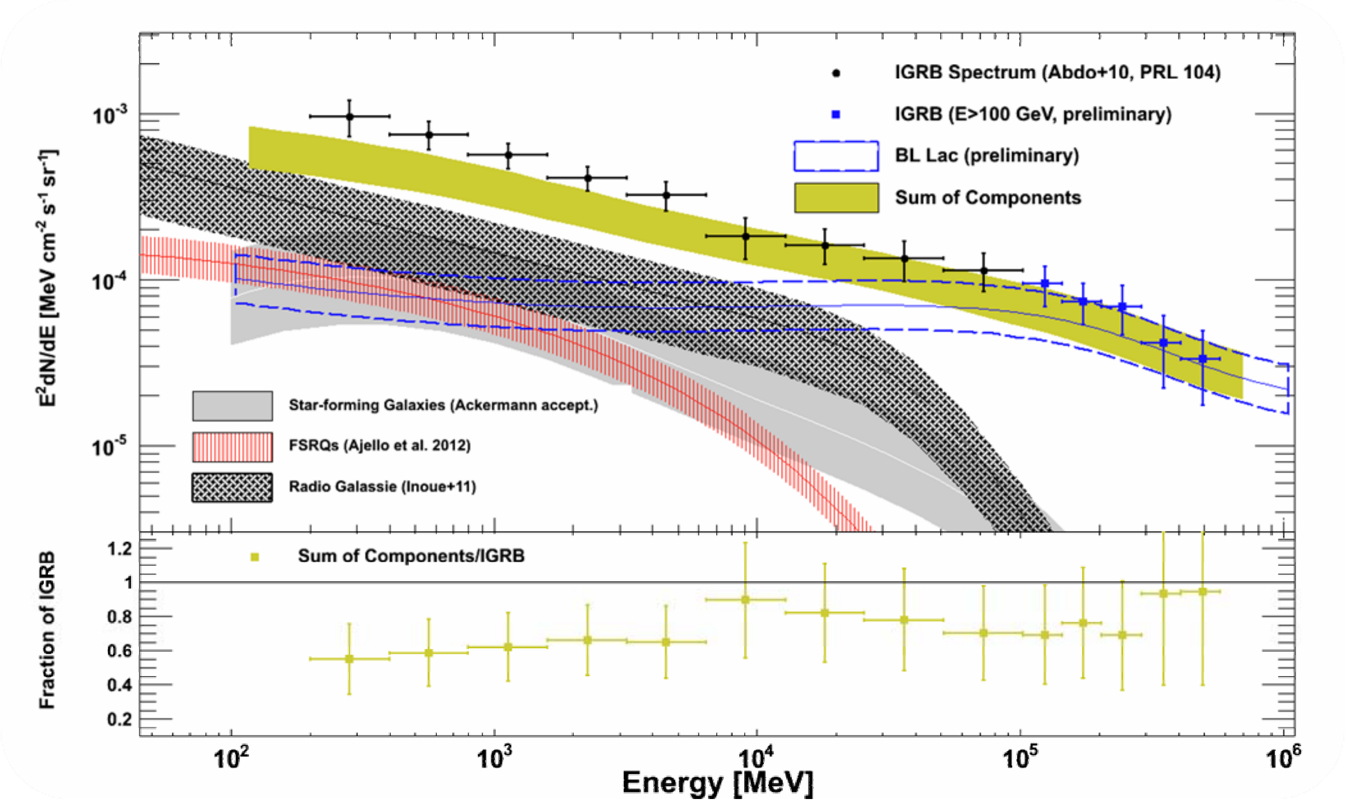
Excellent target for HESS - II

Sources contributing to the isotropic γ-ray background

Two-pronged approach:

* measure the background carefully

* understand the contribution of unresolved point sources



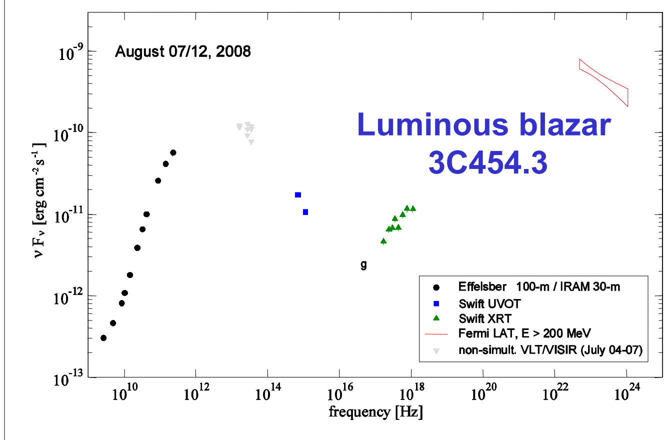
Slide from Ajello et al. 2012, AAS presentation)

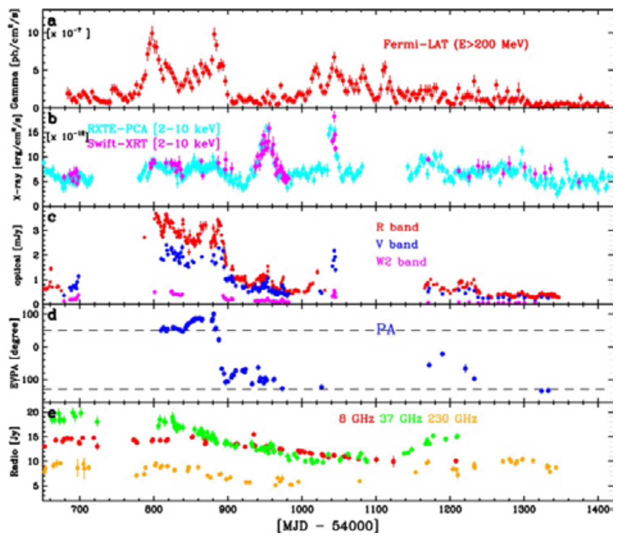
Future observations of blazars: including hard X-rays

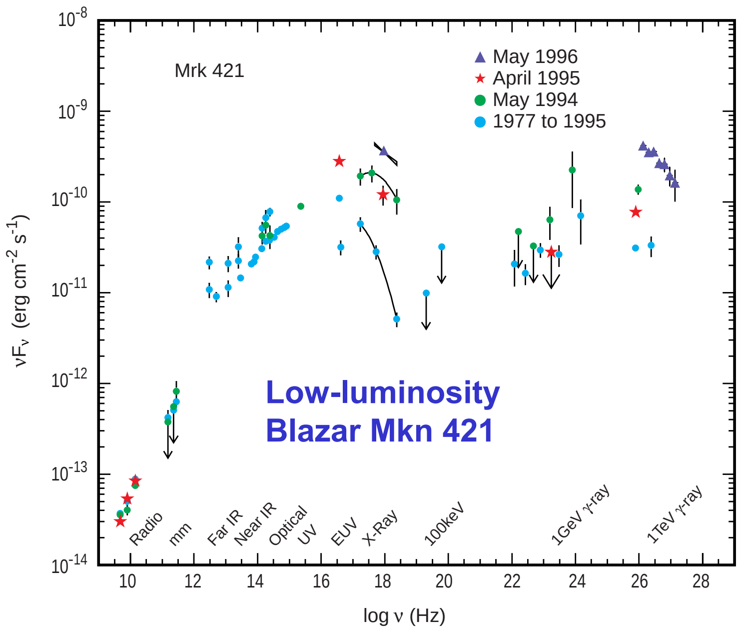
NuSTAR

In luminous blazars, hard X-rays reflect the low-energy end of the inverse Compton flux, and thus of the most numerous part of the electron energy distribution
- total content of the jet

- In low-luminosity blazars (those detected in the TeV band) hard X-rays sample <u>the most energetic radiating particles</u> (TeV energies!)
- Recent multi-band studies: while variability in optical and γ-rays is simultaneous, X-ray flares are not simultaneous: What's their origin?







NuSTAR optics

NuSTAR and its components

NASA's "Small Explorer" mission ($130 M), launched to an equatorial orbit 16 months ago

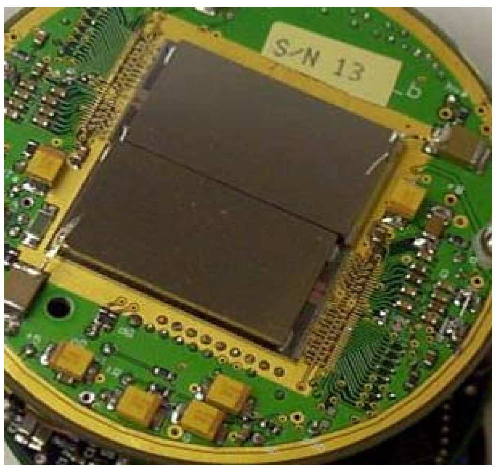
NuSTAR features three key novel technologies:

- **Co-aligned multi-coated focusing hard X-ray telescopes: excellent angular resolution will allow surveys at unprecedented sensitivity**

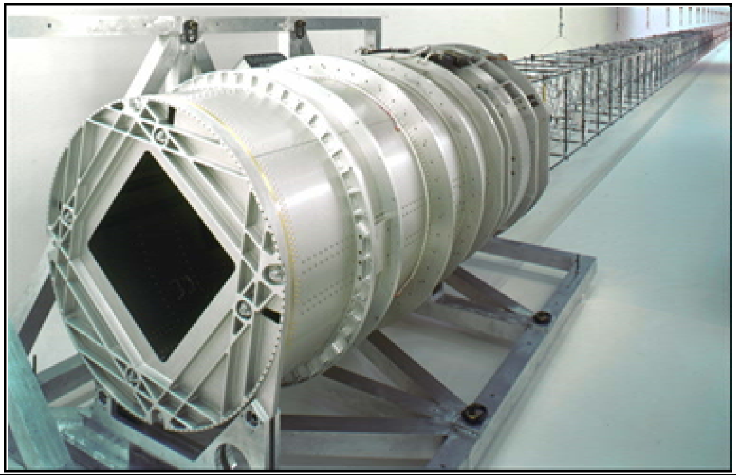
- **Pixellated CdZnTe detectors: bandpass well matched to the telescope reflectivity**

- **Deployable mast, enabling the ~ 10 m focal length**

| Field of view: ~ 10 arc min
|
|
|
|------------------------>



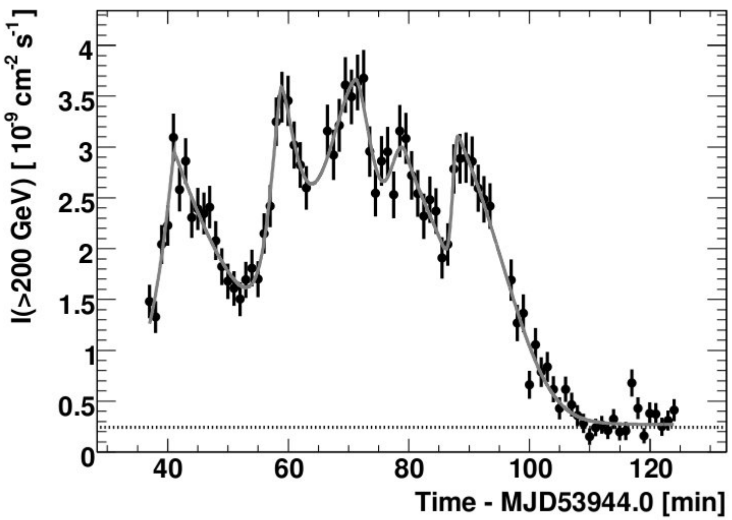
CdZnTe detectors:
pixel size 0.6 mm (~ 12"), 64x64
Max. count rate: 300 cts/s
HEFT heritage



Low-luminosity (TeV) blazars and observational challenges

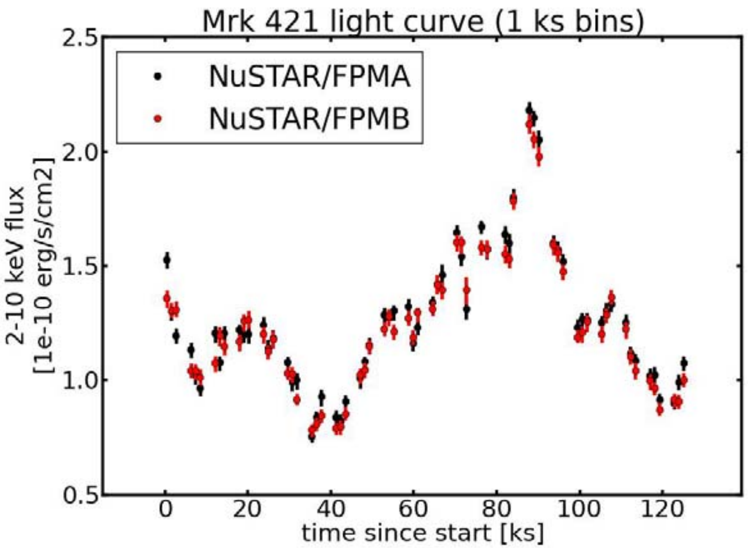
NuSTAR

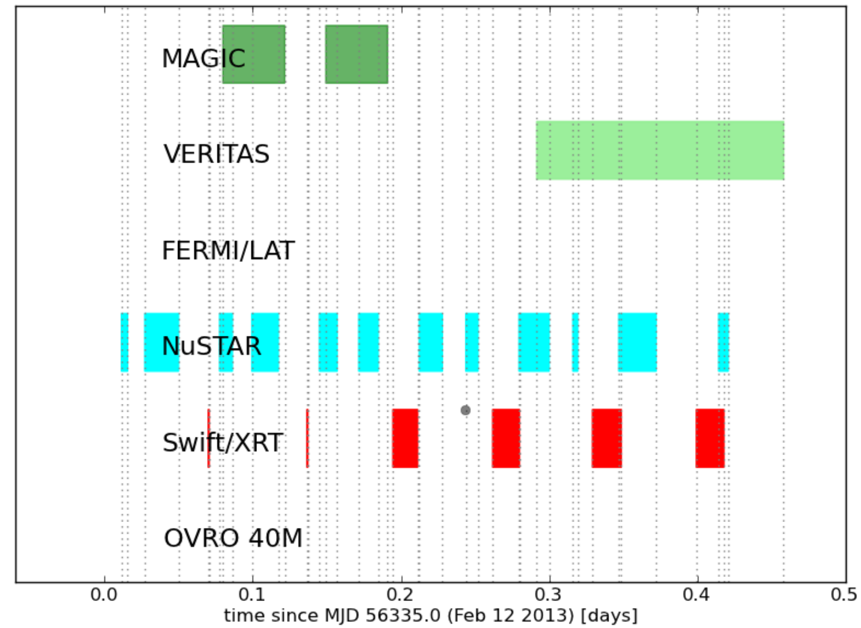
- Strictly simultaneous observations essential
- Most constraining are the TeV observations, requiring:
- Roughly anti-Solar location on the sky for long night visibility –
  - optimal observations only during a part of the year
- Dark sky –
  - moonless conditions, + night-time at a TeV observatory, weather considerations, …



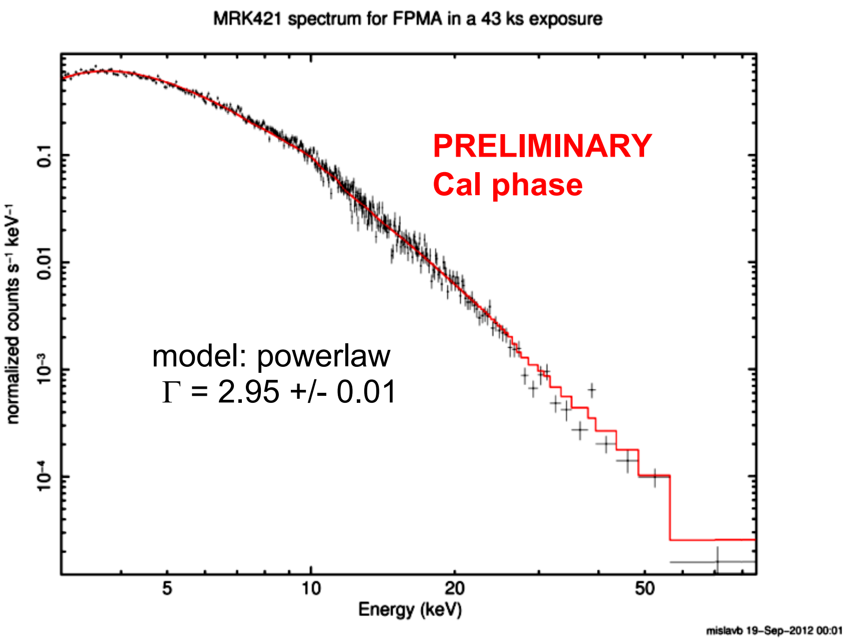
TeV flux time series for blazar PKS 2155-304

Cal data + 1st blazar campaign: Mkn 421



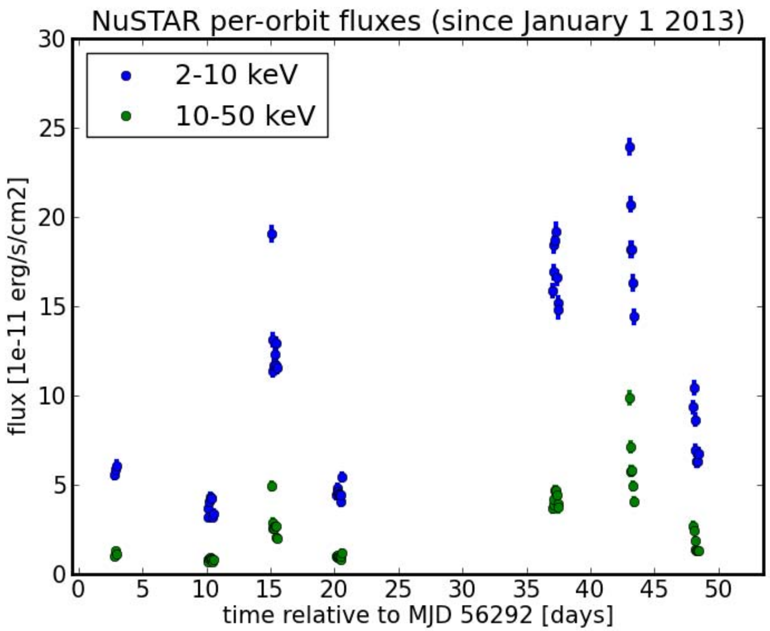


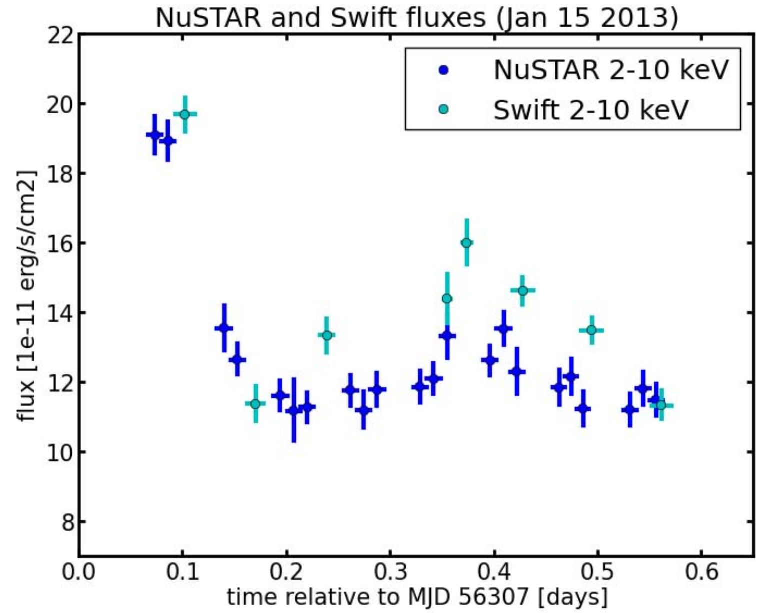
Example of time coverage during one of the Mkn 421 “snaphots”



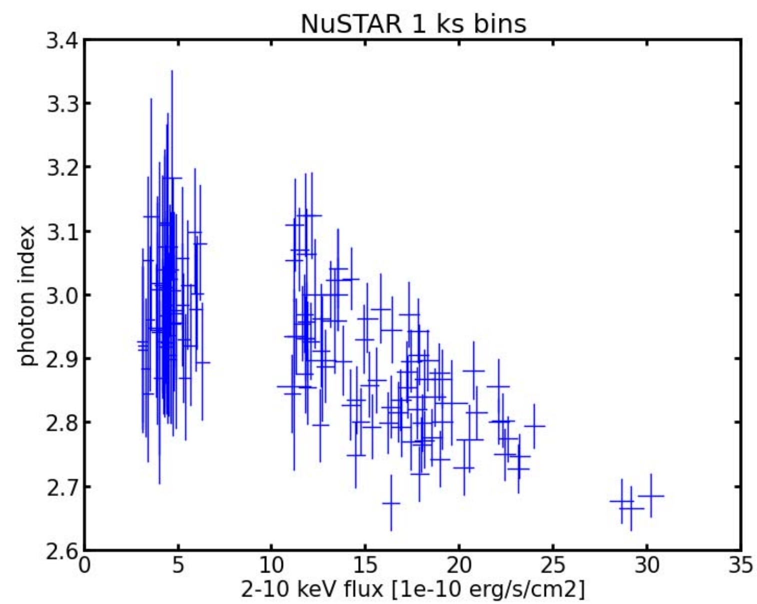
- Analysis led by Mislav Balkovic (Caltech)
- Bright BL Lac – type blazar, strong X-ray emitter, the first AGN measured in the TeV band
- Rapidly variable in all bands, but intra-band relationship of variability (opt., X-ray, γ) not understood
- First observation was for calibration purposes
- We have an ongoing campaign joint w/Swift, TeV

First results for the Mkn 421 campaign

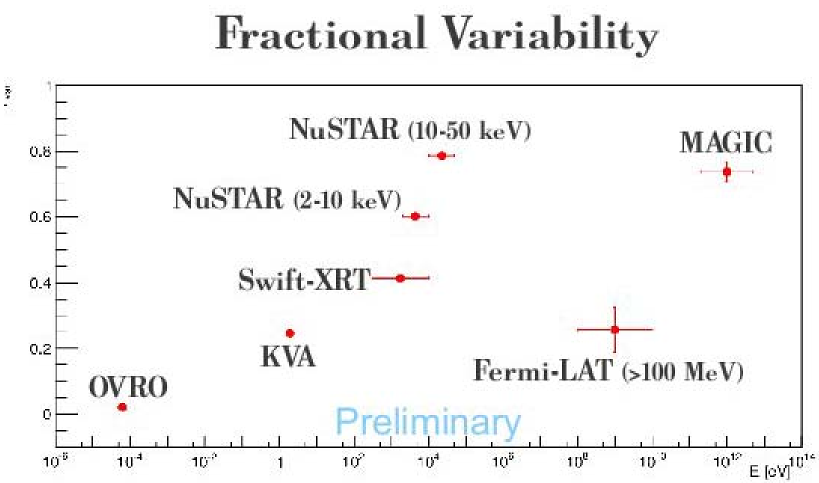




- Source is clearly variable with large amplitude in X-ray and TeV bands, ground-based and Swift coverage is good, weather (mostly) cooperated
- Spectrum is gradually steepening power law (electron distribution?) – NOT exp. cutoff
- Spectrum generally hardens as the source brightens
- No “hard X-ray tail” in NuSTAR (onset of IC comp.)

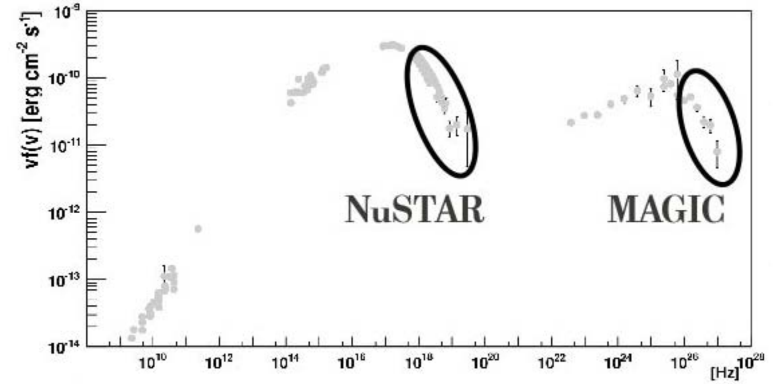


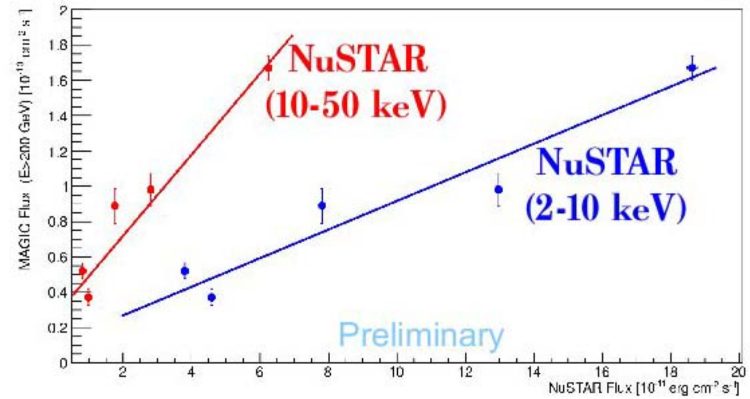
First results for the Mkn 421 campaign cont'd



$$F_{var} = \sqrt{\frac{S^2 - \langle \sigma_{eff}^2 \rangle}{\langle F_\gamma \rangle^2}}$$

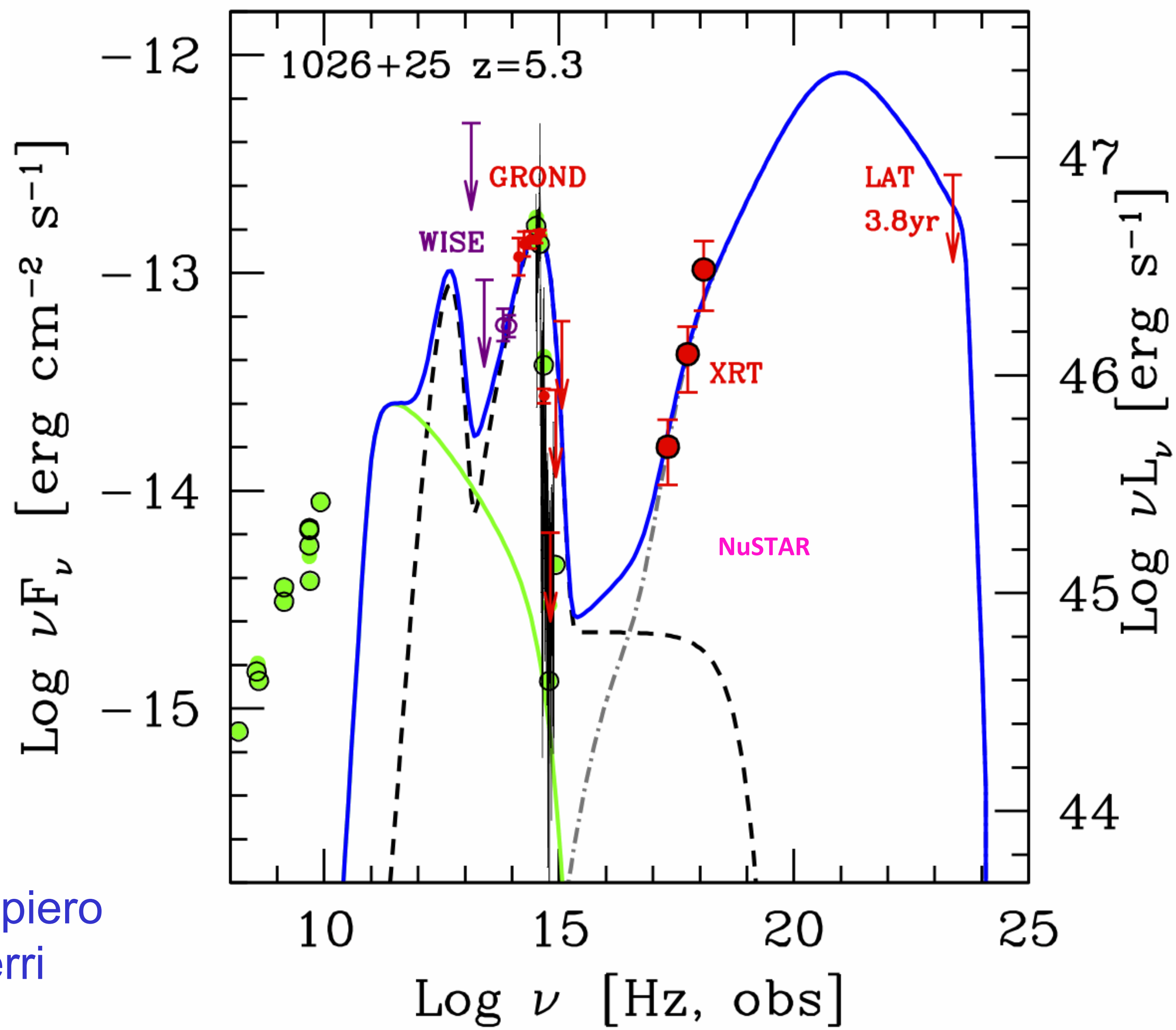
according to Vaughan et al. (2003)





- Much of the work is by Francesco Borracci w/David Paneque as well as Mislav Balokovic
- Fractional variability of hard X-rays and TeV gamma-rays is largest
- There is a clear correlation between the hard X-ray and TeV gamma-ray flux
- Relationship is linear – suggests that we are in the Klein-Nishina regime

NuSTAR observation of the blazar candidate B2 1023+25



From Gianpiero Tagliaferri

NuSTAR observation of the blazar candidate B2 1023+25

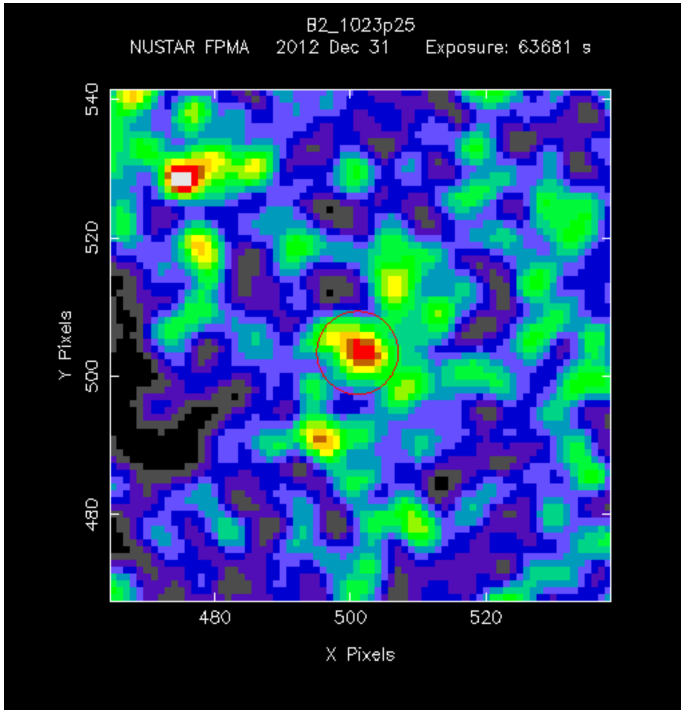
NuSTAR

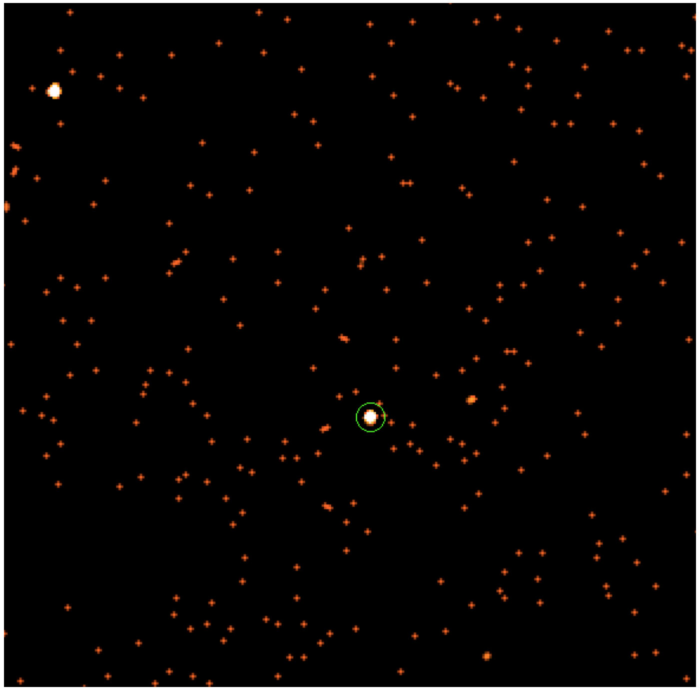
- Quasar-type blazar at z=5.3 with a BH of $>10^9\ M_\odot$
- NuSTAR band is crucial to establish its blazar nature
- For each blazar, there are $2\,\Gamma^2 = 200(\Gamma/10)^2$ analogous radio–loud AGN with their jets directed in random directions => Γ ?
- Requires rapid growth of the most massive black holes at high redshifts

Comparison Chandra-NuSTAR

NuSTAR

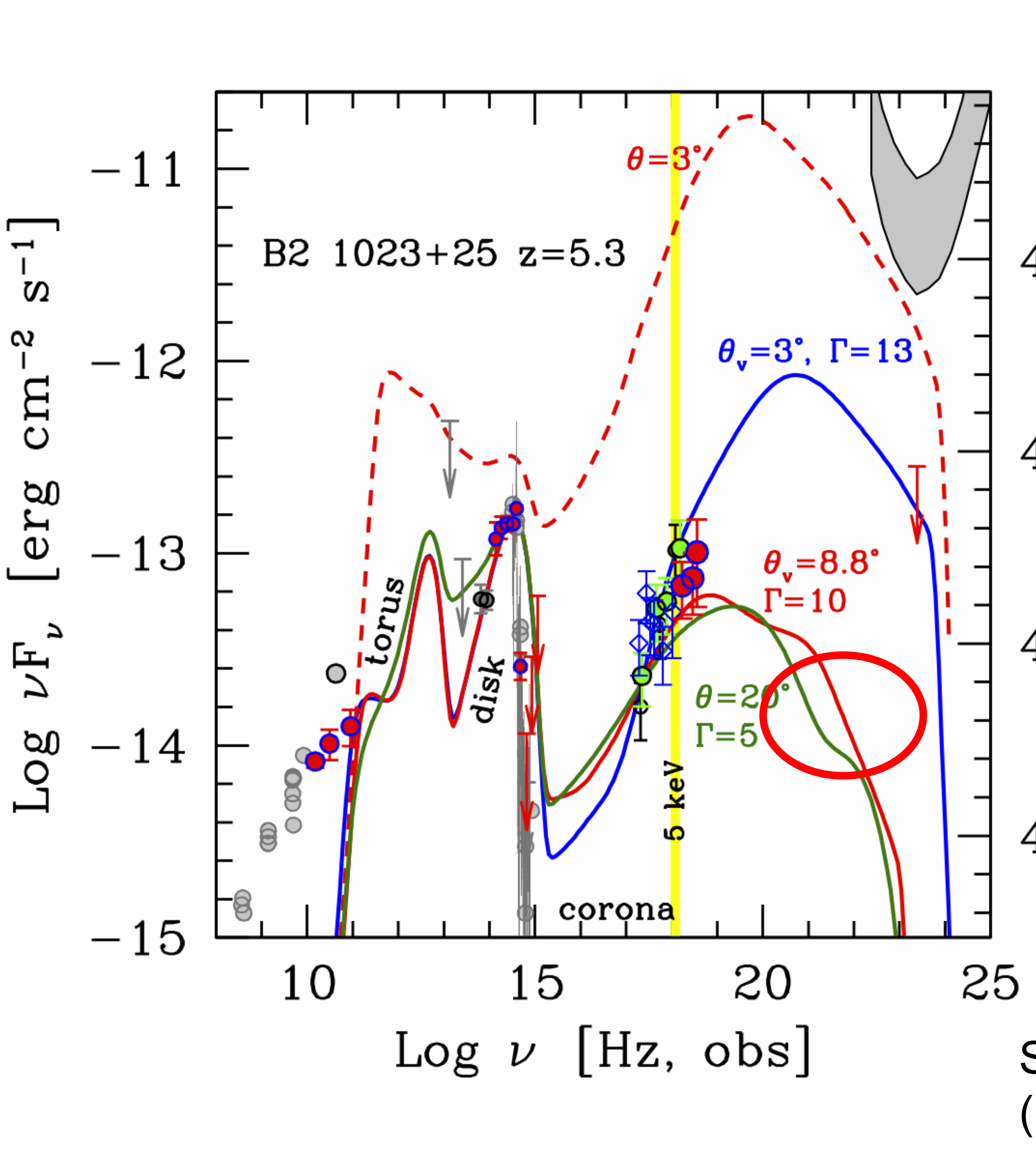
Chandra





Not super-bright, but clearly detected by Chandra in 20 ks, and by NuSTAR in 60 ks in the energy band: 4-24 keV

B2 1023+25: Syn + IC modelling implies Γ ~ 10



Sbaratto et al.
(NuSTAR team) 2013

B2 1023+25: Conclusions

- 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? (Salpeter argument)

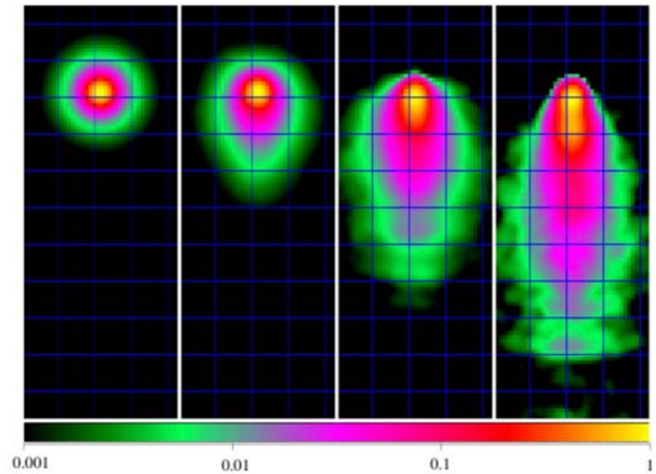
Compelling target: TeV blazar 1ES0229+200

•A unique blazar, TeV emitter with hard TeV spectrum, but v. weak in Fermi (last TeV source detected by Fermi!)

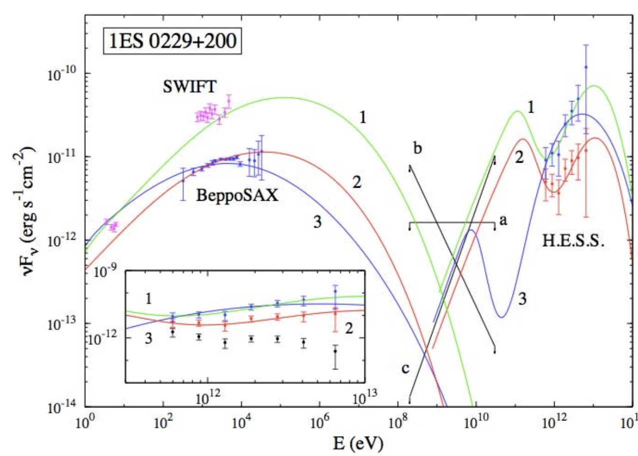
* Interesting model explaining the spectrum:
  - Peculiar γ-ray spectrum due to pair production of γ-rays against intergalactic IR
  - Resulting pairs deflected by the intergalactic magnetic field Results in some angular spread of photons – "pair halo"

=> Limits on IG B field (Vovk et al.)

• Variability measurements in gamma-ray band would argue against such model



Neronov et al. 2010



What's next?

"Standard model"

- Synchrotron + SSC In low-L sources

- Synchrotron + ERC in high-L sources

What are the unsolved questions?

Theory:

* Transport to the dissipation region

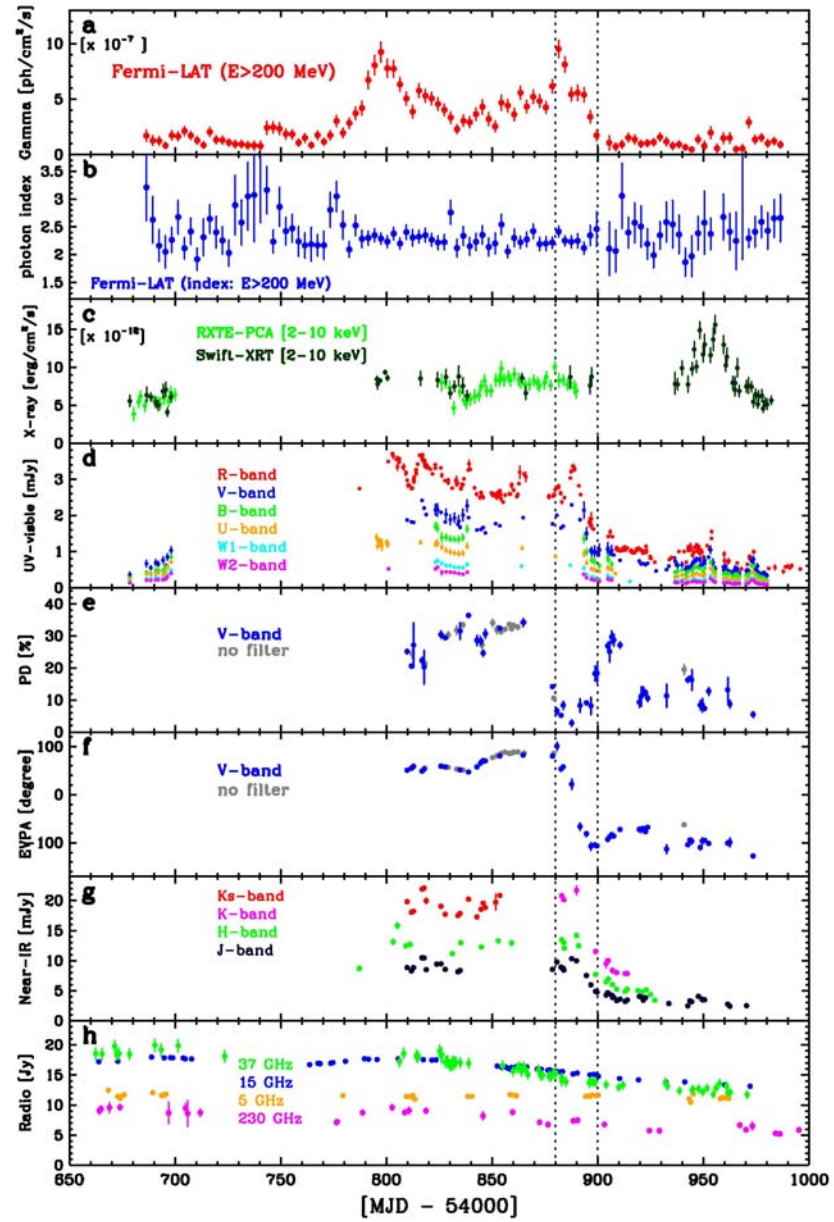
* Collimation / stability of the jet

Phenomenology:

* X-rays in FSRQs still a mystery

* TeV blazars – interactions of γ-rays

Joint multi-band observations essential!



Abdo et al., 2010, Nature;
Hayashida et al. 2012, ApJ