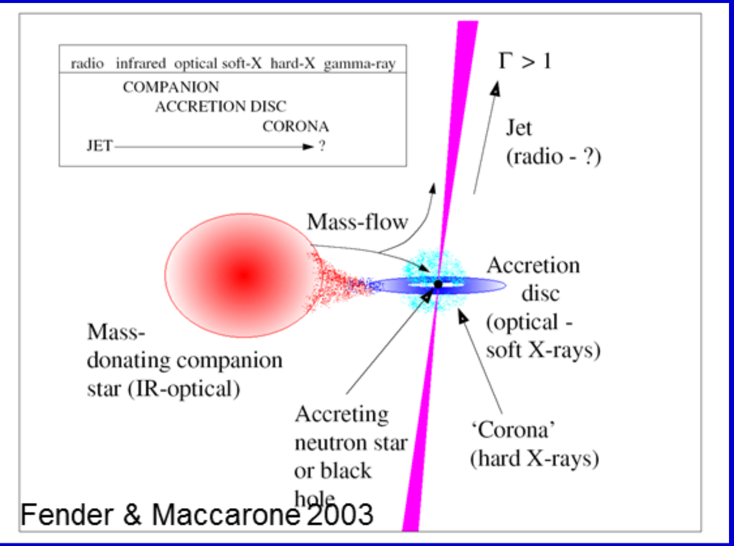
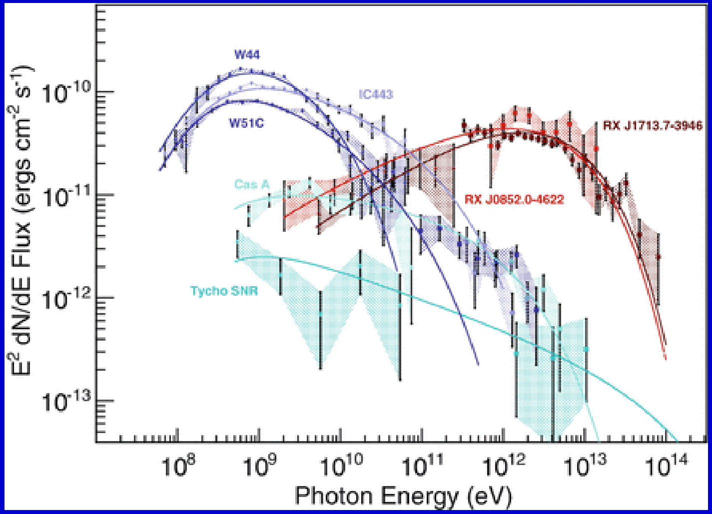
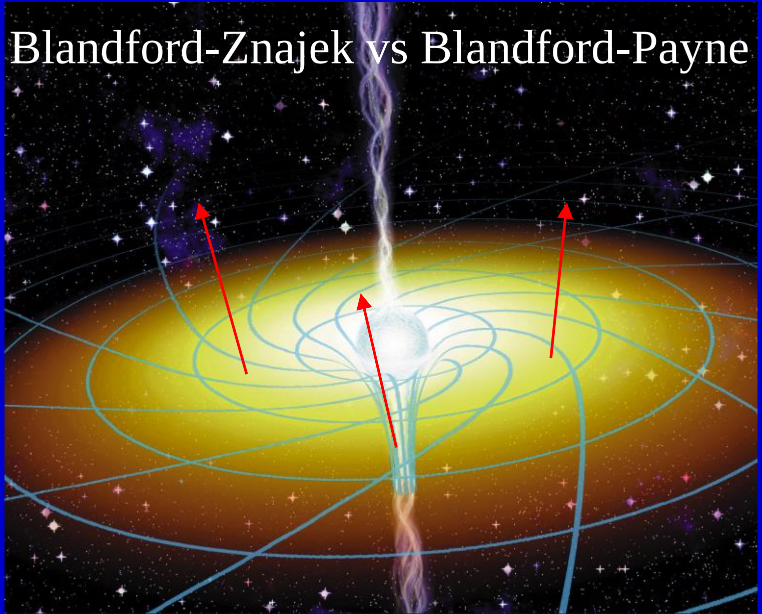
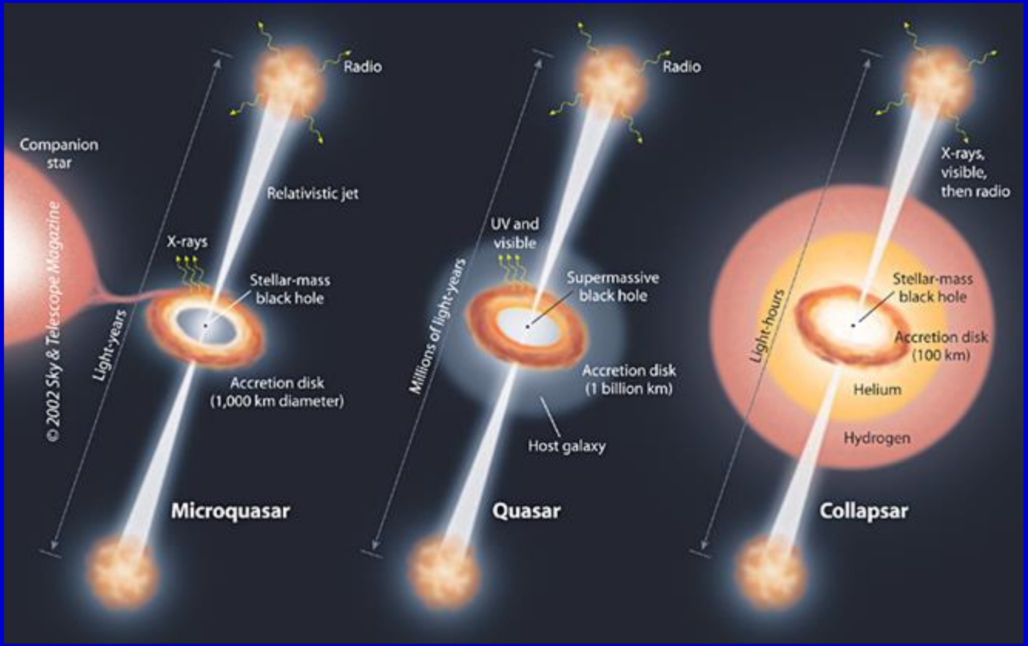
# High-Energy Processes in AGN

P. Coppi, Yale

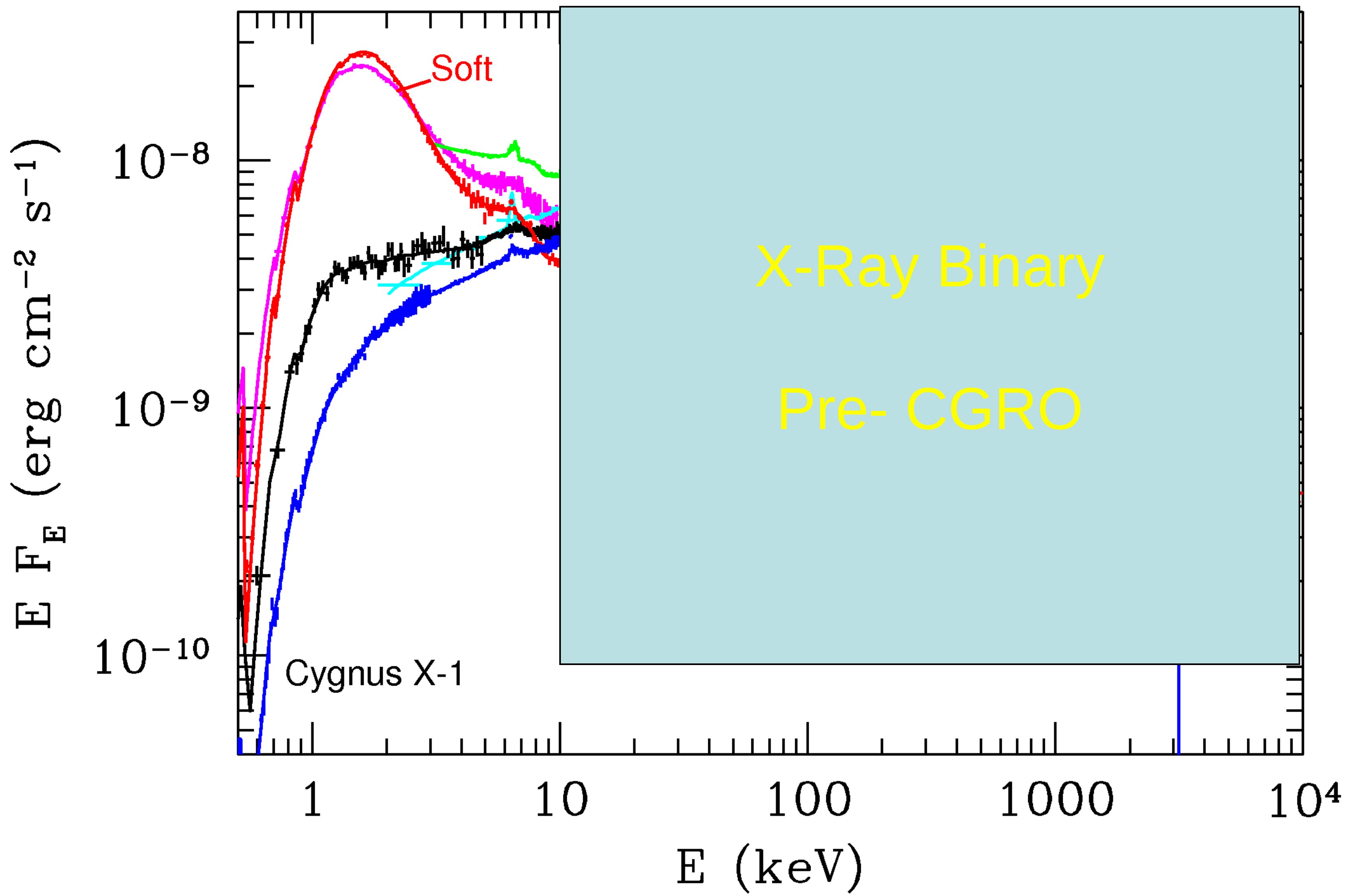


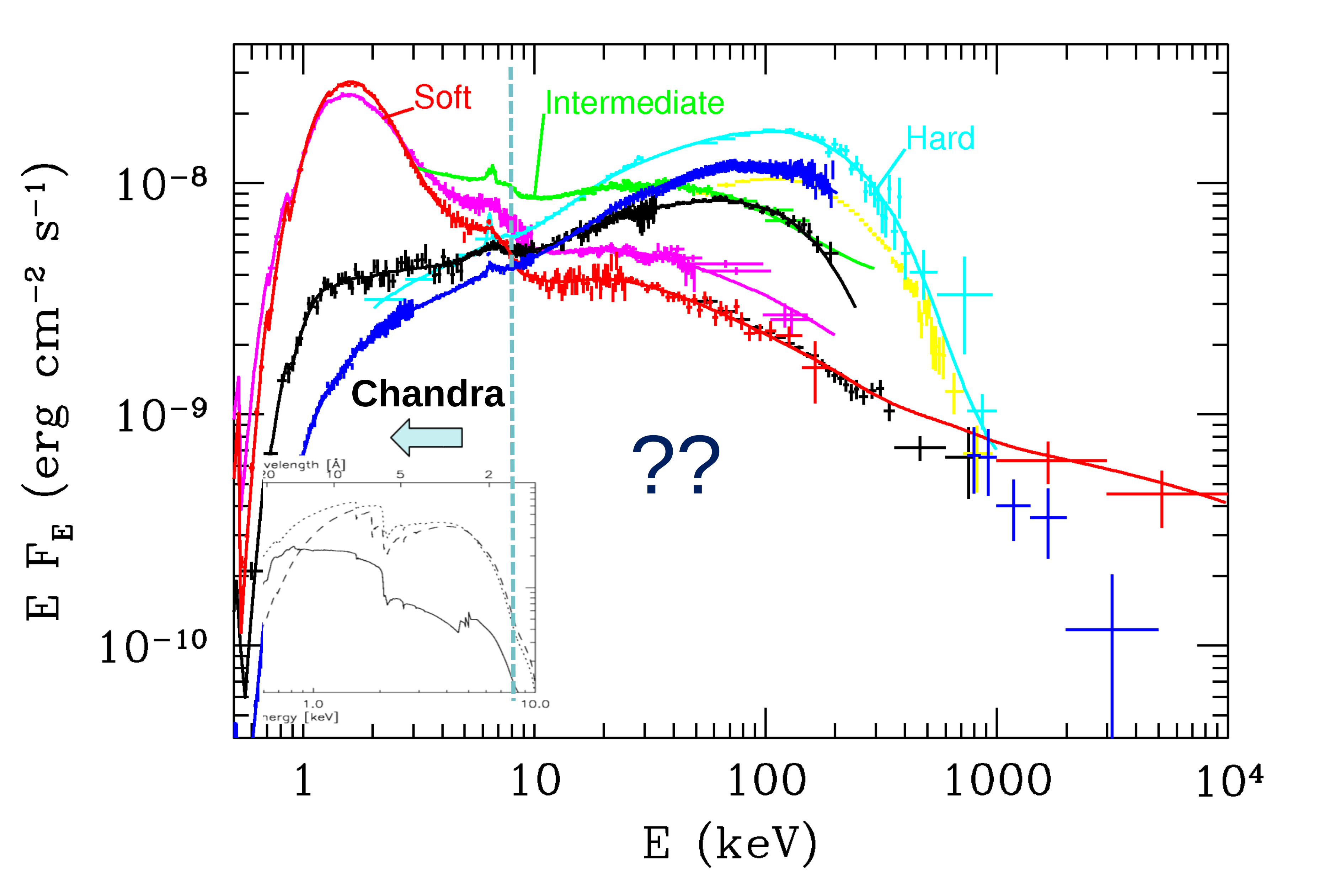



Why (soft) gamma-rays for non-jet AGN? Need broad-band spectra to constrain physics, reprocessing, measure bolometric luminosity, etc…



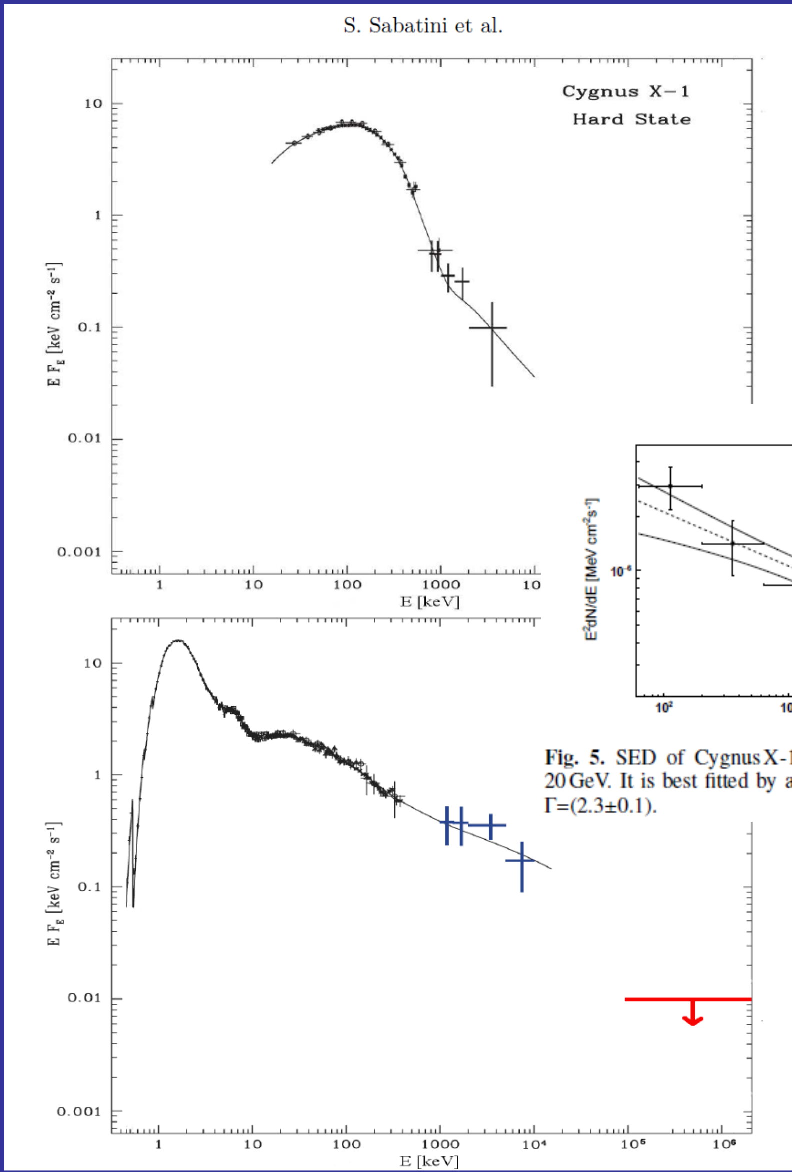

Compilation by A. Zdziarski

# Cygnus X-1  [Spectra of this quality generally do not exist for AGN!]




[Possible AGN spectral “states” not well-sampled]!

# In stellar mass black hole systems, there is HE/VHE emission (!)




**Detection of gamma rays of likely jet origin in Cygnus X-1**


R. Zanin[1], A. Fernández-Barral[2], E. de Oña Wilhelmi[3], F. Aharonian[1,4,5], O. Blanch[2], V. Bosch-Ramon[6], and D. Galindo[6]

*(Affiliations can be found after the references)*


September 21, 2021

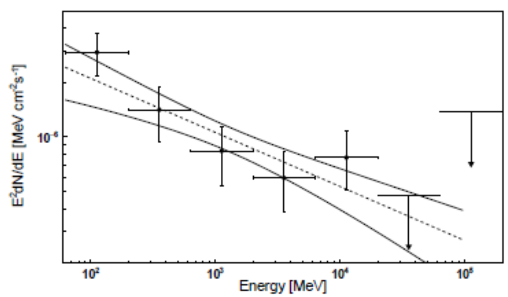
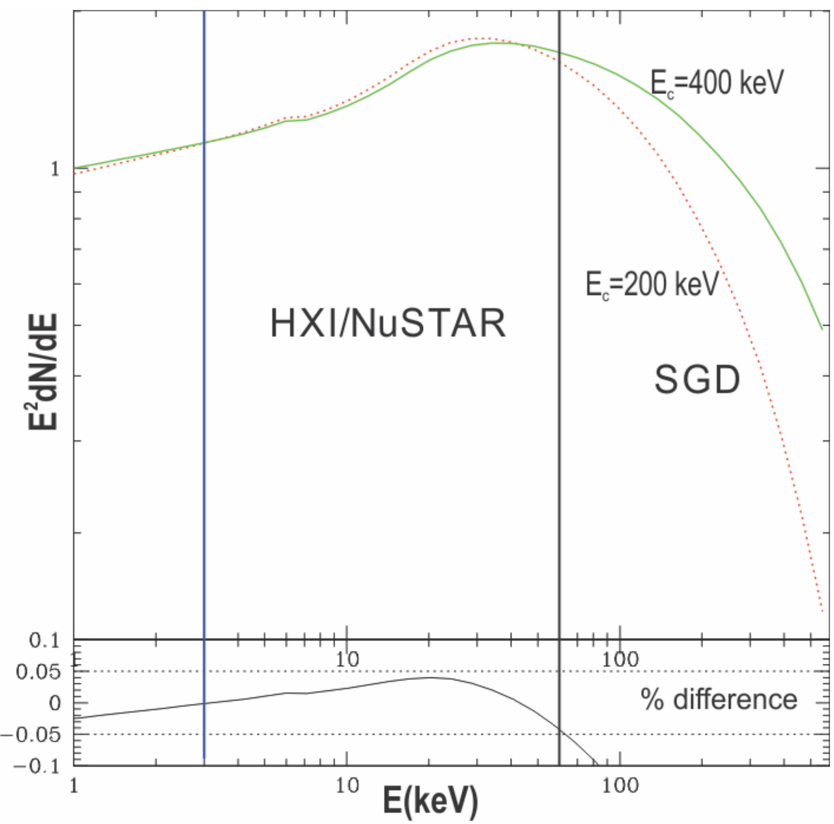



**Fig. 5.** SED of Cygnus X-1 in the HS, extending from 60 MeV to 20 GeV. It is best fitted by a power-law function with a photon index $\Gamma=(2.3\pm0.1)$.

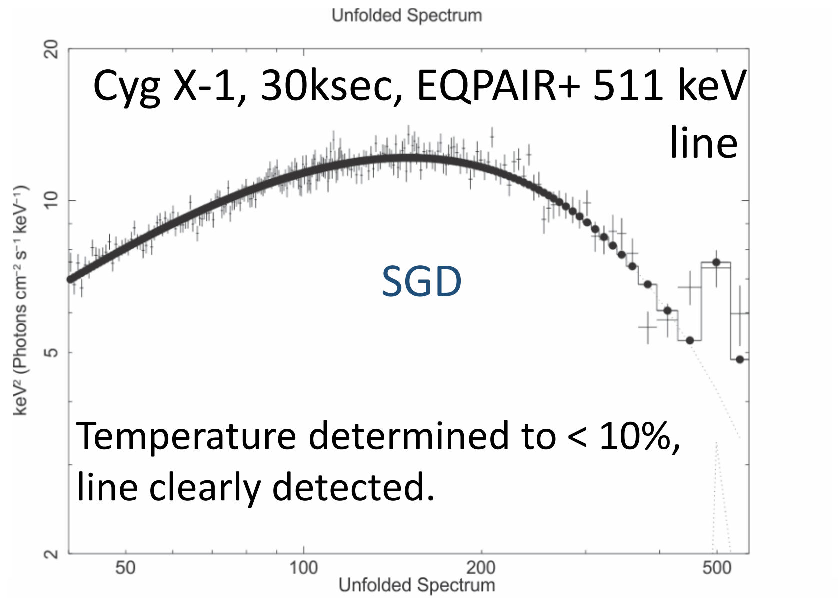
Some may be from extendend jet, but some could be from "corona" (base of jet). Cyg X-1 is not really microquasar
(bulk Lorentz factor of jet < 2, no huge jet outbursts like Cyg X-3, GRS 1915)

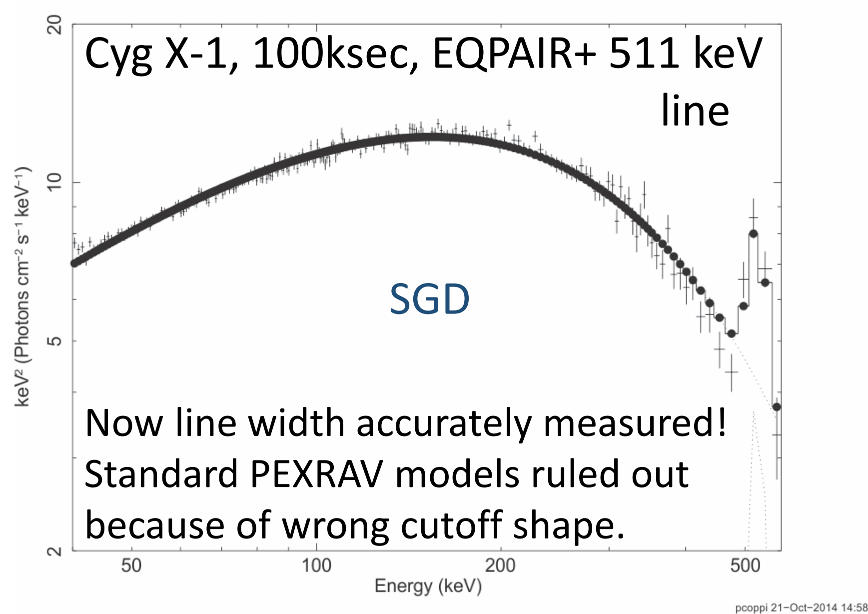
Same for AGN? [~3C273 level emission o.k. for EGRB]

# The high-energy break in the hard state of Cyg X-1: Another example of how the SGD/ASTRO-H comes into its own for brighter sources (>$10^{-10}$ erg cm$^{2}$ s$^{-1}$), e.g., enabling science that cannot be done by NuSTAR alone.

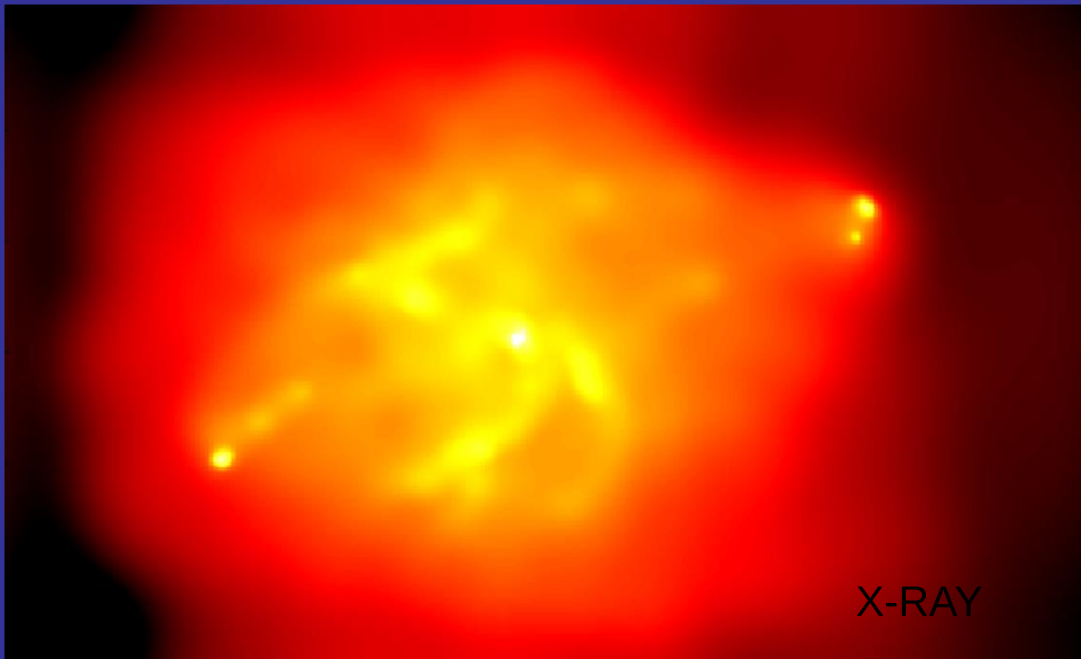



Even with sensitivity to ~60 keV, i.e., past the peak of the Compton reflection hump, modeling degeneracies remain for NuSTAR/HXI alone. Above, the temperature of the Comptonizing electrons cannot be constrained to better than a factor 2.

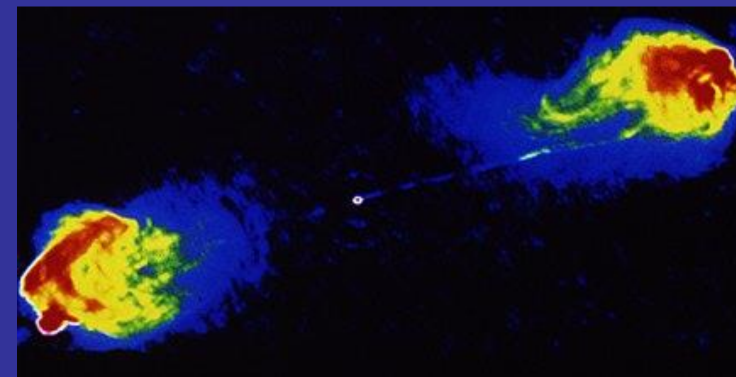


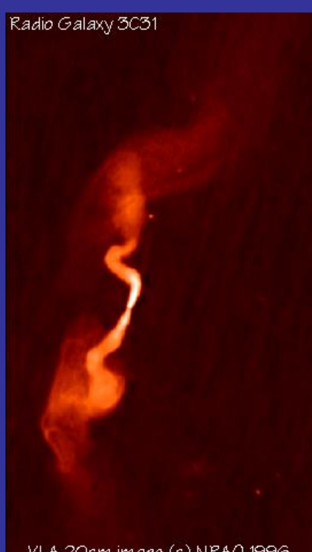



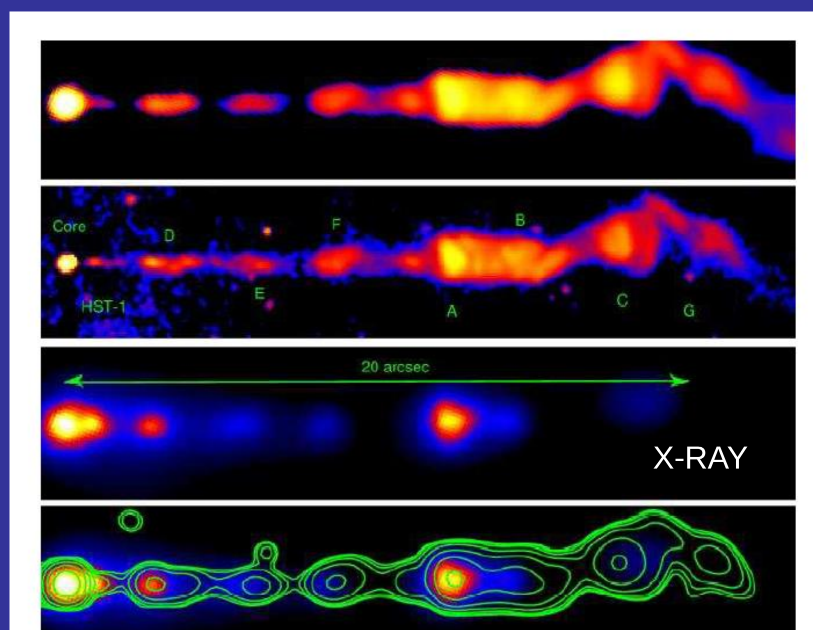
# Extended X-Ray Emission from Jets!! – Potential GeV/TeV Sources!



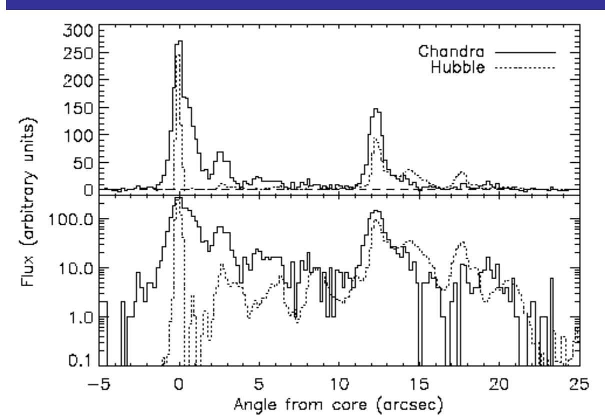

Cygnus A - FRII (powerful jet?)

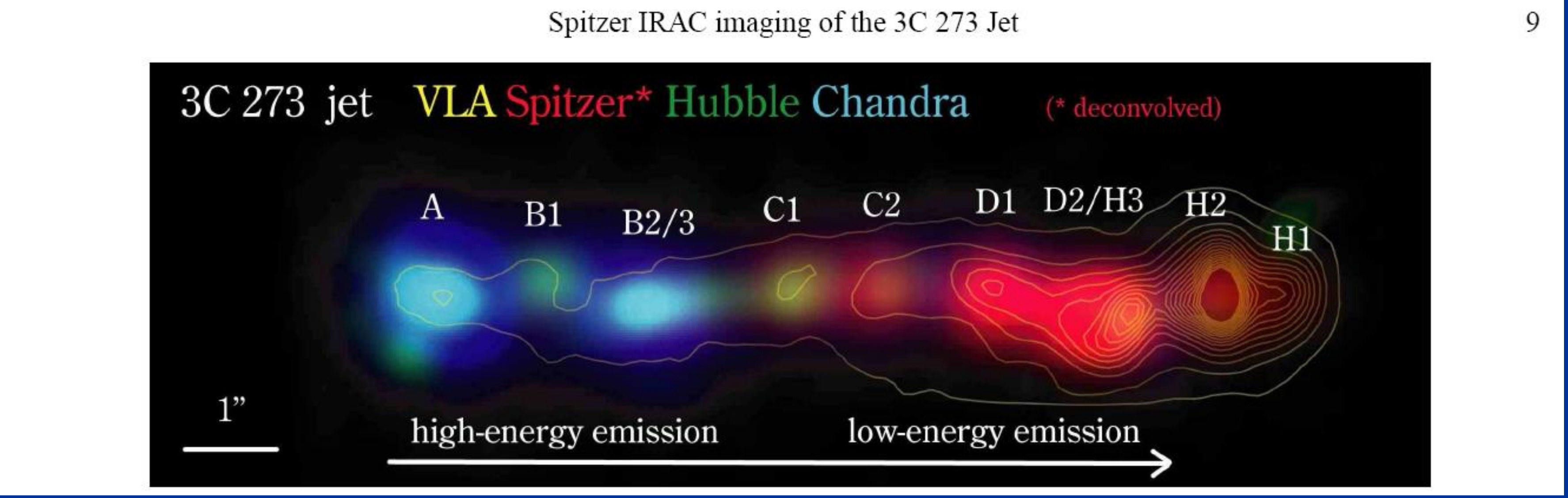


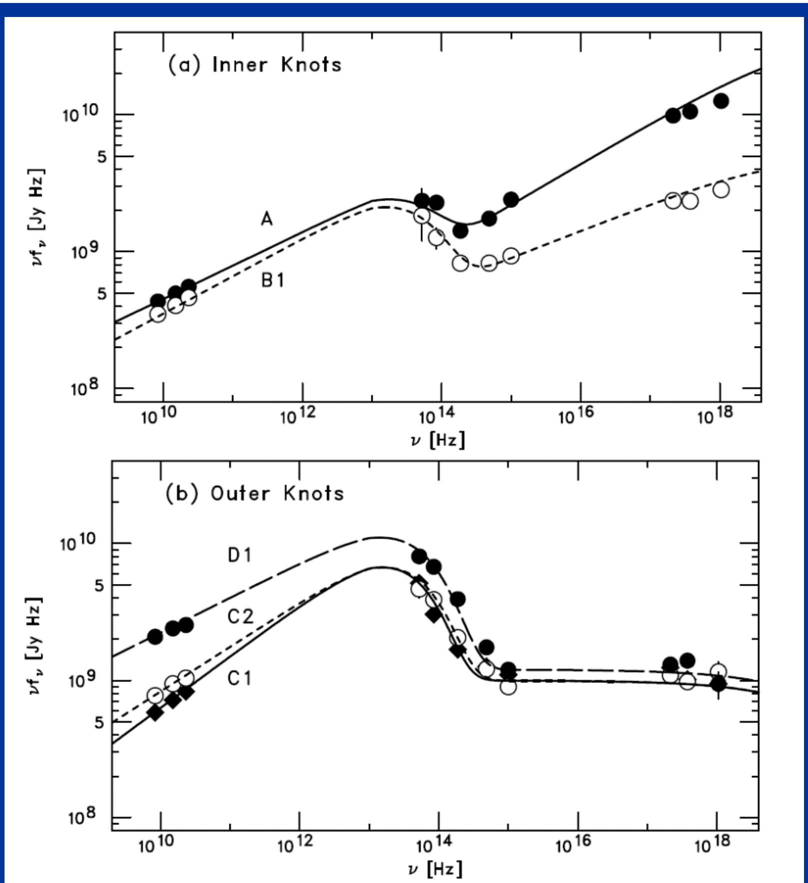



M87 – FRI (weak jet)





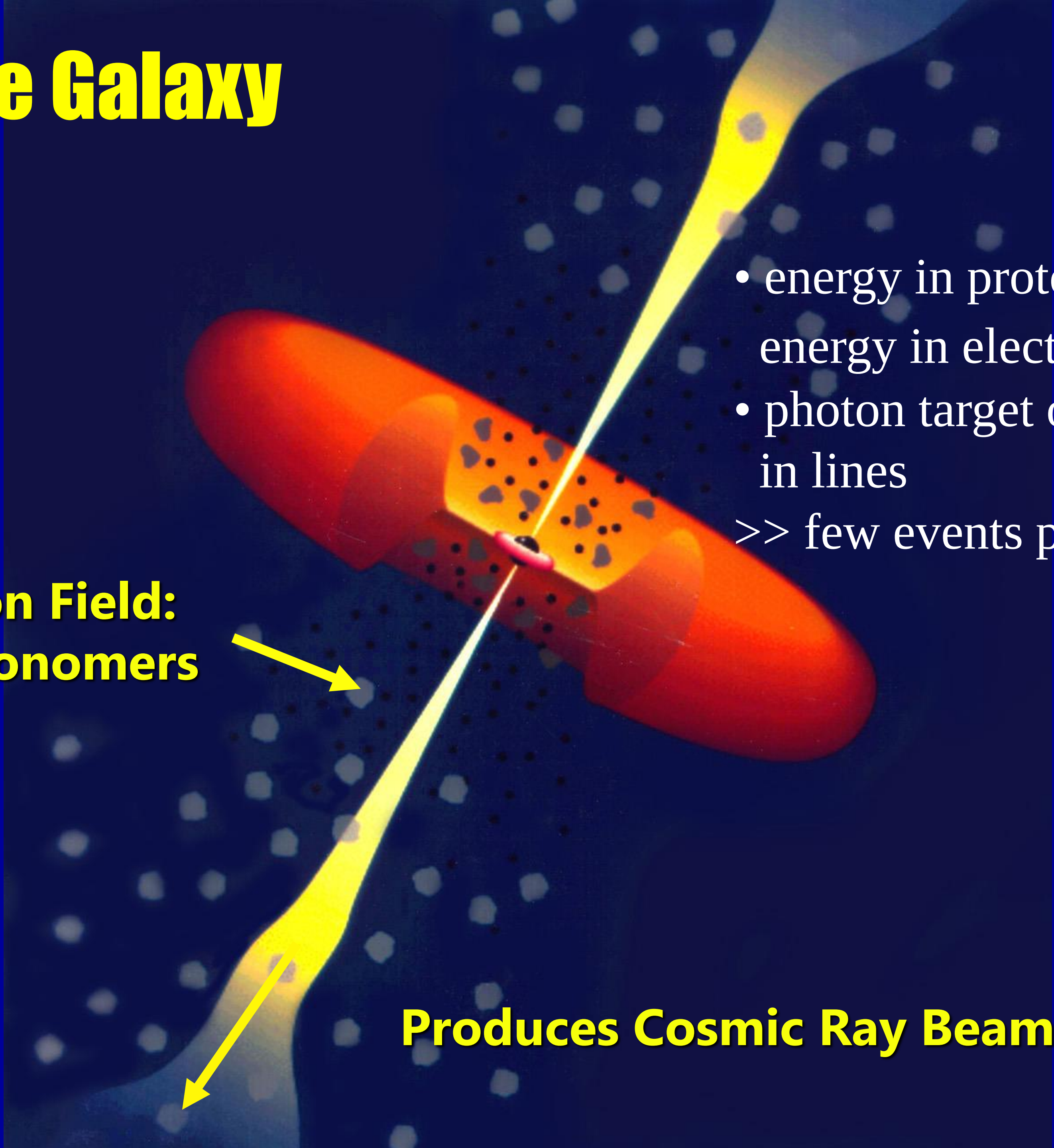




Two components!

Optical polarized
⇒Synchrotron
⇒ TeV+ electrons!

Uchiyama et al. 2007

# Active Galaxy



- energy in protons ~ energy in electrons [??]
- photon target observed in lines

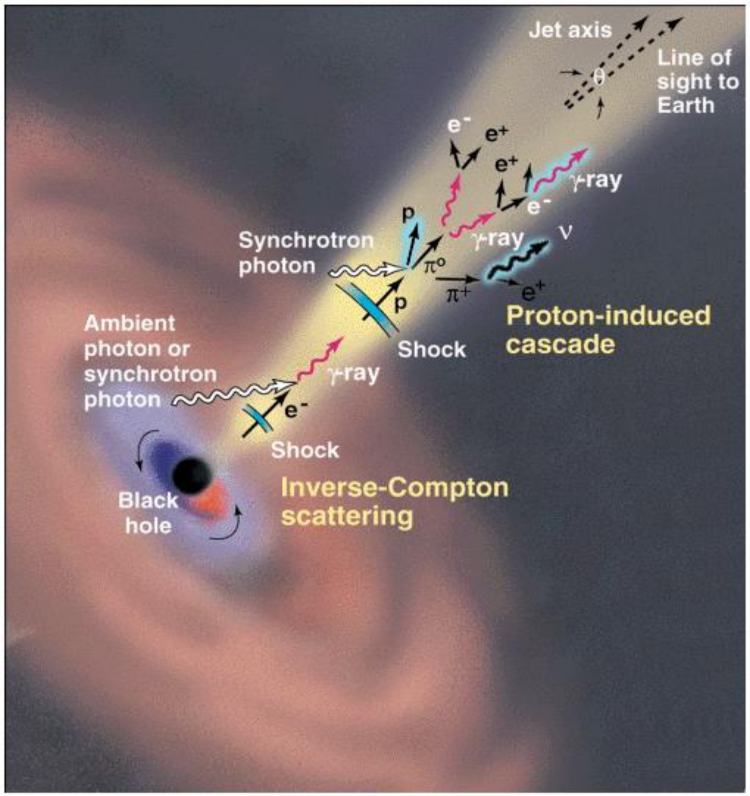
>> few events per year km$^2$

**Radiation Field: Ask Astronomers**

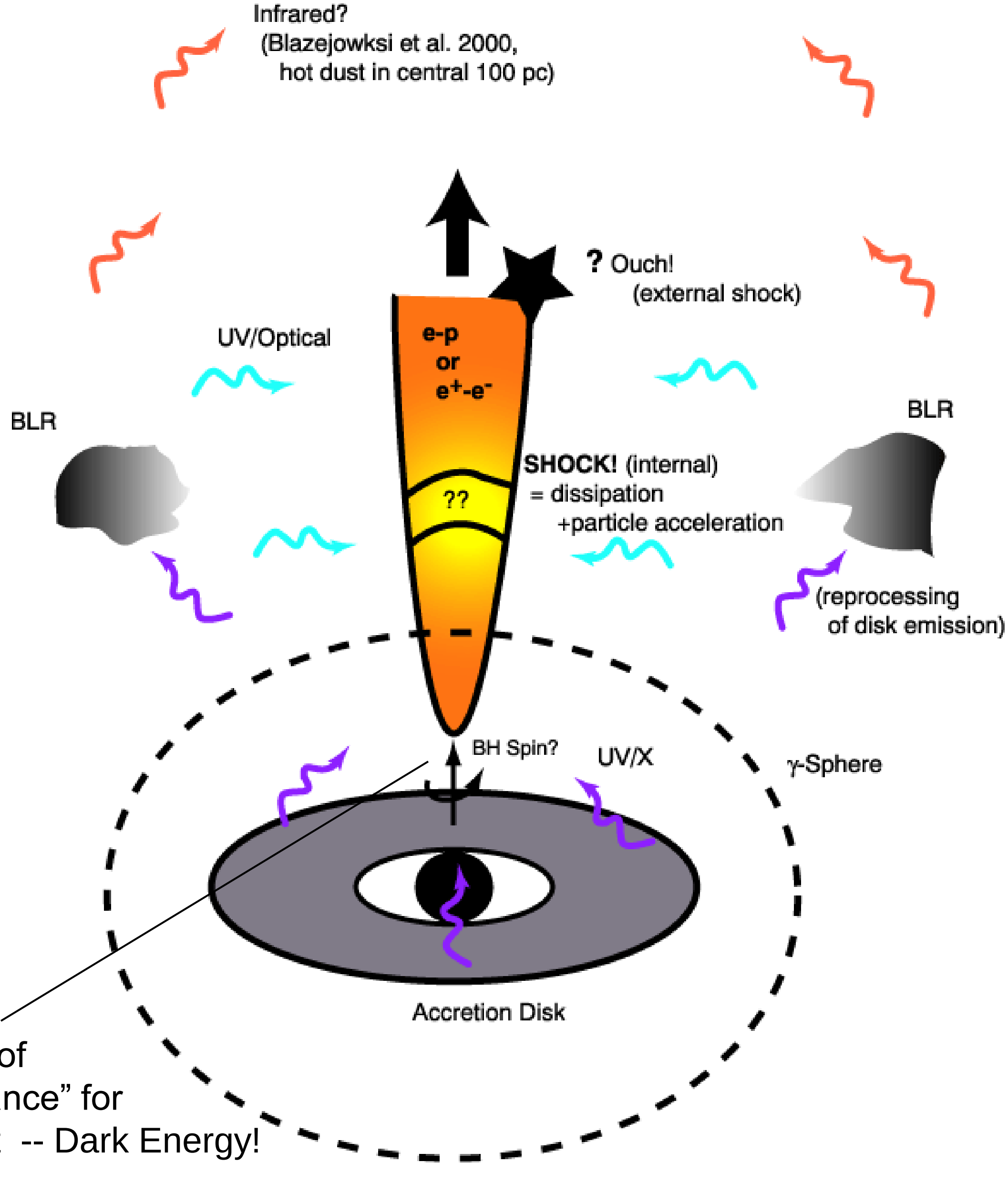
**Produces Cosmic Ray Beam?**

F. Halzen, 2004

# Blazar Emission Mechanisms: Idealized vs. Real Life




(Buckley, Science, 1998)

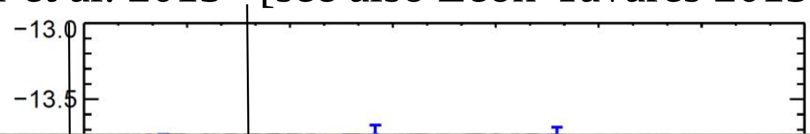



The central engine of a generic gamma-ray blazar is a MESSY place!

# Disk-Jet Connection?

Time Resolved BLR Behavior of 3C 454.3 7

Isler et al. 2013 [see also Leon-Tavares 2013]



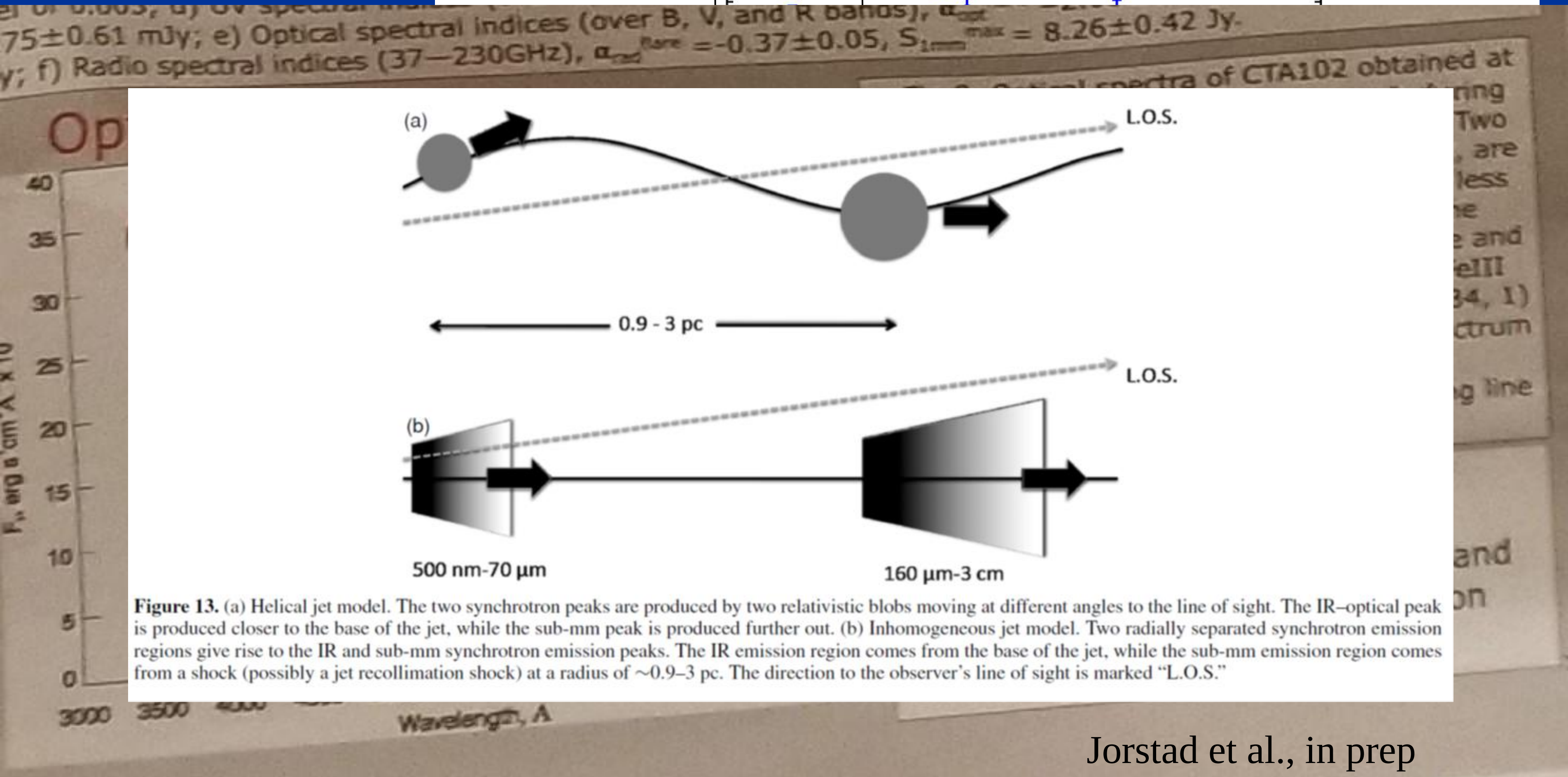



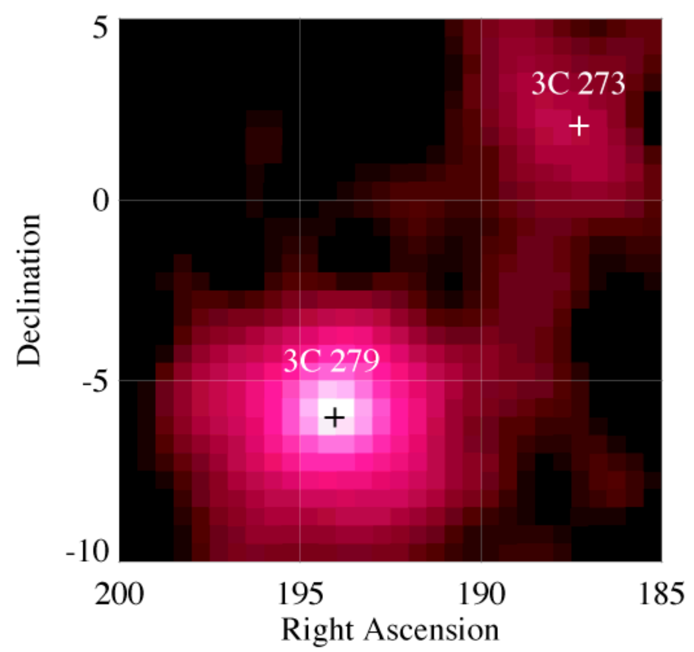

**Figure 13.** (a) Helical jet model. The two synchrotron peaks are produced by two relativistic blobs moving at different angles to the line of sight. The IR–optical peak is produced closer to the base of the jet, while the sub-mm peak is produced further out. (b) Inhomogeneous jet model. Two radially separated synchrotron emission regions give rise to the IR and sub-mm synchrotron emission peaks. The IR emission region comes from the base of the jet, while the sub-mm emission region comes from a shock (possibly a jet recollimation shock) at a radius of ∼0.9–3 pc. The direction to the observer's line of sight is marked "L.O.S."

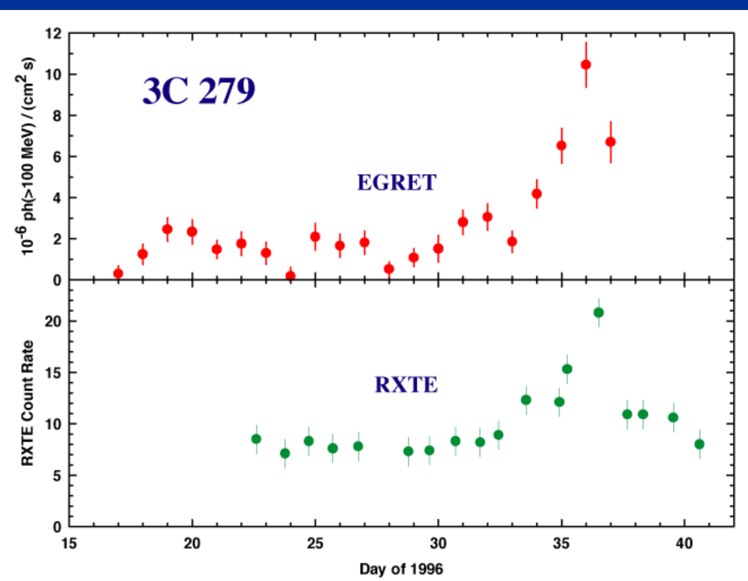
Jorstad et al., in prep

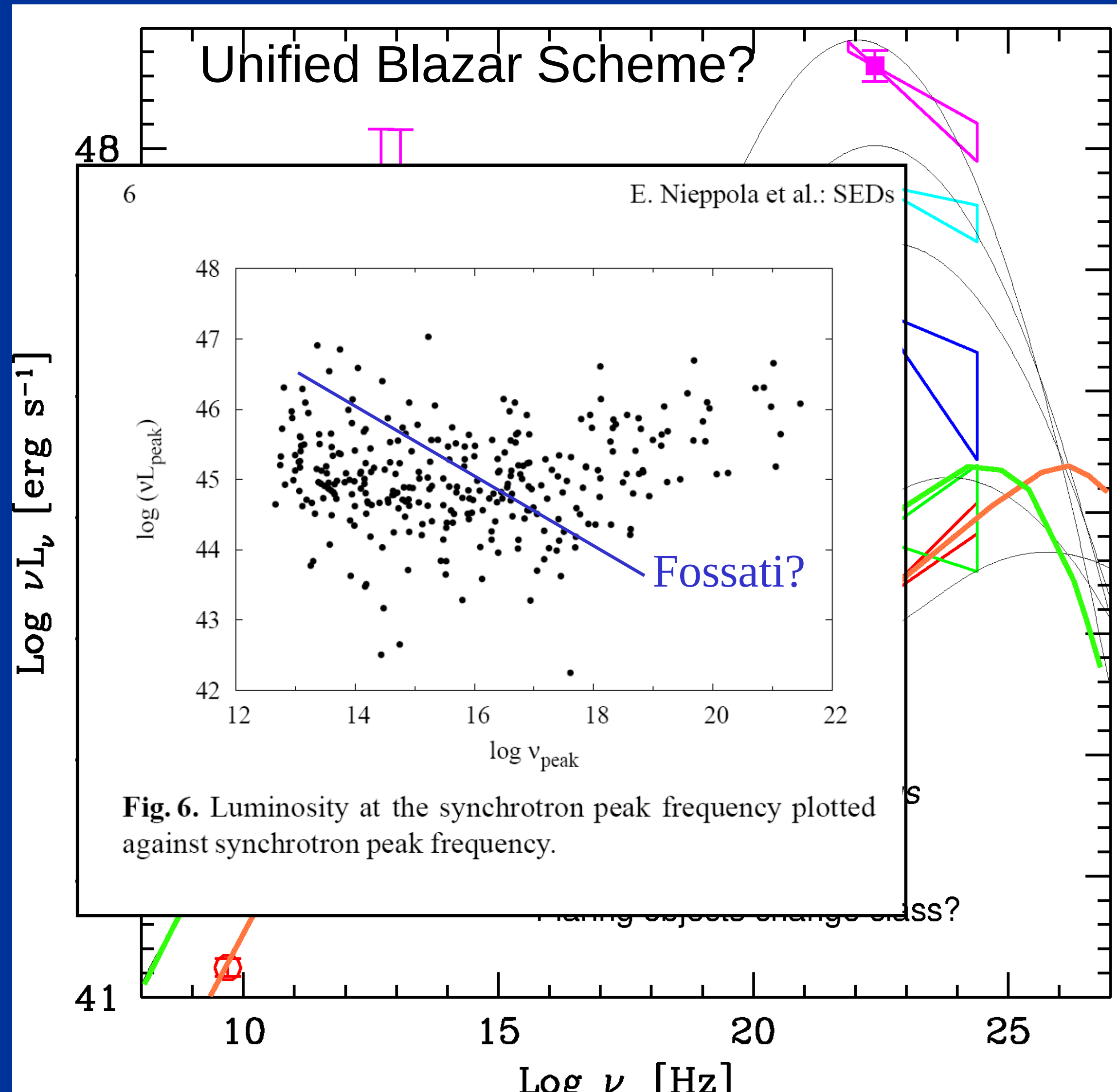
# Central Engine vs. Jet?

FIG. 4.— Broad emission line flux light curves for Mg II (blue circles), H$\beta$ (cyan squares) and H$\gamma$ (purple stars). The bottom panel shows the *Fermi* $\gamma$-ray light curve (TS >25) for the same MJD (filled diamonds) and over the total observed interval (grey points). The average flux of each emission line is represented by the dashed lines and 2$\sigma$ deviations are marked by dot-dashed lines. Over the 3.3 years of observation, the line fluxes deviate by more than 2$\sigma$ above the mean only on MJD 55165 and 55518 in Mg II and H$\gamma$. This lack of strong detectable variability in the line emission is in stark contrast to the factor of nearly 100 variations in gamma-ray flux over the same time period, as seen in the bottom panel. However, the highest $\gamma$-ray flare phases (MJD 55167 and 55520) correspond to the greatest deviation in the H$\gamma$ and Mg II line fluxes. The rise and fall of the H$\gamma$ line flux, in particular, appears to trace the rise and fall of the $\gamma$-ray flux. Both epochs during which the H$\gamma$ and Mg II emission lines deviate from the mean are also coincident with 7mm core ejections (Jorstad et al. 2012).

# CGRO/EGRET and the "GeV" Blazars




Donato et al. 2002,
Fossati et al. 1998

## Bla:

## a blazar sequence??

Lee et al., U Wash.

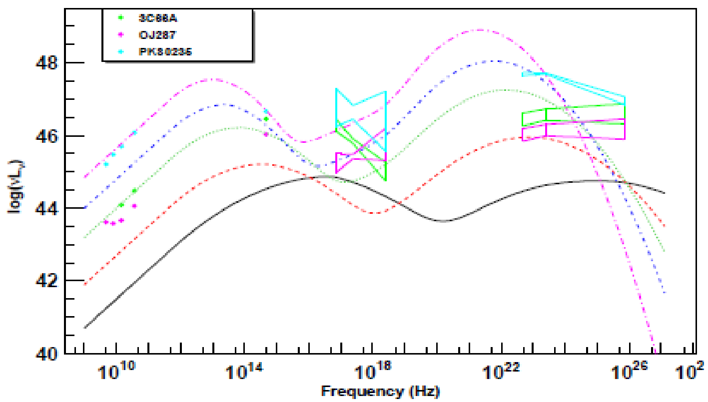
?

### Model Parameters

| | $B$ [G] | $\delta$ | $R$ [$10^{15}$cm] | $n_e$ [ergs cm$^{-3}$] | $E_{break}$ [log eV] | $E_{max}$ [log eV] |
|---|---|---|---|---|---|---|
| 3C 66A | 0.05 | 50 | 28 | 0.03 | 9.8 | 10.8 |
| 0235+164 | 0.05 | 50 | 58 | 0.04 | 9.3 | 10.8 |
| OJ 287 | 0.05 | 50 | 16 | 0.1 | 9.5 | 10.8 |
| 3C 273 | 0.05 | 50 | 16 | 0.6 | 8.8 | 9.7 |
| 3C 279 | 0.05 | 50 | 2.8 | 15 | 9.4 | 10 |
| 1502+106 | 0.05 | 50 | 13 | 0.9 | 10 | 10 |
| 1510-089 | 0.05 | 50 | 2.5 | 15 | 9.7 | 9.8 |
| 3C 454.3 | 0.05 | 50 | 11 | 5 | 9.3 | 9.8 |

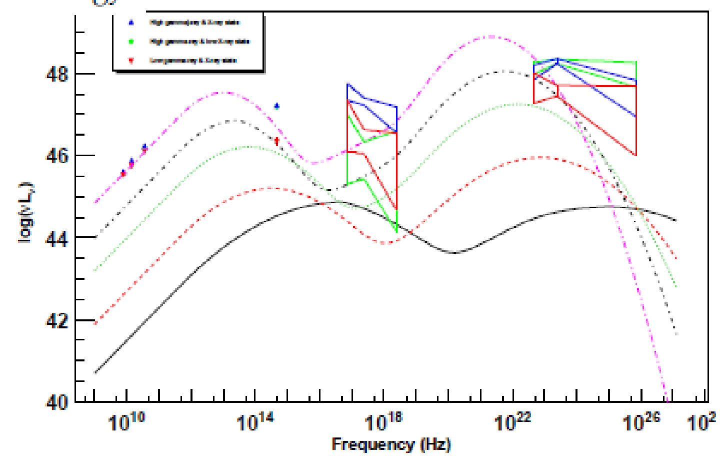
$B$: magnetic field; $\delta$: Doppler factor; $R$: radius of the emission region; $n_e$: electron energy density; $E_{break}$: break energy; $E_{max}$: maximum energy

The time-av… the blazar s… while some …



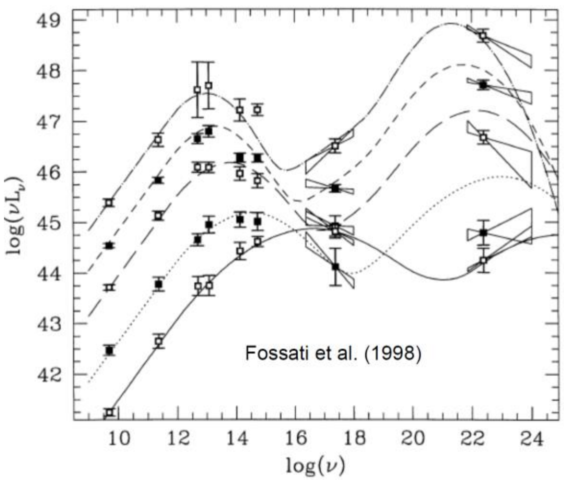

The time-averaged SEDs of the three BL Lac sources are superimposed on the blazar sequence. The three BL Lac sources do not fit well into the blazar sequence. The observed low energy component extends to X-ray energies.

## )ifferent Gamma-ray and X-ray Emission States



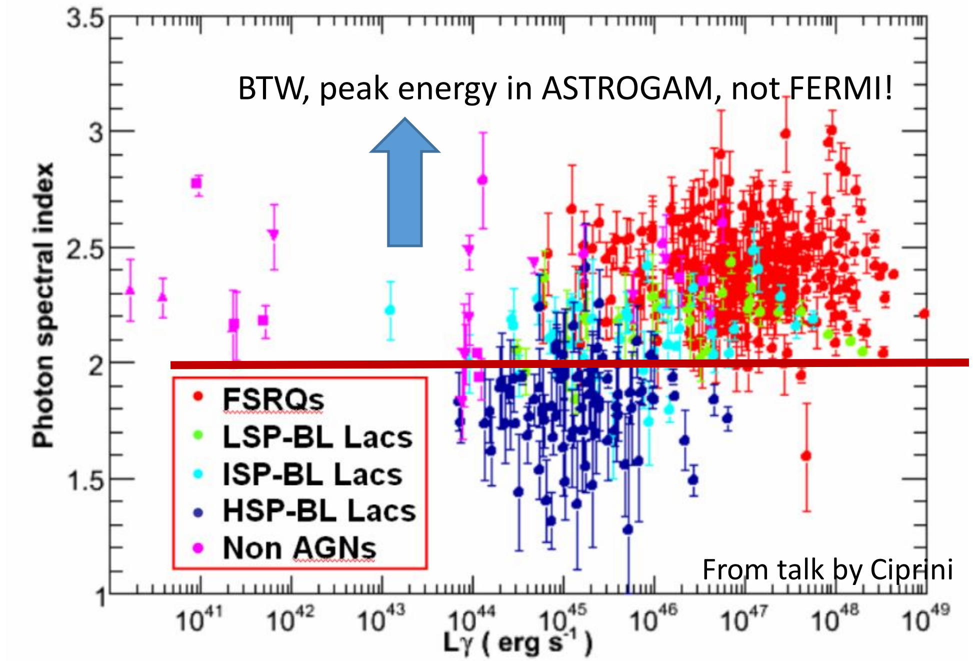

The SEDs of PKS 0235+164 in three different gamma-ray and X-ray emission states are superimposed on the blazar sequence. The variability is more pronounced at X-rays than at gamma-rays, and the observed gamma-ray energy spectra are harder than expected.

Blazar Sequence ??




The Fossati (yes) vs.
Giommi-Padovani (no!) controversy:

Best guess answer – sort of, but huge scatter and overlap of classes?

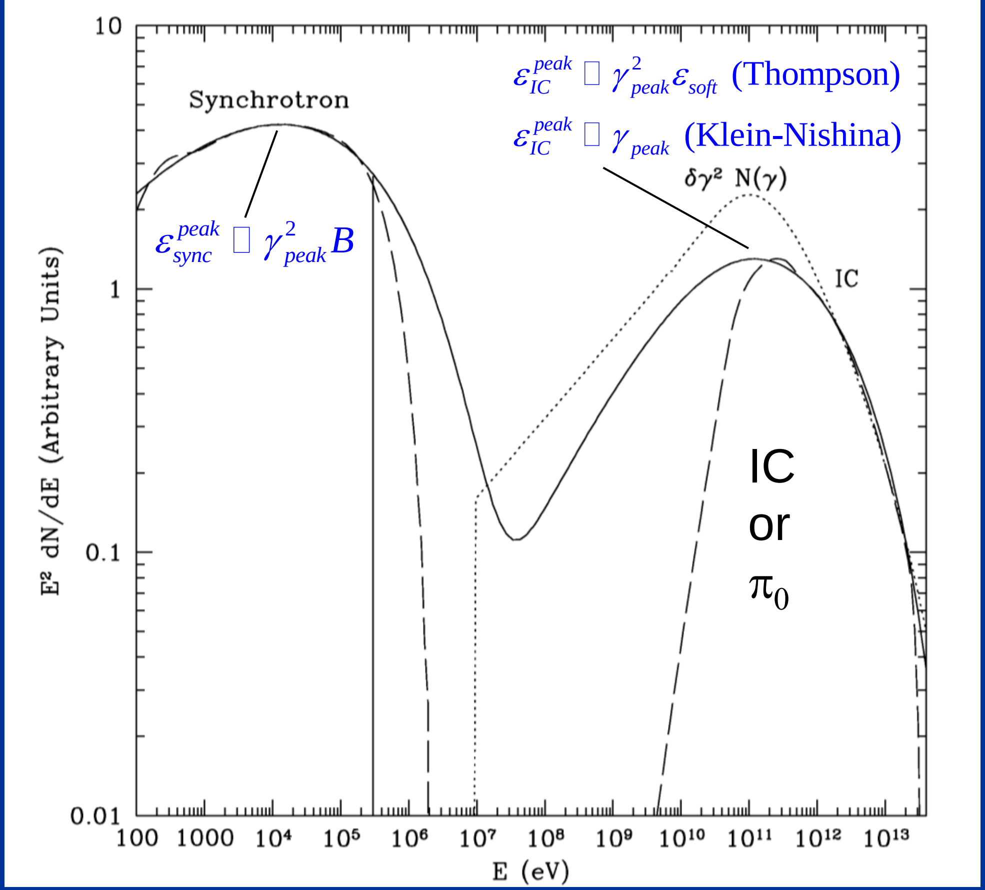



In real life, individual objects change peak energy/class! (E.g., 3C279, next slide)

# VHE Astrophysics I.
# A Generic Source ….

## Multiwavelength observations very powerful/critical!

E.g., if have synchrotron/IC model $L_{IC}/L_{syn}=U_B/U_{rad}$, constrain B if know $U_{rad}$.
Also, *correlated* IC/synch. spectra!




Process(es) directly responsible for observed X-ray/γ-ray emission?

- Compton scattering $(e\gamma \rightarrow e\gamma)$
- synchrotron radiation $(eB \rightarrow eB\gamma)$

lowest order, most "efficient"

- Bremsstrahlung $(ee \rightarrow ee\gamma, pe \rightarrow pe\gamma)$
- $\pi^0$ decay $(\pi^0 \rightarrow \gamma\gamma)$ — almost always accompanied by $\pi^{\pm} \rightarrow ...e^{\pm}$
- proton synchrotron $(pB \rightarrow pB\gamma)$

# VHE Astrophysics II

O.K. Where do we get required GeV/TeV electrons/pairs/pions?

- Acceleration (bottom-up)

  Direct acceleration by $\vec{E}$ (e.g., pulsar)

  Stochastic shock/wave acceleration (e.g. $1^{st}/2^{nd}$ order Fermi process)

  "leptonic" models

- Creation at desired energies (top-down)

if $p\gamma \to x$ dominates, generically get E.M. cascade (P.I.C.).

$$\left\{\begin{array}{l} p\gamma \to pe^+e^- \\ (p/n)\gamma \to (n/p)\pi^\pm \\ \gamma\gamma \to e^+e^- \\ \gamma e \to ee^+e^- \end{array}\right. \quad ..e^\pm, \nu$$

don't need to be ultrarelativistic, e.g., SNR

or $pp \to pp\pi$

but need large target matter densities

"hadronic" models

Neutrinos: "smoking gun" for hadronic models

Big advantage of hadronic models: protons easier to accelerate to very high energies
Big disadvantage … : protons harder to extract energy from *(INEFFICIENT!)*

# Code units for leptonic source, recap

Good choice allows us to scale code to many environments, keep variables ~ unity (helps with numerical precision), and often let's us quickly do order of magnitude estimates.

Convenient choice: $E' = \text{Energy} = E/m_e c^2$, $T' = \text{Time} = T/(R/c)$,

$L' = \text{Length} = L/(\sigma R)^{1/3}$, $N' = \text{Density} = N(\sigma R) = \tau$

Makes kinetic equations >dimensionless!

$$L_{source,iso} = 4\pi D^2 F_{obs}.$$

$$L_{source} = (Source\ Volume) \times U_{rad} \times (c/R) = (4\pi/3) R^2 c \times U_{rad}$$

$$U_{rad} = \frac{3}{4\pi R^2 c} L_{source}$$

$$N = U_{rad}/(m_e c^2 < \varepsilon >) = \frac{3}{4\pi R^2 m_e c^3 < \varepsilon >} L_{source}$$

$$\tau = N' = (\sigma_T R) N = \frac{3\sigma_T R}{4\pi R^2 m_e c^3 < \varepsilon >} L_{source} = \frac{3\sigma_T}{4\pi m_e c^3 < \varepsilon >} \left(\frac{L_{source}}{R}\right) = \frac{1}{< \varepsilon >} l!$$

# Now let's play some with physics expressed in these units…

Compton Scattering: $\epsilon' = \frac{4}{3}\gamma^2 \epsilon_0, \quad \frac{dn}{dt}_{scat} = \sigma_T c n(\epsilon_0) \rightarrow \frac{d\gamma}{dt} = -\frac{4}{3 m_e c^2}\gamma^2 \sigma_T c(\epsilon_0 n(\epsilon_0))$

$$\frac{dn'}{dt'} = \mathrm{n}'(\epsilon_0'), \quad \frac{d\gamma}{dt'} = -\frac{4}{3}\gamma^2[\epsilon_0' n'(\epsilon_0')]$$

Now integrate over $\epsilon_0'$ (seed target photon distribution):

$$\frac{d\gamma}{dt'}_{total} = -\frac{4}{3}\gamma^2 U'_{rad} = -\frac{4}{3}\gamma^2 \frac{\sigma_T R}{m_e c^2}\left(\frac{3}{4\pi R^2 c}\right) L_{seed} = -\frac{4}{3}\gamma^2 l_{seed}\,!$$

And characteristic electron energy loss time is

$$t'_{cool,C} = \frac{\gamma}{\left|\frac{d\gamma}{dt'}\right|} = \frac{3}{4}\gamma^{-1} l^{-1}_{seed}$$

Synchrotron Losses: $\frac{d\gamma}{dt} = -\frac{4}{3 m_e c^2}\gamma^2 \sigma_T c U_B$ where $U_B = \frac{B^2}{8\pi}$

$$\rightarrow \frac{d\gamma}{dt'} = -\frac{4}{3}\gamma^2\left(\frac{\sigma_T R}{8\pi m_e c^2} B^2\right) = -\frac{4}{3}\gamma^2 l_B,$$

$$t'_{cool,S} = \frac{\gamma}{\left|\frac{d\gamma}{dt'}\right|} = \frac{3}{4}\gamma^{-1} l^{-1}_{B}$$

Coulumb losses suffered by high-energy electron scattering of low-energy (Maxwellian) electrons:

$$t'_{exch} = \frac{\gamma}{\left|\frac{d\gamma}{dt'}\right|_{Coul}} = \frac{\gamma}{\tau_{T,Max}\ln\Lambda}$$

Now, some simple inferences:

What's another reason "hybrid" plasmas may be important for "compact" (:-)) sources?

$t'_{cool} \propto \gamma^{-1}$ while $t_{exch} \propto \gamma \;\Rightarrow\;$ for $\gamma > \gamma_{th} = (\pi \ln\Lambda \dfrac{\tau_{T,Max}}{l_{seed,B}})^{1/2}$ electrons lose energy to photons

before can share it with Maxwellian electrons, stay in non-thermal tail!

For AGN/GBHC, $\tau_T \sim 1,\; l_{seed} \square\, 10,\;\; \ln\Lambda \square\, 20,$ so $\gamma_{th}\; 2...$

Now, let's say source/electrons are unconfined and after R/c source or electrons are gone:

If $t'_{cool} << 1,$ electrons radiate effectively (lose most of energy in time); If $t'_{cool} > 1,$ don't.

Assuming $t'_{cool} << 1,$ what is ratio of Compton to synchrotron power of the source (ratio of two "humps")?

$$\frac{L_c}{L_S} = \frac{U_{rad}}{U_B} = \frac{t'_{cool,S}}{t'_{cool,C}} = \frac{l_{seed}}{l_B}!$$

Now I'm trying to model an *observed* blazar and want to know effect of changing source size R ...

Well, $l_{seed} \propto R^{-1},\; l_B \propto R,$ so $\dfrac{L_c}{L_S} \propto R^{-2}$ ... done, very sensitive to R (as we will see is $L_{SSC}$).

# Theoretical Considerations [Complications] III.

If electrons/pairs are primary particles, what is acceleration energy spectrum?

$$\frac{dN}{dE} \propto E^{-\alpha} \ ?$$

$$E_{\max} \ ?$$

$$E_{\min} / E_{peak} \ ?$$

(or just $t_{\rm cool}$ vs. $t_{\rm escape/expansion}$)

If they are instead secondary particles, similar considerations for primary protons ….
(relativistic e/p behave in same way for given energy)

Good questions!!

Relativistic shock theory $\Rightarrow \alpha$ 2, but $\exists$ range (1.7-2.4),
depends on details like pitch angle diffusion ... (messy).

$$E_{\max} = f(B, R_{shock}, t_{cool})$$

e.g., if particle too energetic, $r_g > R_{shock}$ and particle escapes
often before get to this, though,

$$t_{accel} \sim r_g / c \sim t_{cool} \propto E^2 B^2 \text{(synch. radn.)}$$

(Bohm limit, $r_g = eB/mc$)

Maybe $\alpha$ reaches asymptotic value during strong flare,
but would not be surprising to see $E_{\max}$ vary
as source region varies....

# Theoretical Considerations [Complications] IV.

## Is the observed high energy cutoff in some objects intrinsic or simply due to photon-photon pair production (inside source or intergalactic)?

Depends on ambient radiation field, but for 3C279

$\gamma$-sphere: $r_{\mathrm{emission}} \lesssim 100\, R_g$ ($\sim 10^{15}$ cm), $\tau_{\gamma\gamma} > 1$ for E $\gtrsim$ 10 MeV

$r_{\mathrm{emission}} \lesssim 10^{17}$ cm (BLR), $\tau_{\gamma\gamma} > 1$ for E $\gtrsim$ 50 GeV

$r_{\mathrm{emission}} \lesssim$ parsecs (dust torus), $\tau_{\gamma\gamma} > 1$ for E $\gtrsim$ 1 TeV

[N.B. Estimates don't apply to Mrk 421/501 -- BL Lacs appear to have weak central radiation fields. Accretion disk underluminous for black hole mass]

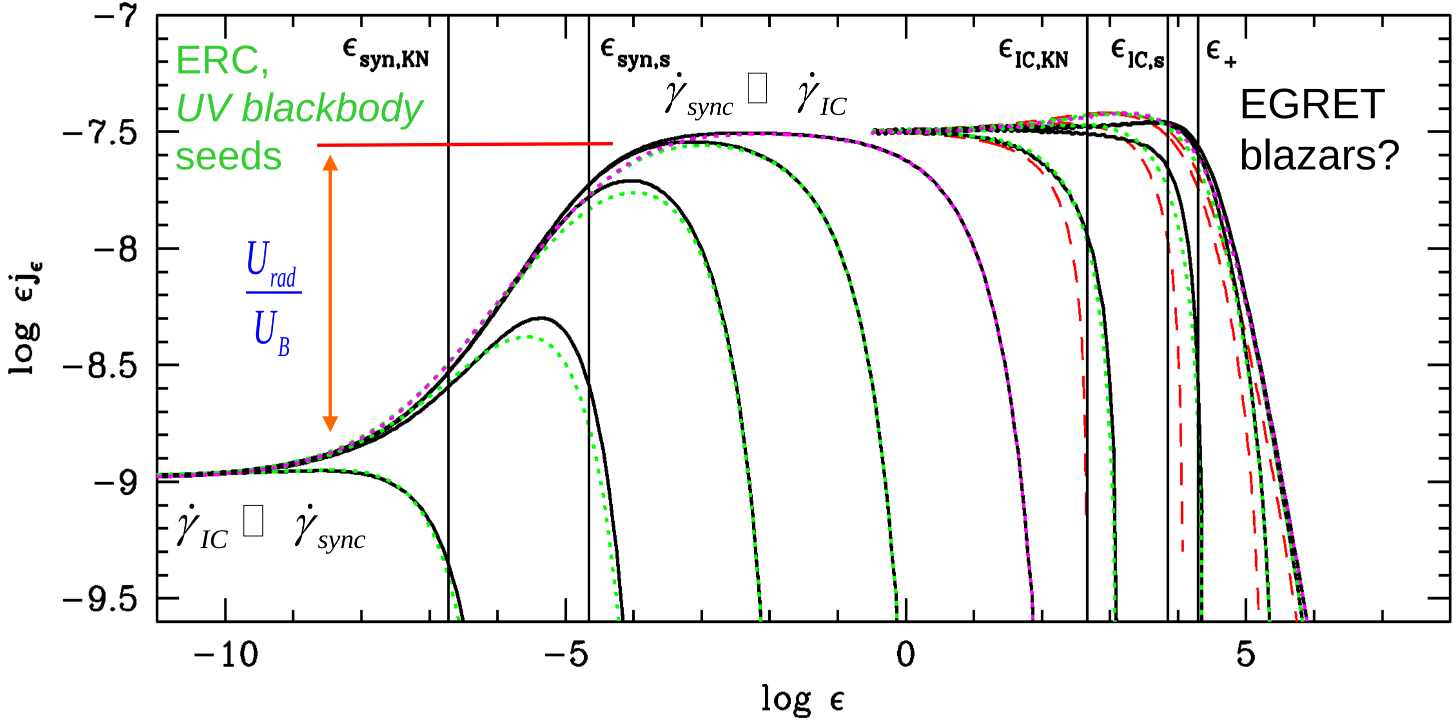
## What is the origin of the spectral breaks seen in X-rays/gamma-rays?

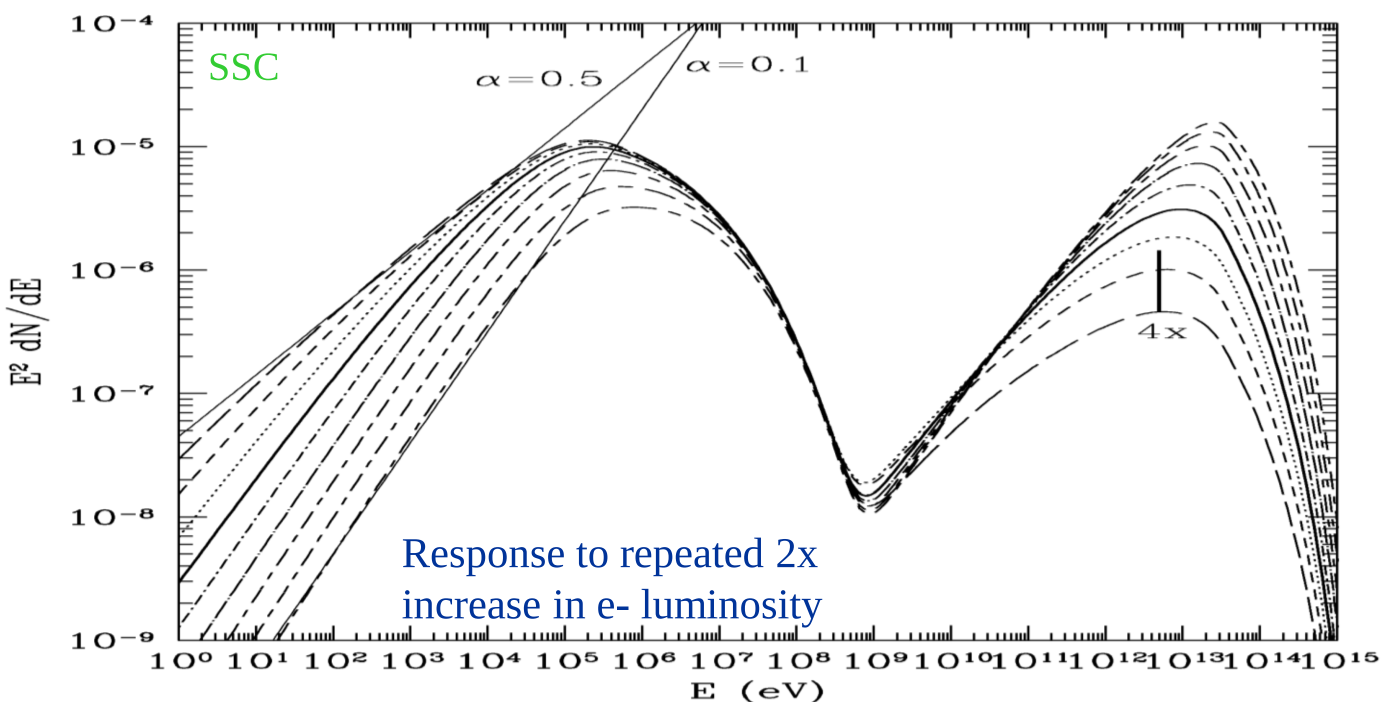
- Superposition of different emission components?
- Transition from efficient to “inefficient” cooling (particles escape before cooling)?
- Acceleration process: E_max or E_min?
- *Klein-Nishina effects?*

When (external) photon field dominates energy density, be careful if *Klein-Nishina* effects important.

Be careful in interpreting origin of spectral features such as “bumps” and break energies!

Can get spectral Index *harder* than 0.5!



# The trouble with AGN jets and ICECUBE neutrino(s)…

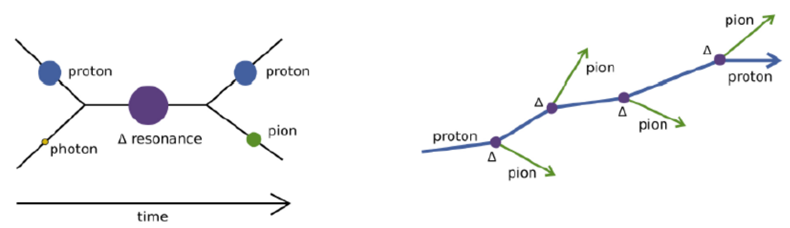



Figure 3: Left: Photo-pion production via excitation of a Δ-resonance in collision of an ultra-high energy cosmic ray proton with a CMB photon. Right: Trajectory of a super-GZK proton through the CMB, suffering attenuation due to repetitive photo-pion production [Credits: W. Bietenholz, arXiv:1305.1346].

- If one particle is a photon ($e_2 = p_2$ and $m_2 = 0$), then threshold energy

$$e_2 \left( \gamma_1 - \sqrt{\gamma_1^2 - 1}\ \cos\theta \right) = \delta m\ c\ \left( 1 + \frac{\delta m}{2m_1} \right)$$

**Example:** Consider reaction $p+\gamma \rightarrow p+\pi^0$ on CMB photons (mean energy $E_2 =< h\nu > \simeq 3kT \simeq 7 \times 10^{-4}$ eV [SI], $e_2 = E_2/c$). Threshold energy for most favourable collision angle ($\cos\theta = -1$ head-on) for high $\gamma_1$:

$$\Rightarrow 2\gamma_1 \simeq \frac{m_{\pi^0} c}{e_2} \left( 1 + \frac{m_{\pi^0}}{2m_p} \right) \quad \text{or} \quad \gamma_1 \simeq 10^{11}$$

Rieger lecture notes

In delta-function approximation, pion has ~0.1-.2 energy of proton, and neutrino has ~.3 of energy of pion. ICECUBE sees neutrinos from ~1 TeV – 1 PeV. To make TeV neutrino, need proton of energy ~20 TeV, or $\gamma$~2x10$^4$. => need target photon E~3.5 keV [X-rays], and lots of them (for efficient production)… where do you get these? Compactness (pair production) problem…

# "Orphan" $\gamma$-Ray Flares and Stationary Sheaths of Blazar Jets

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### Abstract

Blazars exhibit flares across the entire electromagnetic spectrum. Many $\gamma$-ray flares are highly correlated with flares detected at longer wavelengths; however, a small subset appears to occur in isolation, with little or no correlated variability at longer wavelengths. These "orphan" $\gamma$-ray flares challenge current models of blazar variability, most of which are unable to reproduce this type of behavior. MacDonald et al. have developed the *Ring of Fire* model to explain the origin of orphan $\gamma$-ray flares from within blazar jets. In this model, electrons contained within a blob of plasma moving relativistically along the spine of the jet inverse-Compton scatter synchrotron photons emanating off of a ring of shocked sheath plasma that enshrouds the jet spine. As the blob propagates through the ring, the scattering of the ring photons by the blob electrons creates an orphan $\gamma$-ray flare. This model was successfully applied to modeling a prominent orphan $\gamma$-ray flare observed in the blazar PKS 1510−089. To further support the plausibility of this model, MacDonald et al. presented a stacked radio map of PKS 1510−089 containing the polarimetric signature of a sheath of plasma surrounding the spine of the jet. In this paper, we extend our modeling and stacking techniques to a larger sample of blazars: 3C 273, 4C 71.01, 3C 279, 1055+018, CTA 102, and 3C 345, the majority of which have exhibited orphan $\gamma$-ray flares. We find that the model can successfully reproduce these flares, while our stacked maps reveal the existence of jet sheaths within these blazars.

What could happen in a messy environment? "Compton Mirror" and "external/internal" (moderately beamed?) photons from a jet sheath?

[often see limb brightening in FRI radio images?]

Acceleration in sheath (boundary, shear layer)?

``Stratified" jet w/structure, e.g., $\Gamma(\Theta)$?

Pair sheath?

The Astrophysical Journal, 850:87 (14pp), 2017 November 20 MacDonald, Jorstad, & Marscher

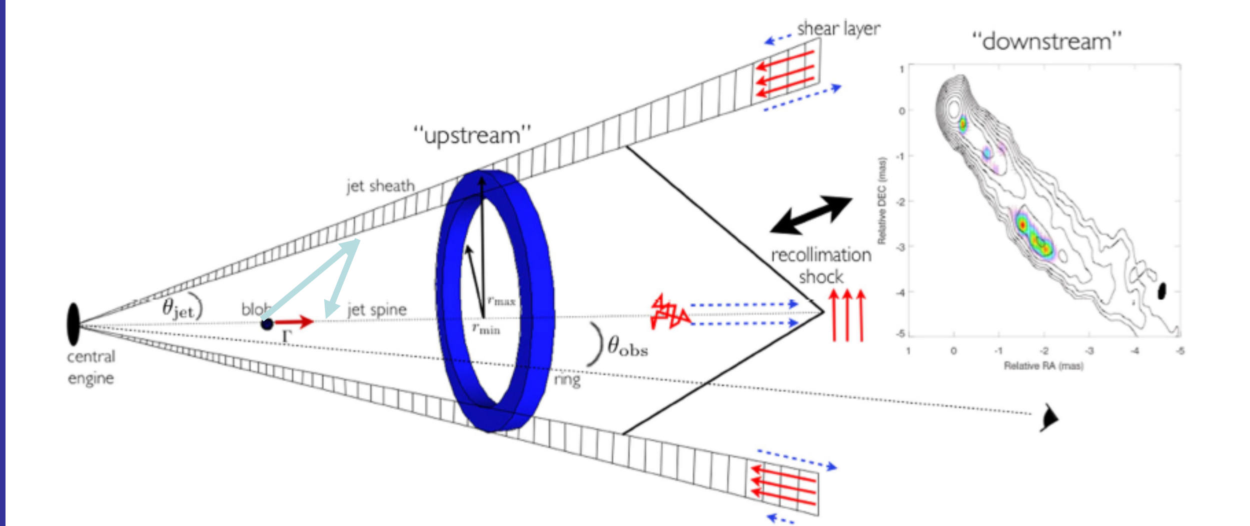
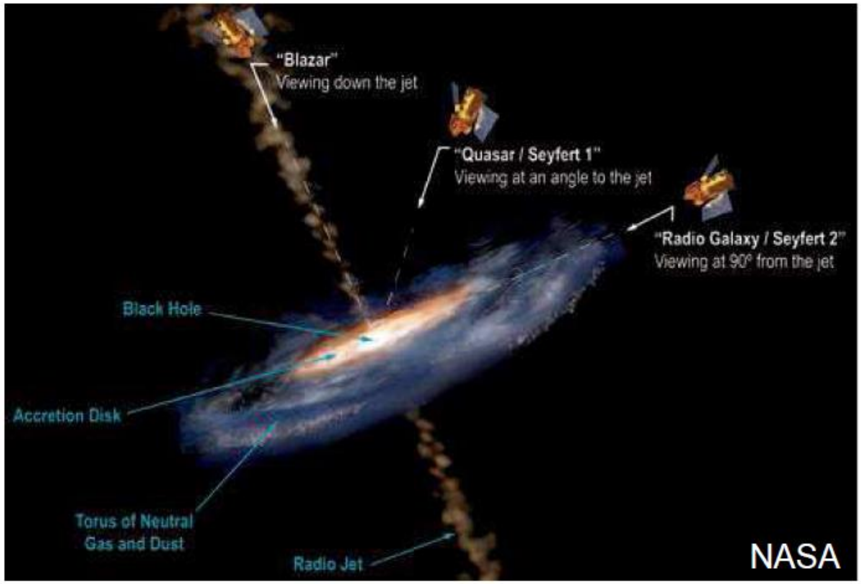



**Figure 1.** Schematic of the relative locations along the jet of both the ring of shocked sheath plasma in our model and the location of the radio core/sheath detected farther "downstream" in the stacked radio images of 3C 273 (see Figures 2 and 3). This sketch is projected onto the plane of the sky. We posit that the ring is located ~4 pc from the central engine, while the radio cores in our stacked maps are located farther downstream from the central engine (at a scale of $\gtrsim$10 pc). We propose that the radio core in 3C 273 is associated with a recollimation shock that compresses initially tangled magnetic field along the spine of the jet and orders that field perpendicular to the jet axis (the red vectors just to the right of the recollimation shock). The jet has an opening angle $\lesssim 2°$ and the recollimation shock subtends an angle to the jet axis $\lesssim 10°$. In contrast to the spine, velocity shear between the sheath and the ambient medium (blue vectors denote relative speed) aligns the magnetic field lines on the outer edges of the jet to be roughly parallel to the jet axis, resulting in the spine-sheath polarization signature we detect in our stacked map of 3C 273 (shown in the "downstream" portion of this figure and in Figure 3).

# What’s up after 10+ years of Fermi/IACT blazar observations??

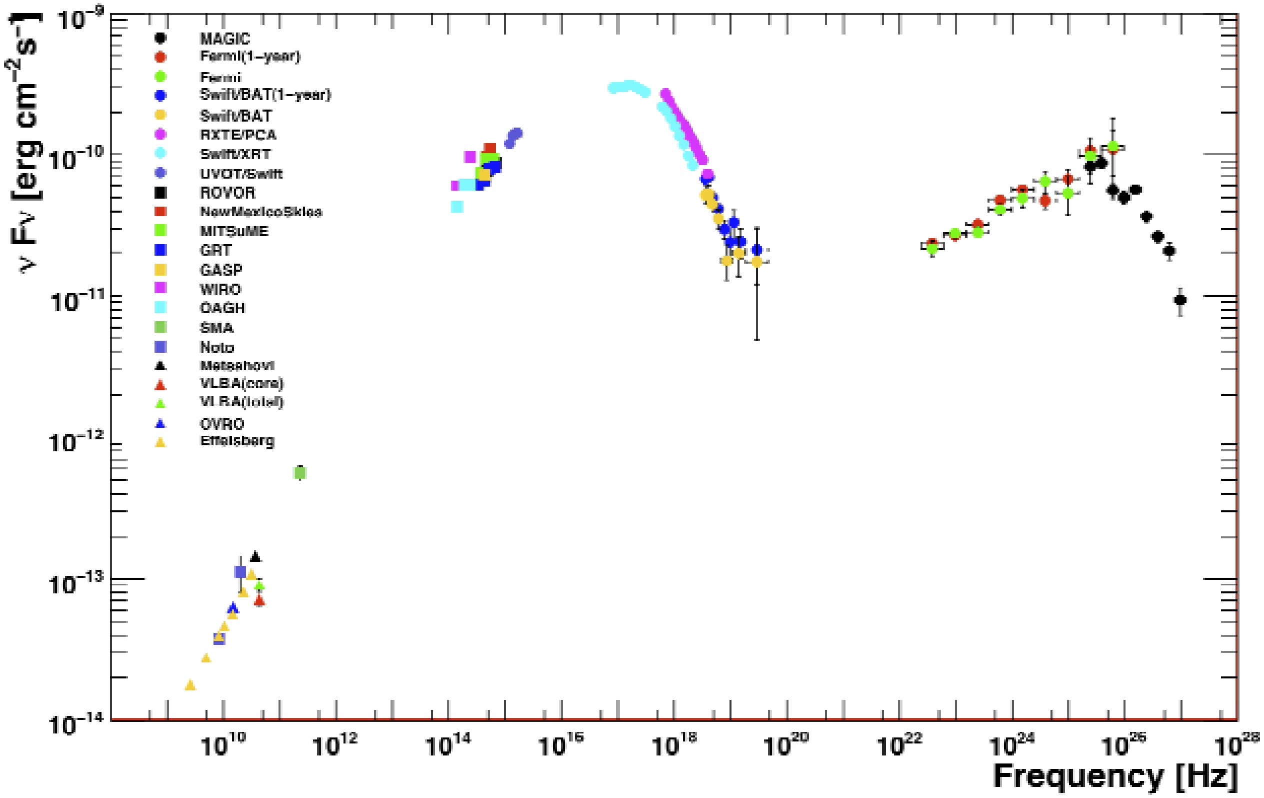
## Key questions on blazars

- Emission mechanisms (for HE component)
  - Leptonic (IC of synchrotron or external photons) vs hadronic ($\pi^0 \rightarrow \gamma\gamma$, proton synchrotron)
- Emission location
  - Single zone for all wavebands (completely constraining for simplest leptonic models)
  - Opacity effects and energy-dependent photospheres
- Particle acceleration mechanisms
  - Shocks, magnetic reconnection, turbulence acceleration
- Jet composition
  - Poynting flux, leptonic, ions
- FSRQ/BLLac dichotomy
- Jet confinement
  - External pressure, magnetic stresses
- Accretion disk—black hole—jet connection
- Effect of blazar emission on host galaxies and galaxy clusters
- Blazars as probes of the extragalactic background light (EBL)



# MW campaign on Mrk421

- 4.5 months long (Jan 20th – June 1st , 2009)
- ~20 instruments participated covering frequencies from radio to TeV
- 2-day sampling at at optical/X-ray and TeV (when possible: breaks due to moon, weather…)



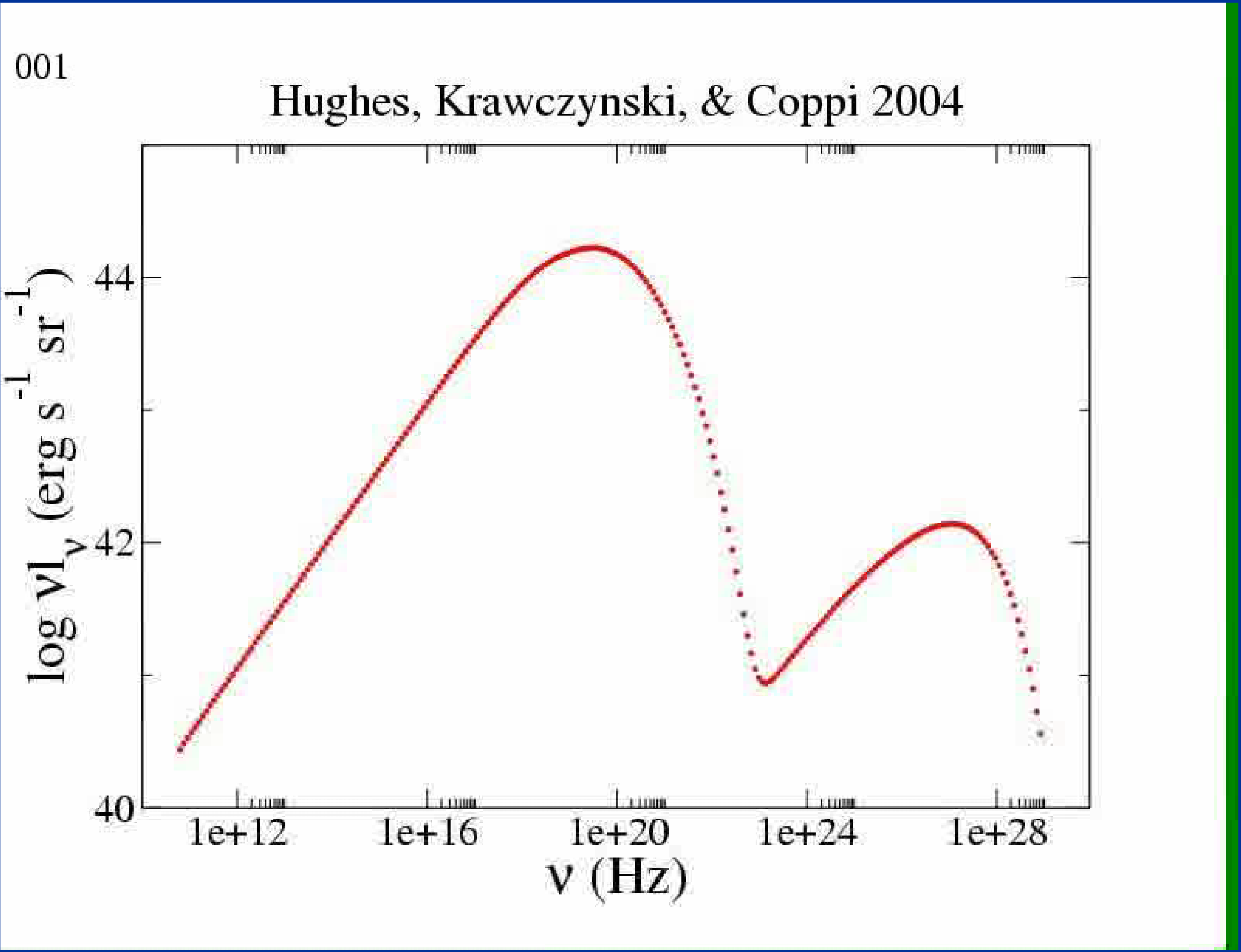

Most complete SED collected for Mrk421 until now

First time that the high energy bump is resolved without gaps from 0.1 GeV to almost 10 TeV

*Poster P1-53, D. Paneque et al.*

Preliminary

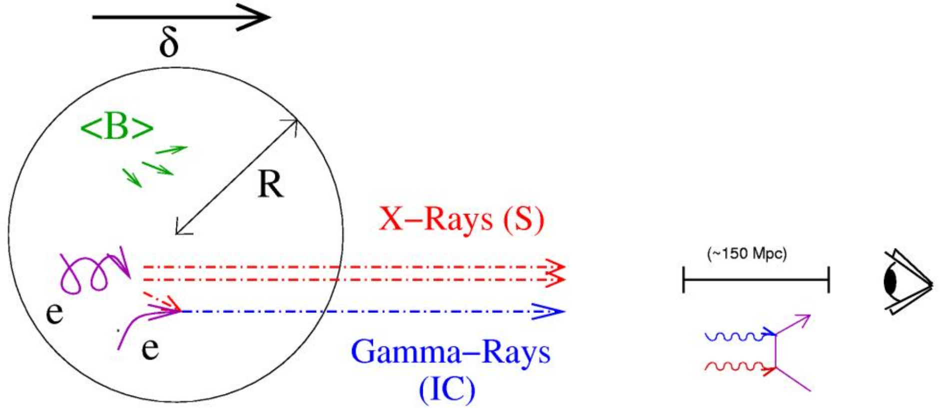
# Variability "in principle" very constraining:
## simple (?) TeV blazar [one zone SSC, no "external" radiation]




Shows hard-soft vs intensity hysteresis, cooling lags, and L_Compton ∝ L_Sync$^2$

… monitoring both peaks allows one to unambiguously determine model parameters

# Mkn 501 – Synchrotron Self–Compton Models




Model parameters:

- $\delta$ Doppler Factor
- R Size
- <B> Magnetic field
- e Electron Distribution:
  - Intensity
  - Acceleration Spectrum

Model Constraints:

$\Delta t < 1$ day
=> Small Radius ( $\delta 10^{15}$ cm)

Cooling Times: B>0.025

SSC Photons =>
Accounts already for
TeV Flux ( $\delta = 25$)

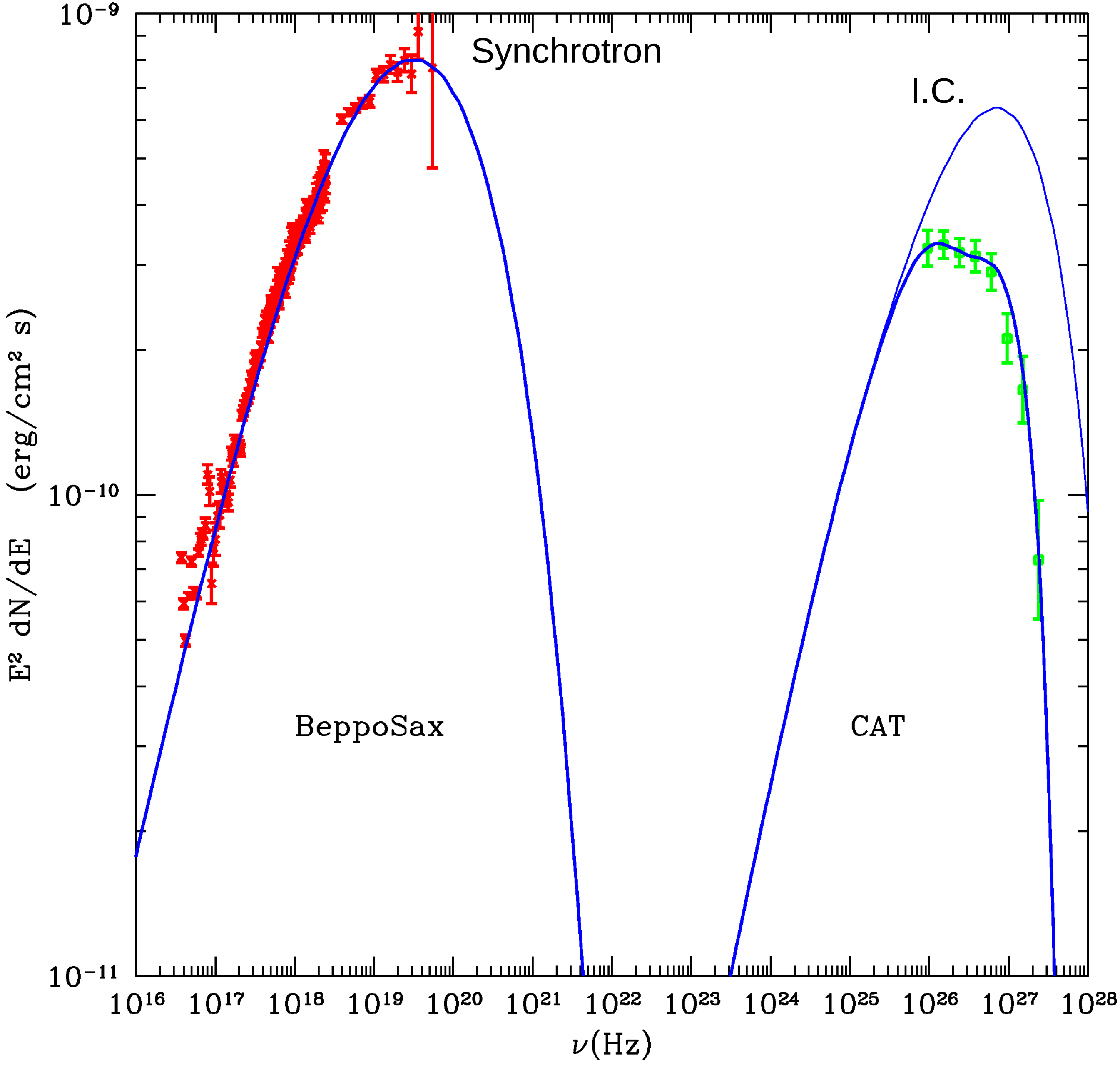
Optically Thin: Doppler Factor >15

Approaches:

– Reconstruct e–Spectrum from X–Ray Spectrum

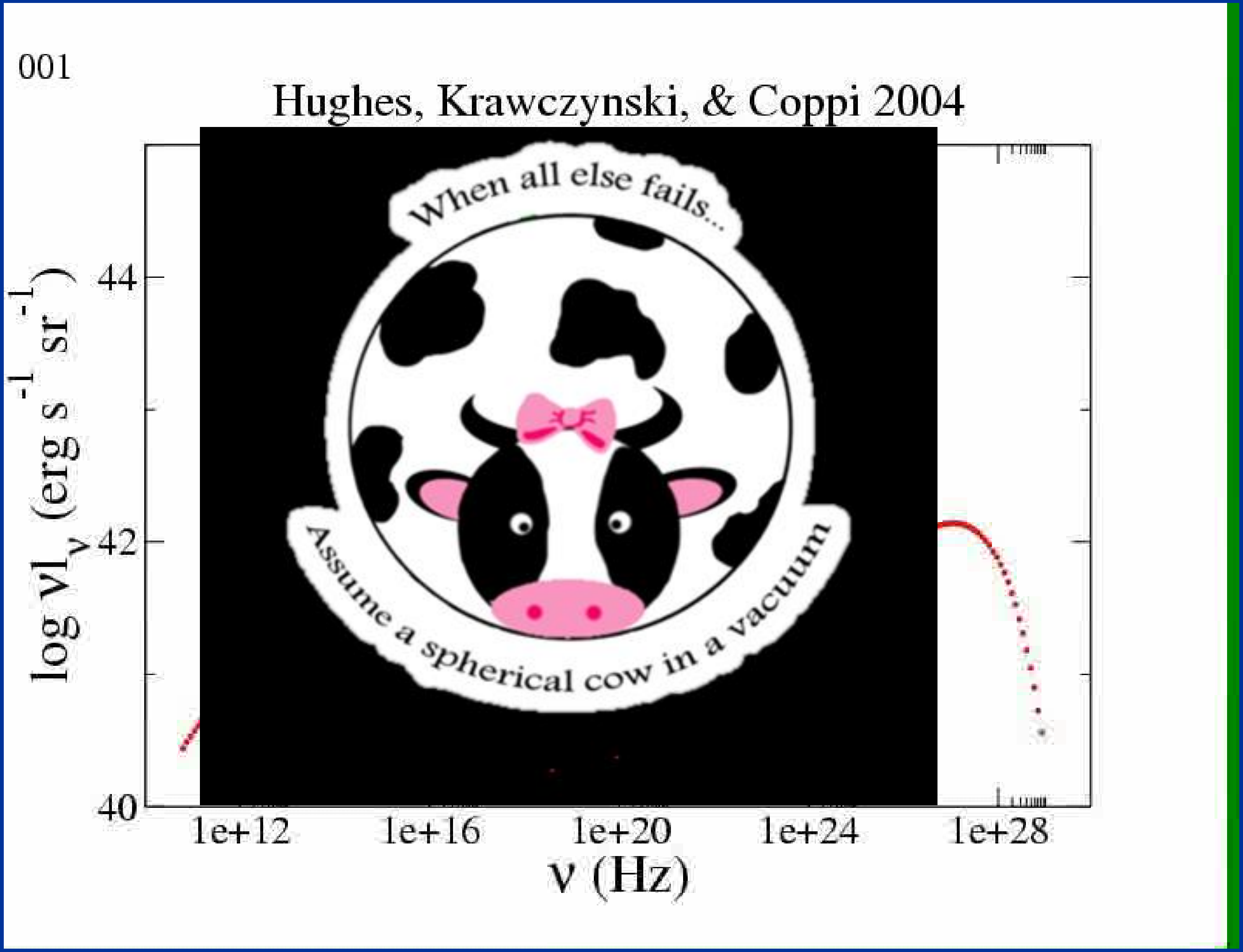
– Time Dependent Model of X–Ray and TeV Gamma–Ray Emission

Krawczynski, Coppi, & Aharonian 2002

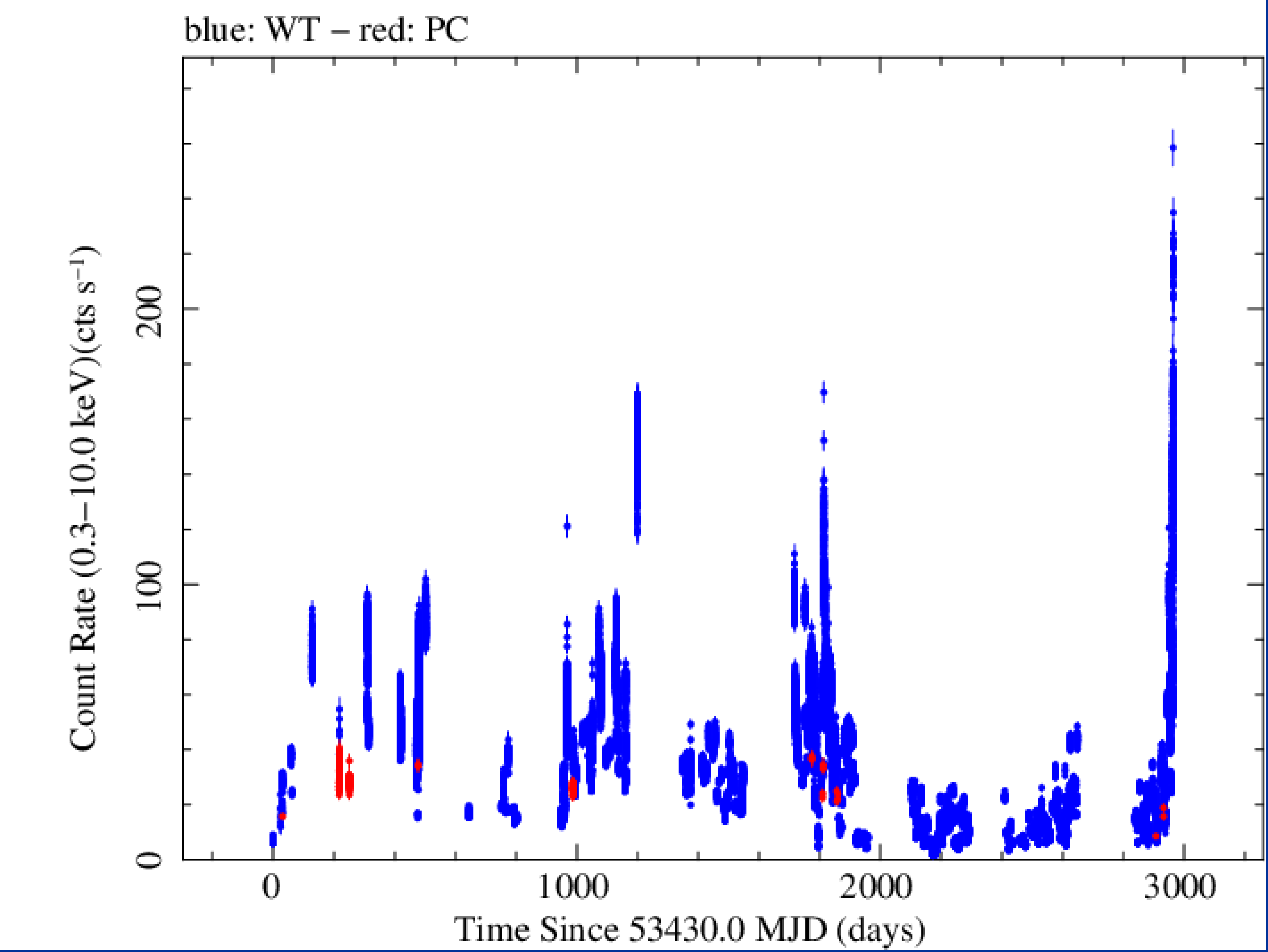



Simultaneous SSC fit to BeppoSax and CAT for Mrk 501 flare of April 16, 1997 using fully self-consistent model.

# Unfortunately, this matches observations only some of the time …
(or *never* in some objects!)



# Mkn 421 goes haywire! Multiple Personalities…

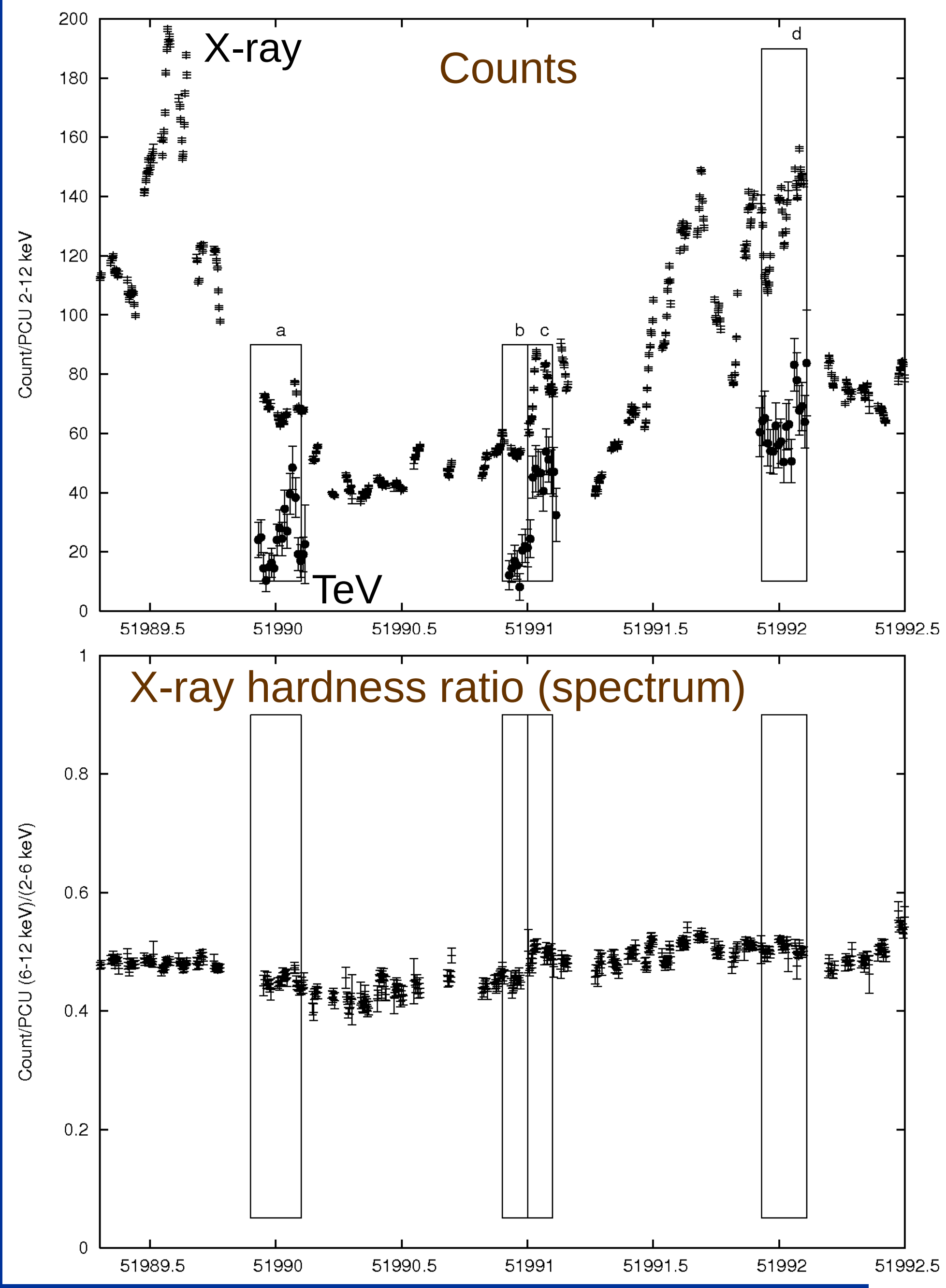


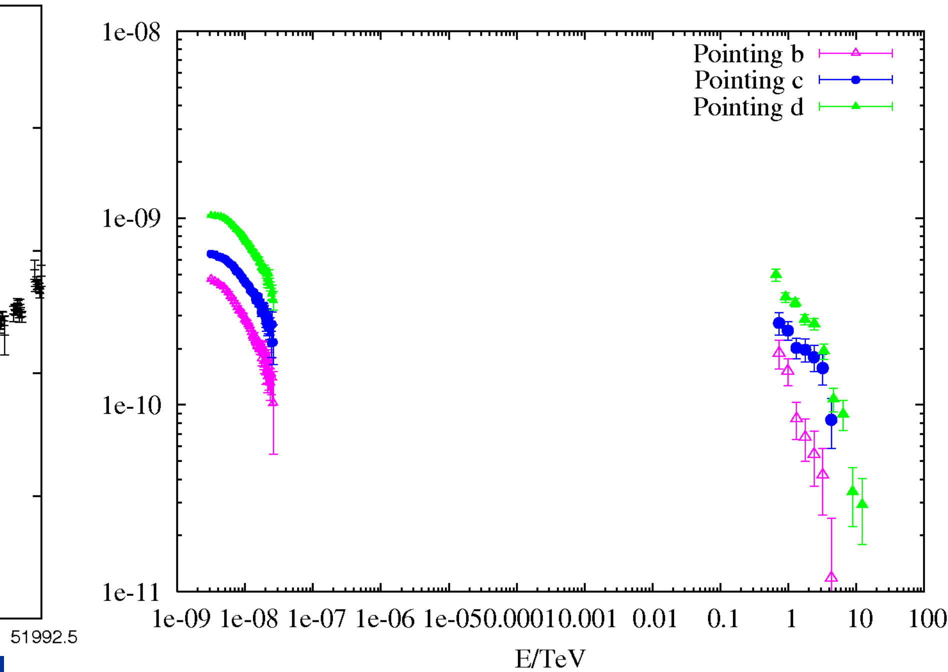

Public SWIFT XRT lighcurves (Falcone et al. 2012)

In case you still thought things were simple…

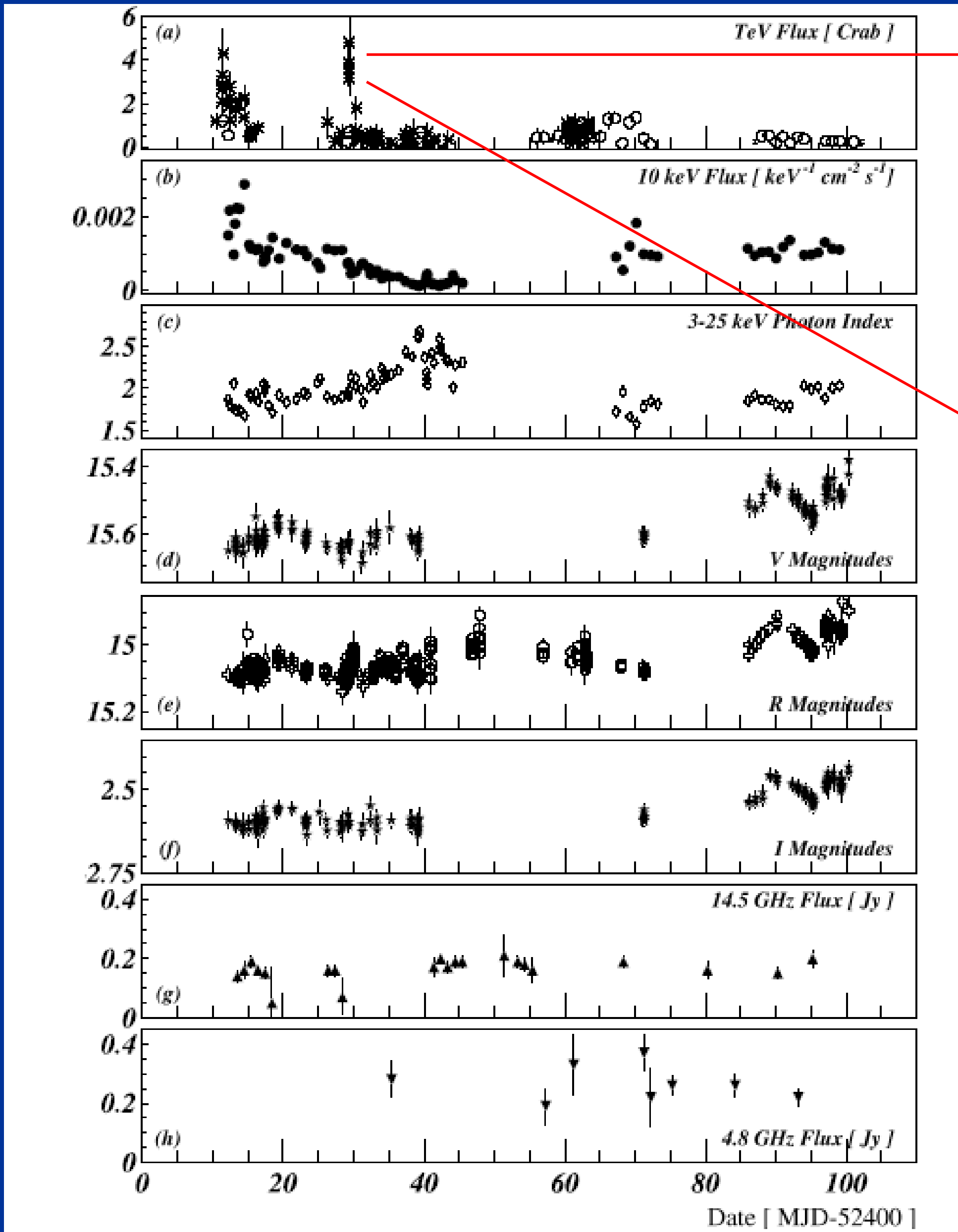
Mkn 421 2002 X-ray/TeV campaign

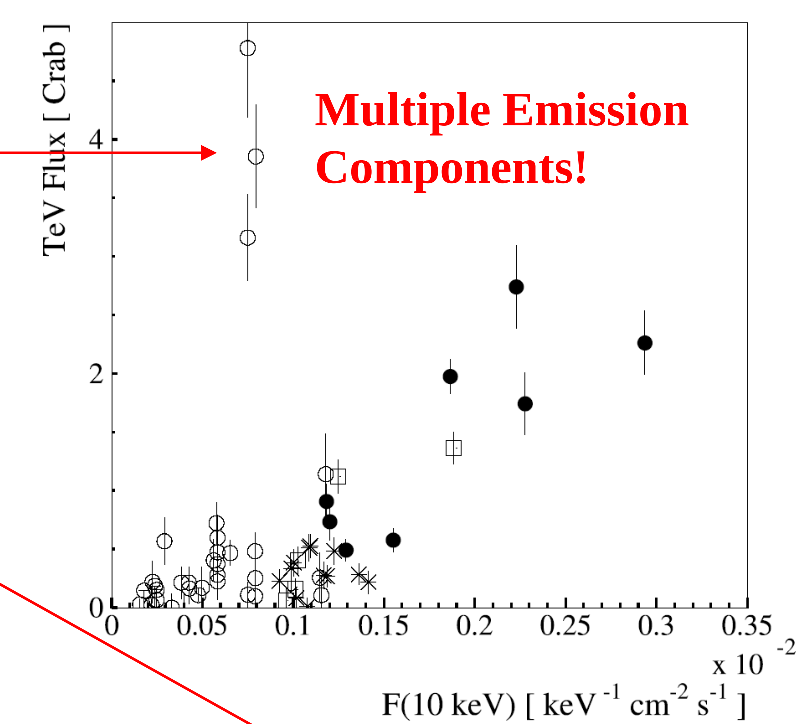
(Dieter Horns, preliminary)

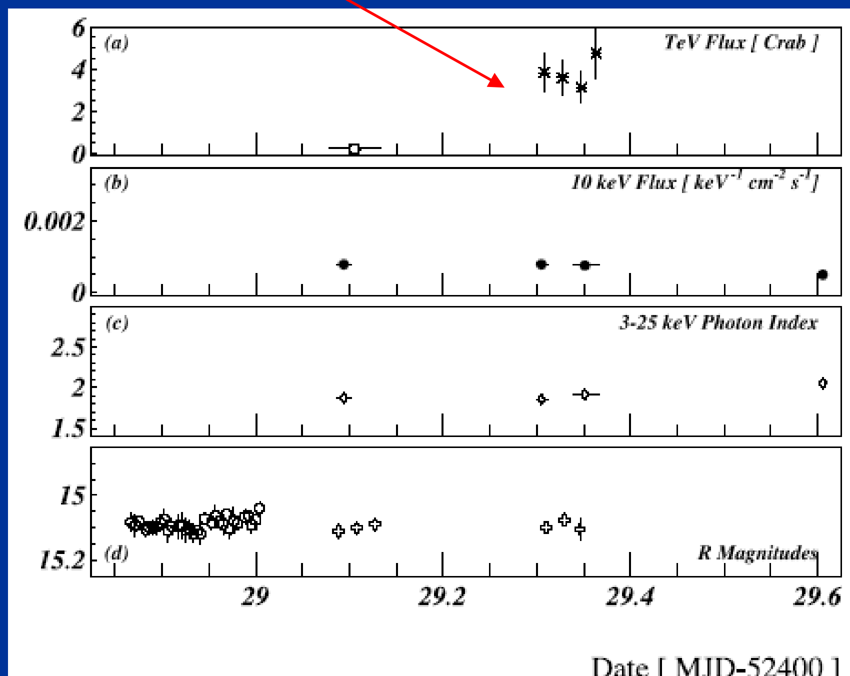


# Oops!! -- 1ES1959 May-Aug 2002



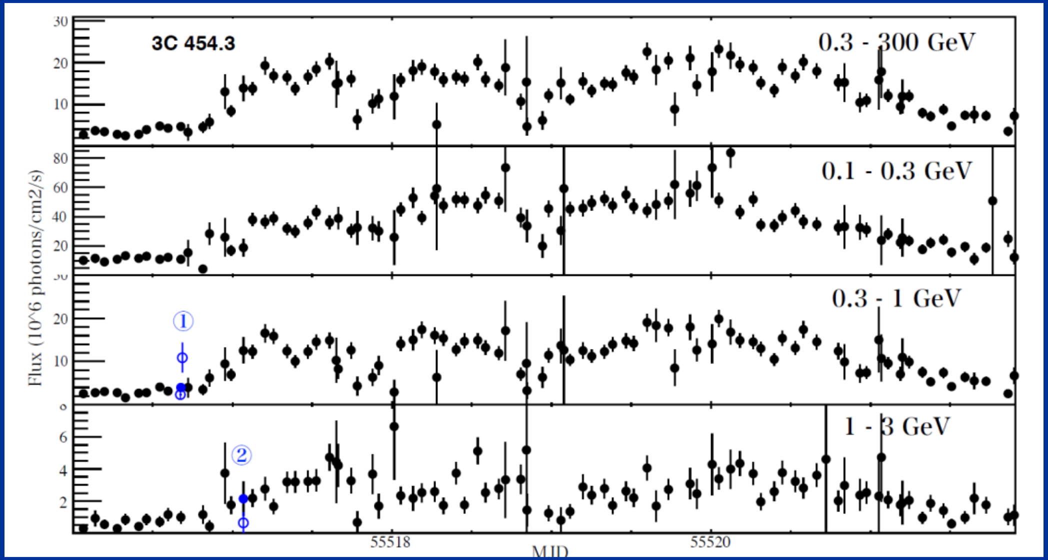



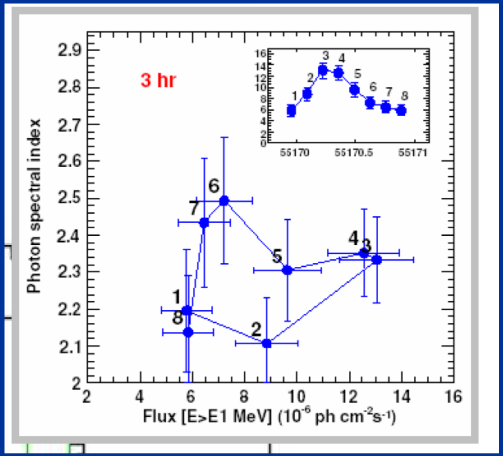

Krawczynski et al. 2004

This is what we really need to fit ☺

Saitoh, in prep.




From Ciprini 2014 talk




Need to solve time-dependent equations (+ allow spatial inhomogeneities)!

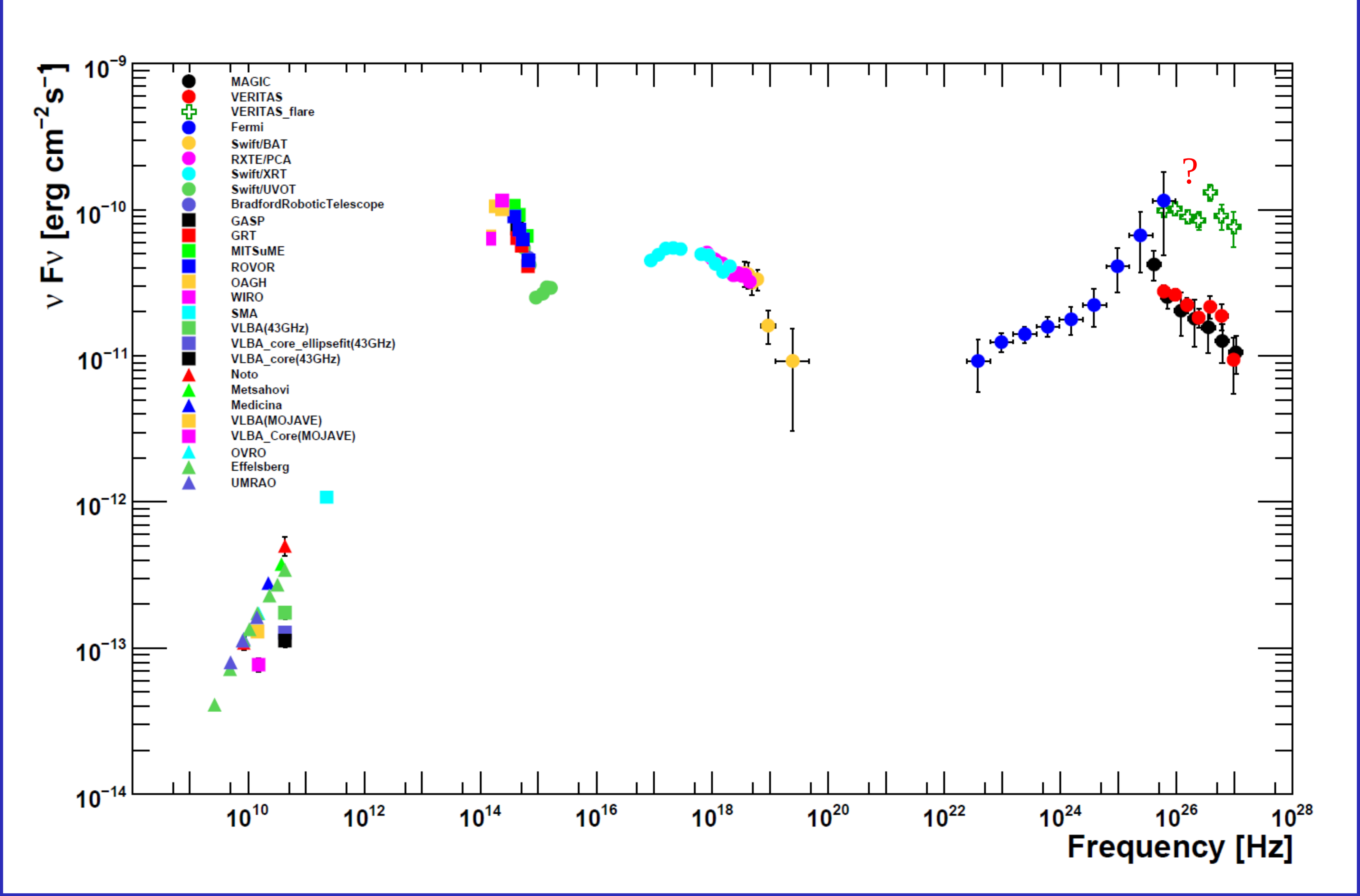
Fact (??) that rapid [<day] optical variability amplitude in FSRQ never as great as gamma amplitude

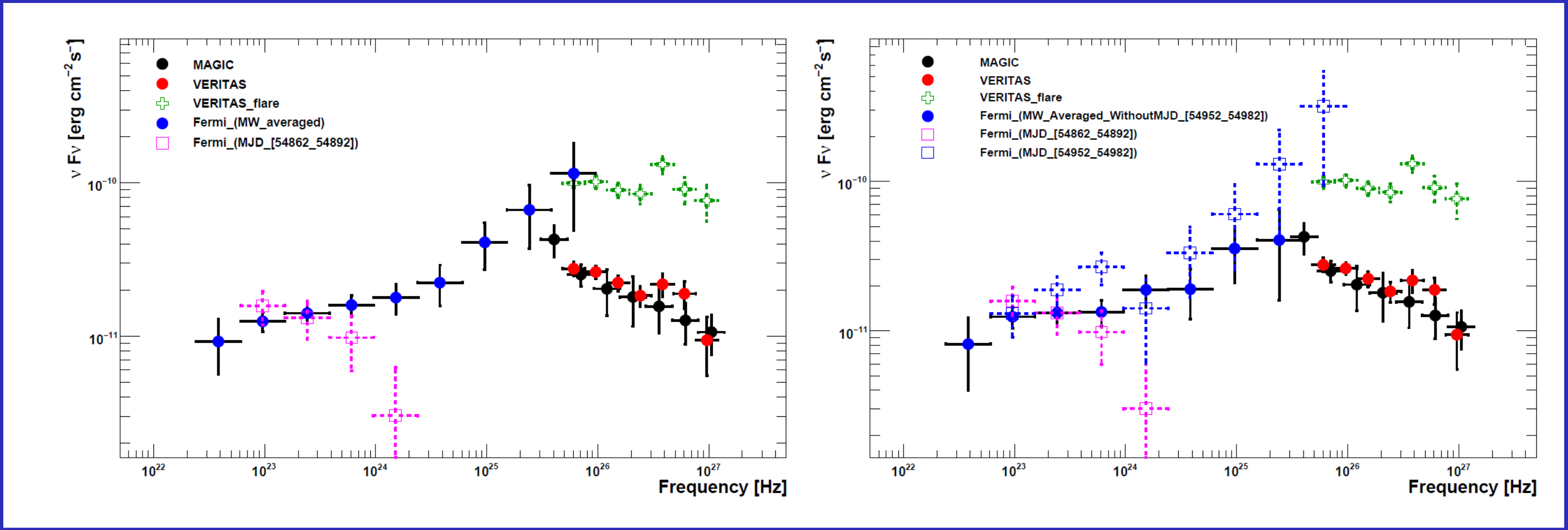
=> (i) dilution of optical? Multi-zone

(ii) Compton dominance of short flares even larger than already large Compton dominance of time-averaged spectrum (one zone: rest-frame $U_{rad} >> U_B$)

=> Klein-Nishina [cutoff ?] complications [E.g., Moderski et al. 2005]

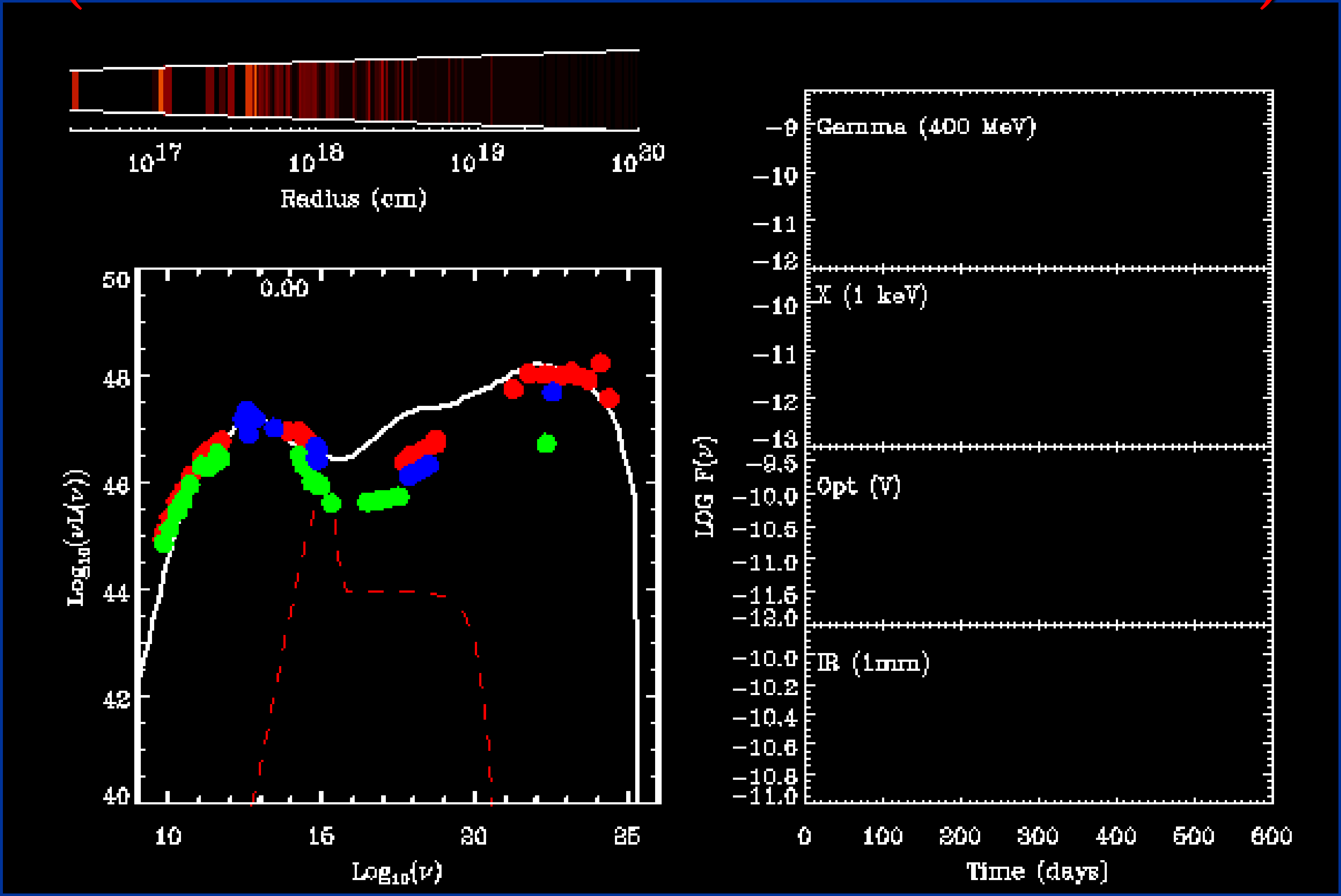
# Mrk 501 – extra VHE component? Barely seen by Fermi (Mrk 501 is “boring” Fermi source)





MAGIC
VERITAS
VERITAS_flare
Fermi_(MW_averaged)
Fermi_(MJD_[54862_54892])
$\nu$ F$\nu$ [erg cm$^{-2}$s$^{-1}$]
Frequency [Hz]
MAGIC
VERITAS
VERITAS_flare
Fermi_(MW_Averaged_WithoutMJD_[54952_54982])
Fermi_(MJD_[54862_54892])
Fermi_(MJD_[54952_54982])
$\nu$ F$\nu$ [erg cm$^{-2}$s$^{-1}$]
Frequency [Hz]

# Numerical simulations for 3C 279. Spada et al. 2001 (Internal shock – "Christmas tree"-like model)



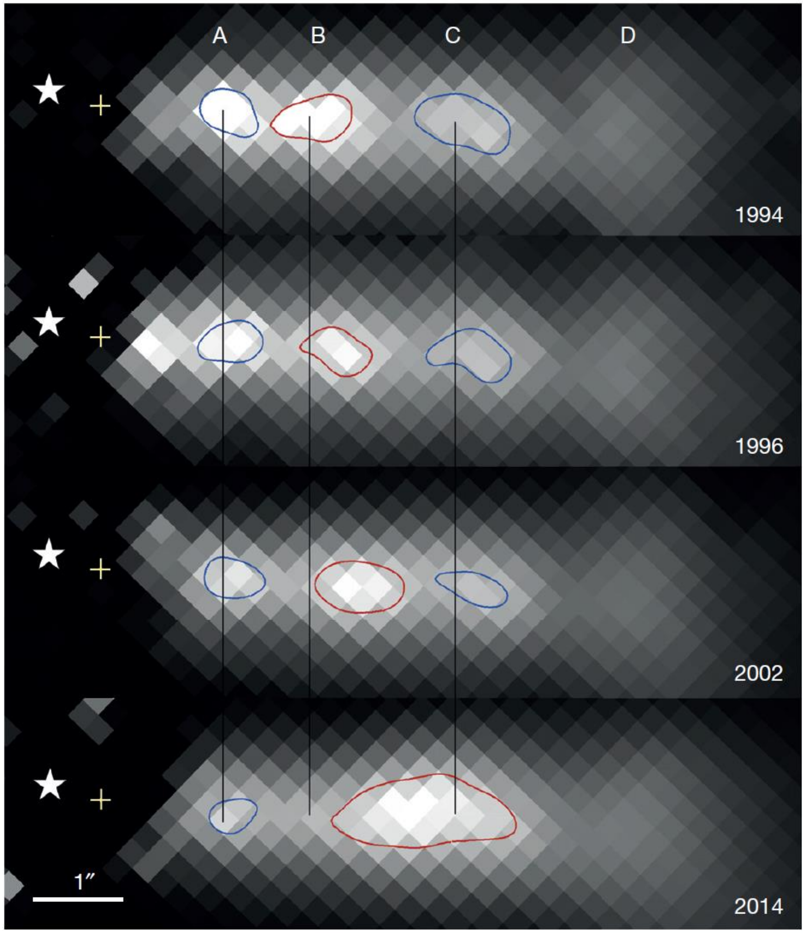
# LETTER

doi:10.1038/nature14481

# A kiloparsec-scale internal shock collision in the jet of a nearby radio galaxy

Eileen T. Meyer[1,2], Markos Georganopoulos[2,3], William B. Sparks[1], Eric Perlman[4], Roeland P. van der Marel[1], Jay Anderson[1], Sangmo Tony Sohn[5], John Biretta[1], Colin Norman[1,5] & Marco Chiaberge[1,5,6]

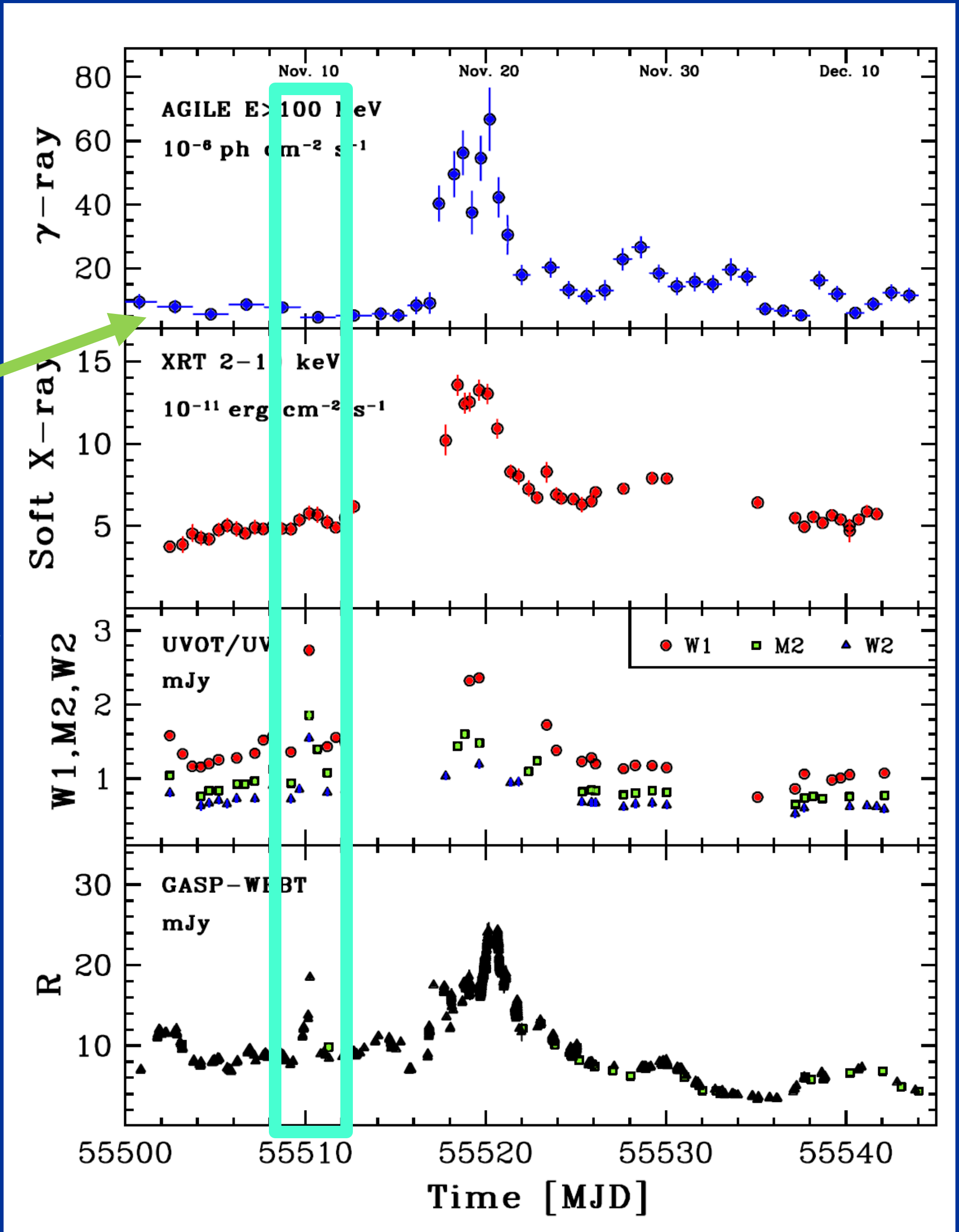
**Jets of highly energized plasma with relativistic velocities are associated with black holes ranging in mass from a few times that of the Sun to the billion-solar-mass black holes at the centres of galaxies[1]. A popular but unconfirmed hypothesis to explain how the plasma is energized is the 'internal shock model', in which the relativistic flow is unsteady[2]. Faster components in the jet catch up to and collide with slower ones, leading to internal shocks that accelerate particles and generate magnetic fields[3]. This mechanism can explain the variable, high-energy emission from a diverse set of objects[4–7], with the best indirect evidence being the unseen fast relativistic flow inferred to energize slower components in X-ray binary jets[8,9]. Mapping of the kinematic profiles in resolved jets has revealed precessing and helical patterns in X-ray binaries[10,11], apparent superluminal motions[12,13], and the ejection of knots (bright components) from standing shocks in the jets of active galaxies[14,15]. Observations revealing the structure and evolution of an internal shock in action have, however, remained elusive, hindering measurement of the physical parameters and ultimate efficiency of the mechanism. Here we report observations of a collision between two knots in the jet of nearby radio galaxy 3C 264. A bright knot with an apparent speed of (7.0 ± 0.8)*c*, where *c* is the speed of light in a vacuum, is in the incipient stages of a collision with a slower-moving knot of speed (1.8 ± 0.5)*c* just downstream, resulting in brightening of both knots—as seen in the most recent epoch of imaging.**



Vercellone et al. 2011

Gamma-Ray "Plateau" State

-- NO short-term variability

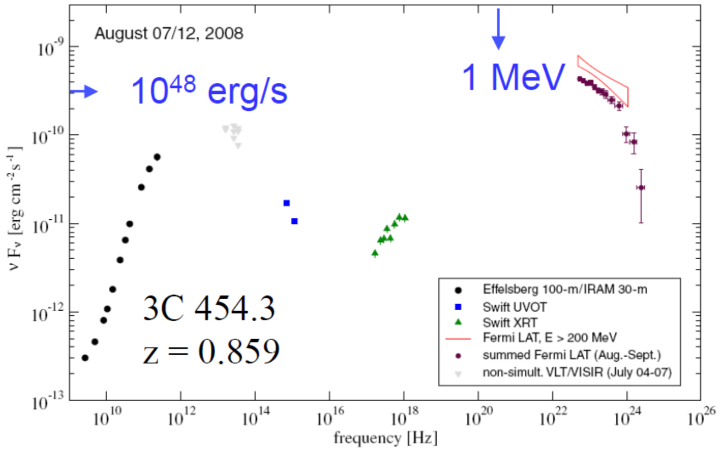


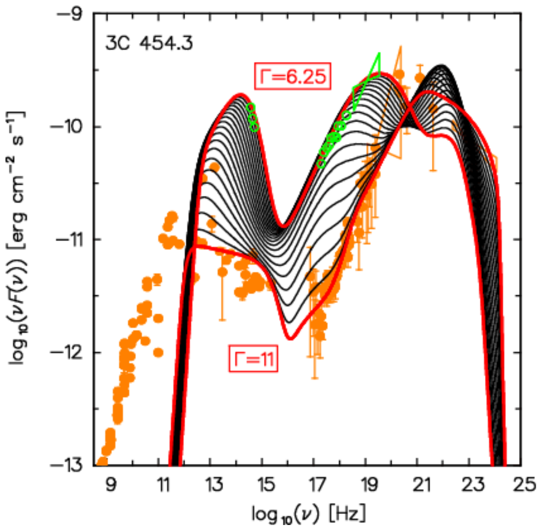

"The Flare"

- 3C 454.3

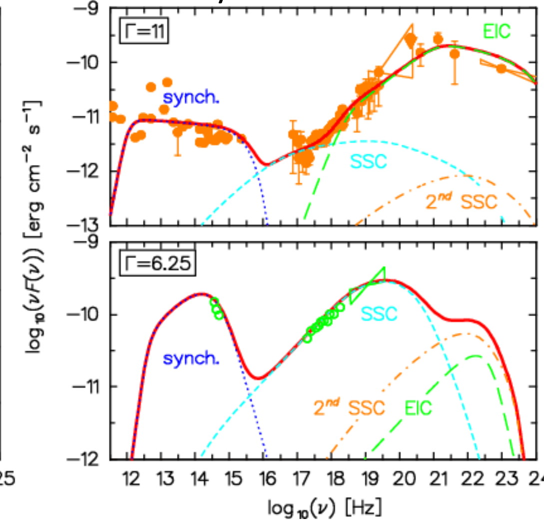
(Nov. 2010)

# Another examples of why need ASTROGAM [Amego-X?]:
## Here is well-known (?) MeV blazar, 3C 454 (at least in low state)

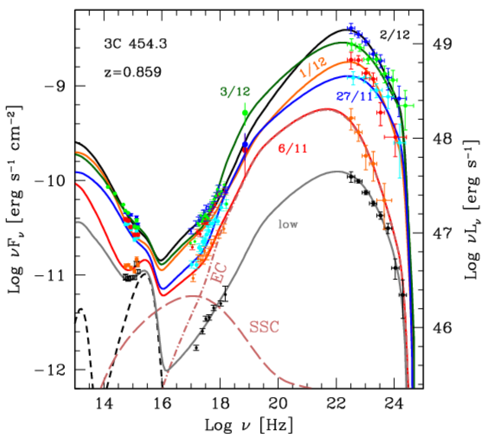


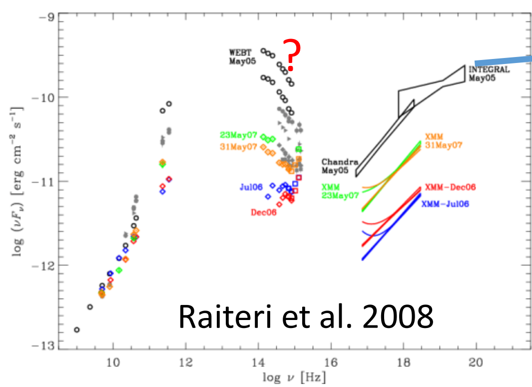




Katarzynski & Ghisellini



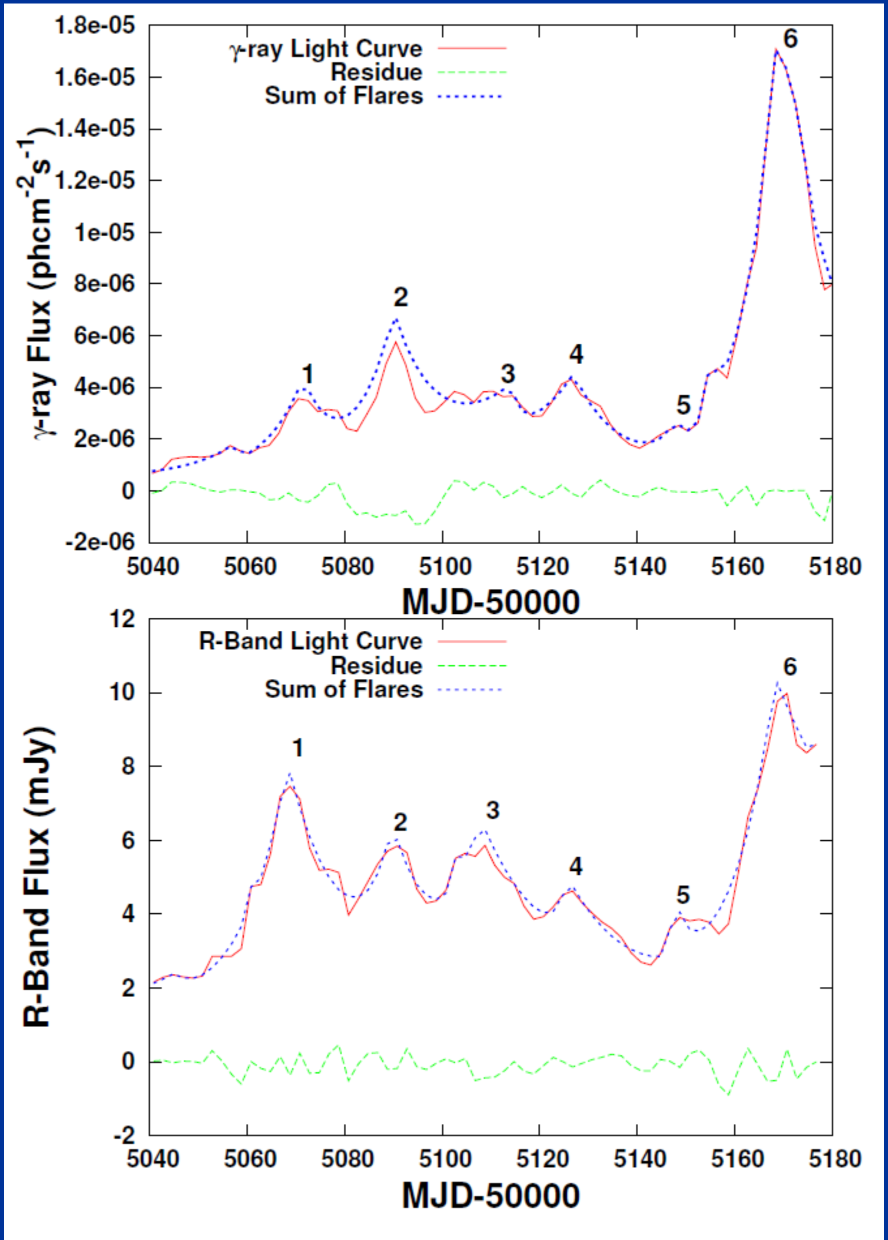

Tavecchio & Ghisellini

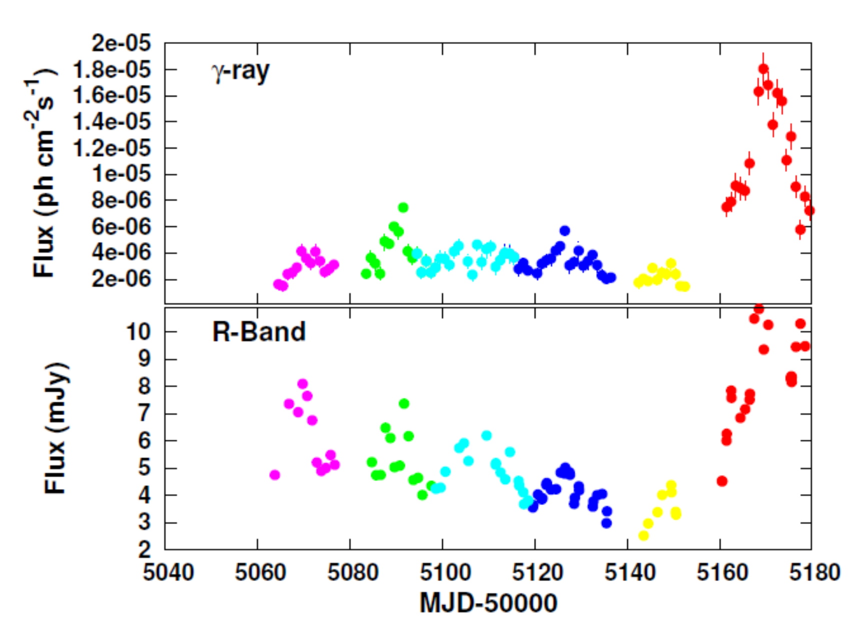


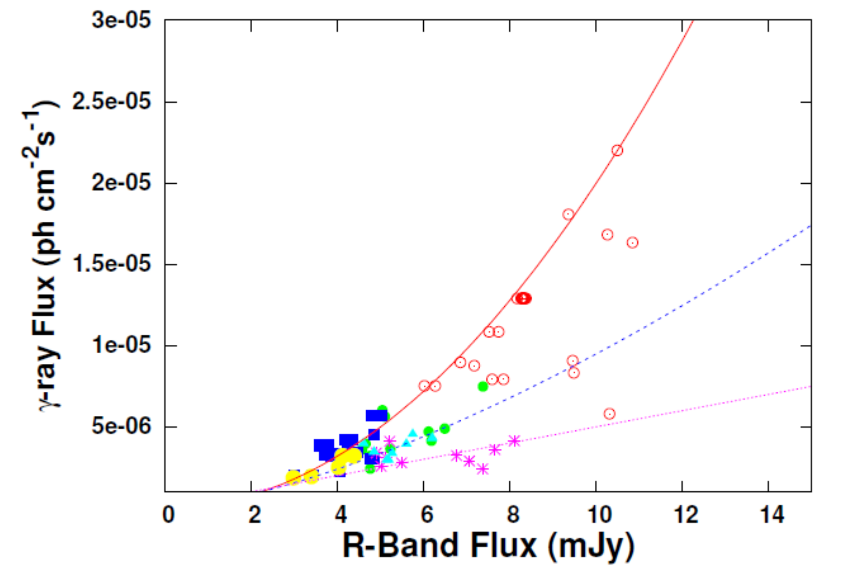




??, If spectrum really rolls over as INTEGRAL suggests,what about Compton dominance?
(May 05 is huge flare
for synch component… )

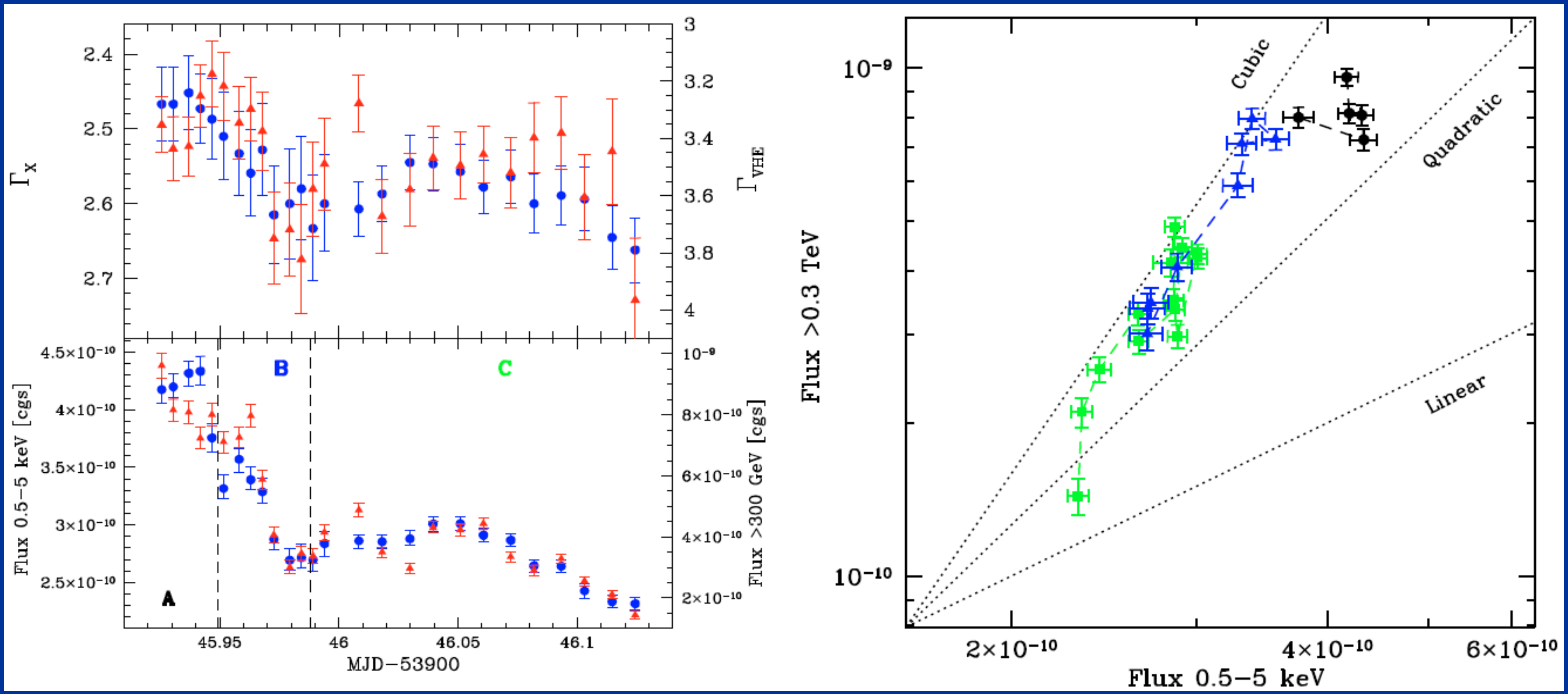
# 3C 454.3 2009 Flare – SMARTS + Fermi (Chatterjee et al.)



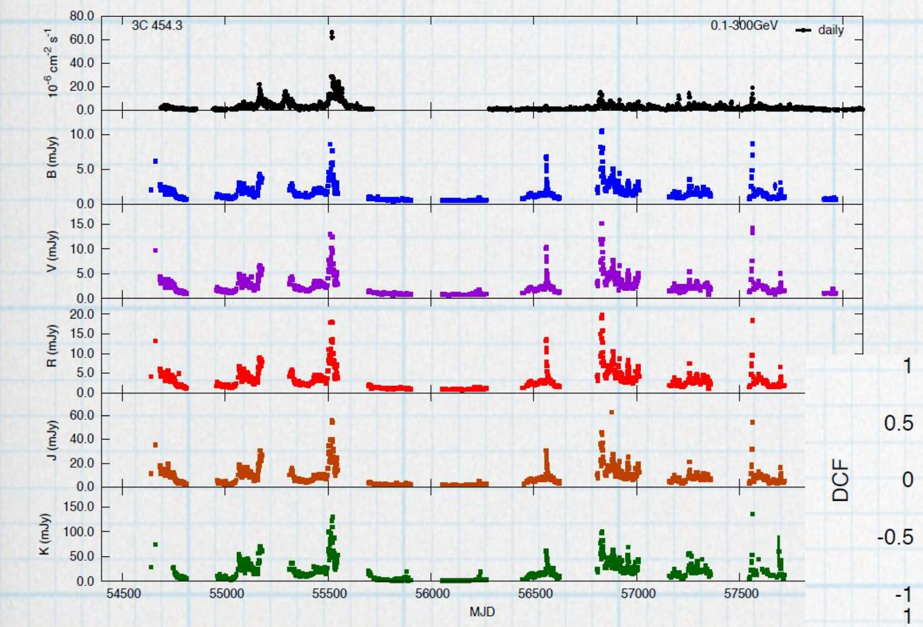



# Famous PKS 2155 (HESS) Flare
# Multiple Emission Components – Dilution!?

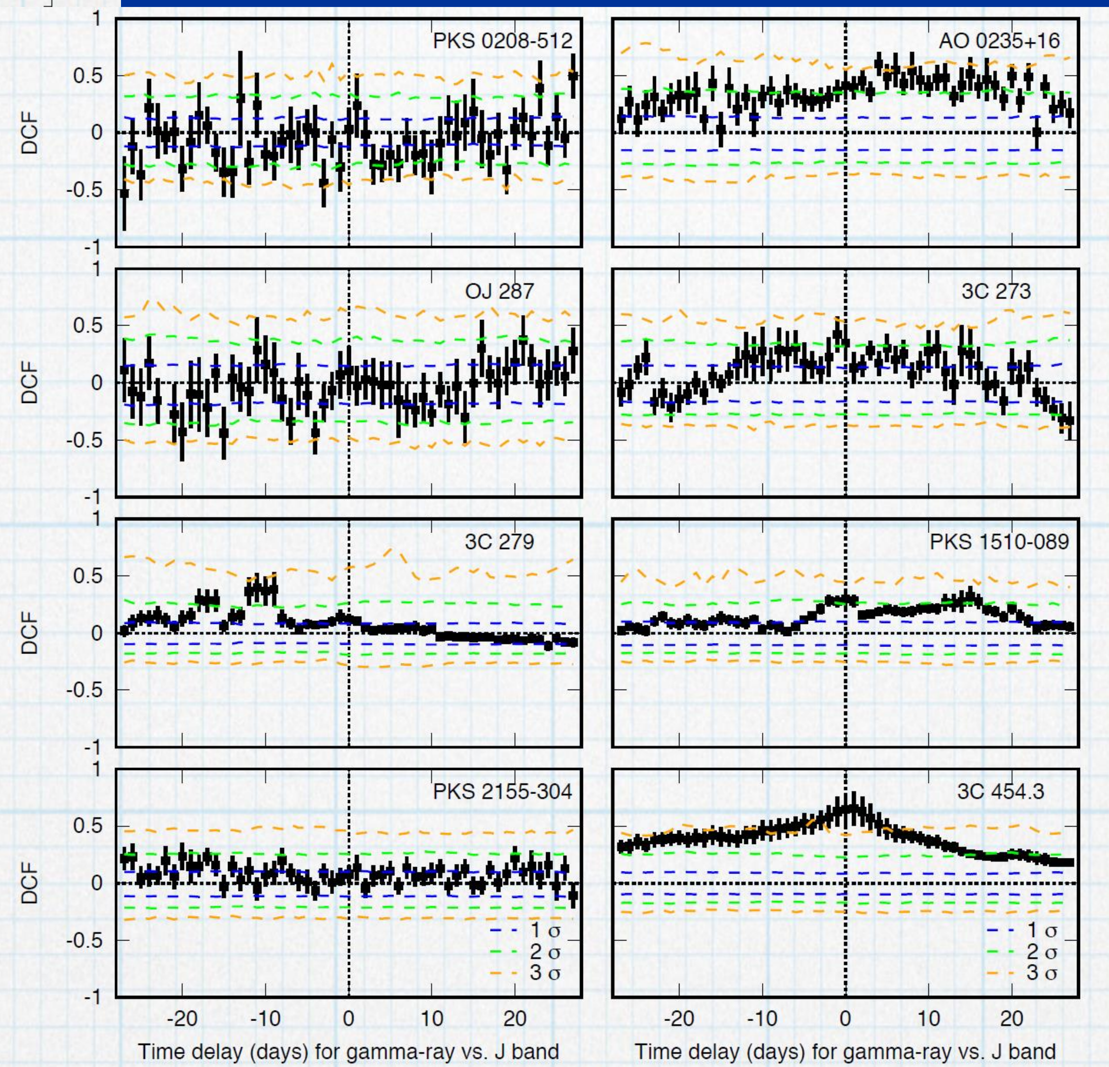


Now have ~10 years of gamma-ray/MW data on behavior of two humps ….

And the answer is ….. [SMARTS data]!




**SMARTS optical/infrared (B:blue, V:dark-violet, R:red, J orange, and K:dark-green points) light curves and Ferm gamma-ray light curves in 0.1–300GeV [1] for 3C 454.3.**

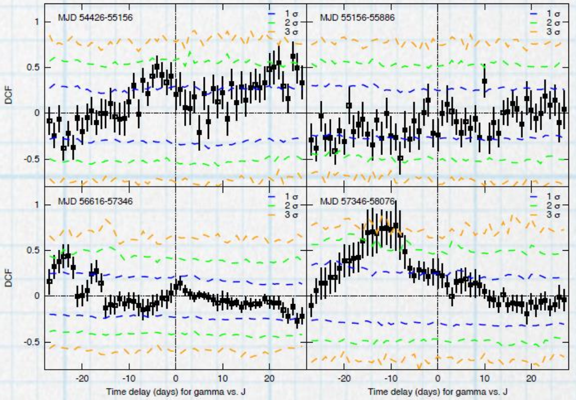



# Uh, oh…

No correlation at ~0 lag except for 3C454.3!

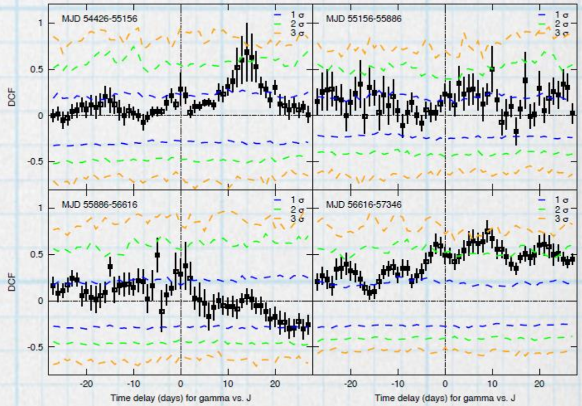
In fact, no correlations…

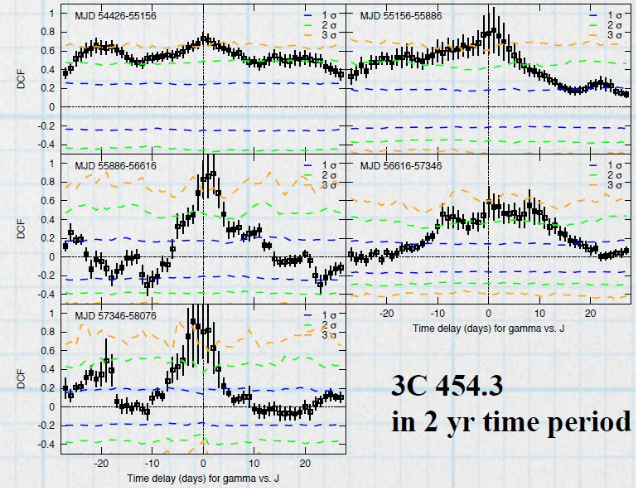
DCFs between gamma-ray and J-band fluxes of 3C 279, PKS 1510-089, and 3C 454.3 for every 2 year period.




3C 279 in 2 yr time period

PKS 1510-089 in 2 yr time period



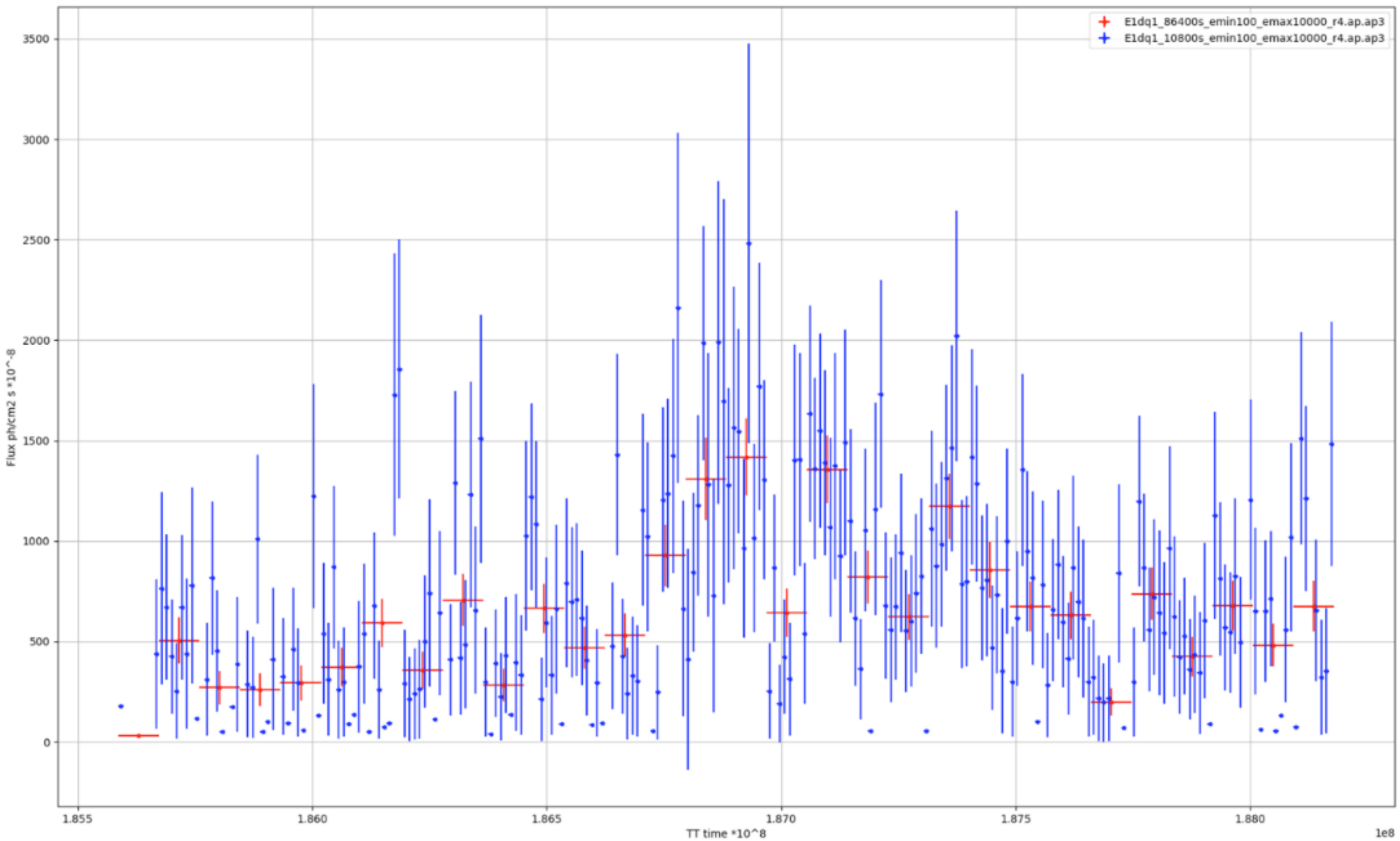

3C 454.3 in 2 yr time period

Sources change nature!

[= correlation function not well-defined…]

On shorter timescales, can see borderline significant correlations in objects besides 3C454.3 .. But at ~2 weeks…???

# Big complication – even in FSRQ, rapid variability present at GeV energies on 5 min (3C279) - ~hour timescales!



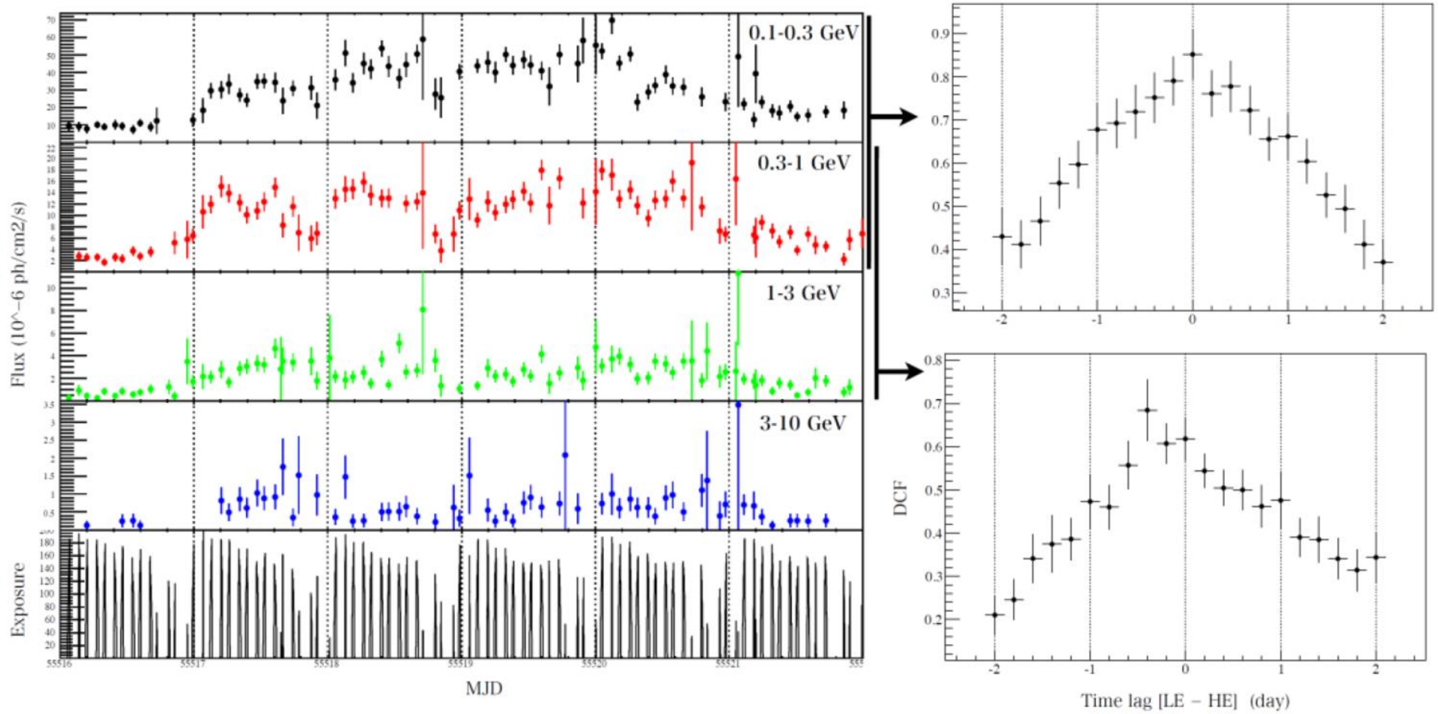

Bulgarelli et al., In prep.

Preliminary aperture photometry analysis of AGILE data for 3C 454.3 flare data, blue = 3hr binning, red =daily binning … N.B. is continuous, pointed observation! (Not Fermi scanning.) Now imagine we only had one 3hr observation/day (not atypical for IACT), i.e., we dropped 7/8 of the blue points … GAPS=BAD!

# Spectral Evolution on Short Timescales?

[work by S. Saitoh]

## 3C454.3 2010 flare




TS>10, Γ=2

**Fig. 2:** ***(left panel)*** Sample light curves from the giant flare of the blazar 3C454.3 in 2010 shown for four different energy bands. The light curve points are obtained by integrating flux over the ~30 minute exposure windows shown in the bottom graph, properly taking into account the variation in exposure during the window. Note that there is clear evidence for fast and repeated variability (greater than factor 2 on ~0.5-1 hour timescales.) ***(right panels)*** Discrete correlation function computed between the 0.1-0.3 and the 0.3-1 GeV energy bands *(top)* and the 1-3 GeV *(bottom)* energy bands as a function of time lag/lead between the bands. Fluxes in the various bands do not behave identically, i.e., there is spectral evolution during the flare, and there is a moderate (~2 sigma) detection of a high-to-low energy lag above ~1 GeV.

# 3C454.3 2009 flare

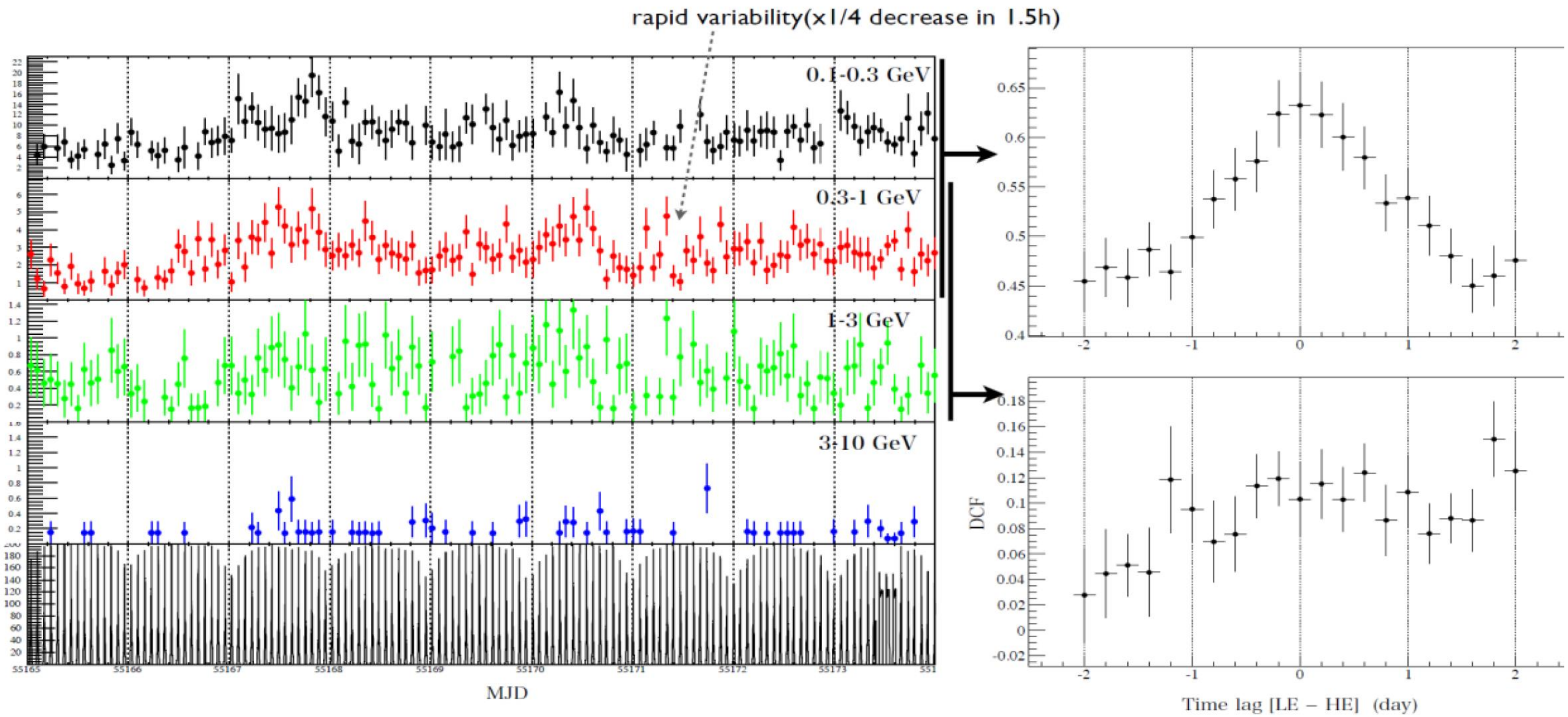
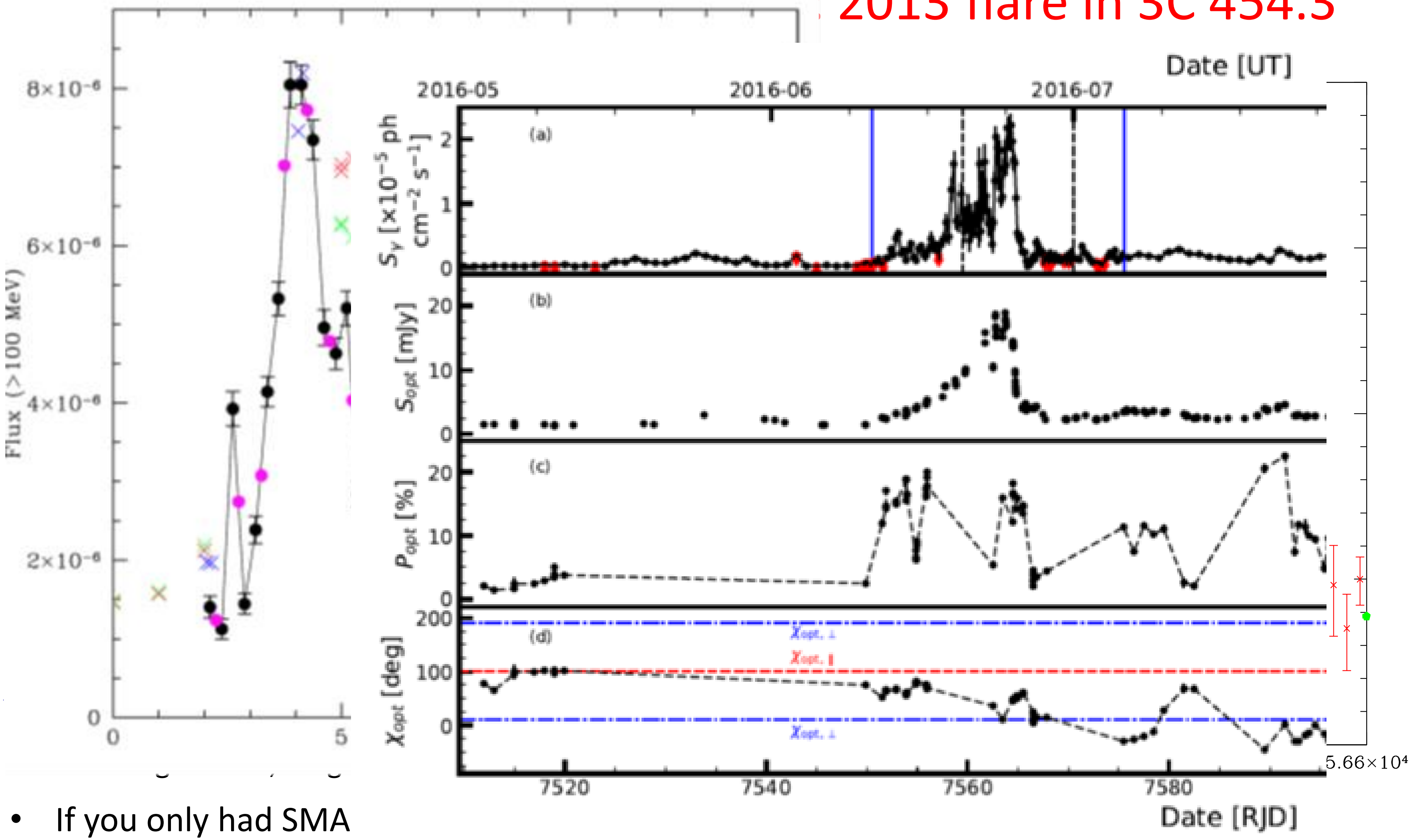



**Fig. 3**: Similar to Fig. 2, except the data is for the large 3C454.3 in 2009. Interestingly, the short timescale behavior below ~1 GeV is qualitatively similar, but *not* above 1 GeV – compare the 0.3-1 vs 1-3 GeV correlation functions in the lower of the two right panels.

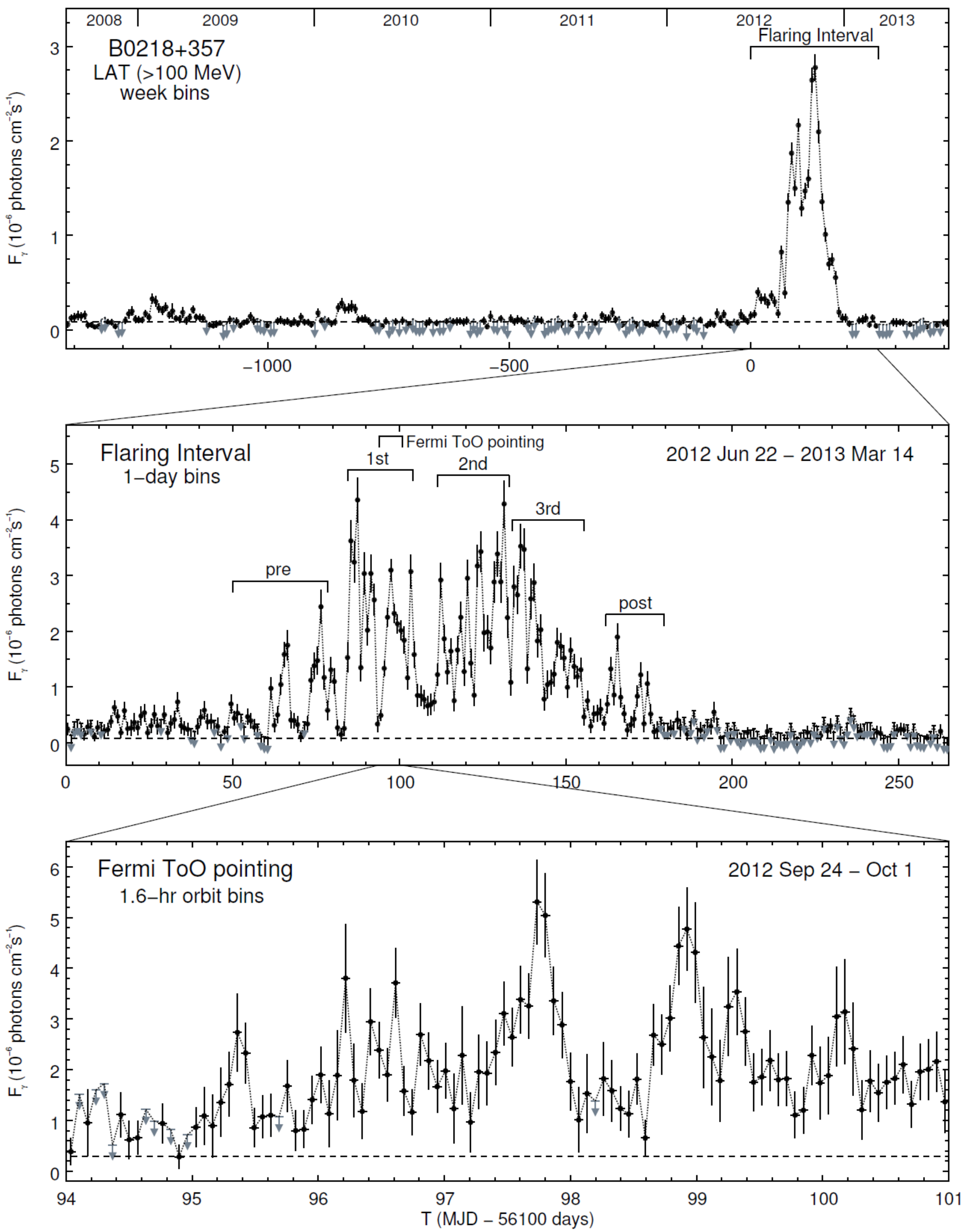
# 2013 flare in 3C 454.3




- If you only had SMA (e.g., SMARTS missed peak).
- On 2hr timescales, QUEST typically sees <10% variability (~15% at flare peak). But if as before (TBD), gamma-rays will have ~2x(+) variability on that timescale!?
- Yet on ~daily timescales, optical and gamma-ray fluxes track well??

Gravitational Lens Delayed Gamma-ray Flares in B0218+357

Cheung et al. 2014



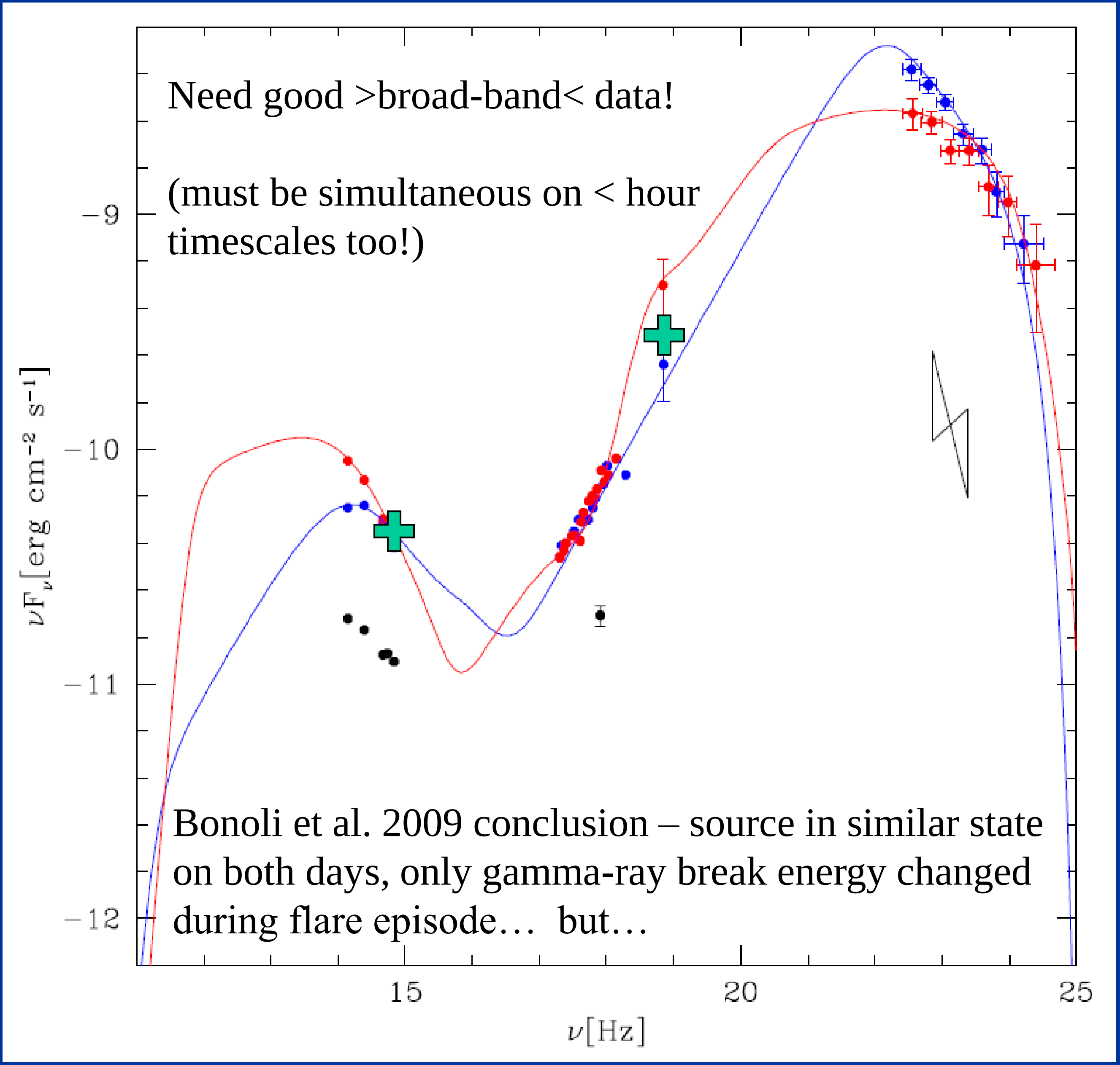
# Take-Away Points

- In the brightest flares, there is strong evidence for variability on < 3hr timescales, the shortest binning time typically used in Fermi light-curve analysis.
- <30 minutes variability possible, but not so common
- Spectral variability *is* present on these short timescales too.
- => DON'T USE DAILY bins for SED analysis!
- Variability characteristics useful for identifying "states"
- *Pointed mode* Fermi observations + ~*continuous* multi-wavelength coverage (not one or two snapshots per night) are essential for unraveling what's going on. *THERE is action on < Fermi scanning timescale, e.g., initially missed Crab flares…*

- Rapid variability is a problem for GeV blazars too…!!

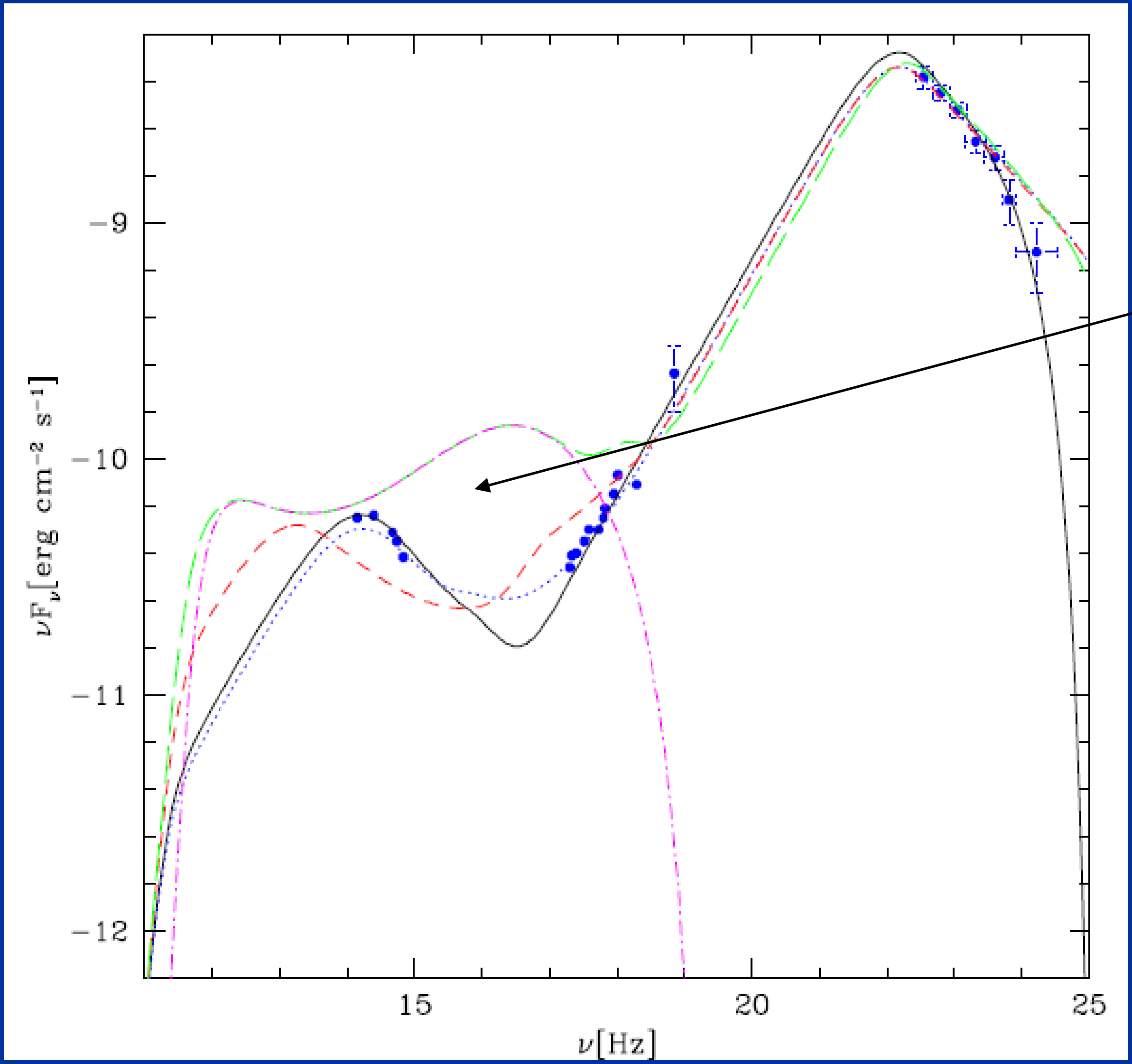
- Connection between optical/NIR and GeV not entirely obvious...

One zone fit to 3C 454.3 Dec 2-3 2009, Follow Bonoli et al. 2009…. Except Include SMARTS NIR/opt



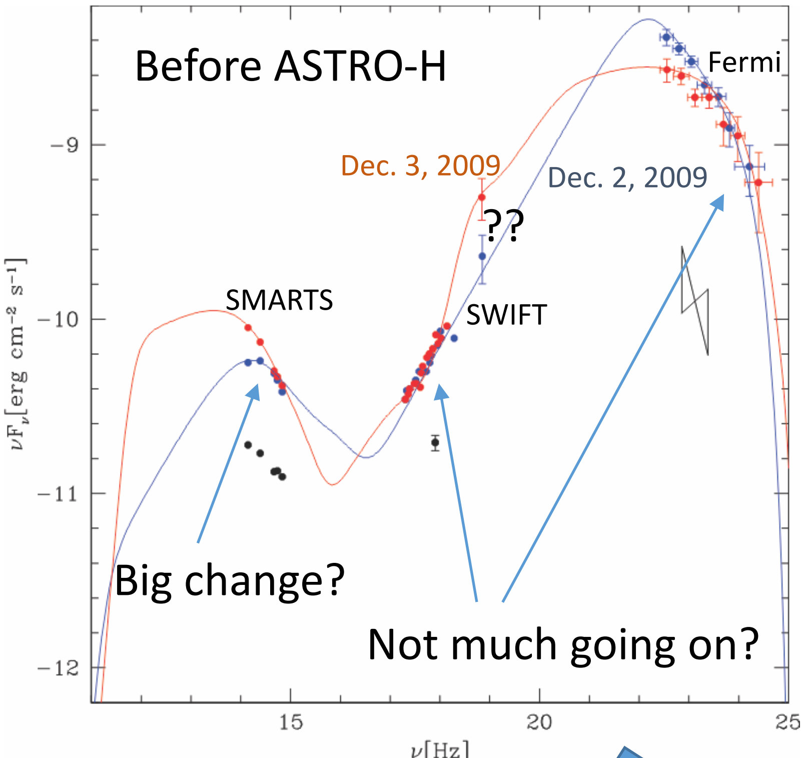
Keep Basic Model Same –

Fiddle With Bulk Lorentz Factor and High-Energy Electron Cutoff

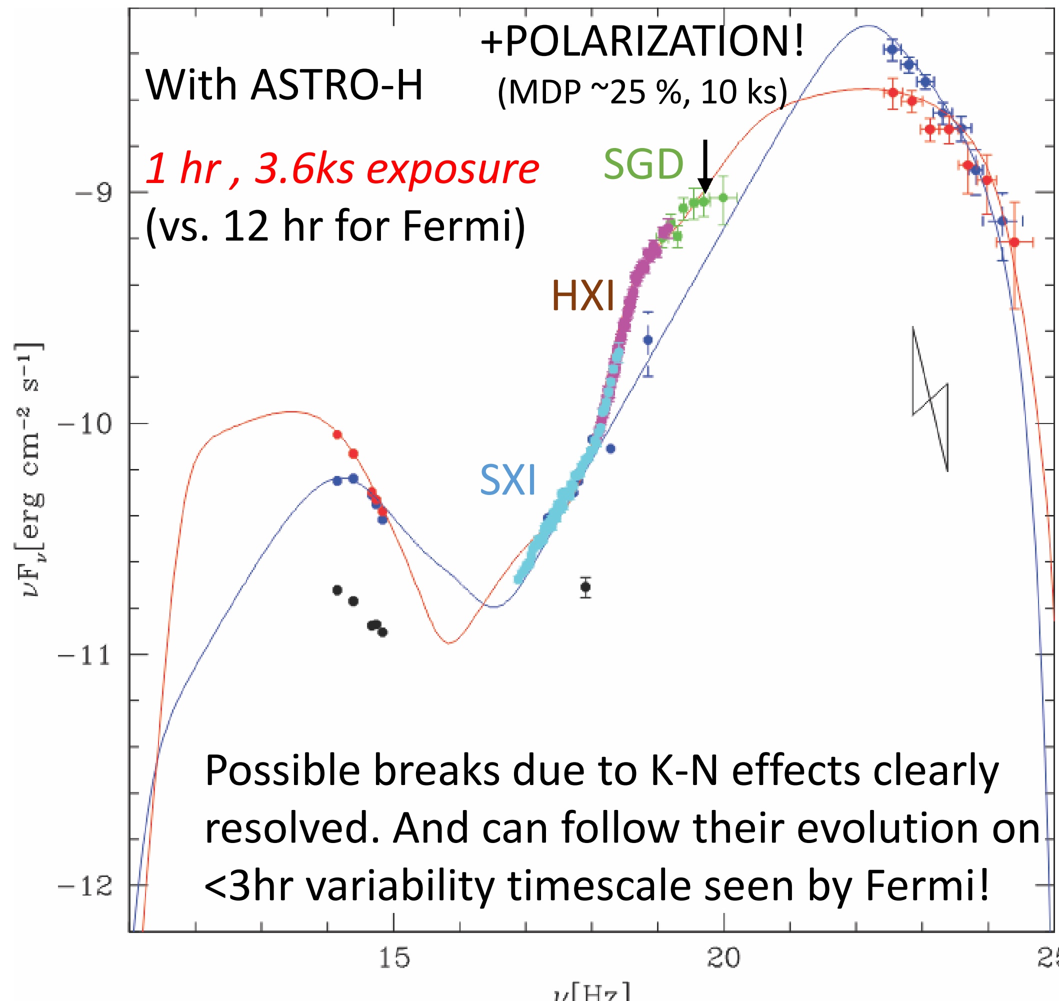



Is this kind of behavior ruled out?

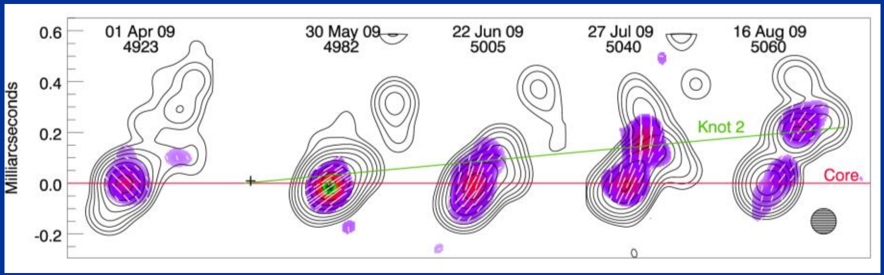
If ASTRO-H had been available during big Fermi blazar flares, we would have significantly better understanding of source like 3C454.

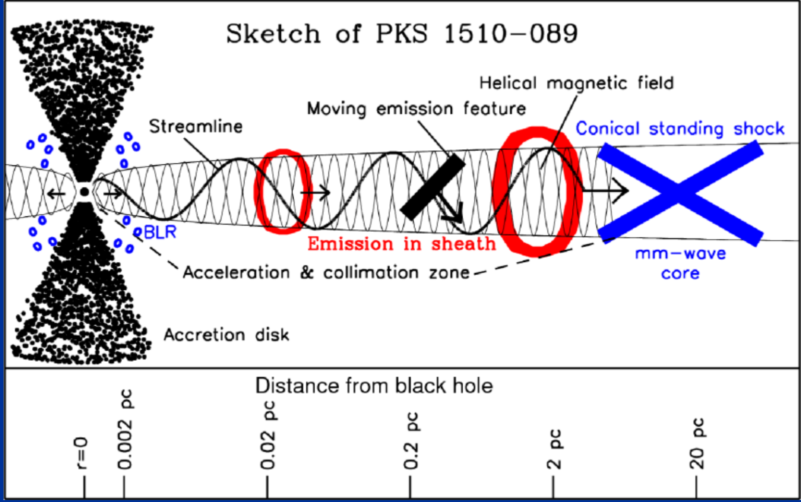



3C454 on two nights in December 2009…



# What to do?[A. Marscher]



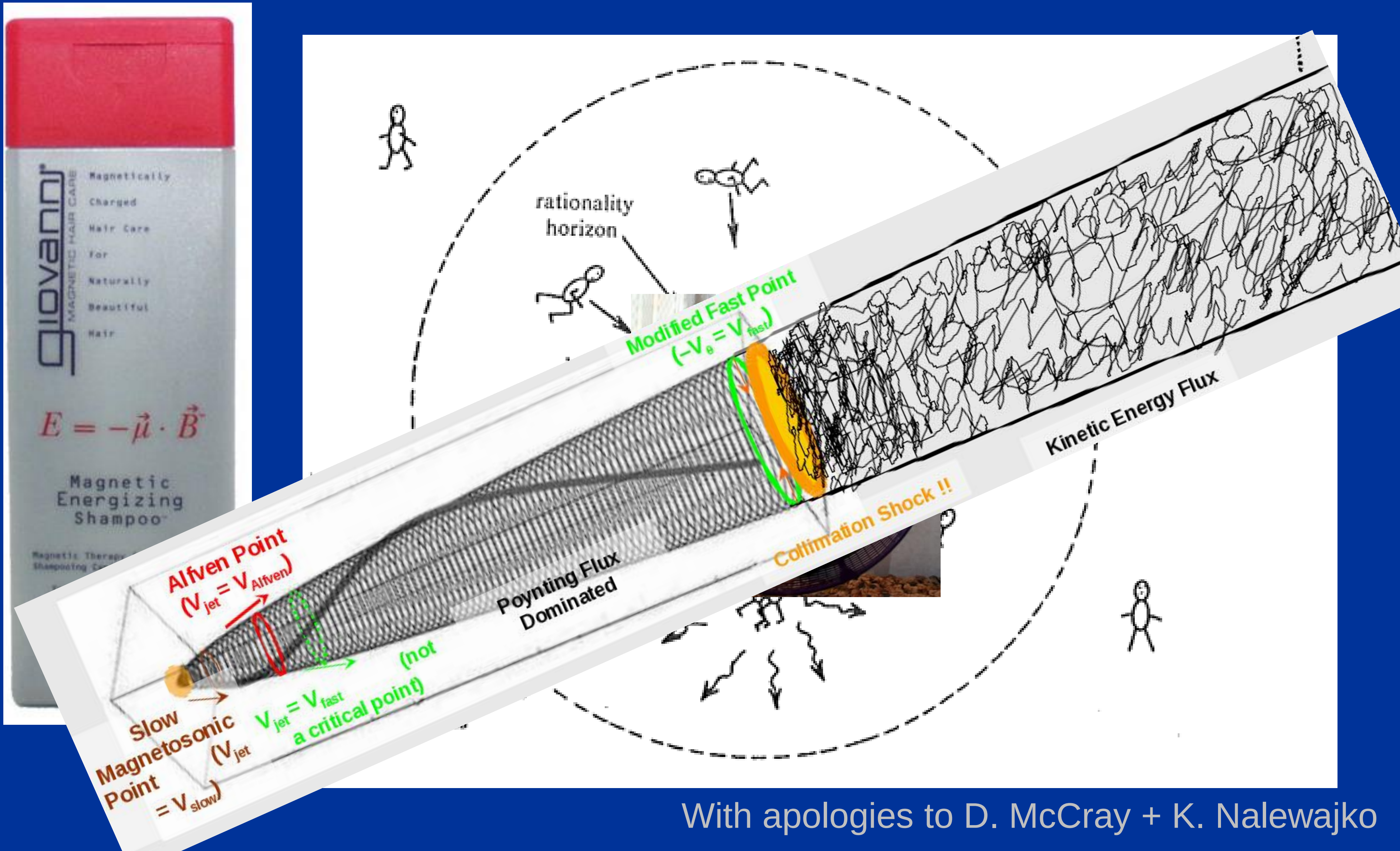

1. Many γ-ray flares occur as "blob" passes through or continues downstream of core, a "steady" feature, e.g., standing (recollimation?) shock.

2. Some flares - include multiple wavebands, others are "orphans" → energy range of power-law distribution of electrons is sometimes broad, sometimes narrow; not all events accelerate electrons to high enough energies or involve enough seed photons to make γ-rays.

3. It is clear that the multi-waveband emission of blazars is complex, *with multiple components possibly active at any given time* and some having low duty cycles.

4. This means: (1) less complete observational programs can give misleading results, [need large sample + good broad-band variability sampling] , (2) we need to maintain a long-term comprehensive program to sample the range of behavior in order to develop realistic models.

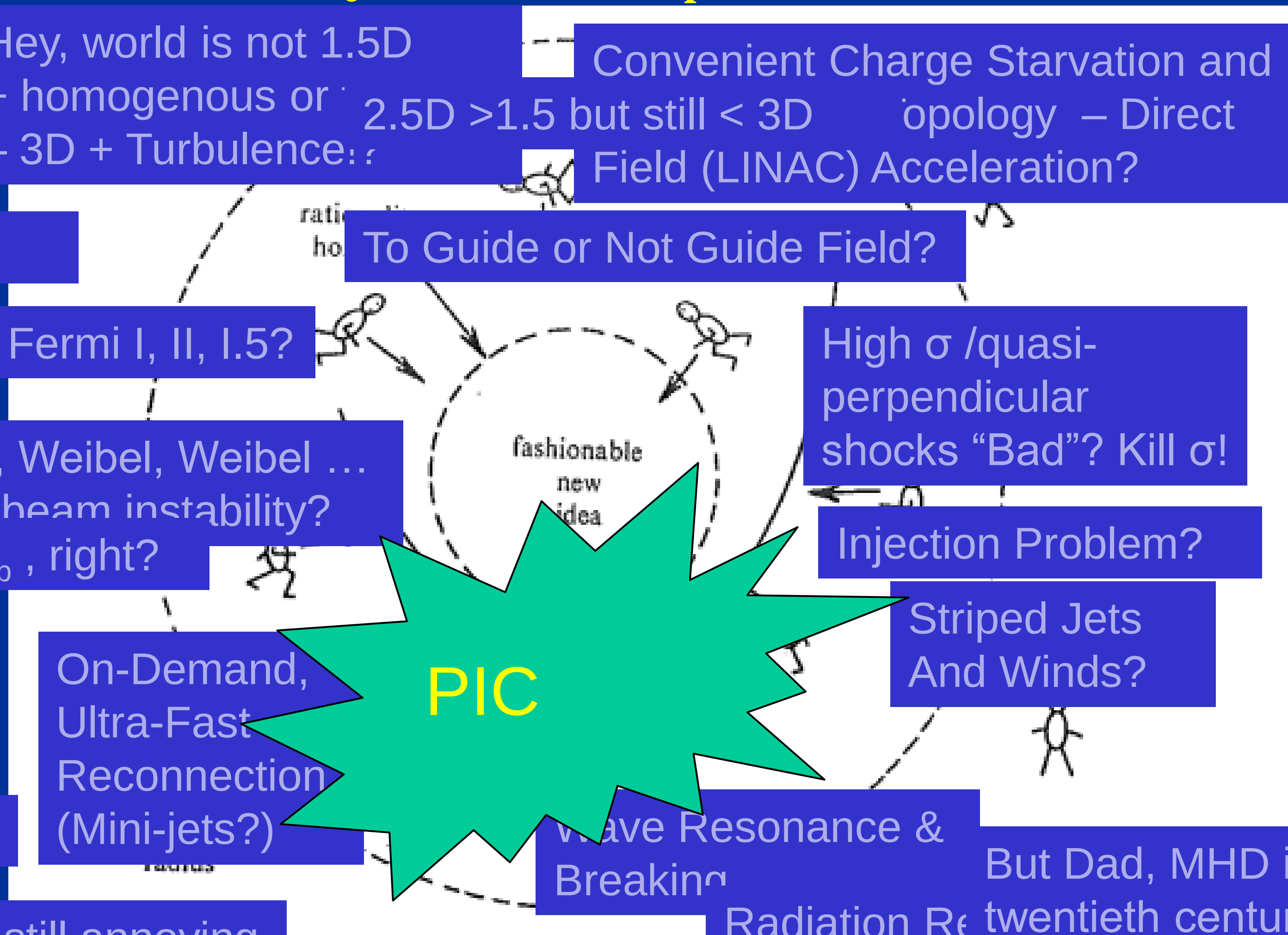
# Recent Progress in Understanding Particle Acceleration in Astrophysical Sources?




With apologies to D. McCray + K. Nalewajko

# Recent Progress in Understanding Particle Acceleration in Astrophysical Sources:

## Better Observations + Bigger Computers = Neither Sources nor Acceleration Theories Quite What Expected ....




Hey, world is not 1.5D
+ homogenous or
– 3D + Turbulence:

2.5D >1.5 but still < 3D

Convenient Charge Starvation and
opology – Direct
Field (LINAC) Acceleration?

Drift, Kink Mode?

To Guide or Not Guide Field?

Fermi I, II, I.5?

High σ /quasi-perpendicular shocks "Bad"? Kill σ!

Weibel, Weibel, Weibel …
Two beam instability?

$L_{AGN/GRB} \sim 40\ c/\omega_p$ , right?

Injection Problem?

Striped Jets
And Winds?

Tearing Modes

On-Demand,
Ultra-Fast
Reconnection
(Mini-jets?)

PIC

Ion Ring Instability

Wave Resonance &
Breaking

But Dad, MHD is so
twentieth century …

Radiation Re
Feedback/Drag?

$m_e$ vs. $m_p$ still annoying

Wi … (1979)

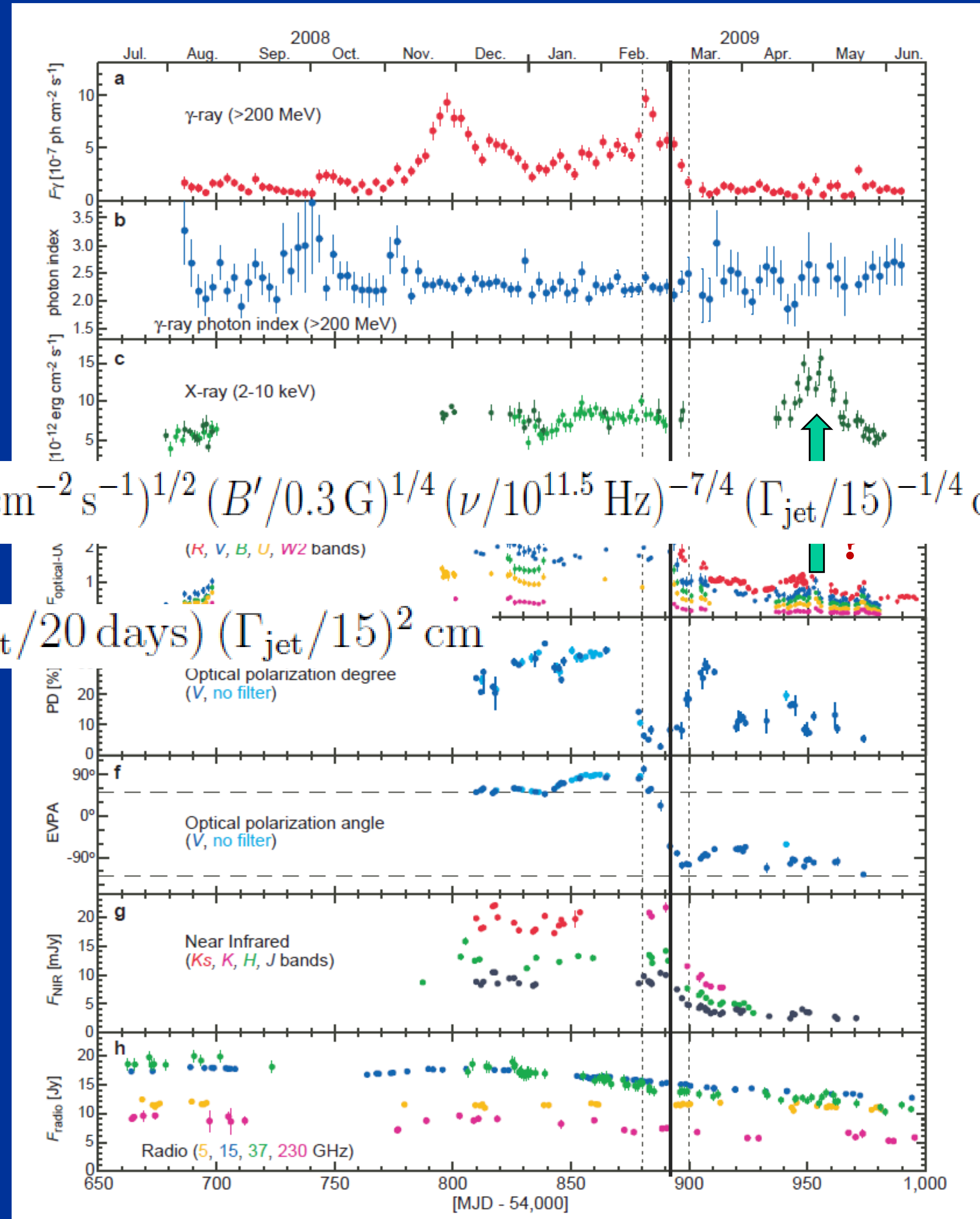
## General Conclusions:

- AGN, both jetted and non-jetted, are more interesting/extreme than we had thought. EGRET showed us we were only seeing the tip of the iceberg. With 2000+gamma-ray blazars, Fermi has shown a lot more of the iceberg, but there are still only ~30 flare events bright enough to probe the shortest variability timescales at GeV energies… More to discover! [Polarization too?]
- Lots more TDE/changing look AGN coming – gamma-rays important to unraveling what is going on… (both in corona + jet)
- To address variability issues, need photon bucket. APT? Low-threshold IACT? (in principle could go down to ~10 GeV) STARLINK approach – launch lots of Fermi's?
- Time coverage gaps = bad. For IACT, spread in longitude so can provide *CONTINUOUS time coverage?*
- There is other cool science can do at gamma-rays like nuclear astrophysics, and follow-up of multi-messenger sources (LIGO) and low-duty cycle AGN flaring => don't try to do everything with one mission?!

3C279 Fermi Multi-Wavele ngth Campaign

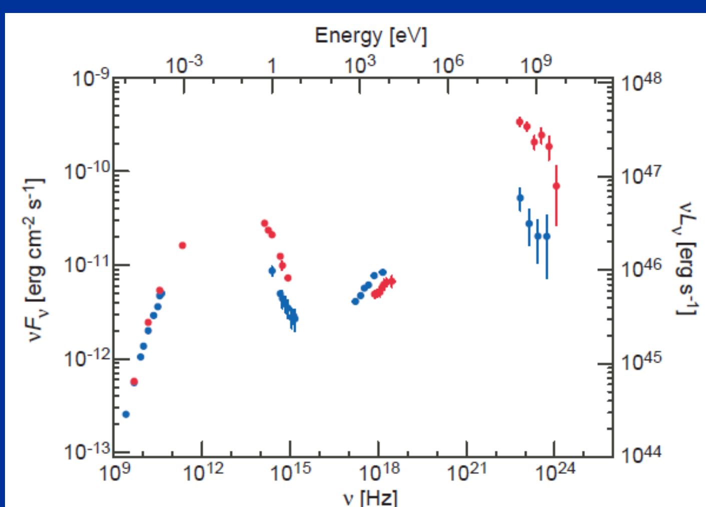
(Polarization Swing)

Abdo et al. (Hayashida) 2010




$$R_{\rm blazar} < 5\times 10^{16}\,(\nu F_\nu/2\times 10^{-11}\,{\rm erg\,cm^{-2}\,s^{-1}})^{1/2}\,(B'/0.3\,{\rm G})^{1/4}\,(\nu/10^{11.5}\,{\rm Hz})^{-7/4}\,(\Gamma_{\rm jet}/15)^{-1/4}\,{\rm cm}$$

$$r_{\rm event} \geq \Delta r_{\rm event} \sim 10^{19}\,(\Delta t_{\rm event}/20\,{\rm days})\,(\Gamma_{\rm jet}/15)^2\,{\rm cm}$$



# A different kind of flare from the "canonical" 3C 454.3….



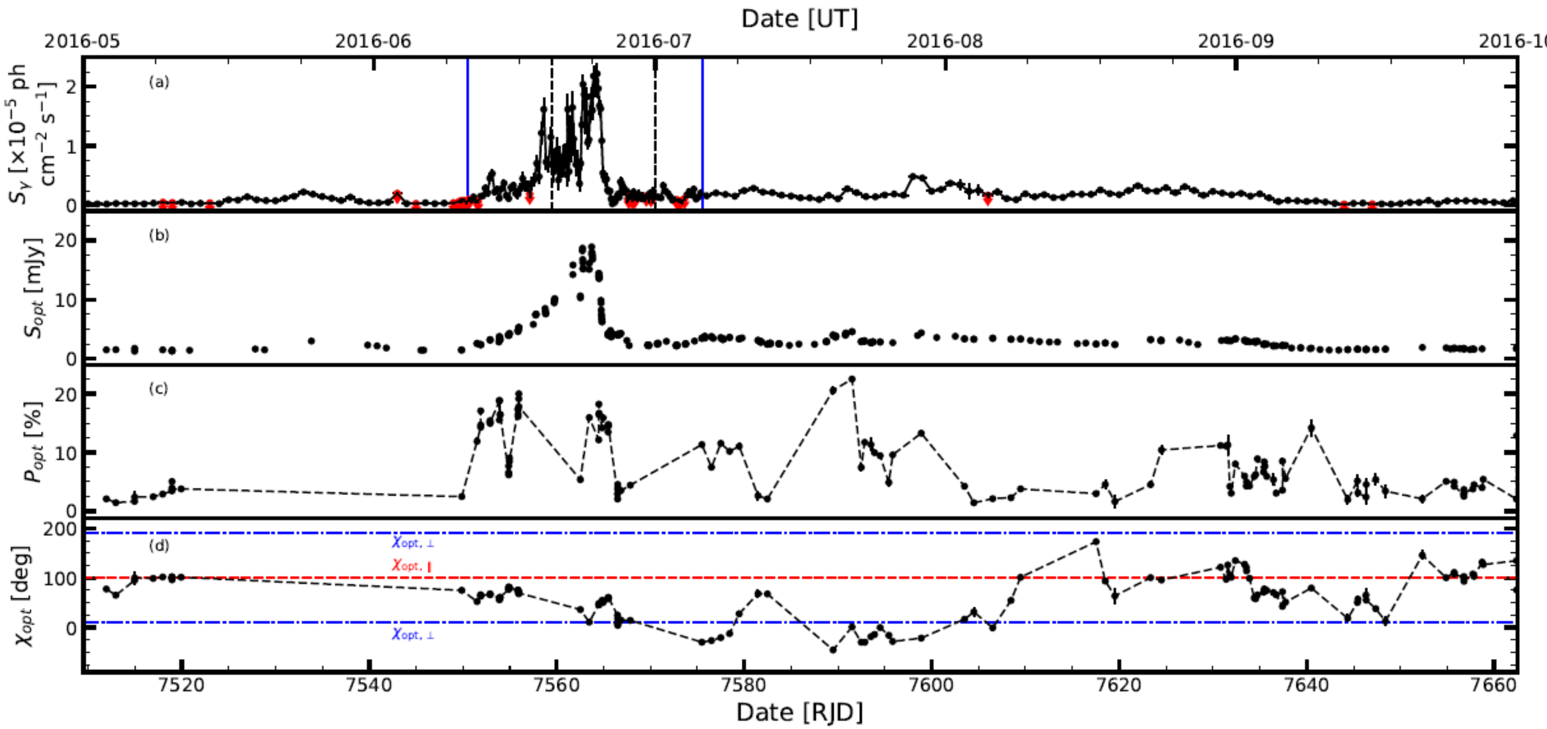



**Figure 1.** Flux and polarization vs. time of 3C454.3. The date 2016 July 1 is RJD: 7570.5. (a) *Fermi*-LAT $\gamma$-ray flux with varying time bins; (b) optical light curve in $R$ band; (c) degree of optical linear polarization; (d) position angle ($\chi_{\rm opt}$) of optical polarization. In (a), the outer, blue, vertical, solid lines mark the division between one-day and six-hour $\gamma$-ray binning, while the inner pair of black, vertical, dashed lines mark the division between six-hour and three-hour binning. Upper limits on 24 *Fermi*-LAT data points are marked with a downward-facing, red arrow. In (d), the horizontal lines correspond to polarization angles that are parallel ($\chi_{\rm opt,\parallel}$, red dashed) and perpendicular ($\chi_{\rm opt,\perp}$, blue dash-dot) to the average parsec-scale jet direction of -79° determined using 43 GHz VLBA imaging of the blazar between Jan 2016 and Jun 2017 (see §5.1.1).