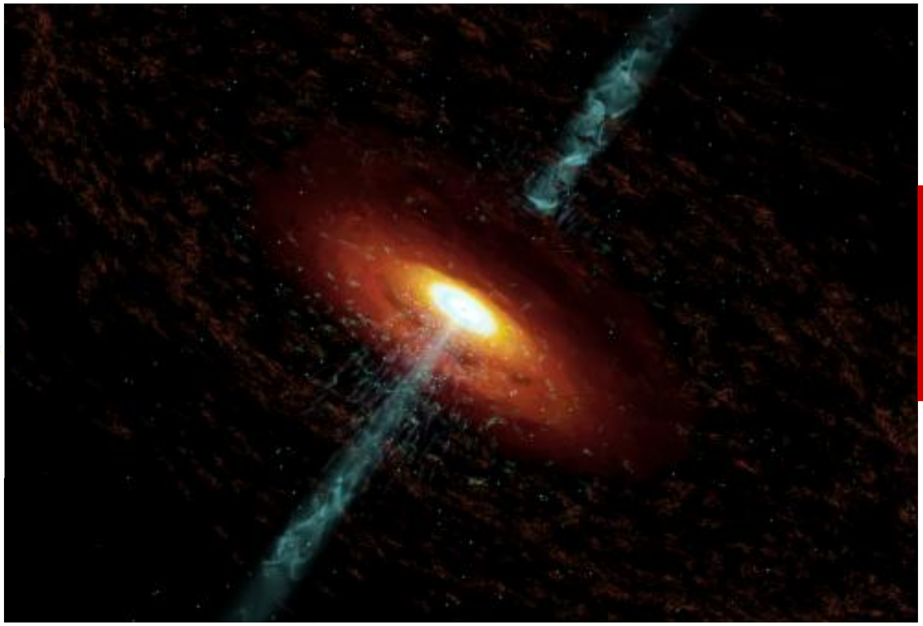

Analysis of Multi-waveband Observations of Blazars

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Research Web Page: www.bu.edu/blazars

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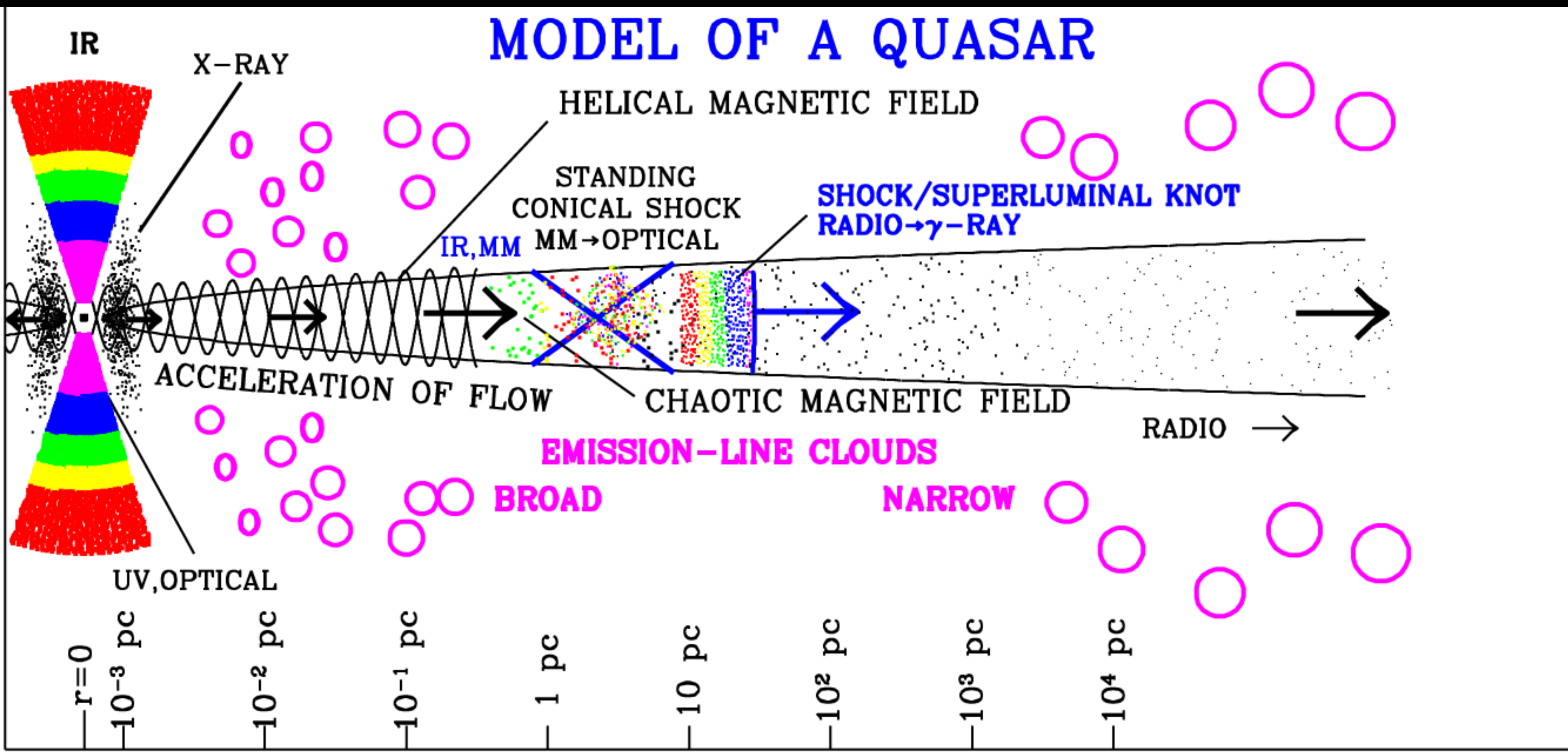
Emission Regions in a Blazar

- Many possible sources of "seed" photons that electrons in jet scatter to X-ray & γ-ray energies

But where/how are photons at different wavebands actually generated?

➔Need multi-waveband analysis to determine



Forming Spectral Energy Distributions (SEDs)

SED: plot of $\log_{10} \nu F_\nu$ vs. $\log_{10} \nu$

Radio – far-IR: observations measure flux density F_ν

Near-IR, optical, UV: observations measure magnitude *m*

- **Need to correct for extinction (from NED or, if available, from a paper where it is determined more accurately for the object)**
- **Cardelli et al. (1989, ApJ, 345, 245) give relations between visual extinction & that at IR & UV wavelengths**
- **Convert to flux density according to formula**

$F_\nu = 10^{k-0.4m}$ mJy   where *k* depends on filter used. Examples:

Band	log ν_{center}	*k*	Band	log ν_{center}	*k*	Band	log ν_{center}	*k*
K	14.140	5.824	I	14.574	6.407	B	14.833	6.629
H	14.262	6.031	R	14.670	6.489	U	14.920	6.258
J	14.387	6.205	V	14.736	6.561			

For Swift UVOT bands, see Poole et al. (2008, MNRAS, 383, 627)

Forming SEDs (part 2)

X-ray observations: Measurement of photon counts is usually made in a number of photon-energy bands. If these are wide, spectrum is modeled, including intervening photoelectric absorption. For blazars, either a single or broken power-law spectral model is fit to the data. This is done with XSPEC (or equivalent) to determine:

"Normalization" N and "photon index" Γ

Photon flux $\phi = N\, E_{\mathrm{keV}}^{-\Gamma}$ phot cm^{-2} s^{-1} keV^{-1}

- **Need to multiply by photon energy E & apply conversion 1 keV = 1.602x10^{-9} erg; ν (1 keV) = 1 keV/h = 2.42x10^{17} Hz**

→ $F_\nu = 660\, N\, E_{\mathrm{keV}}^{-\alpha}$ μJy

→ where $\alpha = \Gamma - 1$ is the spectral ("energy") index

Forming SEDs (part 3)

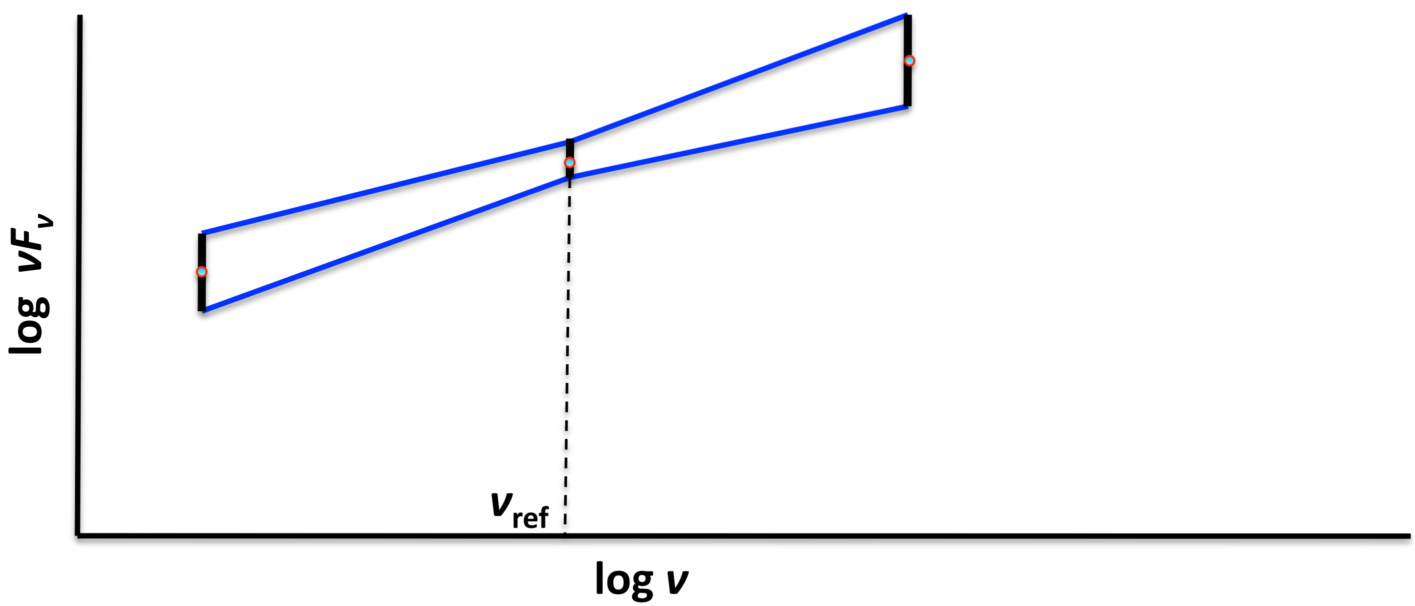
$F_\nu = 660\, N\, E_{\mathrm{keV}}^{-\alpha}$ μJy   where $\alpha = \Gamma - 1$

- Both N and Γ have observational uncertainties (from χ^2 analysis), so spectrum is usually represented by "bow-tie" shape

Center at 1 keV: uncertainty only from error in N (x conversion factors)

Low- & high-frequency ends: F_ν from above formula; uncertainty:

$\sigma_F(\nu) = (\nu/\nu_{\mathrm{ref}})^{-\alpha}\, [\ln(\nu/\nu_{\mathrm{ref}})^2 \sigma_\alpha^{\;2} + \sigma_F^{\;2}(\nu_{\mathrm{ref}})]^{1/2}$, usually $\nu_{\mathrm{ref}} = 2.42 \times 10^{17}$ Hz



Forming SEDs (part 4)

γ-ray observations: Measurement is in photon counts at different energies. Because point-spread function (PSF) is relatively large & energy-dependent, need to model flux & spectra of potential sources in entire field.

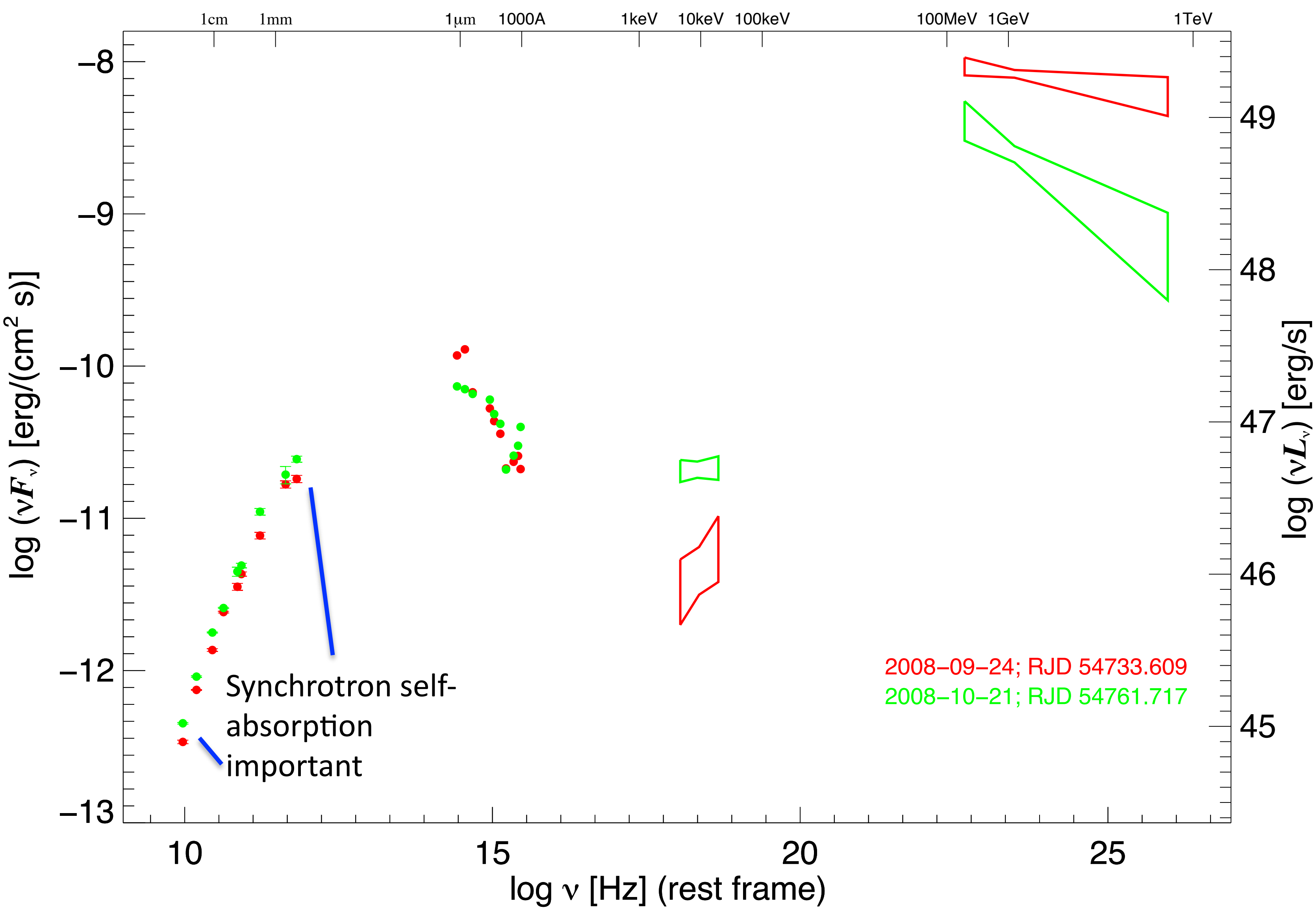
For blazars, either a single or broken power-law, or log-parabolic spectral model is fit to the data. Use Fermi documentation for spectral analysis to find how to convert result to flux density in ergs cm^{-2} s^{-1} Hz^{-1} (note that 1 GeV = 2.42×10^{23} Hz)

Best: do full spectral fitting to get flux in each of a number of energy bins – requires a high photon count

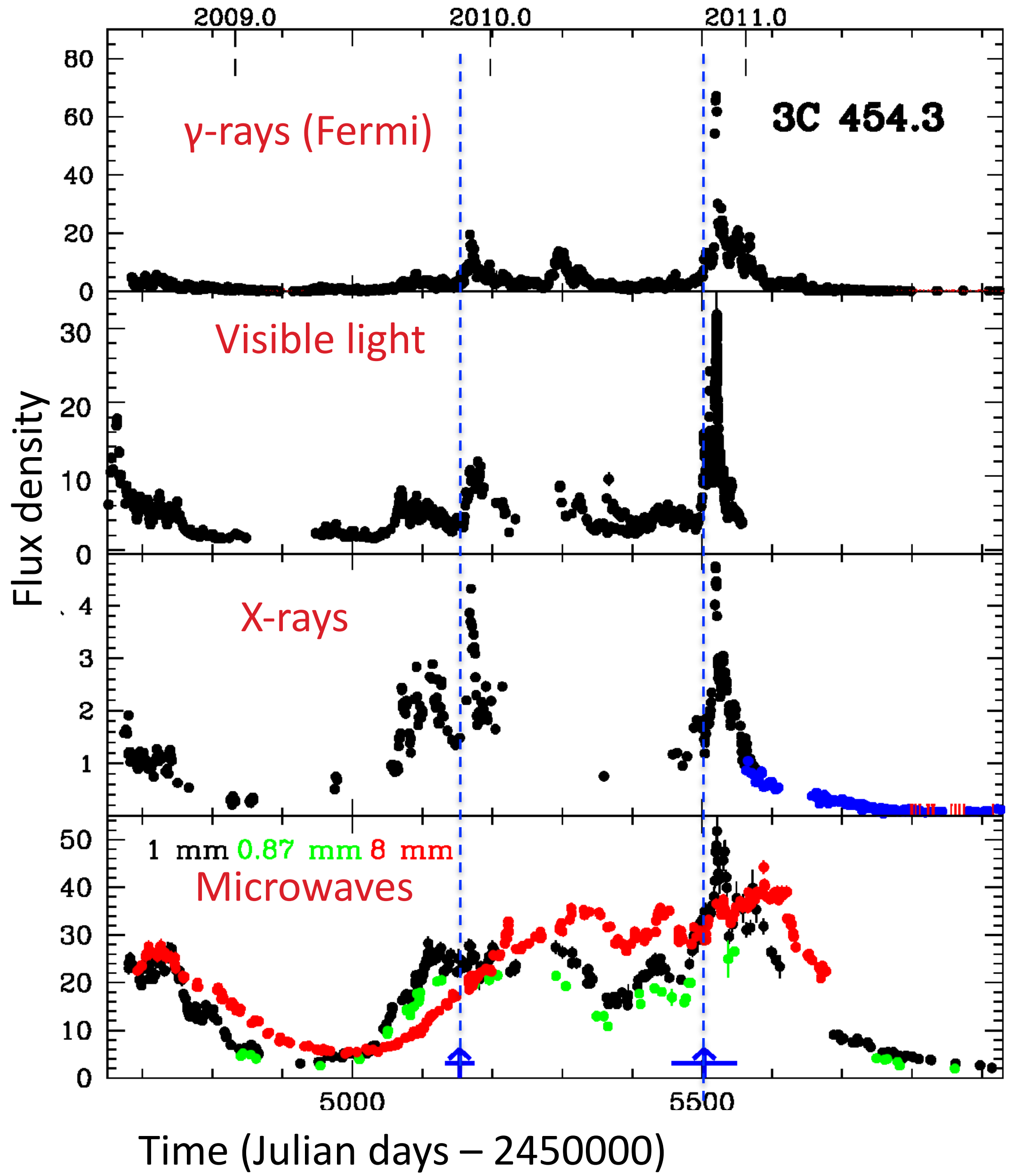
Alternative: assume a given spectral model, solve for free parameters

Low photon counts: perform alternative over weeks or months to get spectral parameters, then adopt these parameters to determine flux on shorter time-scales

Sample SED (BL Lac object AO 0235+164)



Analysis of Light Curves of Blazars



Seems possible to describe as quiescent periods plus well-defined flares

-Can we confirm with objective analysis?

Simultaneity or time delays of variations at different wavebands can provide relative locations of flares at different wavebands

- But are variations across bands really correlated, and if so, how can we measure the time lags?

Analysis of Light Curves (part 2)

Power Spectra ("power density spectrum," PDS, or "power spectral density," PSD

- **Determines amplitude of flux variations as a function of time-scale (or its inverse, variational frequency)**

Advantages:

1. **Objective method**
2. **Can reveal periodicities (as spikes at single time-scale) if they exist in the data**

Problems to overcome:

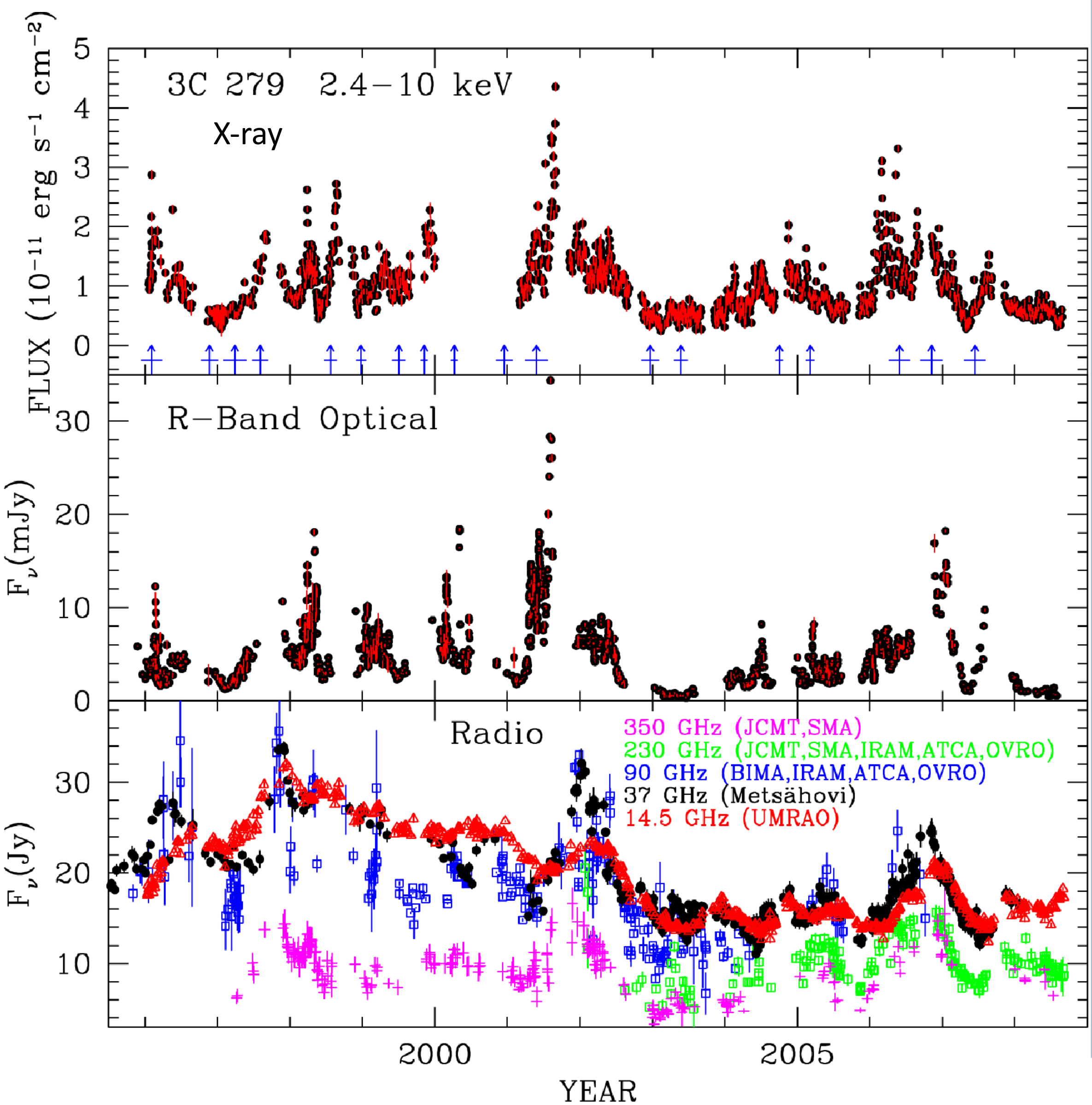
1. **Uneven sampling of data**
2. **Limited time over which data are available**

   - Light curve is affected by variations occurring on longer time-scales than light curve covers ("red noise leak")

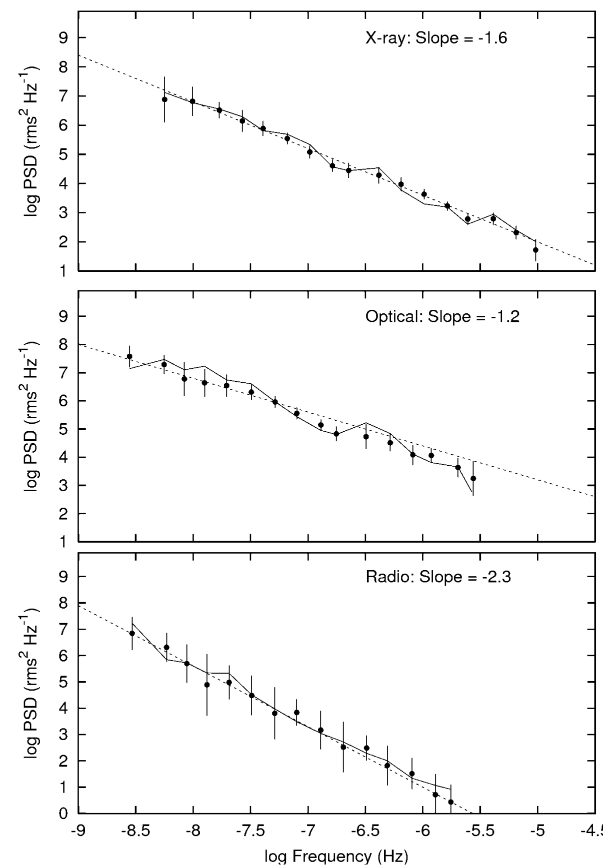
→ Need to simulate light curves (see description of Uttley et al. method by Chatterjee et al. 2008, ApJ, 689, 79)

- Generally, slope of underlying PSD will be different from "raw" slope

Flux Variability of Blazars: Power-law Power Spectra

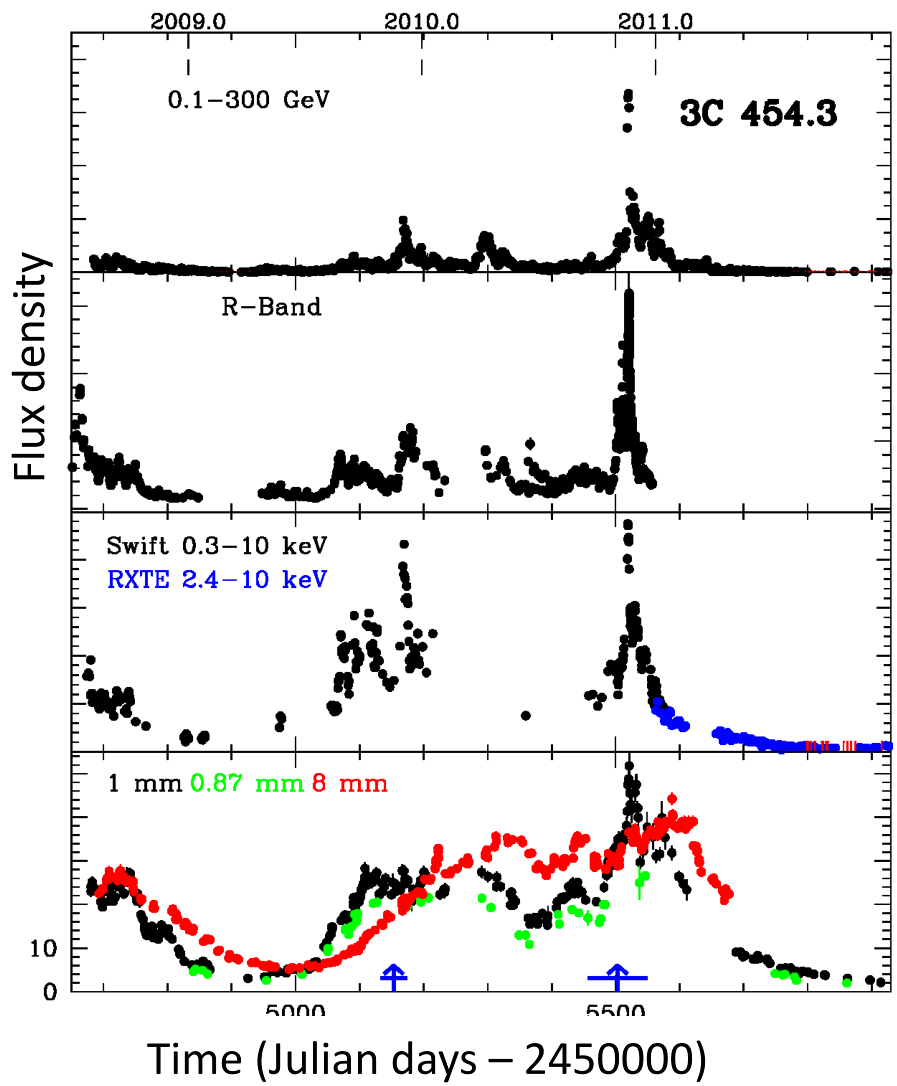


Power spectrum of flux changes follows a "red noise" power law → long-term random fluctuations dominate



Chatterjee et al. 2008 ApJ

Analysis of Light Curves of Blazars (Part 3): Correlations of variations across wavebands



Correlations are often obvious by eye, but

1. **More subtle correlations than are obvious may be present**
2. **Some apparent correlations might occur by random chance**
3. **We need a method to determine significance of correlations**
4. **We want to determine the time lag of variations across frequencies**

Analysis of Light Curves (part 4)

Discrete Cross-Correlation Function (Edelson & Krolik 1988, ApJ, 333, 646) – most commonly used

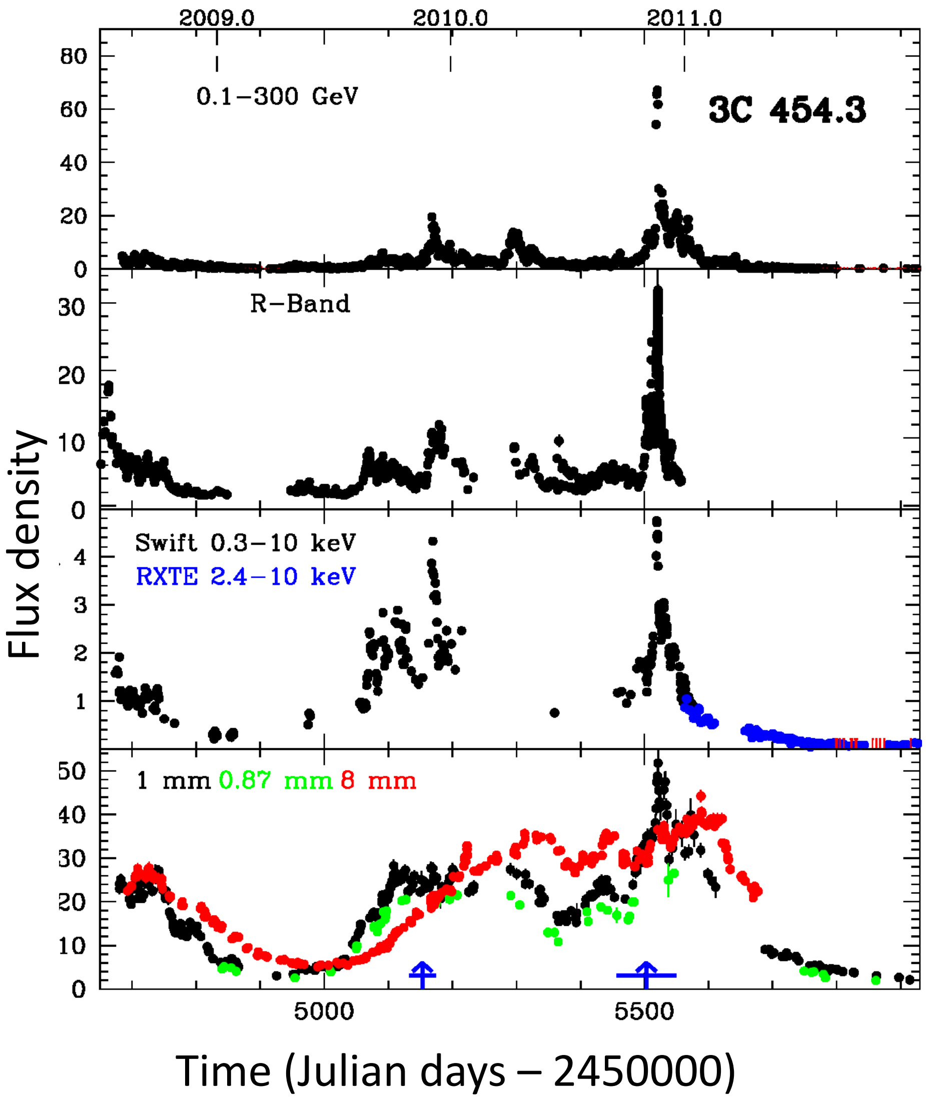
- **Light curve can be unevenly sampled**
- **Usually one still needs to average data within time bins**

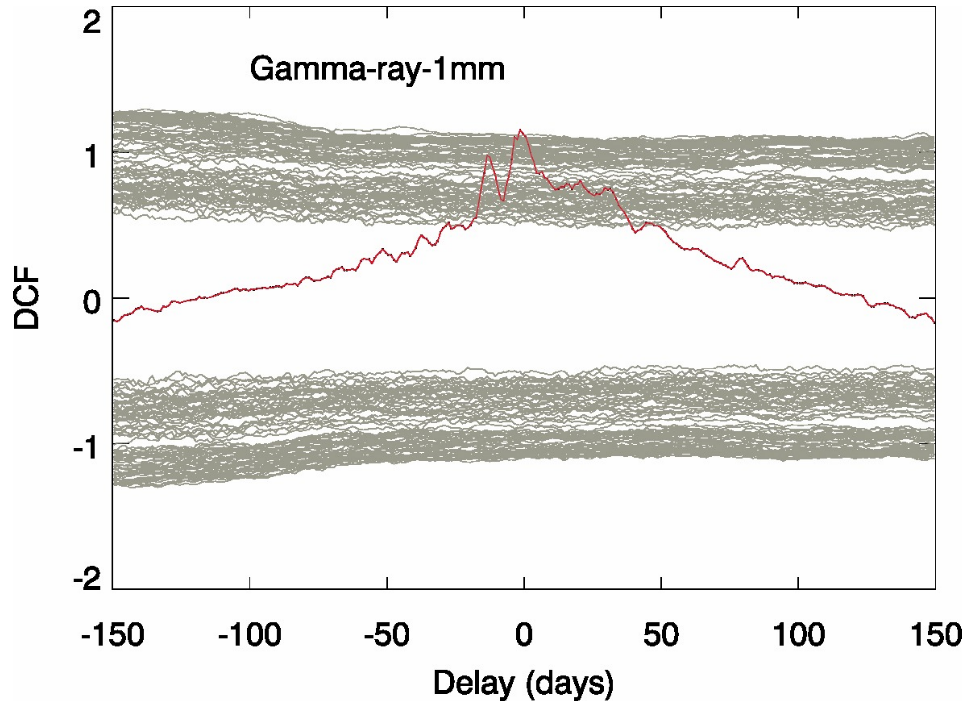
Evaluation of significance of correlations is tricky because blazars are highly variable, so correlations of events at different wavebands often occur by random chance

→ Need simulations (refer to Chatterjee 2008 for description)

1. **Determine PSD of variations over as long a time period as possible**
2. **Use this PSD as basis for obtaining many (100s, even 1000s) of simulated light curves *<u>with the same time sampling as the actual data</u>***
3. **Determine fraction of simulated light curves where similar correlation occurs**

Example of Correlation Study (Wehrle et al. 2012)





Red: DCF

Gray: Probability of DCF occurring by chance = 0.3% (i.e., 3-σ confidence)

Lowest positive: PSD slope = -1.0

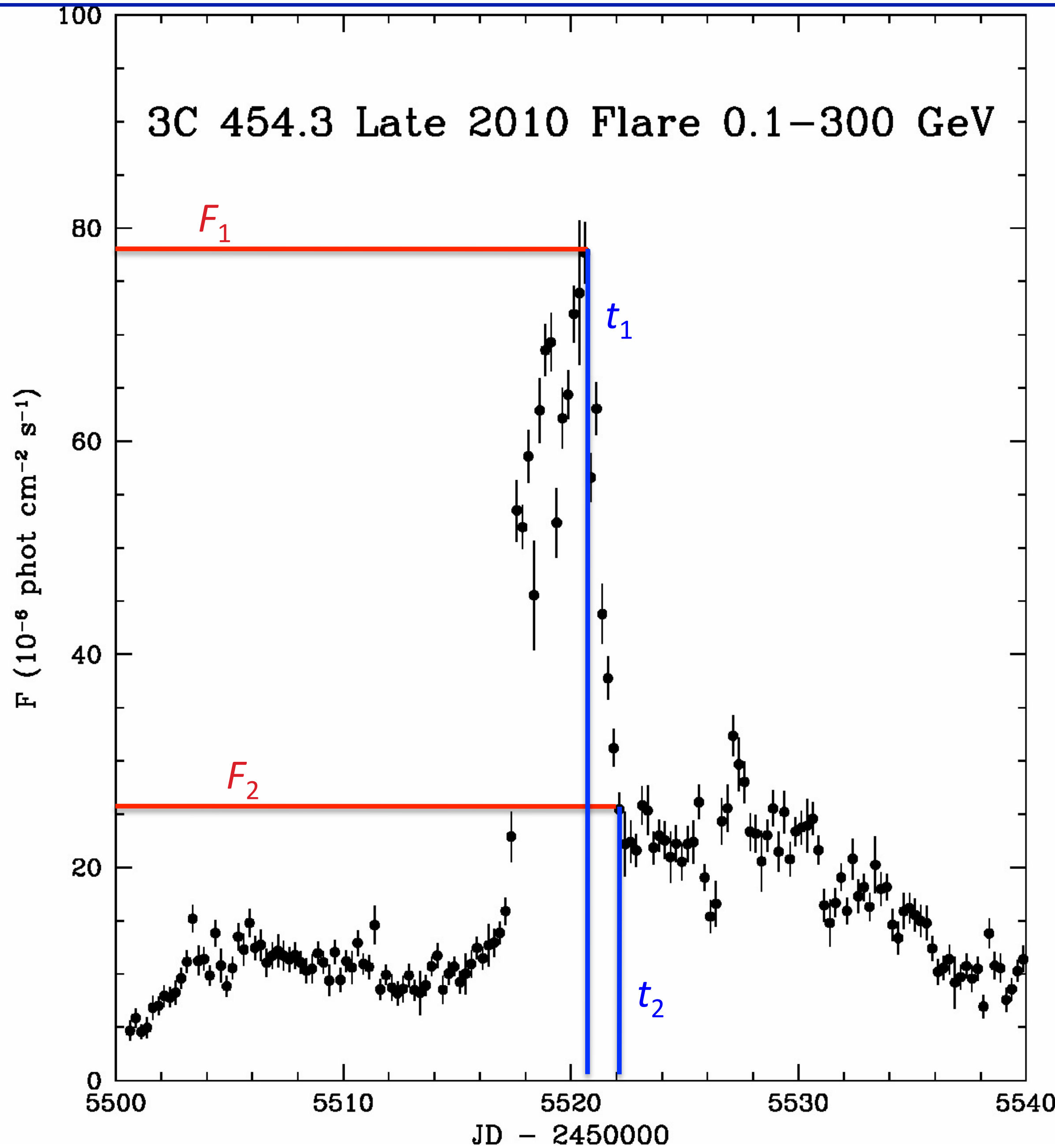
Highest positive: PSD slope = -2.5

→Peak in DCF is statistically significant for any value of slope from -1 to -2.5

Time lag of γ-ray variations is 1.0±2.5 days

- But lower peak at ~−20 days may indicate complexity in flares

Time Scale of Variability of Flux Density in Blazars



Burbidge, Jones, & O'Dell (1974, ApJ, 193, 43) definition:

$t_{var} = (t_2 - t_1)/\ln|F_2/F_1|$

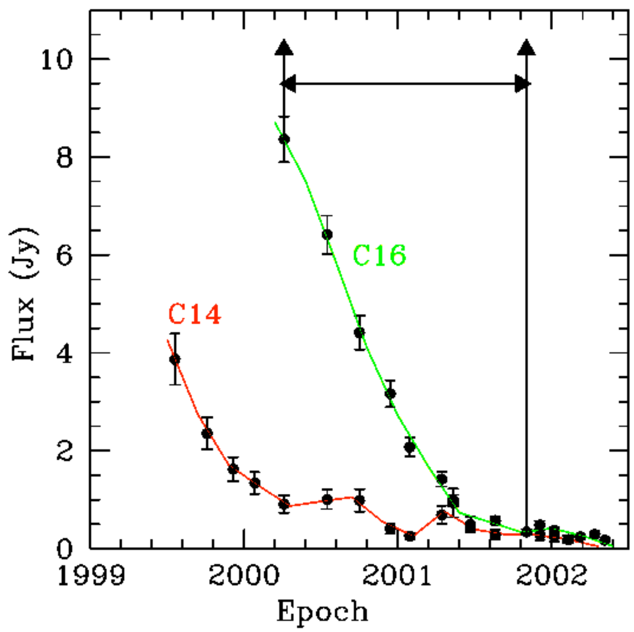
- **Best to do during a decline in flux**

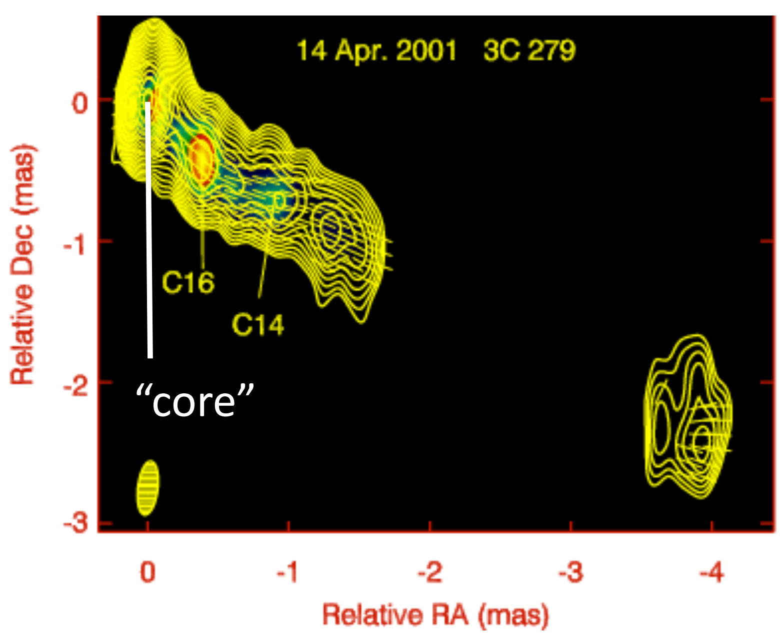
In order to change flux this fast, source cannot be larger than

$R_{var} \sim c\,[\delta/(1+z)]\,t_{var}$

where z is redshift &
δ is the Dopper factor for relativistically moving plasma:
$\delta = [Y(1-\beta\cos\theta)]^{-1}$
where β is speed in light units, Y is Lorentz factor, & θ is angle of velocity to line of sight

Time Scale of Variability of Flux Density in Blazars (Part 2)





Determining Doppler Factor

$\delta_{var} \approx R/[c\, t_{var}\,(1+z)]$

Jorstad et al. (2005, AJ, 130, 1418): Use VLBI to measure size, apparent speed, & light curve of a knot (“blob”) → δ_{var}

$\beta_{app} = \beta \sin\theta/(1 - \beta \cos\theta)$

$\delta = [\Upsilon(1-\beta \cos\theta)]^{-1}$

→Can solve for both Υ and θ

-method requires that light-travel effects determine time-scale (works at 43 GHz)

Cruder method: assume $\Upsilon \sim \beta_{app}$, $\theta \sim 1/\beta_{app}$

E. Valtaoja’s group: Use light curve of entire source to get t_{var} & get R by assuming that magnetic field & electron energy densities are equal (Readhead 1994)

-Hovatta et al. (2009, 494, 527): The two methods usually give similar results

Consequences of Rapid Variability of Flux Density in Blazars

If X-ray & Y-ray flares are simultaneous → produced in same location
If region is too compact, highest-energy Y-rays may pair produce before escaping

Threshold: $E_x E_Y > [mc^2]^2$ (m = mass of electron) in rest frame of plasma
Cross-section: $\sigma_{pp} \approx 2\text{x}10^{-25}$ cm^2 [falls as ~ $[mc^2]^2/(E_x E_Y)$ above threshold]

If the luminosity of X-ray photons with observed energy ~ E_x (perhaps between E_x & $2E_x$ is L_x, then the density of X-ray photons is $n_x \sim L_x/[4\pi R^2 c(1.5E_x)(1+z)/\delta]$ and the optical depth to $e^{\pm}$ pair production is

$$\tau \sim \sigma_{pp} n_x R \sim 600\, F_{x,\,\mu Jy}\, t^{-1}_{var,days}\, (1+z)^{2\alpha}\, d^2_L\, \delta^{-(4+2\alpha)}$$

The final expression is from Dondi & Ghisellini (1995, MNRAS, 273, 583).

Here, d_L is the luminosity distance (can get from Ned Wright's cosmology calculator), α is the X-ray spectral index, and the X-ray flux $F_{x,\,\mu Jy}$ is measured at the observed X-ray energy of 0.26 $E_{Y,GeV}$ $[\delta(1+z)]^2$ keV