Modeling polarization from relativistic outflows

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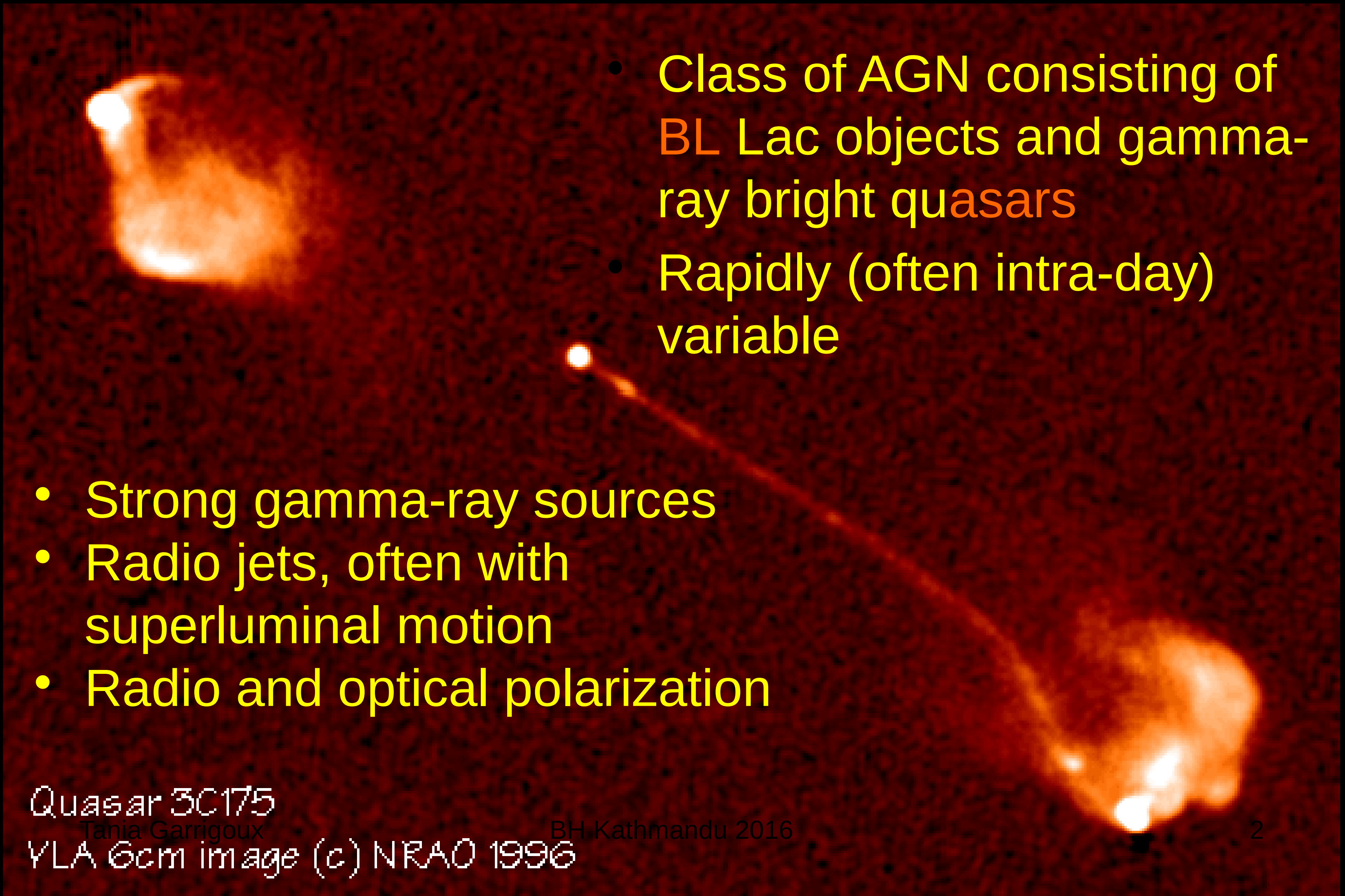
Blazars

- Class of AGN consisting of BL Lac objects and gamma-ray bright quasars
- Rapidly (often intra-day) variable

- Strong gamma-ray sources
- Radio jets, often with superluminal motion
- Radio and optical polarization

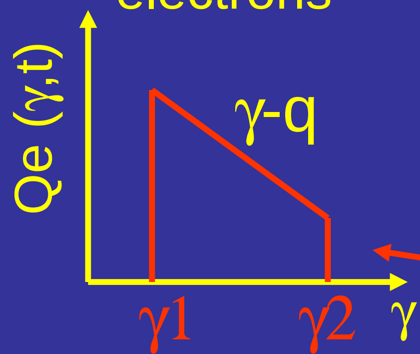


Open Physics Questions

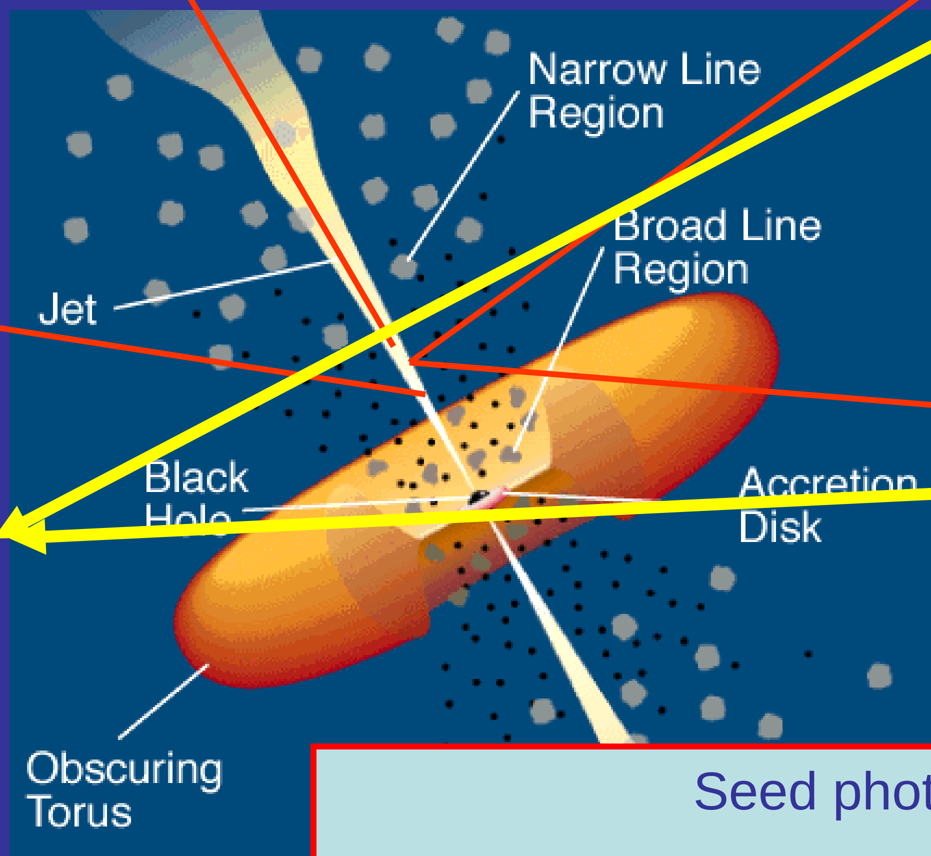
- Source of Jet Power (Blandford-Znajek / Blandford/Payne?)
- Physics of jet launching / collimation / acceleration – role / topology of magnetic fields
- Mode of particle acceleration (shocks / shear layers / magnetic reconnection?) – role of B fields
- Location of the energy dissipation / gamma-ray emission region
- Composition of jets (e--p or e+-e- plasma?) – leptonic or hadronic high-energy emission?

Leptonic Blazar Model

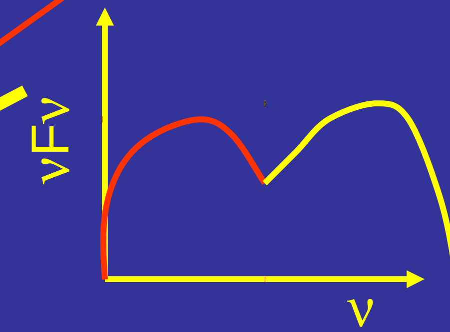
Injection, acceleration of ultrarelativistic electrons



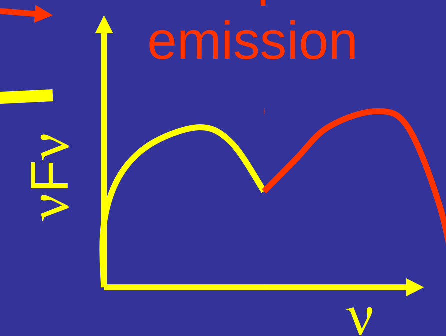
Relativistic jet outflow with Γ ≈ 10



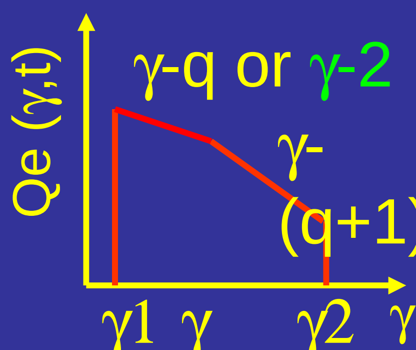
Synchrotron emission



Compton emission



Radiative cooling ↔ escape =>



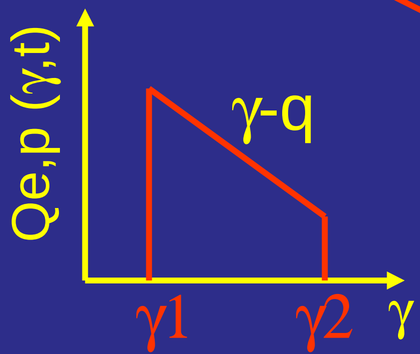
γb: τcool(γb) = τesc

Seed photons:

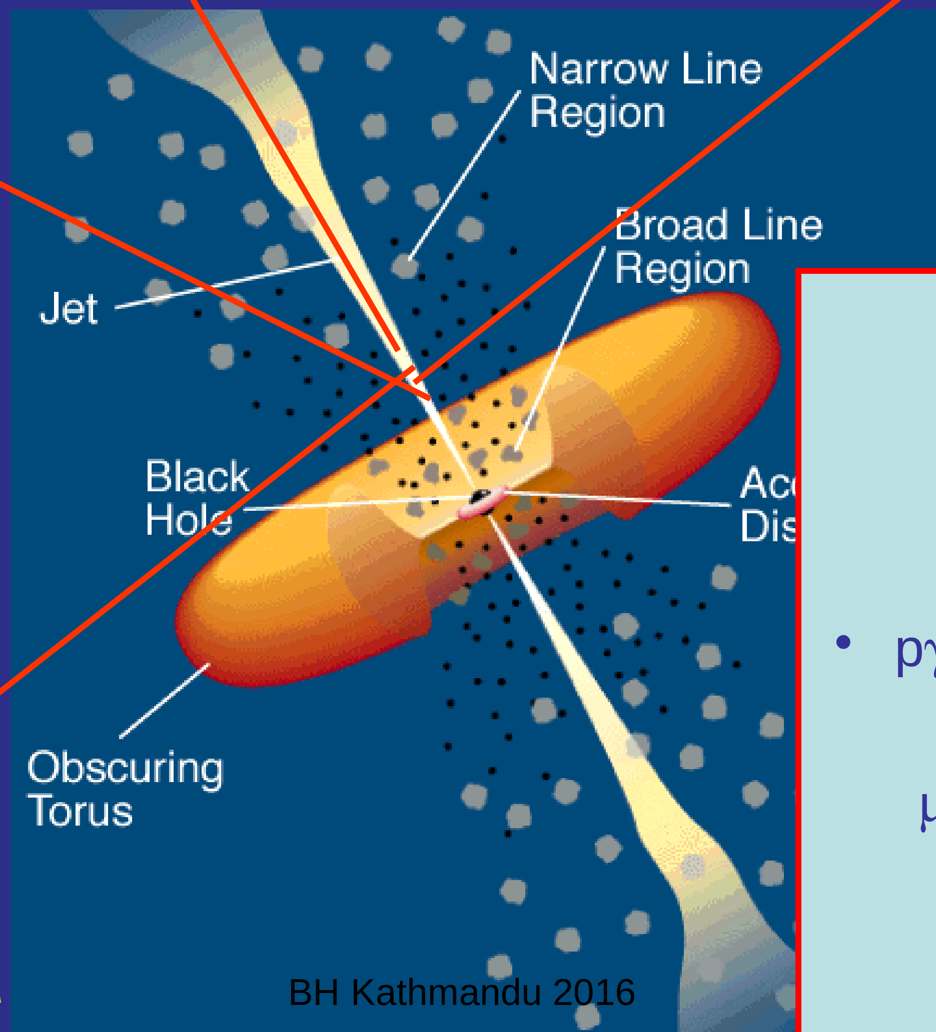
Synchrotron (within same region [SSC] or slower/faster earlier/later emission regions [decel. jet]), Accr. Disk, BLR, dust torus (EC)

Hadronic Blazar Models

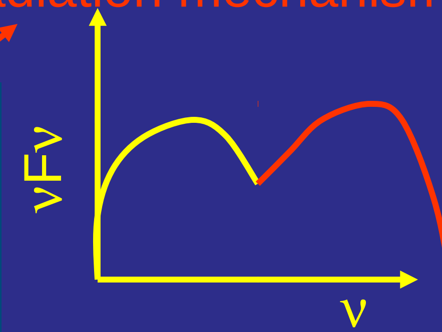
Injection, acceleration of ultrarelativistic electrons and protons



Relativistic jet outflow with $\Gamma \approx 10$

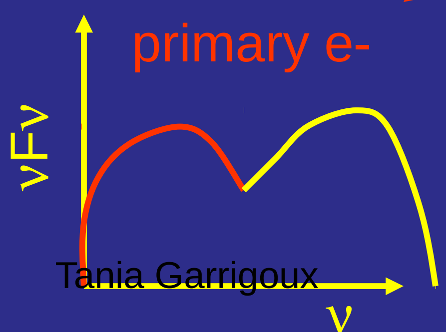


Proton-induced radiation mechanisms

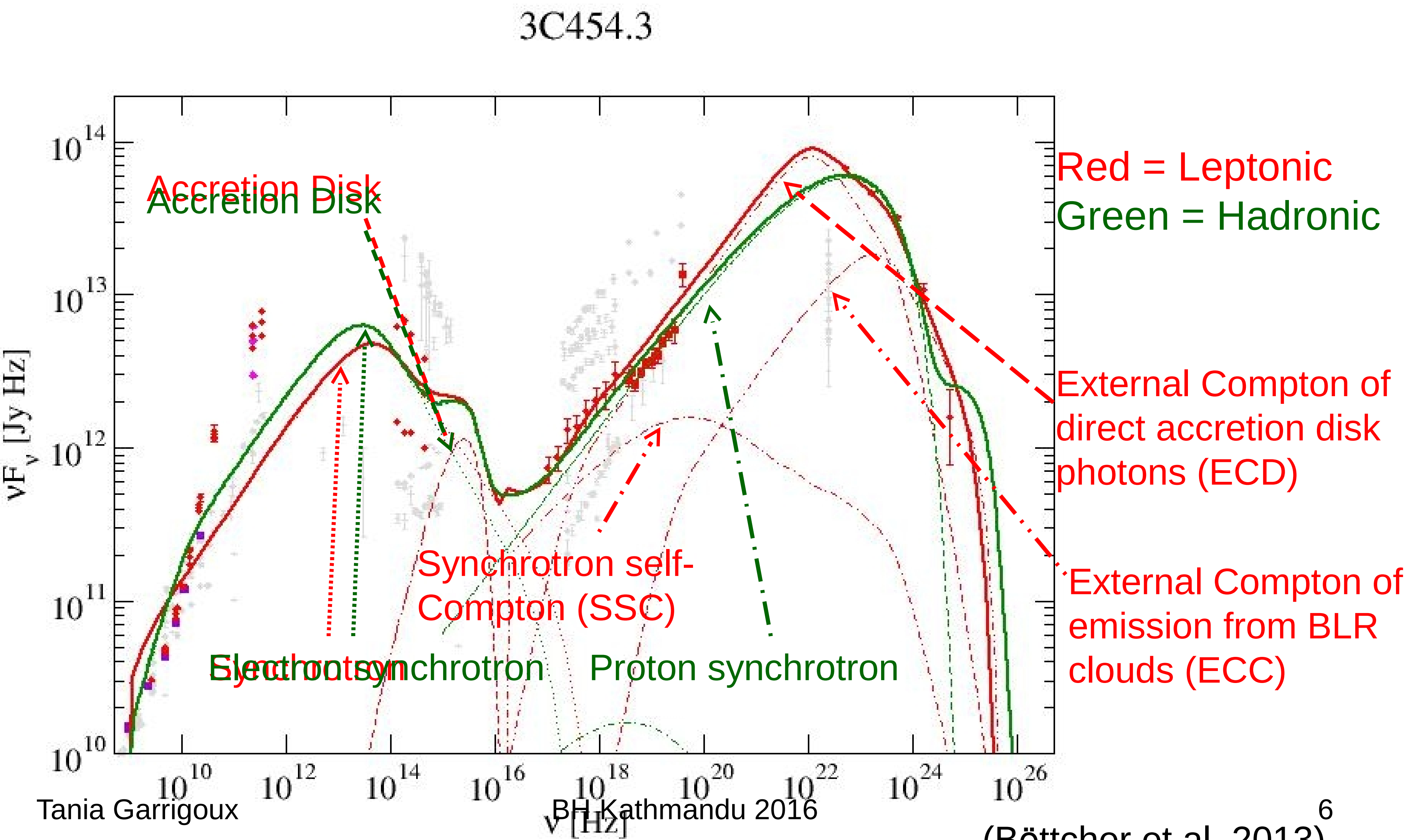


- Proton synchrotron
- $p\gamma \rightarrow p\pi^0$ $\pi^0 \rightarrow 2\gamma$
- $p\gamma \rightarrow n\pi^+$; $\pi^+ \rightarrow \mu^+\nu_\mu$ — $\mu^+ \rightarrow e^+\nu_e\nu_\mu$ → secondary μ-, e-synchrotron
- Cascades …

Synchrotron emission of primary e-



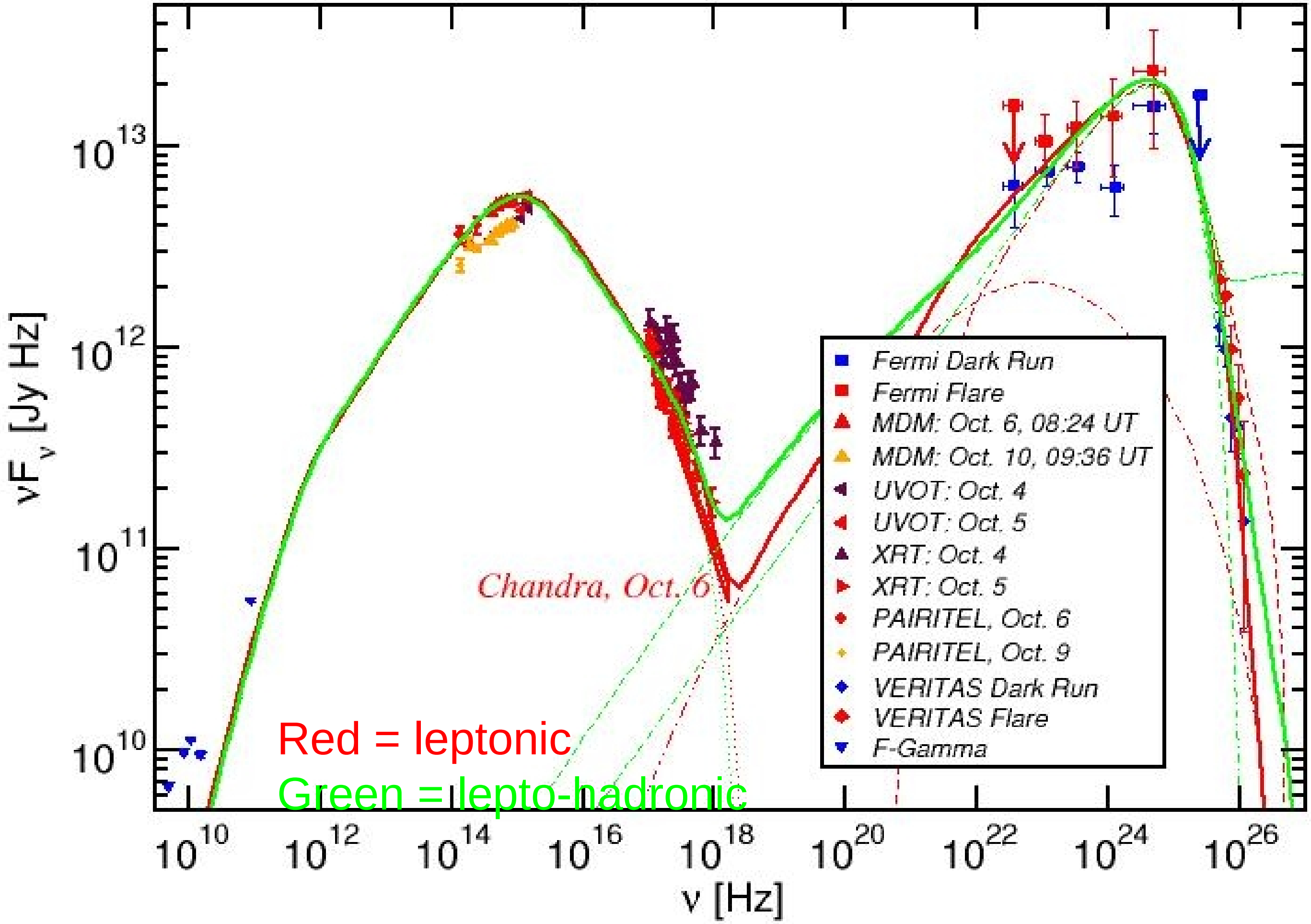
Leptonic and Hadronic Model Fits along the Blazar Sequence



(Böttcher et al. 2013)

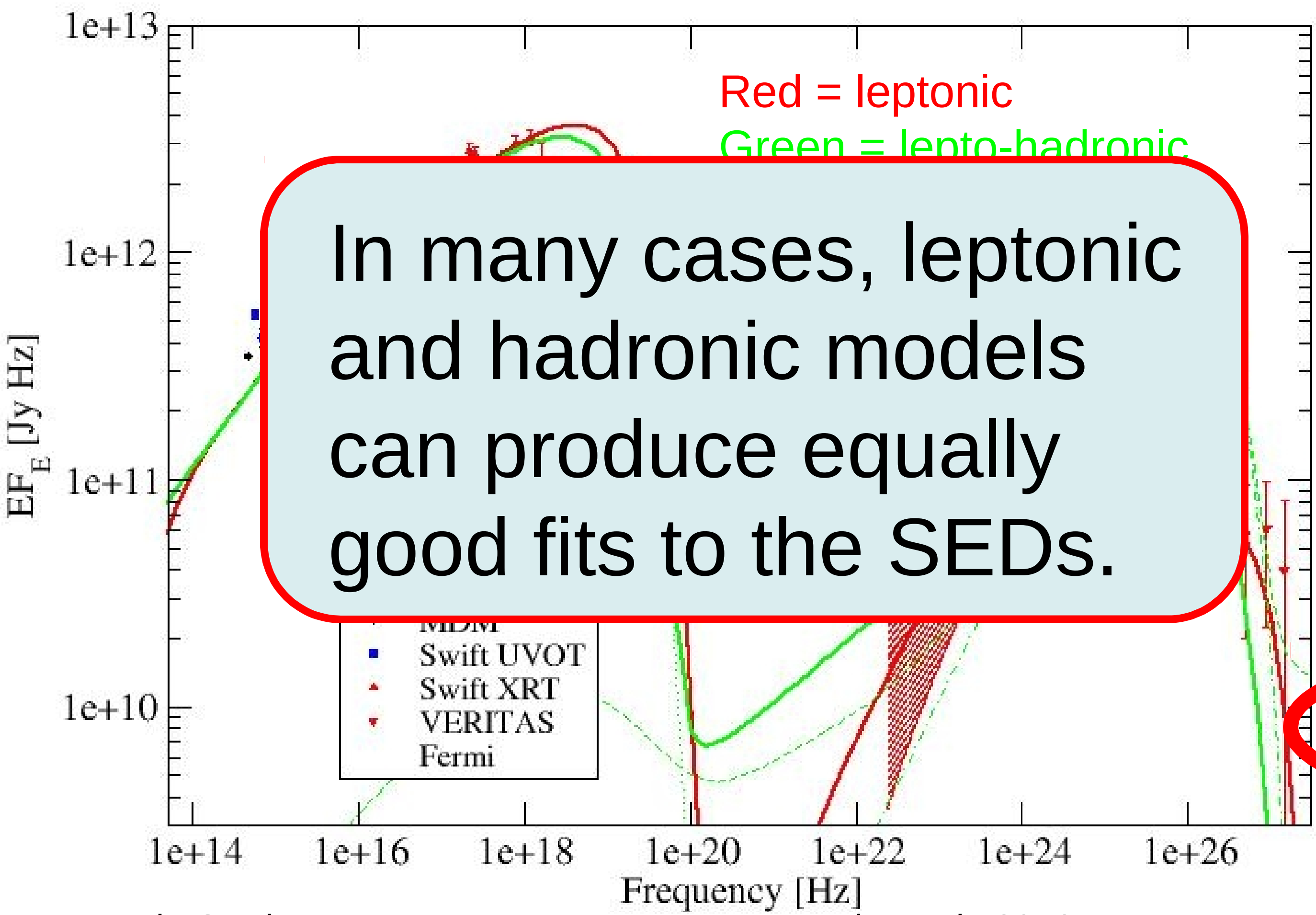
Leptonic and Hadronic Model Fits Along the Blazar Sequence

3C66A (IBL)



Lepto-Hadronic Model Fits Along the Blazar Sequence

RGB J0710+591 (HBL)



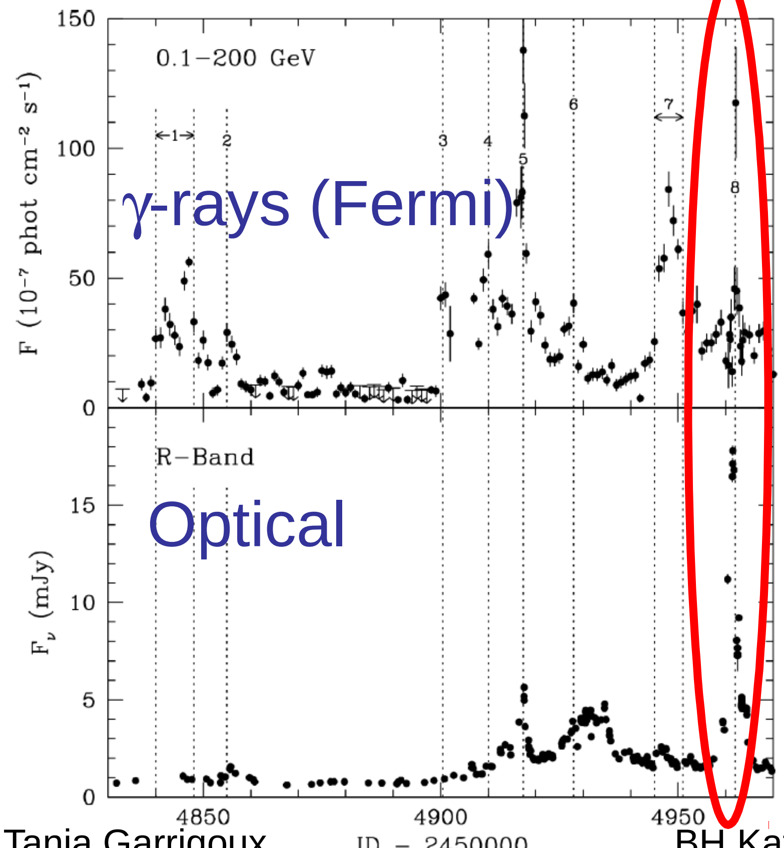
In many cases, leptonic and hadronic models can produce equally good fits to the SEDs.

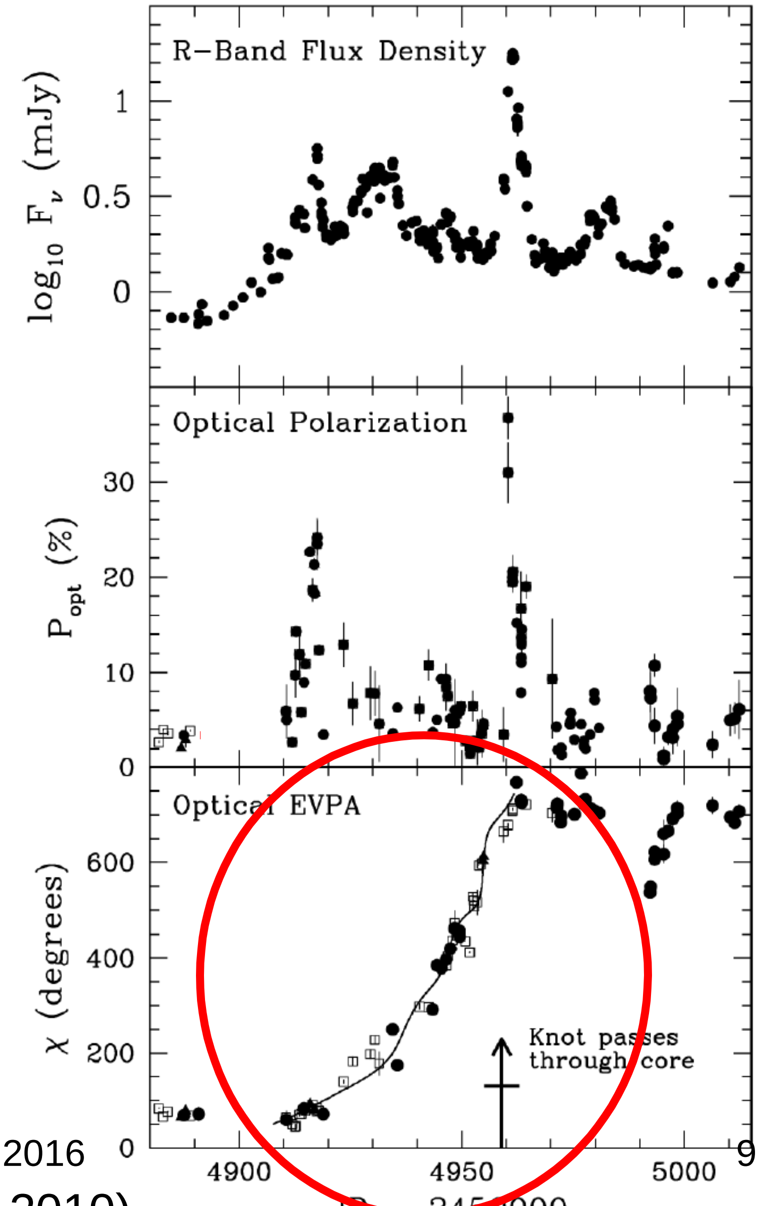
Possible Diagnostics to distinguish:

- Neutrinos
- Variability
- Polarization

Polarization Angle Swings

- Optical + γ-ray variability of LSP blazars often correlated
- Sometimes O/γ flares correlated with increase in optical polarization and multiple rotations of the polarization angle (PA)





Tania Garrigoux BH Kathmandu 2016

PKS 1510-089 (Marscher et al. 2010)

Distinguishing Diagnostic: Polarization

- Synchrotron Polarization

For synchrotron radiation from a power-law distribution of electrons with $n_e(\gamma) \sim \gamma^{-p}$ → $F_\nu \sim \nu^{-\alpha}$ with $\alpha = (p-1)/2$

$$\Pi_{syL} = \frac{p+1}{p+7/3} = \frac{\alpha+1}{\alpha+5/3}$$

p = 2 → Π = 69 %

p = 3 → Π = 75 %

- <u>Compton Polarization</u>

Compton cross section is polarization-dependent:

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{4}\left(\frac{\epsilon'}{\epsilon}\right)^2\left(\frac{\epsilon}{\epsilon'} + \frac{\epsilon'}{\epsilon} - 2 + 4\left[\vec{e}\cdot\vec{e}'\right]^2\right)$$

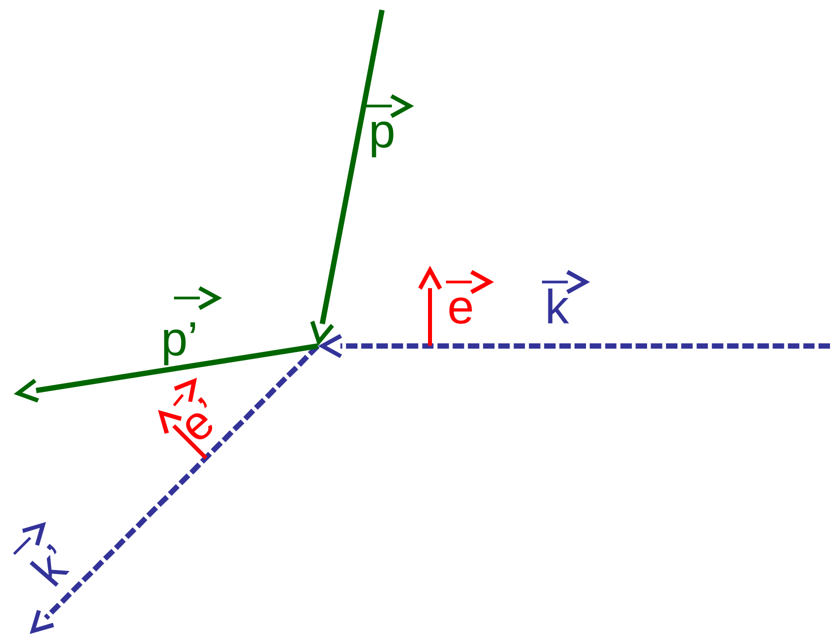
$\varepsilon = h\nu/(m_e c^2)$:

Thomson regime: $\varepsilon \approx \varepsilon'$

$\Rightarrow d\sigma/d\Omega = 0$ if $\vec{e}\cdot\vec{e}' = 0$

$\Rightarrow$ Scattering preferentially in the plane perpendicular to $\vec{e}$!

Preferred polarization direction is preserved



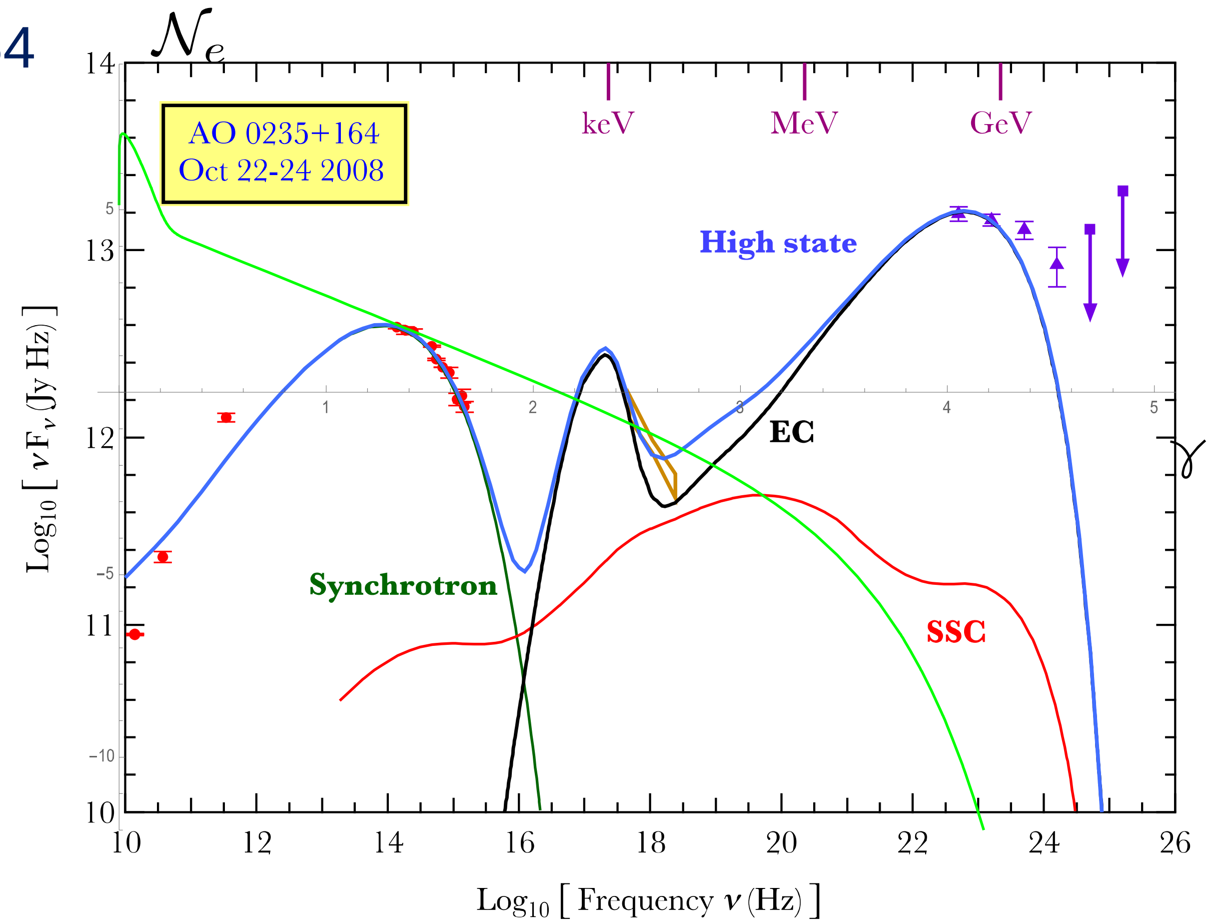
X-Ray Polarization: IC - UV

Modeling of AO 0235+164

Thermal + non thermal electron distribution results self-consistently from MC simulations of DSA

External Compton scattering of thermal distribution

⇒Importance of Bulk Compton process



(Baring et al., *accepted for publication in MNRAS, 2016)*

Polarization in the IC- UV scenario

We define Stokes parameters normalized by I, the total energy density of the photon (*Chang et al*, 2013)

ξ_1^f=U/I ξ_2^f=V/I ξ_3^f=Q/I

The degree of polarization Π is then defined by:

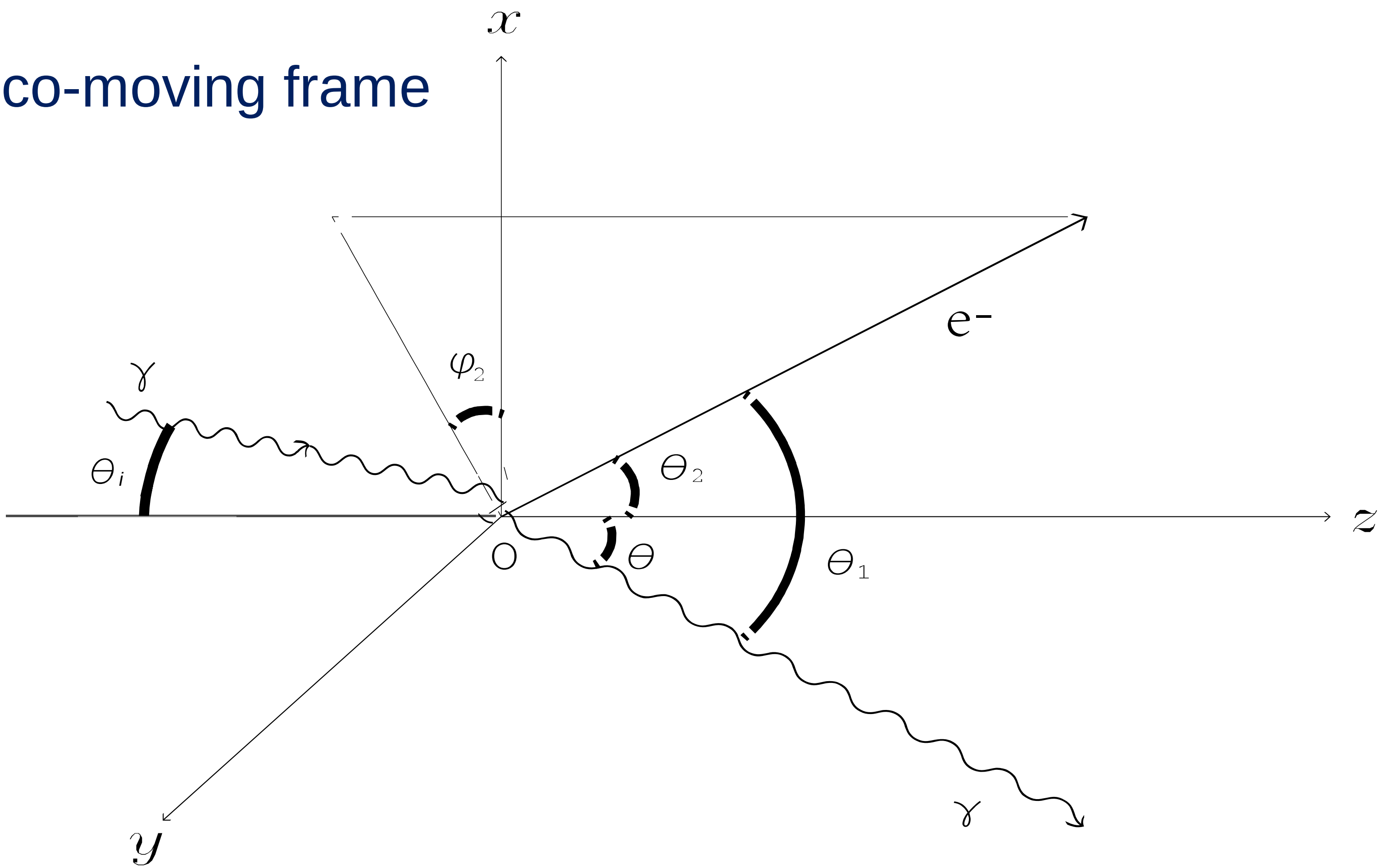
$$\Pi = \sqrt{(\xi_1^f)^2 + (\xi_2^f)^2 + (\xi_3^f)^2}$$

with $\xi_1^f = \dfrac{\xi_1^i \langle F_{11} \rangle}{\langle F_0 \rangle + \xi_3^i \langle F_3 \rangle}$ $\xi_2^f = \dfrac{\xi_2^i \langle F_{22} \rangle}{\langle F_0 \rangle + \xi_3^i \langle F_3 \rangle}$, $\xi_3^f = \dfrac{\langle F_3 \rangle + \xi_3^i \langle F_{33} \rangle}{\langle F_0 \rangle + \xi_3^i \langle F_3 \rangle}$

$$\langle F_a \rangle = \frac{1}{c} \int_{\gamma_1}^{\gamma_2} \frac{dn_e}{d\epsilon d\Omega}(\gamma)\, d\gamma \int \int \int \frac{dn_\gamma}{d\epsilon d\Omega}(\epsilon_i) \left(\frac{\epsilon_f}{\epsilon_i} \right)^2 F_a\ \delta(\epsilon_f - \epsilon_1)\ d\epsilon_i\ d\Omega_e\ d\Omega_\gamma$$

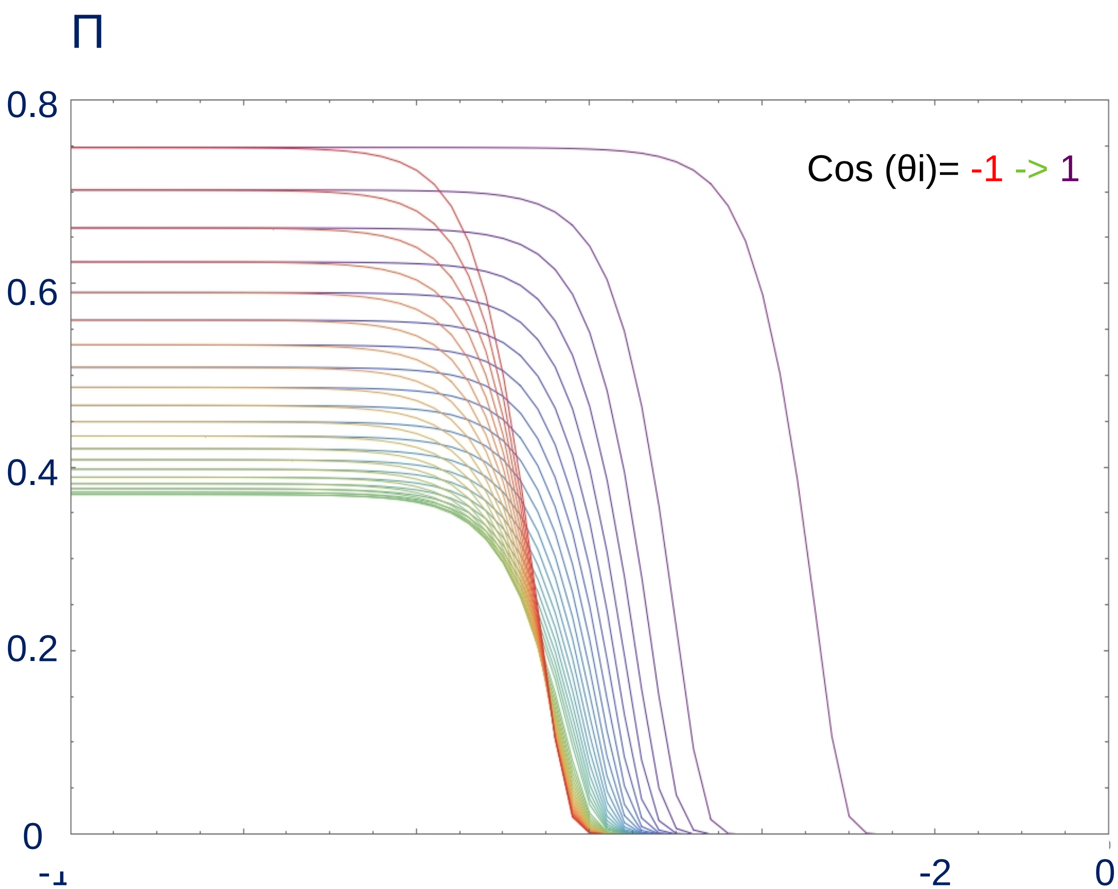
Polarization in the IC- UV scenario

In the co-moving frame



$$\langle F_a \rangle = \frac{1}{c} \int_{\gamma_1}^{\gamma_2} \mathcal{N}_e(\gamma)\, d\gamma \int \int \frac{dn'_\gamma}{d\epsilon d\Omega}(\varepsilon_i) * \frac{d\Omega d\epsilon}{d\Omega' d\epsilon'} \left(\frac{\epsilon_f}{\varepsilon_i}\right)^2 F_a \, \frac{1}{\frac{\partial f_r}{\partial \epsilon i}} \, d\Omega_{\gamma,i} \, d\Omega_{e,2}$$

X-Ray Polarization:
IC - UV



Log10[εf (mec2)]

Initially unpolarized UV photons:

$\Pi = \xi_{3f}$ and $\xi_{3f} = \langle F3 \rangle / \langle F0 \rangle$

Thermal + non-thermal electron distribution

Bulk Lorentz factor Γ = 20

⇒Polarization signatures can characterize the model being developed

Summary

1. Both leptonic and hadronic models can generally fit blazar SEDs well. Possible distinguishing diagnostics: Variability, polarization, neutrinos

2. A model is being developed to study x-ray polarization in the IC-UV scenario, including the Bulk Compton process.

3. Next steps would include integration over θi and study of the influence of different parameters (bulk factor, temperature of electron distribution)

4. Future polarimetry missions can play a determinant role in constraining the models of jet physics

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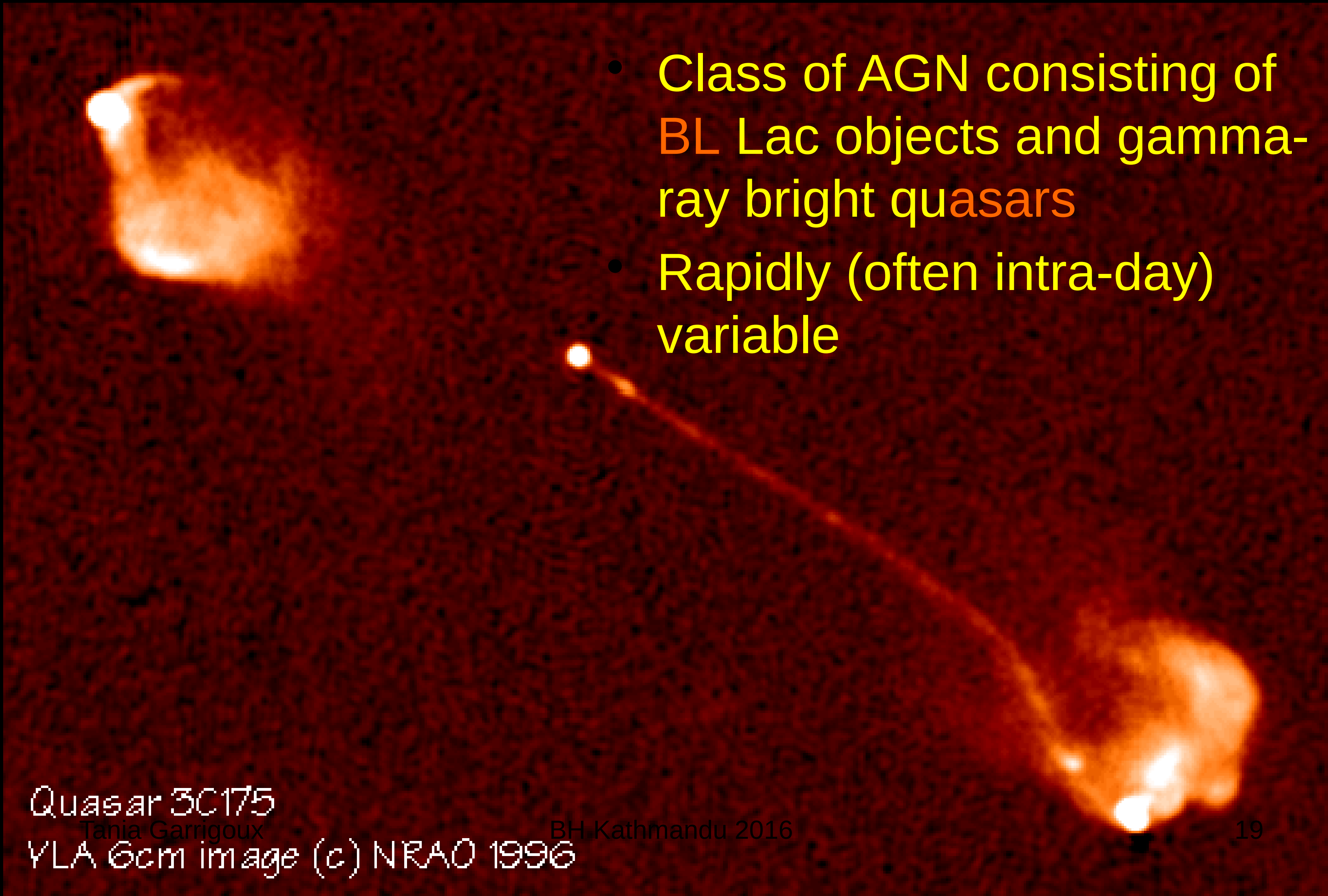
Thank you!

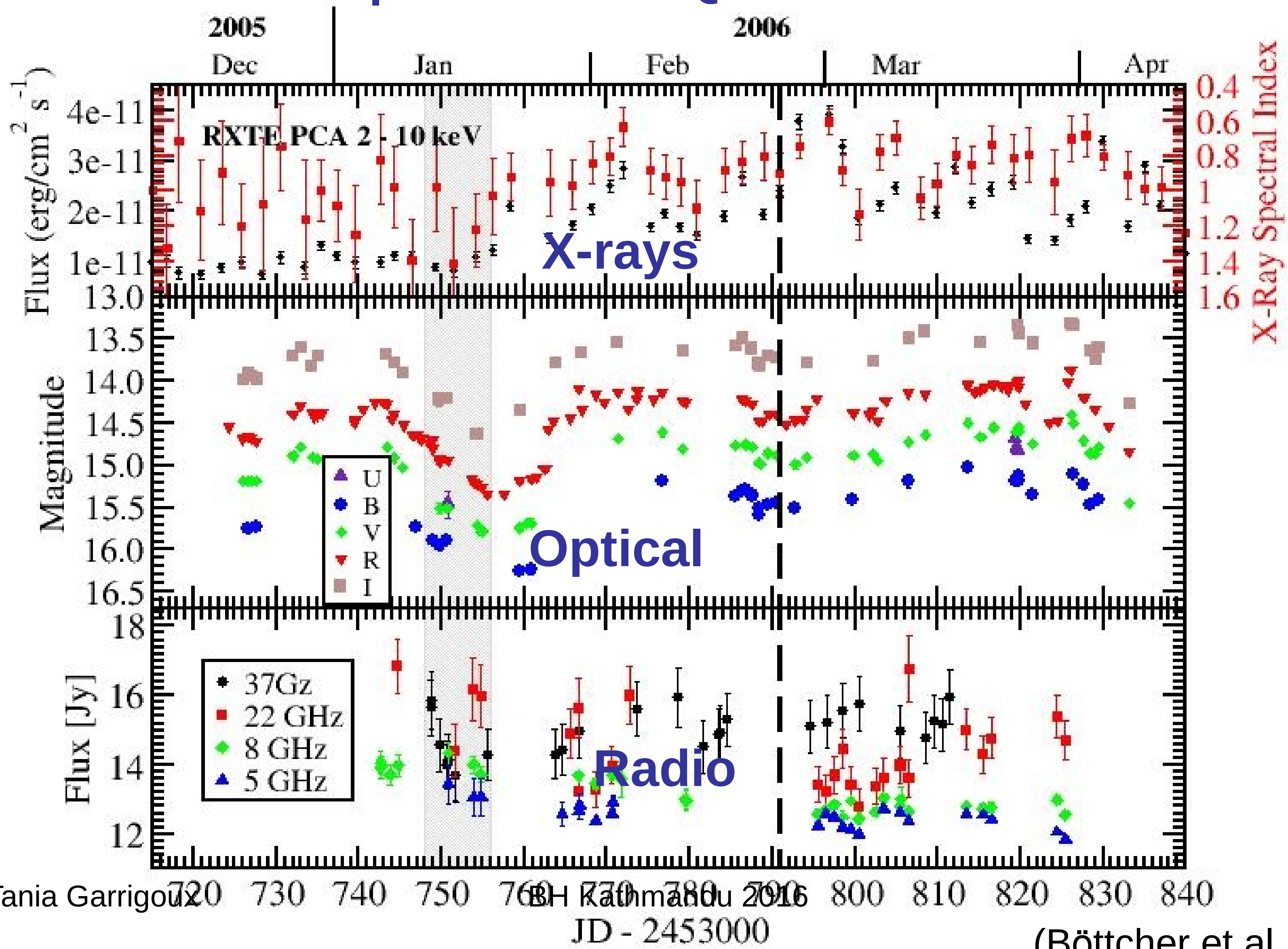
Backup slides

Blazars

- Class of AGN consisting of BL Lac objects and gamma-ray bright quasars
- Rapidly (often intra-day) variable

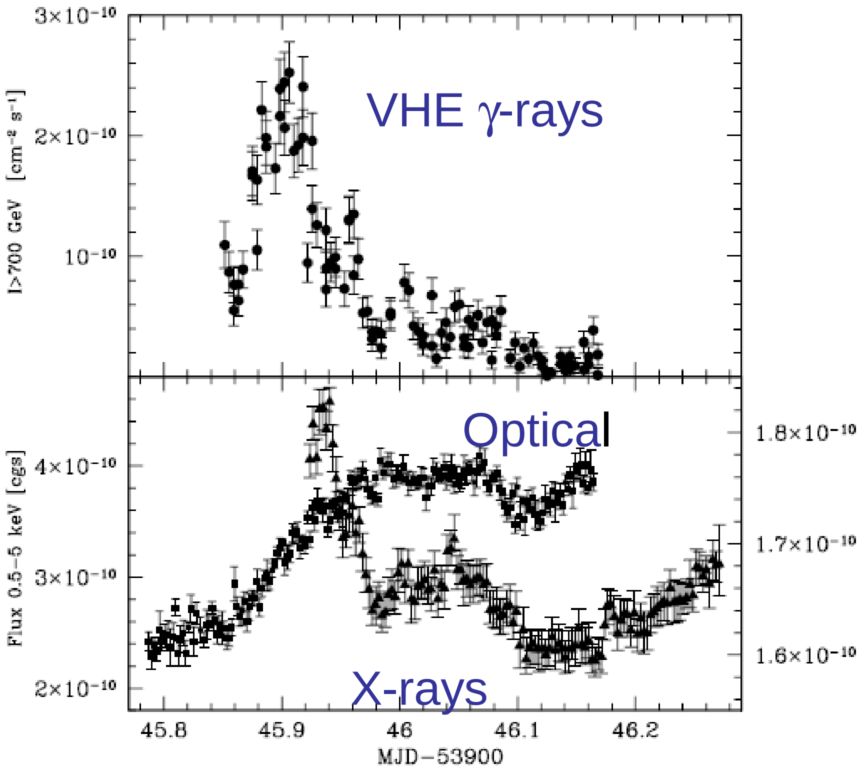


Blazar Variability: Example: The Quasar 3C279

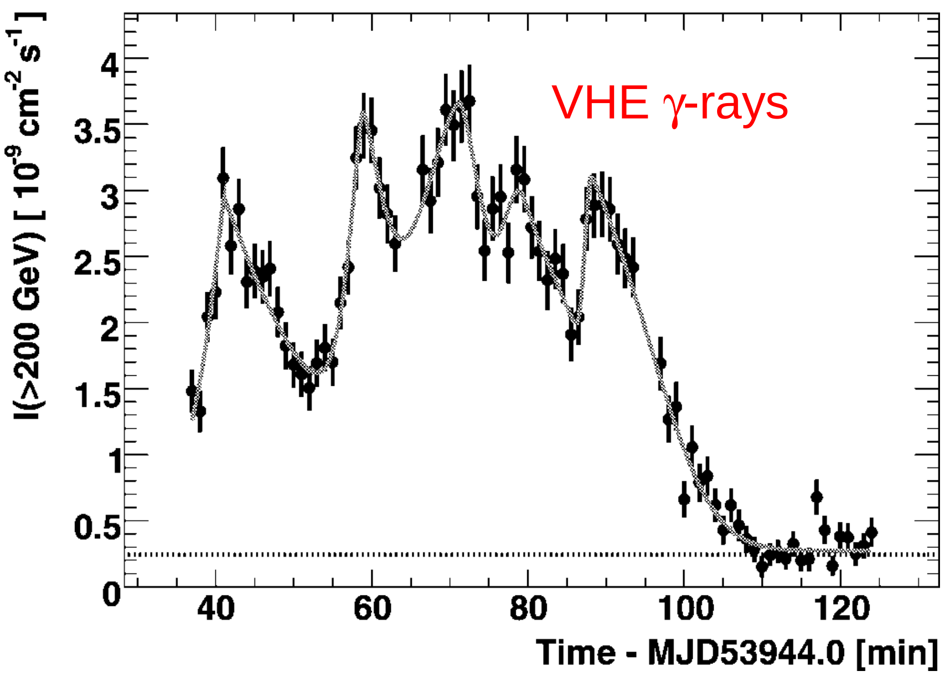


(Böttcher et al. 2007)

Blazar Variability: Variability of PKS 2155-304



(Costamante et al. 2008)



(Aharonian et al. 2007)

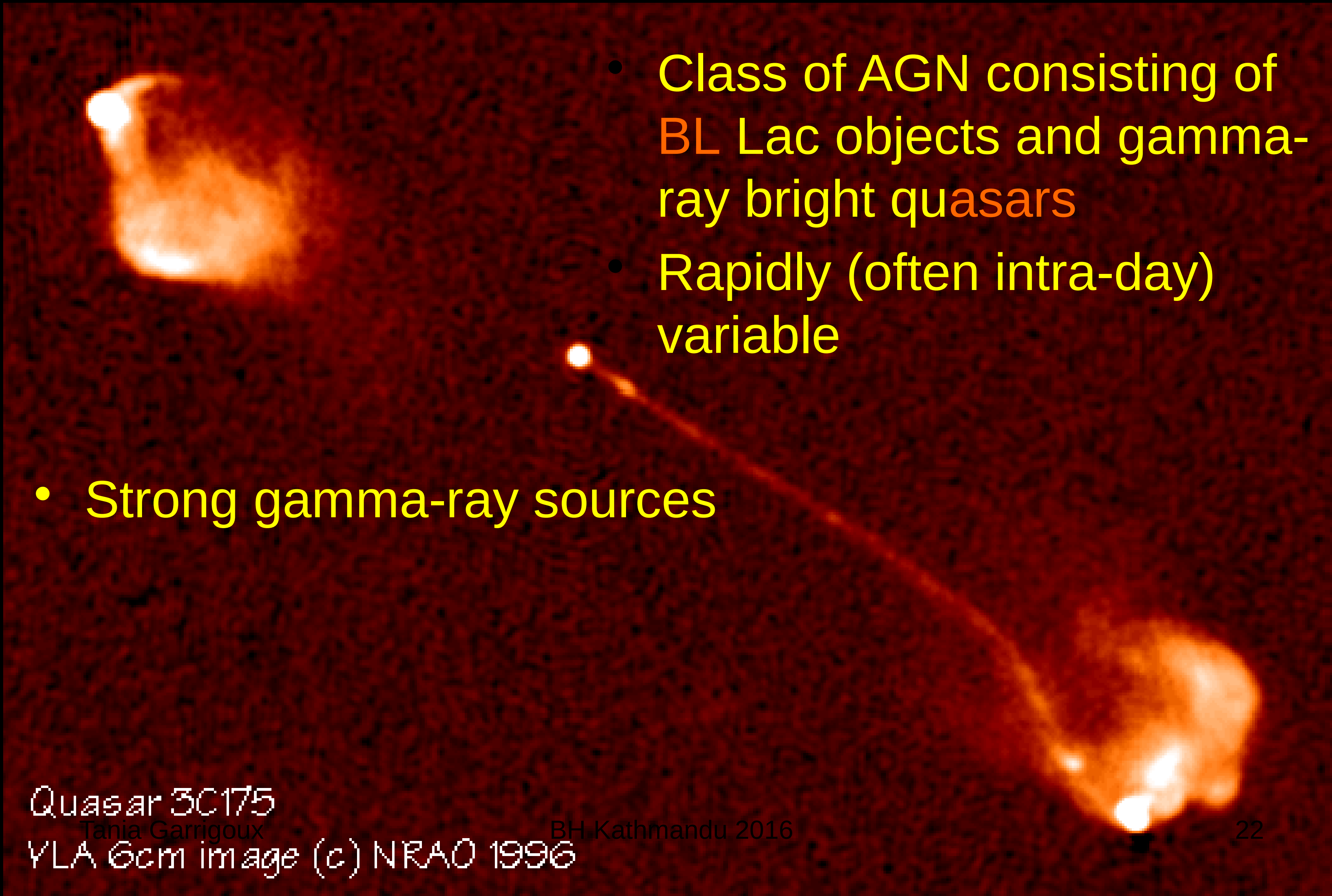
VHE γ-ray variability on time scales as short as a few minutes!

VHE γ-ray and X-ray variability often closely correlated

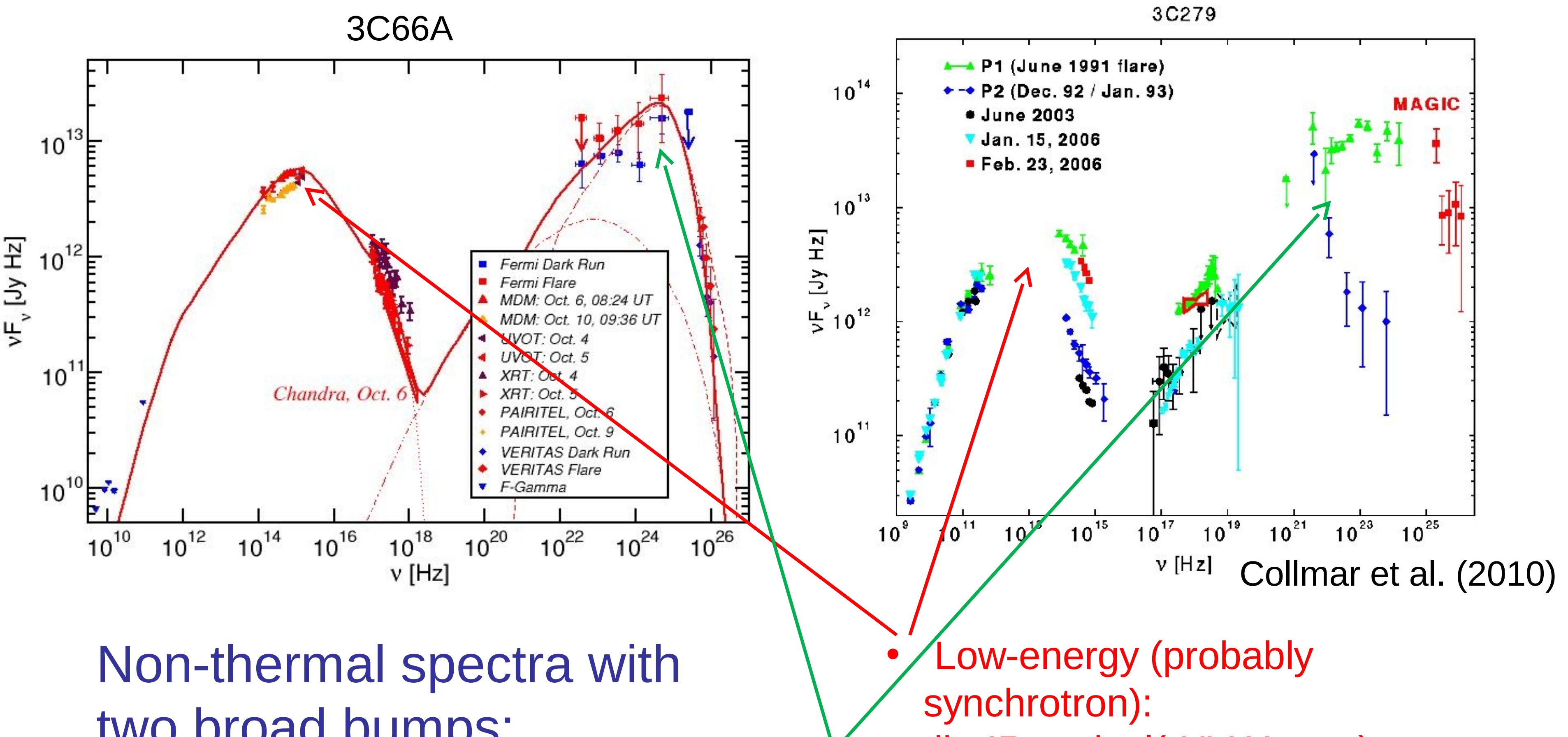
Blazars

- Class of AGN consisting of BL Lac objects and gamma-ray bright quasars
- Rapidly (often intra-day) variable

- Strong gamma-ray sources



Blazar Spectral Energy Distributions (SEDs)

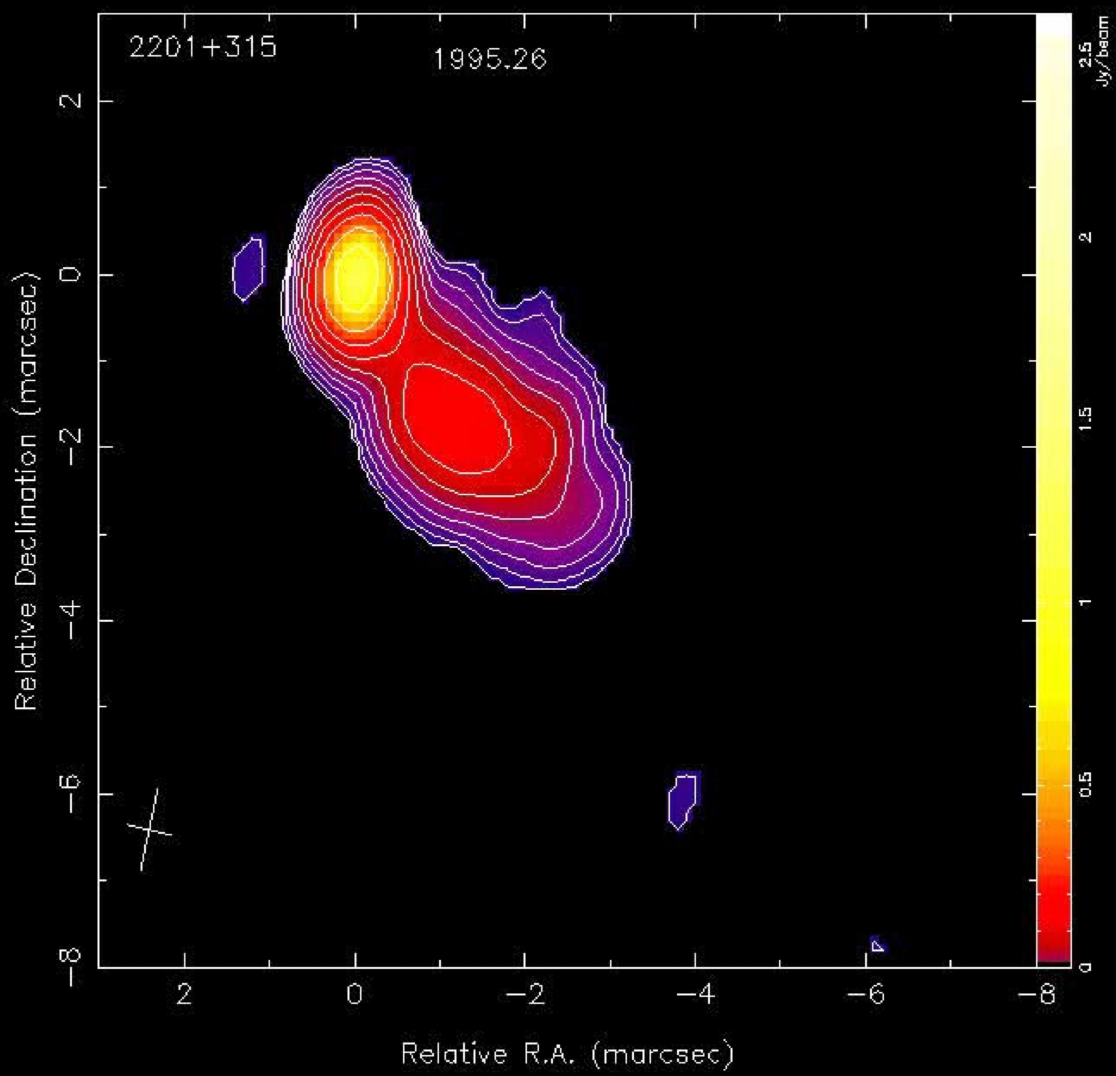


Collmar et al. (2010)

Non-thermal spectra with two broad bumps:

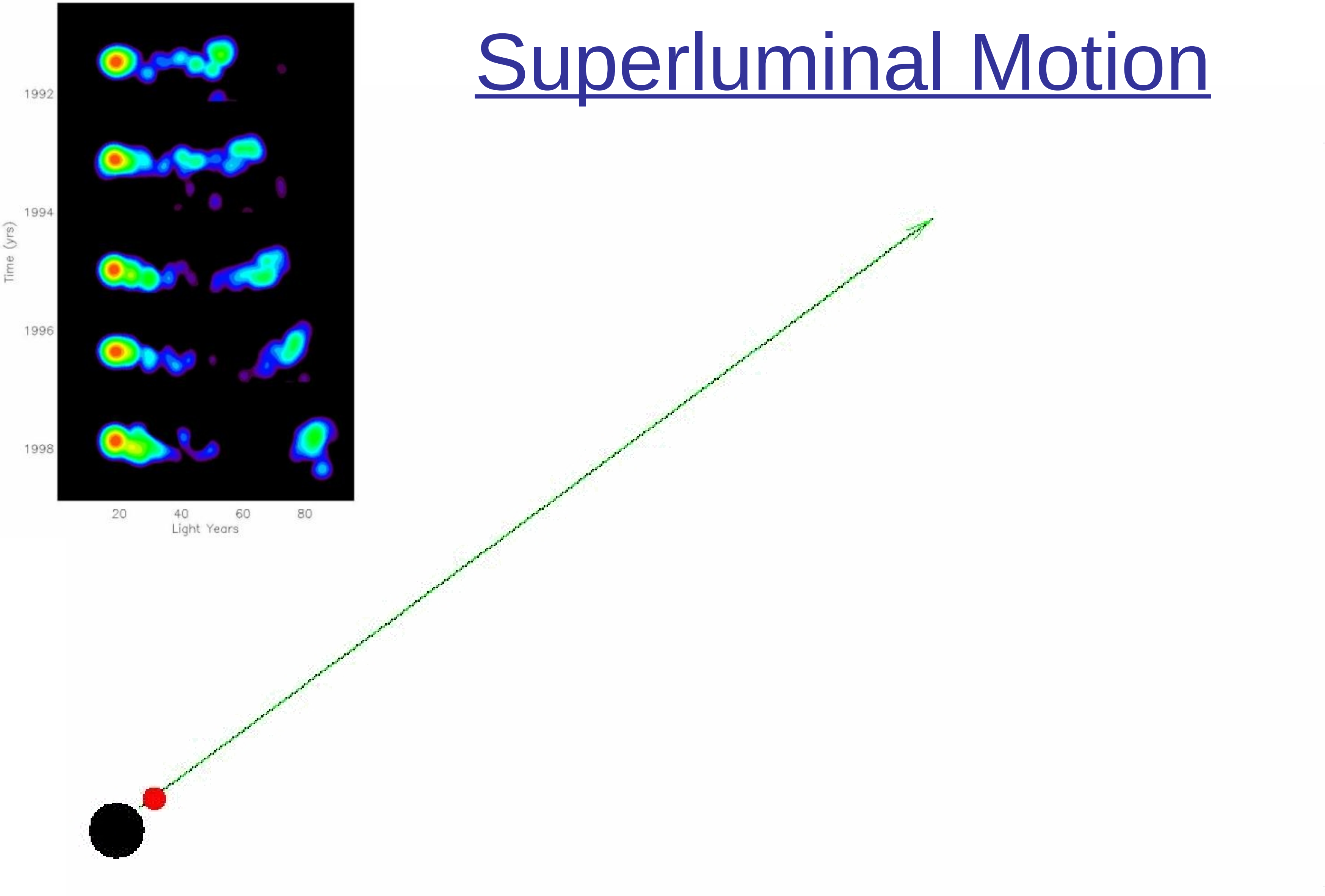
- Low-energy (probably synchrotron): radio-IR-optical(-UV-X-rays)
- High-energy (X-ray – γ-rays)

Superluminal Motion



(The MOJAVE Collaboration)

Superluminal Motion

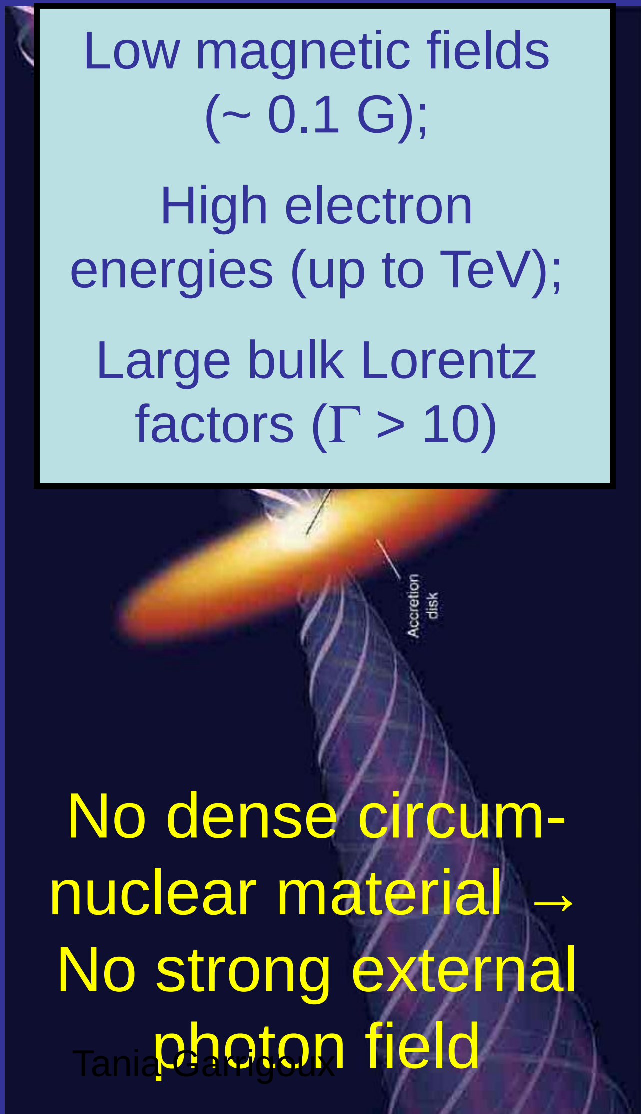


Apparent motion at up to ~ 40 times the speed of light!

Spectral modeling results along the Blazar Sequence: Leptonic Models

High-frequency peaked BL Lac (HBL):

The "classical" picture

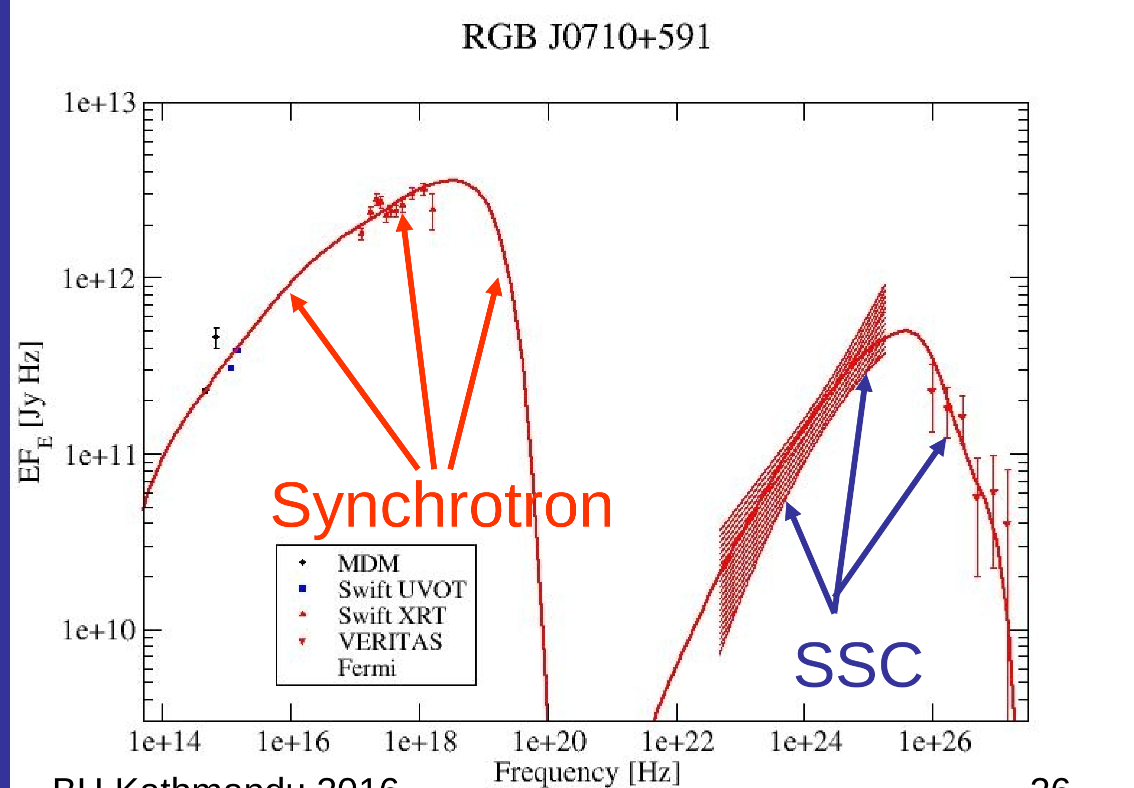


Low magnetic fields (~ 0.1 G);

High electron energies (up to TeV);

Large bulk Lorentz factors ($\Gamma > 10$)

No dense circum-nuclear material → No strong external photon field



(Acciari et al. 2010)

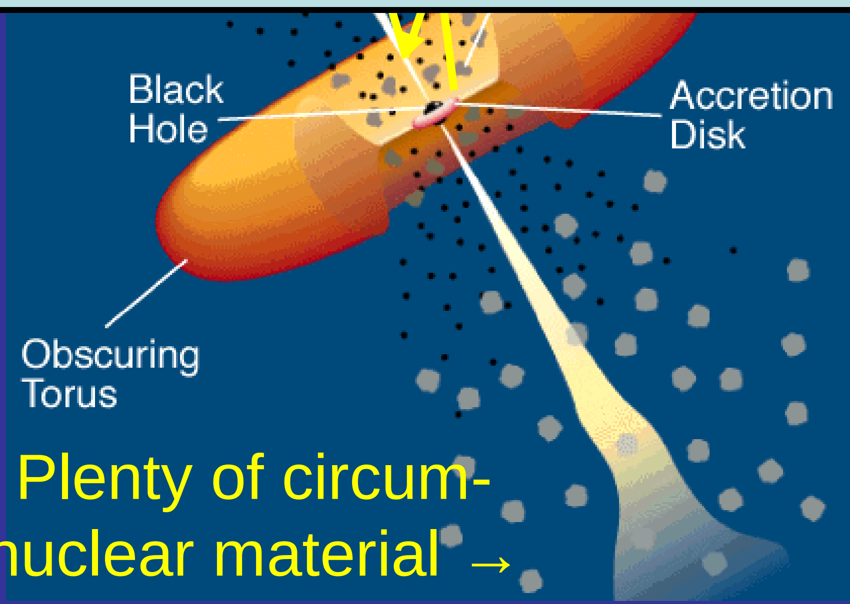
Spectral modeling results along the Blazar Sequence: Leptonic Models

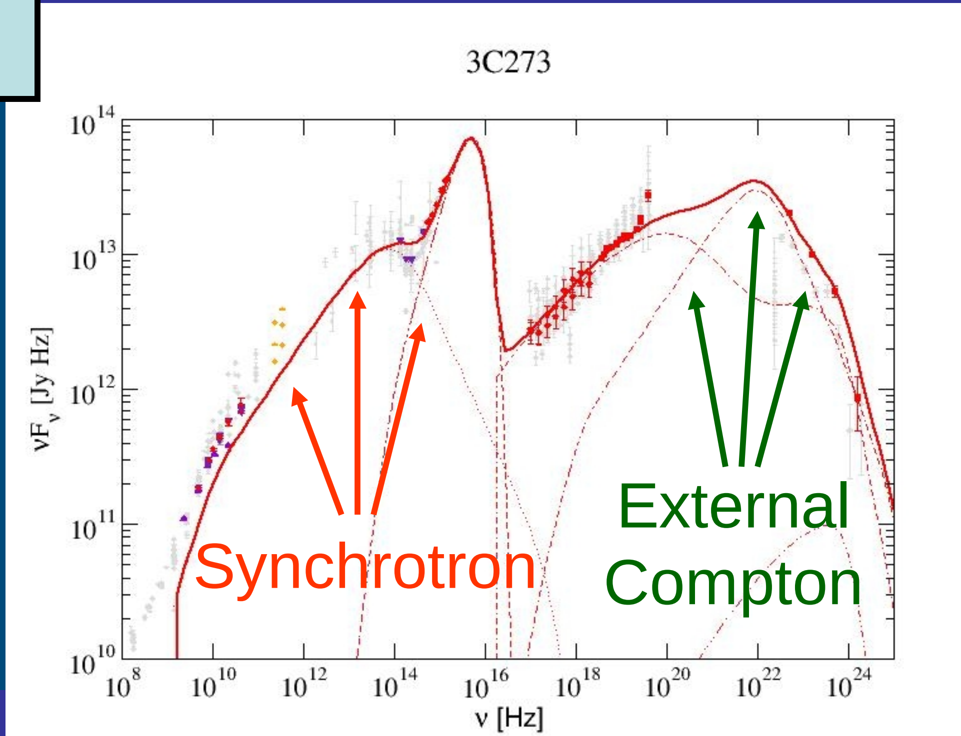
High magnetic fields (~ a few G);

Lower electron energies (up to GeV);

Lower bulk Lorentz factors (Γ ~ 10)

FSRQ





Plenty of circum-nuclear material → Strong external photon field

Tania Garrigoux

Constraints from Observations

If energy-dependent (spectral) time lags are related to energy-dependent synchrotron cooling time scale:

$d\gamma/dt = -\nu_0\gamma^2$ with $\nu_0 = (4/3)\, c\, \sigma_T\, u'_B\, (1 + k)$

and $k = u'_{ph}/u'_B$ (Compton Dominance Parameter)

$t_{cool} = \gamma/|d\gamma/dt| = 1/(\nu_0\gamma)$

$\nu_{sy} = 3.4 \cdot 10^6\, (B/G)\, (\delta/(1+z))\, \gamma^2$ Hz

$\Rightarrow \Delta t_{cool} \sim B^{-3/2}\, (\delta/(1+z))^{1/2}\, (1 + k)^{-1} (\nu_1^{-1/2} - \nu_2^{-1/2})$

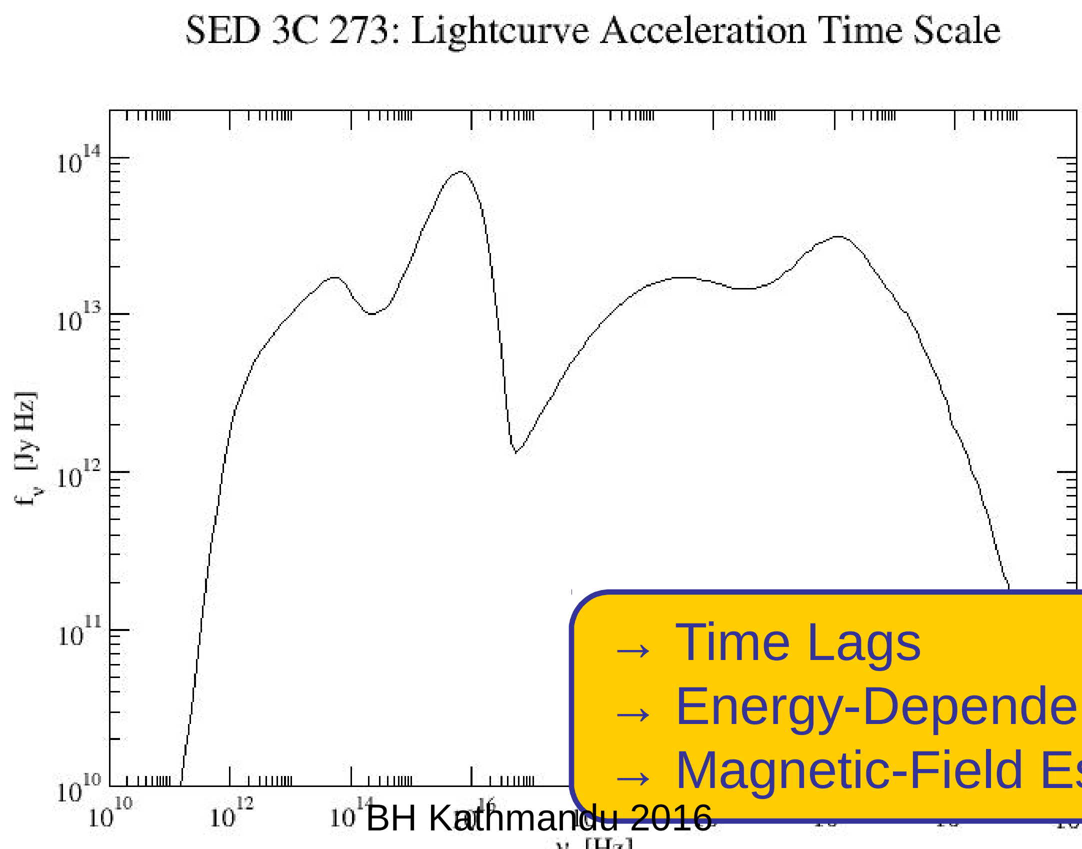
=> Measure time lags between frequencies ν_1, ν_2

→ estimate Magnetic field (modulo $\delta/[1+z]$)!

(Takahashi et al. 1996)

Distinguishing Diagnostic: Variability

- Time-dependent leptonic one-zone models produce correlated synchrotron + gamma-ray variability (Mastichiadis & Kirk 1997, Li & Kusunose 2000, Böttcher & Chiang 2002, Moderski et al. 2003, Diltz & Böttcher 2014)

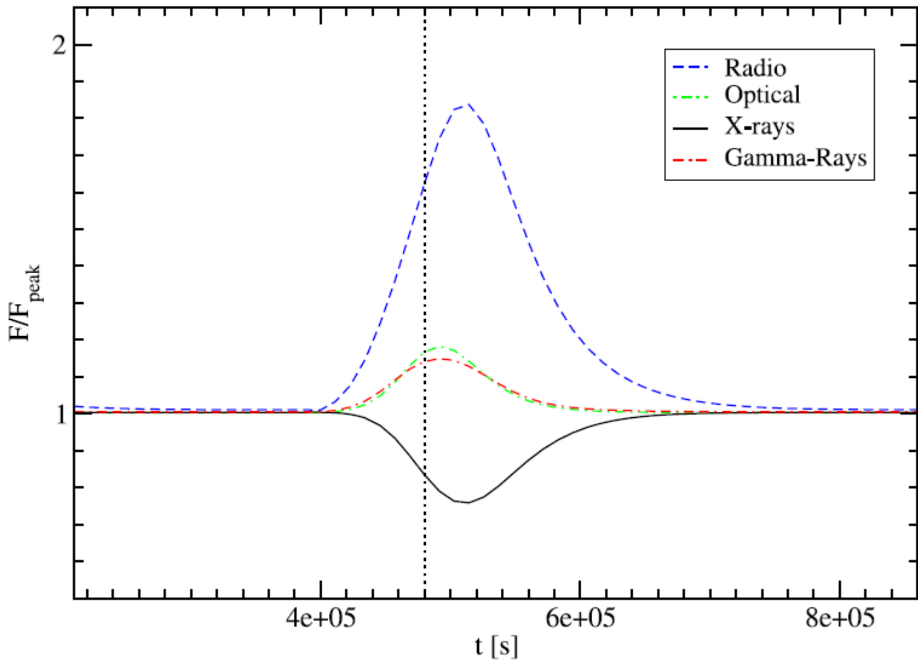


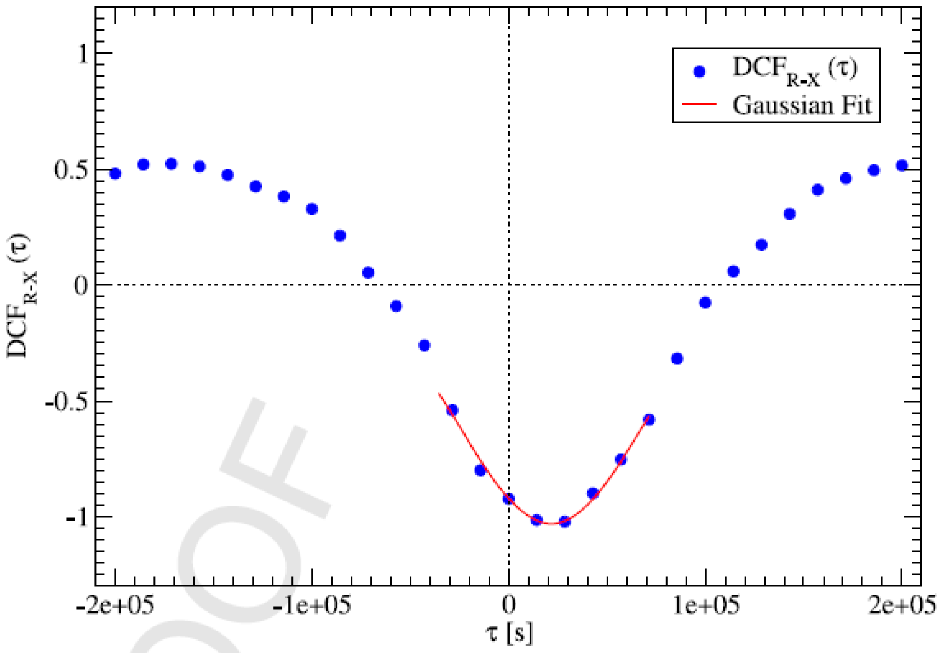
→ Time Lags
→ Energy-Dependent Cooling Times
→ Magnetic-Field Estimate!

Diltz & Böttcher (2014)

Correlated Multiwavelength Variability in Leptonic One-Zone Models

Example: Variability from short-term increase in 2nd-order-Fermi acceleration efficiency





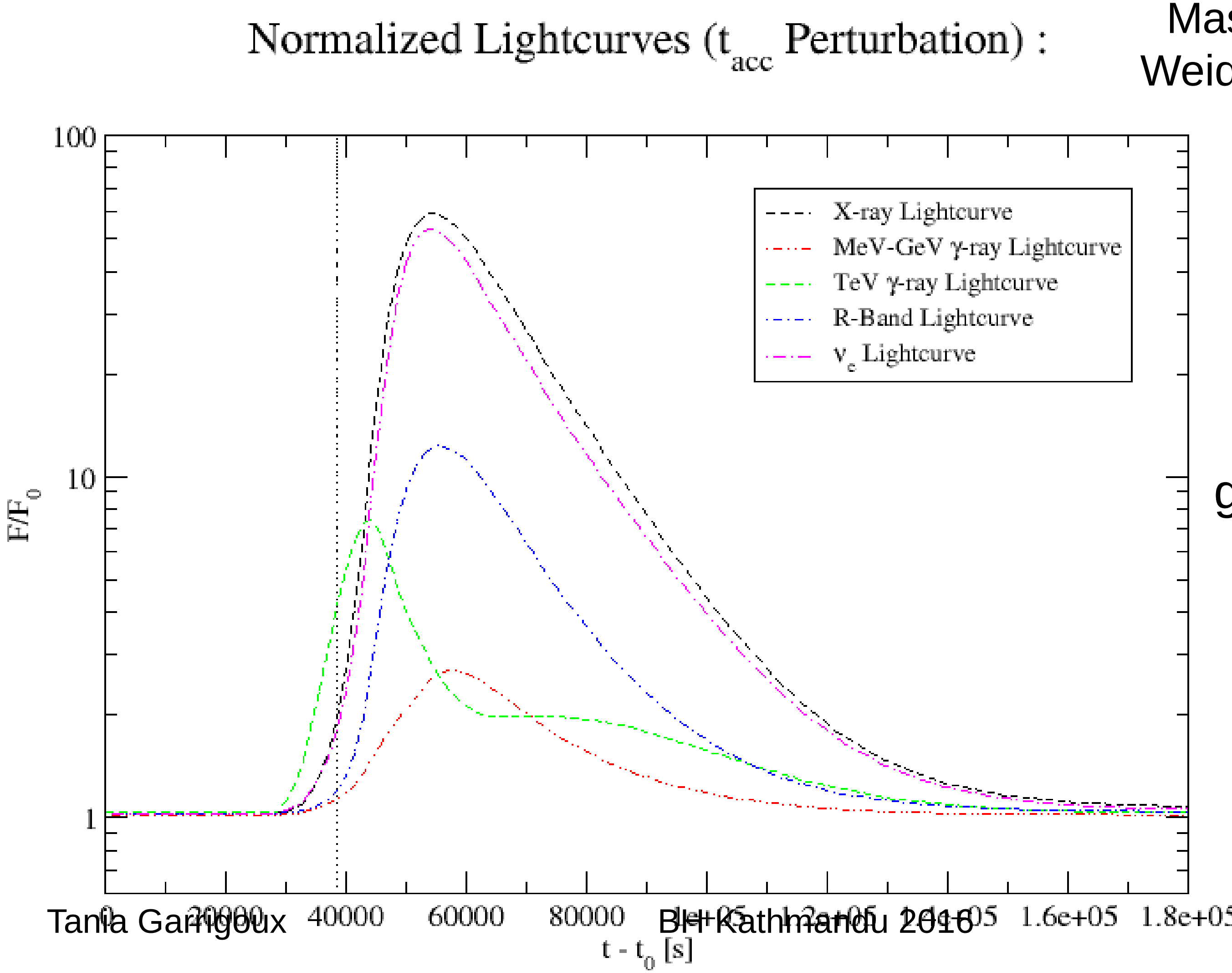
X-rays anti-correlated with radio, optical, γ-rays; delayed by ~ few hours.

(Diltz & Böttcher, 2014, JHEAp)

Distinguishing Diagnostic: Variability

- Time-dependent hadronic models can produce uncorrelated variability / orphan flares

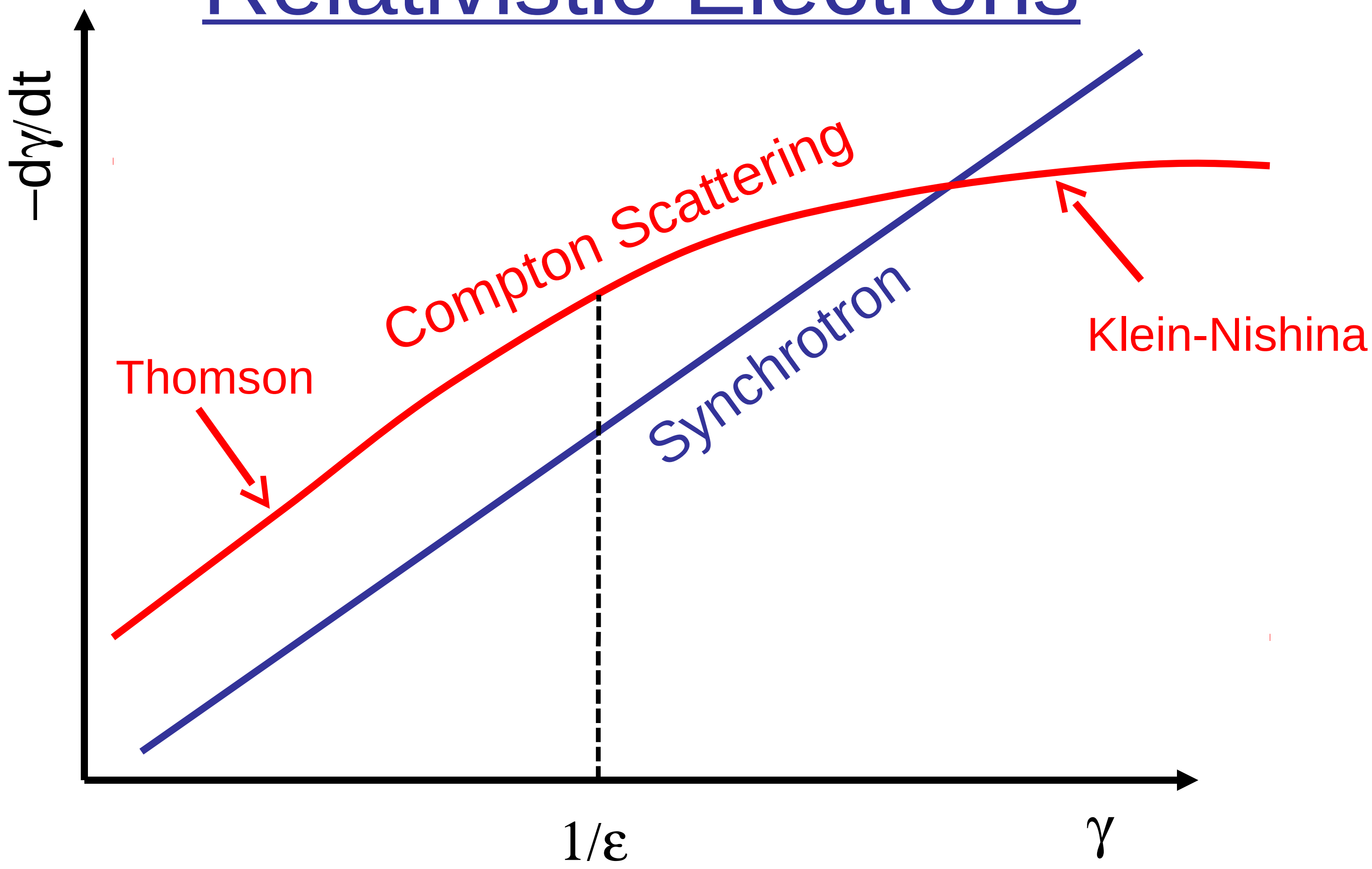
(Dimitrakoudis et al. 2012, Mastichiadis et al. 2013, Weidinger & Spanier 2013, Diltz et al. 2015)



Neutrino flares generally co-incident with X-ray through GeV γ-ray flares

(Diltz et al. 2015)

Total Energy Loss Rate of Relativistic Electrons



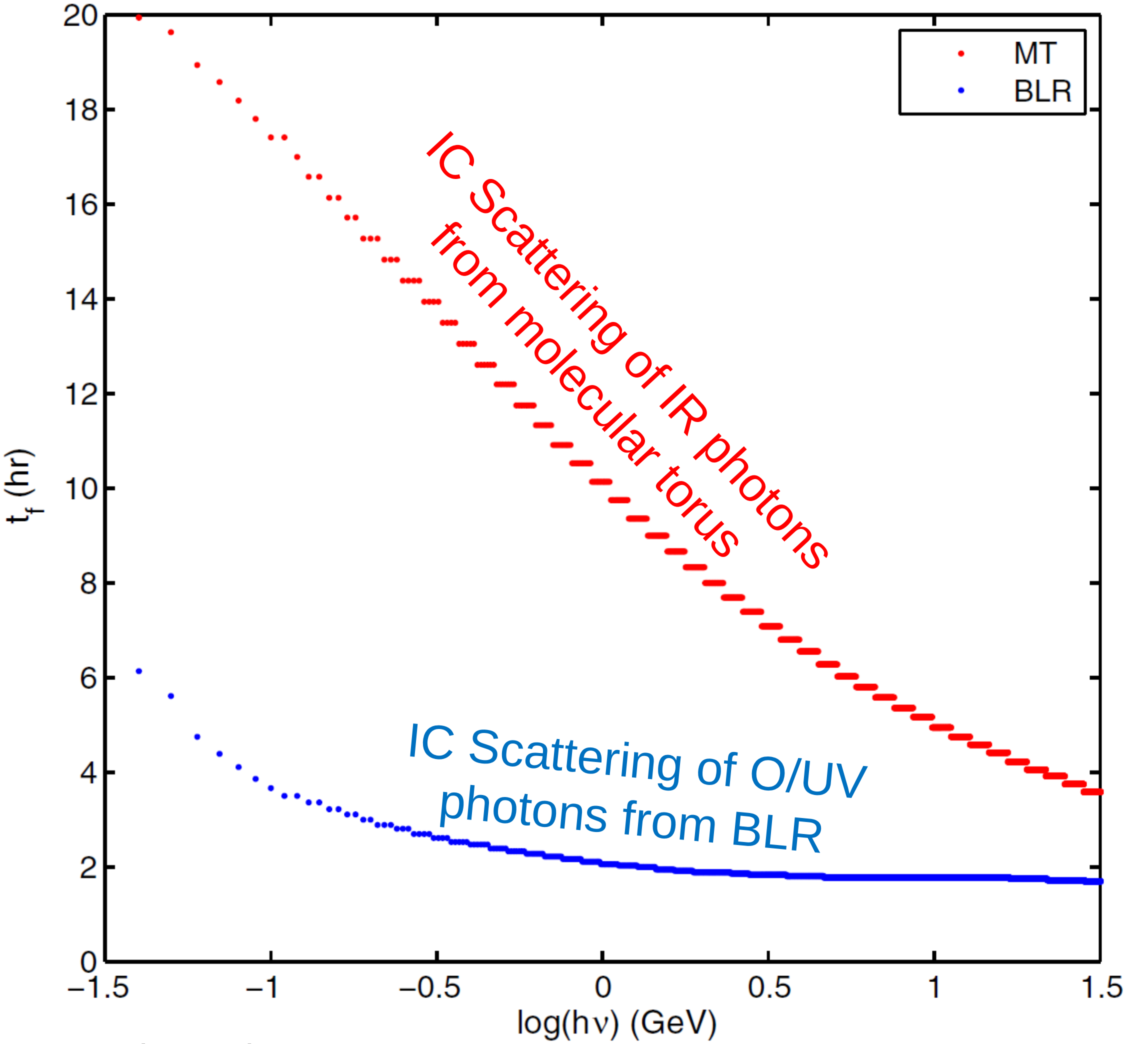
Compton energy loss becomes less efficient at high energies (Klein-Nishina regime).

Diagnosing the Location of the Blazar Zone

FSRQs: Electron cooling dominated by Compton scattering

If seed photons are from IR torus: → Thomson → $\gamma \sim \gamma 2$
→ tcool ~ γ-1

If seed photons are from BLR (optical/UV):
→ Klein-Nishina → $\gamma \sim \gamma\alpha$
$\alpha < 2$
→ tcool ~ const.



(Dotson et al. 2012)

Calculation of X-Ray and Gamma-Ray Polarization in Leptonic and Hadronic Blazar Models

- Synchrotron polarization:
  Standard Rybicki & Lightman description

- SSC Polarization:
  Bonometto & Saggion (1974) for Compton scattering in Thomson regime

- External-Compton emission: Unpolarized.

Upper limits on high-energy polarization, assuming perfectly ordered magnetic field perpendicular to the line of sight (Zhang & Böttcher 2013)