GeV spectroscopy in the Fermi era and supercritical phenomena in relativistic jets

Juri Poutanen

University of Oulu, Finland

Boris Stern

ASC Lebedev Physical Institute & INR, Moscow

Fermi observations of blazars and interpretation:

Poutanen & Stern (2010, ApJ Letters, 717, L118)

Stern & Poutanen (2011, MNRAS Letters, submitted; arXiv:1105.2762)

Photon breeding mechanism:

Stern, Poutanen, 2006, MNRAS, 372, 1217

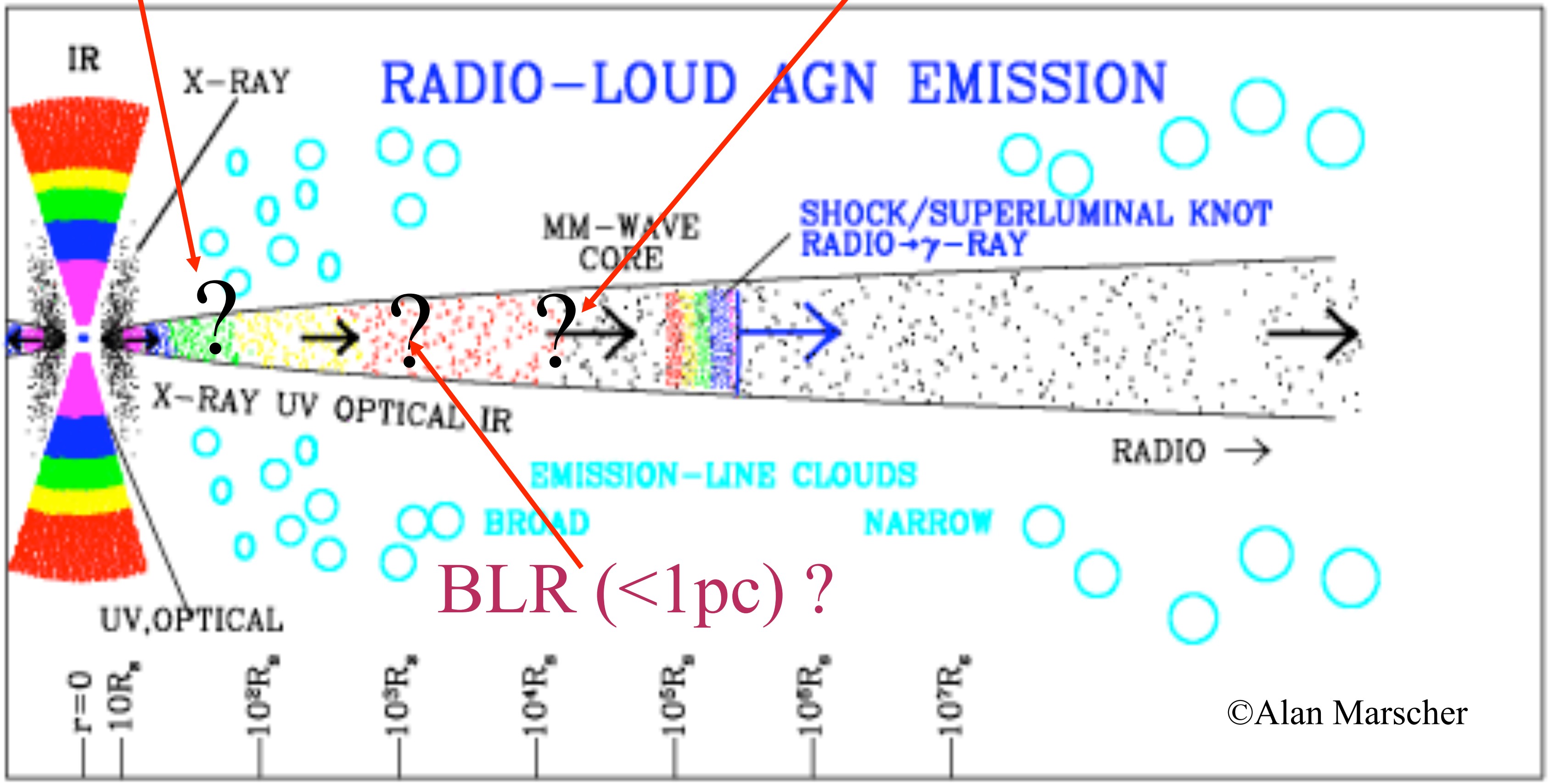
Stern, Poutanen, 2008, MNRAS, 383, 1695

Plan

- GeV spectroscopy in the Fermi era. Blazar spectra.
- Physics of broad-line region (BLR). Photon opacity. Definite proof that gamma-ray emitting region lies within the BLR.
- Formation of the intrinsic spectrum. Supercritical phenomena. Photon breeding.

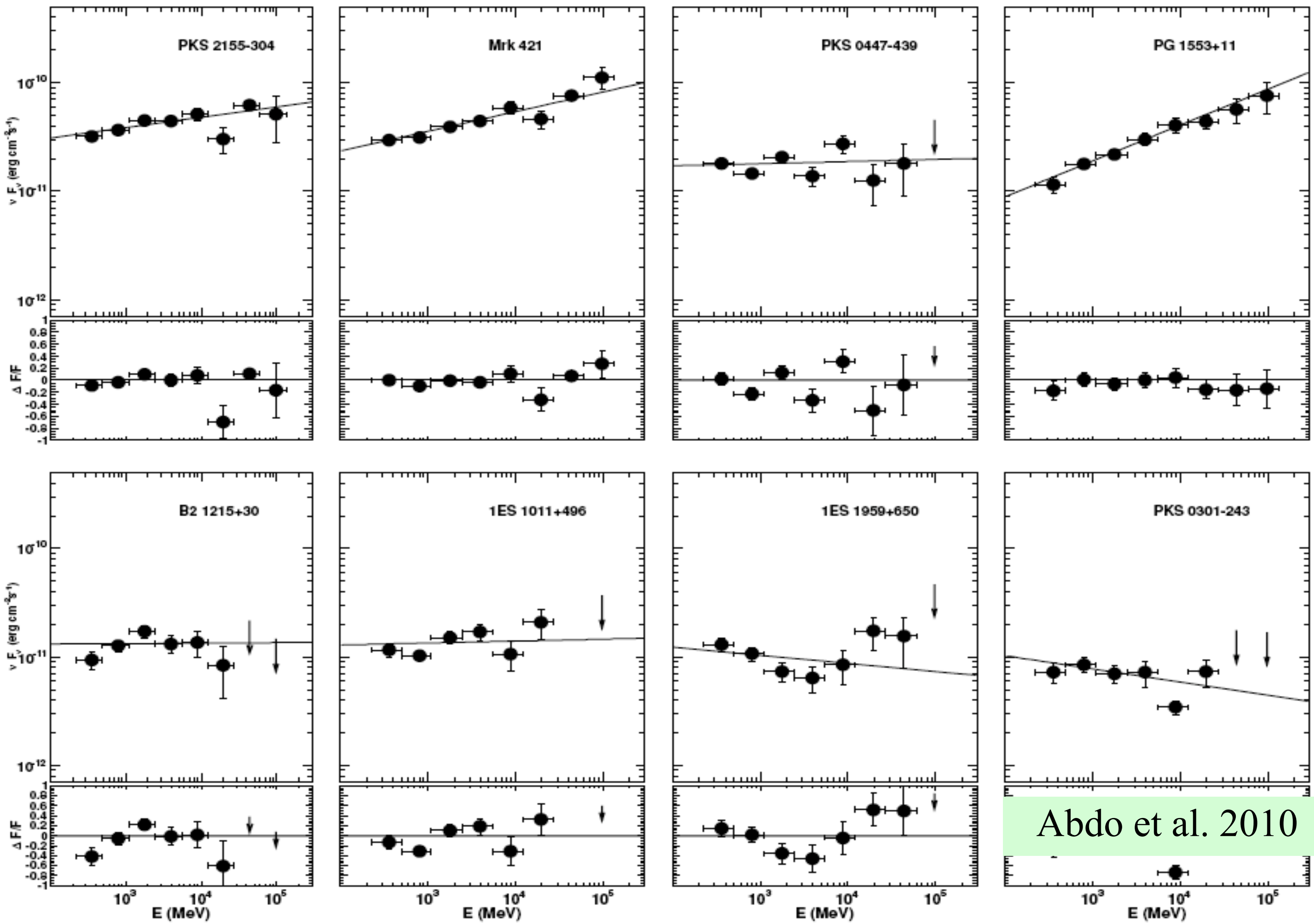
Where the gamma-ray emitting region is situated?

Close to accretion disk? Dusty torus (10 pc)?



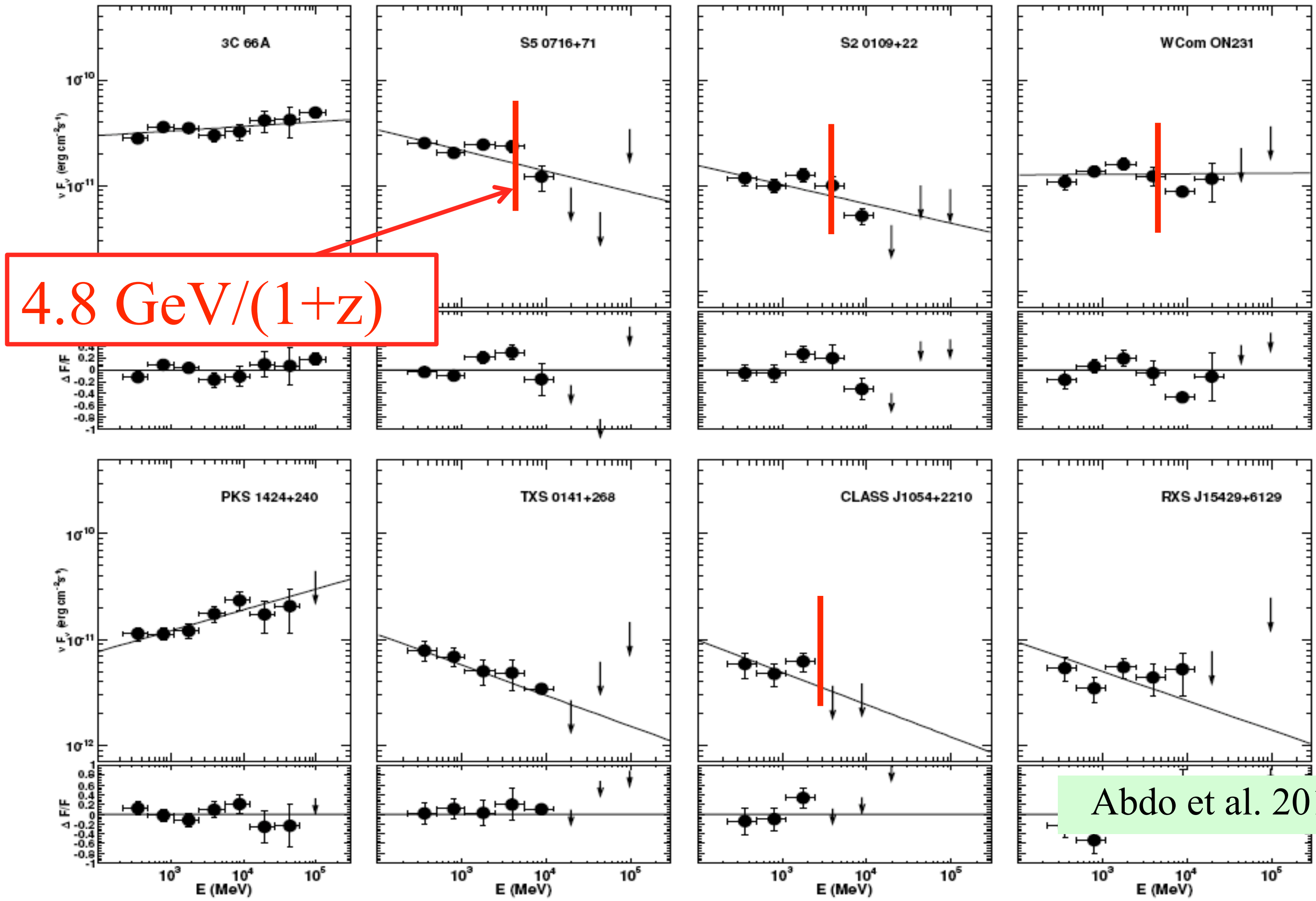
BLR (<1pc) ?

Fermi spectra of high spectral-peak (HSP) BL Lacs



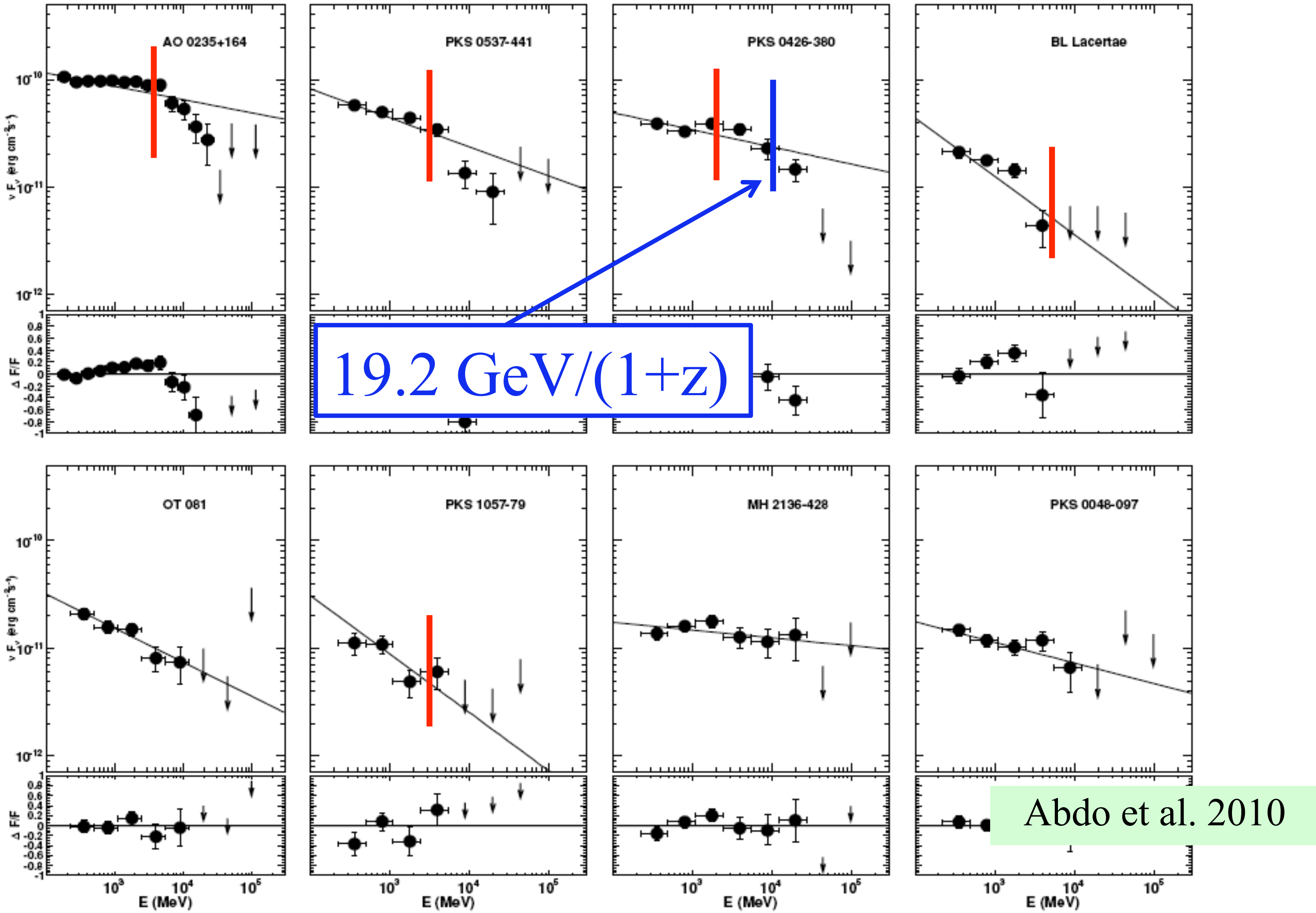
Abdo et al. 2010

Fermi spectra of intermediate spectral-peak (ISP) BL Lacs

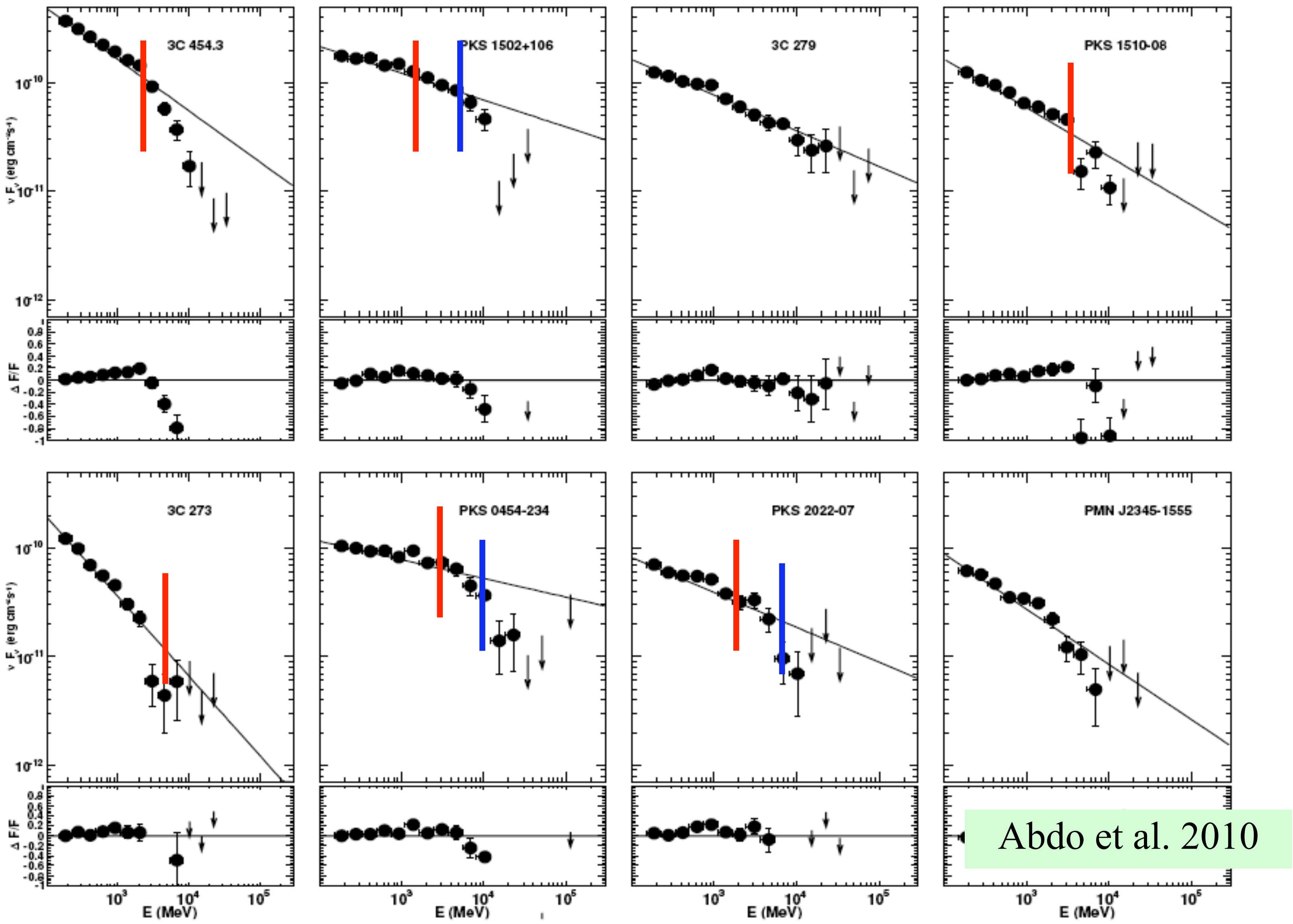


Abdo et al. 2010

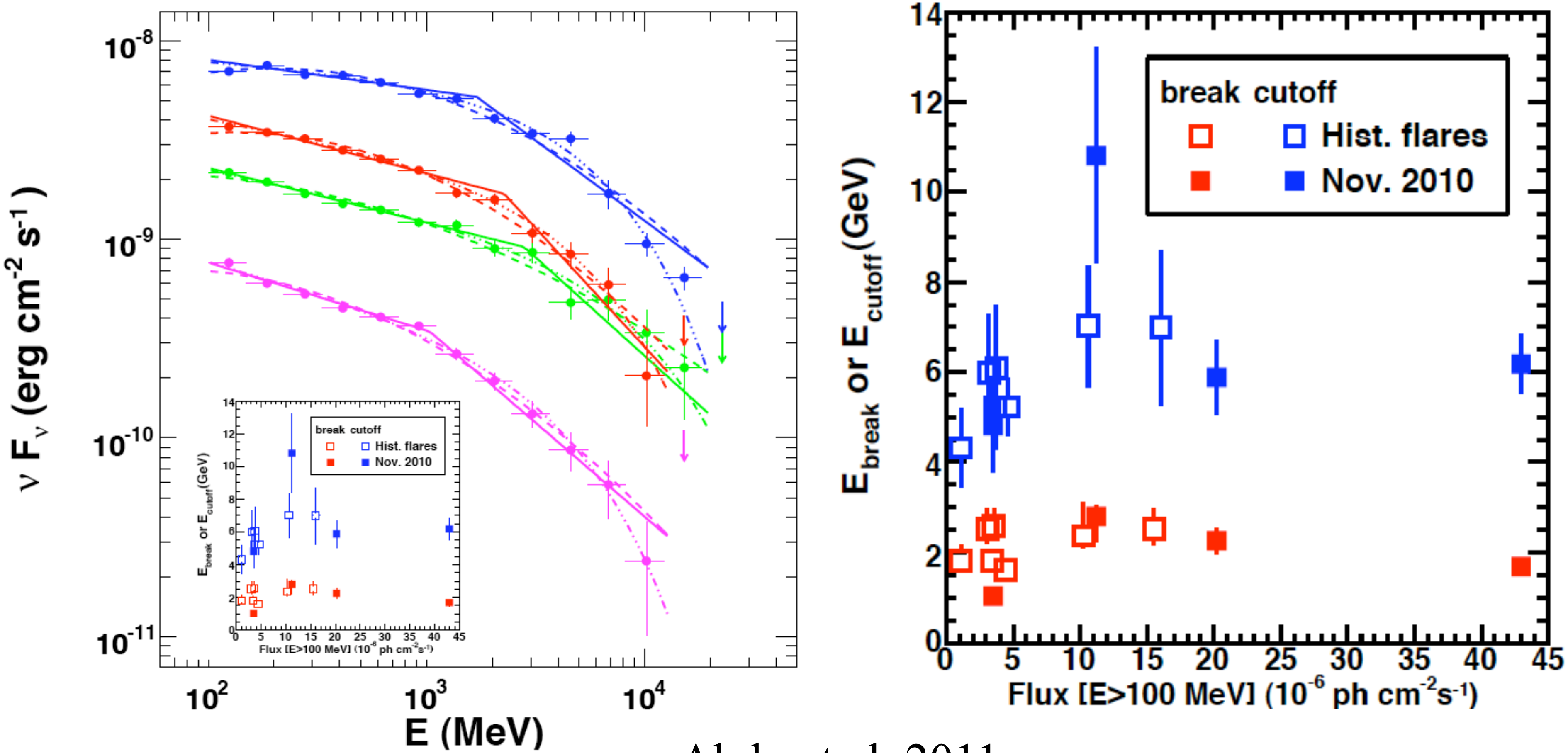
Fermi spectra of low spectral-peak (LSP) BL Lacs



Fermi spectra of flat spectra radio quasars (FSRQ)



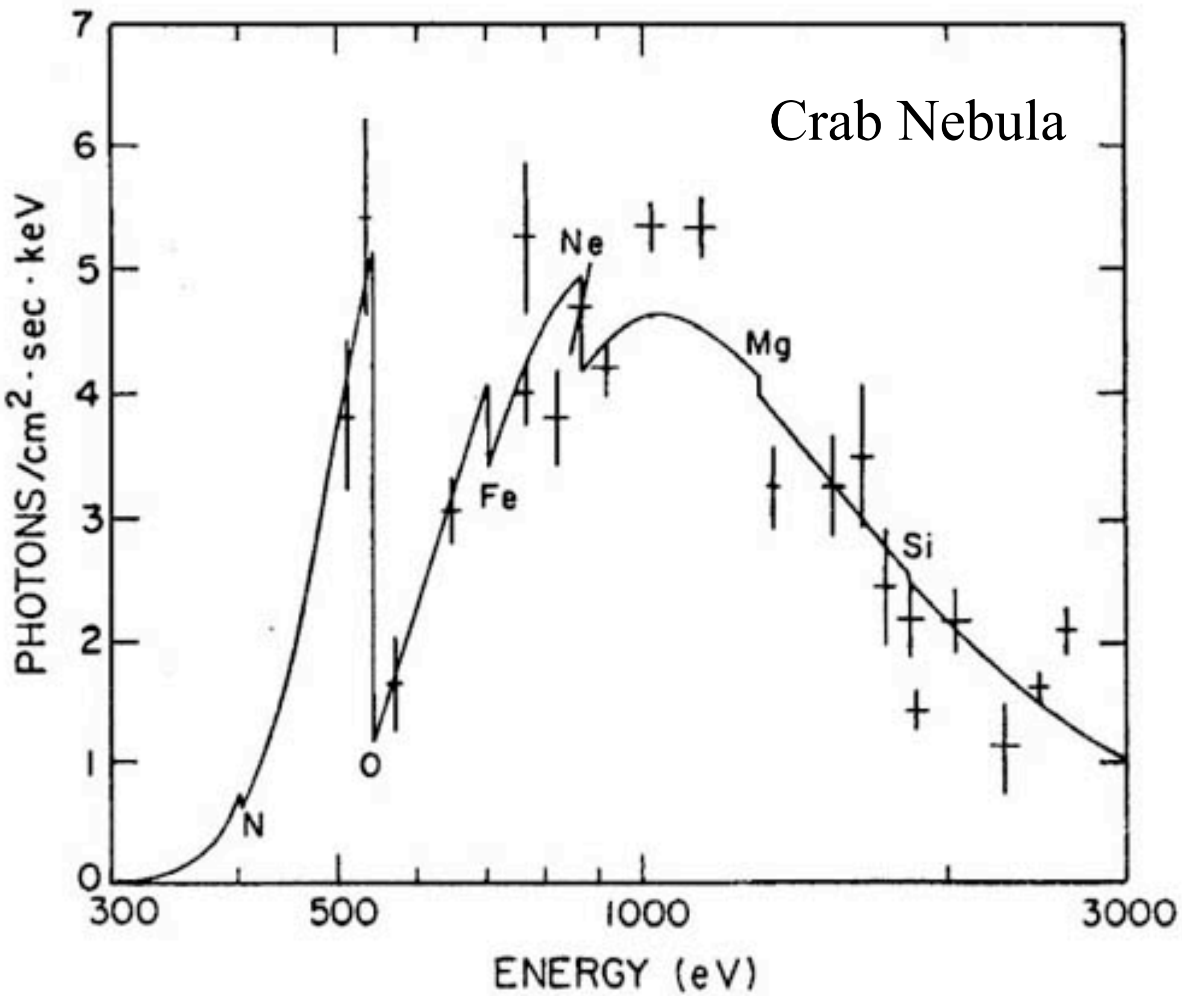
Stability of breaks during flares



Abdo et al. 2011

Break energy is nearly constant ➔ atomic physics

Nature of the edges

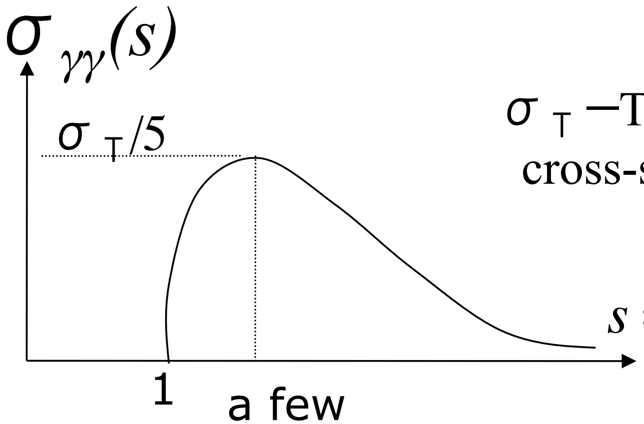


Edge - atomic absorption feature.

What atomic features are doing at GeV energies?

Gamma-ray absorption by photon-photon pair production

<u>Cross-section for pair production</u>



σ_T —Thomson cross-section

$$s = \frac{E_1 E_2}{(m_e c^2)^2}$$

Threshold at s=1:

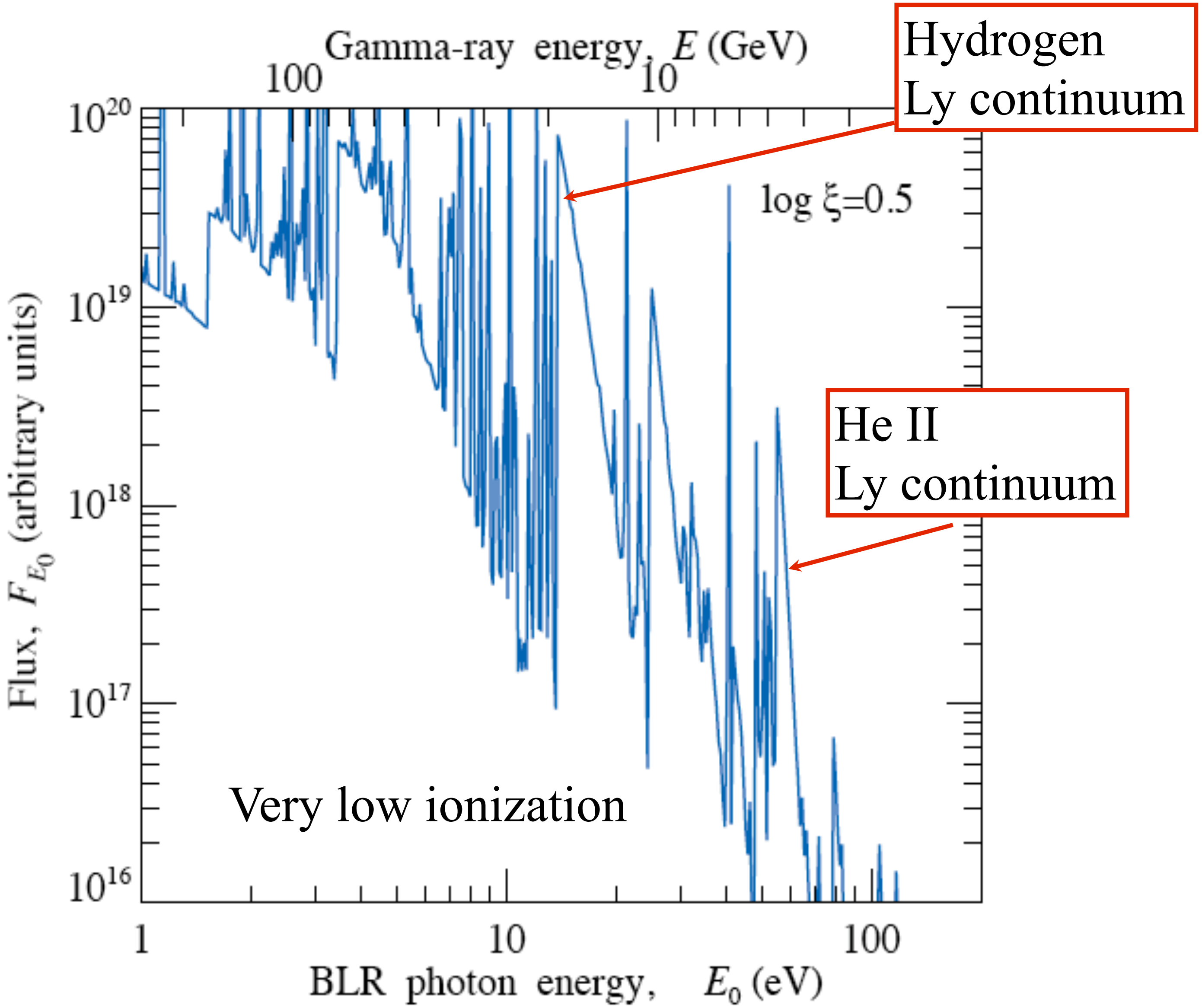
$$\boxed{E = 25.6\ \mathrm{GeV}\frac{10.2\ \mathrm{eV}}{E_0}}$$

	"Line" energy	Threshold
H I Ly α	10.2 eV	– 25.6GeV
H I Ly cont.	13.6 eV	– 19.2GeV
He II Ly α	40.8 eV	– 6.4 GeV
He II Ly cont.	54.4 eV	– 4.8 GeV

Most GeV breaks cannot be produced by Ly α photons!

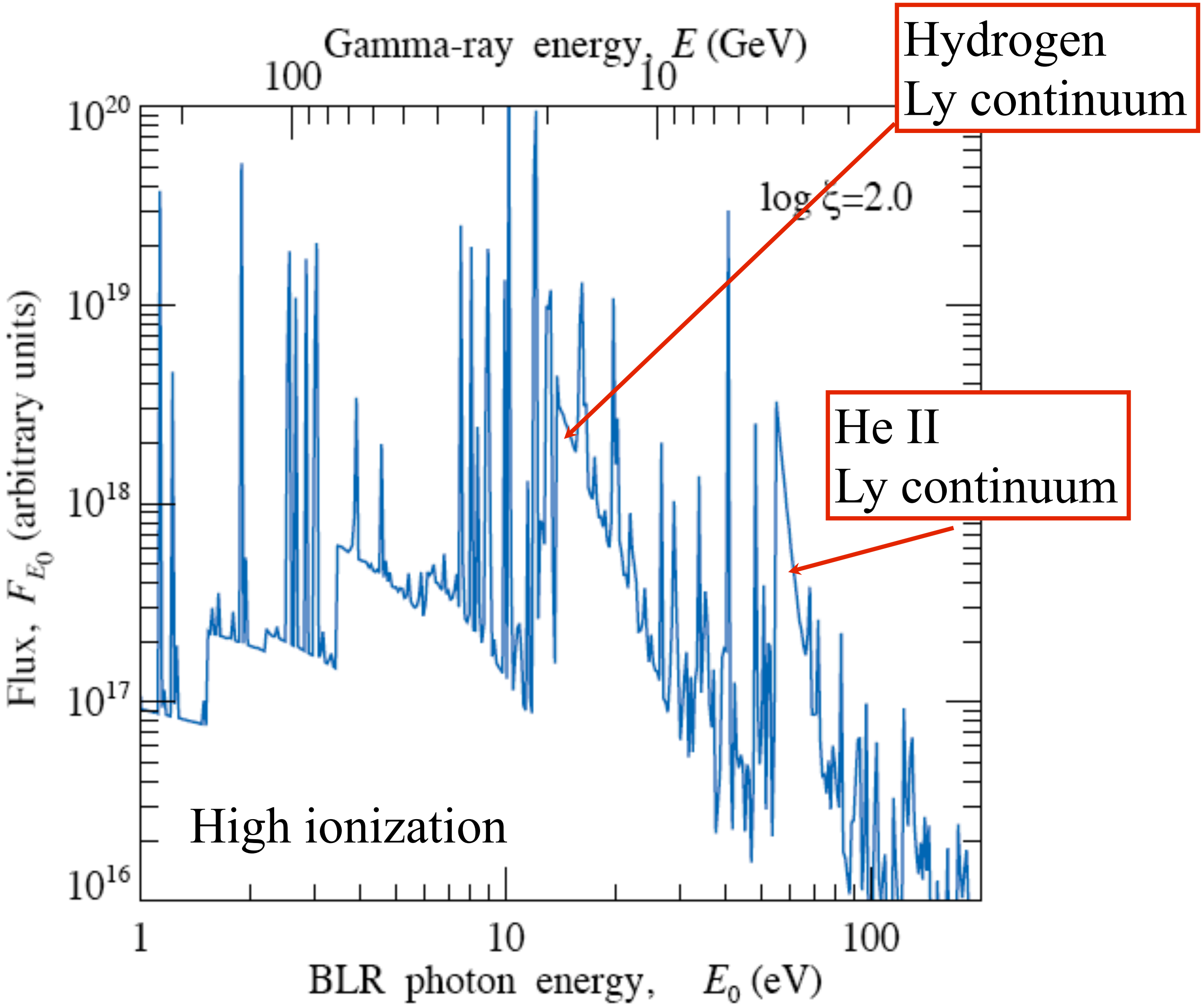
But can be produced by Lyman continuum of ionized helium.

BLR spectra



Gamma-ray energy, E (GeV)
100
10
Hydrogen
Ly continuum
log ξ=0.5
He II
Ly continuum
Very low ionization
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
Flux, F_{E_0} (arbitrary units)
1
10
100
BLR photon energy, E_0 (eV)

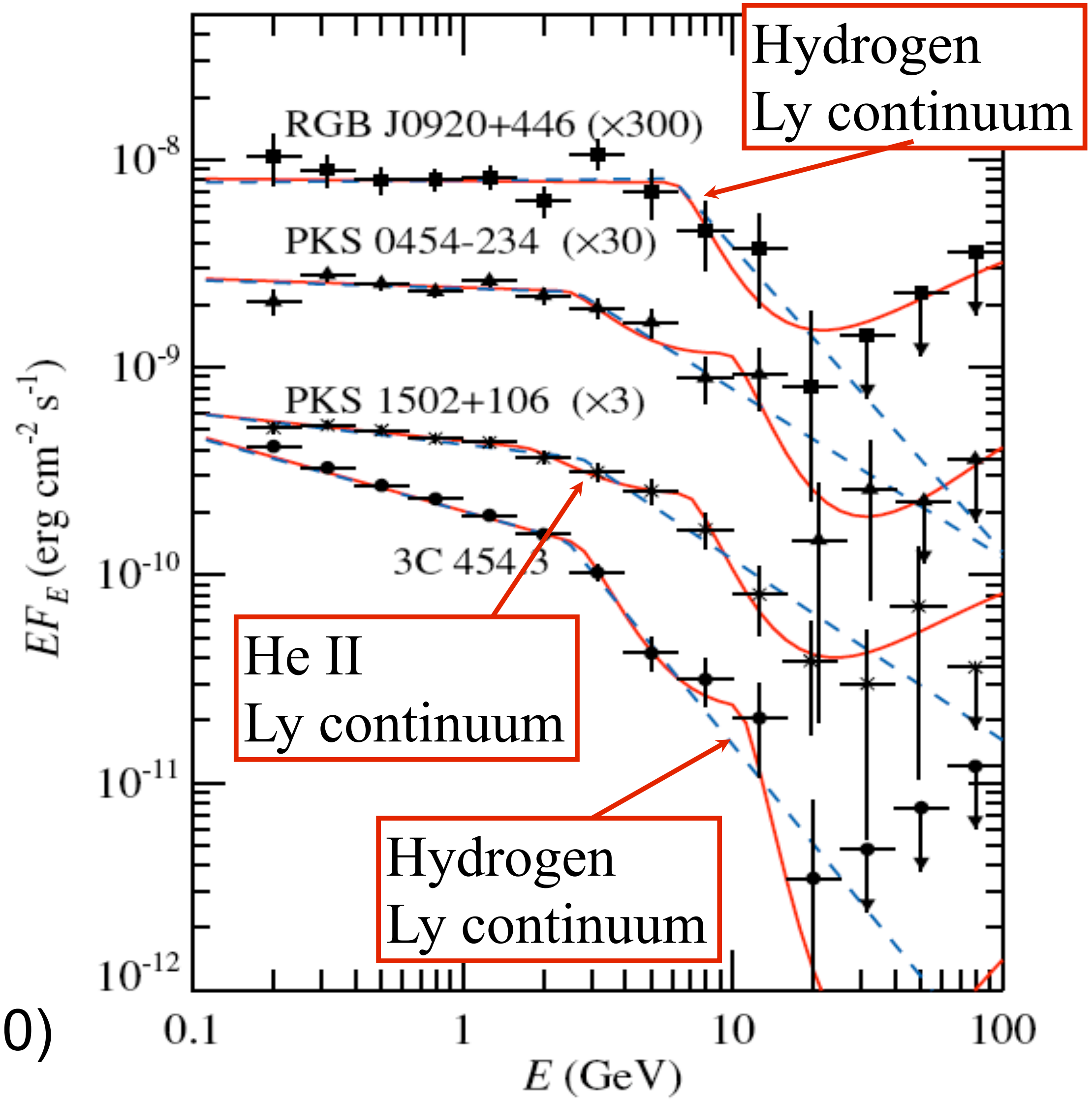
BLR spectra



Gamma-ray energy, E (GeV)
100
10
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
Flux, F_{E_0} (arbitrary units)
log ξ=2.0
High ionization
1
10
100
BLR photon energy, E_0 (eV)
Hydrogen
Ly continuum
He II
Ly continuum

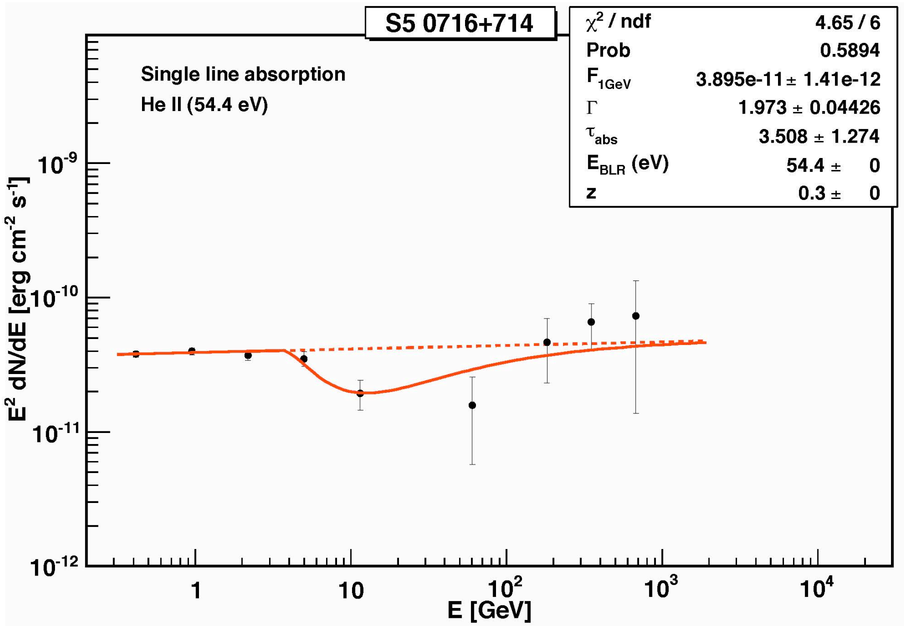
Absorption dips by He II and H I Lyman recombination continuum

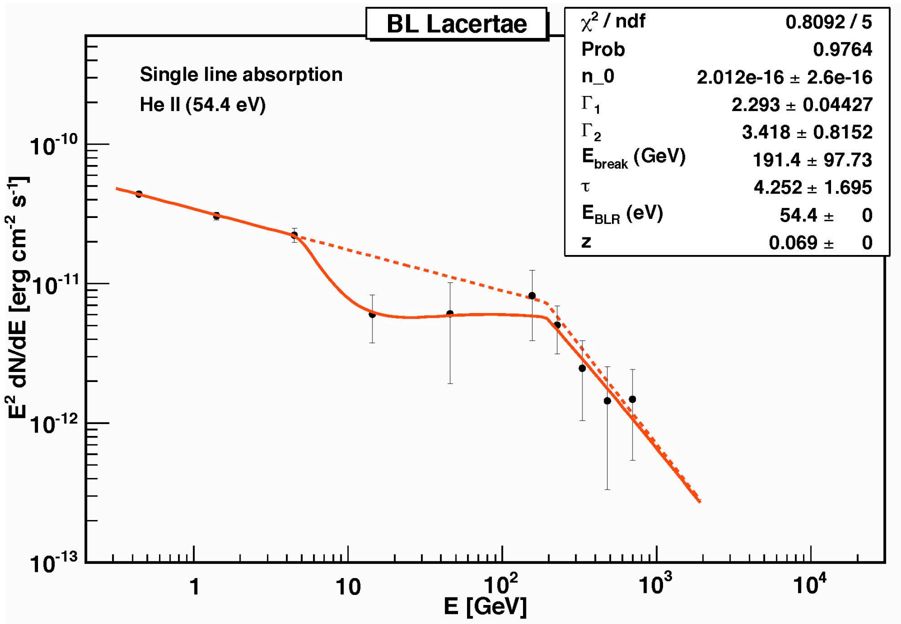
Power law +
dual absorber
(produced by H I and He II Lyman recombination continua)



Poutanen & Stern (2010)

He II breaks and recovering at 100 GeV





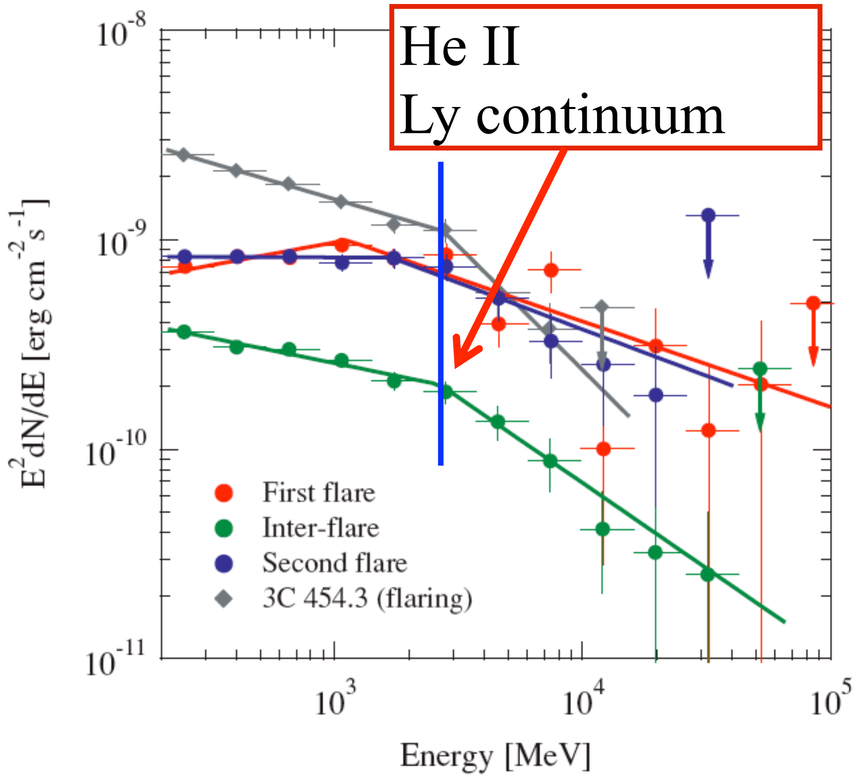
Senturk, Errando, et al., in preparation

The dips are consistent with being produced by He II Lyman recombination continuum.

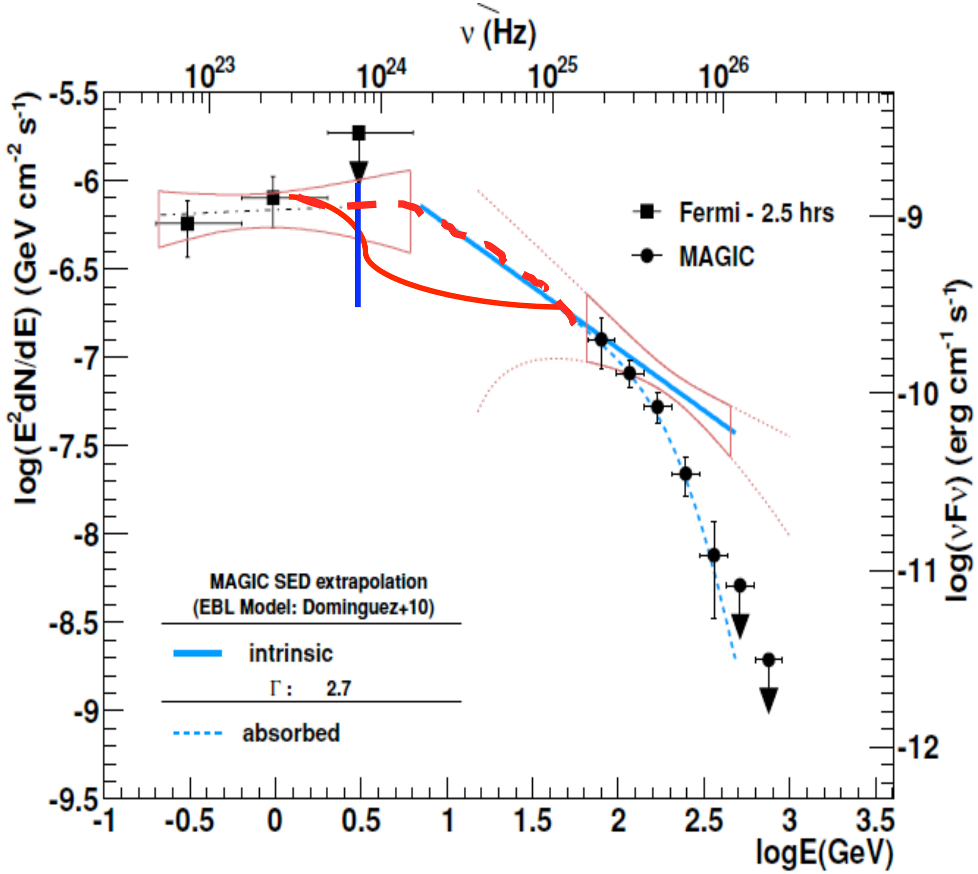
There is no absorption by hydrogen Lyman photons !

He II breaks and recovering at 100 GeV

4C +21.35= PKS 1222+216 z=0.432

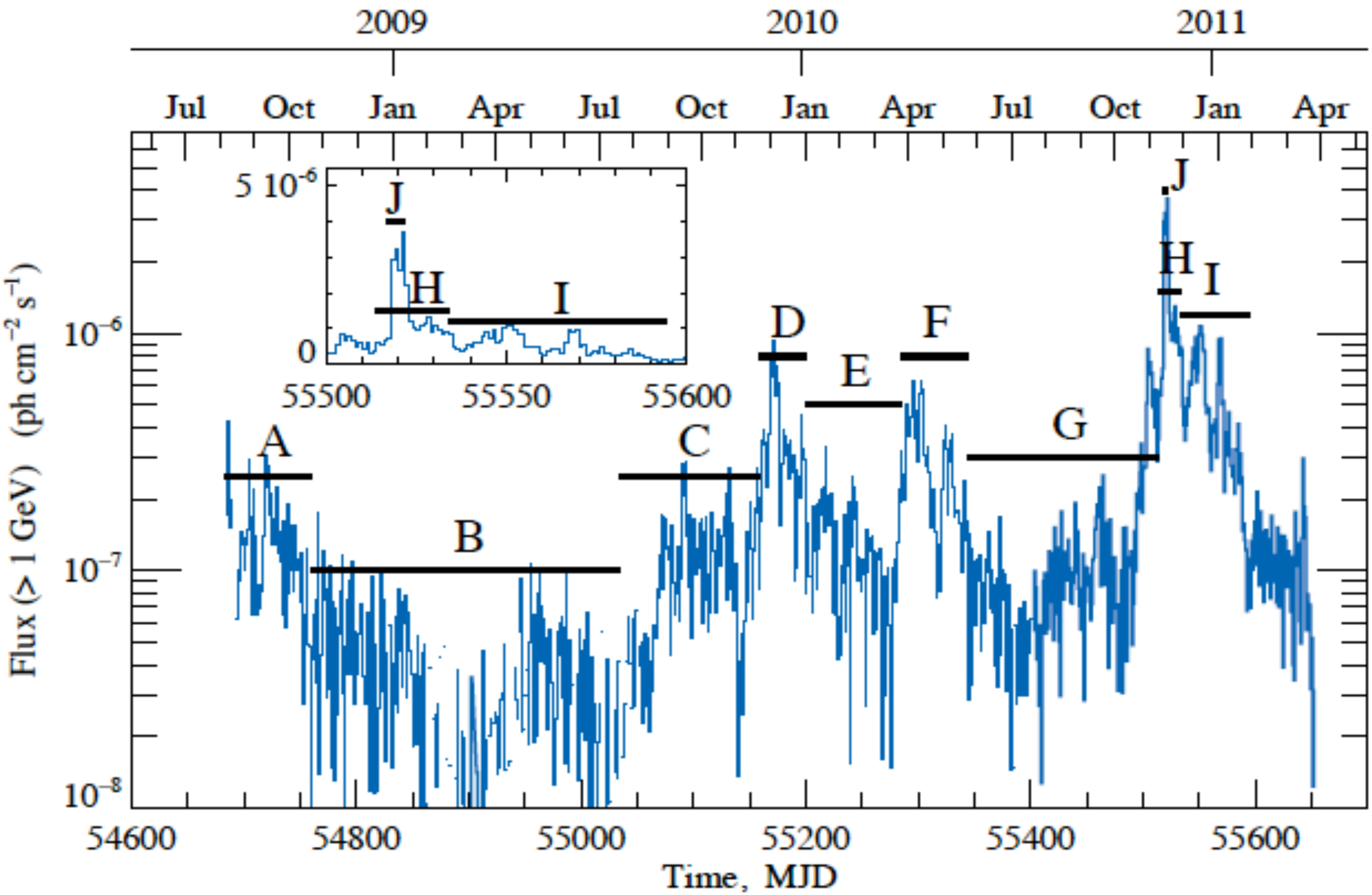


Tanaka et al. 2011

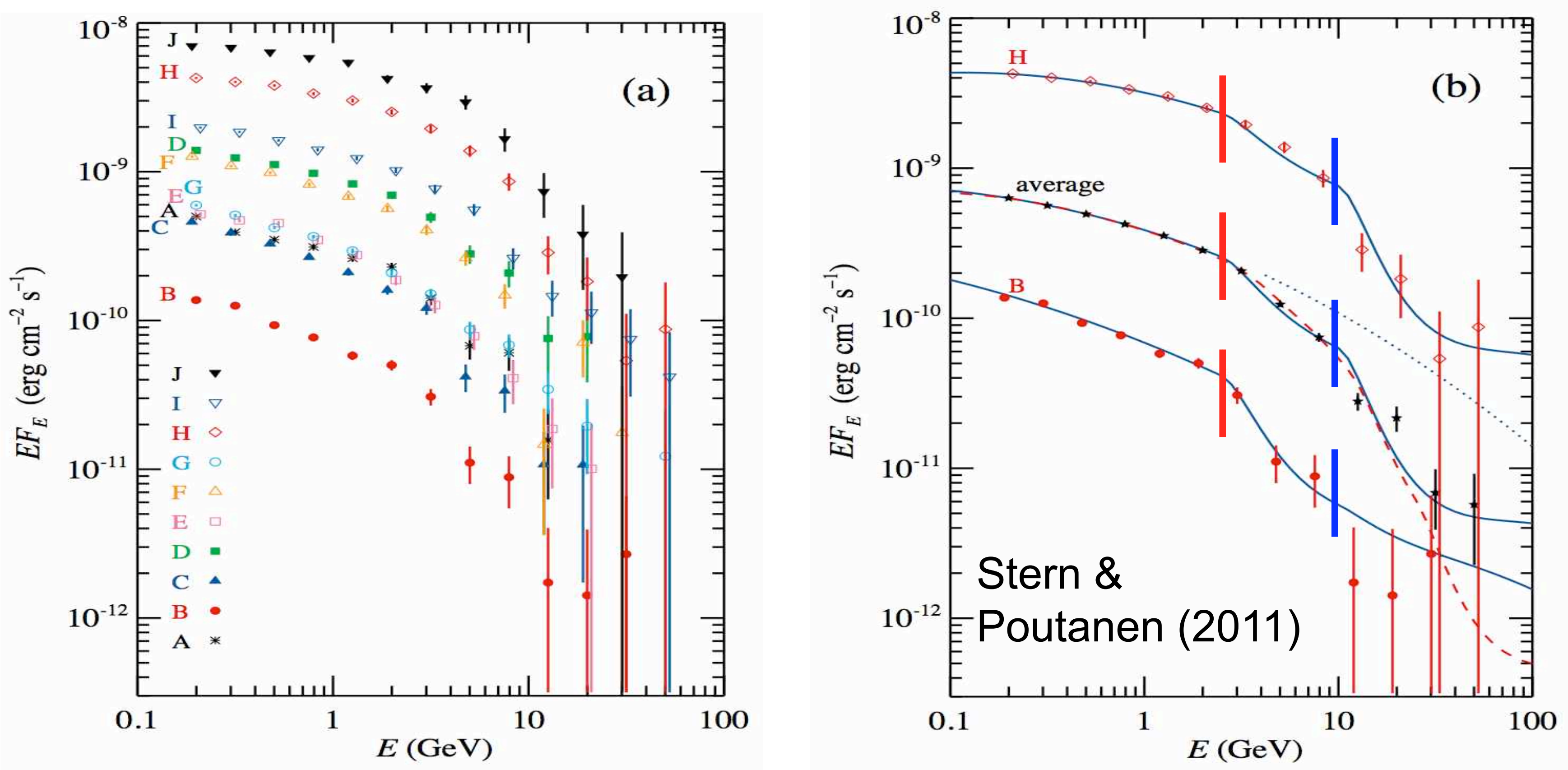


Aleksic et al. 2011

2.5 years from the life of 3C454.3



Spectra of 3C454.3



1. Time-averaged spectra have very significant breaks.
2. Spectra are well represented by a lognormal distribution (log-parabola) with photon-photon absorption by He II and H I “lines”
3. There seems to be an excess above 30 GeV.

Spectral fits to 3C454.3

Interval	Dates[a] MJD	Power-law	PL + DA[b]	Lognormal	Logn + DA[c]
		χ^2/dof			
A	54684–54759	84/12	7.7/10	37/11	7.7/9
B	54759–55034	34/12	8.4/10	16/11	7.3/9
C	55034–55159	65/12	6.8/10	16/11	3.7/9
D	55159–55199	81/12	6.7/10	14/11	2.9/9
E	55199–55284	63/12	40/10	4.4/11	4.4/9
F	55284–55344	112/12	23/10	27/11	17/9
G	55344–55514	72/12	17/10	13/11	7.5/9
H	55514–55534	176/12	23/10	25/11	7.6/9
I	55534–55594	115/12	20/10	18/11	8.4/9
J	55517–55522	79/12	18/10	11/11	5.9/9
A+C+E+G		315/12	33/10	42/11	9.0/9
D+F+I		435/12	42/10	61/11	20/9
All (A–I)	54684–55594	1099/12	85/10	129/11	23/9

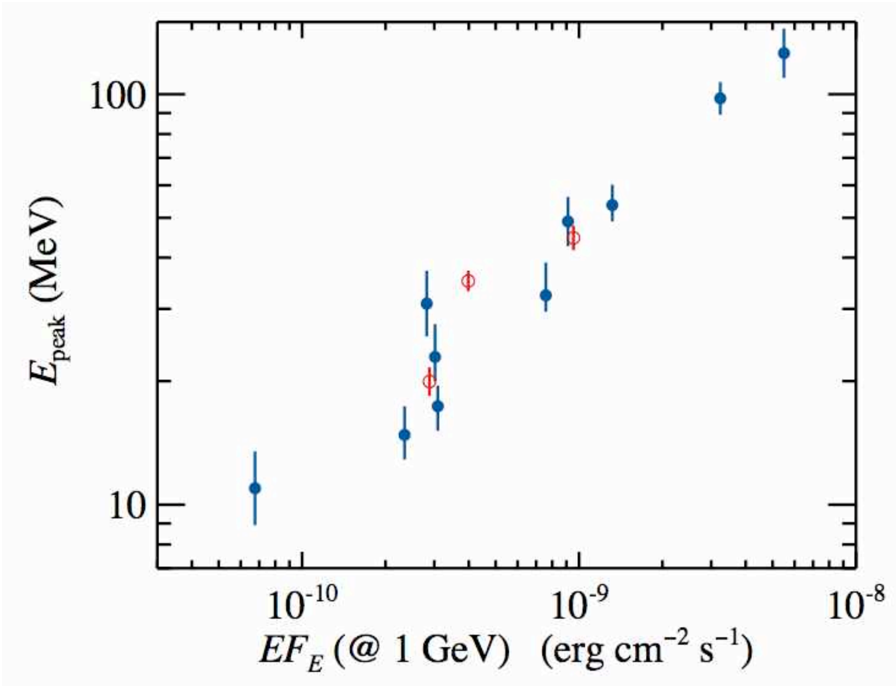
4. Fits by a lognormal distribution with a double absorber are superior to any phenomenological model.

Constraints on the gamma-ray emission site

5. The ratio of opacities due to He and H constrains the ionization parameter of the gamma-ray absorbing medium:

$$\tau_{\mathrm{He}} / \tau_{\mathrm{H}} \geq 1/4 \longrightarrow \boxed{\log \xi > 2}$$

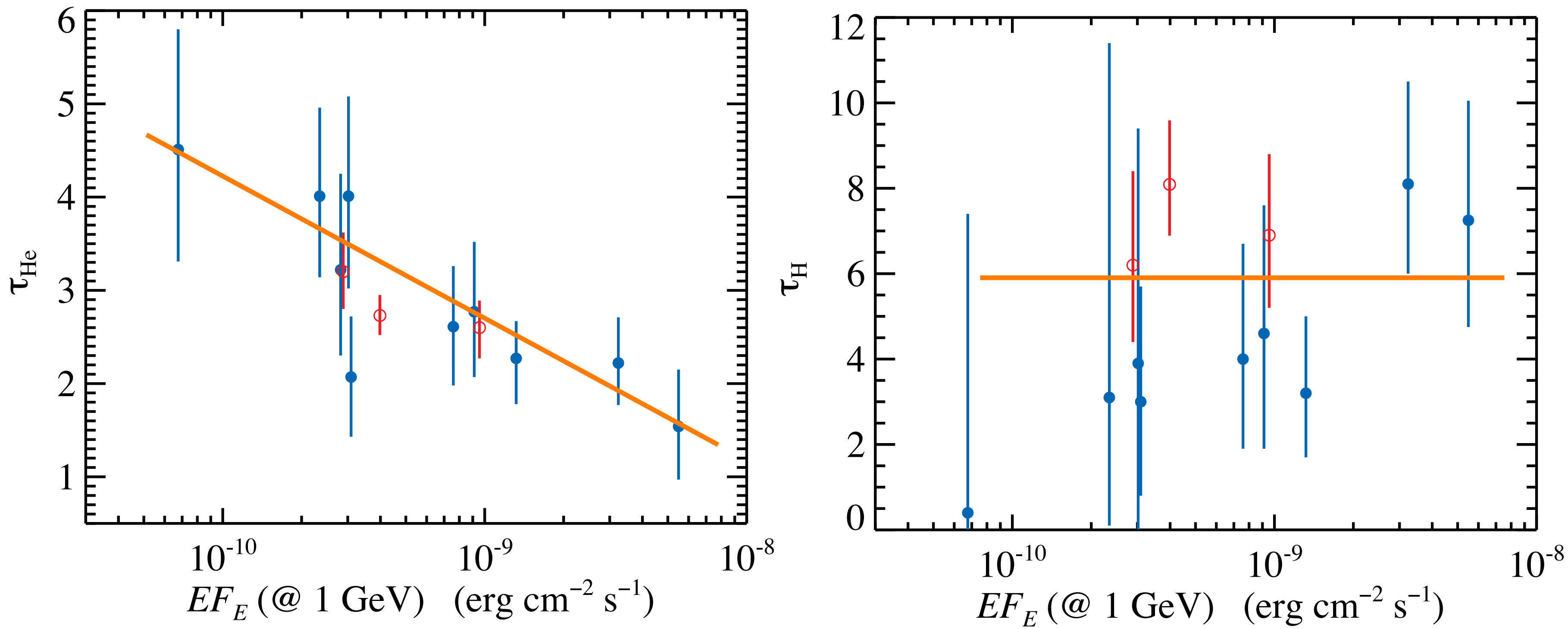
Spectral variations



Stern & Poutanen (2011)

6. There is a significant peak – flux correlation (hardness-flux). Argues against importance of the Klein-Nishina effect.

Opacity variations



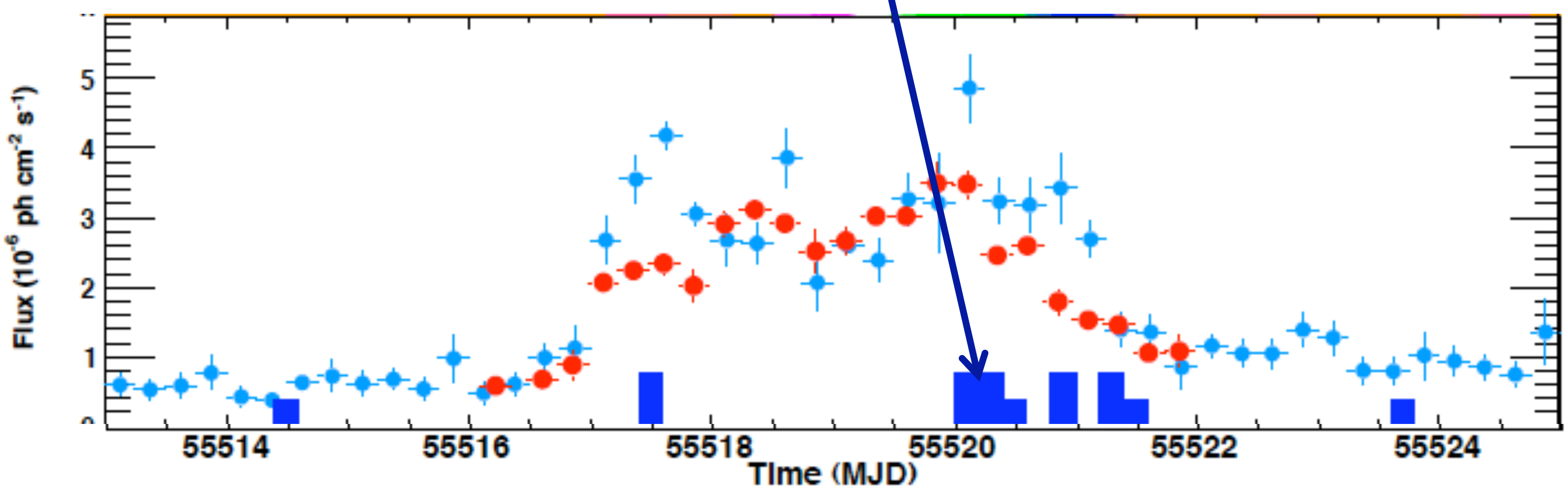
Stern & Poutanen (2011)

7. Opacity in He II drops with flux → the gamma-ray emission region moves away from the BLR high-ionization zone at high fluxes.

8. Opacity in H I does not vary → the gamma-ray emission region lies within the H^+ zone.

Motion of gamma-ray region

Moving away source at high flux is consistent with the arrival of >10 GeV photons in the end of the flare (Abdo et al. 2011).



Estimates of the opacities

The optical depth for pair production on line photons:

$$\tau_T = N_{ph}\sigma_T = \frac{L}{4\pi R^2 c}\frac{1}{E_{\rm line}} R\sigma_T = 35\frac{L_{45}}{R_{pc}}\frac{10\,{\rm eV}}{E_{\rm line}}$$

$$R_{\rm BLR} \propto L_{\rm disk}^{1/2}$$

Kaspi et al. 2007
Bentz et al. 2009

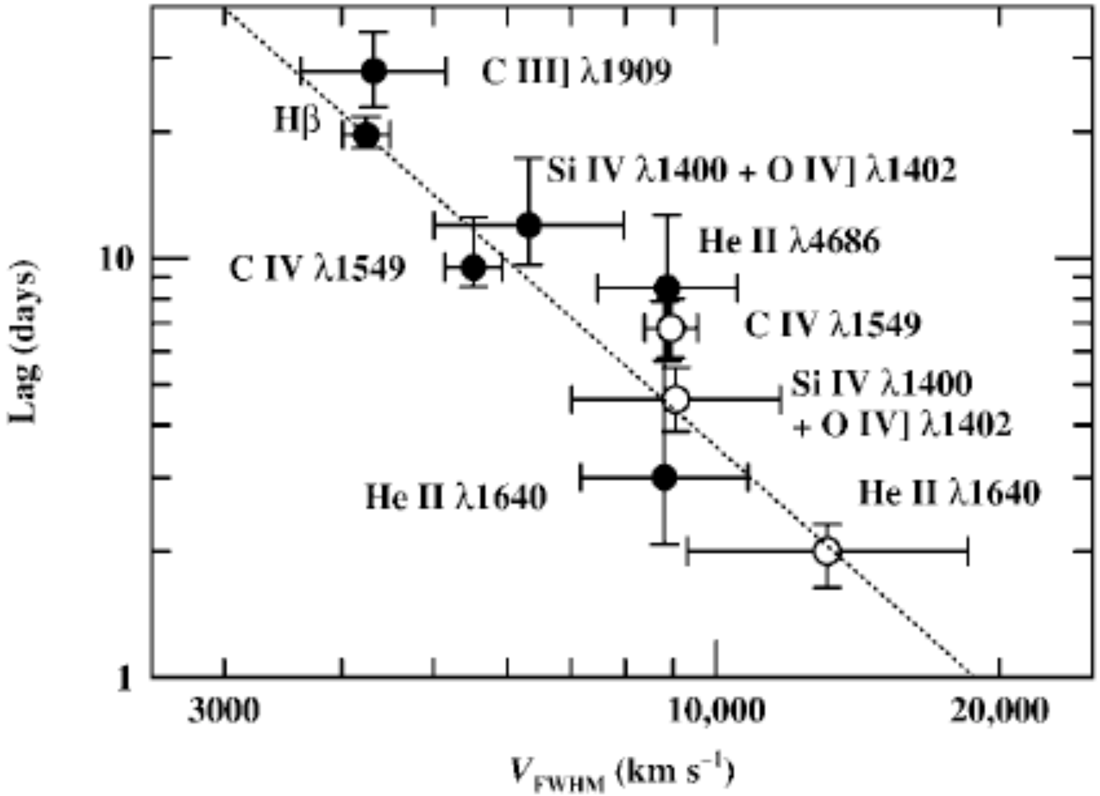
$$\boxed{\tau_T \propto \frac{L_{\rm line,45}}{L_{\rm disk,47}^{1/2}}\frac{10\,{\rm eV}}{E_0} \propto L^{1/2}}$$

This explains why GeV absorption is strong in FSRQ and weak in BL Lacs.

The spectral break is proportional to the optical depth:

$$\Delta\Gamma = -\frac{{\rm d}\ln \exp(-\tau_{\gamma\gamma}(E,E_0))}{{\rm d}\ln E} \approx \frac{\tau_{\rm T}}{\sigma_{\rm T}} \max \frac{\sigma_{\gamma\gamma}(s)}{\ln s} \approx \frac{\tau_{\rm T}}{4}$$

The "size" of broad-line region

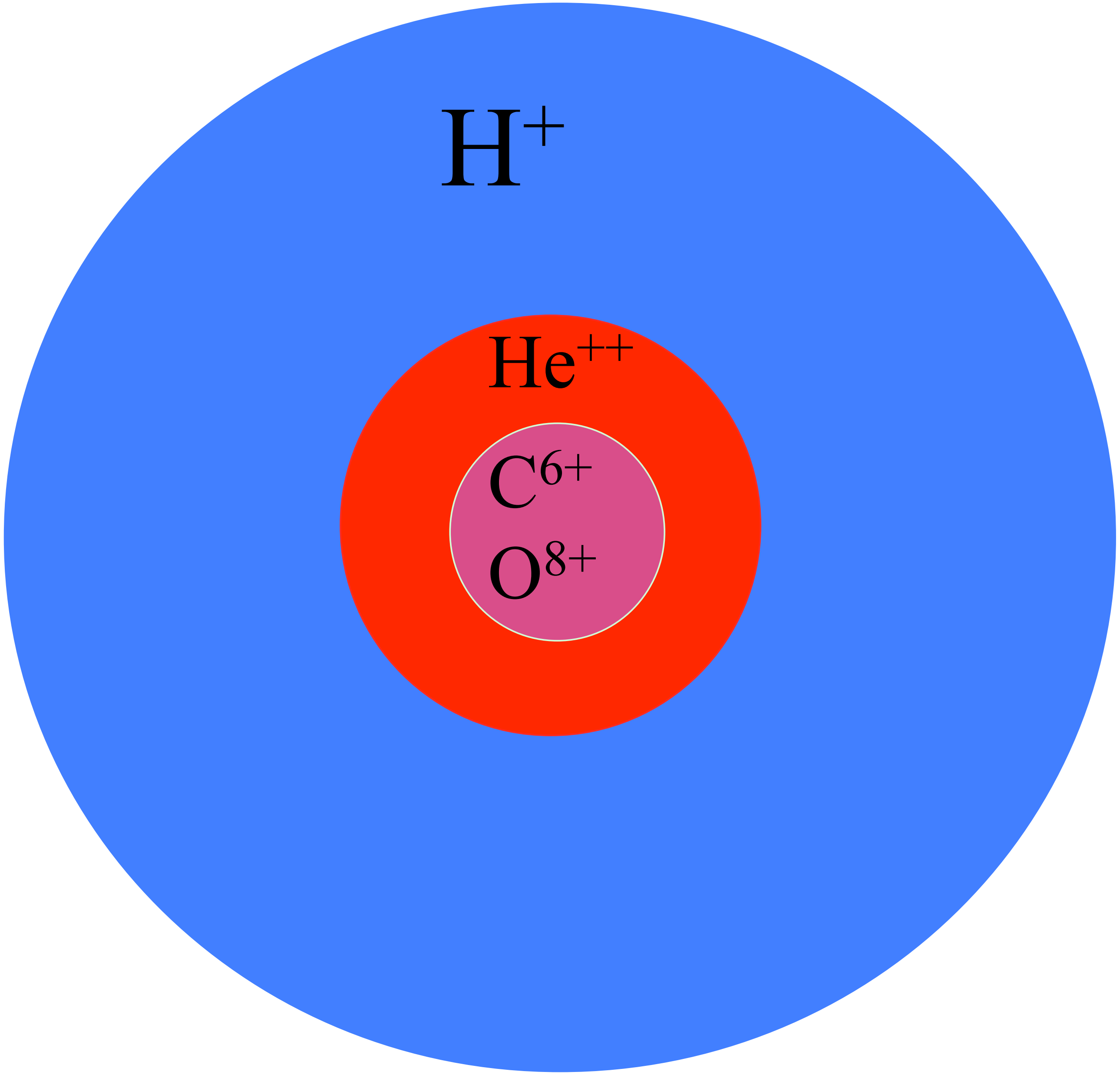


Reverberation in Sy 1 NGC 5548.

Peterson & Wandel (1999)

High-ionization lines (e.g. He II 1640) are produced 10 times closer than the Balmer lines and 5 times closer than C IV 1549.

BLR structure



Opacity depends on compactness! Not luminosity.

The optical depth for pair production on line photons:

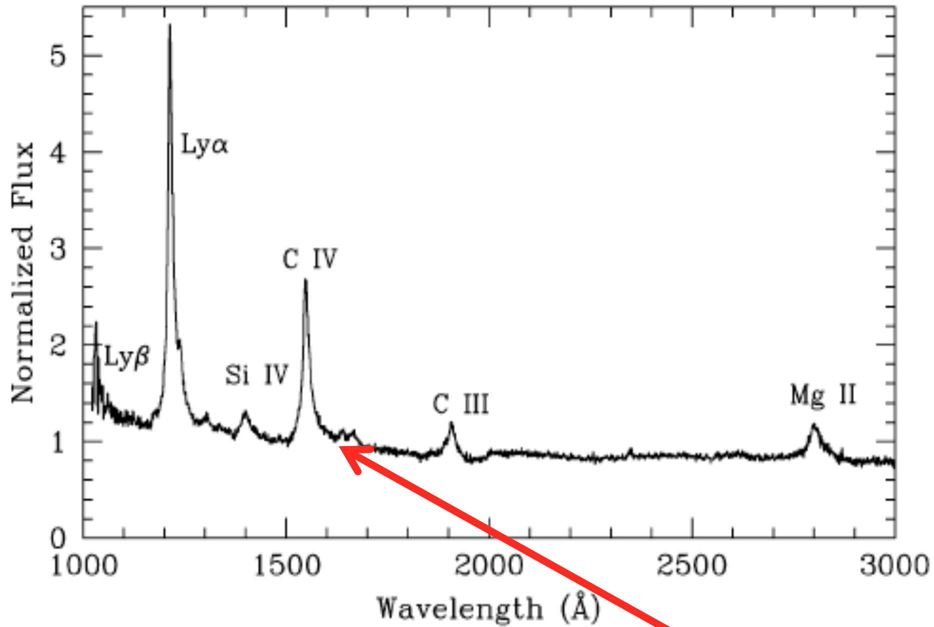
$$\tau_T = N_{ph}\sigma_T = \frac{L}{4\pi R^2 c}\frac{1}{E_{\text{line}}}R\sigma_T = 35\frac{L_{45}}{R_{pc}}\frac{10\text{eV}}{E_{\text{line}}}$$

Weak, high-ionization lines can be more important than strong, low-ionization lines!

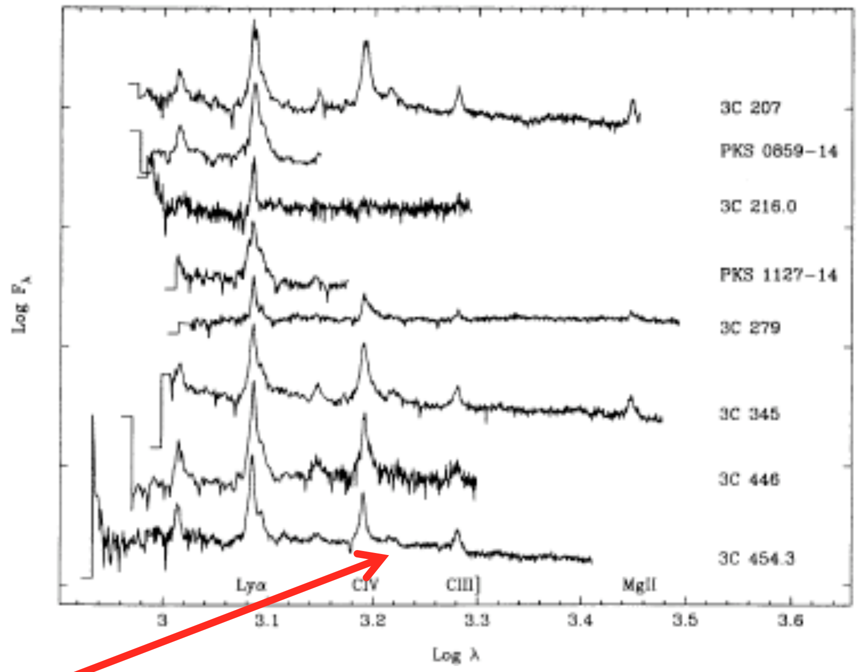
Assuming that all lines are produced at the same distance

1. strongly underestimates the GeV opacity due to high-ionization line
2. strongly overestimates the opacity due to low-ionization lines.

UV spectra of FSRQs



Composite blazar spectrum
(Pian et al. 2005).



HST spectra of blazars
(Wills et al. 1995).

He II 1640Å

In 3C454.3, $L_{Ly\alpha} = 1E45$ erg/s
$L_{He\ II\ 1640} = 6E43$ erg/s =>
$L_{He\ II\ Ly\alpha} = 6E44$ erg/s

A puzzle: BLR size

The optical depth for pair production on line photons:

$$\tau_T = N_{ph}\sigma_T = \frac{L}{4\pi R^2 c}\frac{1}{E_{\rm line}} R\sigma_T = 35\frac{L_{45}}{R_{pc}}\frac{10{\rm eV}}{E_{\rm line}}$$

$$\left.\begin{array}{l} \tau_{\rm H} \approx 5 \\ L_{Ly\alpha,45} = 1 \Rightarrow L_{\rm Ly\ cont,45} \approx 1 \end{array}\right\} \Rightarrow R \approx 10{\rm pc}$$

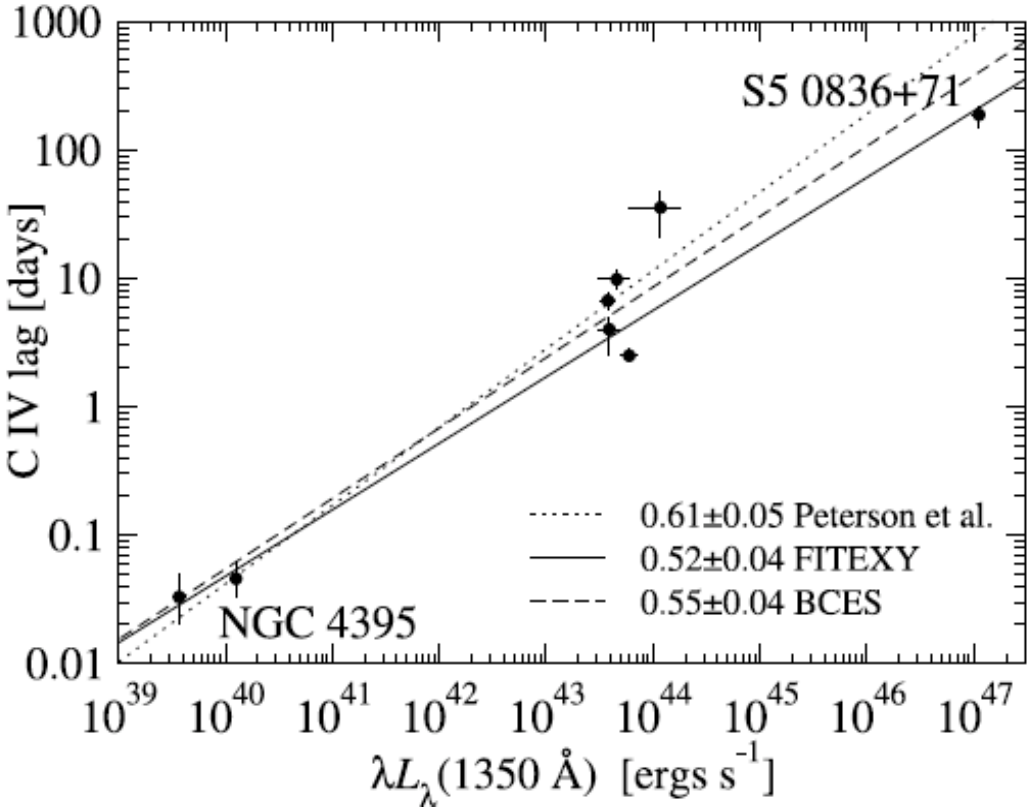
Contradiction with the reverberation results:

$$R_{\rm CIV\ 1549Å} \approx 0.2{\rm pc}\ \ L_{\rm disk,47}^{1/2} \qquad \text{Kaspi et al. 2007}$$

Solutions?

1. The BLR size is underestimated.
2. The gamma-ray emitting region is extended, with multi-GeV photons produced further out.

The “size” of broad-line region



Scaling of BLR size (Kaspi et al. 2007)

$$R_{\mathrm{CIV}\ 1549} \approx 0.02(\lambda L_{\lambda,1350\,\mathrm{Å}})_{45}^{1/2}\ \mathrm{pc}$$

is based on one object and one line!

Size might be in error by a factor of 10 !

Kaspi et al. (2007) write:

“no Lyα variability is detected…”.

Lyα has to be produced further away than CIV.

Conclusions. Part I.

- GeV breaks are powerful diagnostics of the BLR physics and constrain the gamma-ray emitting region. We witness a start of a new era of atomic spectroscopy in the GeV range!
- GeV breaks are consistent with being produced by absorption on He II and H I recombination continua.
- Additional spectral features in the sub-GeV range are predicted due to the high-ionization soft X-ray lines.
- Opacity in He II varies with flux. The gamma-ray emission region moves away from the high-ionization region at high fluxes. Gamma-ray emitting region in 3C454.3 has to lie at the boundary of the high-ionization zone of BLR.

- The BLR “size” seems strongly underestimated in powerful quasars and the sub-TeV opacity is strongly overestimated.

I hope you are convinced now
that gamma-rays in bright blazars
are produced within the BLR

but how to produce intrinsic spectrum
and variability?

Radiative instabilities

- Relativistic proton initiated cascades (Stern & Svensson 1991, Stern, Svensson & Sikora 1991, Kirk & Mastichiadis 1992, Stern, Sikora & Svensson 1992)

$$\boxed{p+\gamma \rightarrow p+e^{\pm}}$$

- Supercritical pile (Kazanas & Mastichiadis 1999, Kazanas, Georganopoulos & Mastichiadis 2002, Mastichiadis & Kazanas 2006)

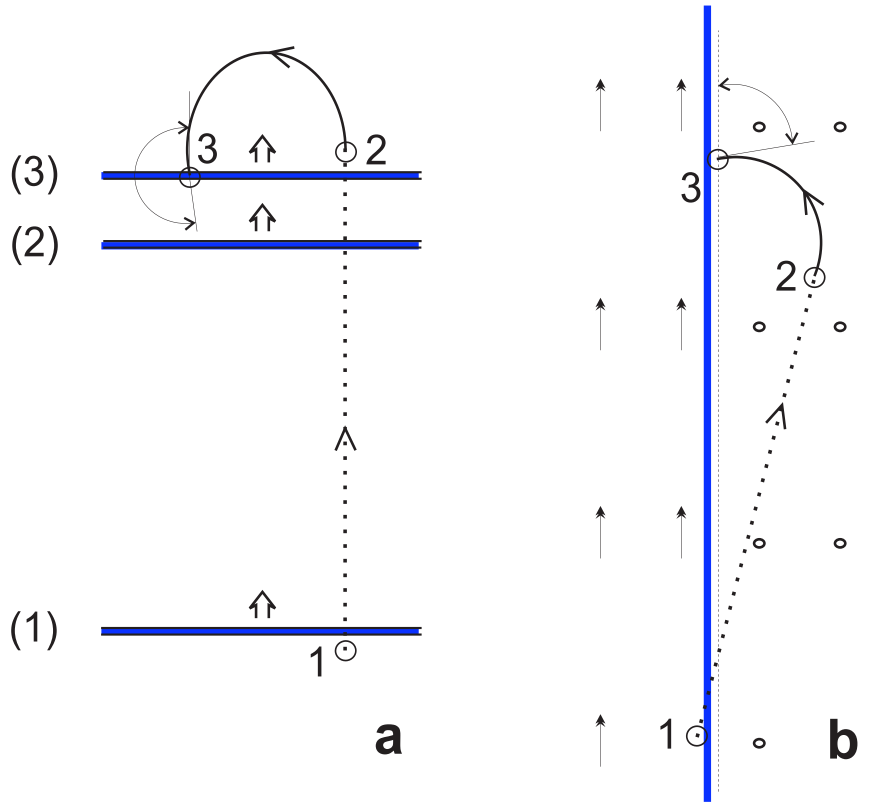
$$\boxed{p+\gamma \rightarrow p+e^{\pm} \quad \text{and reflection from external medium}}$$

- Converter mechanism / Photon breeding (Stern 2003, Derishev et al. 2003, Stern & Poutanen 2006, 2008)

$$\begin{array}{lll}
e^{\pm}+\gamma \rightarrow e^{\pm}+\gamma' & \text{and} & \gamma'+\gamma \rightarrow e^{+}+e^{-} \\
p+\gamma \rightarrow n+\pi^{+} & \text{and} & n+\gamma \rightarrow p+\pi^{-} \\
p+p \rightarrow n+p+\pi^{+} & \text{and} & n+p \rightarrow p+p+\pi^{-}
\end{array}$$

Converter mechanism

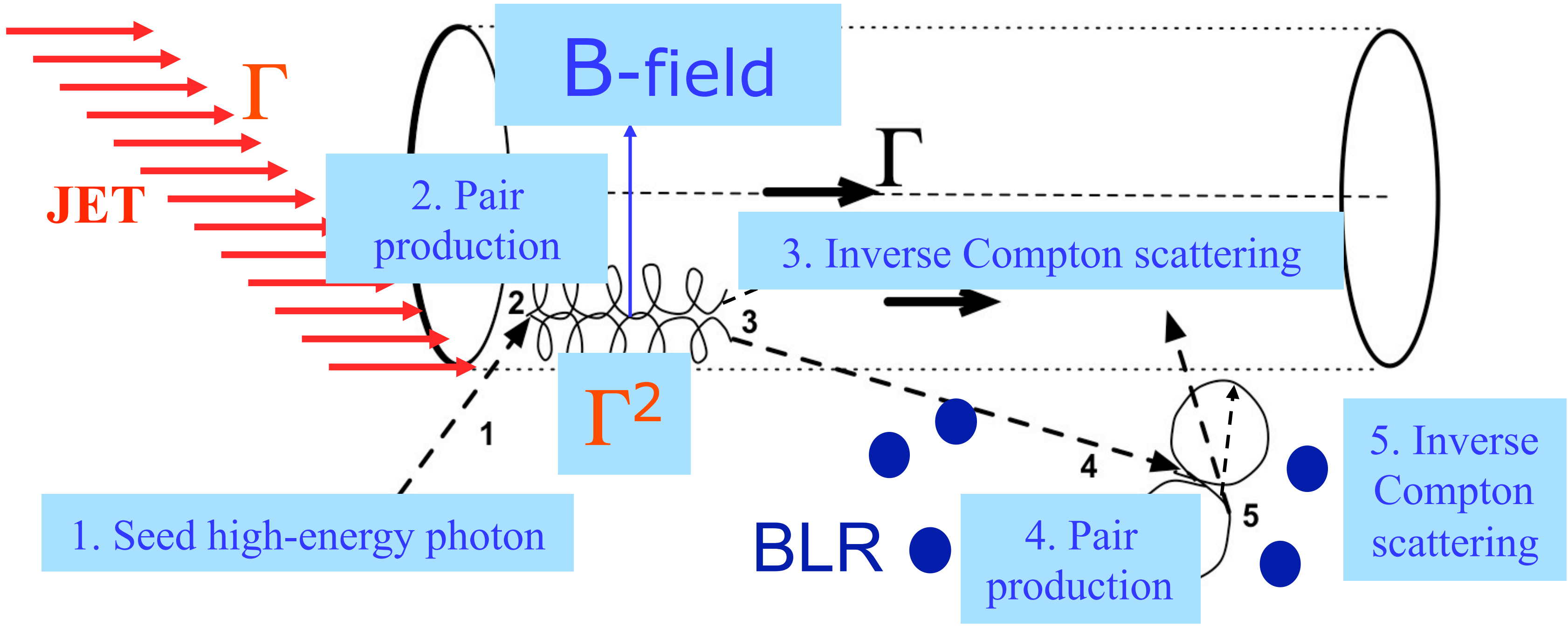
- Energy is transported through the shock by neutral particles, e.g. photons.
- A hard photon is born downstream (1). It is converted in the upstream region to an e^{+-} pair (2) (by $\gamma\gamma$ interaction with a soft photon).
- Pair turns around (3) and is advected back to the downstream flow where it Comptonizes a soft photon and produces another hard photon (1), thus closing the cycle.
- There is a total energy gain of Γ^2 at each cycle!



shock

shear flow

Photon breeding in AGN jets



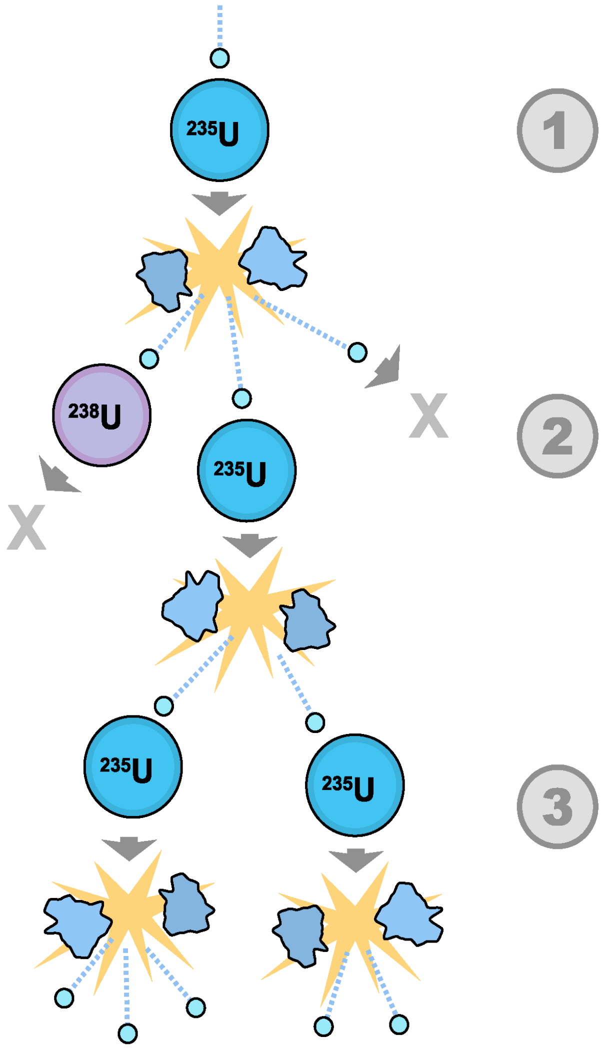
Super-criticality if the total amplification factor through all the steps is larger than unity:

$$A = C_1 C_2 C_3 C_4 C_5 > 1 \quad (\text{for } \Gamma > 4)$$

where C_n is the energy transmission coefficient for step n

(Stern, Poutanen 2006, 2008)

Compare to an atomic bomb



- Atomic bomb:
  supercritical conditions

- Chain reaction: neutron number and energy release increase exponentially.

- Energy is taken from the nuclei binding energy.

$$^{235}U + n \rightarrow \text{fragments} + 2.4n + 192.9\text{MeV} + \nu$$

$$\text{efficiency} = \frac{192.9\text{MeV}}{235 \times 938\text{MeV}} \approx 10^{-3}$$

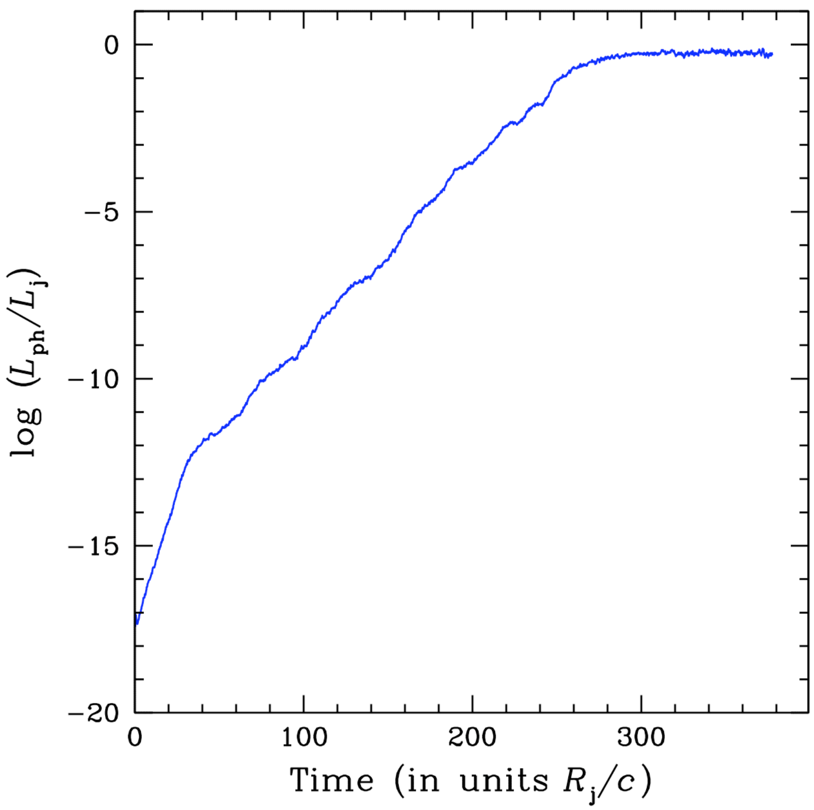
Numerical experiment

- Matter-dominated jet $L_{kin}=10^{45}$ erg/s
- Jet Lorentz factor $\Gamma=10$
- Disk luminosity $L_{disc}=10^{45}$ erg/s
- Isotropic reprocessed luminosity $L_{iso}=10^{44}$ erg/s
- Distance 0.1 pc from the black hole
- High-energy seed photons = extragalactic GeV background.

METHOD

- Radiation part: Large Particle Monte Carlo method (synchrotron radiation, Compton scattering, pair production). Photon and pair distributions are computed self-consistently.
- Tracking particle trajectories in transverse magnetic field.
- Hydrodynamics: dust approximation.

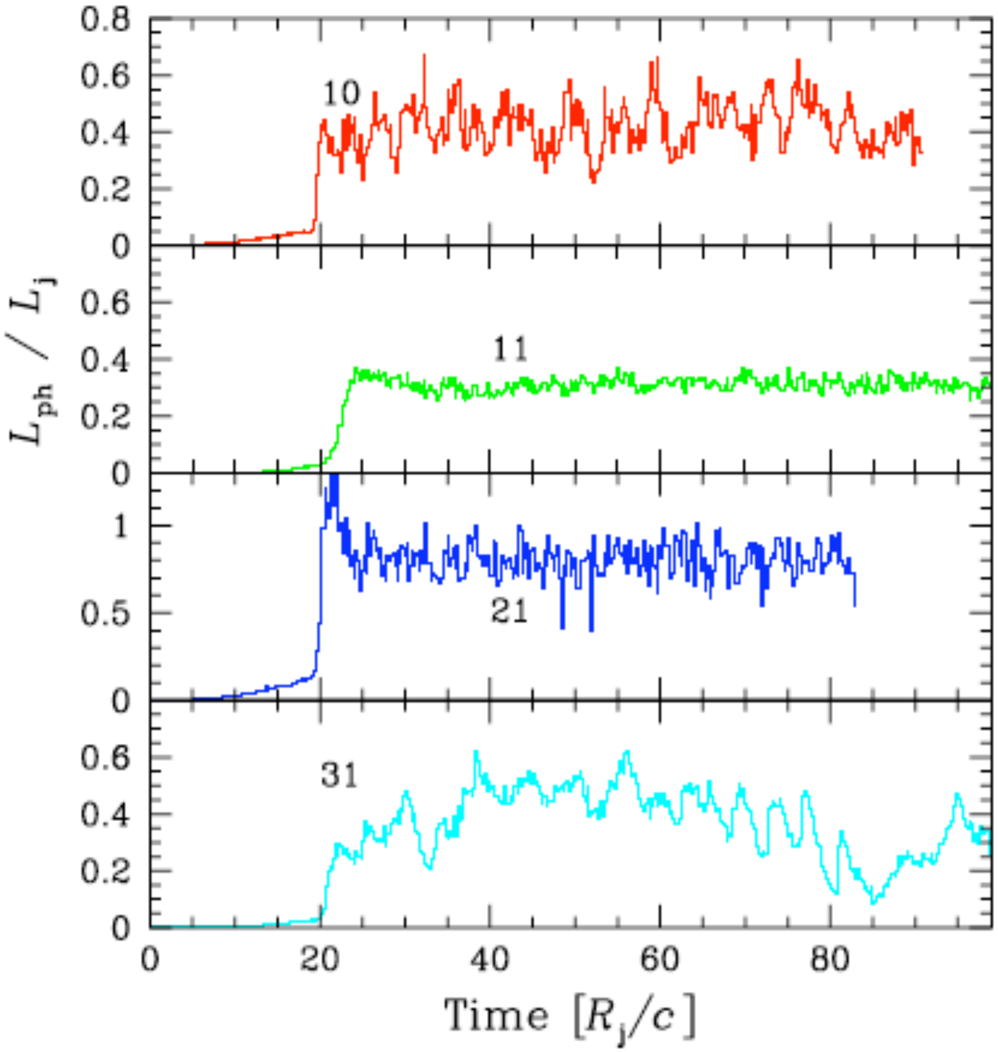
Photon breeding: a super-critical process



Photon breeding is a photon bomb!

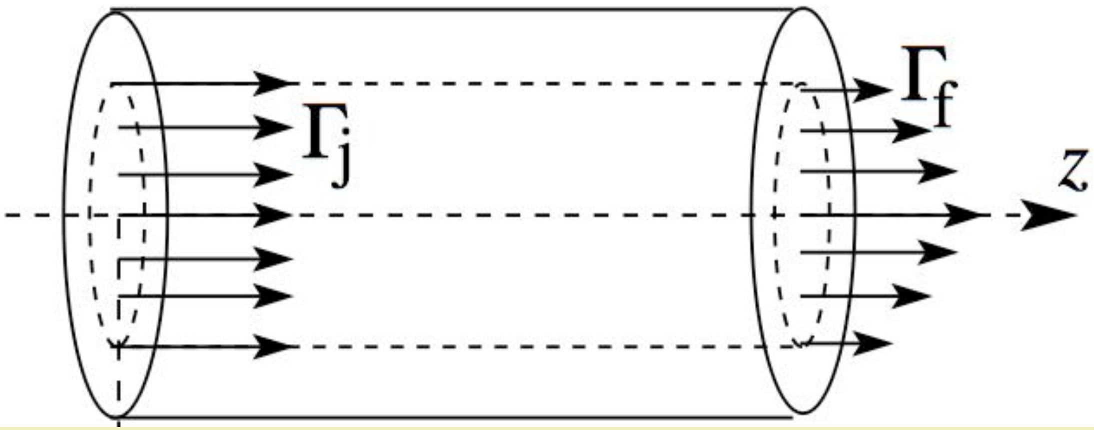
- Seed high-energy photons coming from extragalactic gamma-ray background (also particle acceleration in shocks or shear layers, or secondary particles from cosmic ray interactions can contribute).
- Energy density of high-energy photons grows exponentially with time (by 10^{20} in 3 years!)
- Energy is taken from jet bulk energy.
- Radiative efficiency up to 80%!

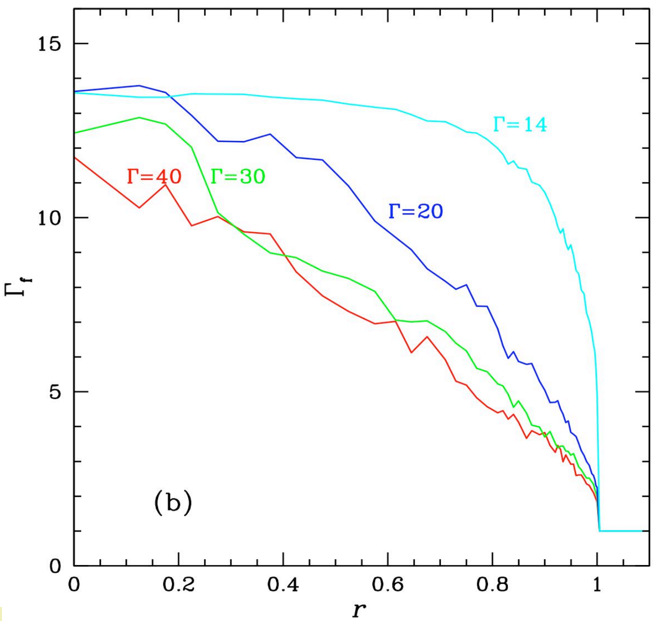
Temporal variability



1. Shows super-critical behaviour with high-amplitude flares (even for a steady input).
2. Is capable of producing short flares by rapidly tapping a fraction of the jet energy.

Jet structure

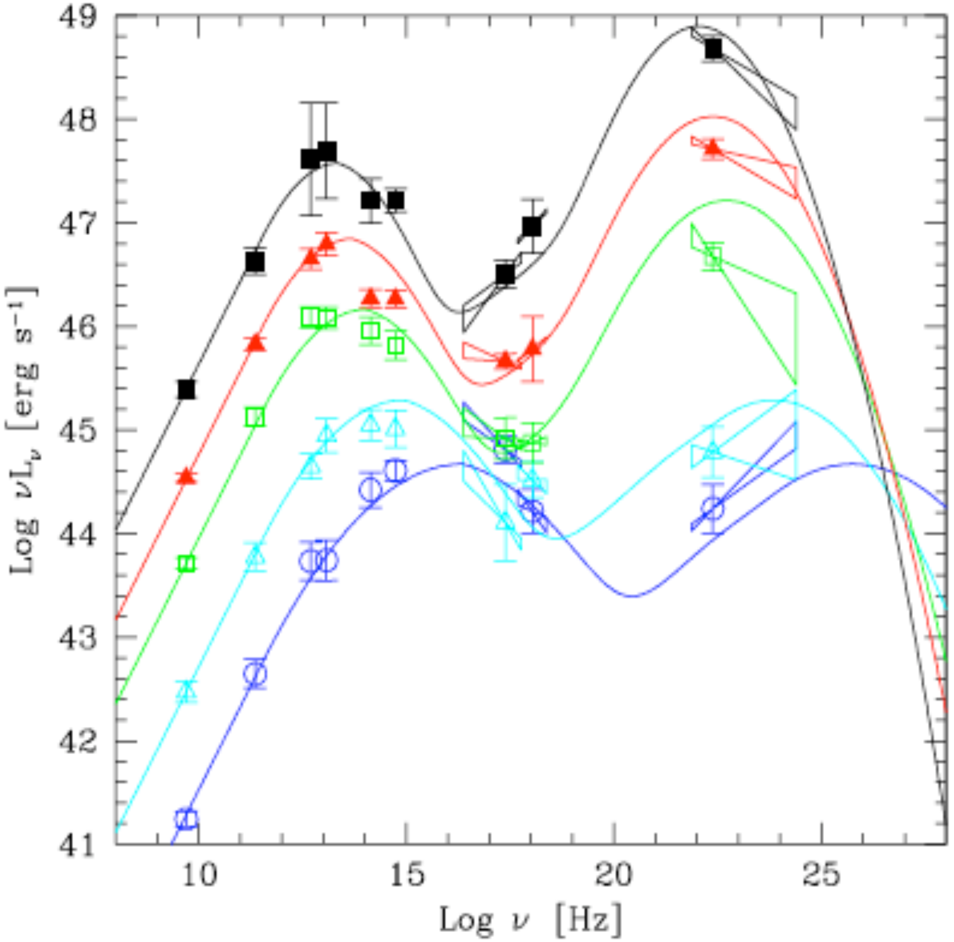




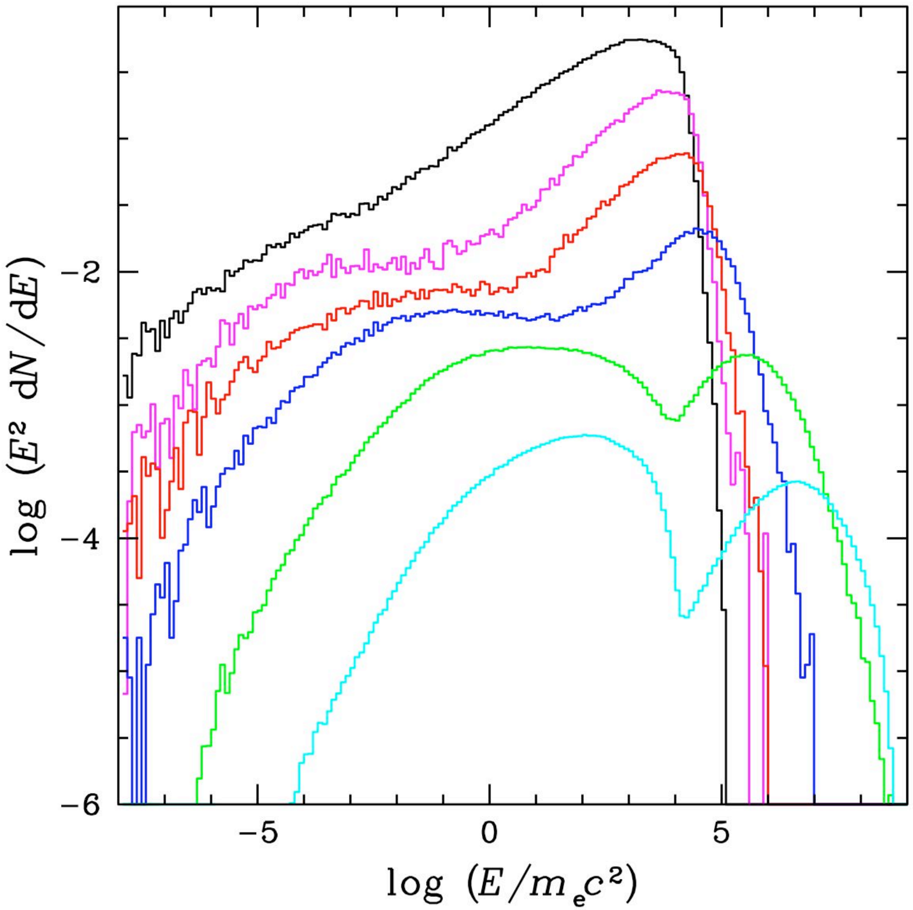
1. Photon breeding provides friction between the jet and the external medium, decelerating and "structured" jet.
2. Gradient of Γ implies broad emission pattern.
3. Solves the Doppler-factor crisis (large $\Gamma=20\div50$ from spectral modeling of TeV blazars, but low apparent velocities at pc scales and low $\Gamma\sim4\div6$ required by unification scenarios of FR I and BL Lac objects from the source statistics and luminosity ratio).
4. Predicts high gamma-ray luminosity in radio galaxies (e.g. M87) by isotropic pairs in the external medium.

Spectral energy distribution: blazar sequence

Observed



Modeled



Low-energy component in high-luminosity source might be produced at larger distances.

Gamma-ray emission sites

- Photon breeding needs soft (isotropic) photon background.

1. Near the accretion disk (if the jet is already accelerated with $\Gamma \geq 10$)
2. Broad emission line region.
3. Dusty torus at 10 pc scale (if still $\Gamma \geq 10$).
4. Stellar radiation at kpc scale (if $\Gamma \geq 10$).
5. Cosmic microwave background at 100 kpc scale (if $\Gamma \geq 10$).

Photon breeding can also operate in gamma-ray bursts (Stern 2003).

Conclusions. Part II.

Photon breeding

1. is based on well-known physics
2. is a self-consistent mechanism for acceleration of high-energy electrons (pairs) in relativistic flows
3. predicts that relativistic jets propagating through soft photon field (e.g. broad-line region) inevitably undergoes transformation into luminous state
4. has extremely high radiative efficiency
5. naturally produces chaotic, flaring behaviour
6. produces decelerating, structured jet with a broad emission pattern. Predicts strong GeV-TeV emission for off-axis objects (radio galaxies)

Super-critical phenomena might well be important for particle acceleration in and emission of relativistic jets.