Fermi observations of blazars and implication for the origin of gamma-rays:

the GeV breaks are produced by He II Lyman photons and the blazar zone lies inside high-ionization zone of the broad-line region

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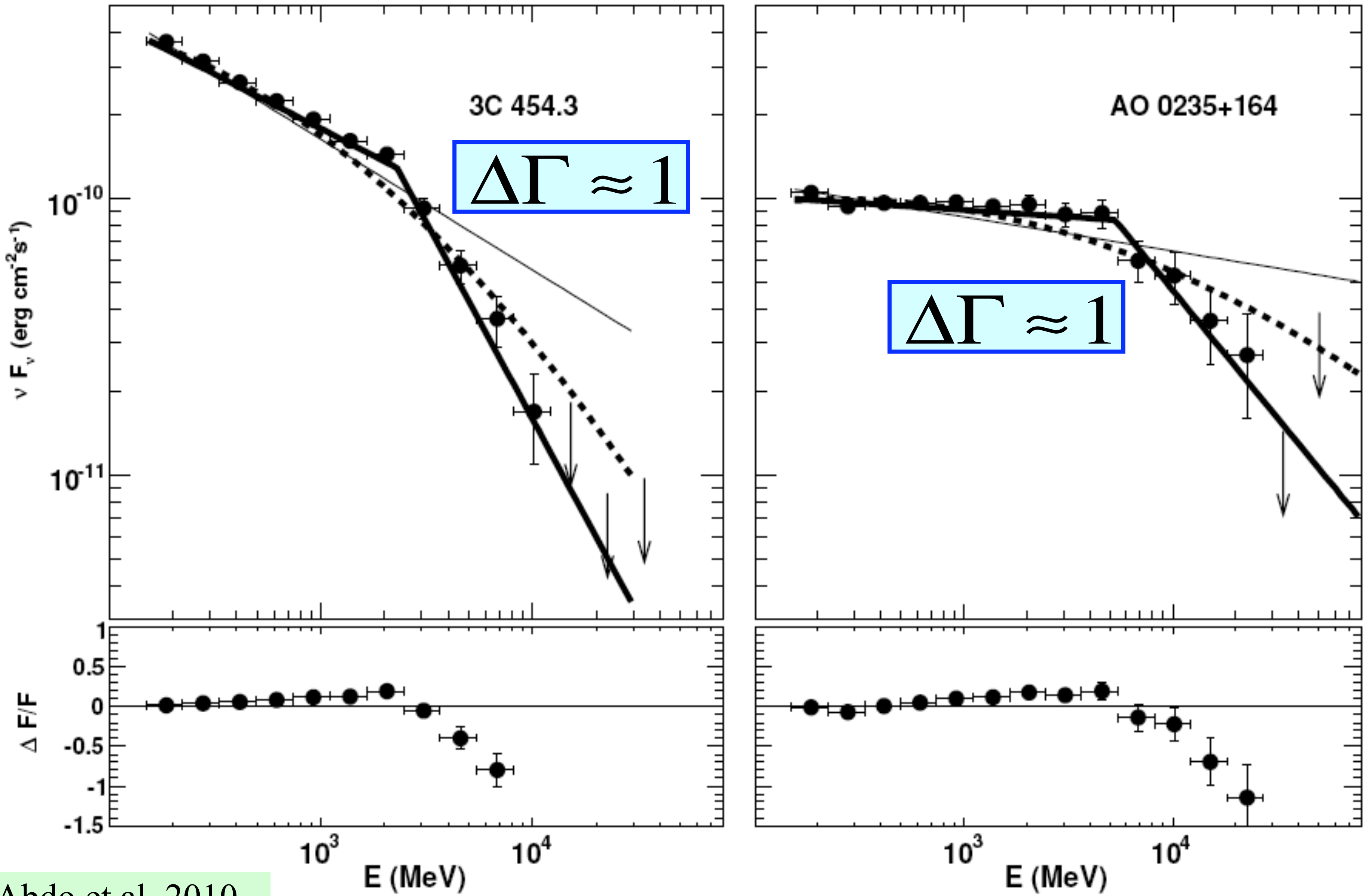
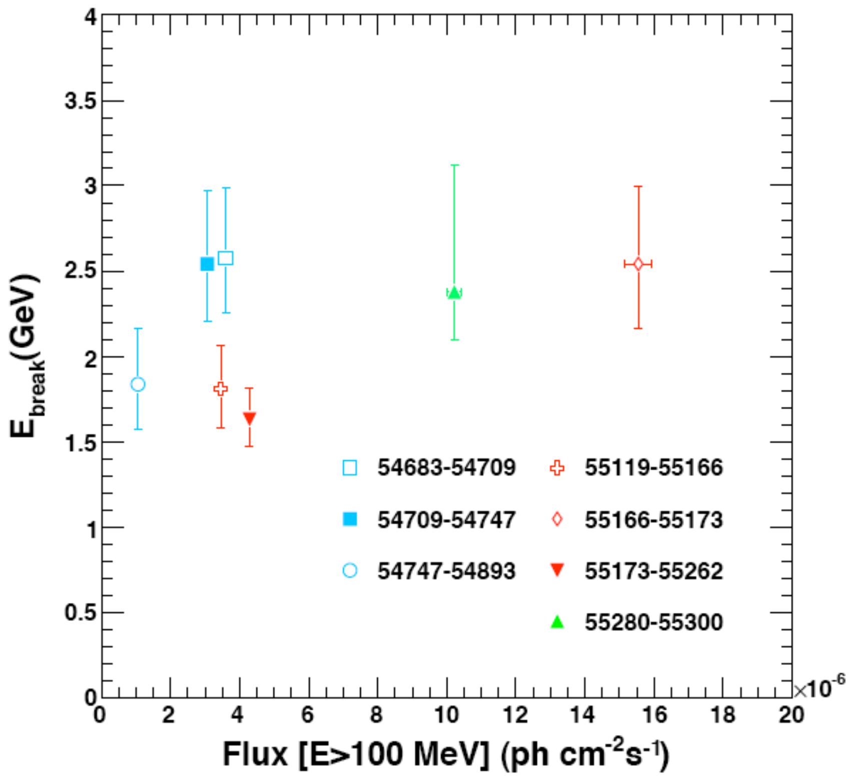
Poutanen & Stern (2010, ApJL), Stern & Poutanen (2011, in preparation)

GeV breaks in FSRQ and LSP BL Lacs

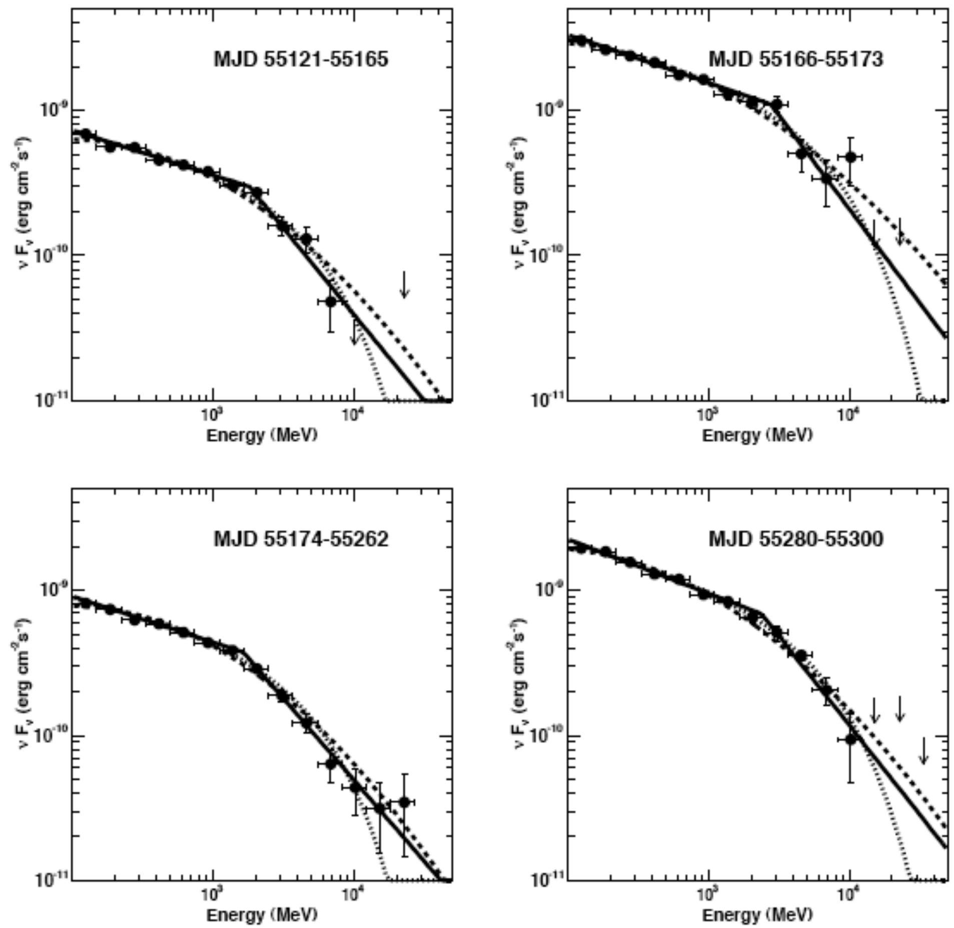


Abdo et al. 2010

Stability of breaks in 3C454.3

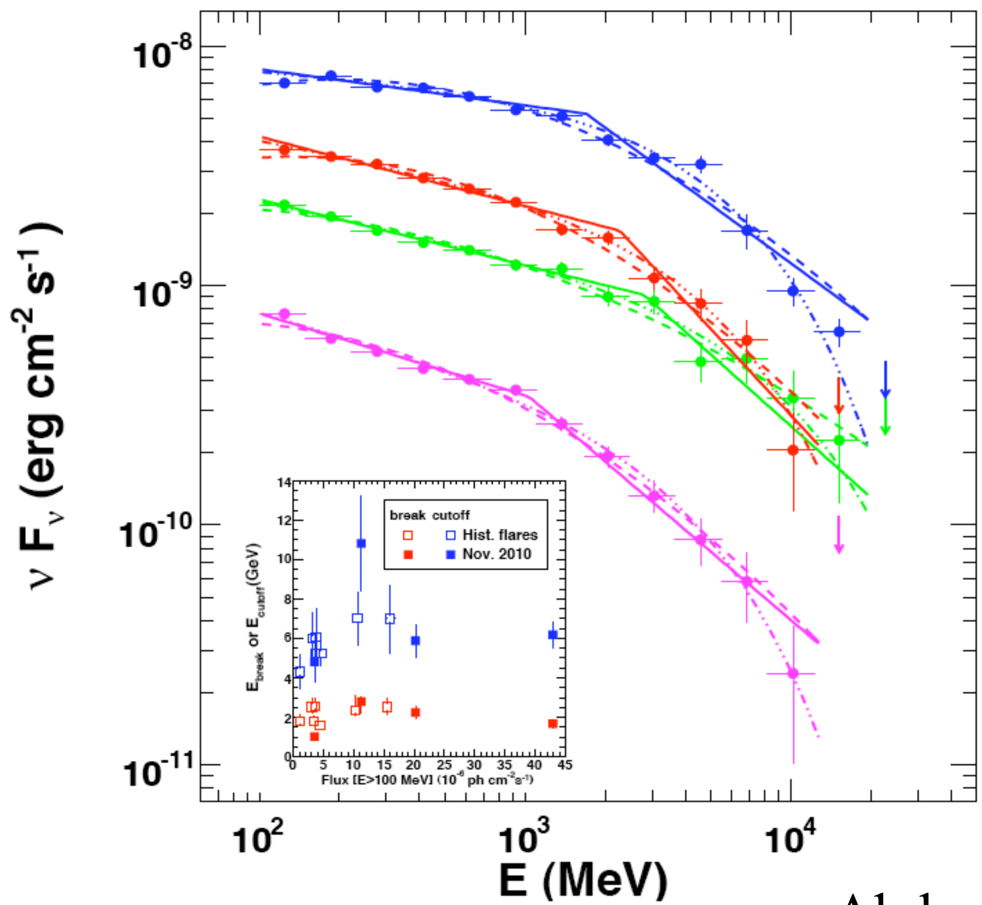


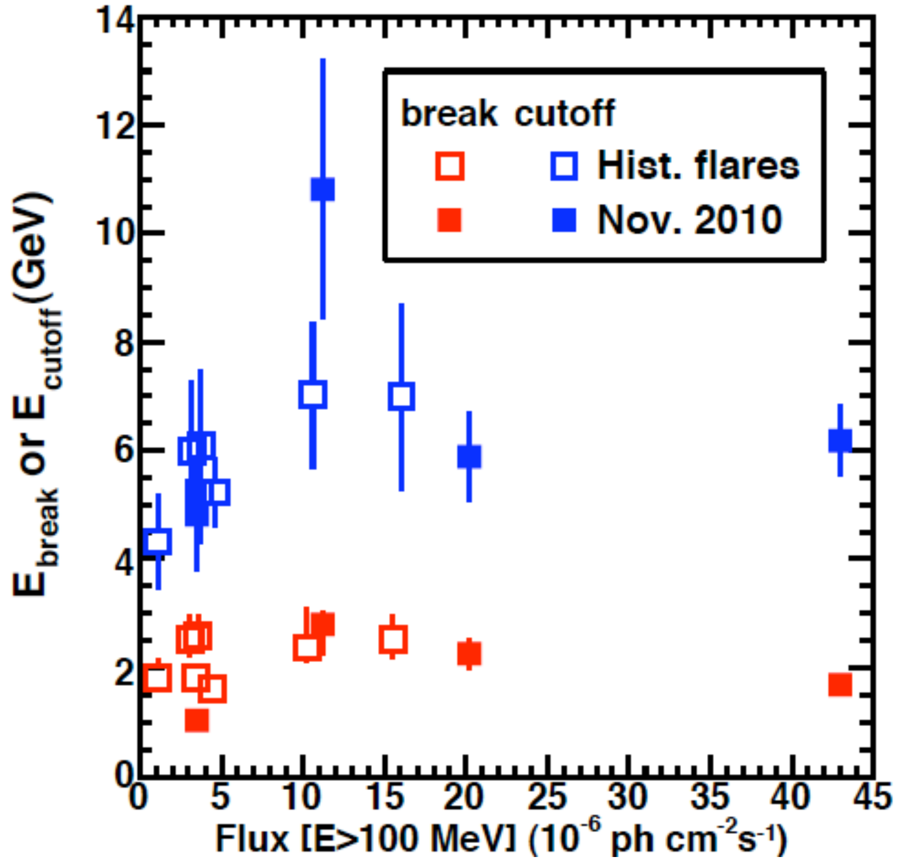
Ackermann et al. 2010



Break energy is constant ➔ atomic physics ➔ consistent with absorption by He II Lyman continuum.

Stability of breaks during flares



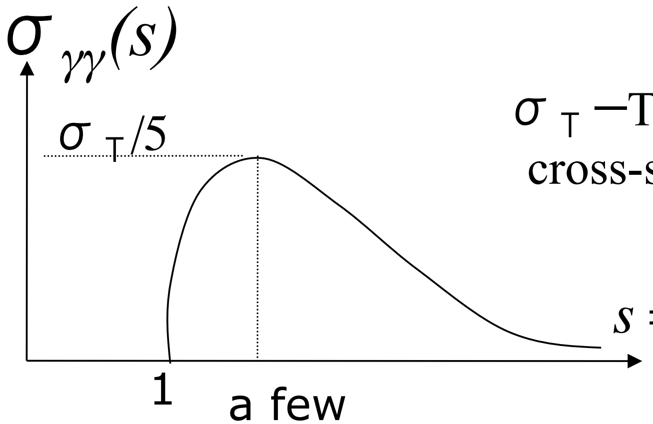


Abdo et al. 2011

Break energy is constant ➔ atomic physics ➔ consistent with absorption by He II Lyman continuum.

Gamma-ray absorption by photon-photon pair production

Cross-section for pair production



σ_T – Thomson cross-section

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

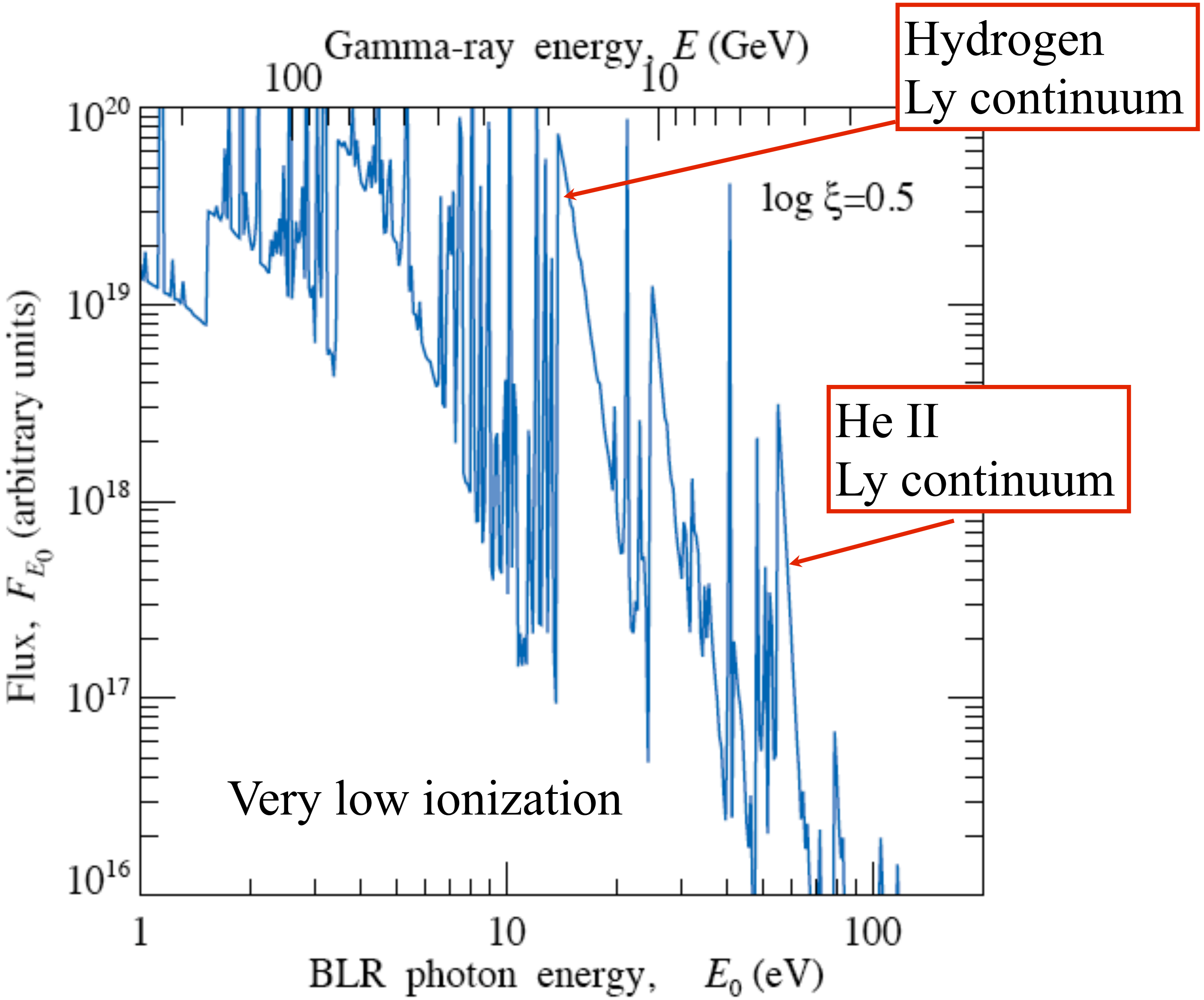
Threshold at s=1:

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

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

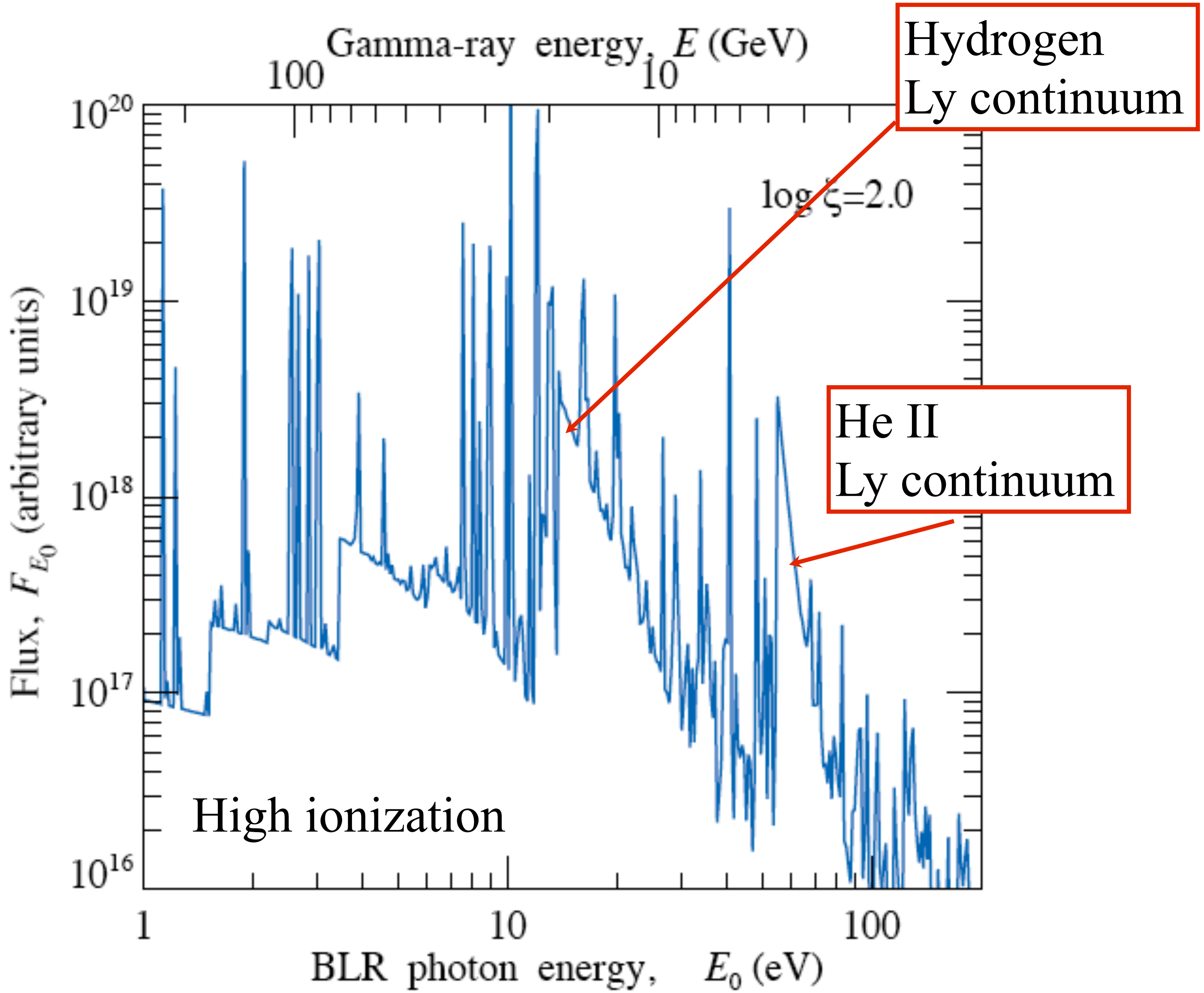
Most GeV breaks cannot be produced by Ly α photons!
But can be produced by Lyman continuum of ionized helium.

BLR spectra



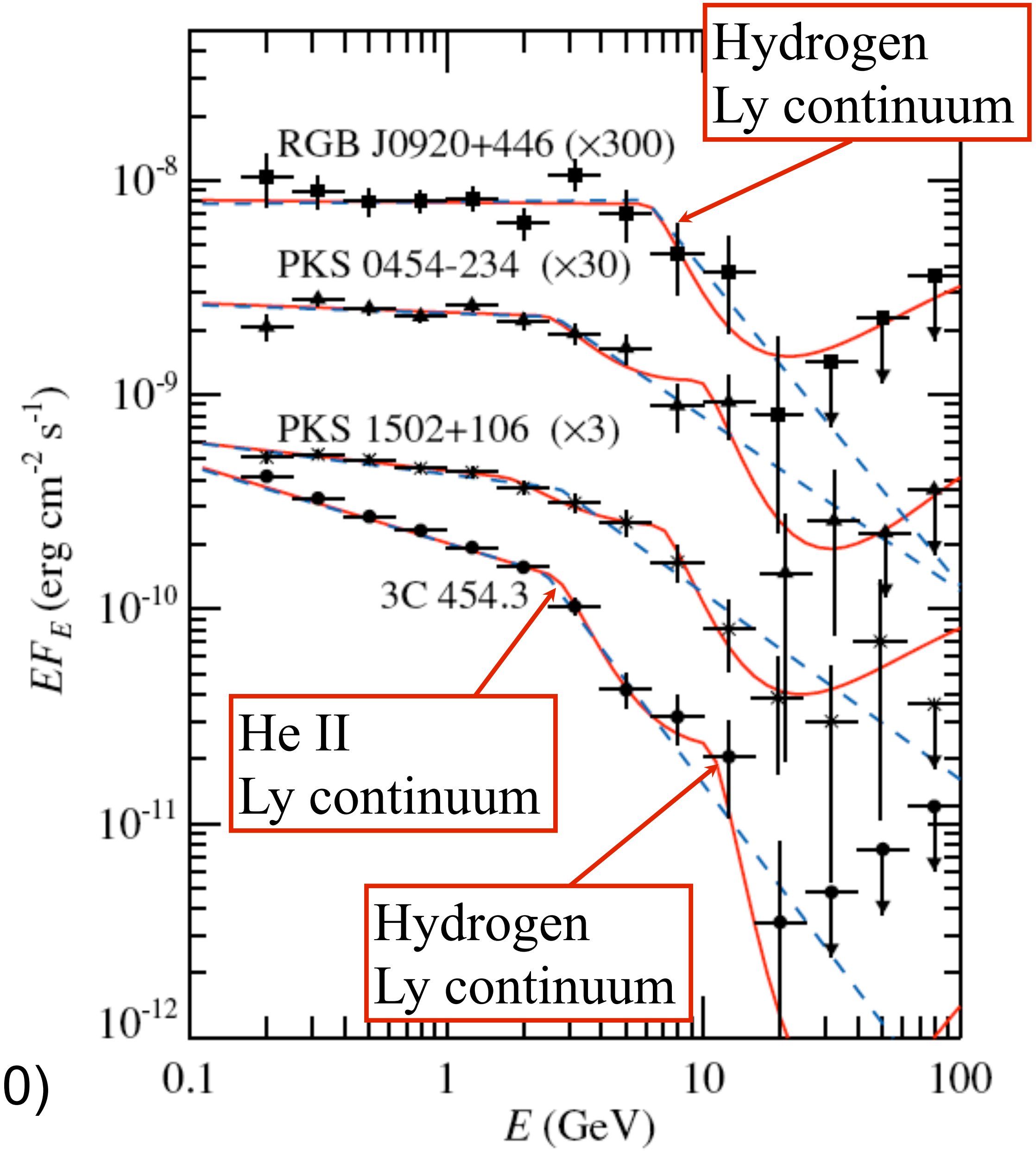
Gamma-ray energy, E (GeV)
100
10
Hydrogen
Ly continuum
log ξ=0.5
He II
Ly continuum
Very low ionization
10^20
10^19
10^18
10^17
10^16
Flux, F_E0 (arbitrary units)
1
10
100
BLR photon energy, E_0 (eV)

BLR spectra


Gamma-ray energy, E (GeV)
100
10
Hydrogen
Ly continuum
log ξ=2.0
He II
Ly continuum
High ionization
10^20
10^19
10^18
10^17
10^16
Flux, F_E0 (arbitrary units)
1
10
100
BLR photon energy, E0 (eV)

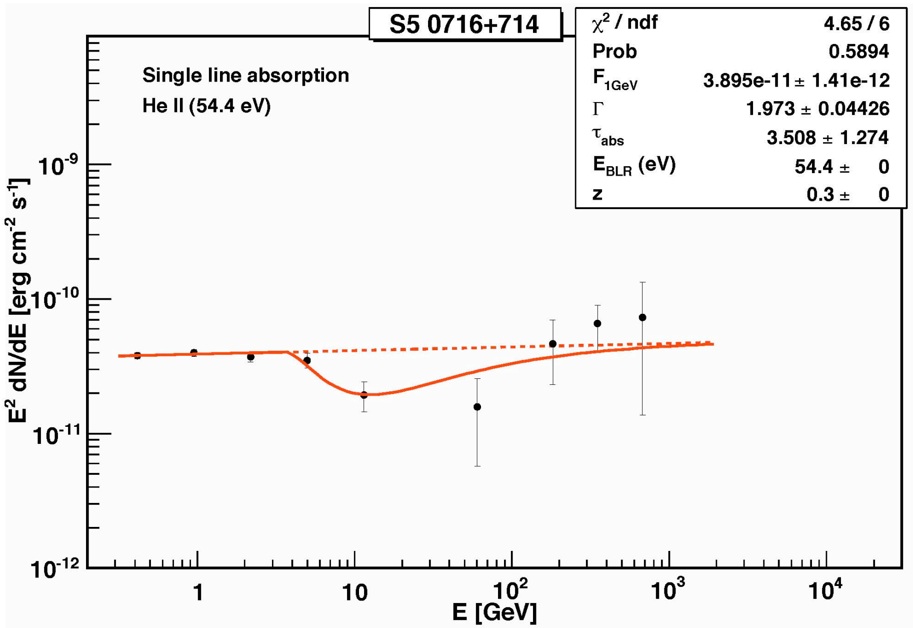
GeV breaks in blazars

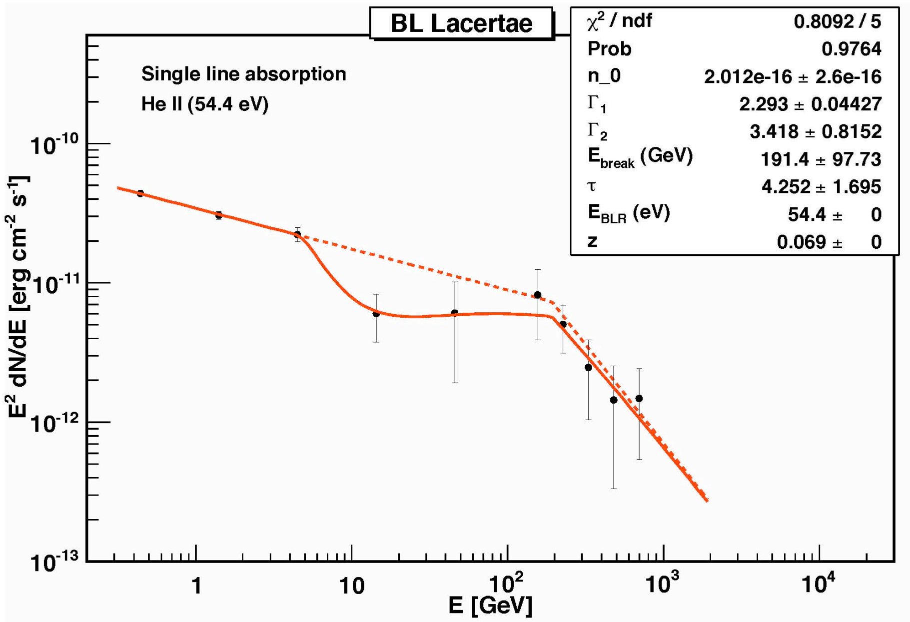
Power law +
dual absorber
(produced by H I and
He II Lyman
recombination
continua)



Poutanen & Stern (2010)

TeV-detected blazars



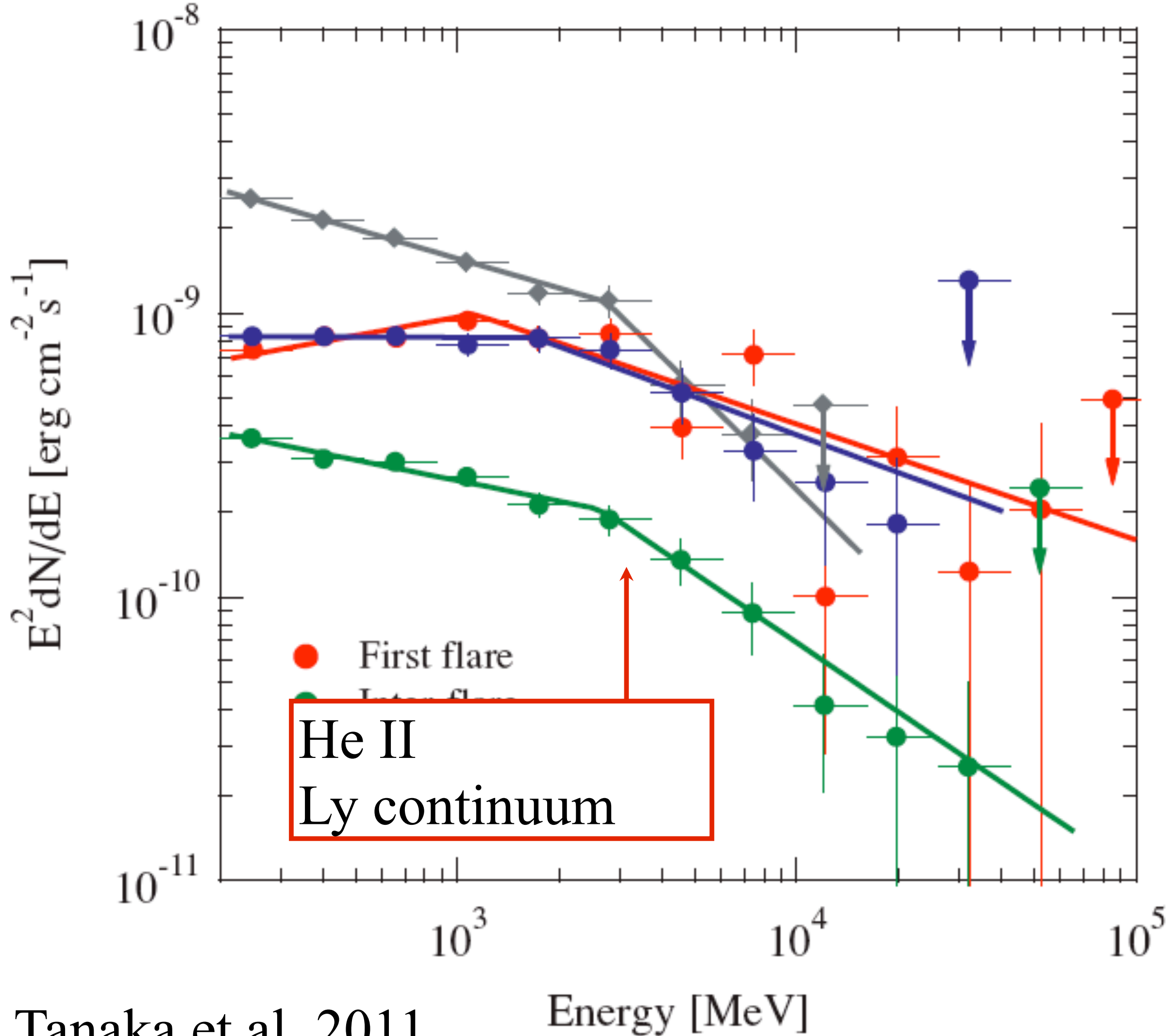


Senturk, Errando, et al., in preparation

The dips are consistent with being produced by He II Lyman recombination continuum.
There is no absorption by hydrogen Lyman photons !

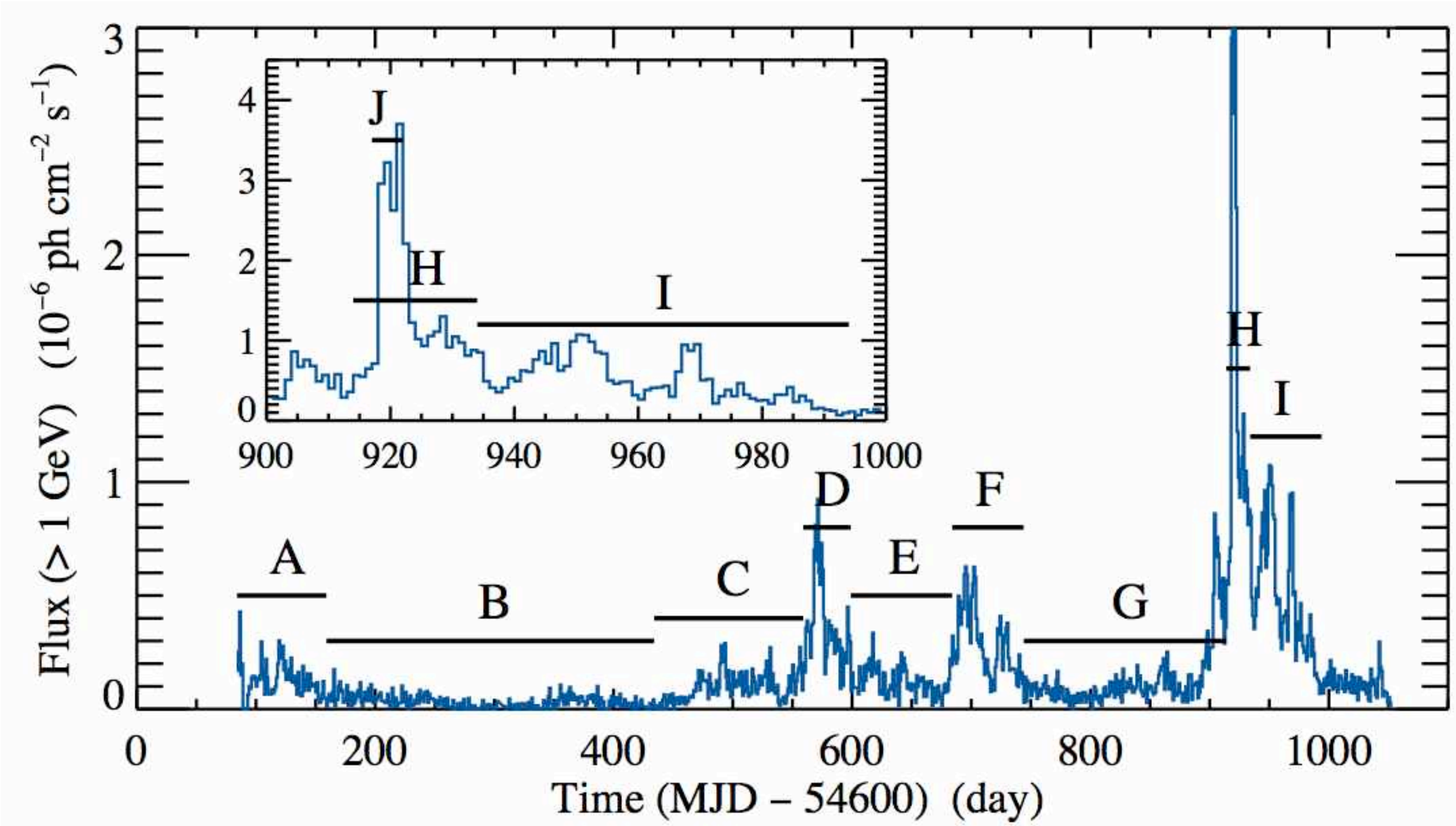
TeV-detected blazars

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

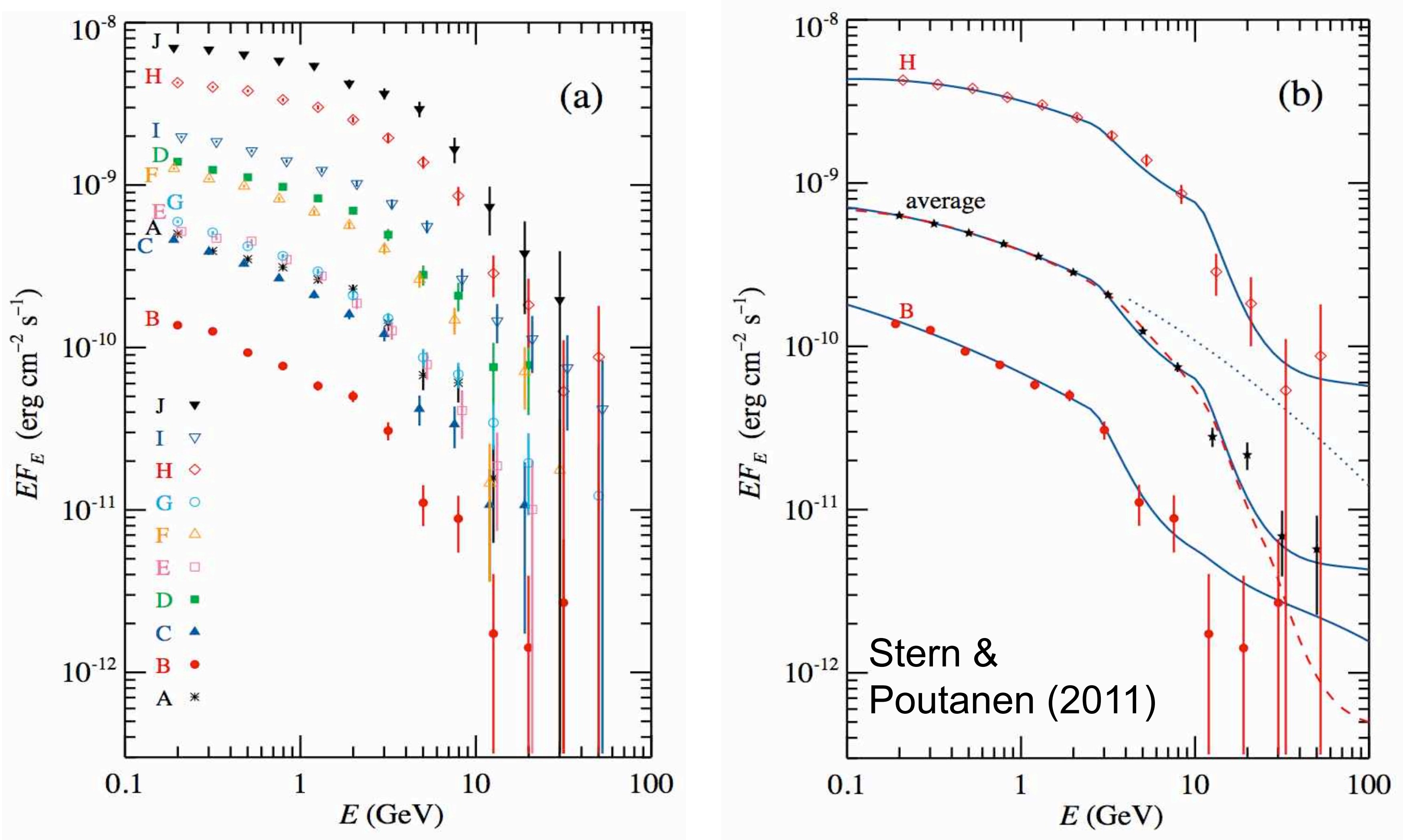


Tanaka et al. 2011

2.5 years from the life of 3C454.3



Spectra of 3C454.3



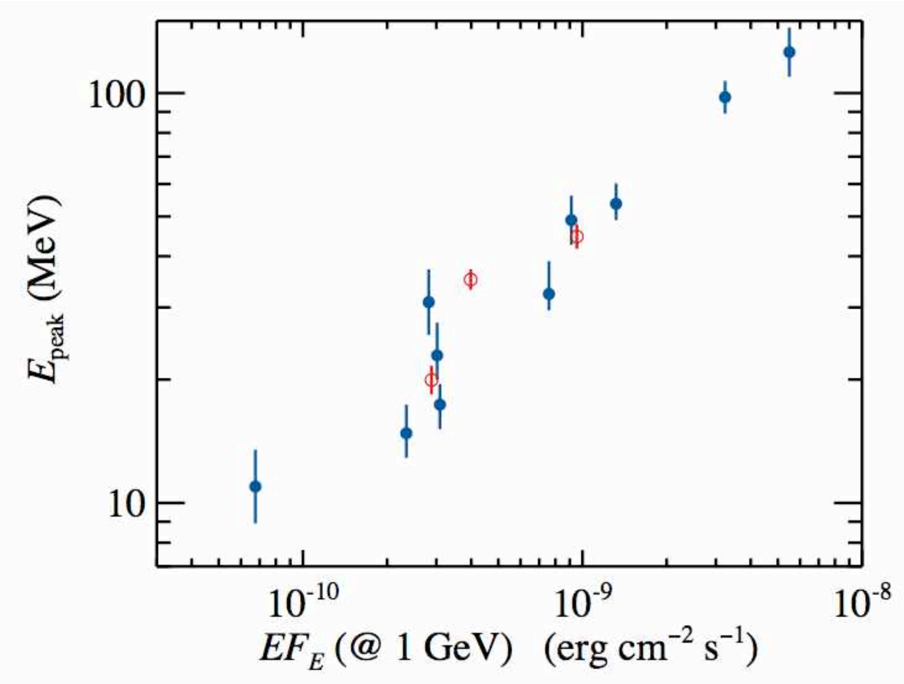
Spectra are well represented by a lognormal distribution (log-parabola) with two features due to photon-photon absorption by He II and H I "lines".

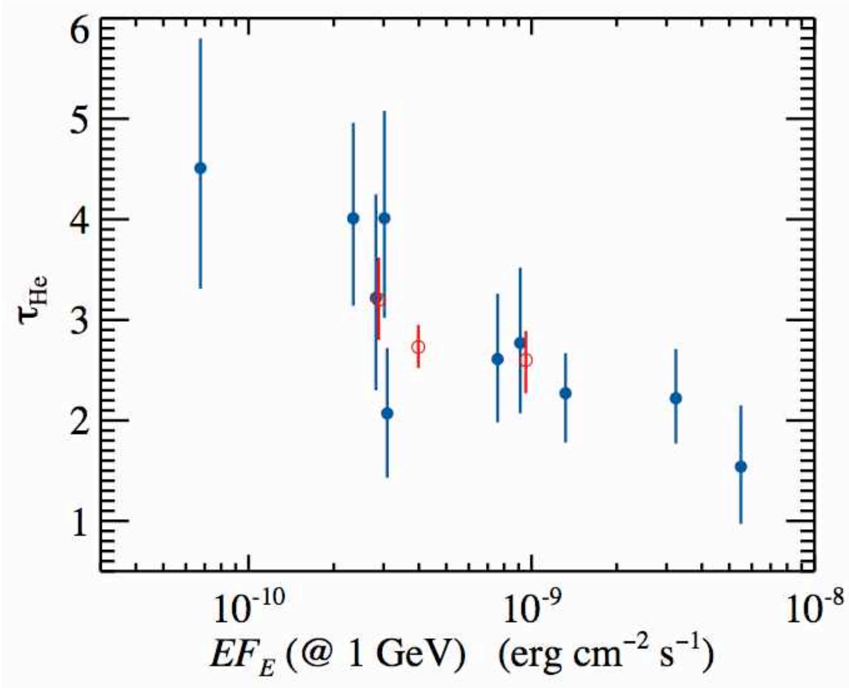
Spectral fits to 3C454.3

Interval	Dates[a] MJD	χ^2/dof Power-law	PL + DA[b]	Lognormal	Logn + DA[c]
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

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

Spectral and opacity variations



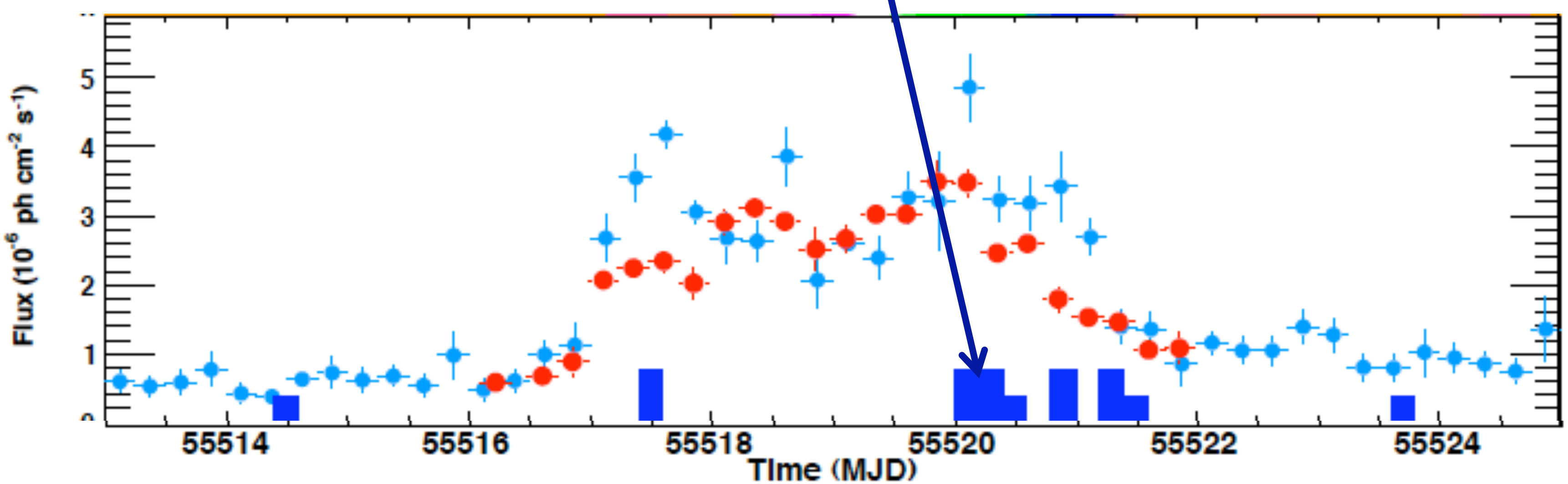


Stern & Poutanen (2011)

Opacity in He II varies with flux →
the gamma-ray emission region moves away
from the black hole at high fluxes.

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).



Constraints on gamma-ray emission size

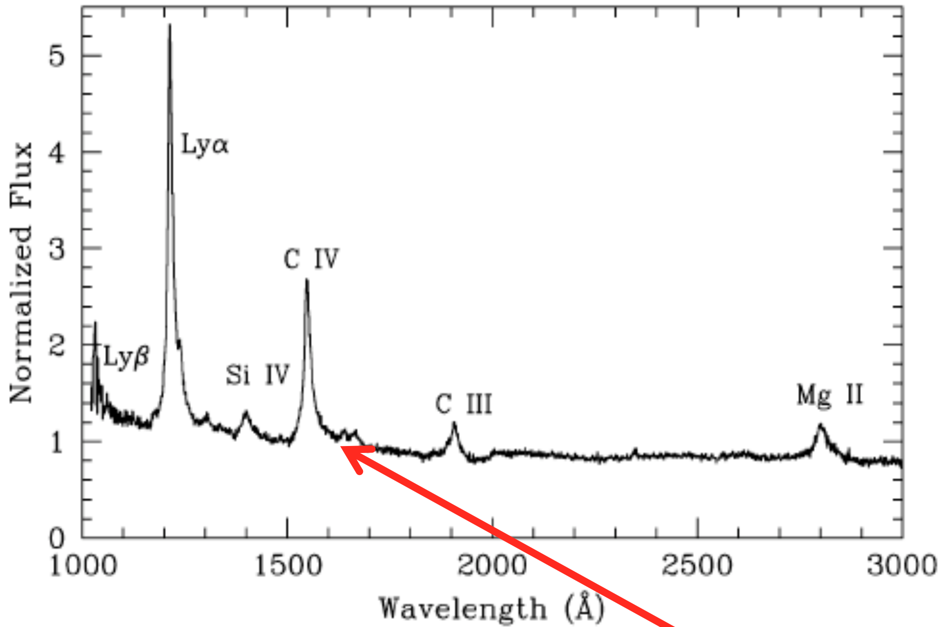
- The ratio of opacities due to He and H constrains the ionization parameter of the gamma-ray absorbing medium:

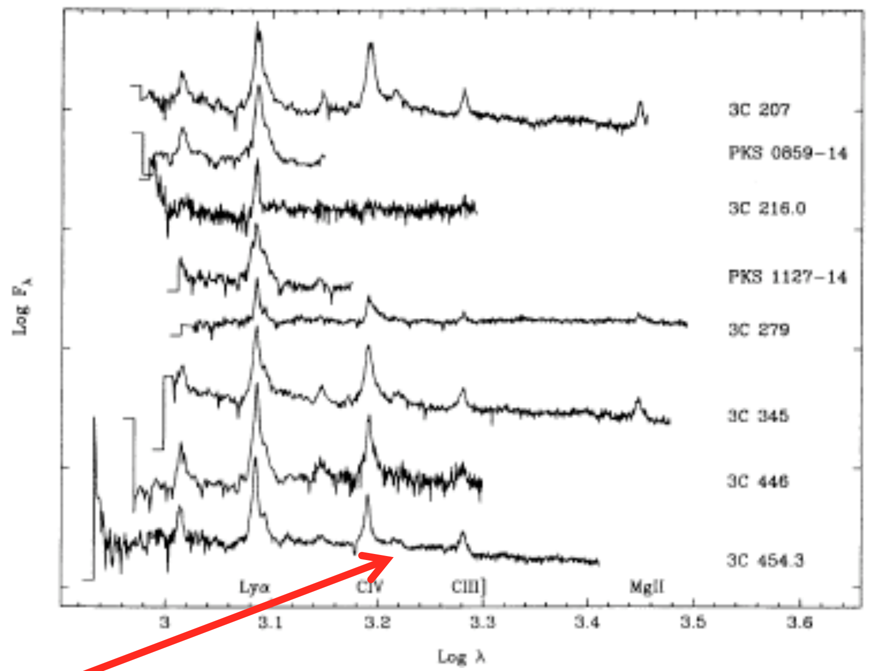
$$\tau_{\mathrm{He}} / \tau_{\mathrm{H}} \approx 1/4 \longrightarrow \boxed{\log \xi > 2}$$

For 3C 454.3, $L_{\mathrm{disk}} \approx 10^{47}$ erg/s ➔

$$\boxed{R < 0.1 \text{ pc} = 10^3 \, R_{\mathrm{Sch}}}$$

UV spectra of FSRQs





Composite blazar spectrum (Pian et al. 2005).

He II 1640Å

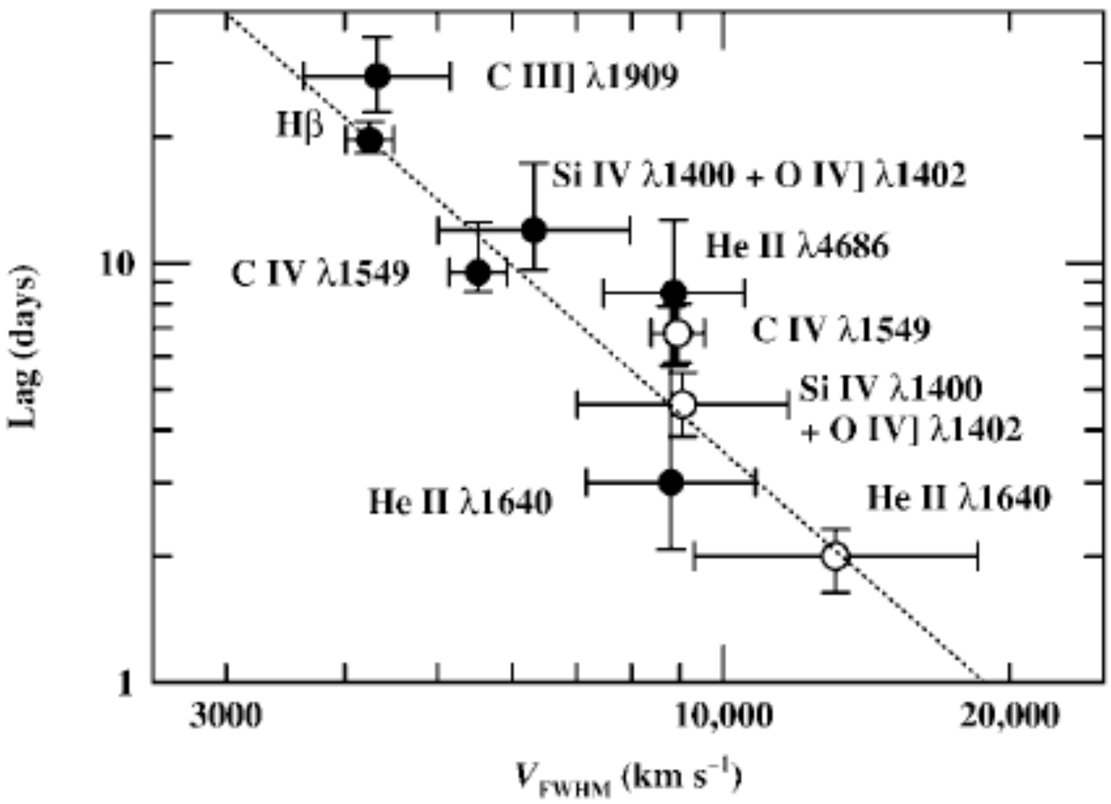
HST spectra of blazars (Wills et al. 1995).

In 3C454.3, $L_{Ly\alpha} = 1E45$ erg/s

$L_{He\ II\ 1640} = 6E43$ erg/s =>

$L_{He\ II\ Ly\alpha} = 6E44$ erg/s

The “size” of broad-line region

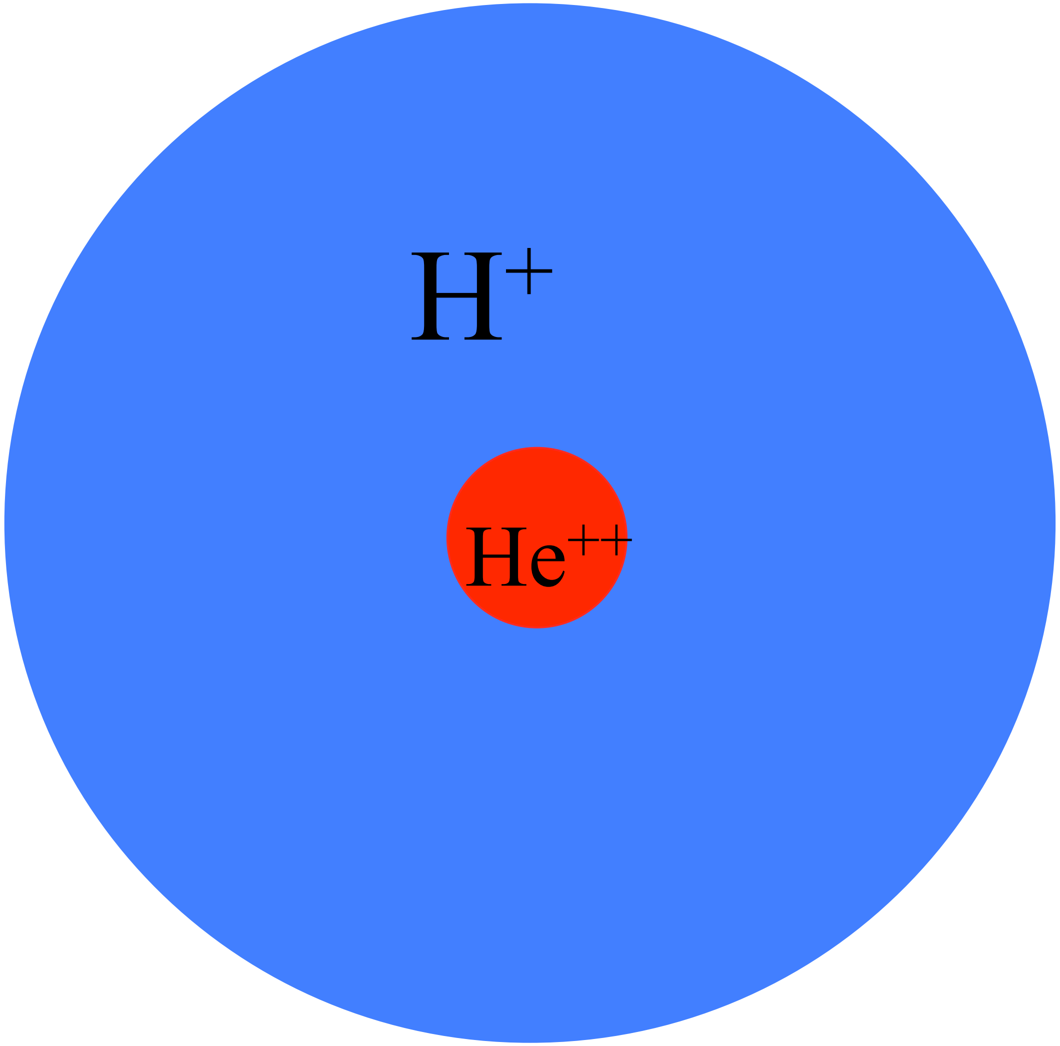


Reverberation in Sy 1 NGC 5548.

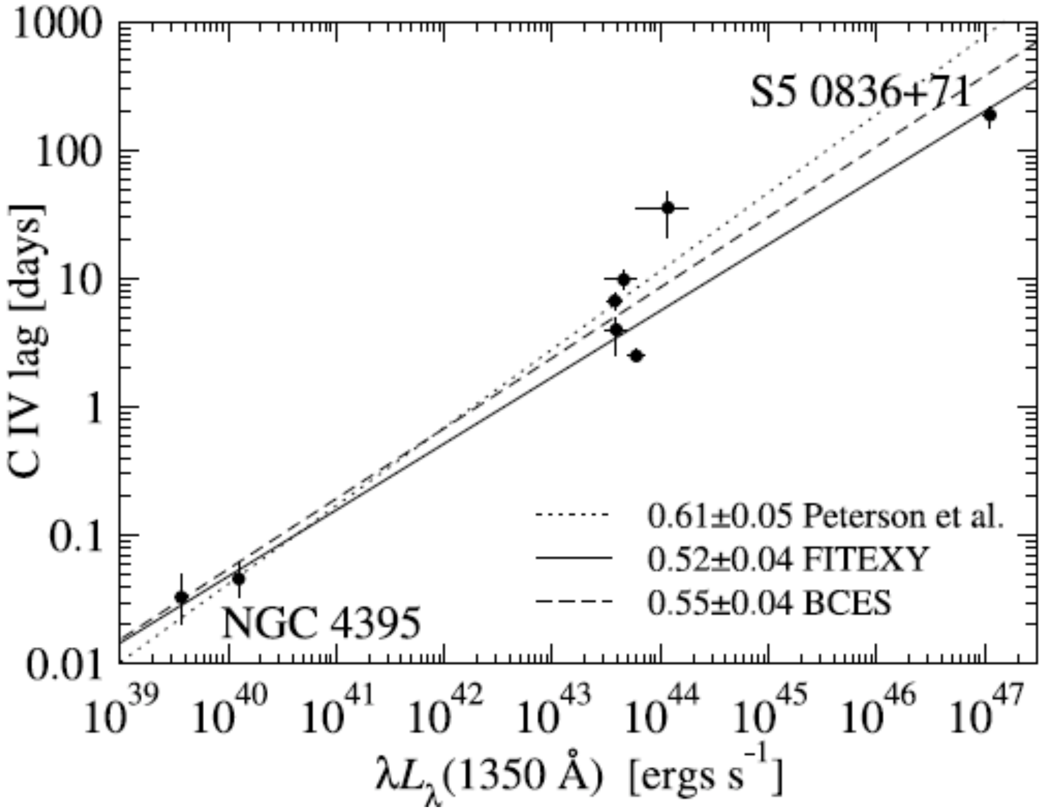
Peterson & Wandel (1999)

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



The “size” of broad-line region



Scaling of BLR size (Kaspi et al. 2007)

$$R_{\mathrm{CIV}\ 1549} \approx 0.1 L_{\mathrm{disk},47}^{1/2}\,\mathrm{pc}$$

is based on one object and one line!

The size might be in error by a factor of 10!

However, Kaspi et al. (2007) write:

“no Lyα variability is detected…”.

Lyα has to be produced further away than CIV.

Opacity depends on compactness! Not luminosity.

The optical depth for pair production on line photons:

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

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

Assuming that all lines are produced at the same distance strongly underestimates the GeV opacity due to high-ionization line and strongly overestimates the opacity due to low-ionization lines.

Sub-TeV photon opacity is much lower than often assumed!

Conclusions

- GeV breaks are consistent with being produced by absorption on He II and H I recombination continua.
- Gamma-ray emitting region in 3C454.3 lies within the highest ionization zone of BLR at sub-parsec distances from the central black hole.
- This implies that the jet is accelerated to relativistic velocities at these distances.
- Additional features in a sub-GeV range are predicted due to the high-ionization soft X-ray lines.
- The underlying continuum does not have a break, but is well represented by a lognormal distribution.
- Opacity in He II varies with flux. The gamma-ray emission region moves away from the high-ionization region at high fluxes.