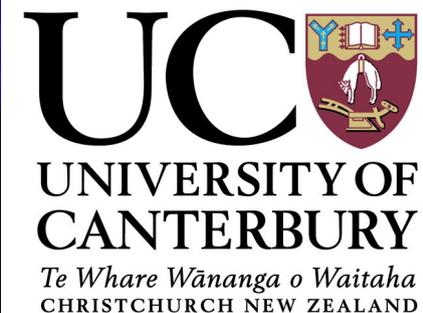
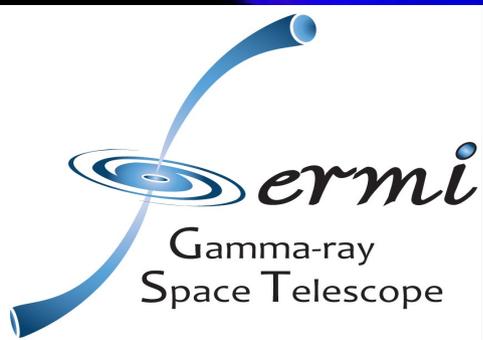


Fermi-LAT observations of Active Galactic Nuclei

CPPM

21st May 2013

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For the next 40 minutes...

- Where, what, how and why for the *Fermi*-LAT detector.
- What does Fermi give us when studying AGN?
- What have I studied?
 - NGC 1275
 - Pictor A
 - PKS 1510-089

What is Fermi??

Gamma-ray Burst Monitor

- Scintillator detector (NaI)
- All sky at once
- 8 keV to 1 MeV
- Looks for GRBs

Large Area Telescope

- Pair conversion telescope
- 20 MeV to 300 GeV



Large Area Telescope

- Pair conversion telescope
- 20 MeV to 300 GeV
- 0.8 deg. ang. res.
- 20 % of sky at any given moment
- LAT detector rocks north/south of orbital plan
- Scans entire sky every 3 hours
- Allows us to probe high-energy activity unbiased by subclass or activity state



Fermi



Launched on a Delta II heavy rocket from Cape Canaveral on June 11th 2008.

3 months of on-orbit
calibration... Started
all-sky survey obs on
the 8th August 2008



Altitude: 565km

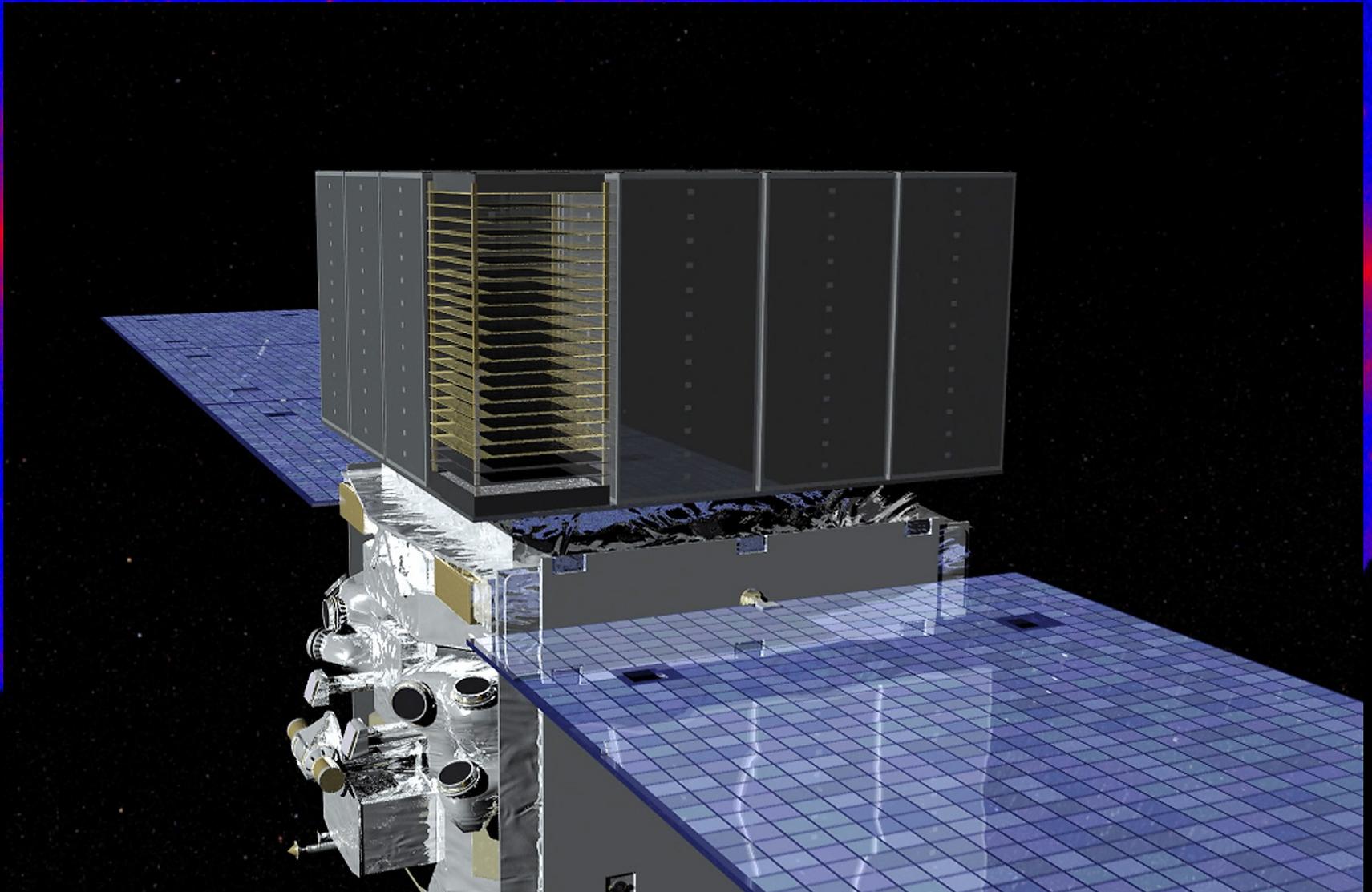
Eccentricity: < 0.01

Orbital Period: 96.5
minutes

3 sub-detectors

- tracker
- calorimeter
- anti-coincidence

The LAT



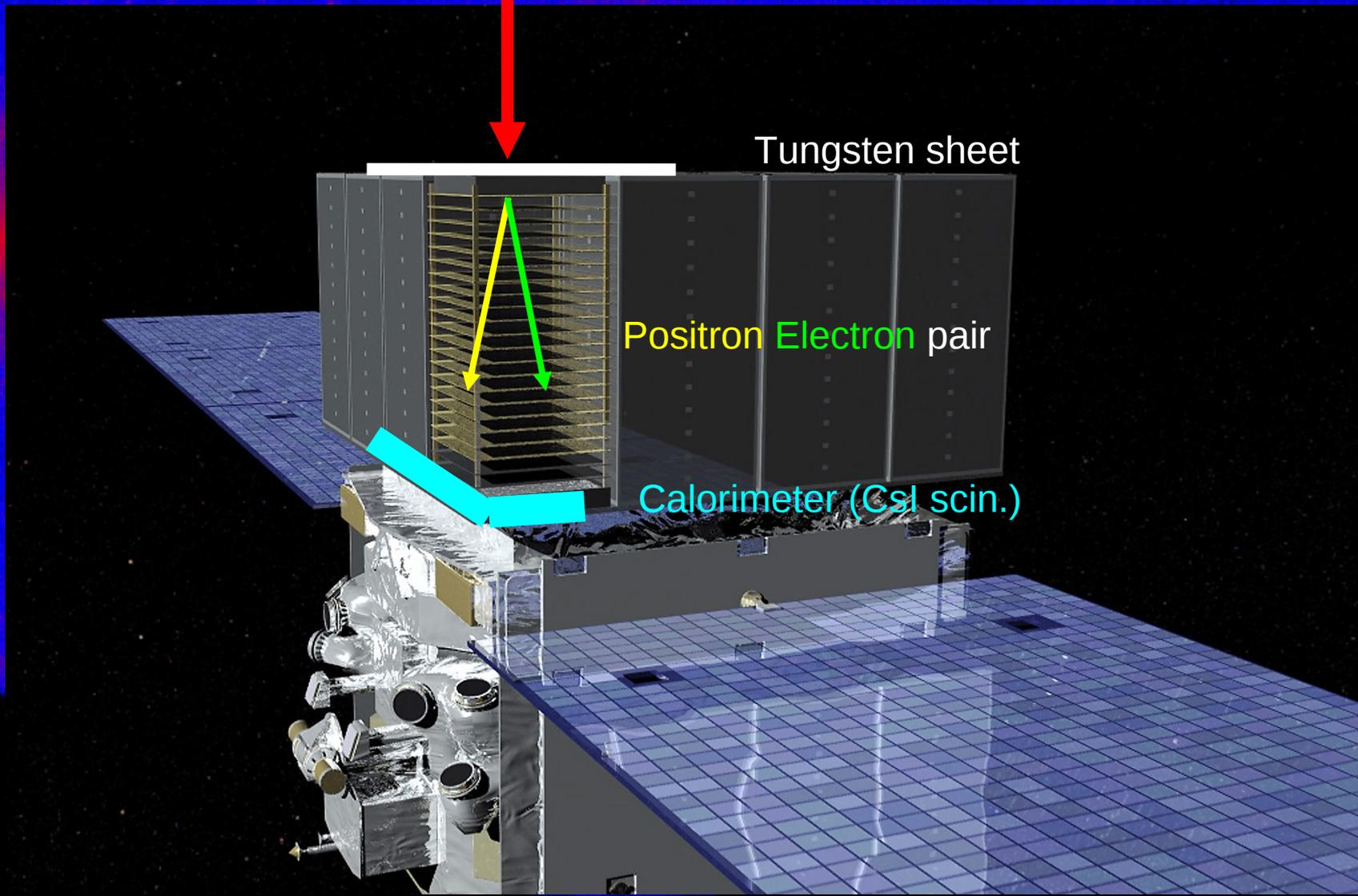
The LAT

Gamma-ray

Tungsten sheet

Positron Electron pair

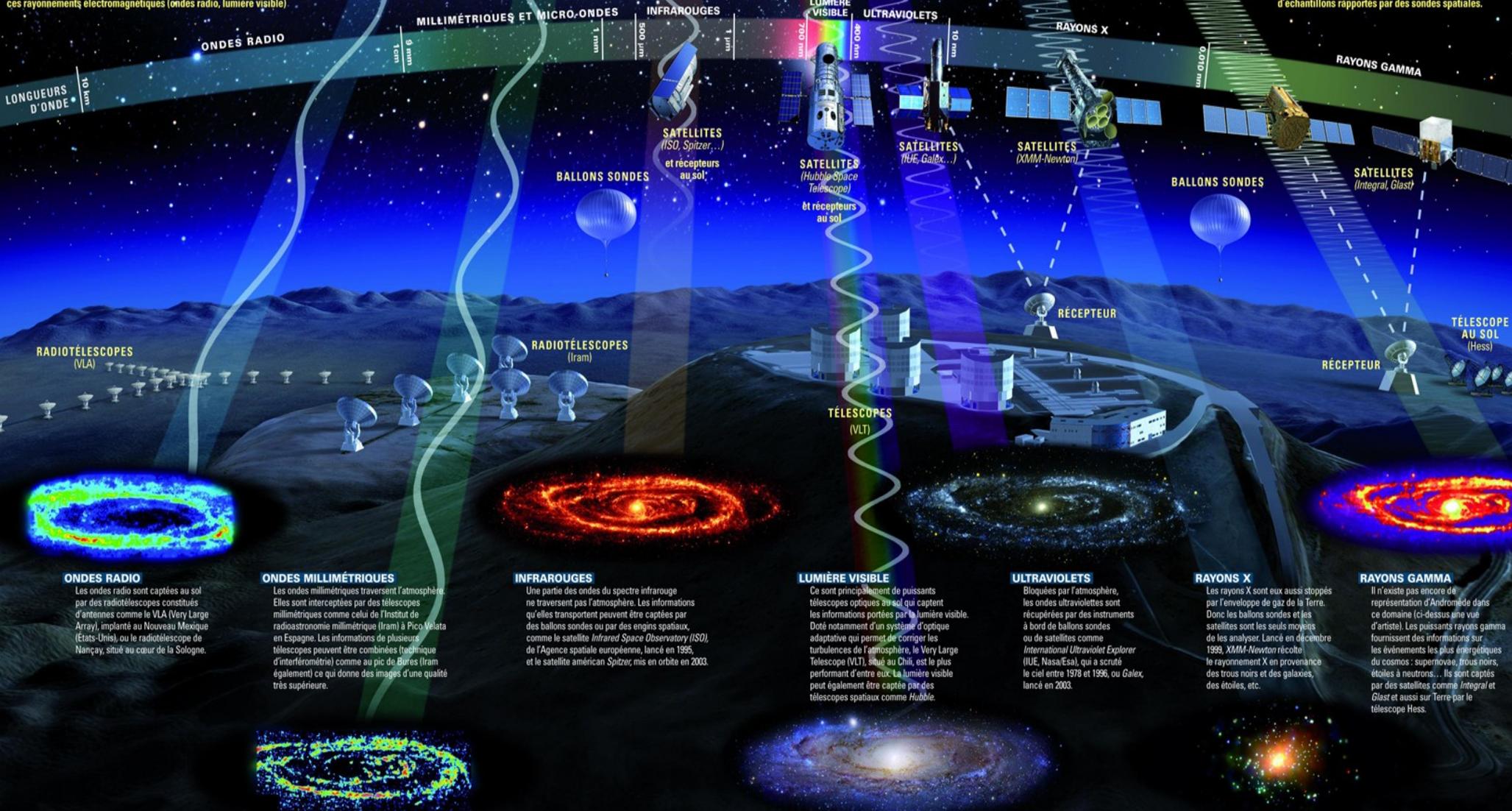
Calorimeter (CsI scin.)



UNE GALAXIE AUX MULTIPLES VISAGES

Cette illustration ressemble à différentes vues de la galaxie d'Andromède, située à « seulement » 2 millions d'années-lumière, qui ressemble beaucoup à notre Voie lactée. Les télescopes au sol, les ballons sondes et les satellites, dont seuls quelques illustres représentants sont figurés ici, permettent en effet d'observer un même objet céleste à différentes longueurs d'onde. Toutes les images constituent les pièces d'un puzzle. Ajoutées les unes aux autres, elles permettent de dresser le portrait global de l'objet céleste. Lorsque le rayonnement est invisible à l'œil nu, les images sont colorisées pour percevoir les nuances de l'intensité du rayonnement transmis par les astres. Tout a commencé au début du XVII^e siècle, lorsque Galilée eut l'idée de tourner sa lunette vers le ciel : il ne capta alors que la lumière visible qui venait des étoiles et des planètes. Aujourd'hui, pour étudier un objet céleste, les astronomes ont à leur disposition les informations transportées par l'immense spectre des ondes électromagnétiques, dont la lumière visible n'est qu'une toute petite partie. Parfois, ces rayonnements électromagnétiques (ondes radio, lumière visible)

traversent l'atmosphère terrestre et il suffit de récepteurs au sol pour les capter et en tirer des informations sur les lointaines galaxies ou les proches planètes. Parfois au contraire, comme les rayons X ou les ultraviolets, ils sont bloqués par l'atmosphère de notre planète et seuls des instruments embarqués à bord de satellites permettent de recueillir les informations qu'ils transportent. Mais toutes ces ondes ne sont pas les seuls messagers de l'Univers. Aujourd'hui en effet, les scientifiques guettent notamment les rayons cosmiques, grâce par exemple à l'Observatoire Pierre Auger, les neutrinos grâce au détecteur sous-marin Antarès, et bientôt les ondes gravitationnelles, avec le détecteur Virgo (lire p. 24). Des informations peuvent également être recueillies au sein d'échantillons rapportés par des sondes spatiales.



ONDES RADIO
Les ondes radio sont captées au sol par des radiotélescopes constitués d'antennes comme le VLA (Very Large Array), implanté au Nouveau Mexique (États-Unis), ou le radiotélescope de Nançay, situé au cœur de la Sologne.

ONDES MILLIMÉTRIQUES
Les ondes millimétriques traversent l'atmosphère. Elles sont interceptées par des télescopes millimétriques comme celui de l'Institut de radioastronomie millimétrique (IRAM) à Pico Velata en Espagne. Les informations de plusieurs télescopes peuvent être combinées (technique d'interférométrie) comme au pic de Bures (IRAM également) ce qui donne des images d'une qualité très supérieure.

INFRAROUGES
Une partie des ondes du spectre infrarouge ne traversent pas l'atmosphère. Les informations qu'elles transportent peuvent être captées par des ballons sondes ou par des engins spatiaux, comme le satellite *Infrared Space Observatory (ISO)*, de l'Agence spatiale européenne, lancé en 1995, et le satellite américain *Spitzer*, mis en orbite en 2003.

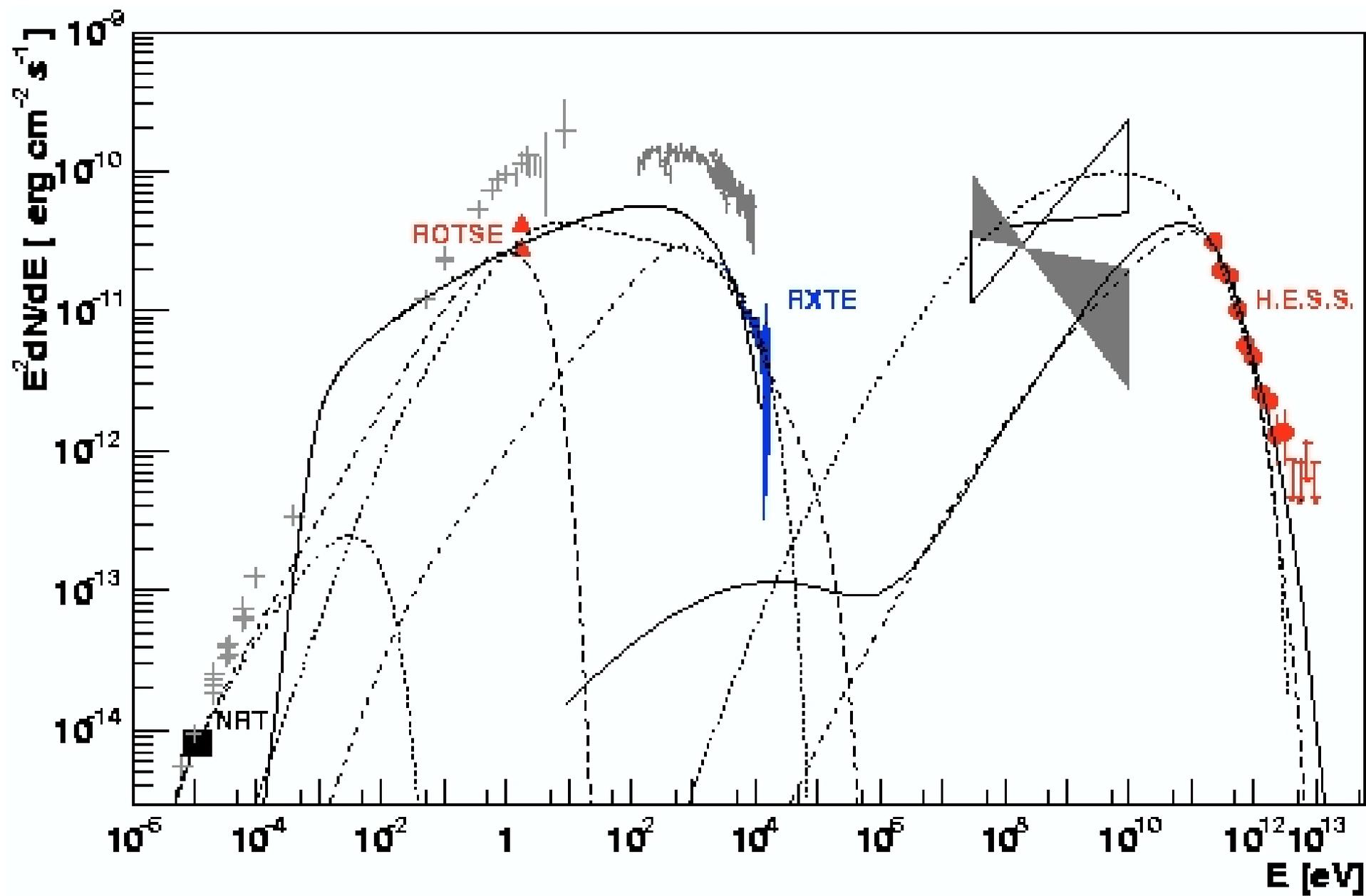
LUMIÈRE VISIBLE
Ce sont principalement de puissants télescopes optiques au sol qui capturent les informations portées par la lumière visible. Doté notamment d'un système d'optique adaptative qui permet de corriger les turbulences de l'atmosphère, le Very Large Telescope (VLT), situé au Chili, est le plus performant d'entre eux. La lumière visible peut également être captée par des télescopes spatiaux comme *Hubble*.

ULTRAVIOLETS
Bloqués par l'atmosphère, les ondes ultraviolettes sont récupérées par des instruments à bord de ballons sondes ou de satellites comme *International Ultraviolet Explorer (IUE)*, Nasa/Esal, qui a scruté le ciel entre 1978 et 1996, ou *Galax*, lancé en 2003.

RAYONS X
Les rayons X sont eux aussi stoppés par l'enveloppe de gaz de la Terre. Donc les ballons sondes et les satellites sont les seuls moyens de les analyser. Lancé en décembre 1999, *XMM-Newton* récolte le rayonnement X en provenance des trous noirs et des galaxies, des étoiles, etc.

RAYONS GAMMA
Il n'existe pas encore de représentation d'Andromède dans ce domaine (ci-dessus une vue d'artiste). Les puissants rayons gamma fournissent des informations sur les événements les plus énergétiques du cosmos : supernovae, trous noirs, étoiles à neutrons... Ils sont captés par des satellites comme *Integral* et *Glast* et aussi sur Terre par le télescope Hess.

© Infographies : P. Carré pour La Presse du CNRS, photos d'illustration : Heston et al., 2006, Journal d'Astronomie & Astrophysique (ESO 2006) ; NASA/JPL/Caltech ; B. Sobolev, V. Harvey/REU program/NOAO/JRANSF ; NASA/Maszi/L & J.D. Wang



Active Galactic Nuclei

Among the most violent objects in our Universe

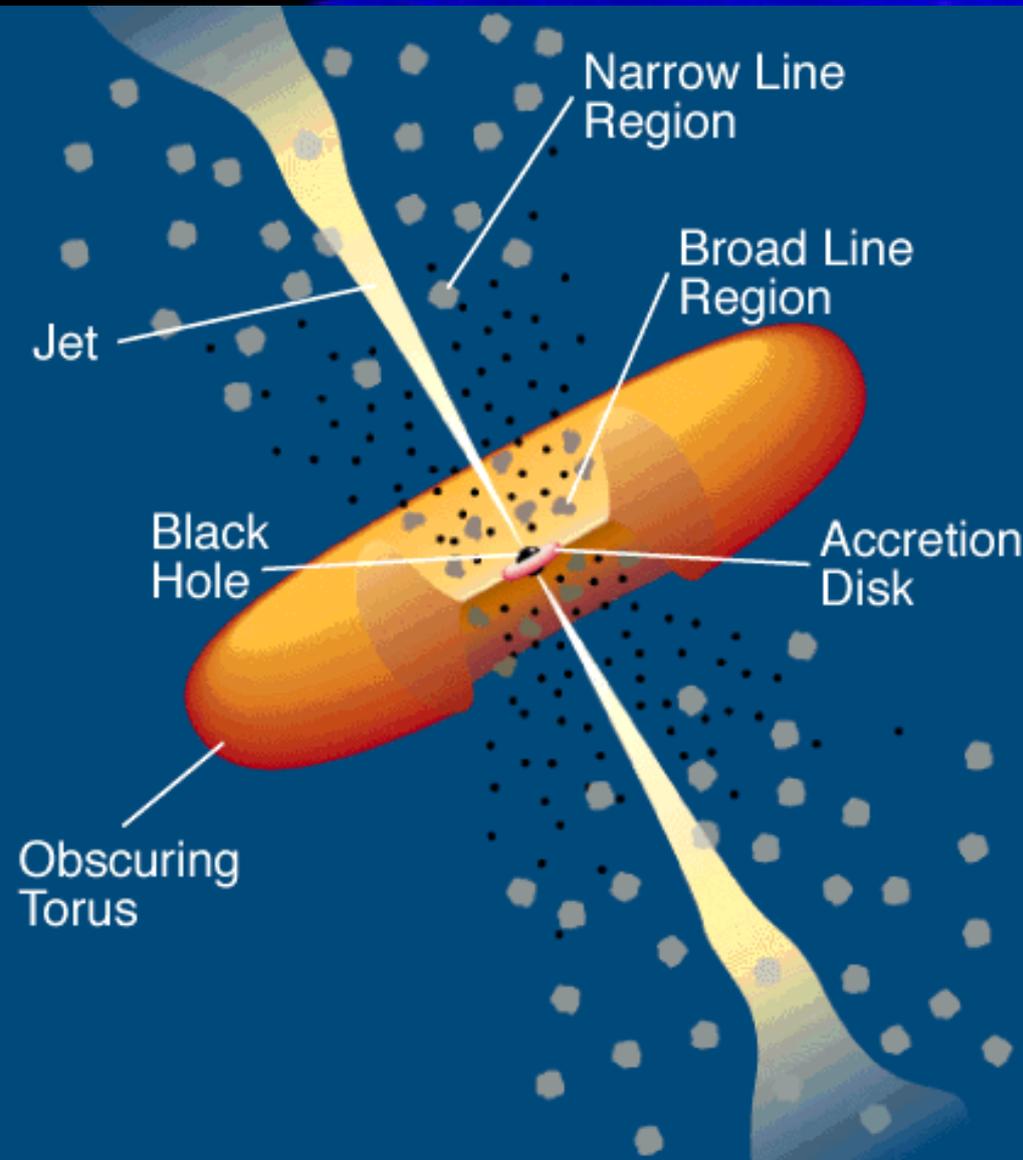
Highly variable

Vast energy output

Relativistic outflows

Model has a large amount of free parameters

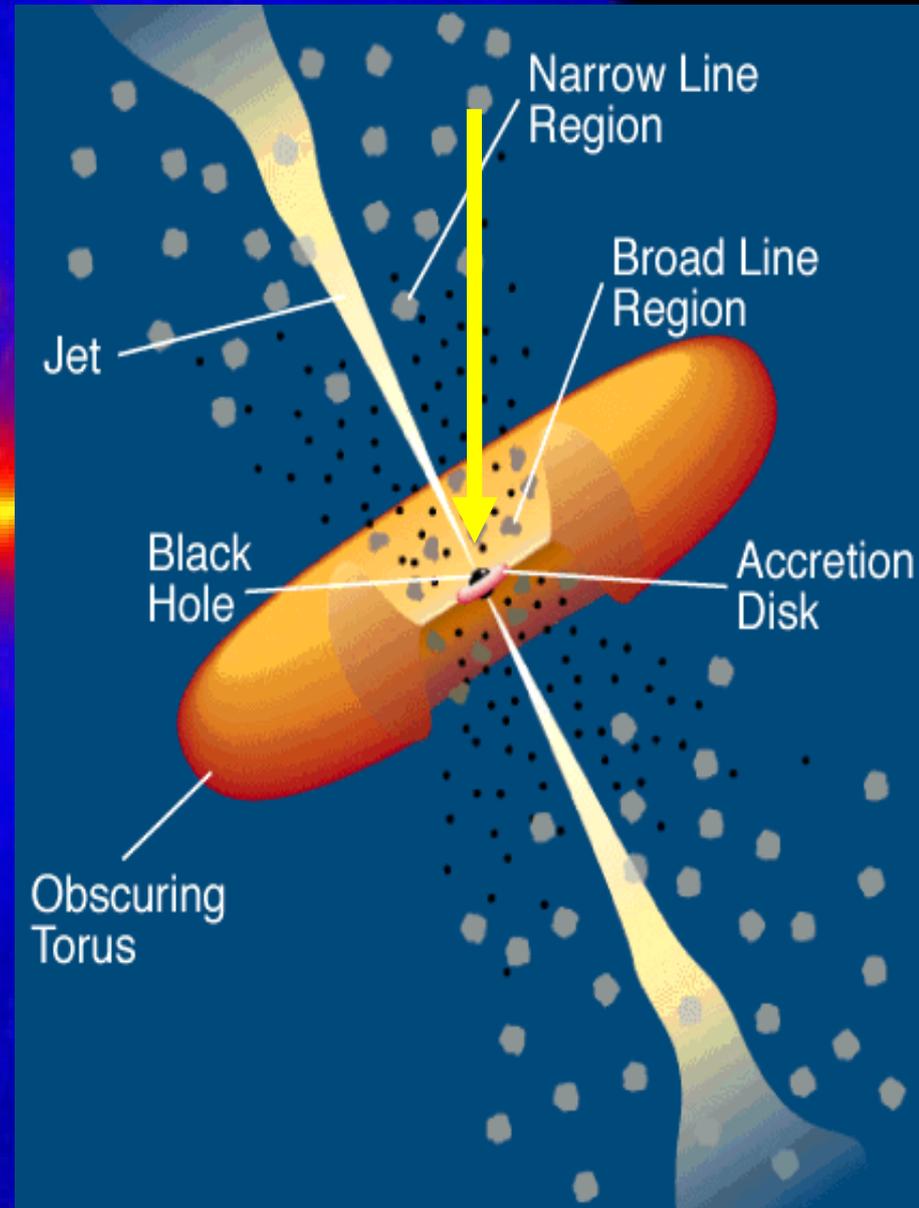
– =>AGN sub-classes





NGC 1275

- FR 1 radio galaxy
- Misaligned AGN -> reduces the relativistic properties (in principle)
- $Z=0.0179$ -> allows us to study relativistic outflows in detail



NGC 1275 and gamma-rays

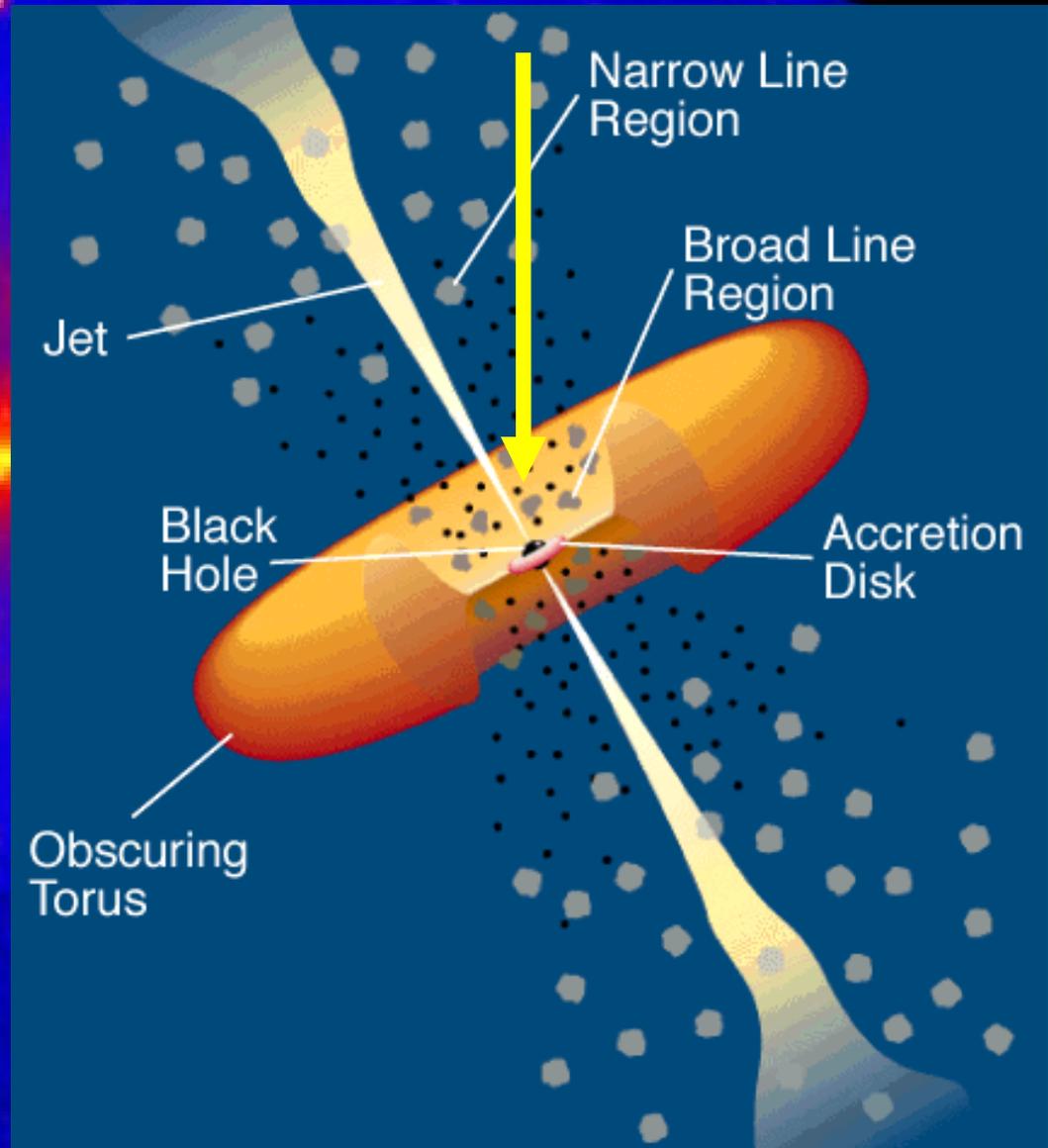
Previous missions saw nothing

Fermi-LAT saw it in 4 months of obs

($10e^{-7}$ ph/cm²/s)

1 year of obs saw spectral variability

What did we get in 2 years?



Variability Studies

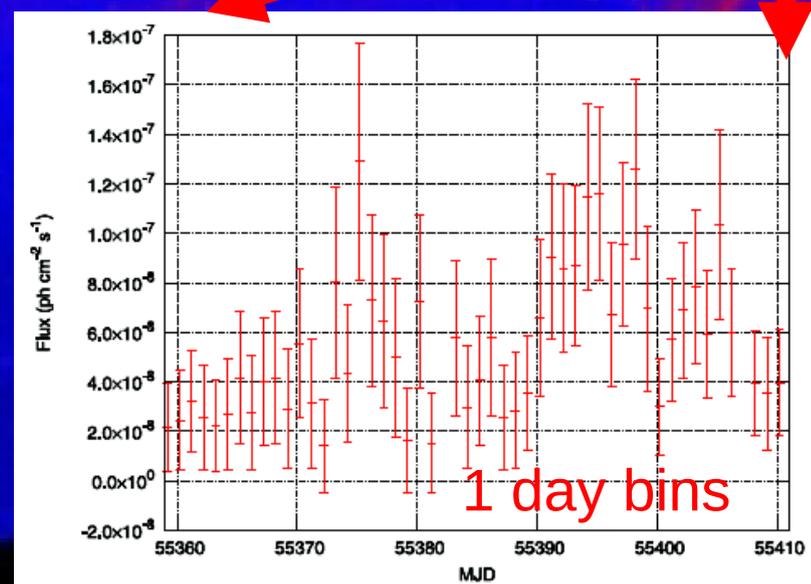
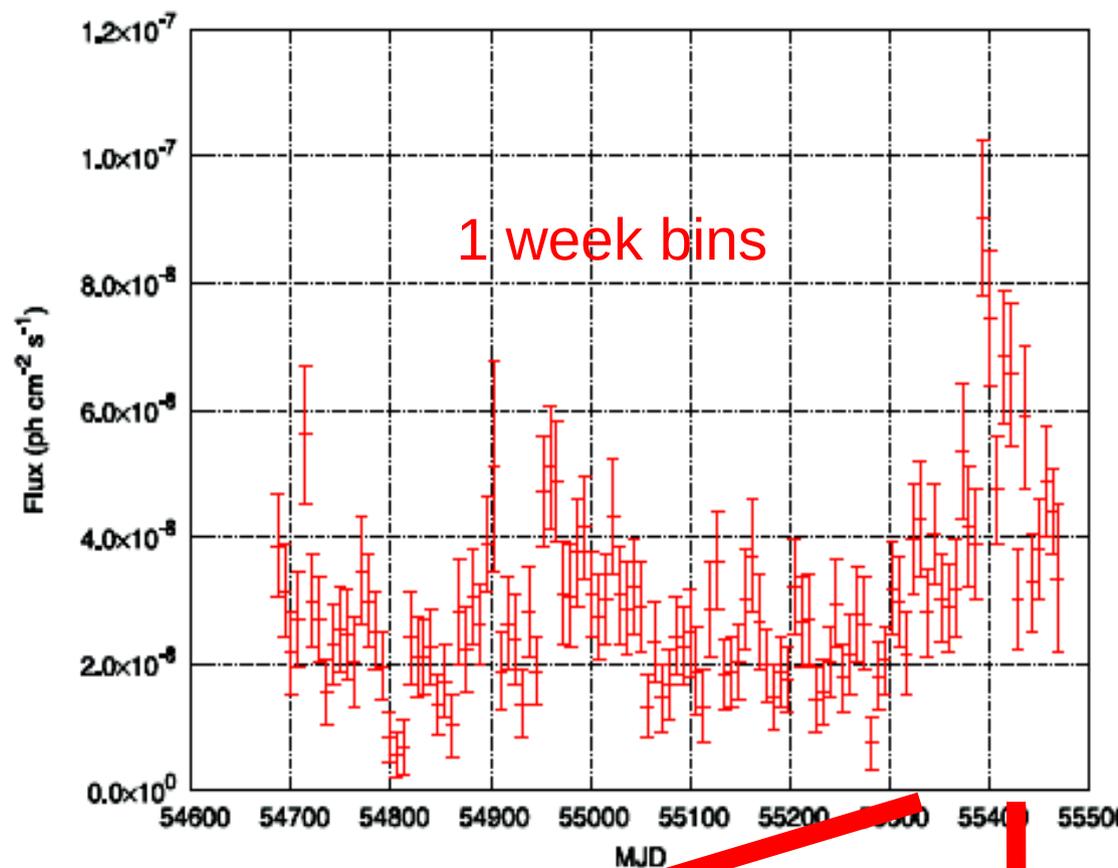
$E > 800$ MeV photon flux
as a function of time

Characterise variability
by e-folding time

$$F(t) = F(t_0) \exp[\tau^{-1}(t - t_0)],$$

$\Delta t = 1.51$ days

(don't expect this
amount of variability
for off axis AGN)

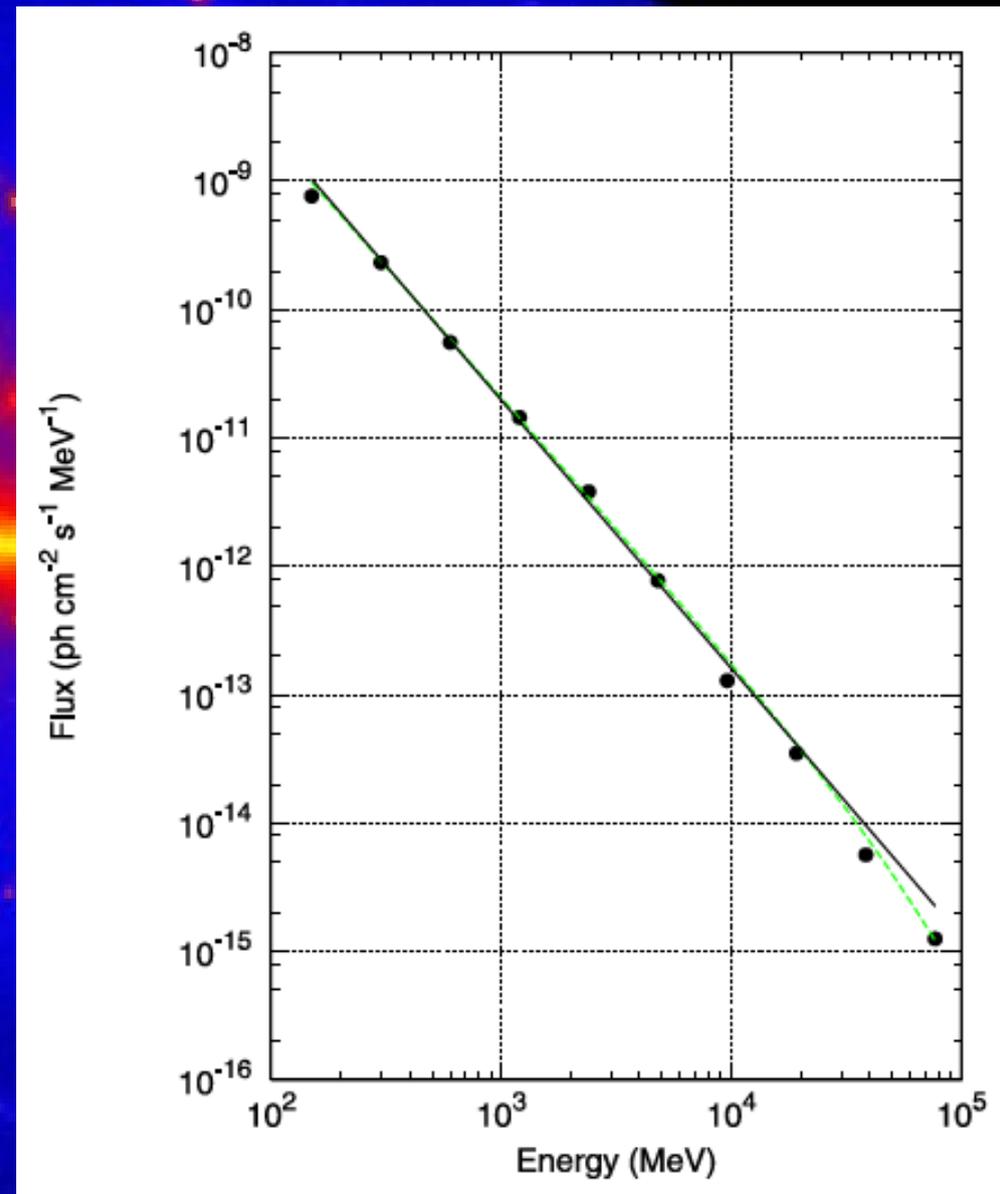


Energy Spectrum I

Probes the energetics of the primary particle population

Possibility of a cut-off (but not statistically significant from Fermi observations alone)

MAGIC observations much steeper, implying cut-off in spectrum



Energy Spectrum II

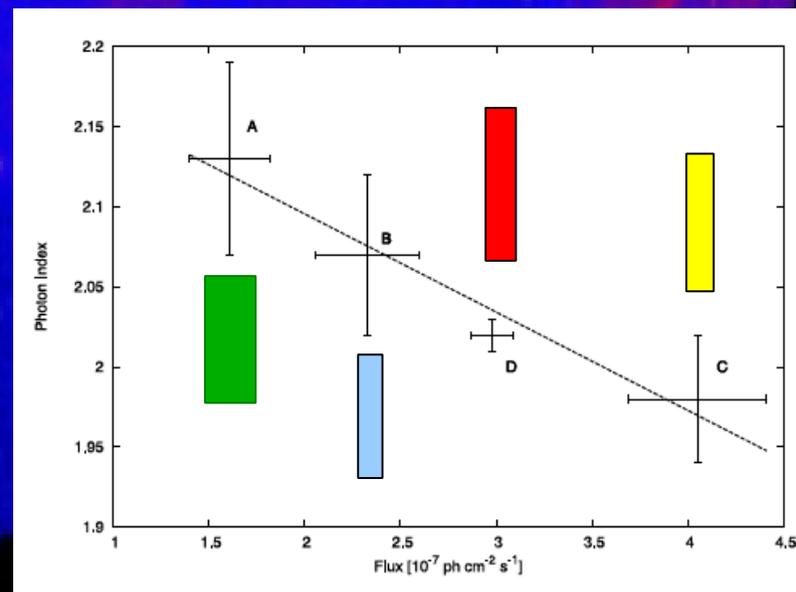
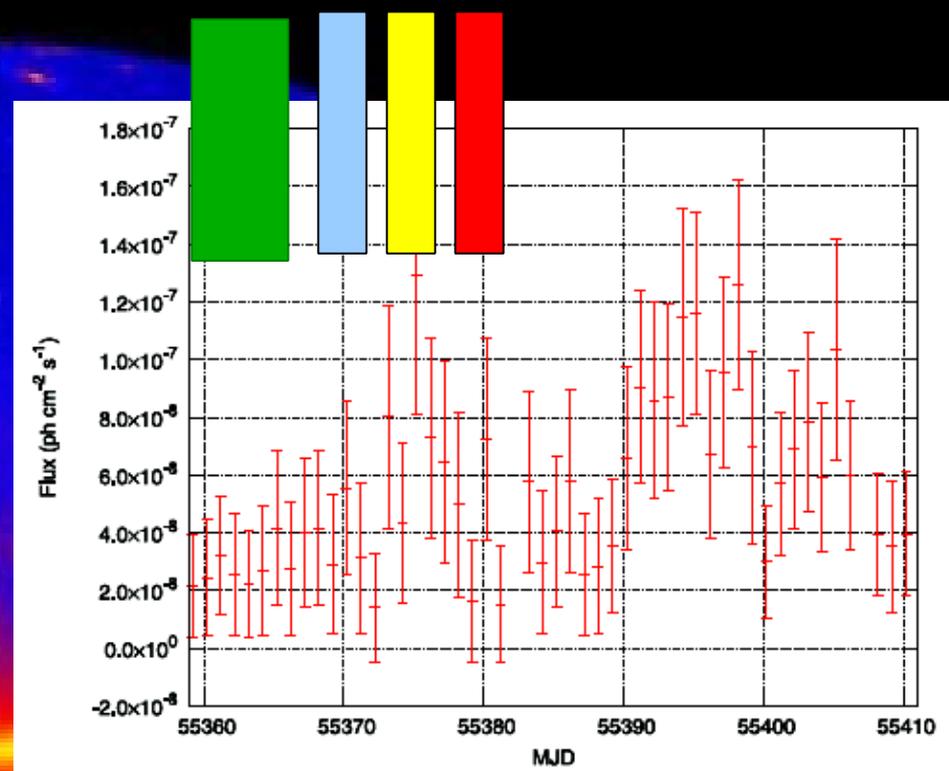
Probes the energetics of the primary particle population

Before, rise, peak, decay of flare

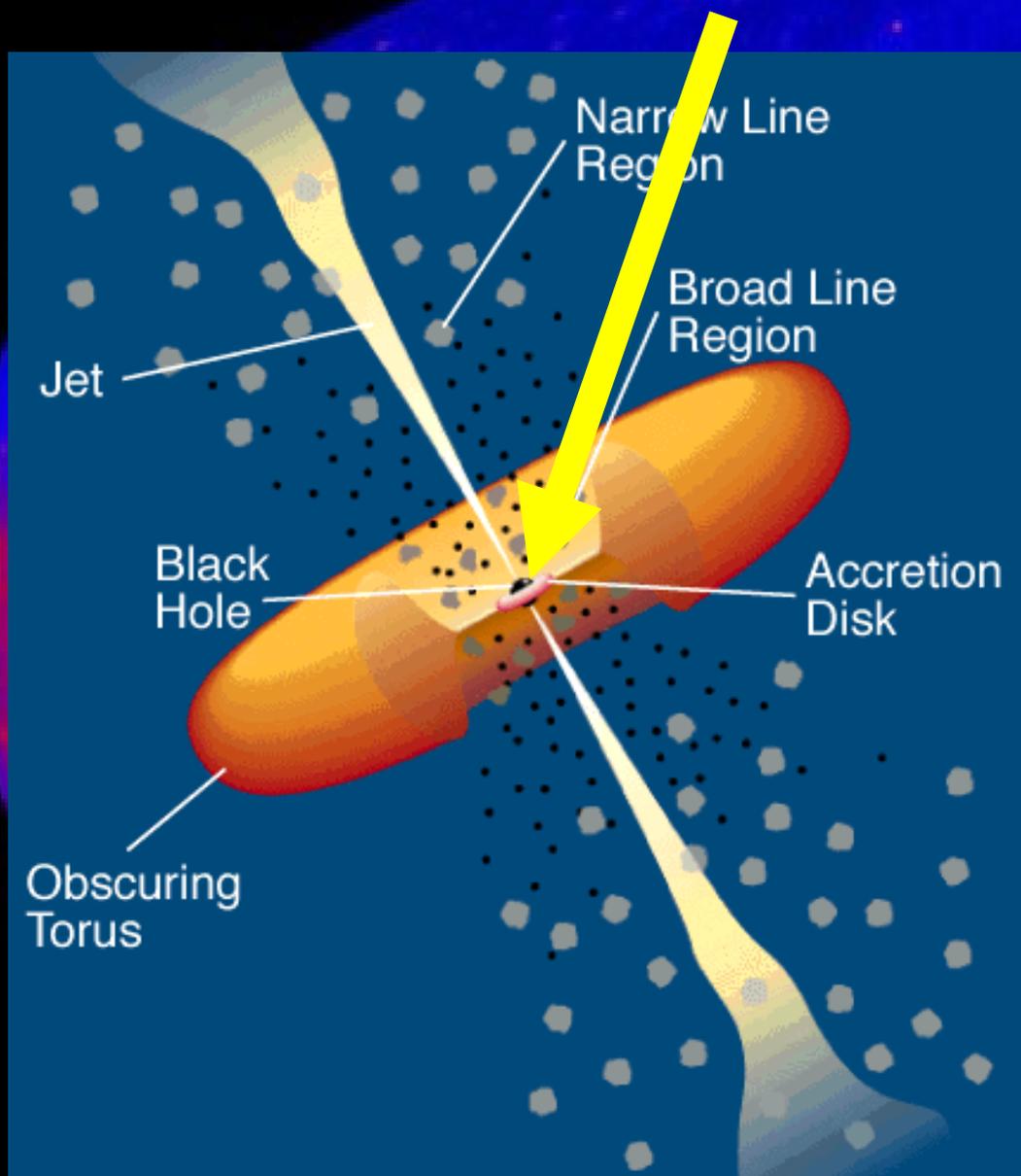
— Harder-when-brighter

> 100 GeV gamma-rays detected by MAGIC when GeV flux peaked

- >GeV emission important for triggering ground-based observations



Pictor A



Broad-Line Radio Galaxy

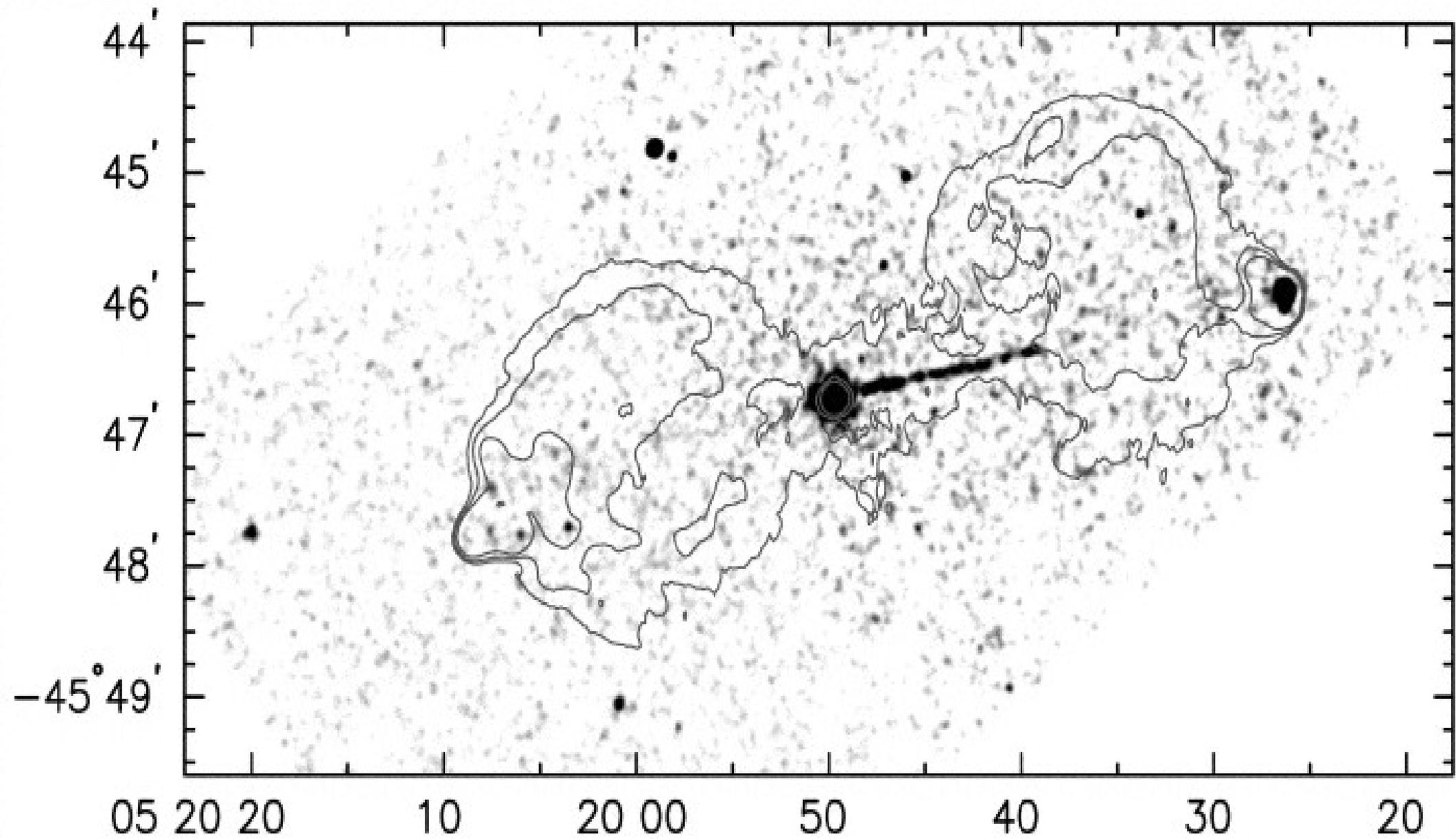
Even more off-axis, allows us a clearer view of inner regions -> how are accretion ejection linked?

Kataoka et al. modeled BLRG candidates and found Pic A to be near *Fermi-LAT* sensitivity

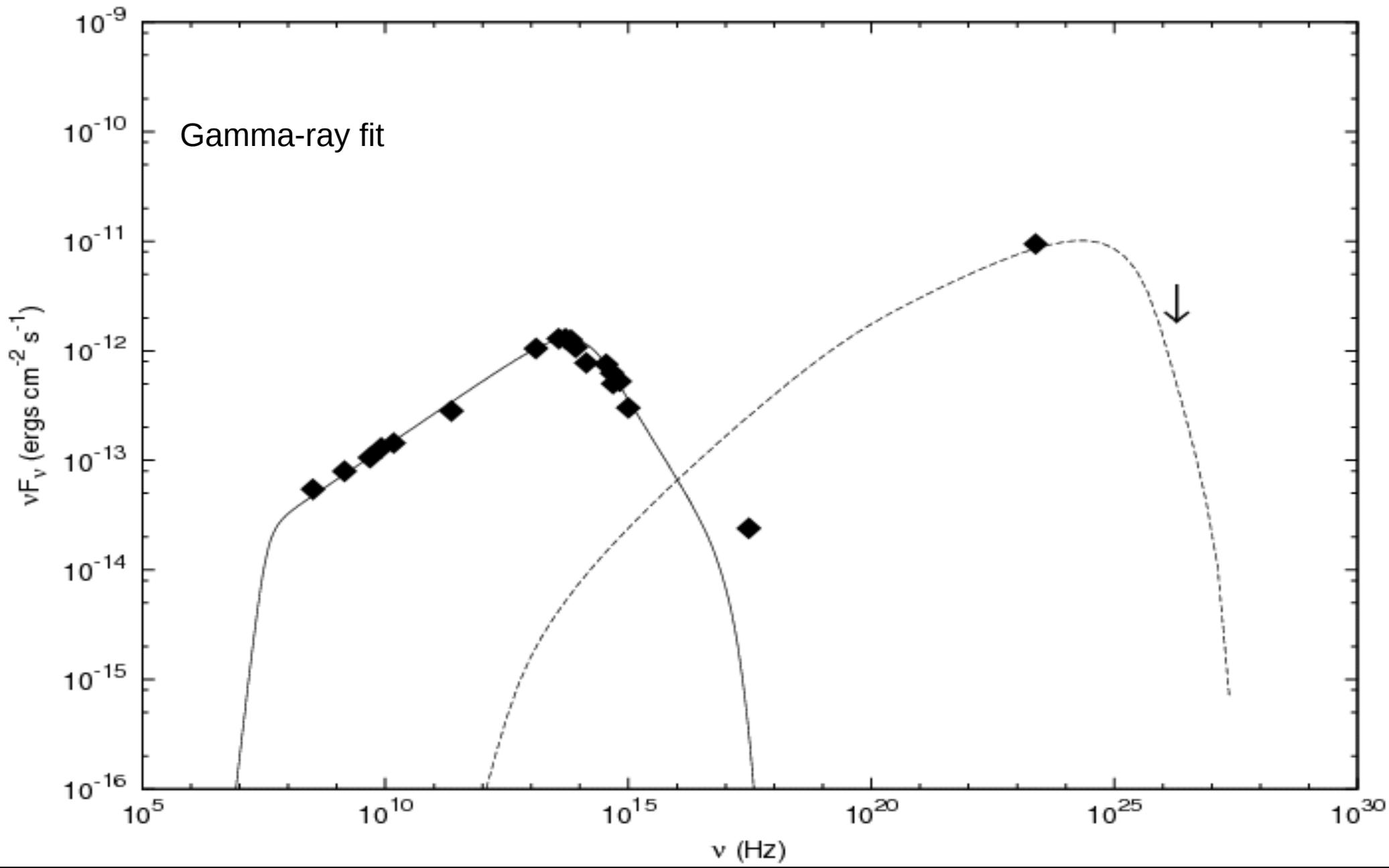
What do we find with 3 years of observations?

5.6 sigma, $(5.6 \pm 0.7) \times 10^{-9}$ ph/cm²/s

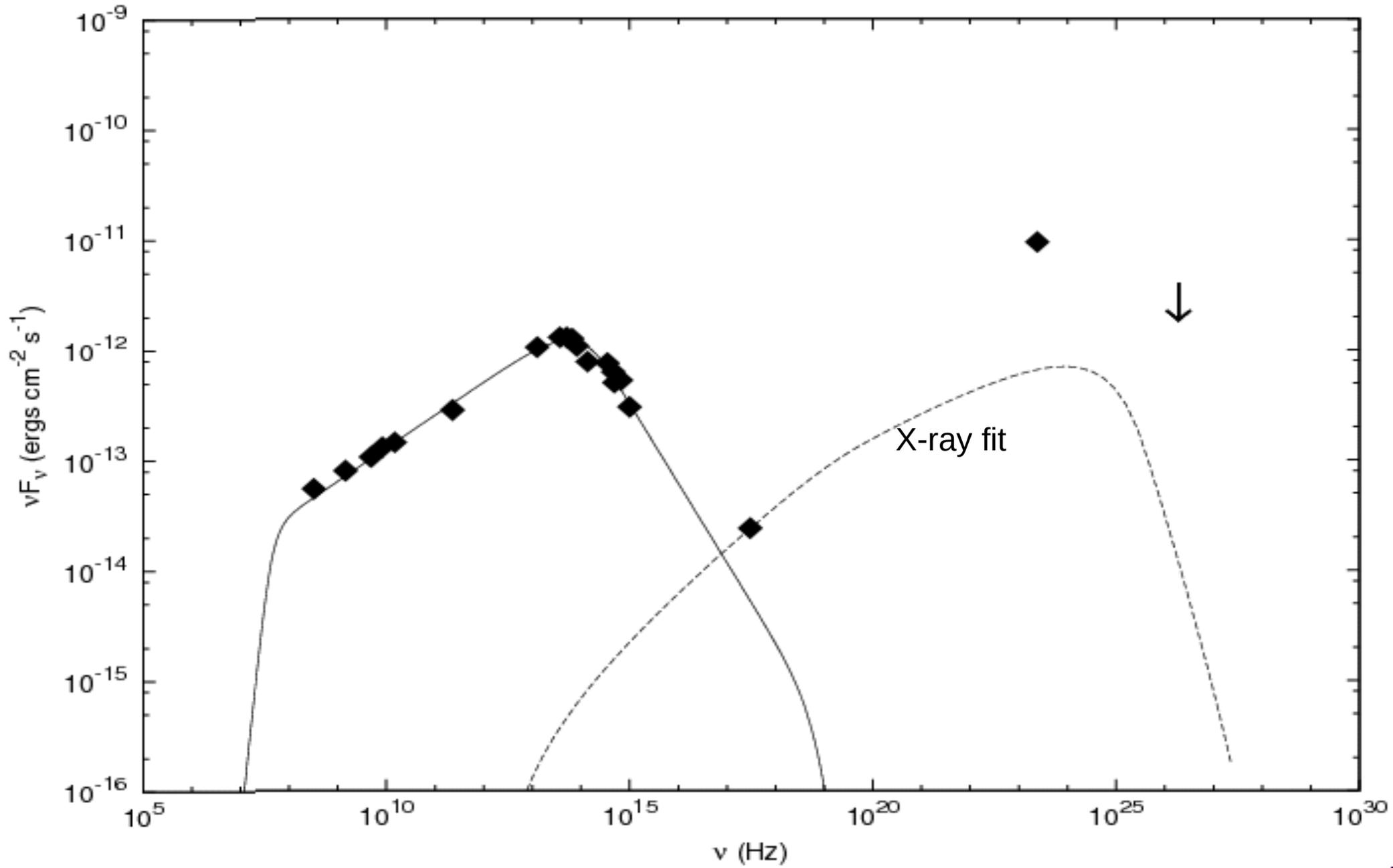
Where are the gamma-rays coming from ?



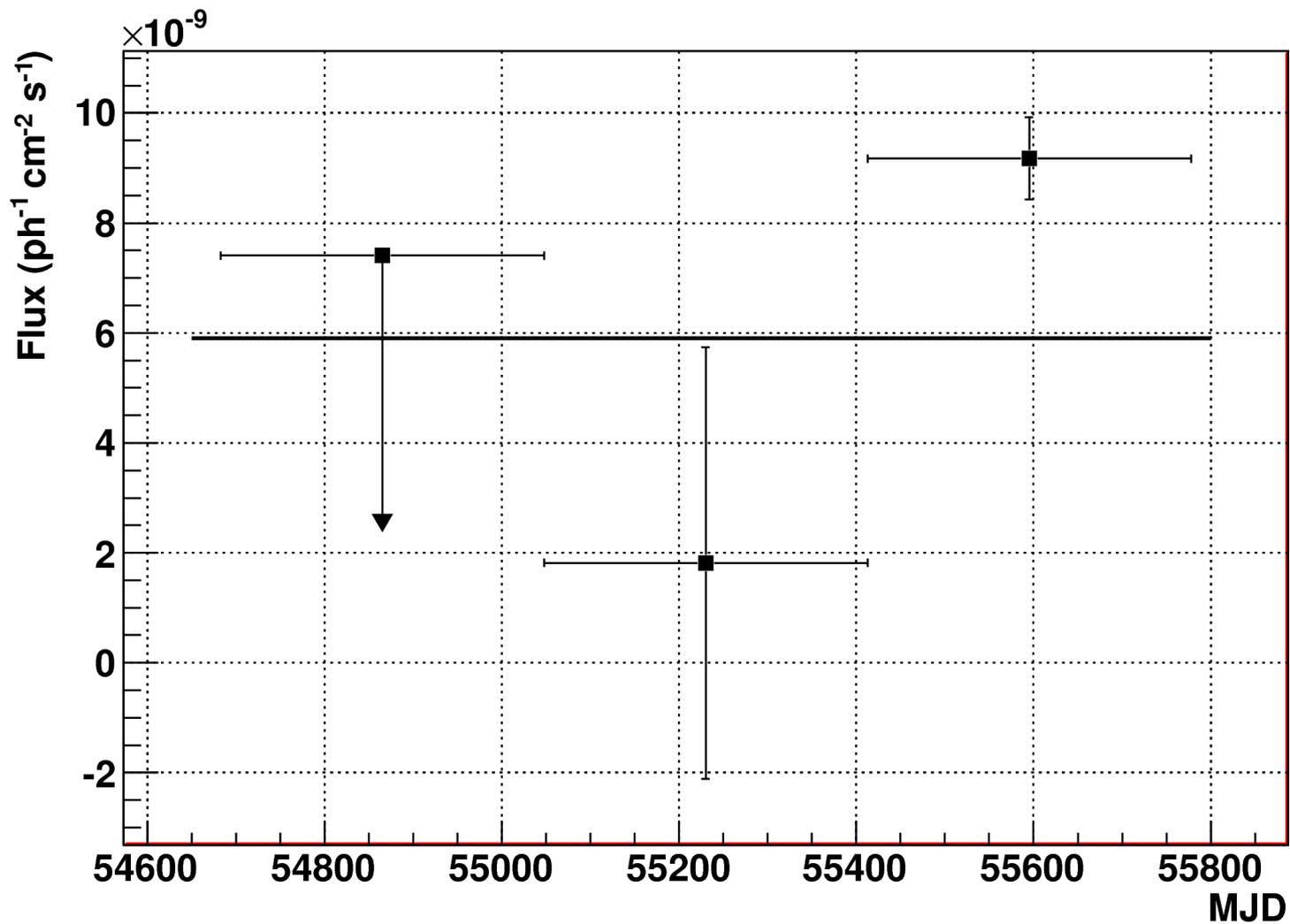
SED modeling...



SED modeling...



Light curve (1 year bins)

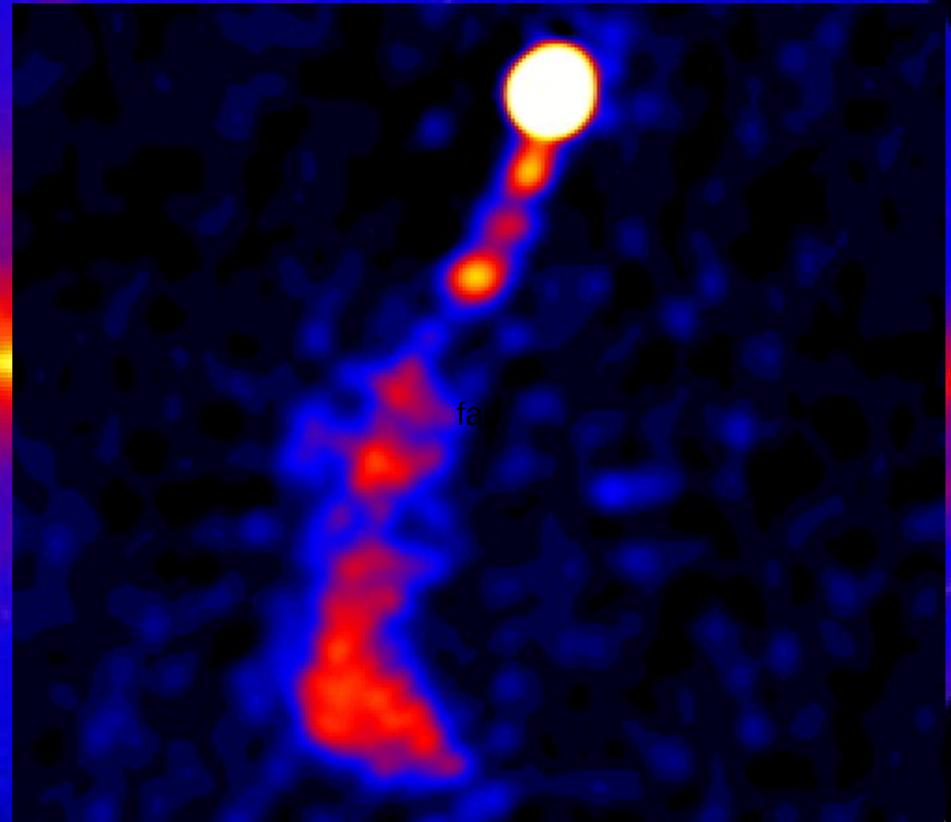


PKS 1510-089

Flat spectrum radio
quasar

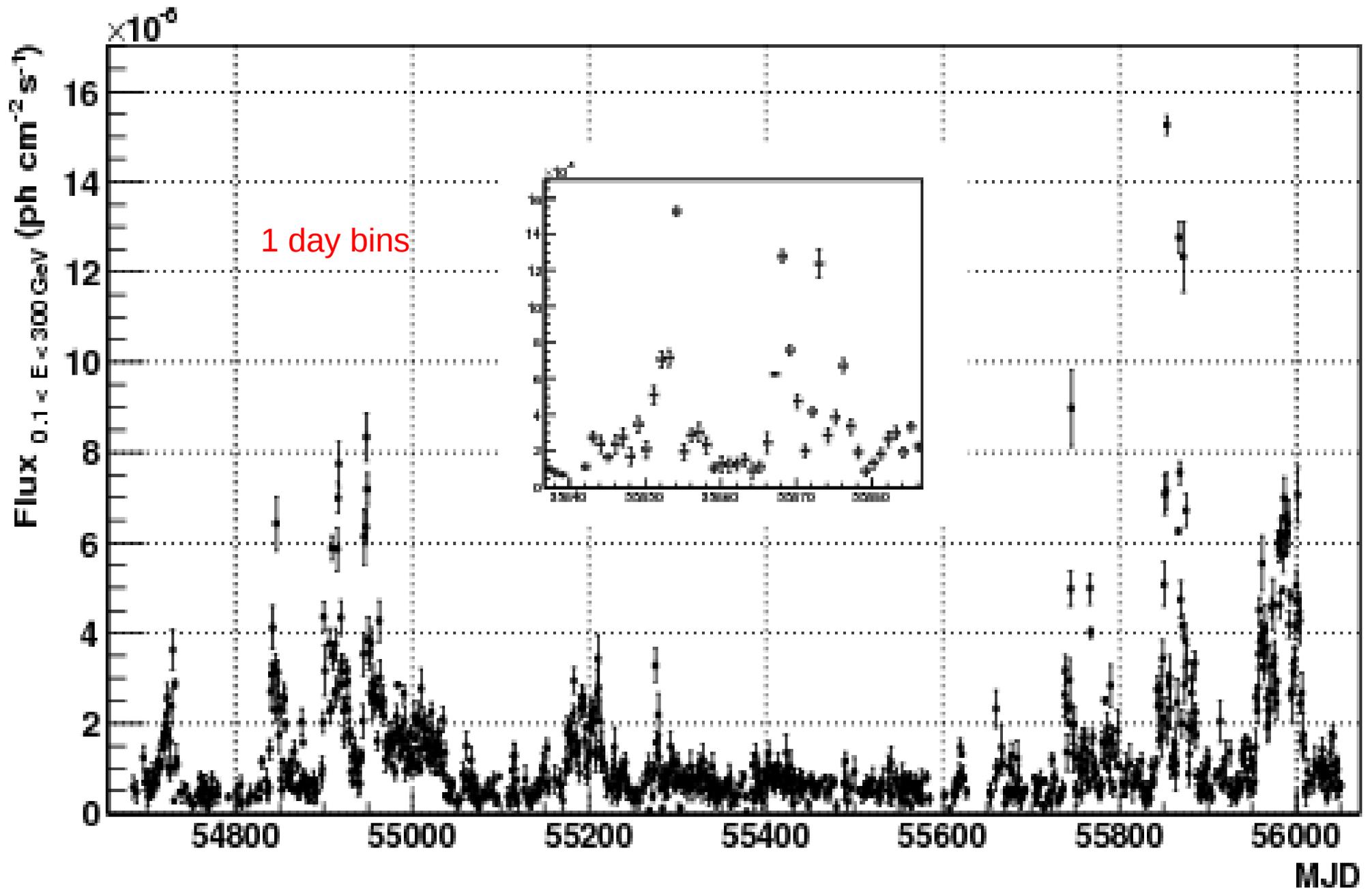
One of the brightest &
most variable AGN
detected by Fermi

Discovered by HESS
>100GeV, confirmed
by MAGIC

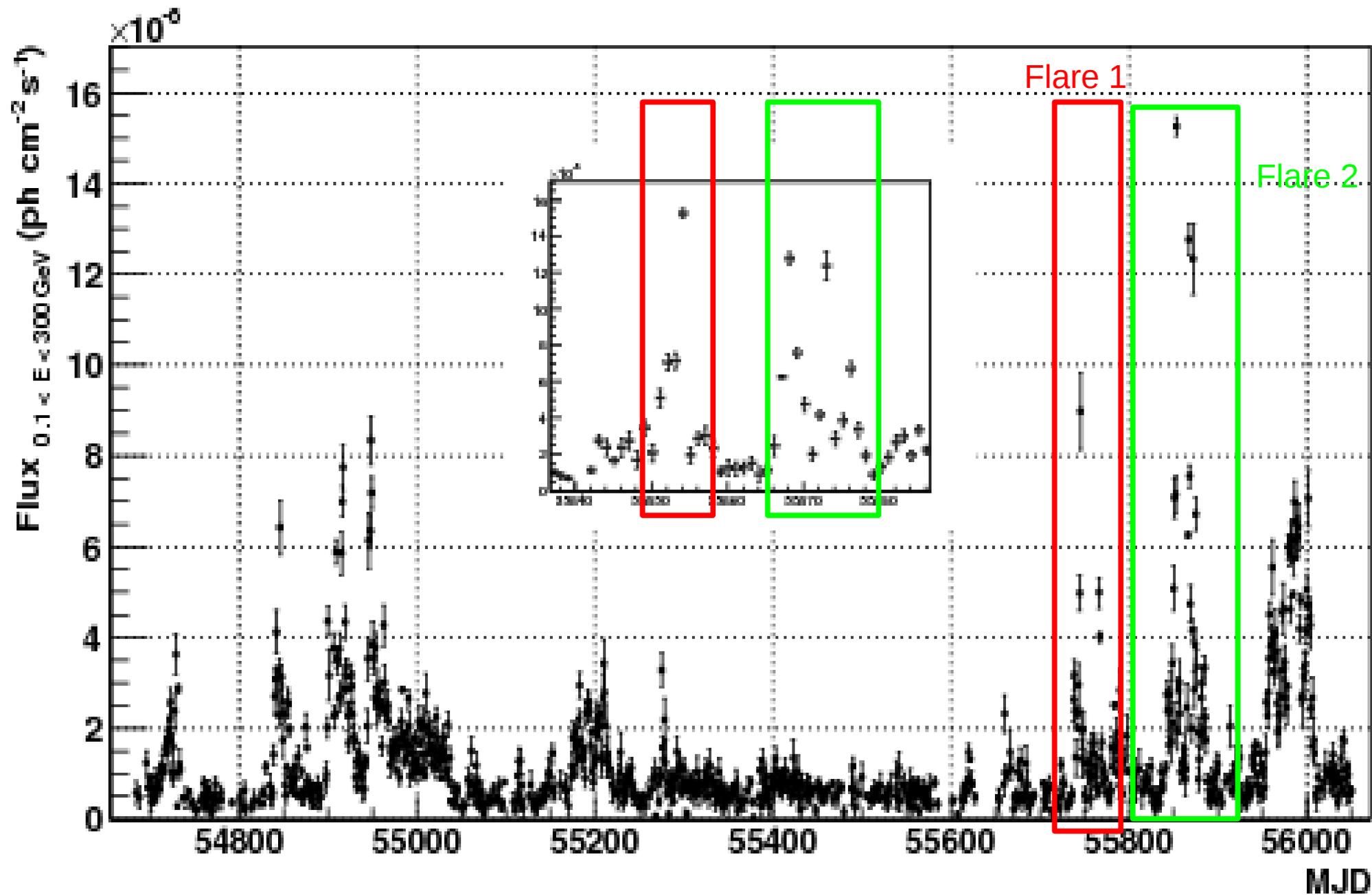


What do we see with Fermi? (in 3.75 years)

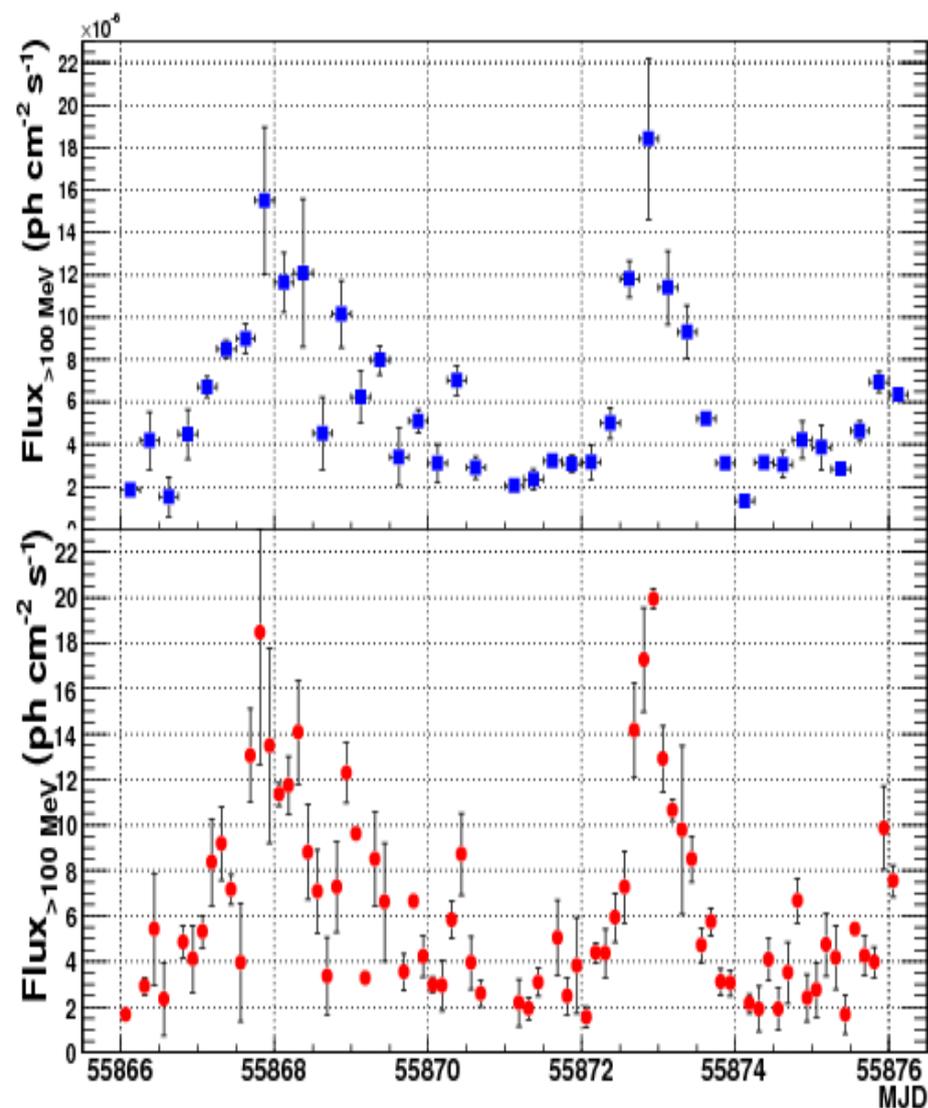
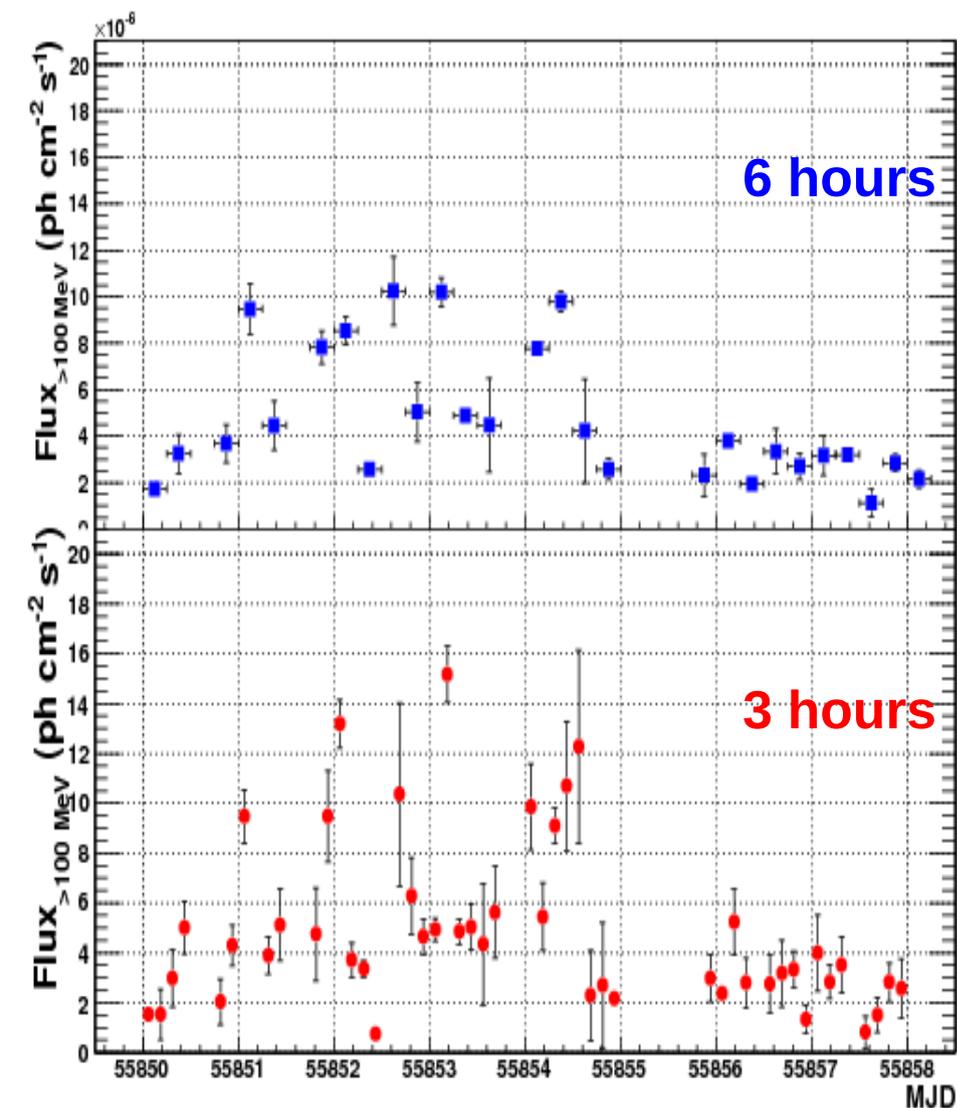
Light curve $(0.1 < E < 300 \text{ GeV})$



Light curve $(0.1 < E < 300 \text{ GeV})$



3 and 6 hour bins



Doubling timescales

Table 1. Summary of quickest variability timescales events of PKS 1510-089 during the 3.75 year period, which are less than 3 hours and have a significance of at least 5σ . The times, T_{start} and T_{stop} , are in MJD, with the fluxes in units of 10^{-6} photons cm^{-2} s^{-1} . The observed characteristic timescale τ , from Equation 1, is converted to the intrinsic variability timescale, τ_{int} , with $\tau_{\text{int}} = \tau(1+z)^{-1}$. The uncertainty in the variability timescale was calculated by propagating the uncertainty in the flux and time values through Equation 1. The last column indicates whether the variability event is an increase (rise) or decrease (decay) in the flux.

T_{start}	T_{stop}	Flux start (F_{α})	Flux stop (F)	τ_{int} (hours)	Rise/Decay
55850.812	55850.437	2.97 ± 1.15	5.00 ± 1.03	2.93 ± 0.41	R
55850.812	55850.937	2.03 ± 0.91	4.30 ± 0.81	2.03 ± 0.39	R
55850.937	55851.062	4.30 ± 0.81	9.46 ± 1.07	1.94 ± 0.22	R
55851.812	55851.937	4.75 ± 1.87	9.48 ± 1.83	2.21 ± 0.39	R
55852.187	55852.312	13.2 ± 0.97	3.71 ± 0.68	-1.21 ± 0.15	D
55853.062	55853.187	4.93 ± 0.45	15.2 ± 1.12	1.36 ± 0.13	R
55853.187	55853.312	15.2 ± 1.12	4.84 ± 0.49	-1.34 ± 0.13	D
55854.062	55854.187	9.86 ± 1.73	5.45 ± 1.37	-2.58 ± 0.32	D
55856.062	55856.187	2.38 ± 0.19	5.23 ± 1.32	1.94 ± 0.17	R
55856.187	55856.312	5.23 ± 1.32	2.79 ± 1.00	-2.42 ± 0.47	D
55866.312	55866.437	2.92 ± 0.38	5.41 ± 2.45	2.48 ± 0.38	R
55867.437	55867.562	7.17 ± 0.64	3.96 ± 2.60	-2.57 ± 0.20	D
55868.812	55868.937	7.27 ± 1.98	12.29 ± 1.32	2.91 ± 0.22	R
55869.062	55869.287	9.62 ± 0.34	3.27 ± 0.29	-1.42 ± 0.07	D
55869.187	55869.312	3.27 ± 0.29	8.50 ± 2.08	1.60 ± 0.19	R
55869.687	55869.812	3.53 ± 0.80	6.65 ± 0.34	2.42 ± 0.11	R
55870.187	55870.312	2.96 ± 1.12	5.82 ± 0.82	2.26 ± 0.30	R
55870.437	55870.687	8.71 ± 1.80	3.95 ± 1.16	-1.93 ± 0.38	D
55872.062	55872.187	1.55 ± 0.47	4.39 ± 0.43	1.47 ± 0.21	R
55872.562	55872.687	7.28 ± 1.58	14.17 ± 2.09	2.29 ± 0.27	R
55873.437	55873.562	8.50 ± 1.02	4.71 ± 0.76	-2.59 ± 0.22	D
55873.687	55873.812	5.74 ± 0.61	3.10 ± 0.58	-2.48 ± 0.21	D
55874.687	55874.812	3.51 ± 1.35	6.67 ± 0.97	2.38 ± 0.31	R
55875.062	55875.187	2.76 ± 1.20	4.74 ± 1.38	2.83 ± 0.54	R
55875.437	55875.562	1.67 ± 0.85	5.41 ± 0.29	1.30 ± 0.12	R
55875.812	55875.937	3.97 ± 0.65	9.87 ± 1.84	1.68 ± 0.28	R

Quickest variability for the FSRQ sub-class of AGN at MeV/GeV energies!

Locating the emission region...

Two schools of thought

- Broad Line Region (BLR) close to the base of the jet (sub-parsec scale)
- 'far-dissipation': on the parsec scale in the Molecular Torus (MT)

Argument//Evidence for and against both

Constrain the origin of the gamma-ray emission region through 3 independent approaches

- i. Variability timescale
- ii. Energy (in)dependent cooling timescales
- iii. Photon-photon pair production

Locating the emission region...

(i) Variability timescales

Rapid variation implies a very small emission region. Radio observations show doppler factors of up to 47, implying a size of < 0.003 parsecs.

Does not automatically point to BLR origin

However, can utilise energy density of BLR and MT diffuse photon fields to constrain the cooling timescales (Tavecchio et al. 2010)

$$\tau_{cool}^{obs} = \frac{3m_e c(1+z)}{4\sigma_T U' \gamma \delta}$$

Points to a BLR origin....

... Tavecchio et al. Assumed IC scattering in the Thompson regime....

Locating the emission region...

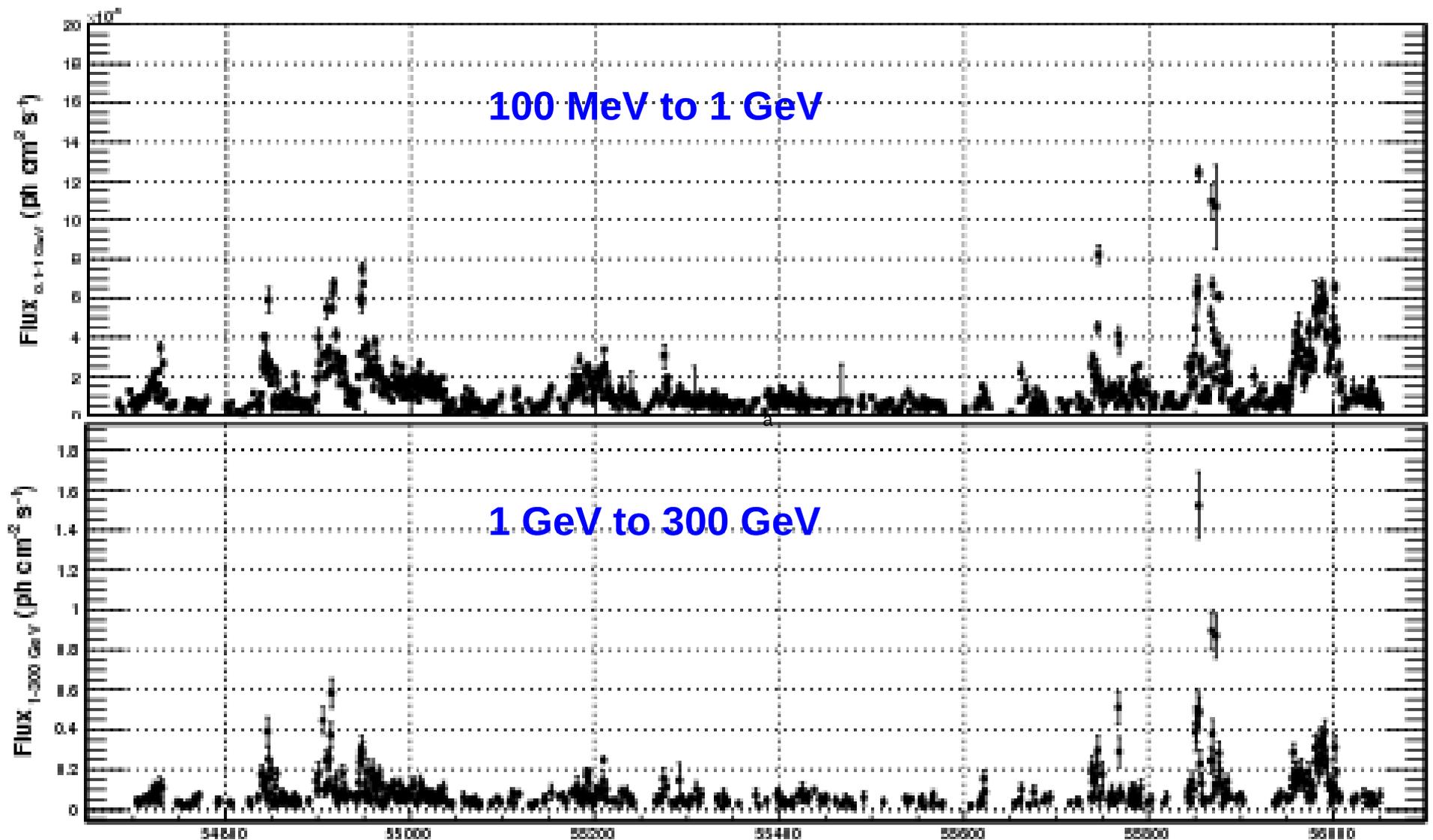
(ii) Energy dependent cooling timescales

Dotson et al. found IC scatter in the BLR to be in the Klein-Nishina regime, while IC in the MT is in the Thompson regime.

Results in an energy (in)dependence in the cooling timescales depending upon the location of the emission region.

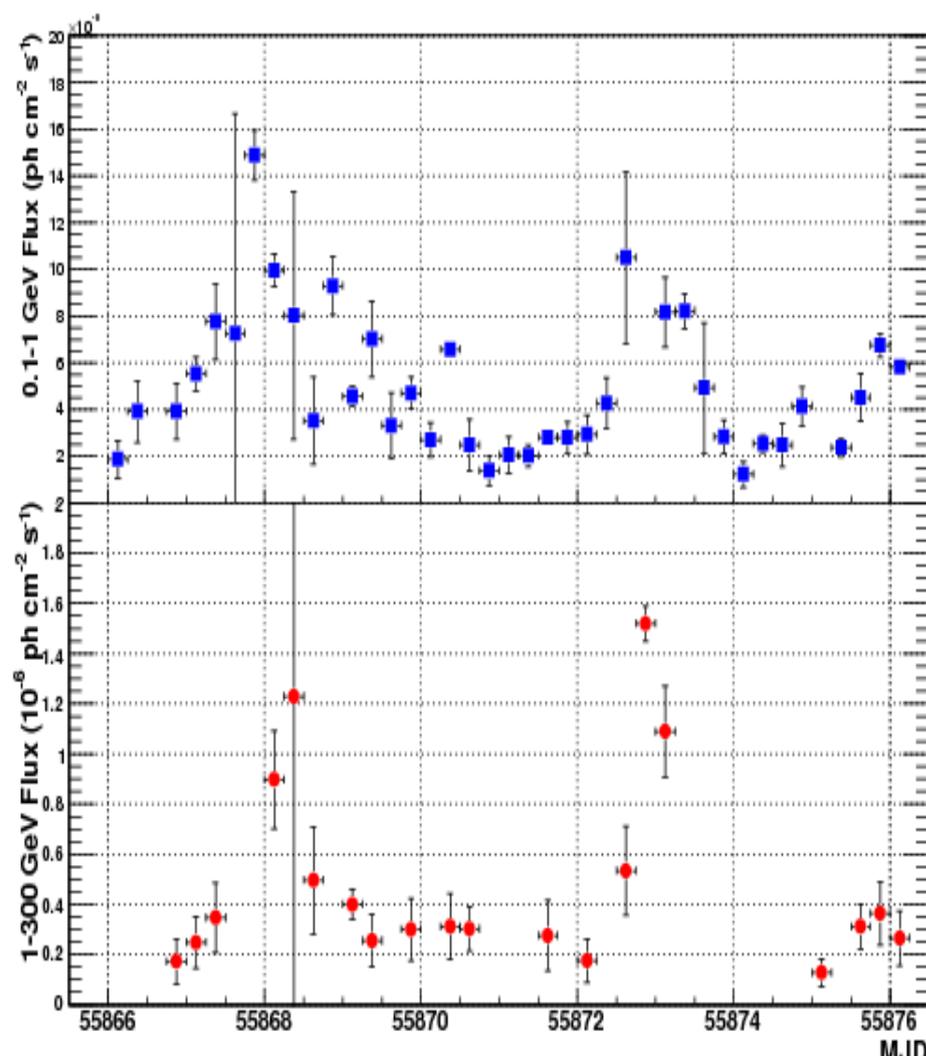
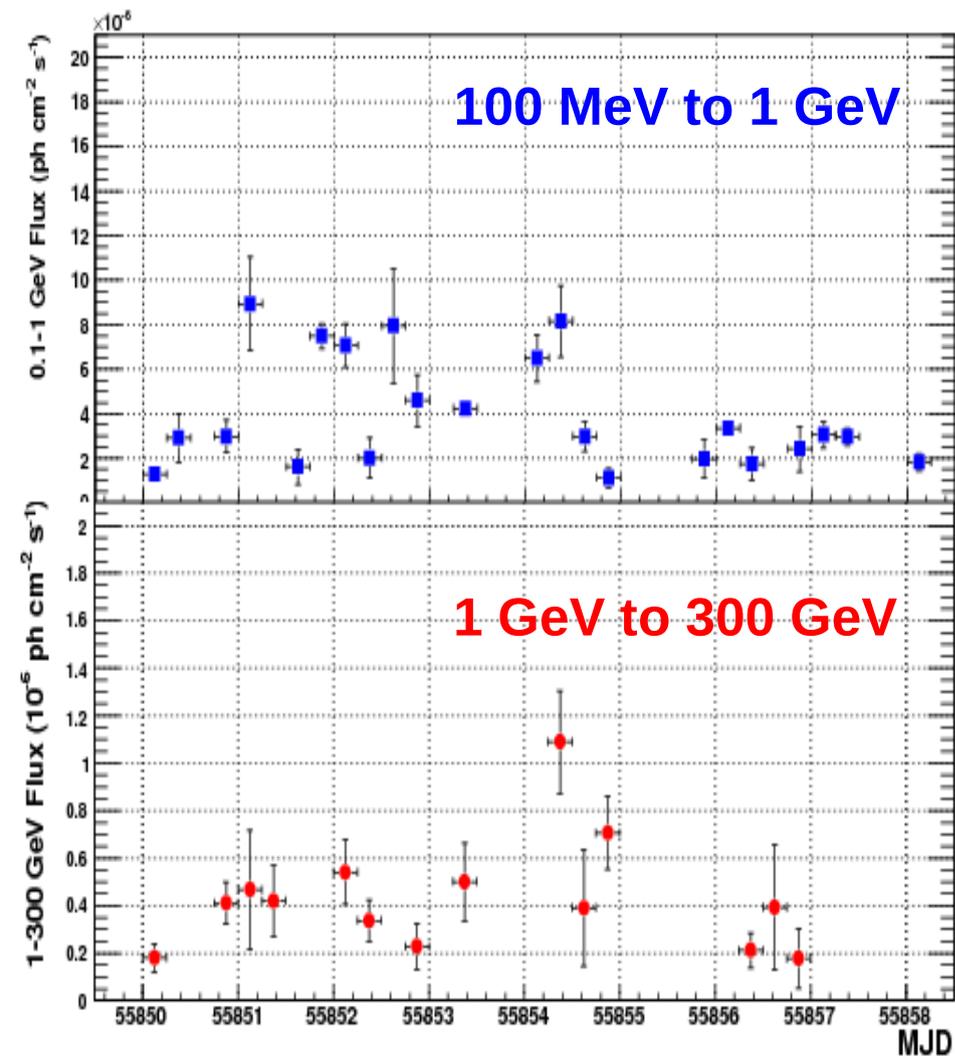
Results in a time lag between the cooling timescales of MeV and GeV photons of a flare

(ii) Energy (in)dependent cooling timescales



Flare 1

Flare 2

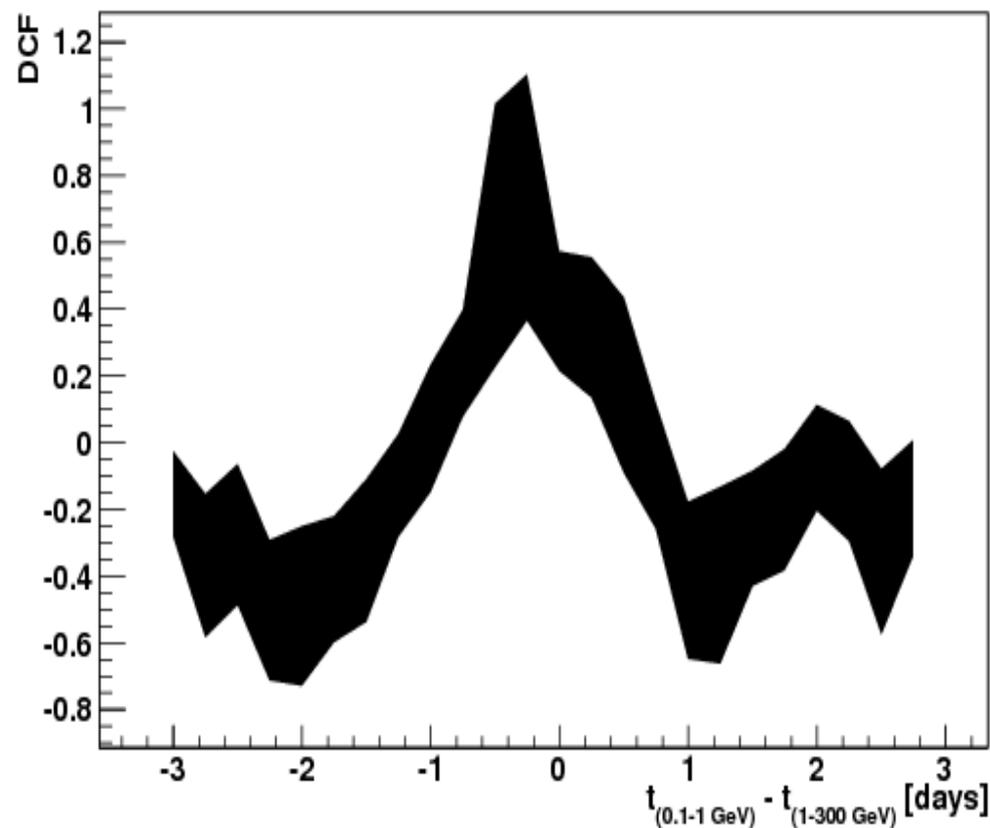
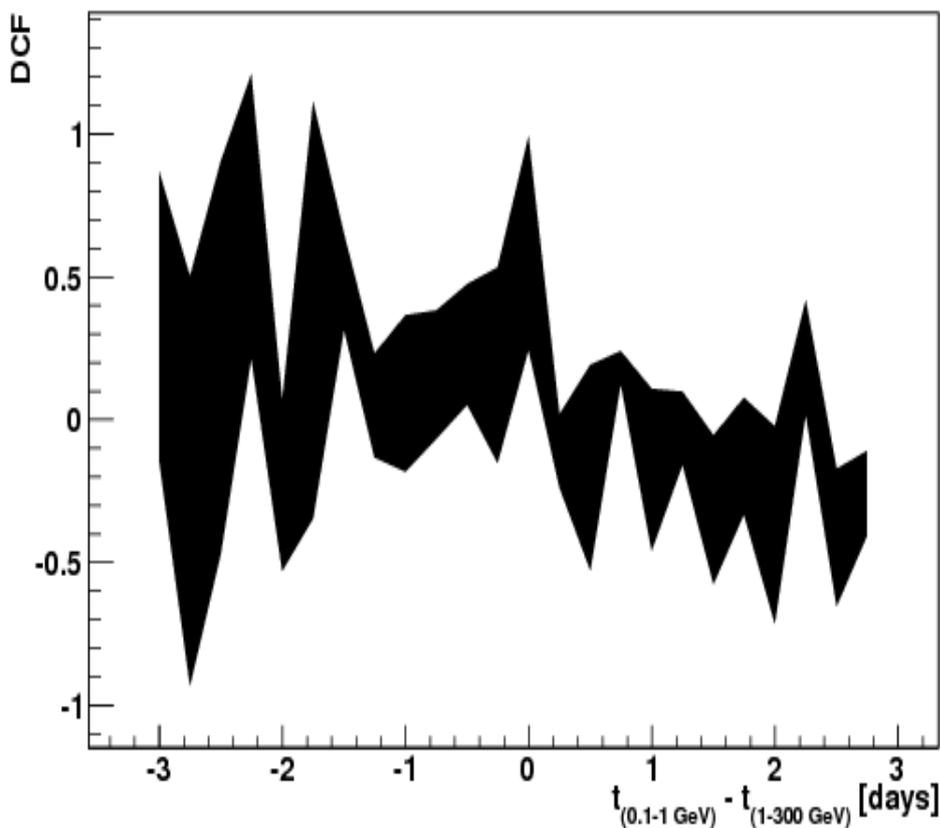


Discrete Correlation Functions

DCFs (Edelson & Krolik, 1988)

Flare 1

Flare 2

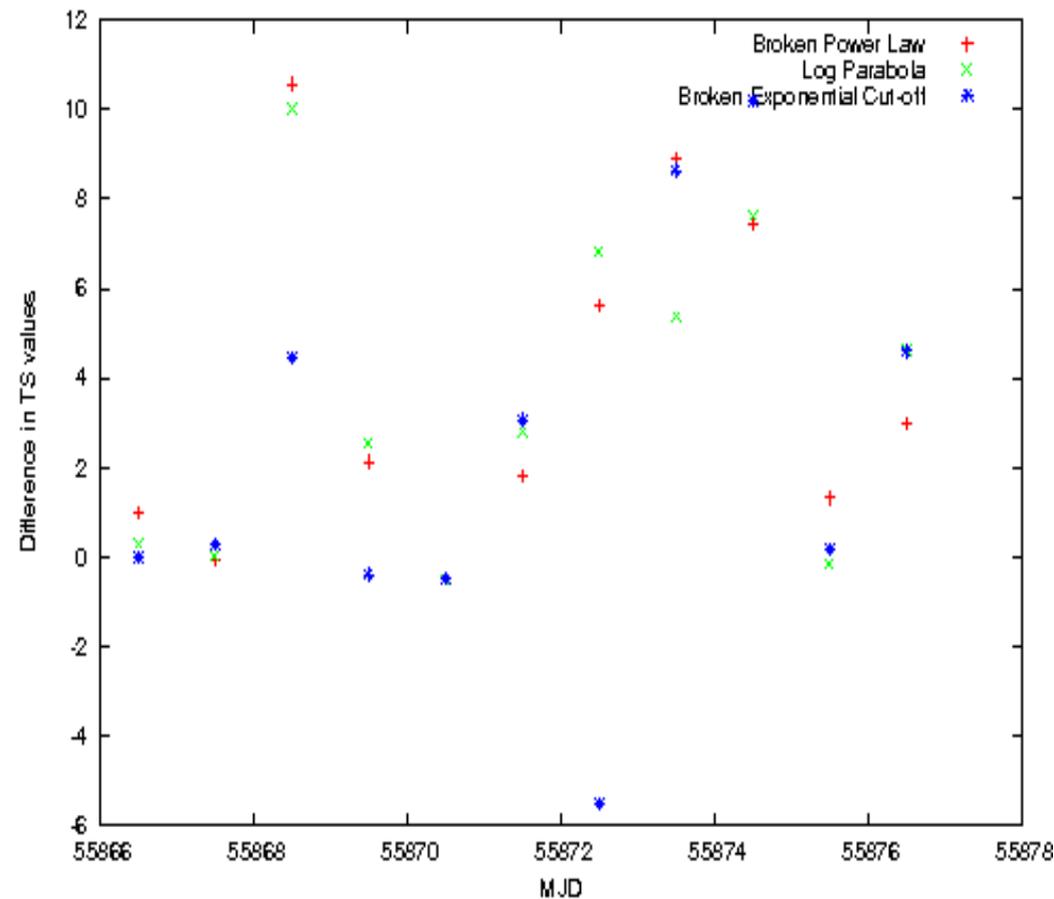
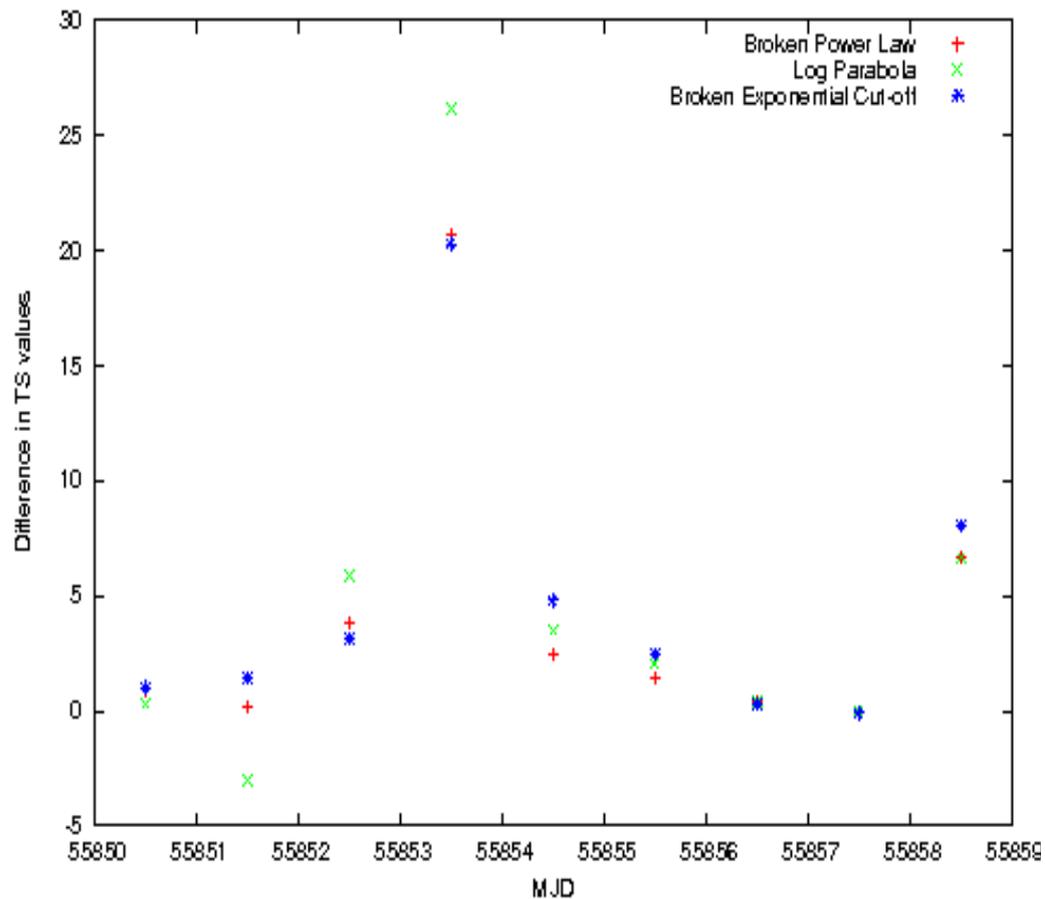


A positive time lag implies that the $< 1 \text{ GeV}$ flux is delayed with respect to the $> 1 \text{ GeV}$ flux \Rightarrow points to a MT origin

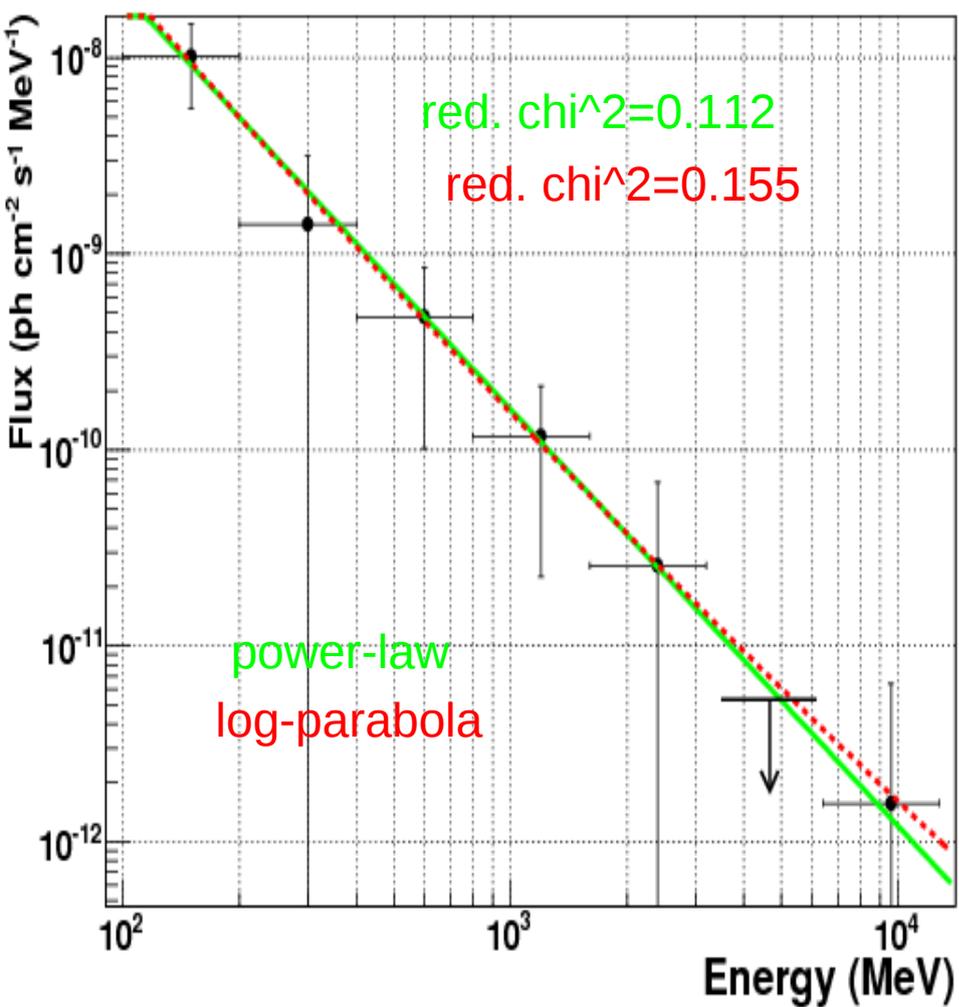
Locating the emission region...

(iii) Photon-photon pair production

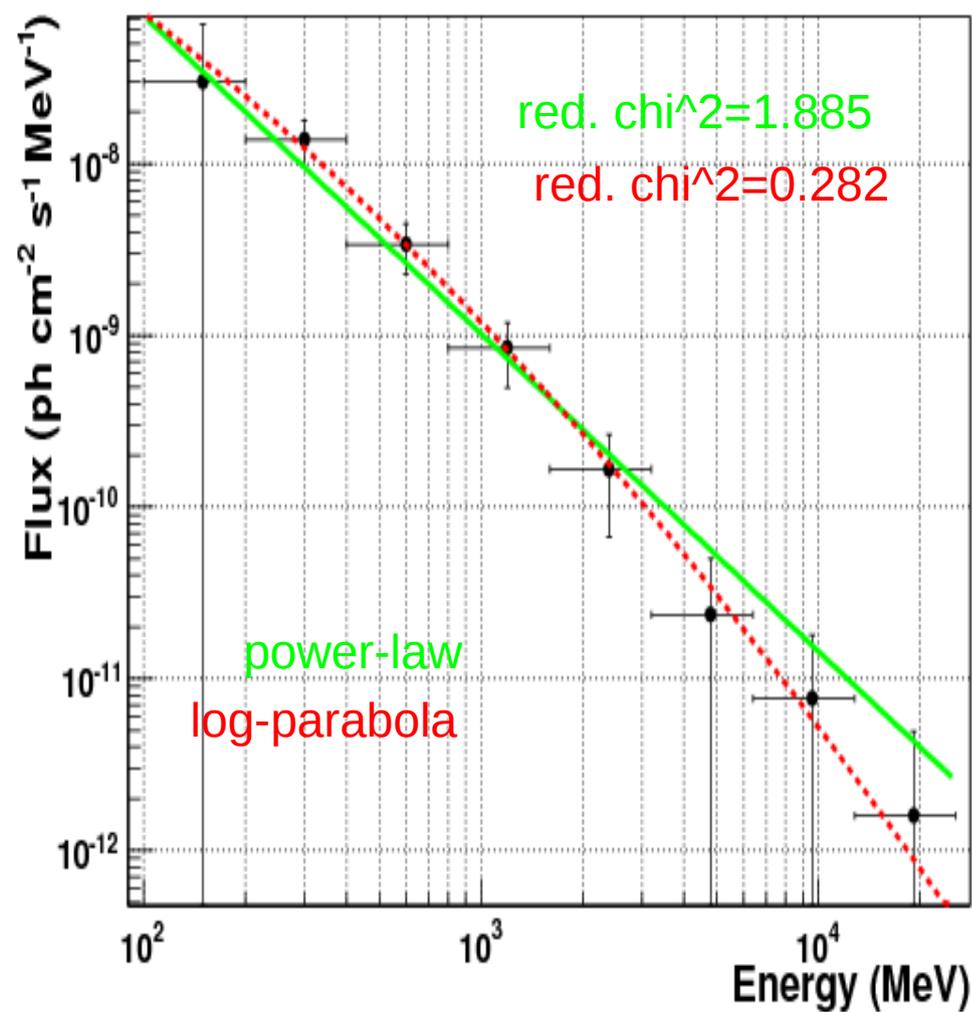
Re-analysed flares with additional spectral models containing cut-offs. Compared to the TS value of a power-law fit to investigate presence of a cut-off



Flare 1 start



Flare 1 Peak



Flare 1

- * spectral cut-off
- * possible DCF peak at 0 but errors too large
- * suggests a BLR origin for flare

Flare 2

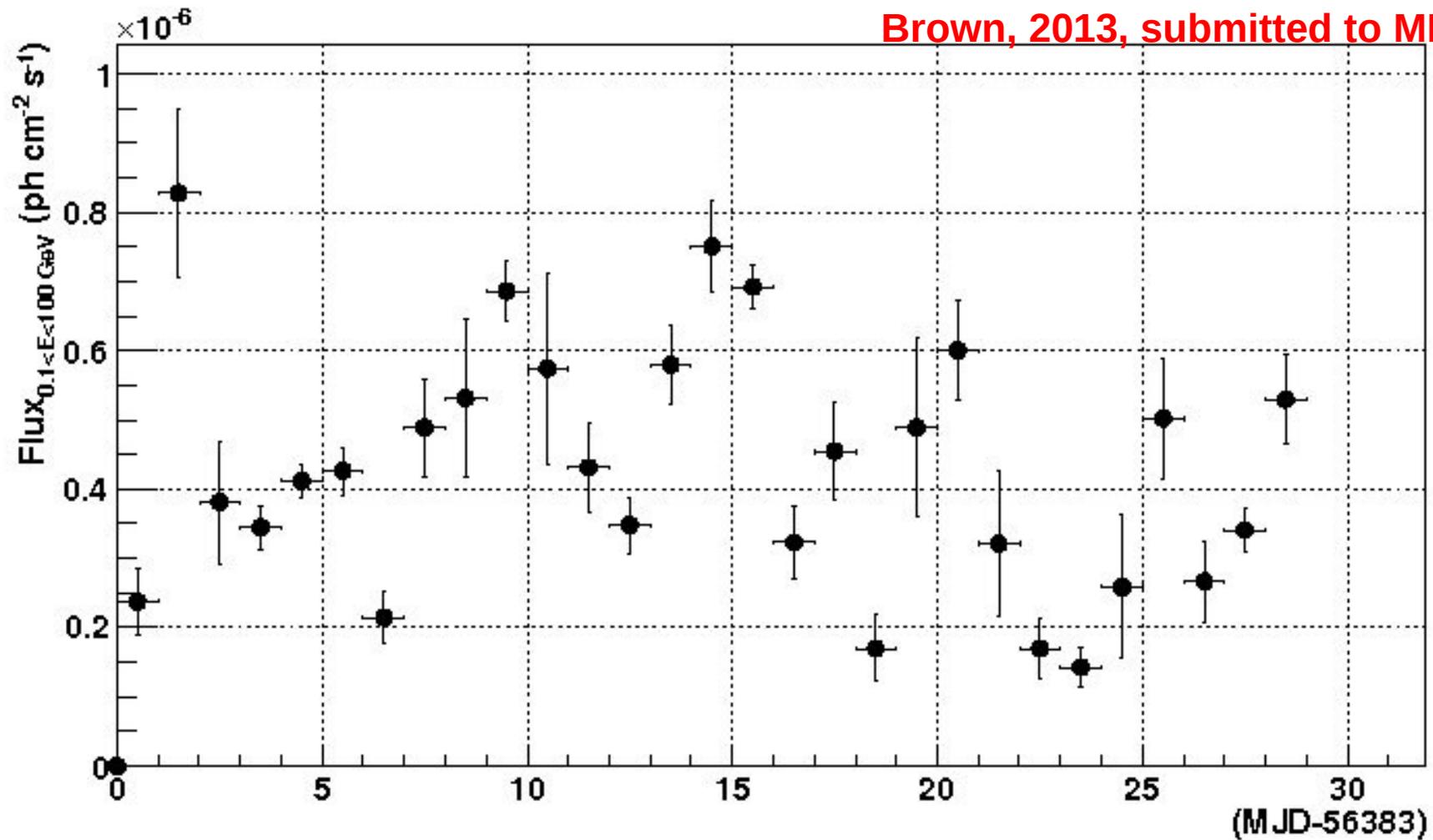
- * no spectral cut-off
- * DCF appears to be dominated by rise-time lag
- * suggests an MT origin for flare

Multi-zone emission regions

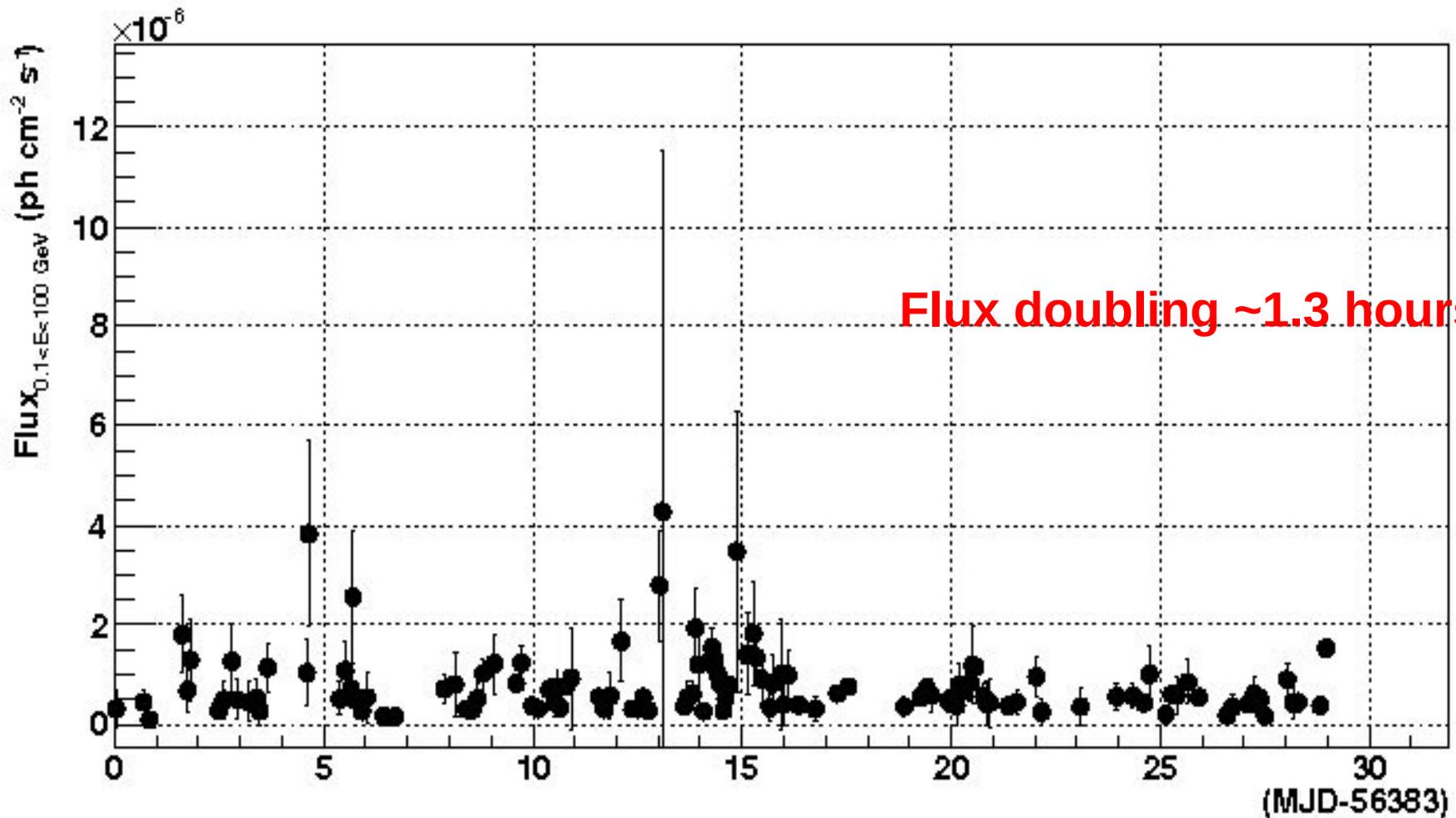
- * 2 flares 8 days apart, evidence to suggest that they are separated by $>$ parsec
- * can be reconciled if there are multiple simultaneously active emission regions along jet
- * also accounts for the $>$ 20 GeV flux (no trend in the hardness ratio and $>$ 20 GeV flux possibly also suggesting multi-zone)

Markarian 421 (HBL)

Brown, 2013, submitted to MNRAS



Markarian 421 (HBL)



Interesting because the flux was an order of magnitude lower than the PKS1510 flare, and yet we see 1.3 hr doubling. I.e., finding quick variability is not necessarily flux dependant

NGC1275

- Harder when brighter
- GeV flux important for VHE emission
- 1.5 day rise-time

Pictor A

- Discovered as a source of gamma-rays
- SSC modeling suggests jet origin
- 1.5 day rise-time

PKS 1510-089

- Flux doubling in 1.3 hours!
- Flux halving in 1.2 hours!
- Spectral cut-off in one flare, not the other
- MULTIPLE EMISSION REGIONS