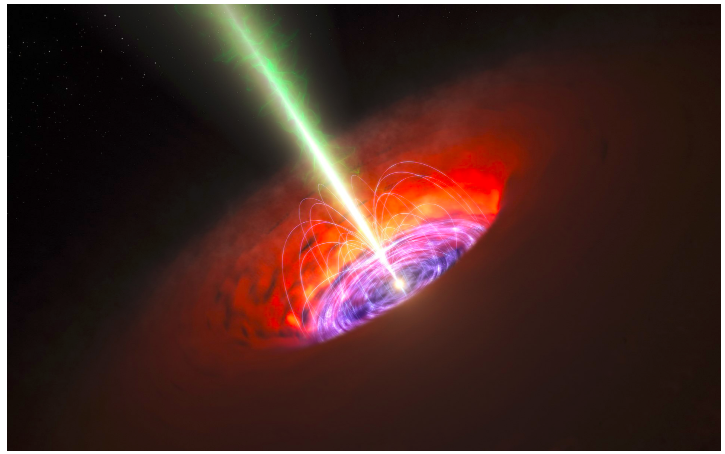
Fermi Gamma-ray Space Telescope

INAF Istituto di Radioastronomia



Jet physics of gamma-ray-emitting narrow-line Seyfert 1 galaxies

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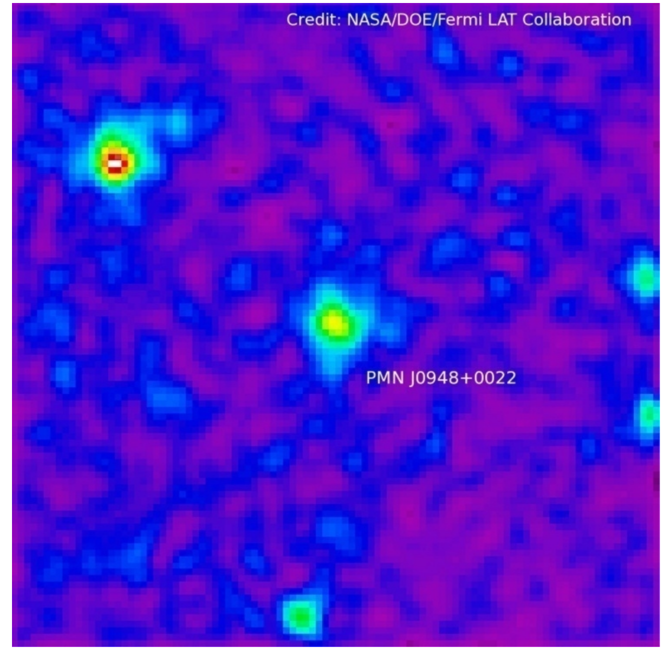
Gamma-ray-emitting NLSy1

- *Fermi*-LAT observations have shown that the known extragalactic γ-ray sky is dominated by blazars and a few radio galaxies (e.g. 4LAC, Ajello et al. 2020, ApJ, 892, 105).

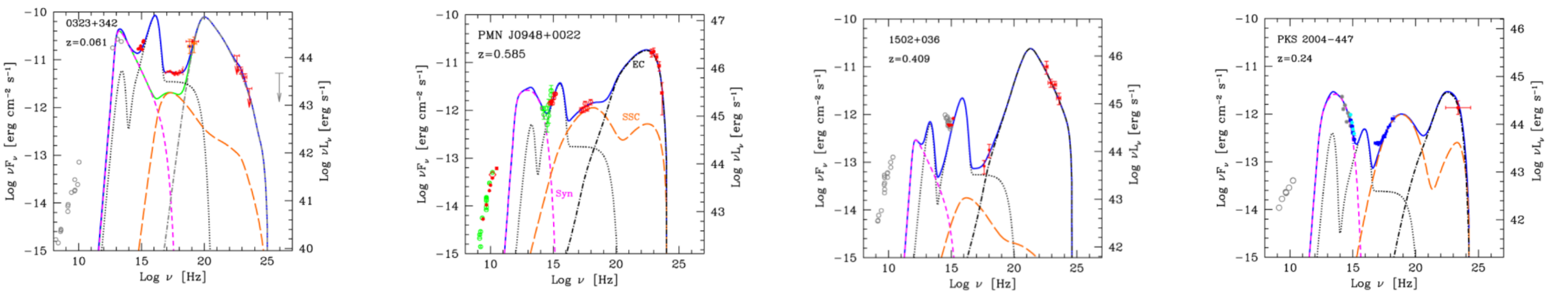
- In this context, the detection in γ rays of a narrow-line Seyfert 1 galaxies was a great surprise that confirmed the **presence of relativistic jets** in this class of AGN!



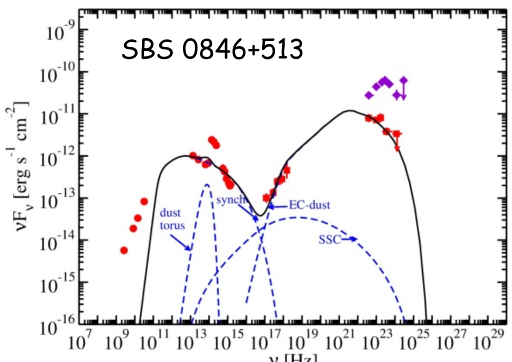
NLSy1 are thought to be hosted in spiral/disc galaxies, with **BH mass of 10^6-10^7 $M_\odot$** and high accretion rate. The presence of a relativistic jet in some of these objects seems to be in contrast to the paradigm that the formation of relativistic jets could happen only in the most massive BH in elliptical galaxies (e.g., Boettcher & Dermer 2002, Marscher 2010)

Narrow-line Seyfert 1 in the 4FGL

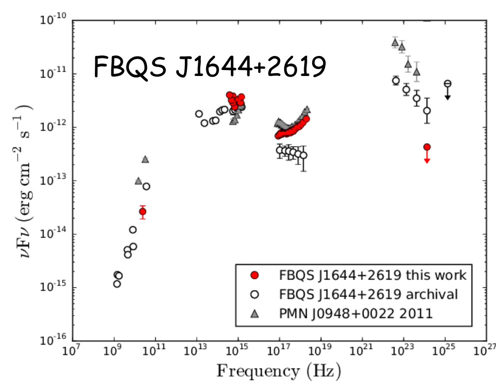
8 bona-fide NLSy1 were reported in the 4FGL



Abdo et al. 2009, ApJ, 707, L142



D'Ammando et al. 2012, MNRAS, 426, 317



Larsson et al. 2018, MNRAS, 476, 43

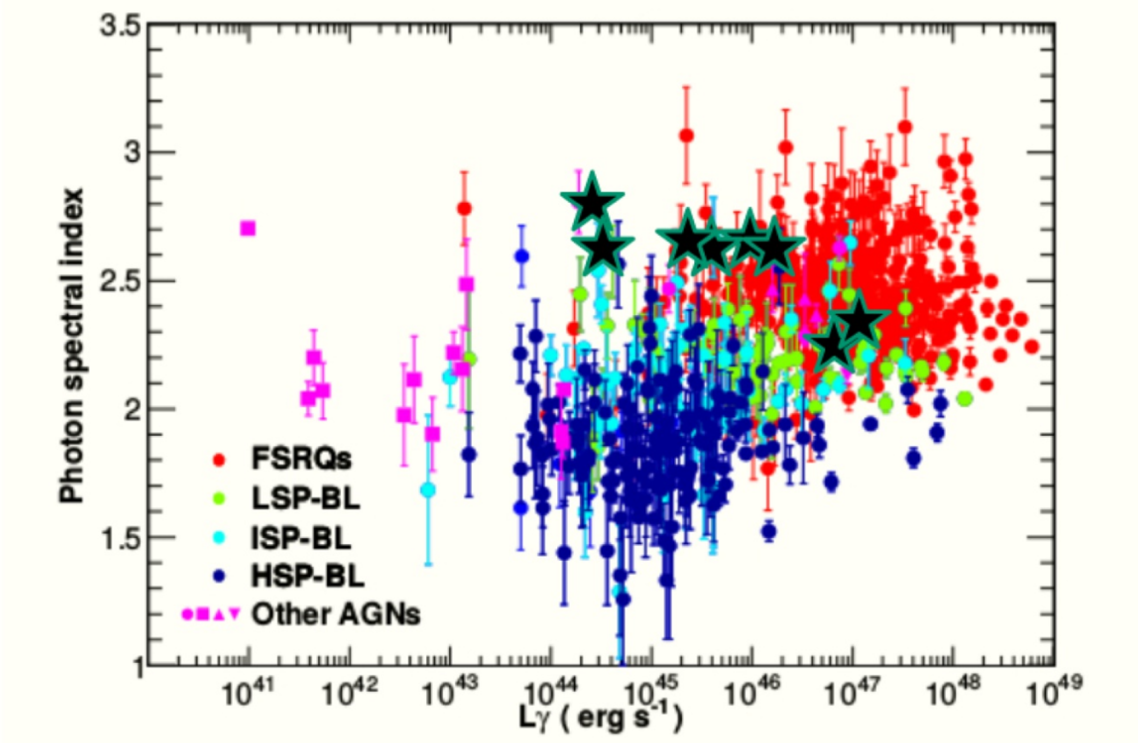
B3 1441+476
(D'Ammando et al. 2016, Galaxies, 4, 11)

IERS 1305+515
(Abdollahi et al. 2020, ApJS, 247, 33)

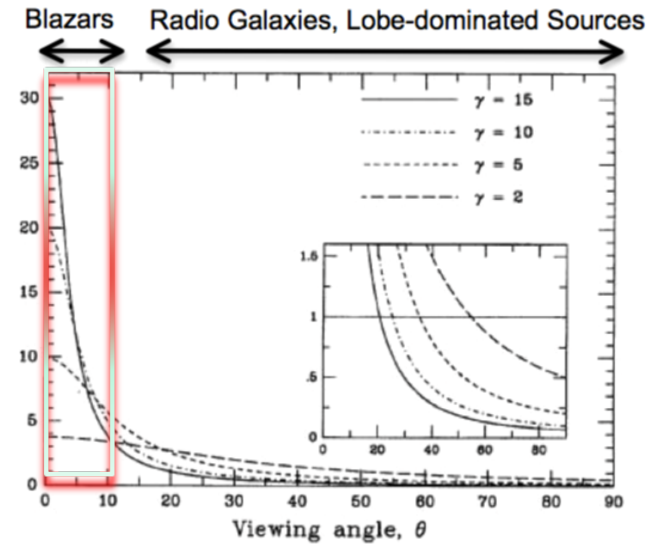
TXS 2116-077 classified as a NLSy1 in the 4FGL has been re-classified as an intermediate-type Seyfert galaxy based on new high-quality spectroscopic data (Jarvela et al. 2020, A&A, 636L, 12)

The *Fermi*-LAT view of NLSy1

Adapted from Ackermann et al. (2015)



D'Ammando et al. 2016, Galaxies, 4, 11

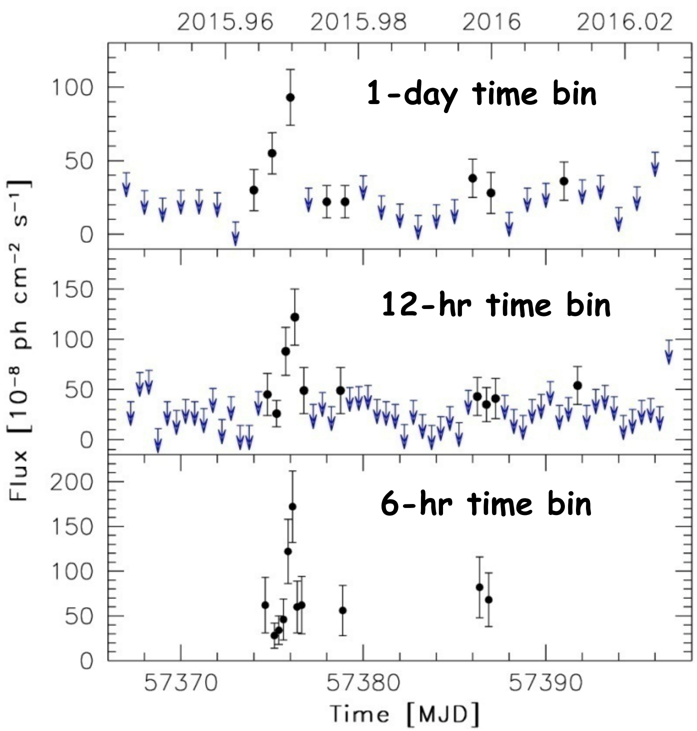


Urry & Padovani 1995

blazar-like properties of γ-ray-emitting NLSy1

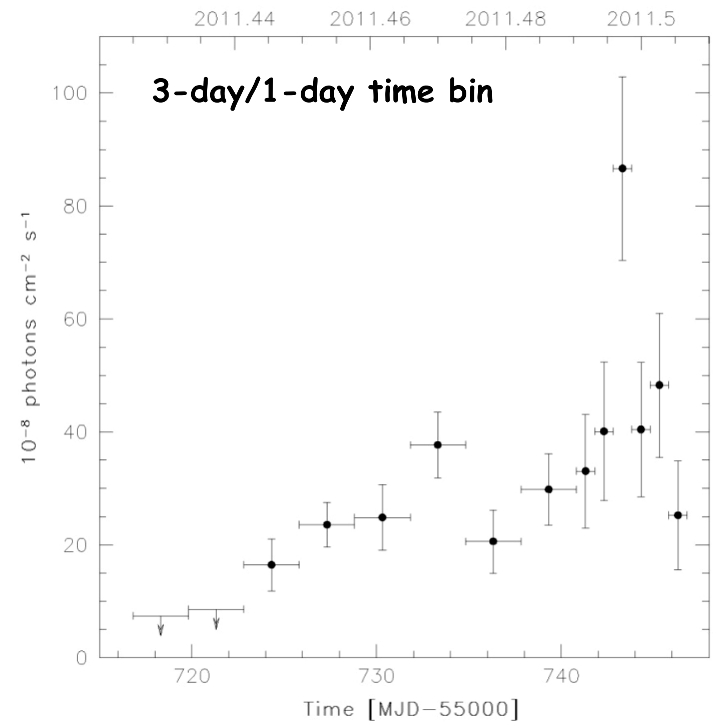
NLSy1 are flaring γ-ray sources!

PKS 1502+036



D'Ammando et al. 2016, MNRAS, 463, 4469

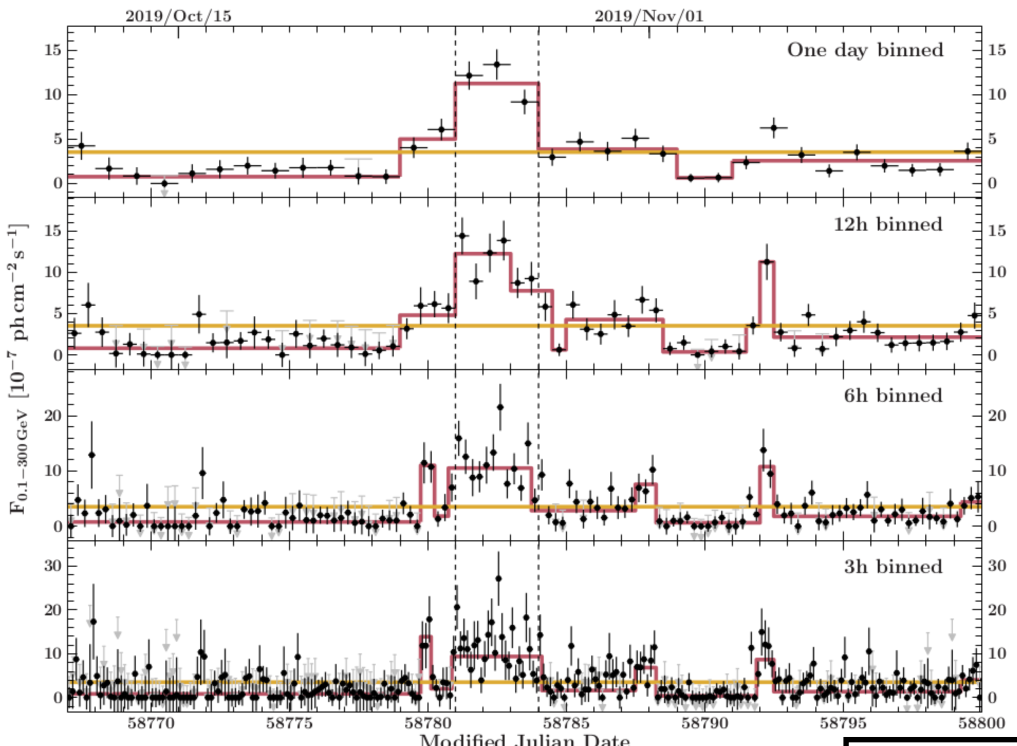
SBS 0846+513



D'Ammando et al. 2012, MNRAS, 426, 317

PKS 1502+036, SBS 0846+513, PMN J0948+0022 showed different flaring episodes with an apparent isotropic γ-ray luminosity of ***~10^{48} erg s^{-1}, comparable to that of the bright FSRQ.***

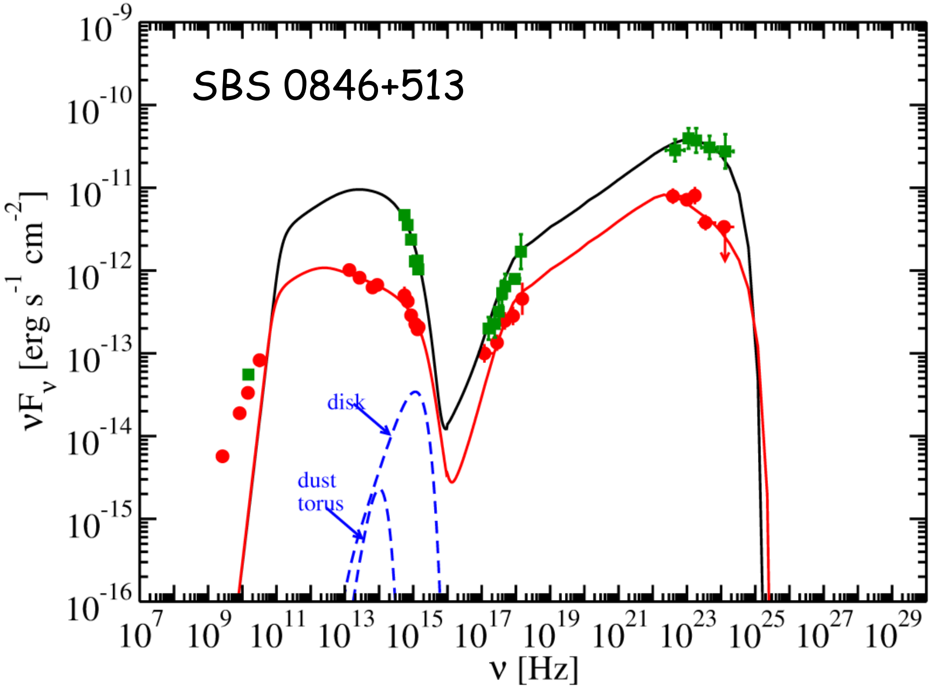
Rapid γ-ray flare from PKS 2004-447



Gokus et al. 2021, arXiv:2102.11633

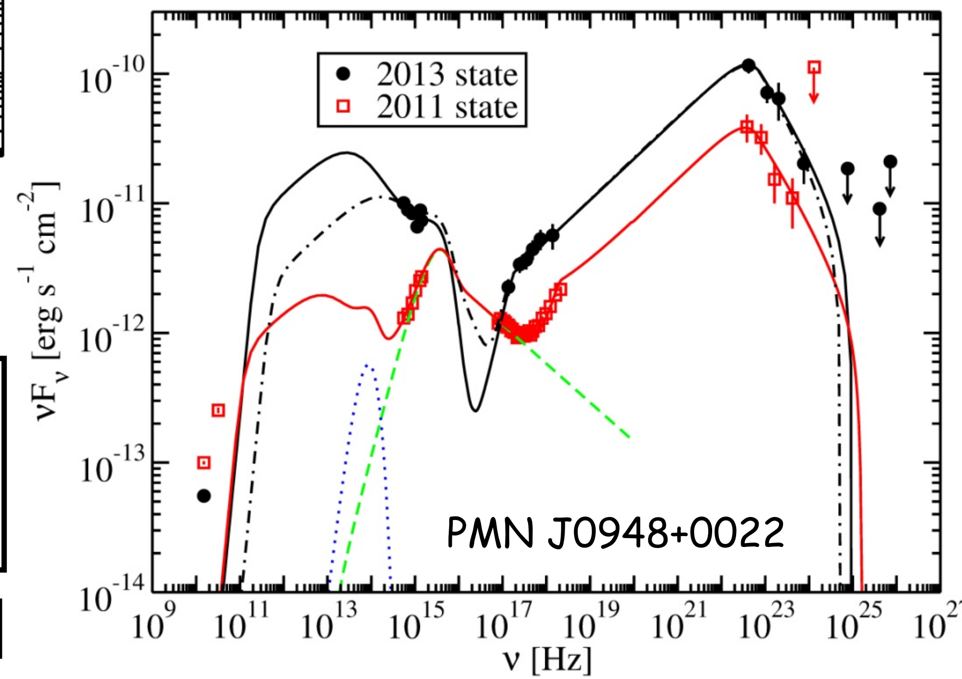
A rapid flaring activity has been observed on 3-hr time-scale for PKS 2004-447 in 2019 October, with flux doubling times as short as 2.2 hours at a 2.8σ level. Short-term variability on sub-daily time-scale has been observed also for 1H 0323+342 (Paliya et al. 2014) and PKS 1502+036 (D'Ammando et al. 2016).

SED modelling of NLSy1



The quiescent and flaring state, modelled by EC (dust), could be fitted by changing the electron distribution parameters as well as the magnetic field

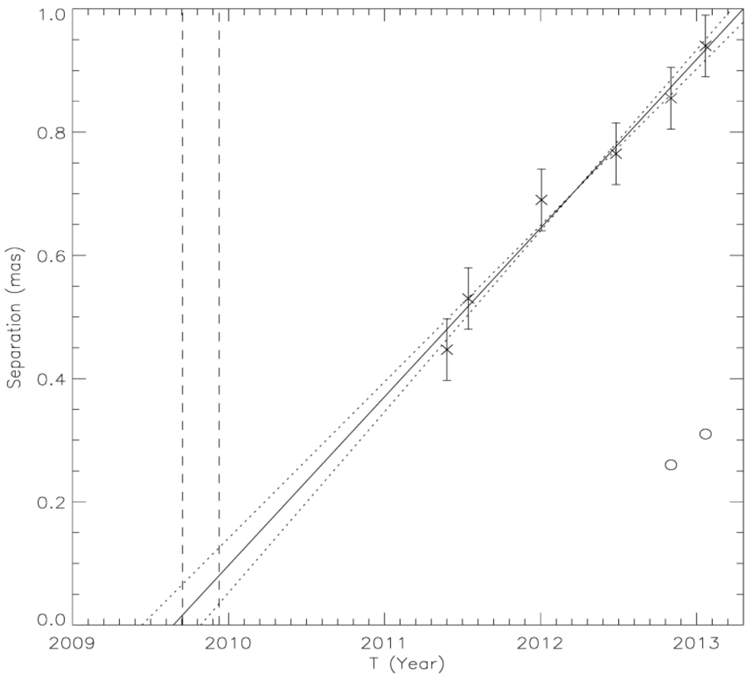
D'Ammando et al. 2013b



The 2013 flaring state may be modelled by EC (dust) or EC (BLR). In the latter, the source is far from the equipartition favouring the EC (dust) model.

D'Ammando et al. 2015

Proper motion of γ-ray-emitting NLSy1



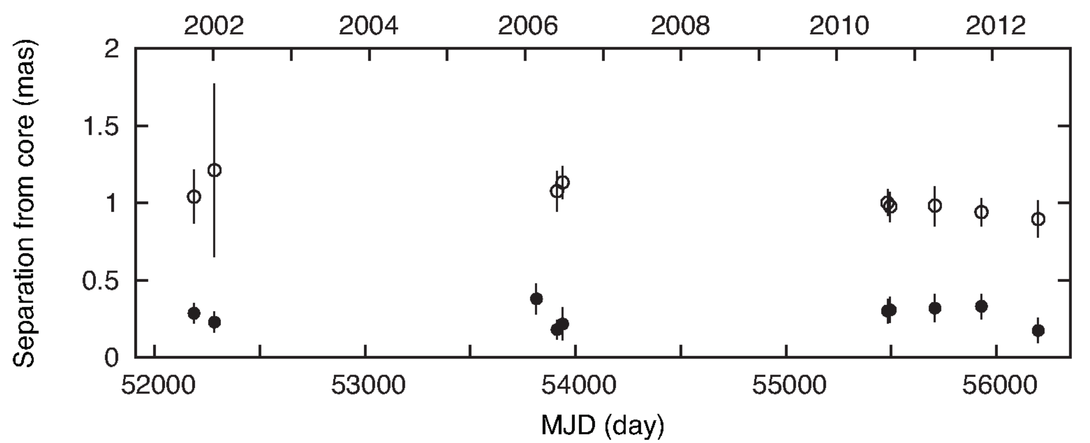
With 6-epoch MOJAVE data for SBS 0846+513 we obtained an apparent velocity of the jet knot **(9.3±0.6)c**, indicating **the presence of boosting effect as well as in blazars**. The time of ejection is **T_0 = 24 August 2009**, likely connected with a radio flare. *No significant γ-ray activity was detected in that period.*

D'Ammando et al. 2013b, MNRAS, 436, 191

Superluminal motion was detected also in 1H 0323+342 and PMN J0948+0022 (Lister et al. 2016, AJ, 152, 12).

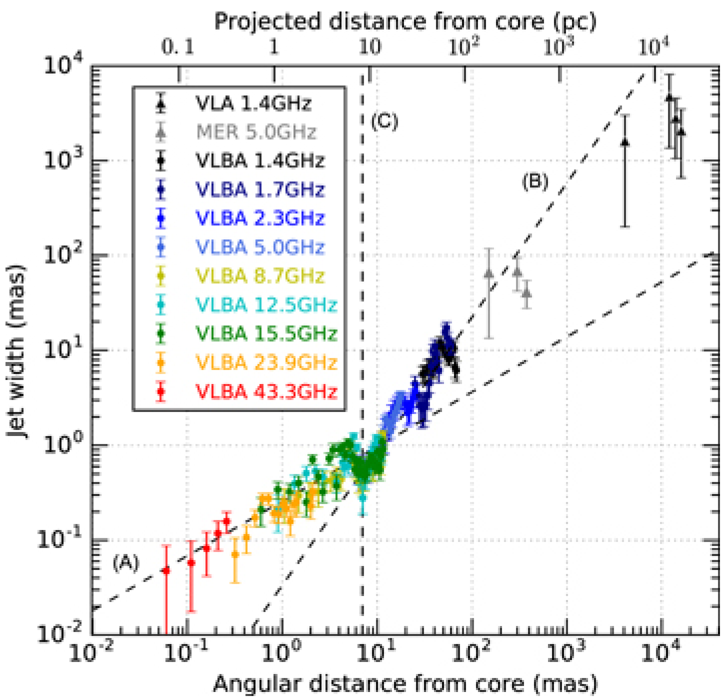
No superluminal motion was detected for the jet components of PKS 1502+036. A sub-luminal component was reported in Lister et al. (2016).

D'Ammando et al. 2013a, MNRAS, 433, 952



VLBA observations of 1H 0323+342

Detailed nine-frequency VLBA observations of the jet in the nearest γ-ray-emitting NLSy1 1H 0323+342 from 1.4 GHz to 43 GHz



Hada et al. 2018, MNRAS, 860, 141

- the morphology of the inner jet is well characterized by a parabolic shape, indicating that the jet is continuously collimated near the jet base up to 7 mas (where a bright stationary feature is located).
- the jet expands more rapidly at larger scales, resulting in a conical shape.
- the collimation region is coincident with the region where the jet speed gradually accelerates, suggesting a *coexistence of the jet acceleration and collimation zone*, ending up with **a recollimation shock, potential site of γ-ray flares**.
- the core shift is small between 1.4 and 43 GHz, in agreement with **a viewing angle of 4-12°**

Host galaxy of γ-ray-emitting NLSy1

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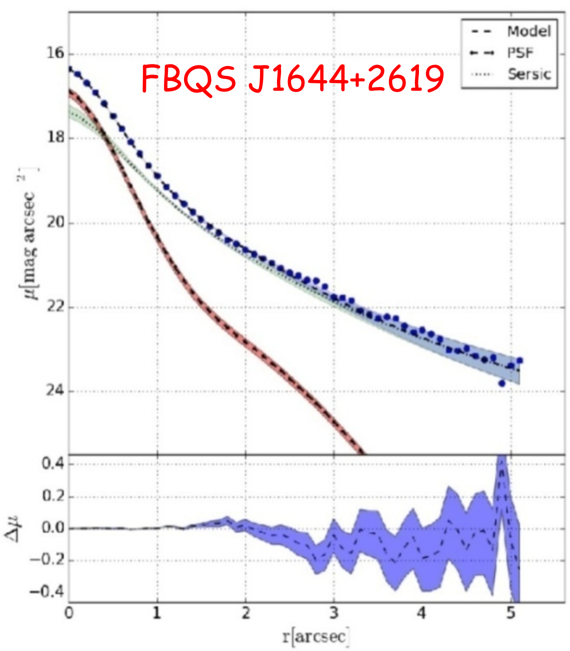
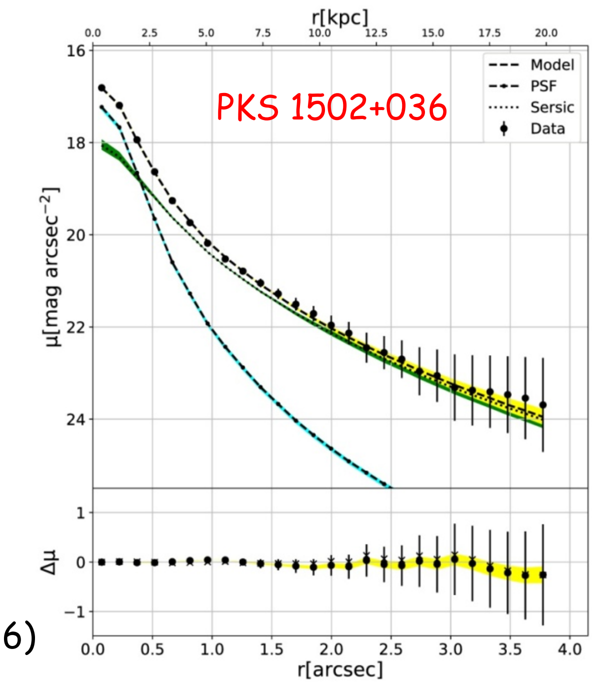
- *1H 0323+342* : **spiral-arm** structure of the host galaxy (Zhou et al. 2007) or asymmetric ring, residual of **a galaxy merger** (Anton et al. 2008, Leon Tavares et al. 2014)
- *PKS 2004-447* : **pseudo-bulge morphology** of the host (Kotilainen et al. 2016)
- *SBS 0846+513* : although not conclusive, **a slight preference for a spiral host** over an elliptical one has been obtained (Hamilton et al. 2020)



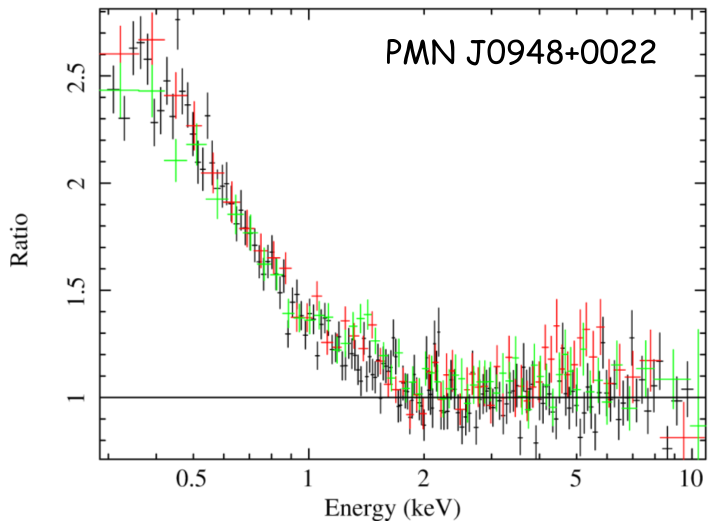
D'Ammando+17 (MNRAS, 469, L11)

D'Ammando+18 (MNRAS, 478, L66)



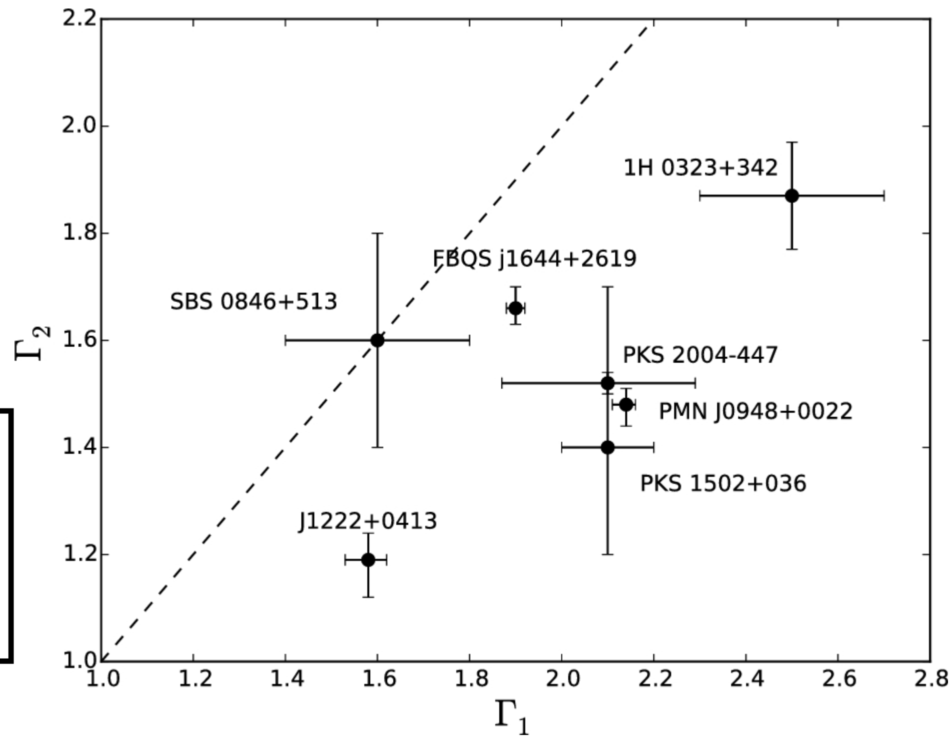
The 2D surface brightness profile of FBQS J1644+2619 and PKS 1502+036 in IR is modelled by a nuclear and a bulge component with *n* = 3.5 and *n* = 3.7, respectively. **Evidence of an E1 elliptical galaxy as host galaxy.** The BH mass estimated by the IR bulge luminosity is **$(2.1\pm0.2)\times10^{8}$ $M_{\odot}$** and **$\sim7\times10^{8}$ $M_{\odot}$**

The X-ray view of γ-ray-emitting NLSy1



D'Ammando et al. 2014, MNRAS, 438, 3521

Notwithstanding the relativistic jet emission, a clear soft X-ray excess is observed in PMN J0948+0022. This feature has been observed only in a few bright blazars (e.g. 3C 273, Page et al. 2004)

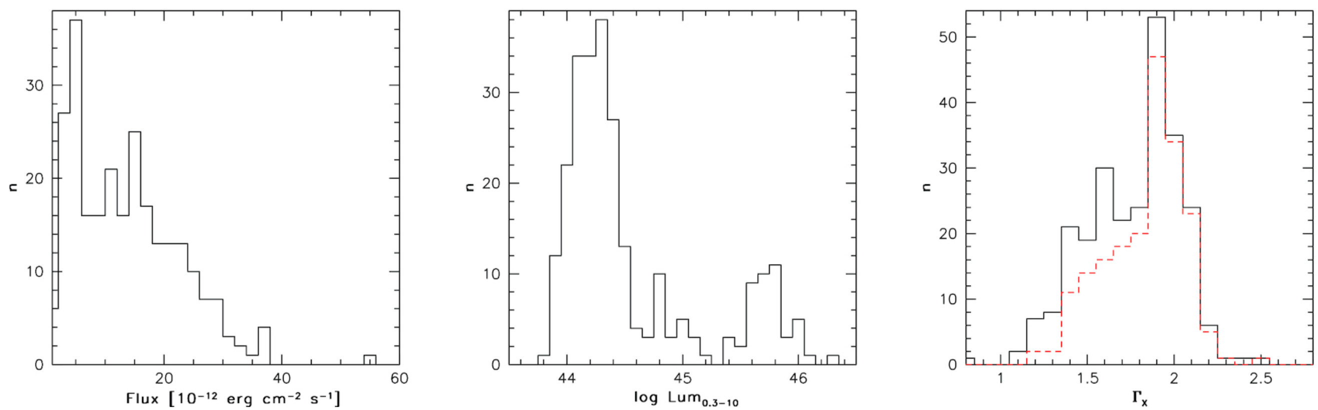


Larsson et al. 2018, MNRAS, 476, 43

The majority of γ-ray-emitting NLSy1 have hard spectra above 2 keV, a soft excess at lower energies, and no evidence for intrinsic absorption

The *Swift* view of γ-ray-emitting NLSy1

Systematic analysis of all *Swift* (XRT and UVOT) observations of the 8 γ-ray-emitting NLSy1 from 2006 July to 2019 April

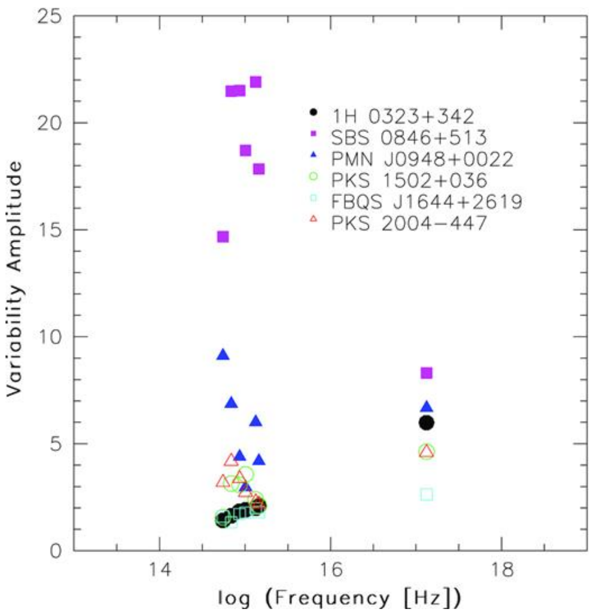


D'Ammando 2020a, MNRAS, 496, 2213

- The distribution of X-ray luminosities indicates that the jet radiation significantly contributes to their X-ray emission, with Doppler boosting making values higher than other radio-loud NLSy1 and comparable to the luminosities of blazars in the same range of redshift.

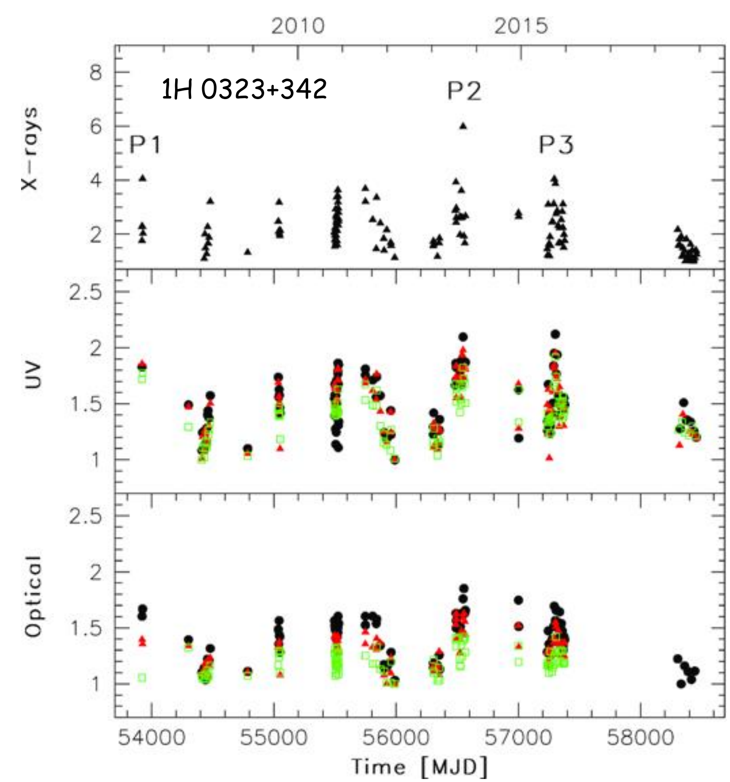
- The 0.3–10 keV photon indices are on average harder with respect to radio-quiet and radio-loud NLSy1, confirming a dominant jet contribution in X-rays

The *Swift* view of γ-ray-emitting NLSy1



The relatively lower variability amplitude observed in X-rays with respect to blazars is an indication that, even if the jet emission produces the dominant contribution, also the corona radiation can be responsible for the X-ray emission in γ-ray-emitting NLSy1.

D'Ammando 2020a



A strong correlation between X-ray, UV, and optical emission and simultaneous flux variations have been observed in 1H 0323+342, SBS 0846+513, PMN J0948+0022, as expected in case the jet radiation is the dominant mechanism.

Correlated multi-band variability favours the jet-dominated scenario also in FBQS J1644+2619 and PKS 2004−447.

Rapid X-ray variability episodes

- **Rapid variability in X-rays** has been found for **1H 0323+342**, **FBQS J1644+2619**, and **PKS 2004−447** with time-scales varying between ~6 ks and ~22 ks, suggesting that the emission is produced in compact regions within the jet, although we cannot ruled that these events are related to changes in accretion rate or in the disc–corona structure in the context of thermal Comptonization from the corona, in particular for *FBQS J1644+2619*.

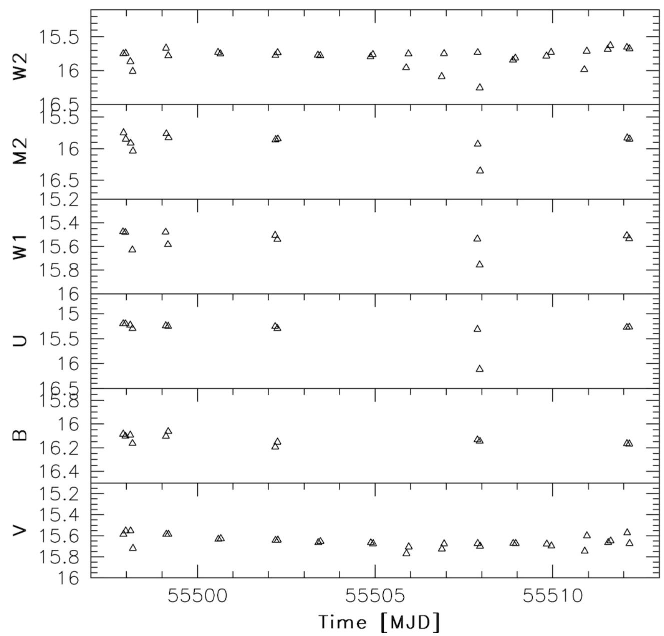
- For *1H 0323+342* the X-ray flaring episode happened **simultaneously to a γ-ray flare**, confirming unambiguously as the **jet** be the origin of this episode.

- In case of *PKS 2004−447* **no clear evidence of Seyfert-like features** (i.e. soft excess, Iron line) has been identified in its X-ray spectrum disfavouring the disc–corona emission as dominant mechanism.

Systematic analysis of single UVOT exposures

- Rapid variability has been significantly (> 3σ) detected on hours time-scale for **1H 0323+342**, **SBS 0846+513**, **PMN J0948+0022**, **and PKS 2004−447** in 18 observations for a total of **34 events**.

- First detection of significant variability on short time-scale **(3–6 ks)** in optical for *PKS 2004-447*, and UV for *1H 0323+342* and *PMN J0948+0022*.



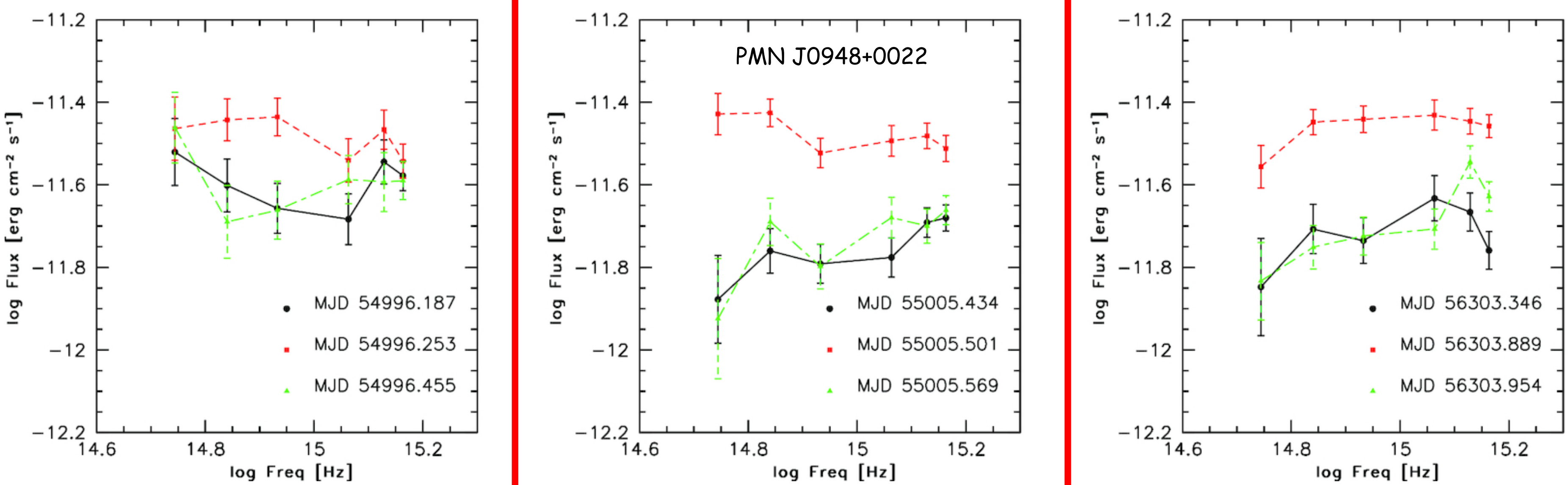
1H 0323+342

All UVOT exposures were checked for possible small scale sensitivity problems

D'Ammando 2020b, MNRAS, 498, 859

- The shortest variability time-scale observed (assuming a Doppler factor δ = 10) gives a lower limit on the size of emission region between **9.7 × 10^{14}** (for SBS 0846+513) and **1.6 × 10^{15} cm** (for 1H 0323+342), suggesting that the optical and UV emission during these events is produced in compact regions within the jet.

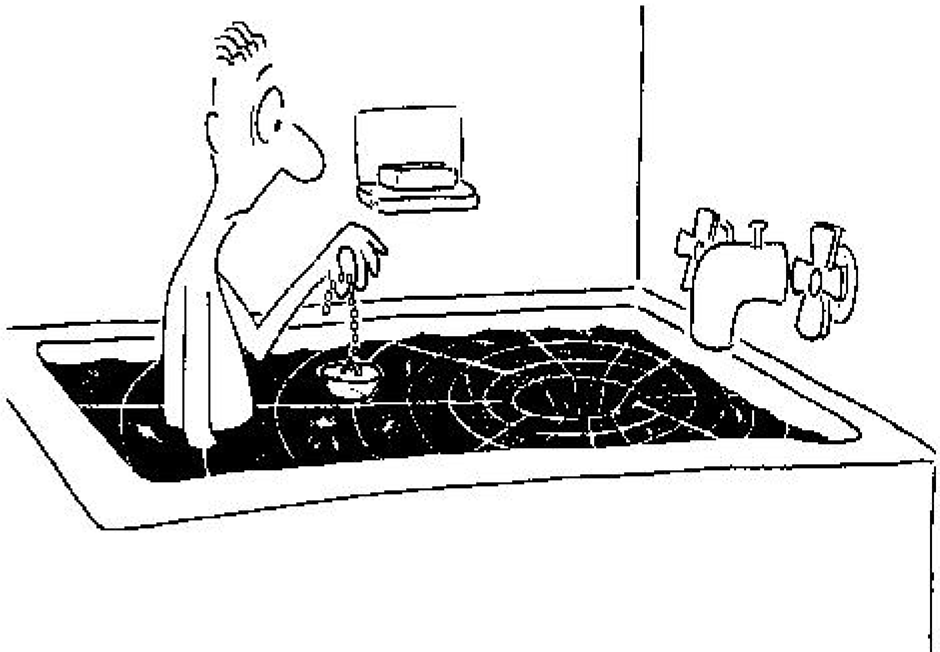
Systematic analysis of single UVOT exposures



D'Ammando 2020b

- A remarkable variability has been observed for PMN J0948+0022 on 2009 June 23 with **an increase from ~1.1 to 0.4 mag** going from v to w2 filter in **~1.6 h** and a decrease at the initial level in a comparable time

- The higher fractional flux change observed for this and other events at lower frequencies suggests that the synchrotron emission is more contaminated by thermal emission from accretion disc at higher frequencies

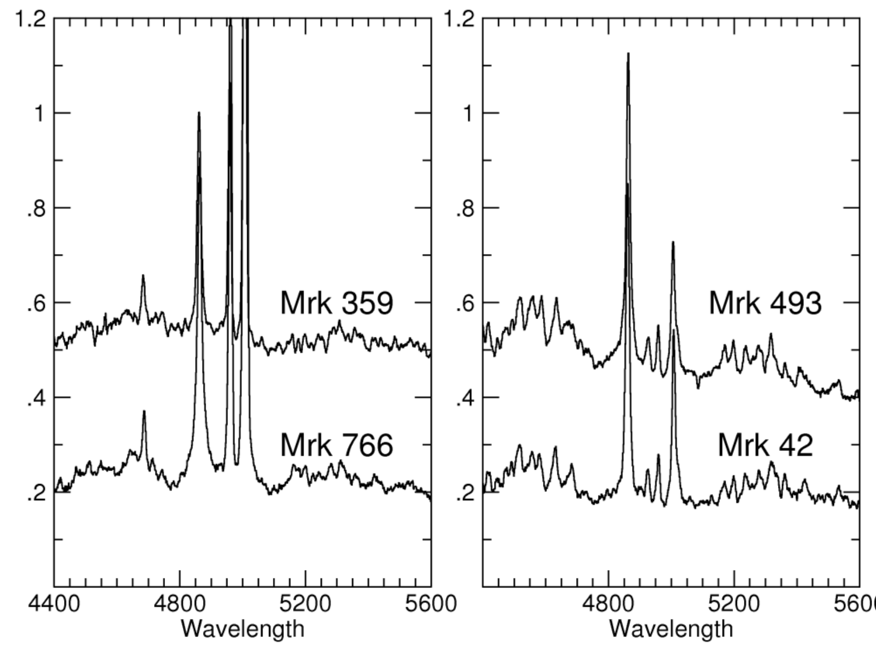


Thanks for your attention


DIRECTOR'S CUT

Narrow-Line Seyfert 1 galaxies

- Optical classification:
  - FWHM (Hβ) < 2000 km s^{-1} (NL)
  - [O III] λ5007/Hβ < 3 (Sy1)



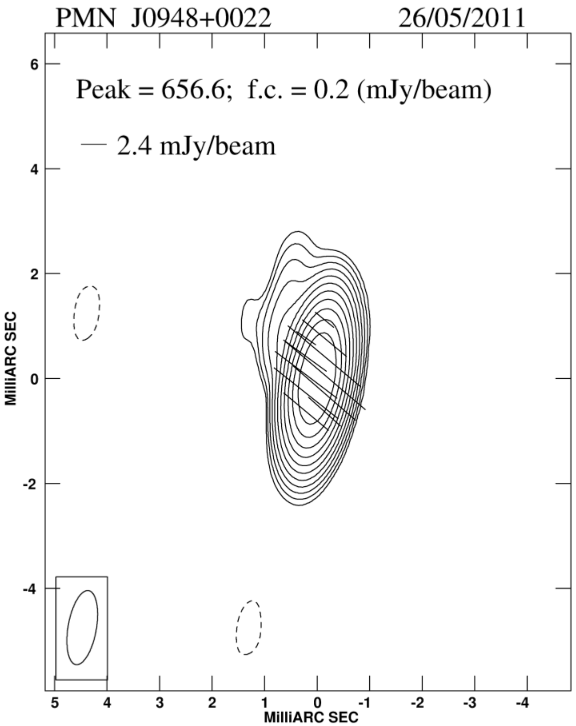
Osterbrock & Pogge 1985

- Other notable properties:
  - strong Fe II bump (Goodrich 1989)
  - relatively low BH masses (10^6-10^8 solar masses)
  - high accretion rates (up to Eddington limit)

Core-jet structures in γ-ray NLSy1

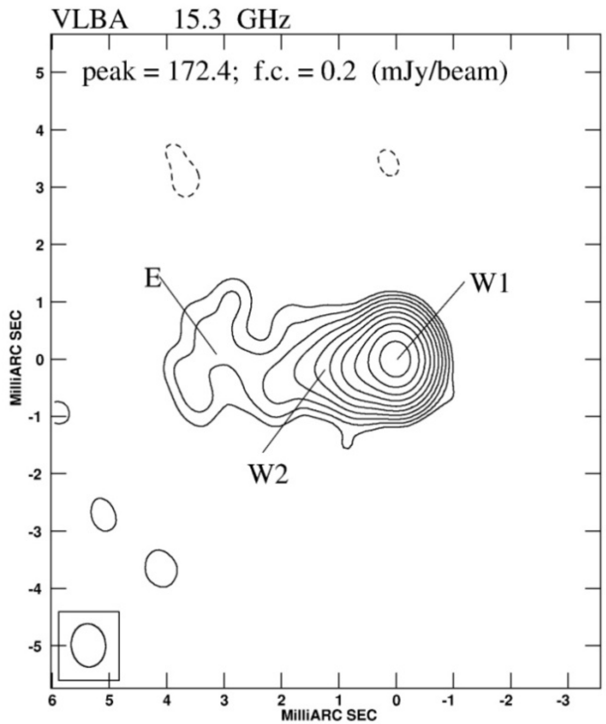
Core-jet structure on parsec scale resolved with the VLBA

PMN J0948+0022



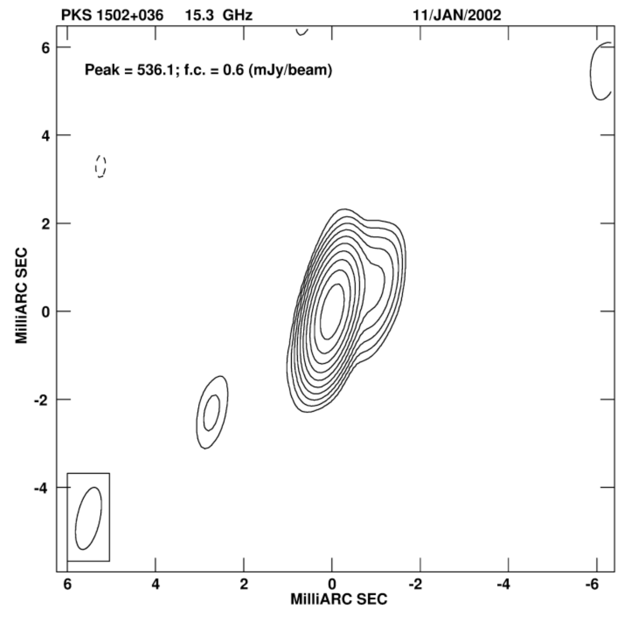
D'Ammando et al. 2014

SBS 0846+513



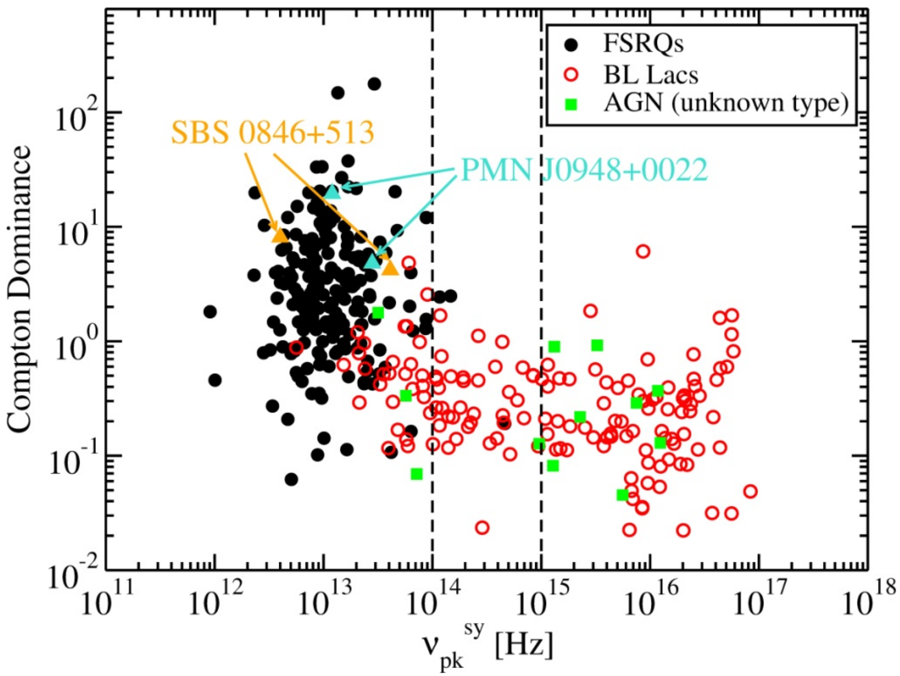
D'Ammando et al. 2012

PKS 1502+036



D'Ammando et al. 2013a

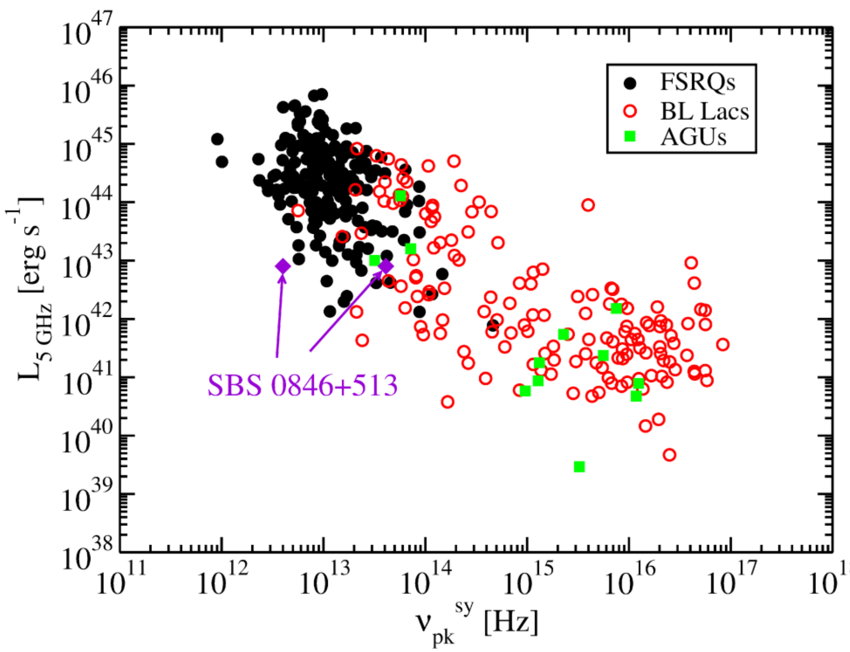
Comparison with γ-ray blazars



SBS 0846+513 and PMN J0948+0022 showed a Compton dominance typical of FSRQs during both the low and high activity state

D'Ammando et al. 2015

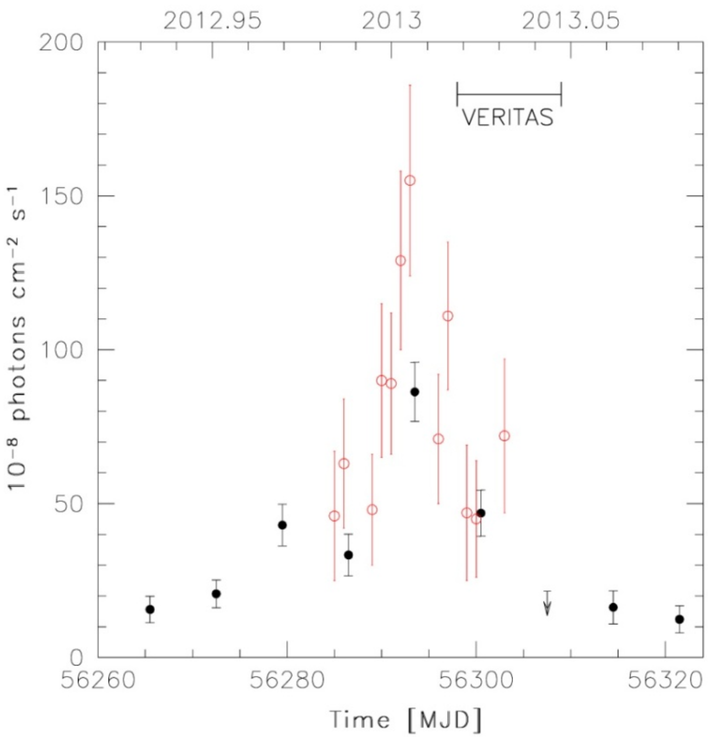
Figures adapted from Finke 2013

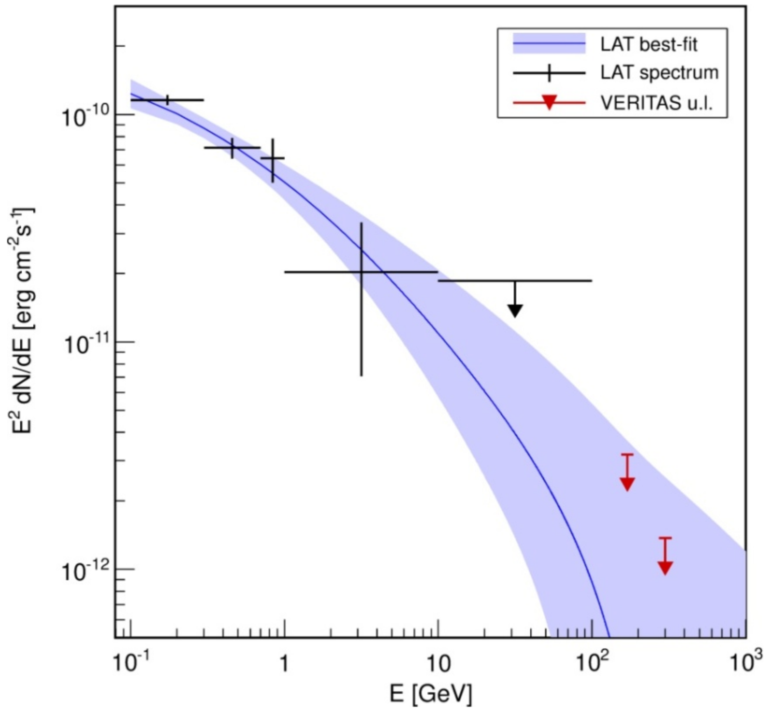


In the "classical" blazar sequence plot SBS 0846+513 seems to lie in the FSRQ region

D'Ammando et al. 2013b

NLSy1 as VHE emitting sources?



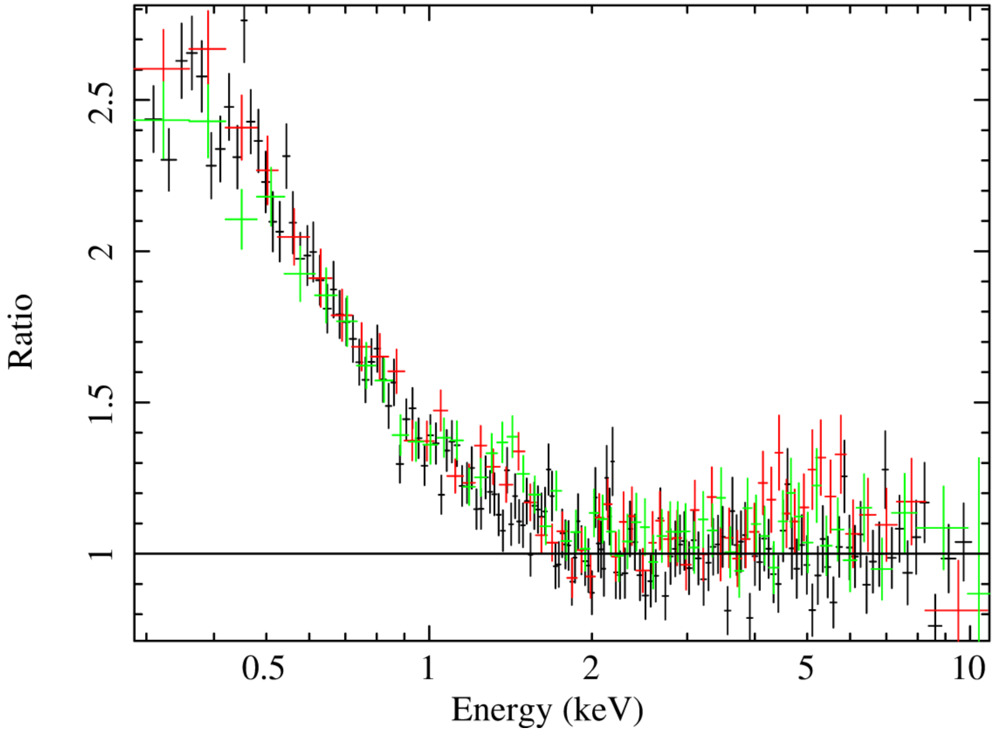


D'Ammando et al. 2015, MNRAS, 446, 2456

Following the most powerful flaring activity from PMN J0948+0022, the detection of VHE emission from this NLSy1 was attempted by VERITAS, resulted in an UL of $F_{> 0.2\ \mathrm{Tev}} < 4\times10^{-12}$ ph $cm^{-2}\ s^{-1}$. Up to now SBS 0846+513 is the only NLSy1 included in the 3FHL catalogue.

Flaring γ-ray emitting NLSy1 are good target for future CTA observations (see e.g. Romano et al. 2018, MNRAS, 481, 5046)

XMM observation of PMN J0948+0022



Γ = 1.88 ± 0.01 in the 0.3-10 keV energy range, χ^2_{red} = 1.87 (1254)

A simple power law in 2-10 keV provides a good fit Γ = 1.48±0.03

A clear soft excess was observed, notwithstanding the non-thermal jet emission!

D'Ammando et al. 2014

A broken power-law provides an acceptable fit, χ^2_{red} = 1.10 (1252), with a break at energy E_{break} = 1.72±0.10 keV and photon indices Γ_1= 2.14±0.03 and Γ_2 = 1.48±0.04. The emission above 2 keV is dominated by the jet component, with no detection of an Iron line in the spectrum and a 90% upper limit on the EW of 19 eV.

The soft component can be also fitted with a black body model with kT ~ 0.18 keV. Such a high temperature is inconsistent with the standard accretion disk theory.

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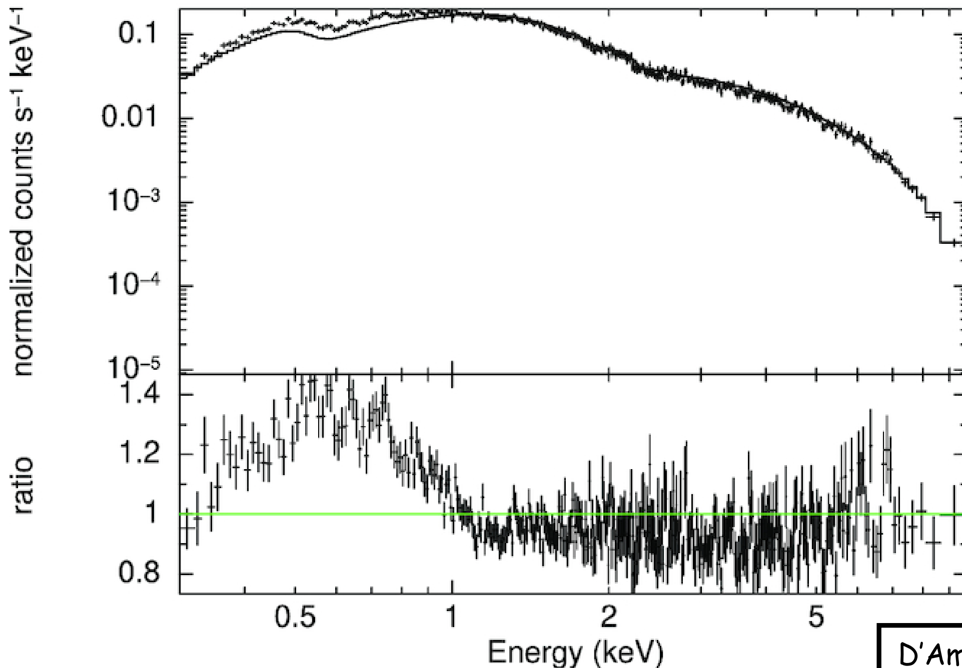
XRT summed spectrum of 1H 0323+342

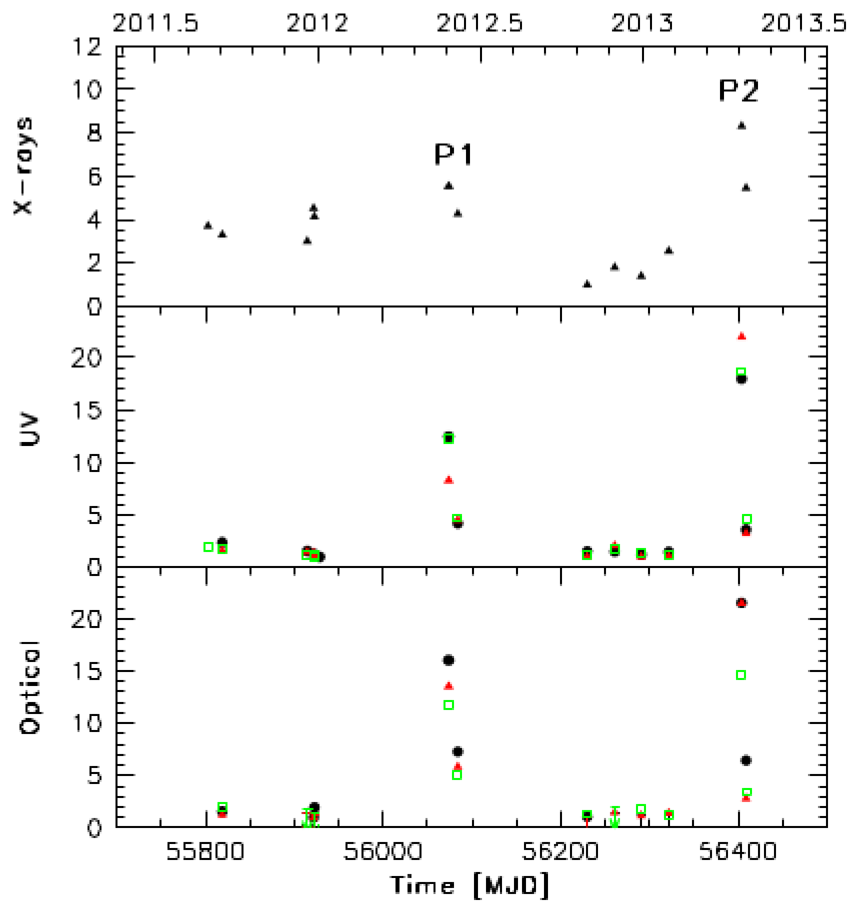


D'Ammando 2020a

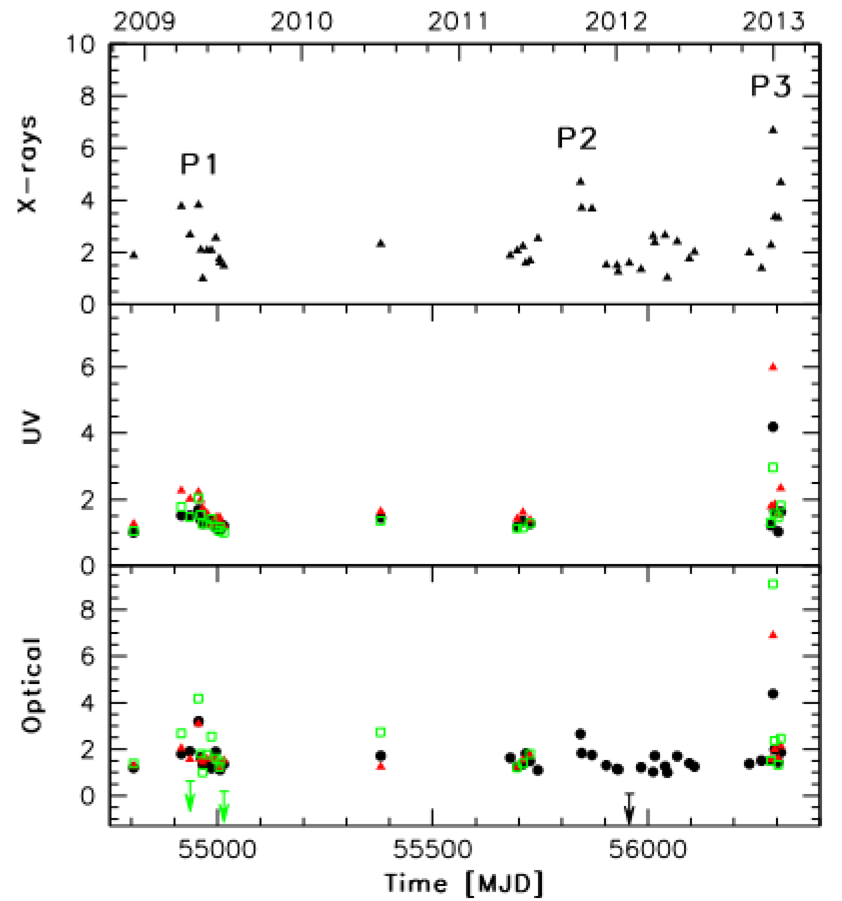
- The summed XRT spectra of 1H 0323+342, SBS 0846+513, PMN J0948+0022, and FBQS J1644+2619 are well fitted by a broken power law with a break around 2 keV
- The spectrum above 2 keV is dominated by the non-thermal emission from a beamed relativistic jet, as suggested by the hard photon index
- A Seyfert-like feature like the soft X-ray excess has been observed below 2 keV, making these γ-ray-emitting NLSy1 different from typical blazars

The *Swift* view of γ-ray-emitting NLSy1

SBS 0846+513

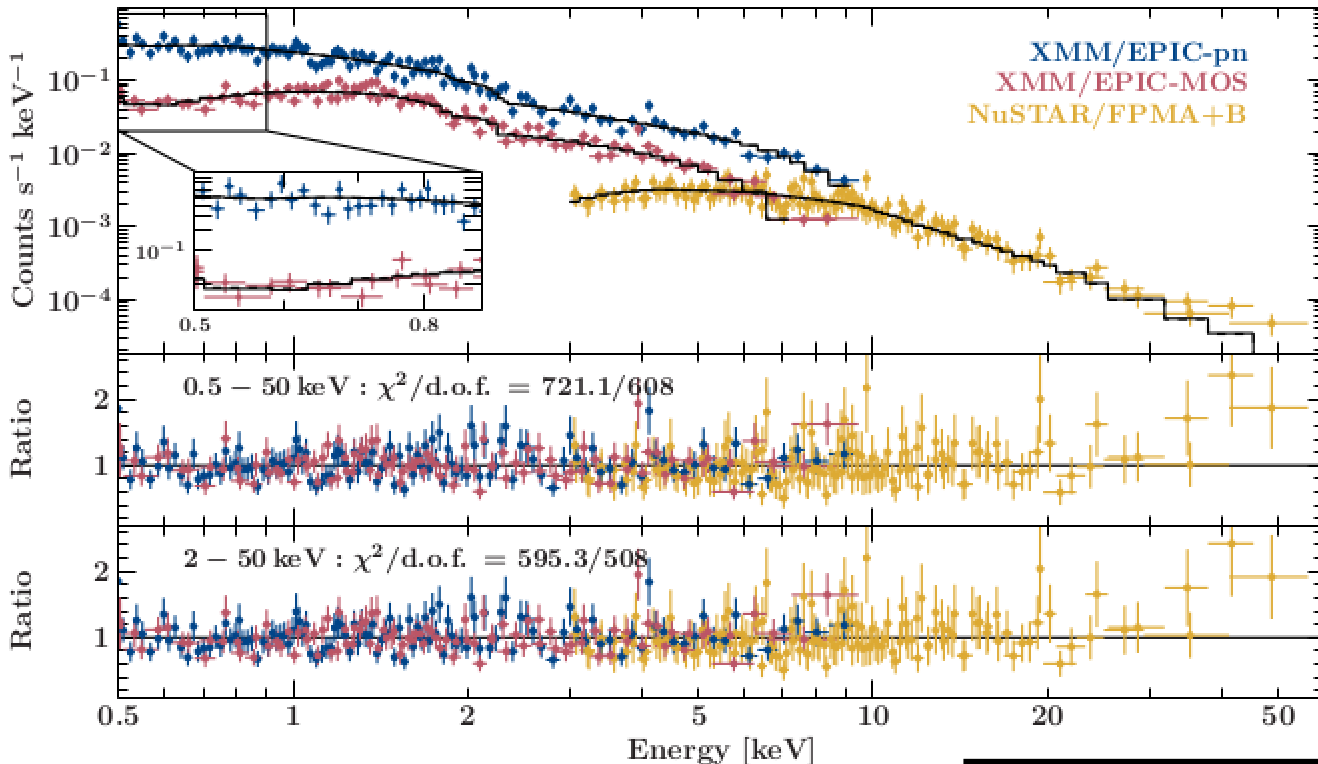


PMN J0948+0022



D'Ammando 2020a

XMM+NuSTAR observation of PKS 2004-447

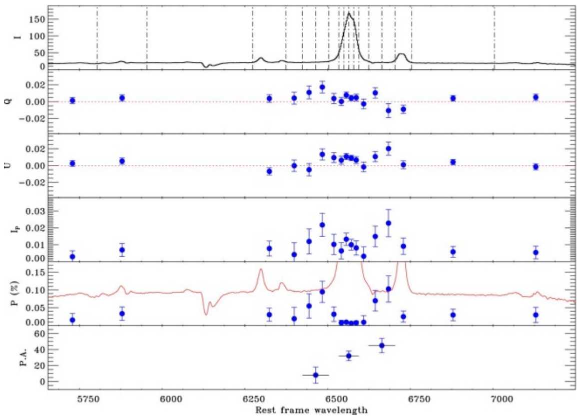


Gokus et al. 2021, A&A, in press

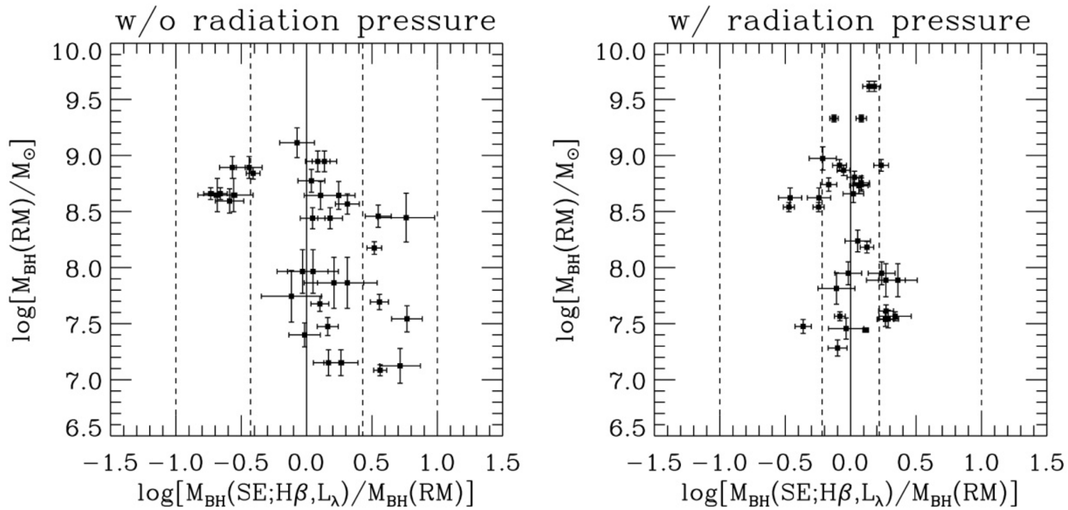
The soft excess frequently observed in the X-ray spectra of NLSy1 galaxies is not found in the *XMM-Newton* spectrum of PKS 2004-447 in 2019 October, in agreement with the analysis of the 2012 low-state *XMM-Newton* spectrum

Black hole mass of NLSy1

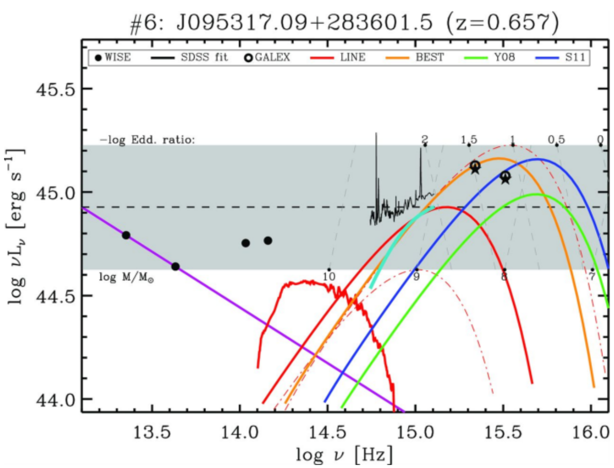
The BH mass of NLSy1 may be underestimated due either to the effect of radiation pressure or to projection effects.



Baldi et al. 2016, MNRAS, 458, L69



Marconi et al. 2008, ApJ, 678, 693



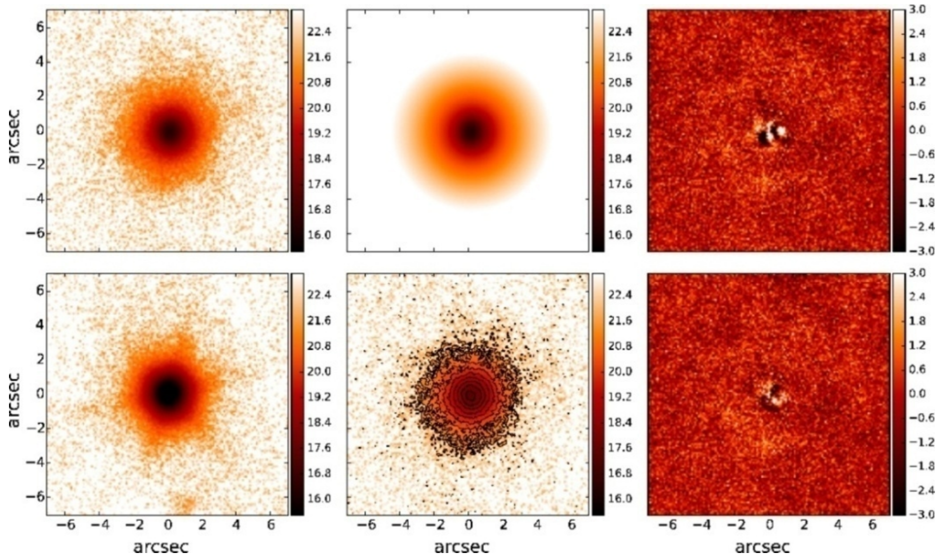
By considering these effects, NLSy1 have BH masses of 10^8 - $10^9 M_\odot$ in agreement with the values estimated by the optical/UV data with a Shakura & Sunyaev disc spectrum

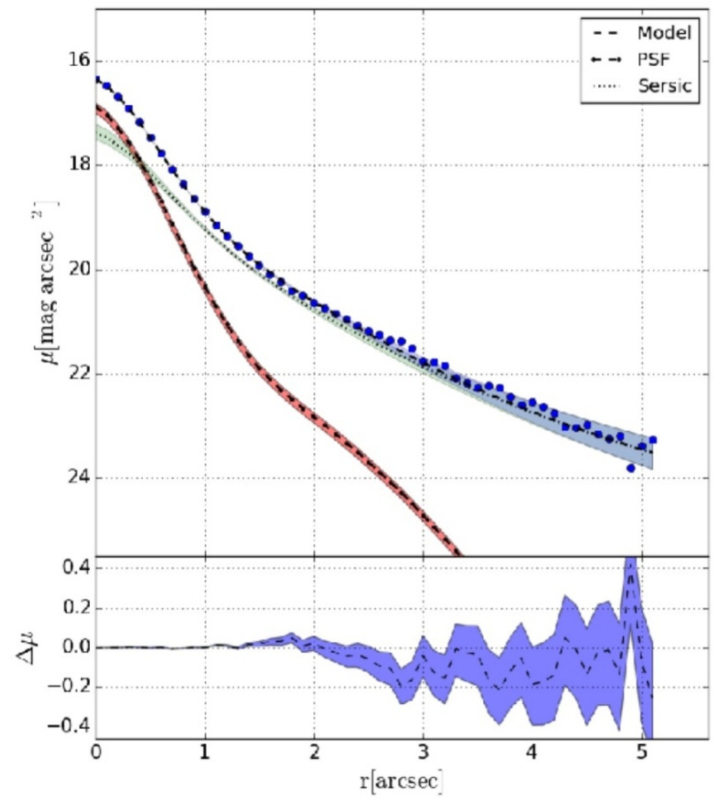
Calderone et al. 2013, MNRAS, 431, 210

Host galaxy of FBQS J1644+2619

Fermi Gamma-ray Space Telescope

INAF Istituto di Radioastronomia





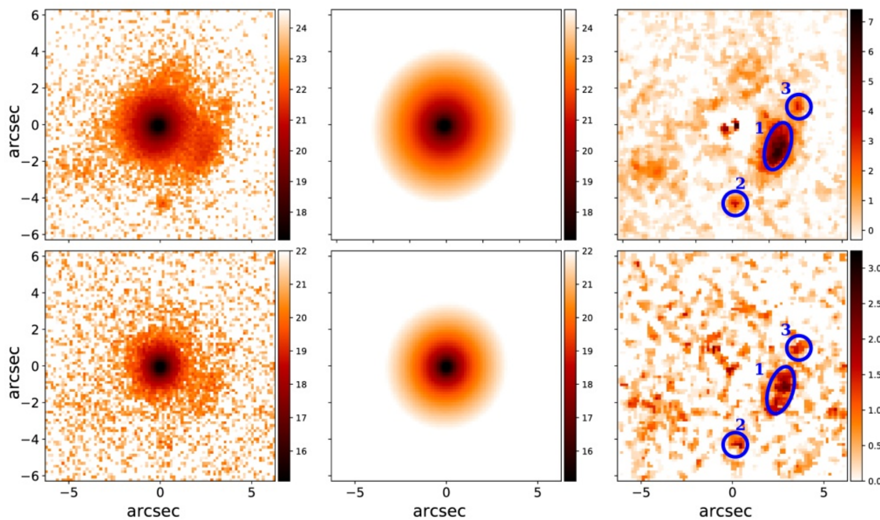
GranTeCan observations of FBQS J1644+2619 in J band. The 2D surface brightness profile is modelled by a nuclear and a bulge component with *n* = 3.7. **Evidence of an E1 elliptical galaxy as host galaxy.**

The BH mass estimated by the IR bulge luminosity is (2.1±0.2)x10^8 $M_{\odot}$, consistent with the values characterizing radio-loud AGN.

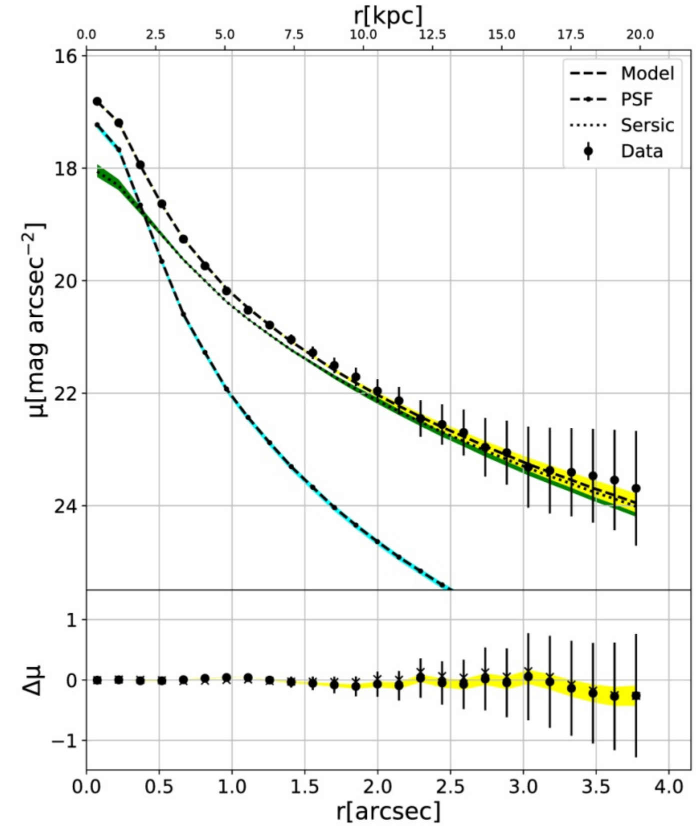
D'Ammando, et al. 2017, MNRAS, 469, L11

in contrast with the results presented in Olguin-Iglesias et al. 2017

Host galaxy of PKS 1502+036



D'Ammando et al. 2018, MNRAS, 478, L66



VLT-ISAAC observations of PKS 1502+036 in J and K band. The surface brightness profile, extened up to ~20 kpc, is well described by a nuclear and a bulge component with *n* = 3.5. **Evidence of an E1 elliptical galaxy as host galaxy.** The BH mass estimated by the IR bulge luminosity is **~7x10^8 M$_\odot$**. A circumnuclear structure observed near PKS 1502+036 may be the result of galaxy interactions.