HEPRO VIII : High Energy Phenomena in Relativistic Outflows

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γ-ray narrow-line Seyfert 1 galaxies: first long-term optical, UV, and X-ray monitoring

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Paris, 23-26/10/2023

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Outline

Narrow-line Seyfert 1 galaxies

Monitoring of the *golden four* sample

Absorbed jet in SDSS J164100.10+345452.7

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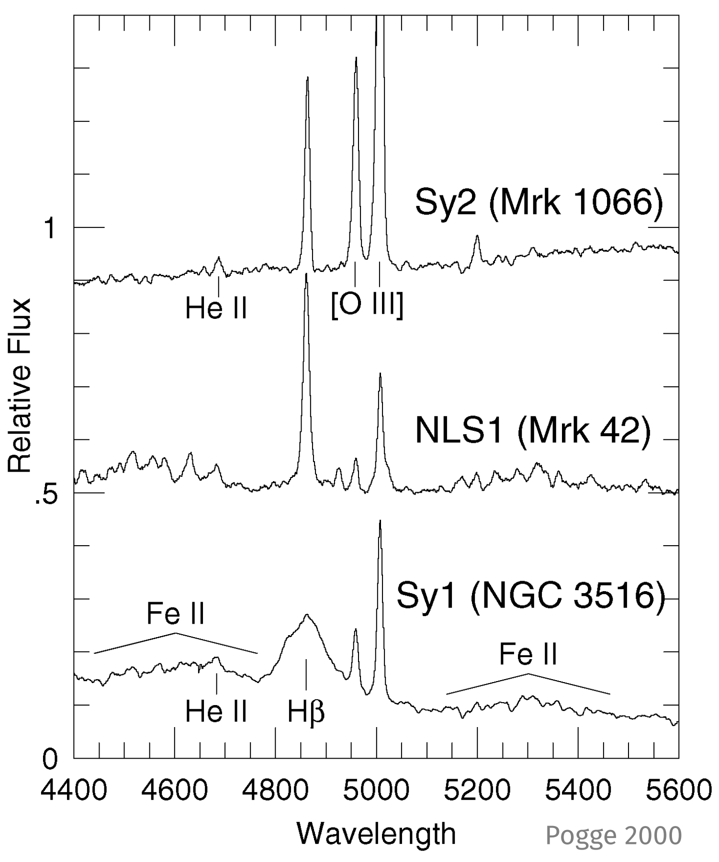
NLS1 – an introduction

Narrow-line Seyfert-1 galaxies are a subclass of active galactic nuclei with

- narrow permitted emission lines
  - **FWHM(Hβ) < 2000 km s^{-1}**
- weak [O III] lines
  - **[OIII] / Hβ < 3**
- strong optical Iron emission lines
  - **high Fe/Hβ ratio**

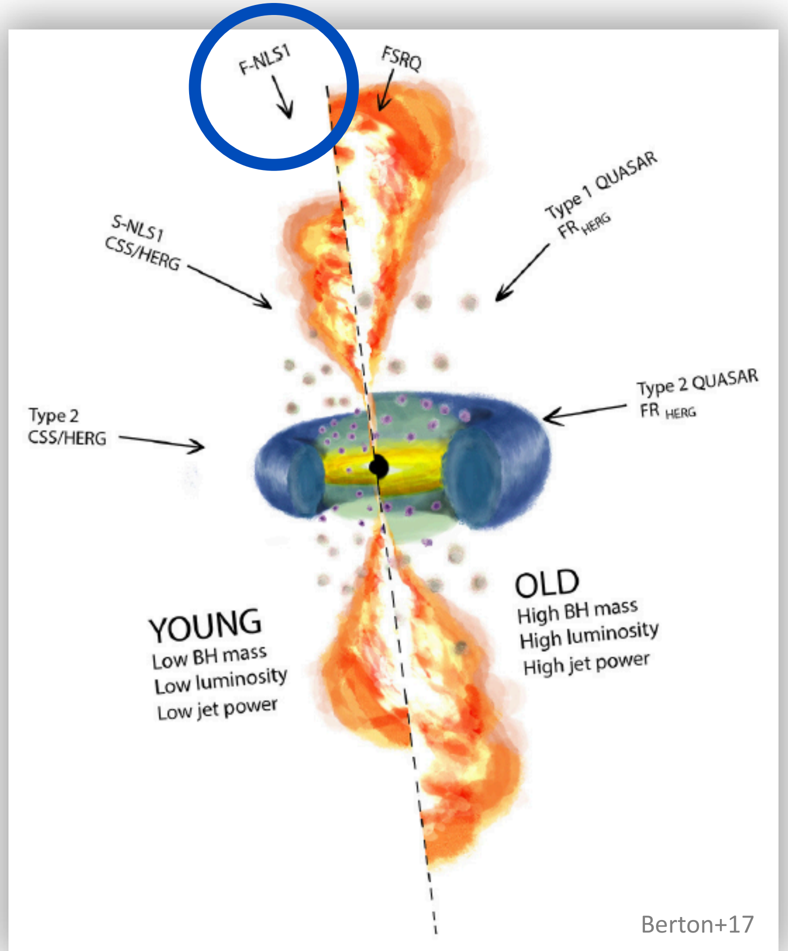
- low-mass **black hole (10^6 - 10^8 $M_\odot$)** accreting close to the **Eddington limit**



Pogge 2000

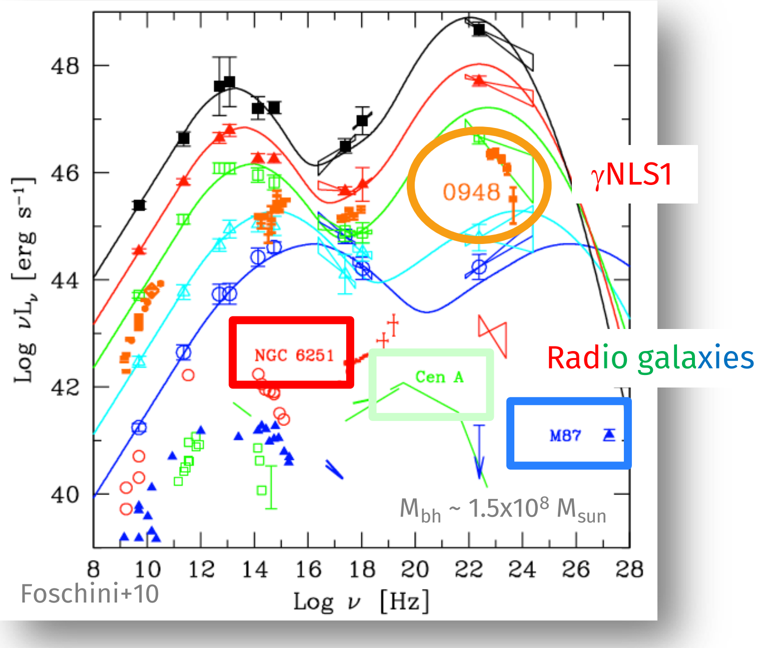
Where do γNLS1 sit ?

- **About 7% are radio-loud** [Komossa+06] [Cracco+16] and present flat radio spectrum [Oshlack+01, Zhou+03, Yuan+08] **resembling jetted sources**
- Hard component in some X-ray spectra observed with *Swift*/XRT and **flux and spectral variability in the hard X-ray** observed with INTEGRAL/IBIS and *Swift*/BAT [Foschini+09]
- About **40 sources** have being revealed to emit **above 100 MeV** [Romano+18, Foschini+22]
- **No positive detection** in the very-high energy band **by Whipple, VERITAS, MAGIC, and H.E.S.S.**

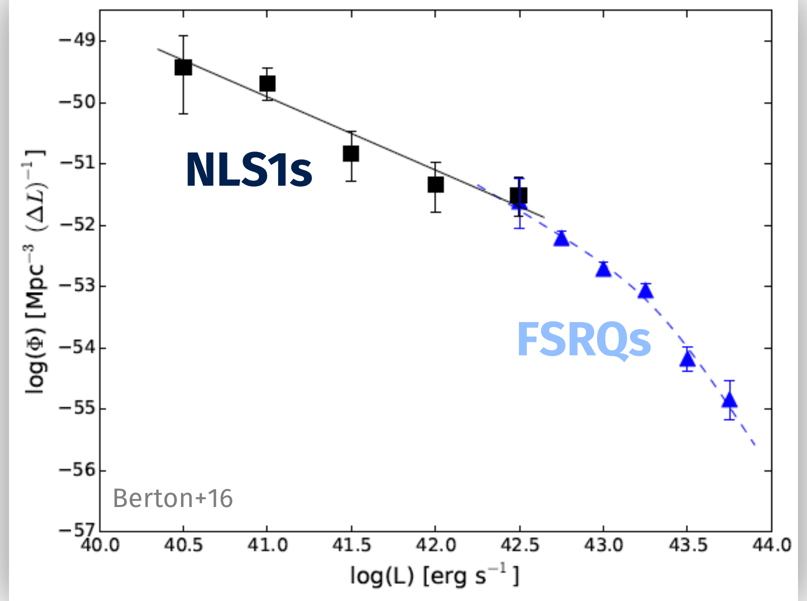


Berton+17

New classes of jetted sources?



Foschini+10



Berton+16

- $M_{bh} \sim 10^6 - 10^8 M_{Sun}$
- High accretion lum. ~ 0.1 – 1 L_{Edd}
- Low jet power ~ $10^{42} - 10^{46}$ erg s^{-1}
- Photon-rich environment
- Super-luminal radio jets (~10c)
- Hosted in disc galaxies

Monochromatic radio luminosity functions of flat-spectrum **NLS1s** and **FSRQs** at 1.4 GHz

Low-mass tail of FSRQs

NLS1s as young sources?

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Absorbed jet in SDSS J164100.10+345452.7

Why X-ray monitoring of γNLS1s ?

- These sources have been observed by *Swift* mainly as **follow-up of flares** at other wavelengths

- This introduces a **bias** in the understanding of their **variability behavior and duty-cycle because they favor high states**

- We started our project with a sample of **4 well-known γ-NLS1s**:
  - SBS 0846+513
  - PMN J0948+0022
  - PKS 1502+036
  - FBQS J1644.9+2619

Good VHE candidates ! [Romano+20]

The “*Master Plan*”: a regular pace

1 observation per week

3 ks each observation

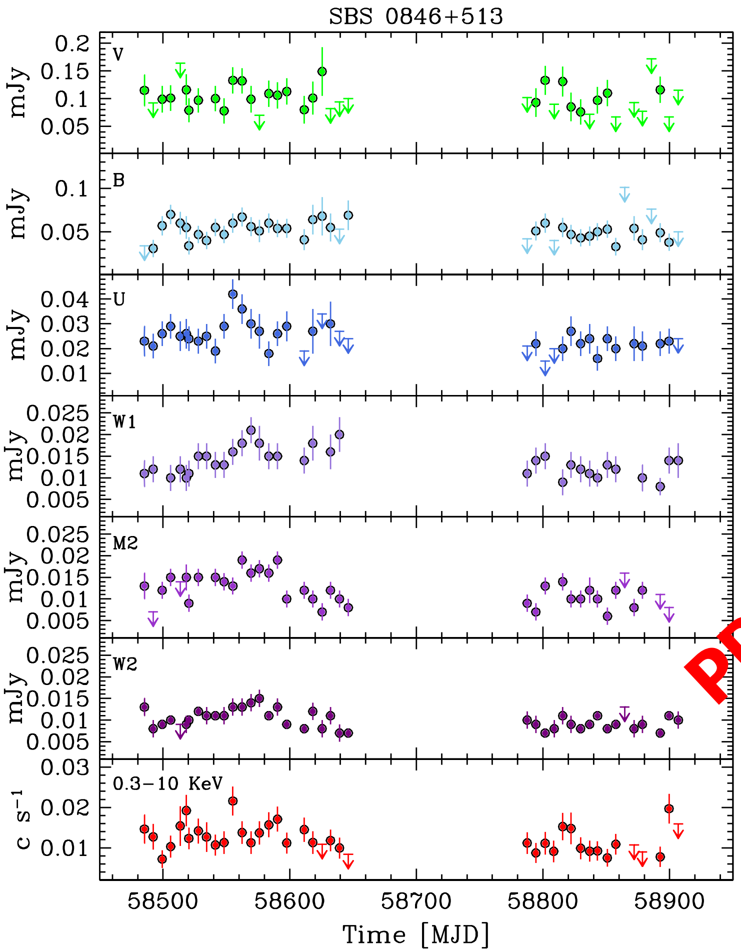
1 year baseline each source

5-year duration in total

Optical + UV + X-ray

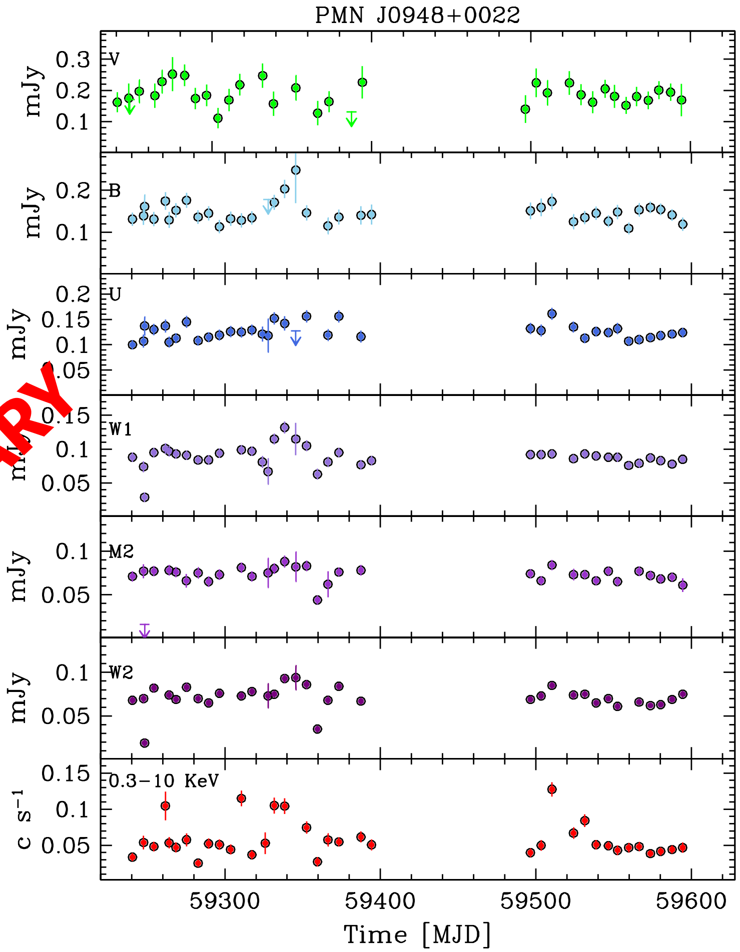
PIs: Vercellone + Romano

MWL light-curves (1)

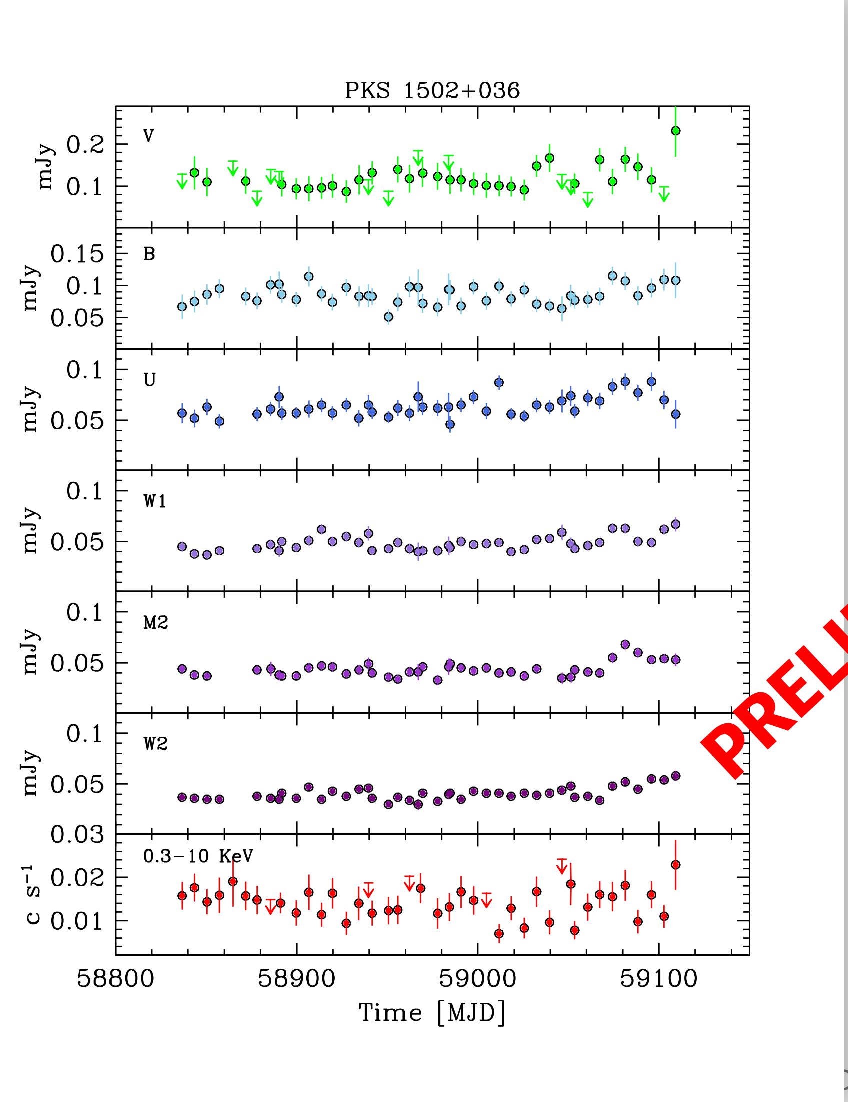


Romano et al., to be submitted

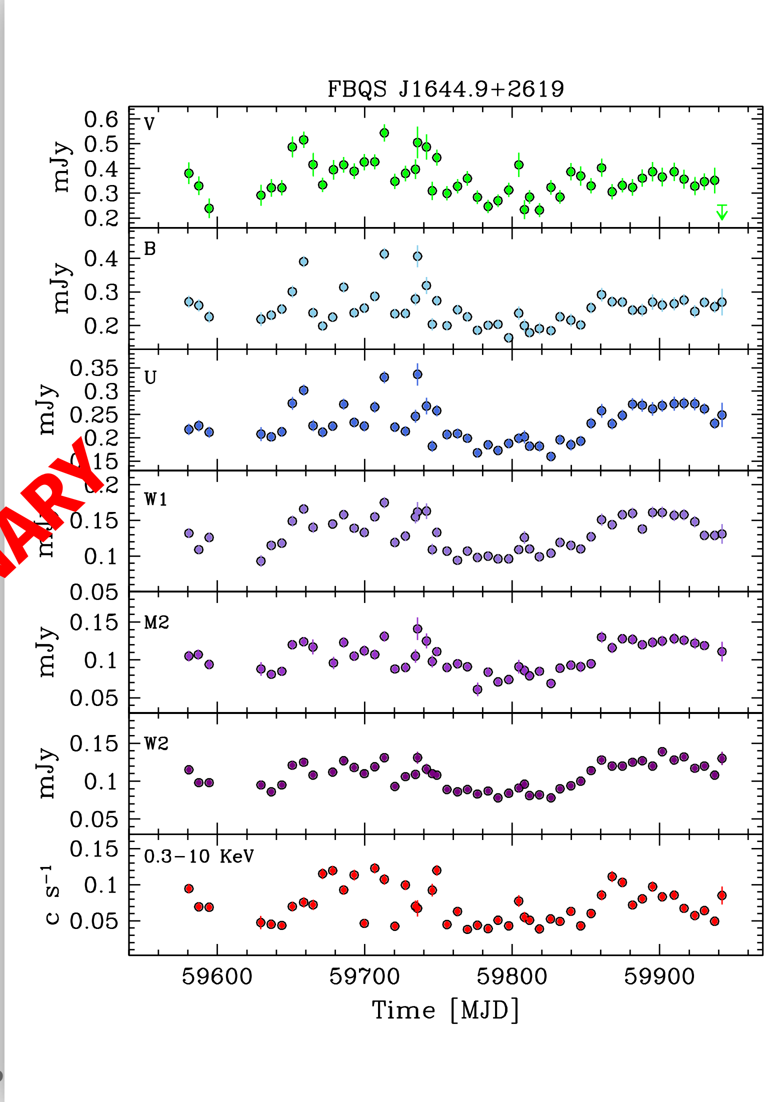
PRELIMINARY



MWL light-curves (2)



PRELIMINARY



Fractional Variability

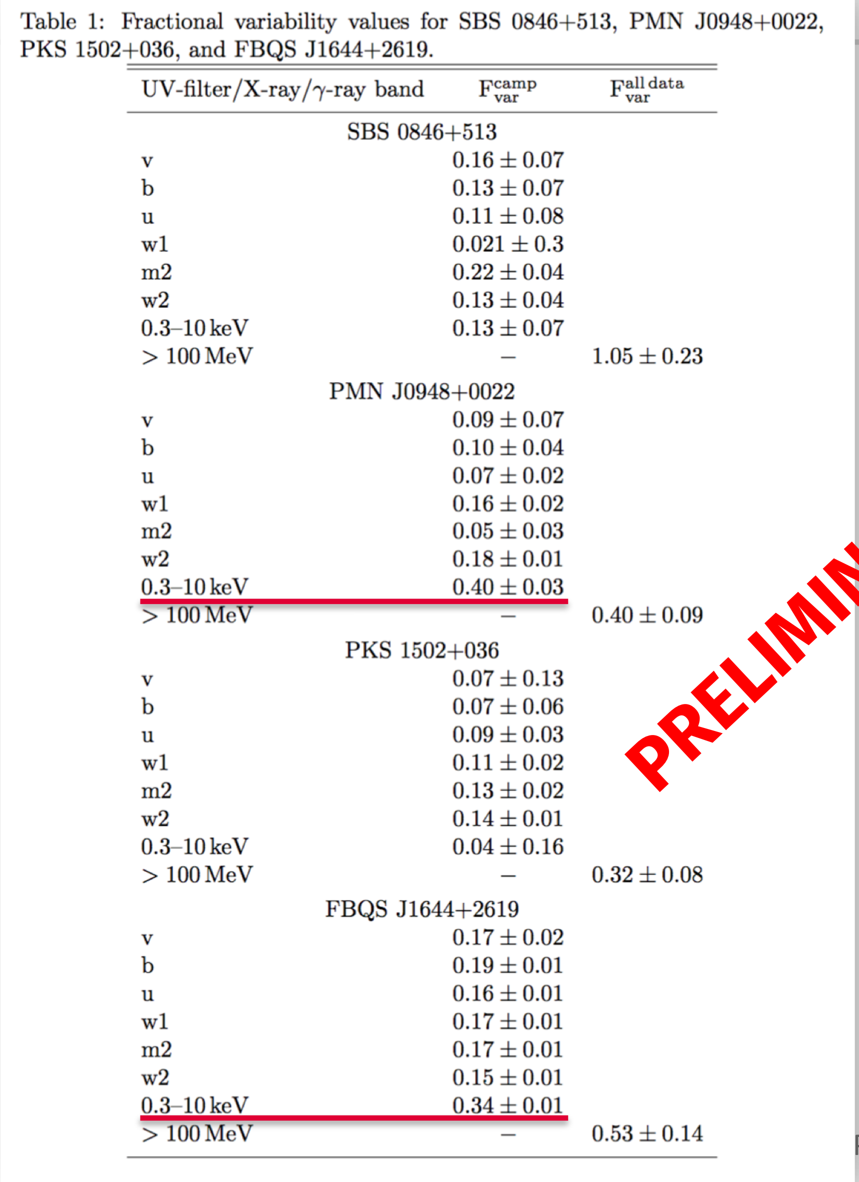


Table 1: Fractional variability values for SBS 0846+513, PMN J0948+0022, PKS 1502+036, and FBQS J1644+2619.

UV-filter/X-ray/γ-ray band	$F_{\rm var}^{\rm camp}$	$F_{\rm var}^{\rm all\ data}$
SBS 0846+513		
v	0.16 ± 0.07	
b	0.13 ± 0.07	
u	0.11 ± 0.08	
w1	0.021 ± 0.3	
m2	0.22 ± 0.04	
w2	0.13 ± 0.04	
0.3–10 keV	0.13 ± 0.07	
> 100 MeV	–	1.05 ± 0.23
PMN J0948+0022		
v	0.09 ± 0.07	
b	0.10 ± 0.04	
u	0.07 ± 0.02	
w1	0.16 ± 0.02	
m2	0.05 ± 0.03	
w2	0.18 ± 0.01	
0.3–10 keV	0.40 ± 0.03	
> 100 MeV	–	0.40 ± 0.09
PKS 1502+036		
v	0.07 ± 0.13	
b	0.07 ± 0.06	
u	0.09 ± 0.03	
w1	0.11 ± 0.02	
m2	0.13 ± 0.02	
w2	0.14 ± 0.01	
0.3–10 keV	0.04 ± 0.16	
> 100 MeV	–	0.32 ± 0.08
FBQS J1644+2619		
v	0.17 ± 0.02	
b	0.19 ± 0.01	
u	0.16 ± 0.01	
w1	0.17 ± 0.01	
m2	0.17 ± 0.01	
w2	0.15 ± 0.01	
0.3–10 keV	0.34 ± 0.01	
> 100 MeV	–	0.53 ± 0.14

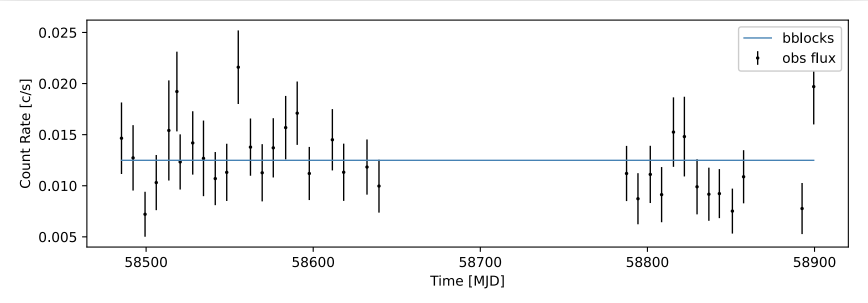
PRELIMINARY

Still missing:

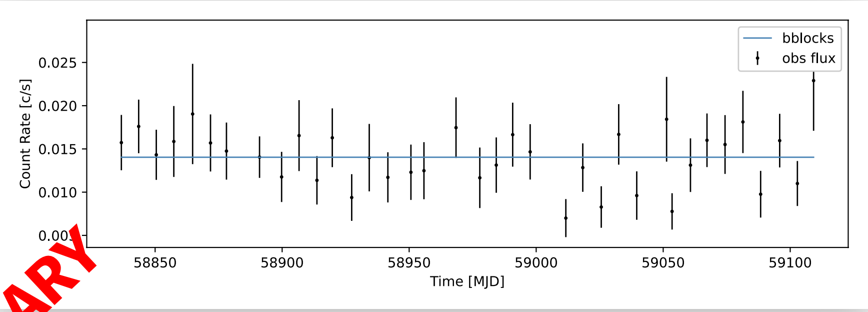
- Analysis of the archival data
- Estimate of the bias introduced by flaring events on variability and duty-cycle

Bayesian Blocks for X-ray LCs

SBS 0846+513

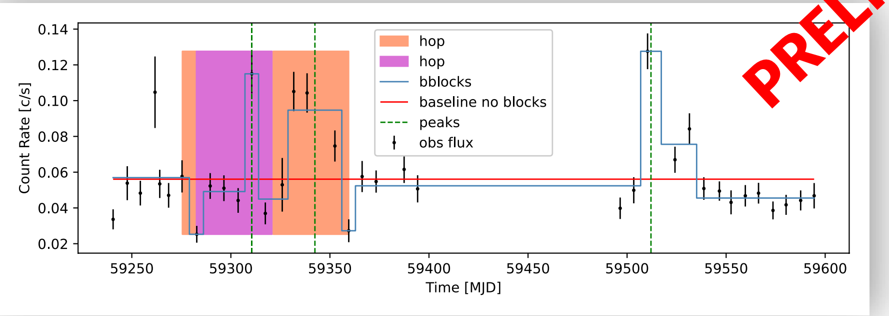


PKS 1502+036

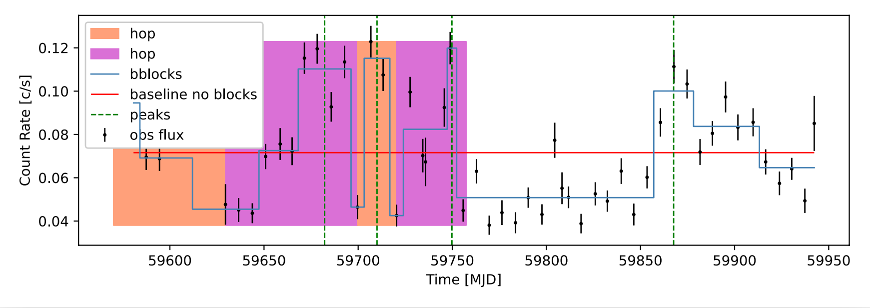


PRELIMINARY

PMN J0948+0022



FBQS J1644+2619



Only two sources undergo flares over a 1-yr campaign

We will include all the available data and update the analysis

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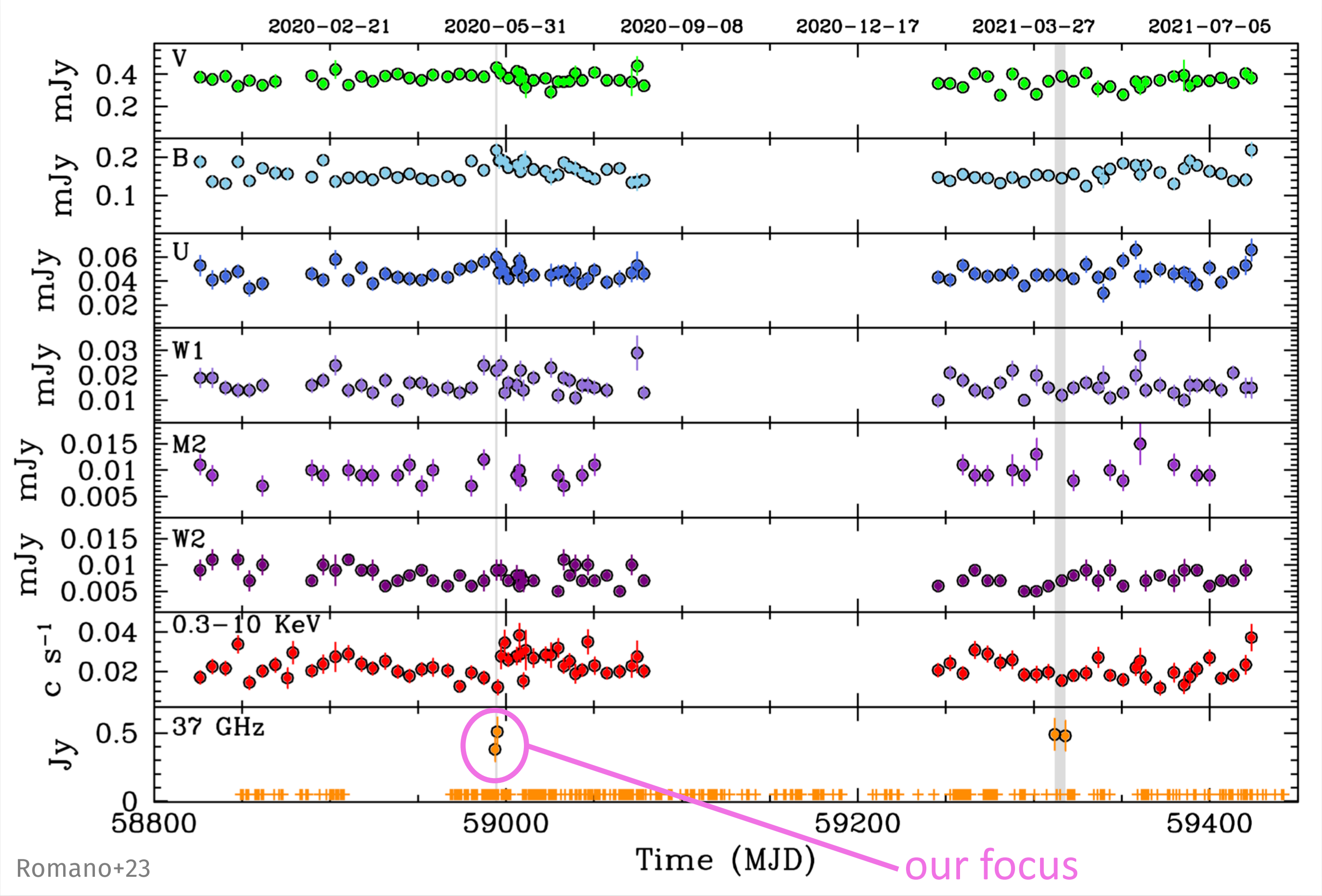
SDSS J164100.10+345452.7

- nearby γNLS1 ($z = 0.16409 \pm 0.00002$) [Albareti+17]
- hosted in a spiral galaxy [Olguín-Iglesias+20]
- initially classified as radio-quiet
- then detected at $\nu = 37$ GHz with F = 0.46 Jy [Lähteenmäki+18]
- and at E>100 MeV with F = $(12.5 \pm 2.18) \times 10^{-9}$ ph cm^{-2} s^{-1} [Lähteenmäki+18]
- → **presence of a jet !**
- → **started a 2-yr *Swift* + Metsähovi monitoring campaign**

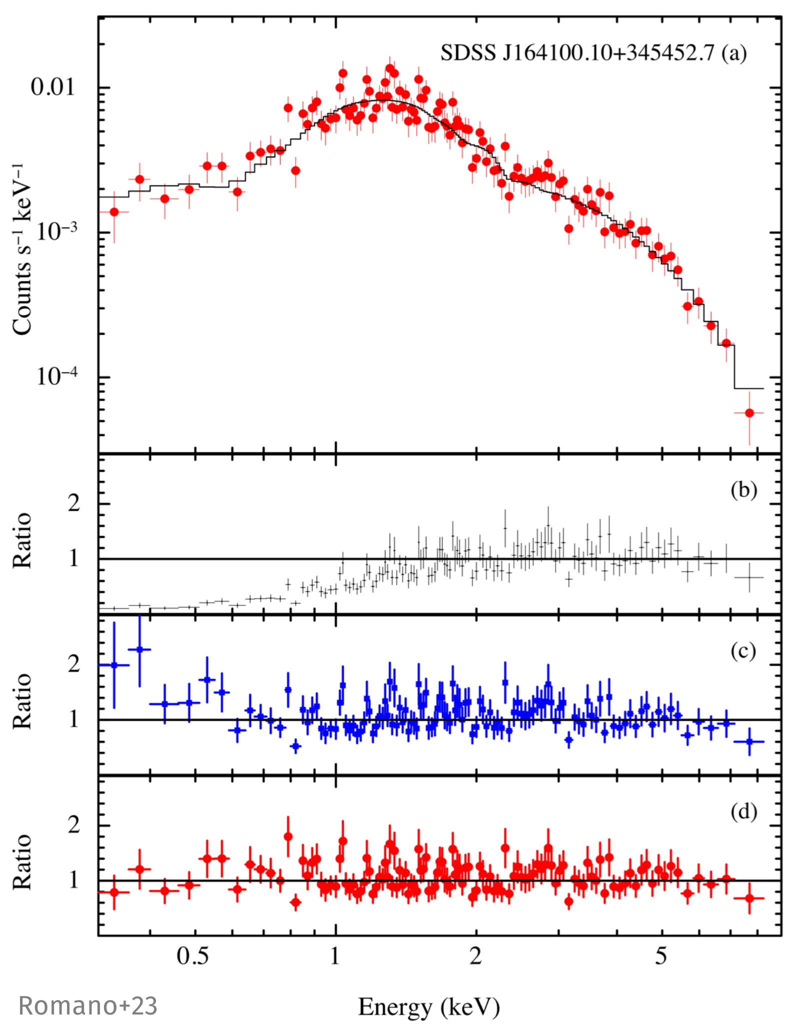
MWL Campaigns



Romano+23

Grey vertical dashed areas mark the epochs of radio flares

Time-selected X-ray spectroscopy



Romano+23

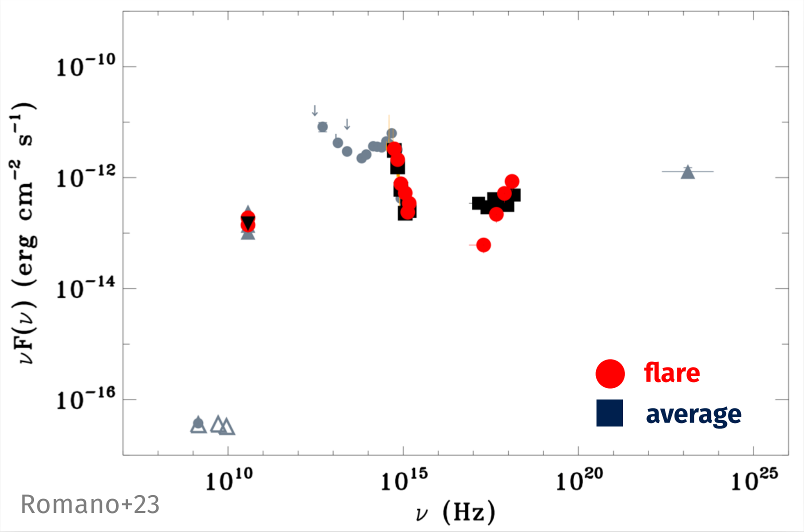
Average spectrum

- ~181 ks
- absorbed power-law model
- photon index $\Gamma = 1.93 \pm 0.12$
- requires a partially covering neutral absorber (panel d)
- `tbabs * zpcfabs * zpowerlw`
- covering fraction $f = 0.91 \pm 0.02$

Flare spectrum (MJD 58994–58997)

- ~3.5 ks
- does not require any such extra absorber
- much harder ($\Gamma_{\mathrm{flare}} \sim 0.7 \pm 0.4$)
- **Possible interpretation: jet emission emerging from a gap in the absorber**

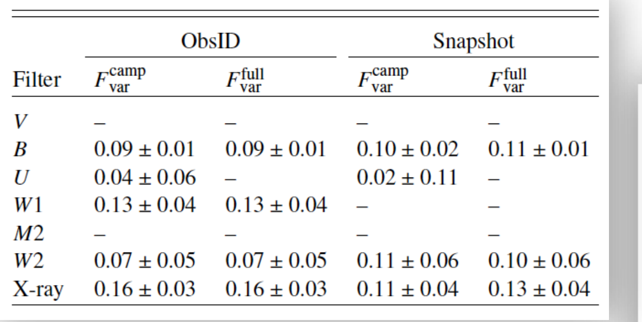
Spectral energy distribution



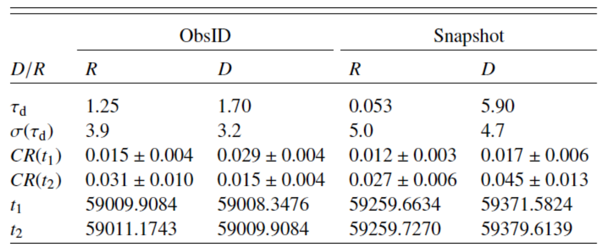
Romano+23

- first almost simultaneous SED for this source
- ≈ of other jetted sources, hint of a double-humped shape
- synchrotron peak below $\nu_{peak} \approx 10^{13}$ Hz, typical of other γNLS1s
- host galaxy component peaking at a few $\times 10^{14}$ Hz (≈ Sb template)
- X-ray data ≈ synchrotron self-Compton component [e.g., Foschini+15]

Variability & Energetics



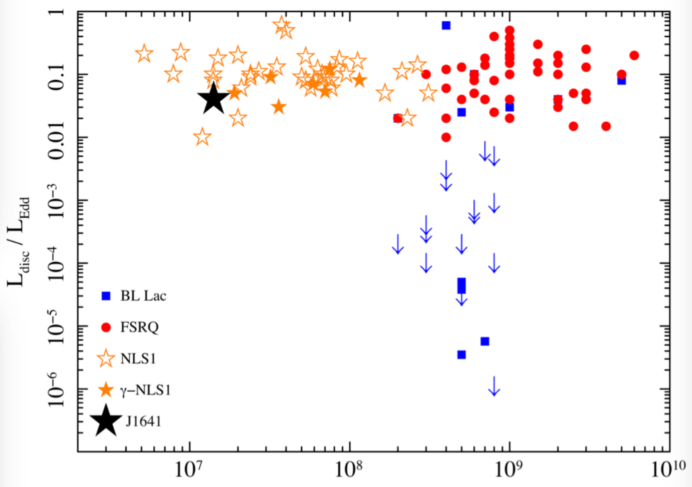
	ObsID		Snapshot	
Filter	$F_{\rm var}^{\rm camp}$	$F_{\rm var}^{\rm full}$	$F_{\rm var}^{\rm camp}$	$F_{\rm var}^{\rm full}$
V	–	–	–	–
B	0.09 ± 0.01	0.09 ± 0.01	0.10 ± 0.02	0.11 ± 0.01
U	0.04 ± 0.06	–	0.02 ± 0.11	–
$W1$	0.13 ± 0.04	0.13 ± 0.04	–	–
$M2$	–	–	–	–
$W2$	0.07 ± 0.05	0.07 ± 0.05	0.11 ± 0.06	0.10 ± 0.06
X-ray	0.16 ± 0.03	0.16 ± 0.03	0.11 ± 0.04	0.13 ± 0.04



	ObsID		Snapshot	
D/R	R	D	R	D
$\tau_{\rm d}$	1.25	1.70	0.053	5.90
$\sigma(\tau_{\rm d})$	3.9	3.2	5.0	4.7
$CR(t_1)$	0.015 ± 0.004	0.029 ± 0.004	0.012 ± 0.003	0.017 ± 0.006
$CR(t_2)$	0.031 ± 0.010	0.015 ± 0.004	0.027 ± 0.006	0.045 ± 0.013
t_1	59009.9084	59008.3476	59259.6634	59371.5824
t_2	59011.1743	59009.9084	59259.7270	59379.6139

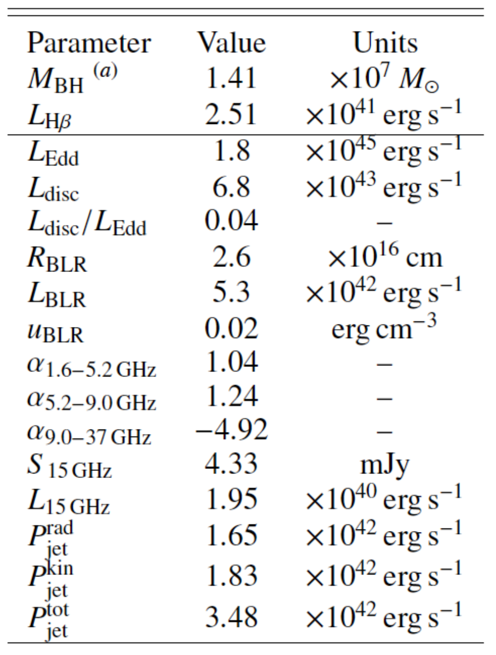
$F_{\rm var}$ (ToO excluded) is lower than in [D’Ammando+20], since we are not flare-biassed

$t'_{\rm var}$(obs) ~ 0.75d
$t'_{\rm var}$(snap) ~ 0.034d



Romano+23

SDSS 1641 fits well in the γNLS1 part of the plane $L_{\rm disc}/L_{\rm edd}$ – $M_{\rm BH}/M_\odot$ [adapted from Foschini+15]



Parameter	Value	Units
$M_{\rm BH}$ (a)	1.41	$\times 10^7\ M_\odot$
$L_{\rm H\beta}$	2.51	$\times 10^{41}$ erg s^{-1}
$L_{\rm Edd}$	1.8	$\times 10^{45}$ erg s^{-1}
$L_{\rm disc}$	6.8	$\times 10^{43}$ erg s^{-1}
$L_{\rm disc}/L_{\rm Edd}$	0.04	–
$R_{\rm BLR}$	2.6	$\times 10^{16}$ cm
$L_{\rm BLR}$	5.3	$\times 10^{42}$ erg s^{-1}
$u_{\rm BLR}$	0.02	erg cm^{-3}
$\alpha_{1.6-5.2\,\rm GHz}$	1.04	–
$\alpha_{5.2-9.0\,\rm GHz}$	1.24	–
$\alpha_{9.0-37\,\rm GHz}$	−4.92	–
$S_{15\,\rm GHz}$	4.33	mJy
$L_{15\,\rm GHz}$	1.95	$\times 10^{40}$ erg s^{-1}
$P_{\rm jet}^{\rm rad}$	1.65	$\times 10^{42}$ erg s^{-1}
$P_{\rm jet}^{\rm kin}$	1.83	$\times 10^{42}$ erg s^{-1}
$P_{\rm jet}^{\rm tot}$	3.48	$\times 10^{42}$ erg s^{-1}

$P_{\rm jet}$(tot) is at the lower-end among the typical γNLS1 ones

Summary

- Dedicated multi-wavelength campaigns allow us to derive **firmer constraints on the variability** behavior of γNLS1

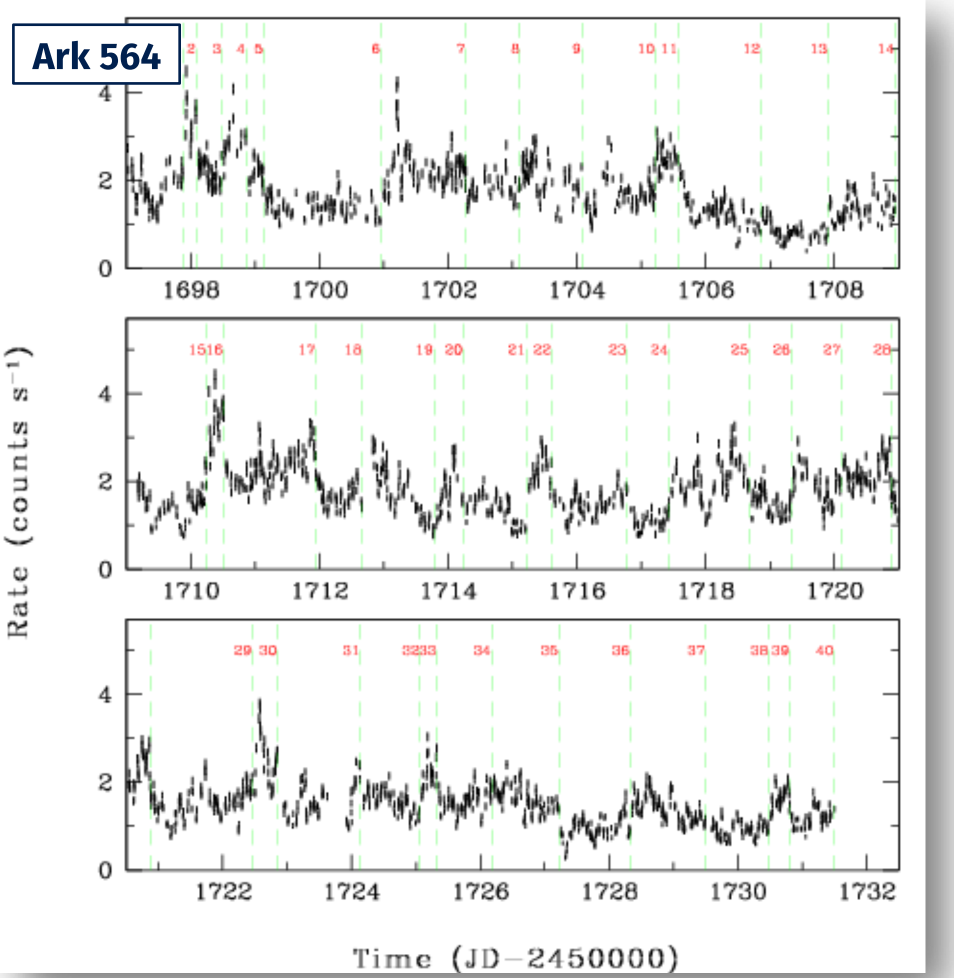
- On a year-based campaign, we can estimate a number of **X-ray flares** $\boldsymbol{0 < N_{\text{X-ray}} < 4}$ (analysis still in progress)

- Thanks to the long-baseline X-ray and radio monitoring, we have detected the **first possible evidence of an absorbed jet** in SDSS J164100.10+345452.7 [see Romano et al., A&A 673, A85 (2023)]

BACKUP

NLS1 galaxies ("X-ray" definition, > ca1995)

- X-ray rapid, large amplitude variability
  - Flares up to a factor of ~100 in days
  - Doubling times as short as minutes



Turner et al., 2001, ApJ, **561**, 131

NLS1 galaxies ("X-ray" definition)

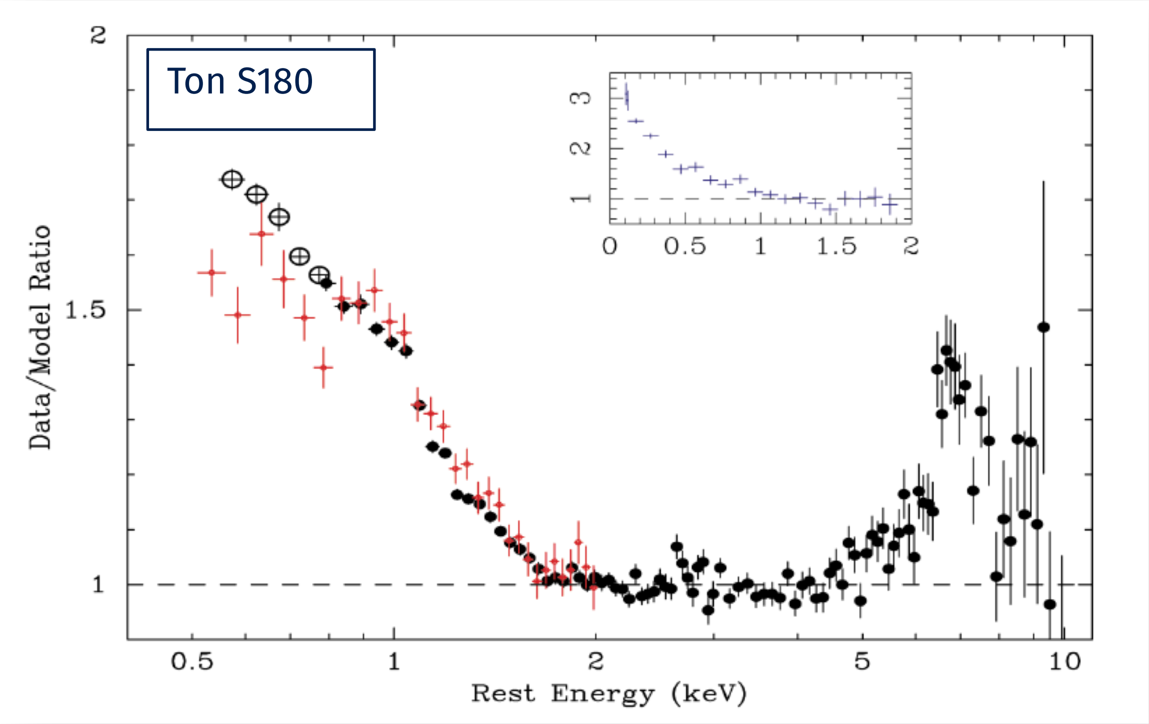
- Steep soft X-ray continuum slopes
  - Photon Index $\Gamma \approx 2.44$ $(P_E \propto E^{-\Gamma})$
  - Soft excess

    EW ~ 94 eV
  - Fe Kα

    Peak at 6.8 keV

    EW ~ 600 eV

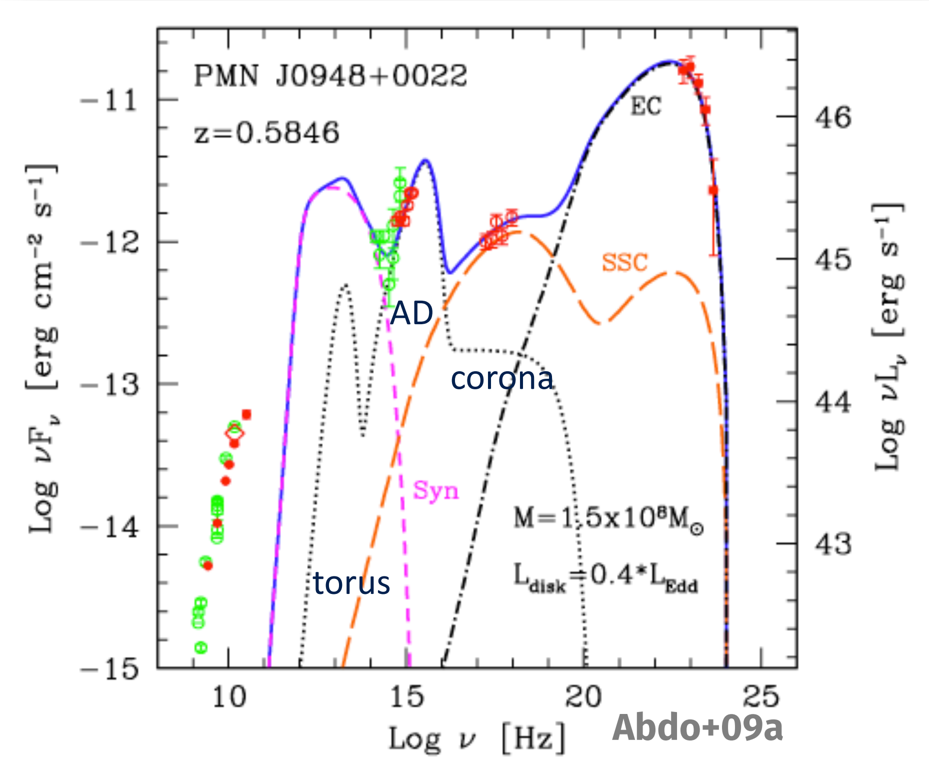
a relatively low-mass black hole (10^6 - 10^8 $M_\odot$) accreting close to the Eddington limit



Romano et al., 2002, ApJ, **564**, 162

NLS1 galaxies as HE sources?

- **The smoking gun observed by *Fermi***
  - Discovery of gamma-ray emission (E>100MeV) with *Fermi*-LAT from PMN J0948+0022 **[Abdo+2009a, Foschini+2010]**
  - The SED fit with the model by **[Ghisellini & Tavecchio 2009]** clearly resembles that of a **blazar-like** source



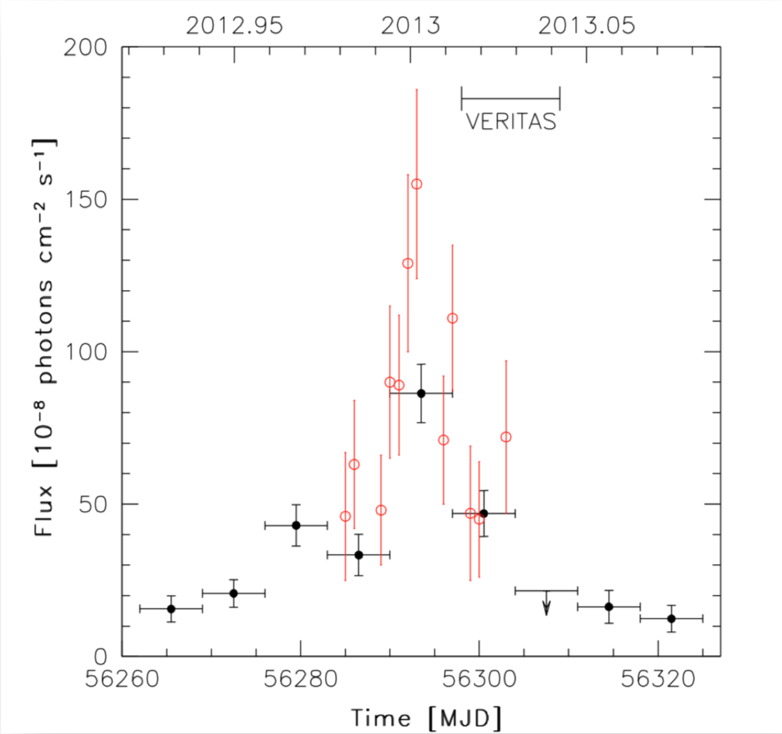
Abdo+09a

Jetted???

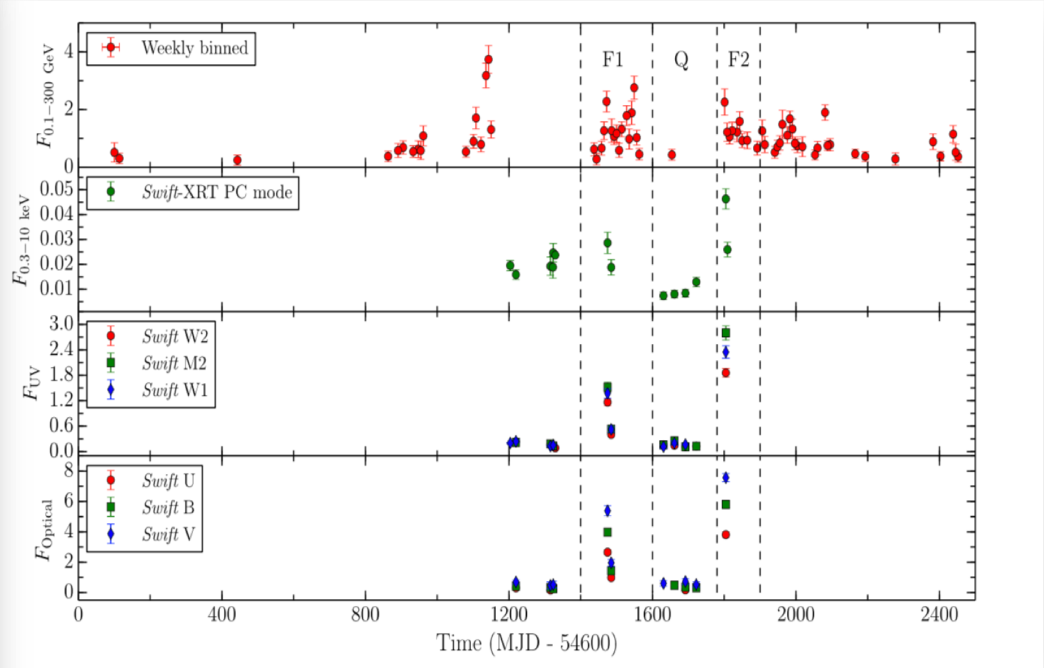
γ-NLS1 timescale variability

Gamma-ray emission is variable too, on time-scale as low as a few hours

[Abdo+09b, Calderone+11, Paliya+14]



D'Ammando, 2015, MNRAS, 446, 2456

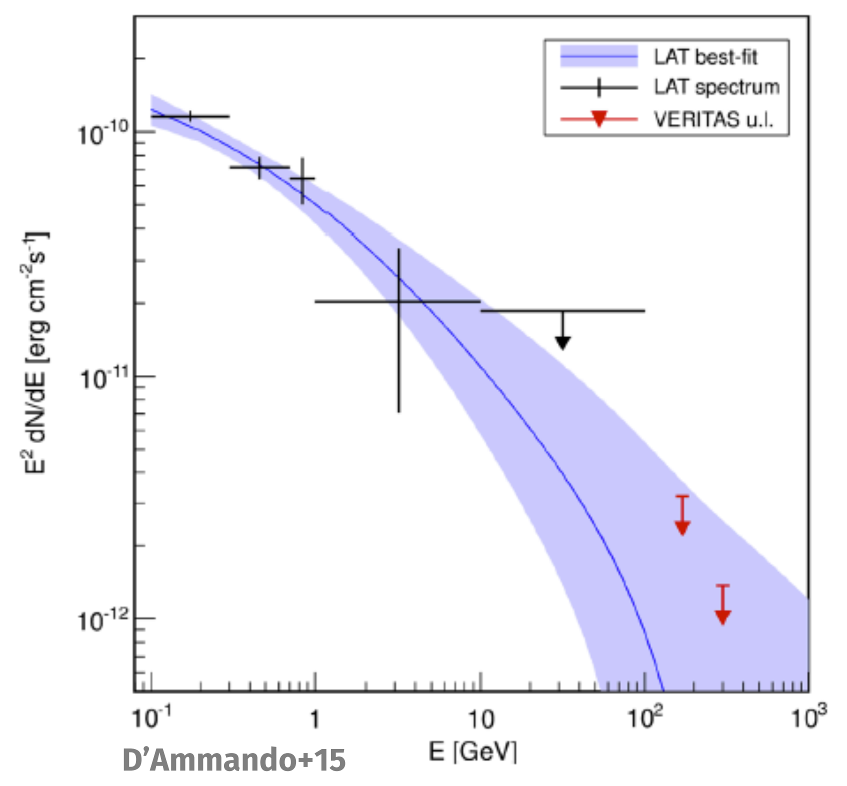


Paliya 2016, ApJ, 819, 121

γ-NLS1 sample

- 20 sources have been recently discovered as gamma-ray emitters.

- **VERITAS** observations (5.25 h) on PMN J0948+0022 allowed to obtain **only UL** (also on nightly and 30m time-scales) for **E>100 GeV**.



D'Ammando+15

An exploratory investigation

- **Detecting high-energy (E > a few tens of GeV) emission from NLS1 galaxies is challenging because:**
  - They have an average rather soft spectrum (Γ~2.5);
  - Some of them have rather high redshift (z > 0.3)
    → high absorption by extragalactic background light (EBL)
  - If broad-line region absorption is present, it could produce a spectral break/cut-off at energies of 20-30 GeV.

- **On the bright side:**
  - Some sources exhibit rather strong gamma-ray flares, on time-scale of the order of a few hours/a day in gamma-rays (PMN J0948+0022 **[Foschini+11, D'Ammando+15]**).
  - The high-state activity can last for several weeks/months, repeated on a multi-year baseline (SBS 0846+513 **[Paliya+16]**)

Simulating γ-NLS1s with CTA

Romano et al 2018, MNRAS, 481, 5046 (Paper I)

Sample of **20 sources** (**4 sources** in several intensity states) simulated with *ctools* (v1.4.2) **[Knödlseder+16]**

- IRFs were selected according to the simulated exposure time & zenith angle
- Input spectral models were derived **extrapolating the best-fit Fermi spectra** to the CTA energy range (PL=power-law, LP=log parabola, BKPL=broken PL)
- including **the effects of the gamma-ray absorption** both
  - inside the source (PL + Exponential cut-off at ~30 GeV) and
  - the EBL **[Dominguez+11]**

Detailed results for **3 sources:**

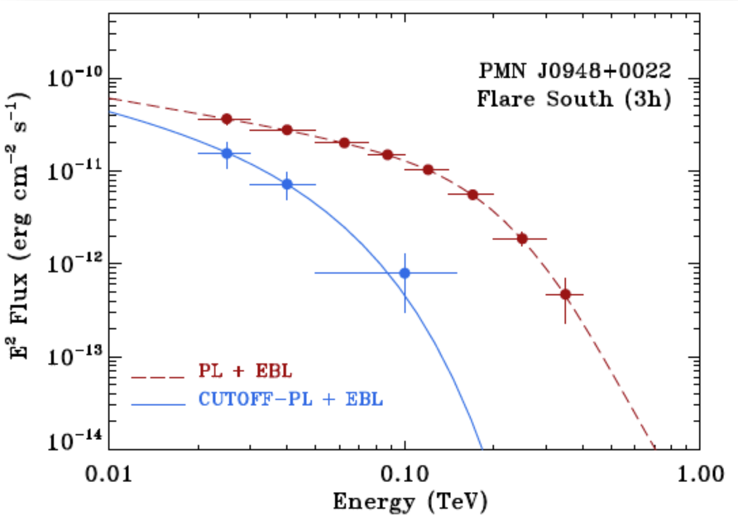
SBS 0846+513, PMN J0948+0022, and PKS 1502+036

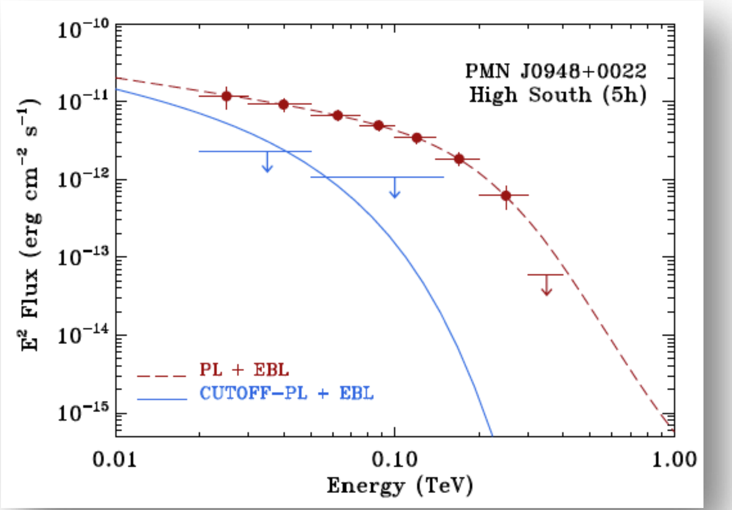
‘Beyond’ the BLR

In blazars the γ-ray emitting region may not always be placed at the same distance from the central black-hole during different flaring episodes of the same source **[Foschini+2011b]**.

Detection of TeV photons **[Albert+08, Ahnen+15]** and the dramatic change of the position of the sync. & IC peaks in some blazars during extreme flares **[Ghisellini+13, Pacciani+14, Ahnen+15]** support the idea of a **dissipation region outside the BLR**.

Investigated the **impact of the position of the emitting region** on the detectability assuming that the **spectrum can extend unbroken** above 30 GeV.





More realistic BLR absorption models

Romano et al 2020, MNRAS, 494, 411 (Paper II)

We consider the only three souces that were good candidates for a perspective CTA detection

SBS 0846+513, PMN J0948+0022, and PKS 1502+036

Simulate their spectra by adopting **more realistic BLR absorption models**.

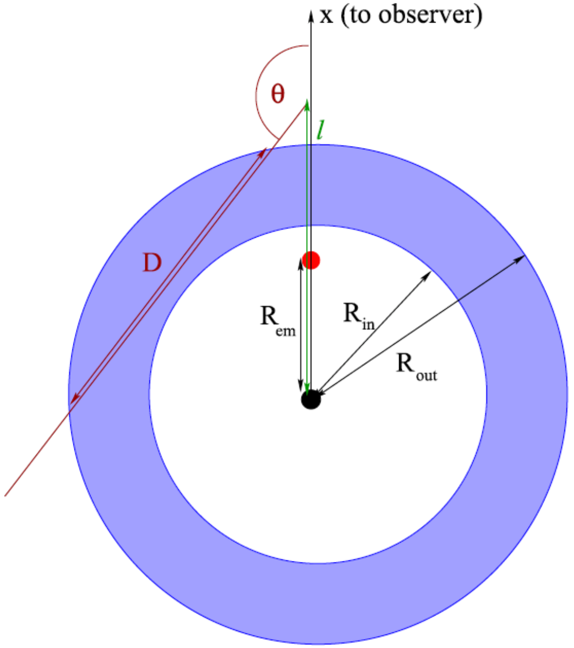
In particular, we consider the **detailed treatment of γ-γ absorption**

in the radiation fields of the BLR of these NLS1s

as a function of the location of the γ-ray emission region

as proposed by **Böttcher & Els+2016**

Gamma-gamma absorption (Böttcher & Els 2016)



Spherical, homogeneous shell BLR emitting within R_{in} and R_{out}

$$R_{\rm in} = 0.9\,R_{\rm BLR} \qquad R_{\rm out} = 1.1\,R_{\rm BLR}$$

Constraints on L_{BLR} and u_{BLR} from **direct observations**

Source Name	State	$L_{H\beta}$[a]	L_{disc}[b]
		[Foschini+2015]	
SBS 0846+513	High	1.32	3.94
PMN J0948+0022	High	3.73	11.8
	"Flare"	-	-
PKS 1502+036	High	0.41	1.12

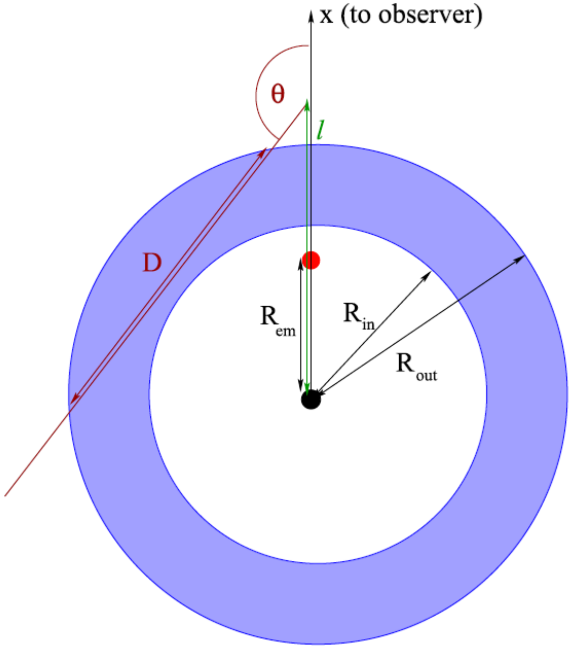
[a] x10^{42} erg s^{-1}. [b] x10^{44} erg s^{-1}.

$$R_{\rm BLR} = 3\times10^{17} L_{\rm disc,45}^{1/2} \quad [\rm cm]$$ [Bentz+2009]

$$L_{\rm BLR} = 21.2\, L_{H\beta} \quad [\rm erg\, cm^{-2} s^{-1}]$$ [Francis+1991]

$$u_{\rm BLR} = \frac{L_{\rm BLR}}{4\pi R_{\rm BLR}^2 c} \quad [\rm erg\, cm^{-3}]$$

Gamma-gamma absorption (Böttcher & Els 2016)



BLR properties adopted for the γ-γ absorption grids

Source Name	$L_{\rm BLR}$ (erg s^{-1})	$R^a_{\rm BLR}$ (cm)	$u_{\rm BLR}$ (erg cm^{-3})	$R^a_{\rm in}$ (cm)	$R^a_{\rm out}$ (cm)
SBS 0846+513	2.8×10^{43}	1.87	2.12×10^{-3}	1.69	2.06
PMN J0948+0022	7.91×10^{43}	3.26	1.98×10^{-3}	2.93	3.58
PKS 1502+036	8.69×10^{42}	1.00	2.29×10^{-3}	0.90	1.10

^{a}Radii in units of $\times10^{17}$ cm.

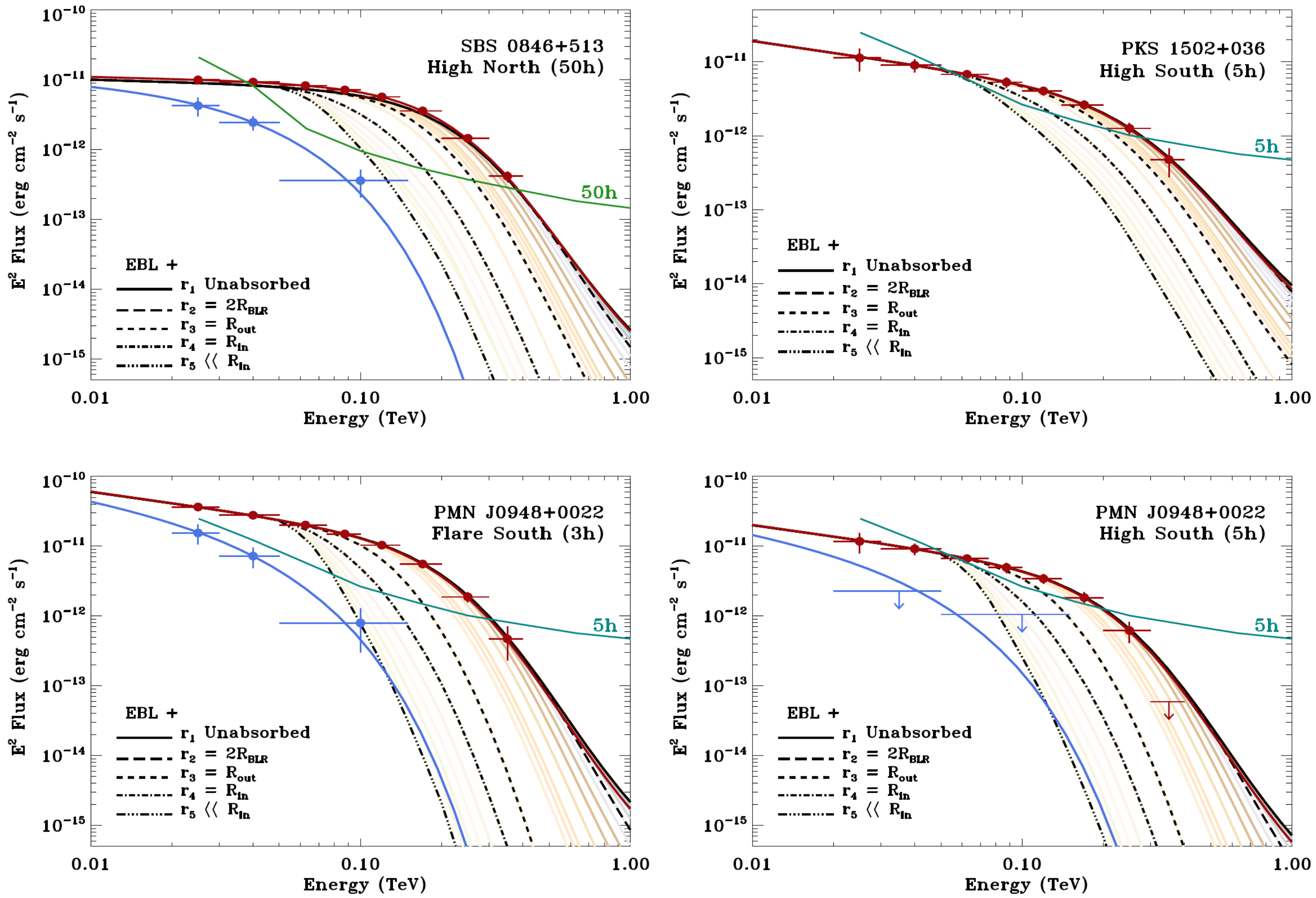
Grid of models for a range of $R_{em} \ll R_{in}$ to $R_{em} \gg R_{out}$, including:

Tailored for each source

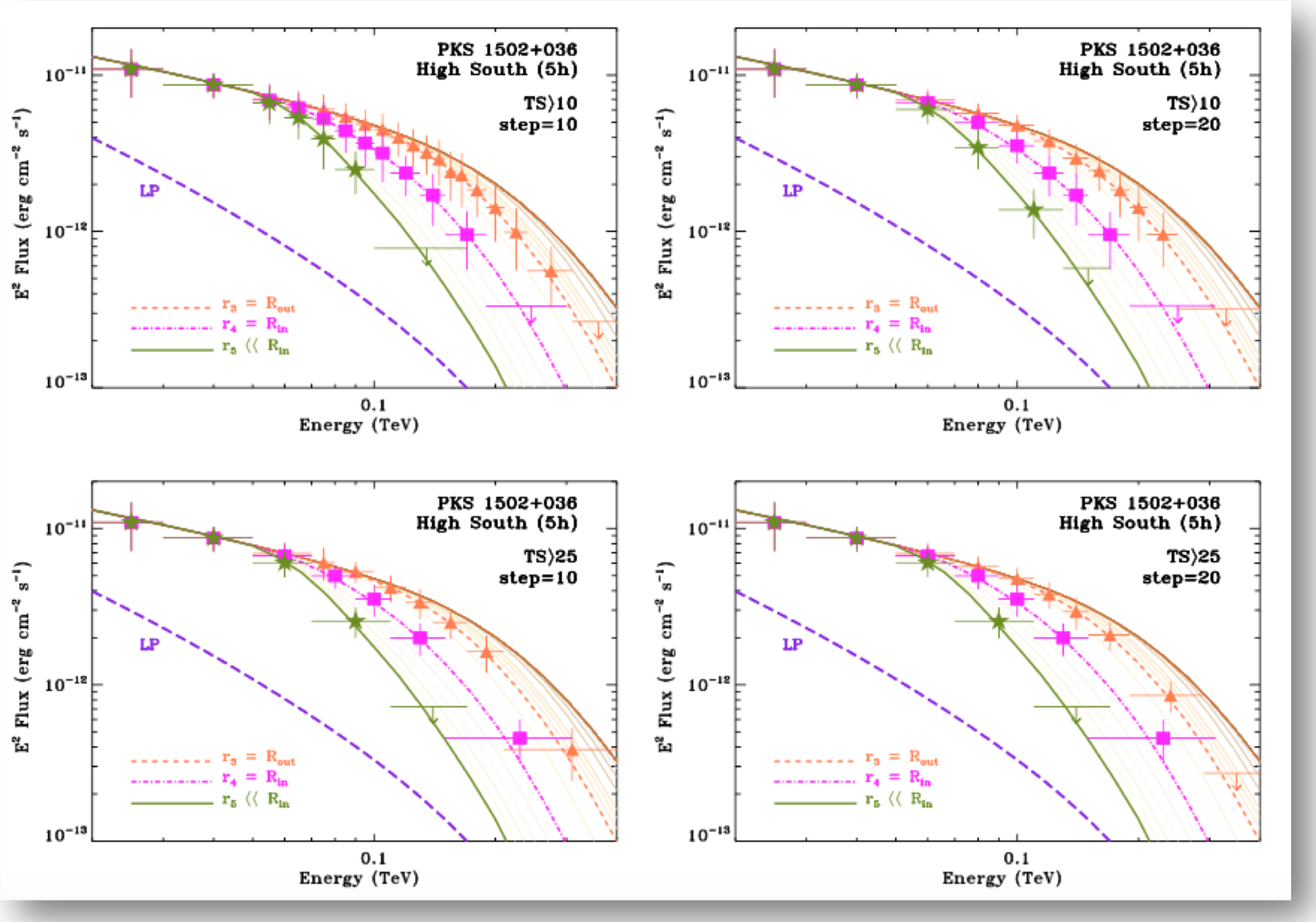
$$R_{\rm in} = 0.9\,R_{\rm BLR}$$
$$R_{\rm out} = 1.1\,R_{\rm BLR}$$

(i) $r_1 \gg R_{\rm BLR}$,
(ii) $r_2 = 2\,R_{\rm BLR}$,
(iii) $r_3 = R_{\rm out}$,
(iv) $r_4 = R_{\rm in}$,
(v) $r_5 \ll R_{\rm in}$.

Input models (BLR+EBL)



CTA can locate the gamma-ray emitting region



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