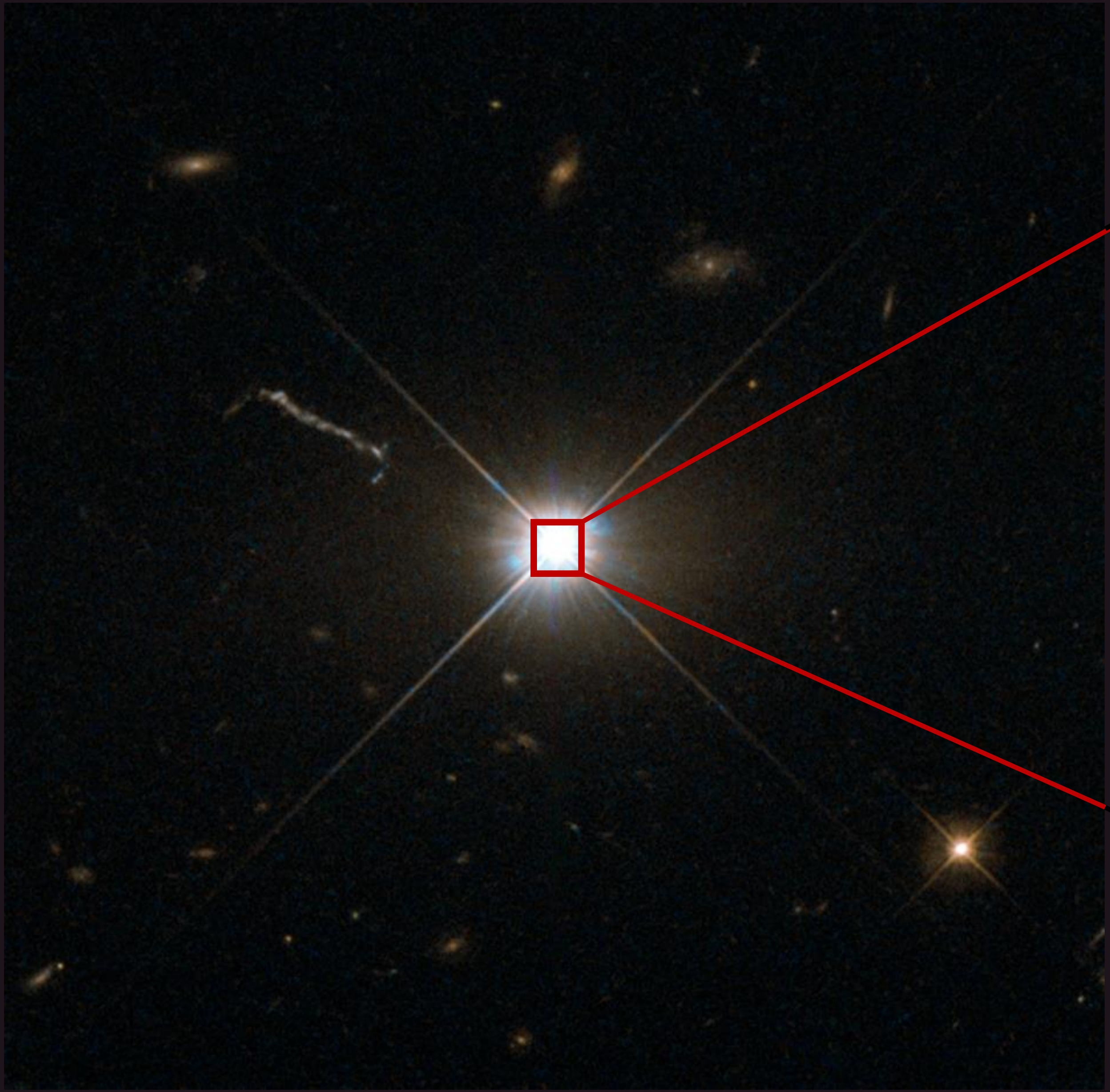
Imprint of “local opacity” effect on γ-ray spectrum of blazar jets

Constraining the sight of gamma-ray emission

Sushmita Agarwal

Amit Shukla, Karl Mannheim, Bhargav Vaidya, Biswajit Banerjee

Gamma 2024
Università di Milano "La Statale"
03 Sept 2024



nasa.gov/

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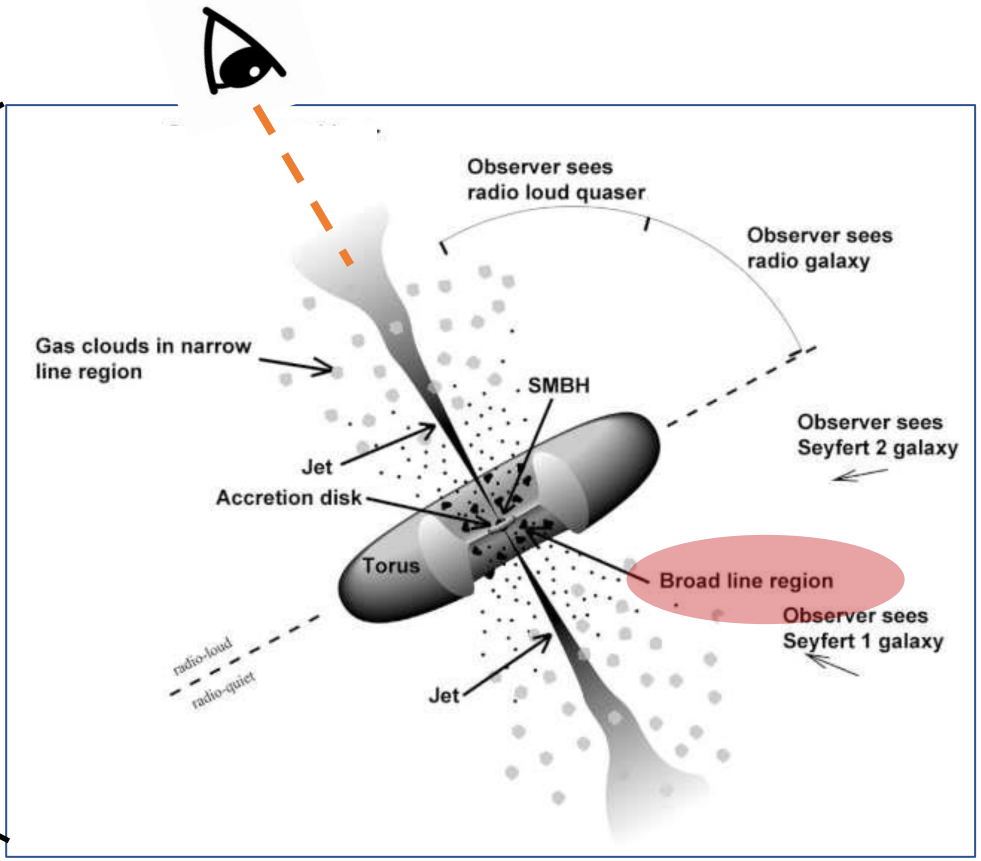
Blazars



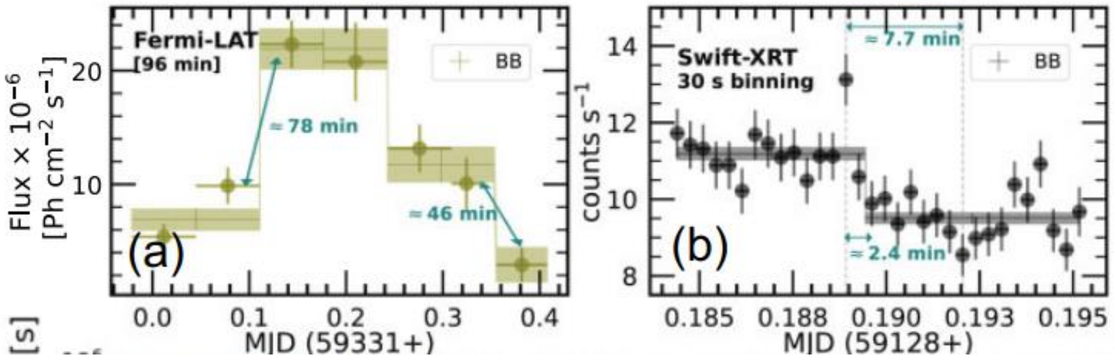
Urry & Padovani (1995)

1. Flat Spectrum Radio Quasar [FSRQ] – Strong optical emission lines

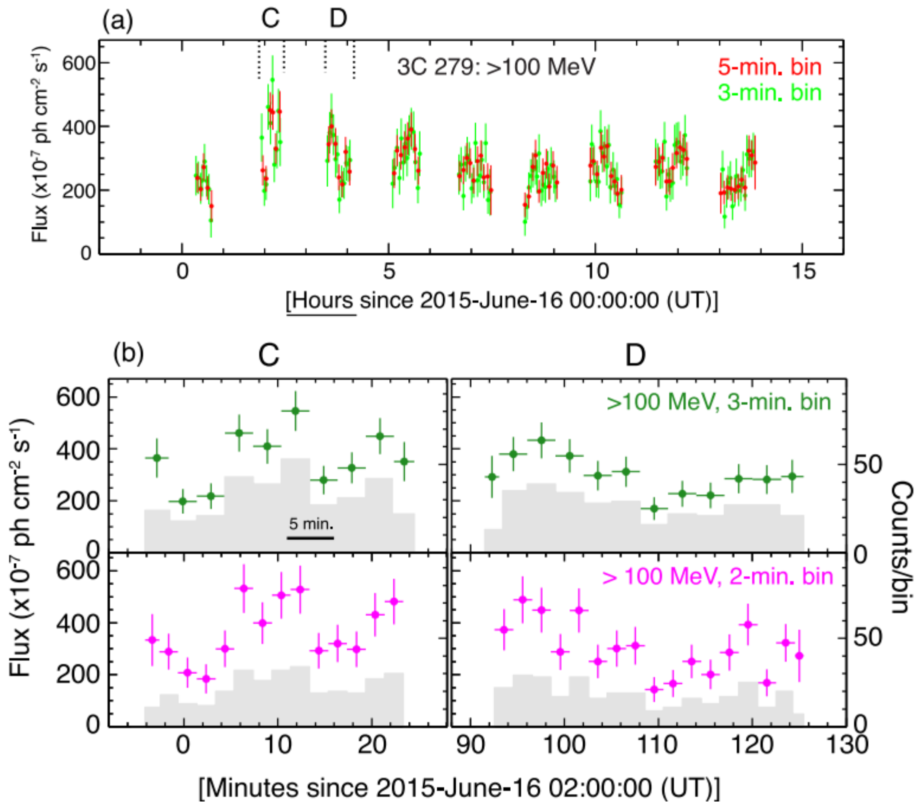
2. Bl Lac – Weak or no optical lines

Rapid Variability in Blazar

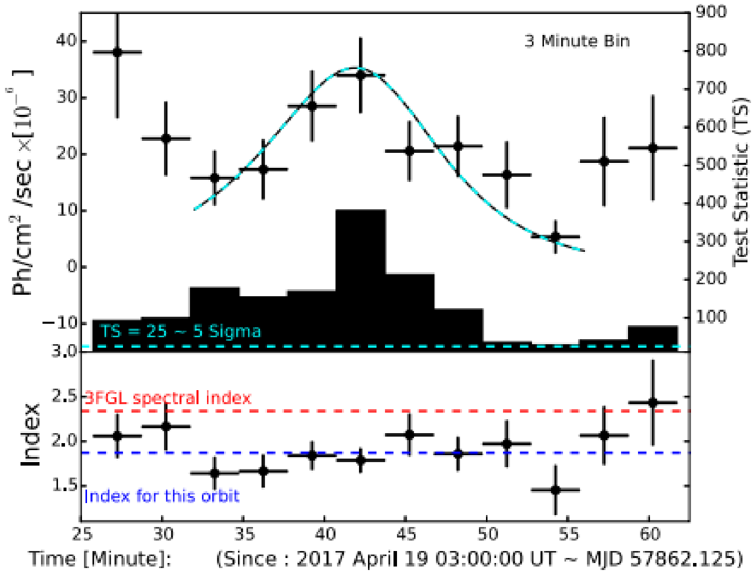
Agarwal et al. 2023



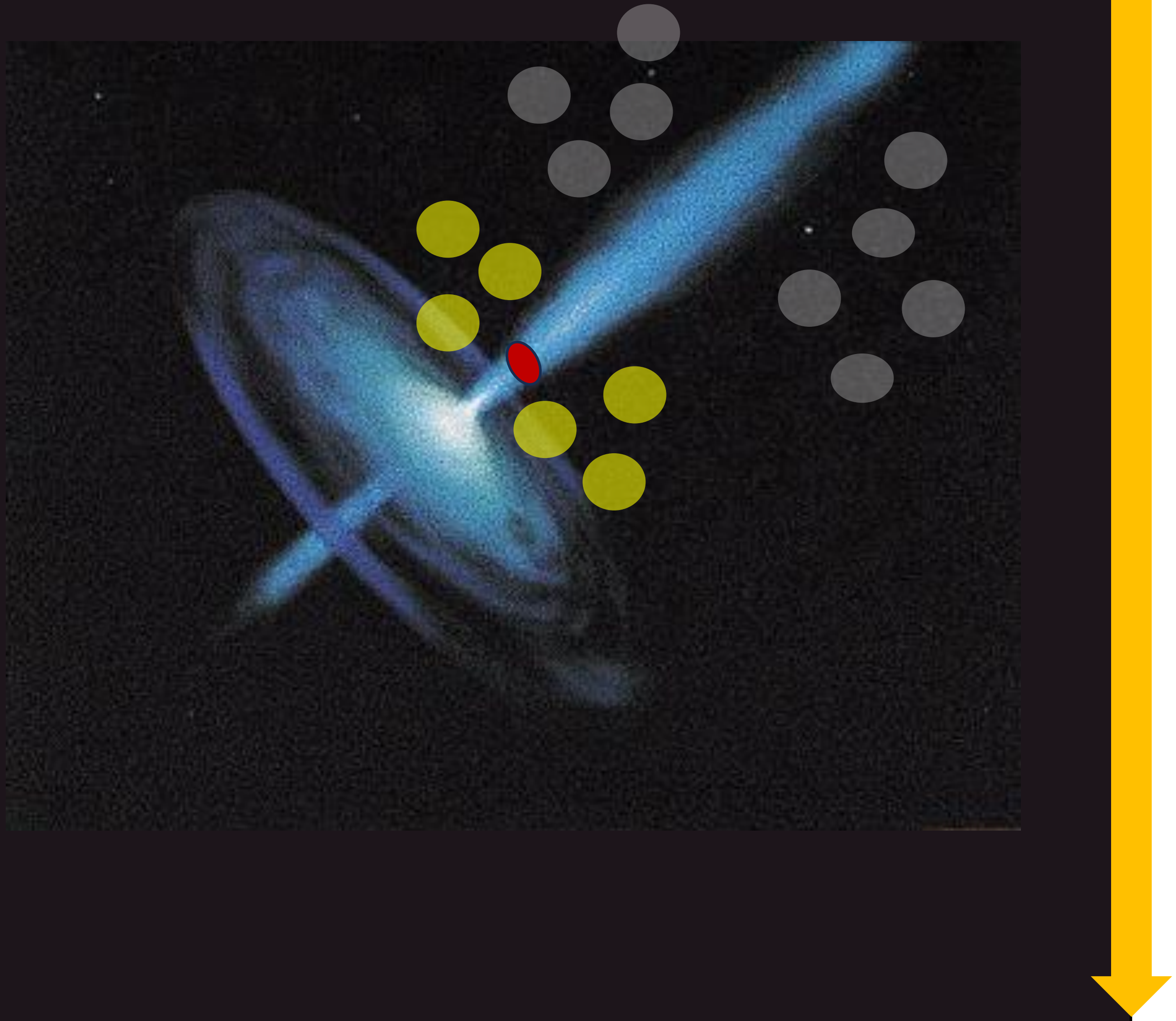
Blazars show variability less than size of Black hole → Small γ-ray emission region



Ackermann et al. 2016



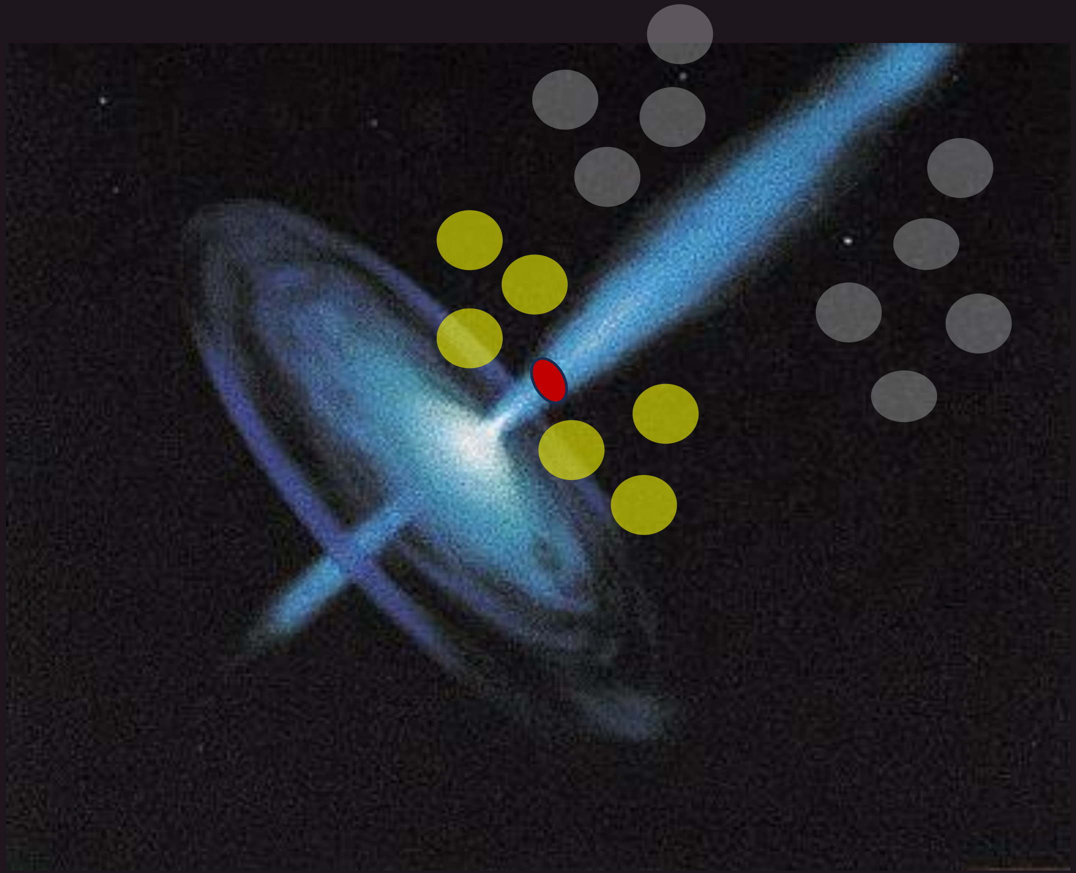
Shukla et al. 2018



Location of γ-ray emission region in FSRQ?

Observed Fast variability in GeV/TeV bands

Small emission zone in Blazar jet



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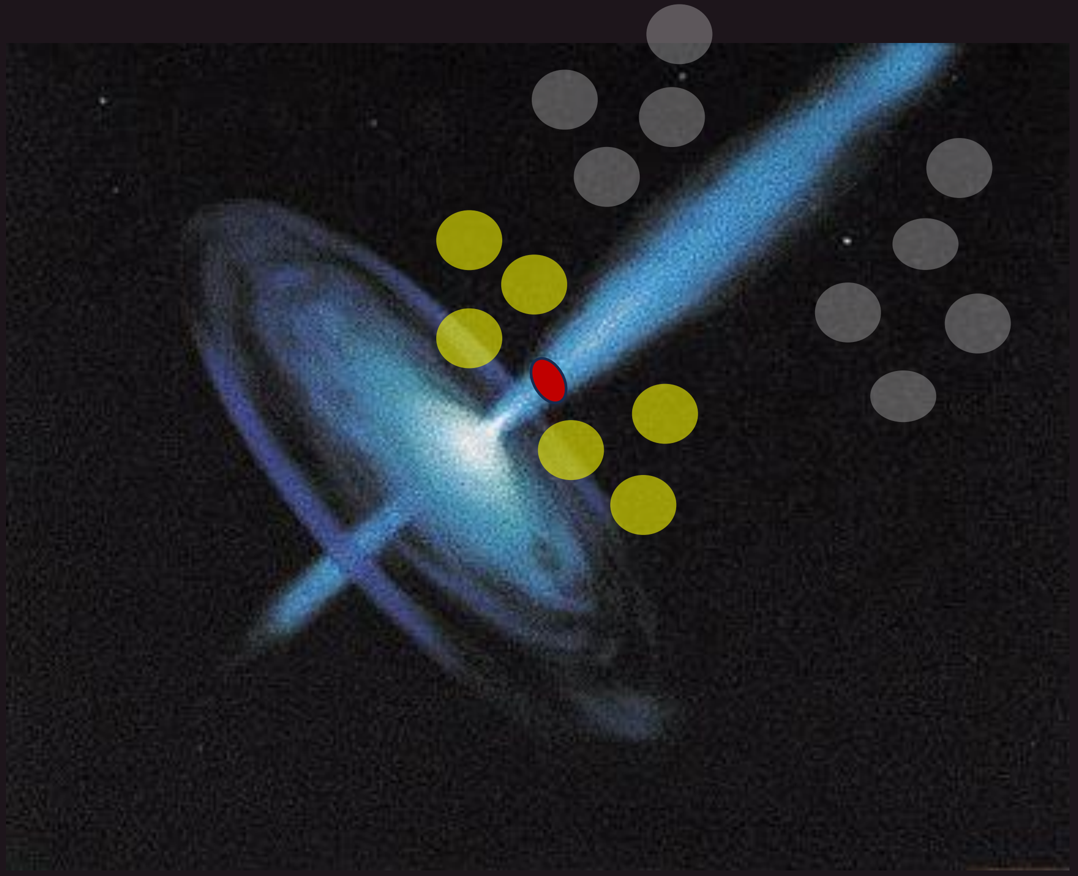
Emission close to the base of the jet?



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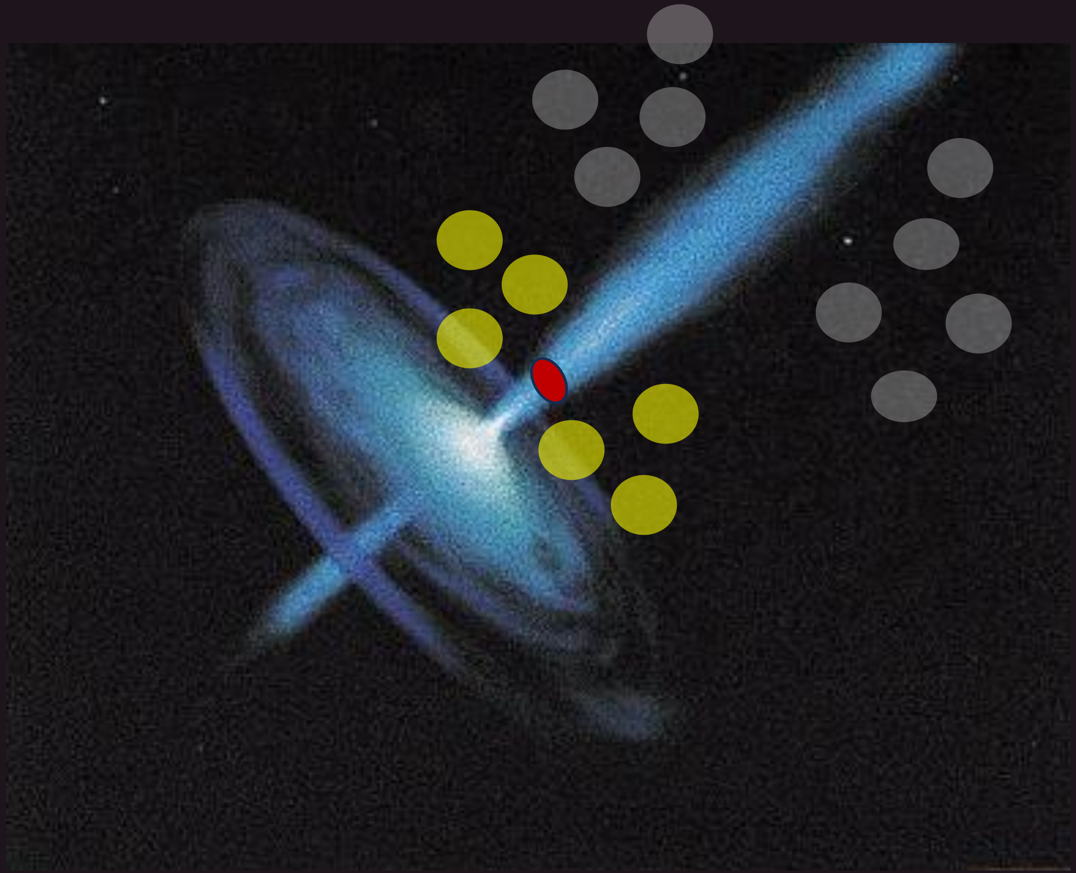

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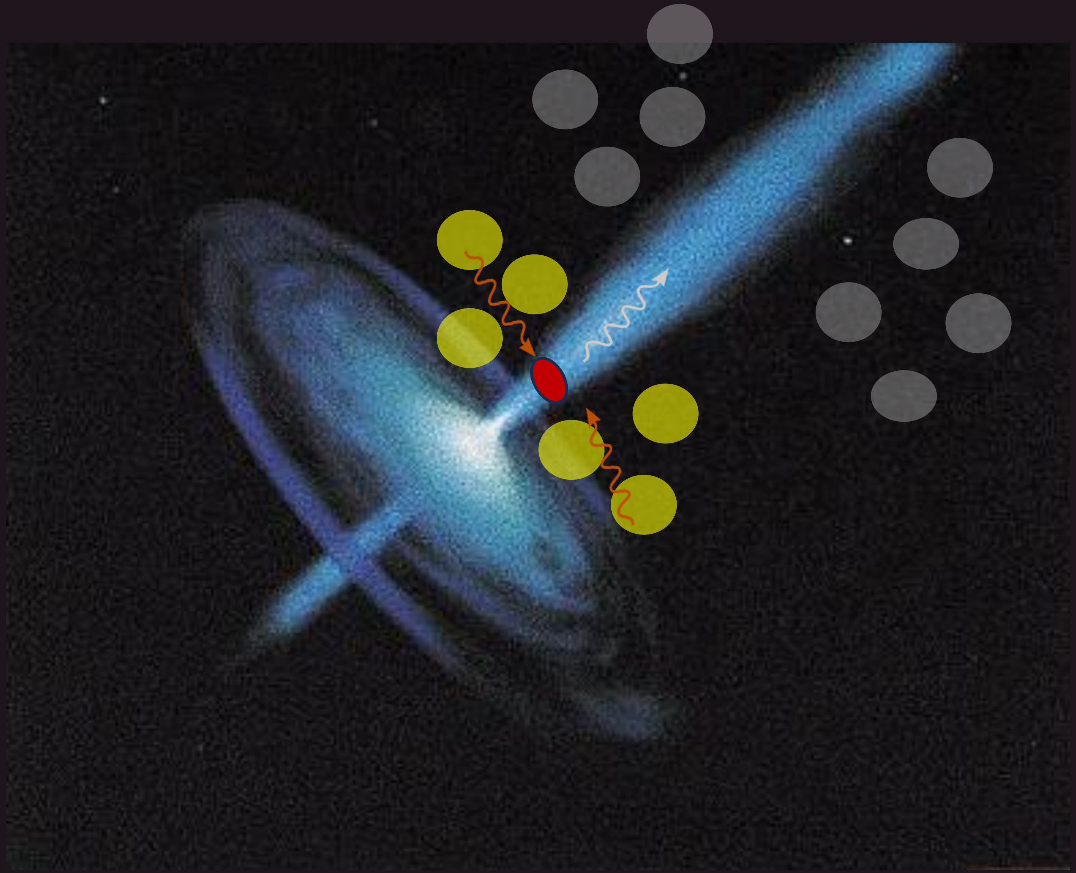

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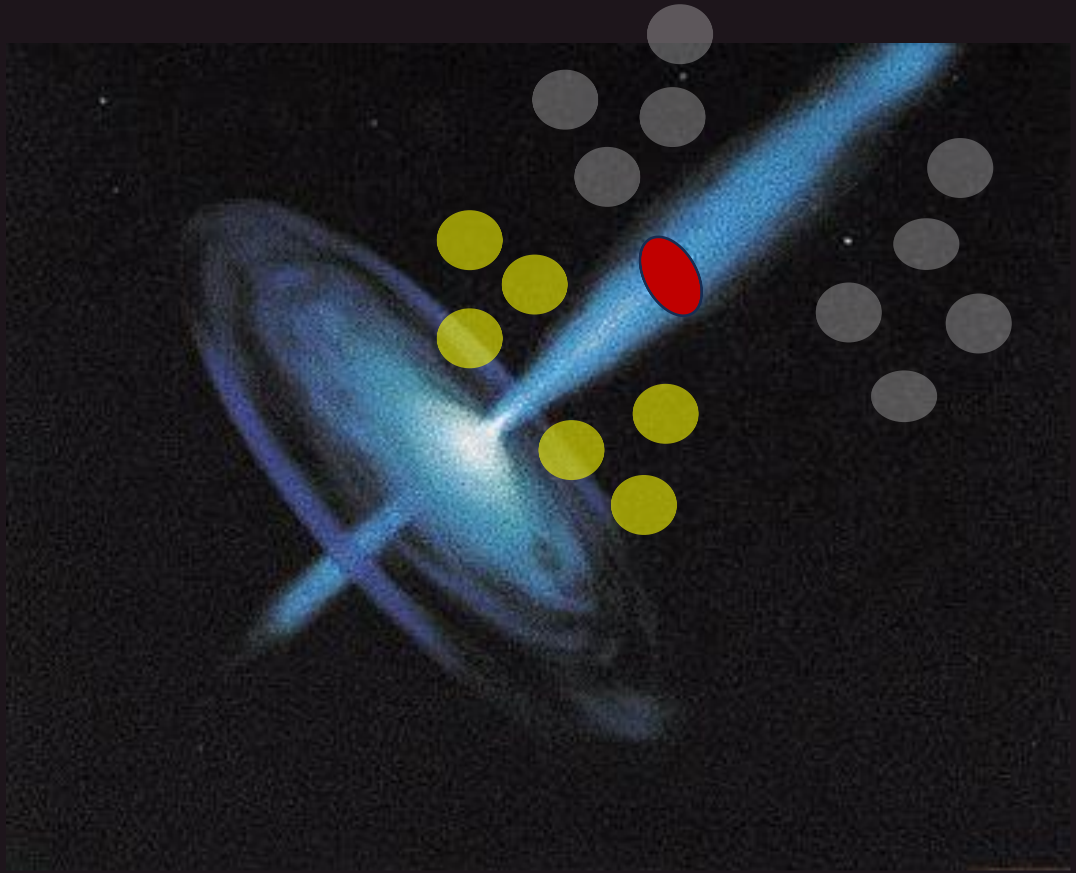
INSIDE BLR:
Chances of gamma-gamma photon absorption from BLR photon



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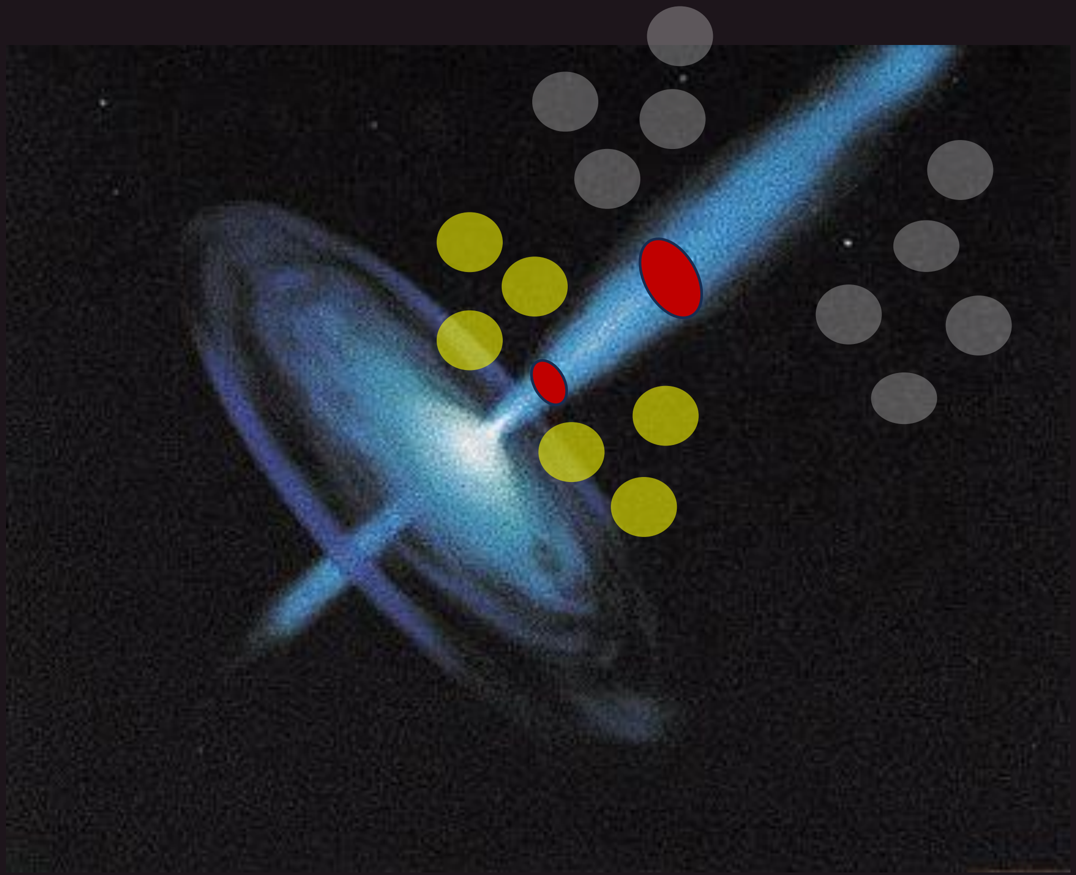
OUTSIDE BLR:
Lack of seed photon to produce strong Compton hump

Location of γ-ray emission region in FSRQ?



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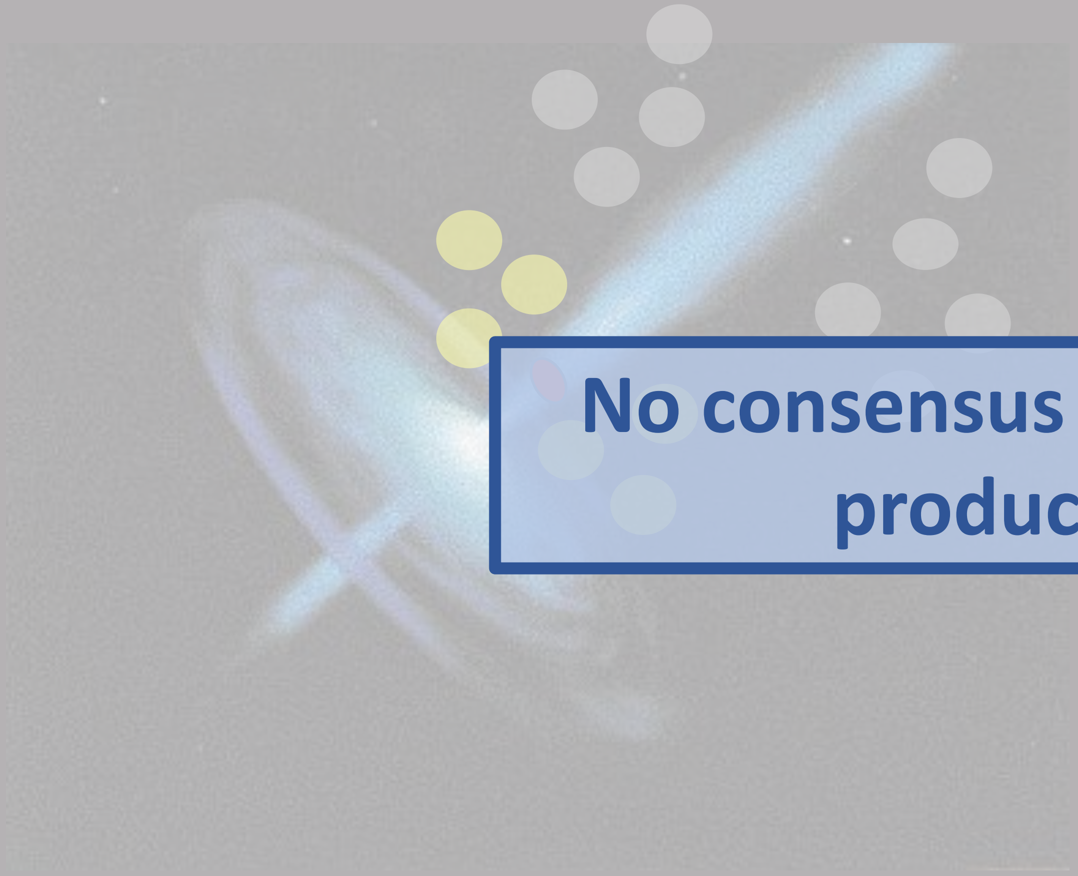

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No consensus on site of gamma-ray production in Blazars

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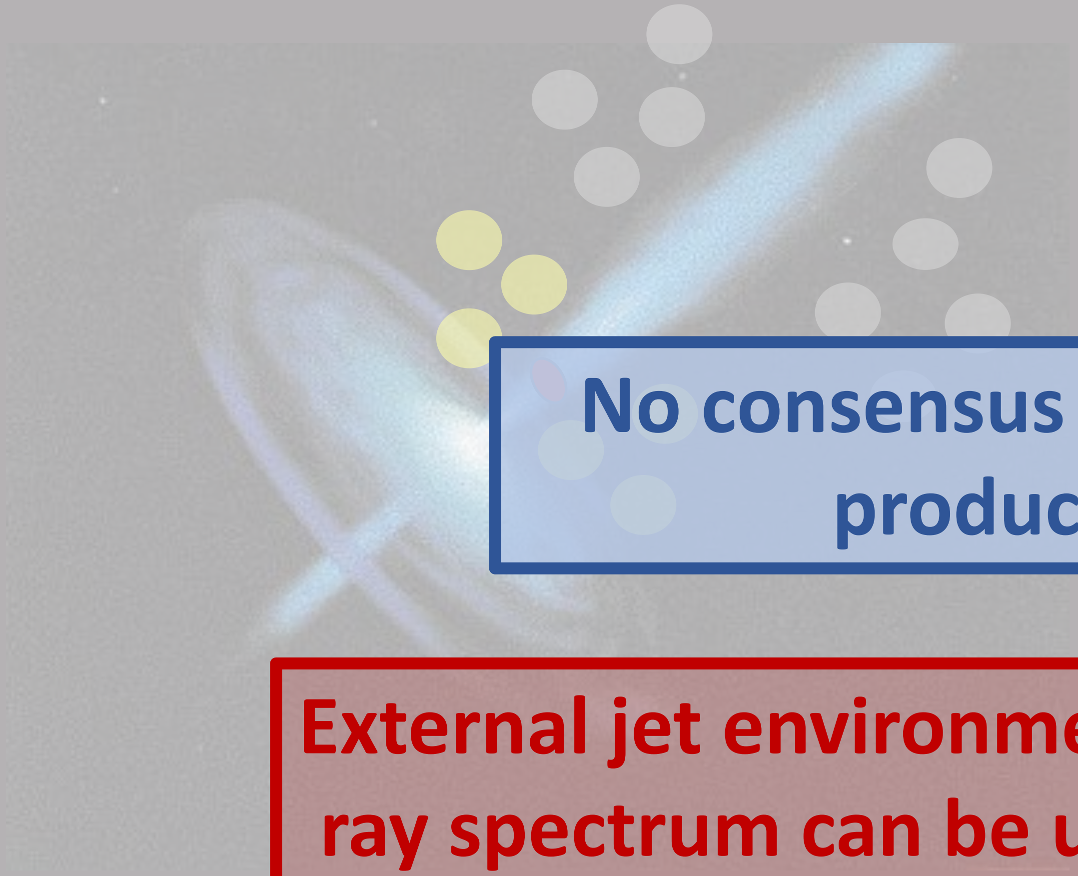

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No consensus on site of gamma-ray production in Blazars

External jet environment and its influence on gamma ray spectrum can be used as a proxy for deciphering origin of gamma-rays

Idea

High Black hole mass FSRQ

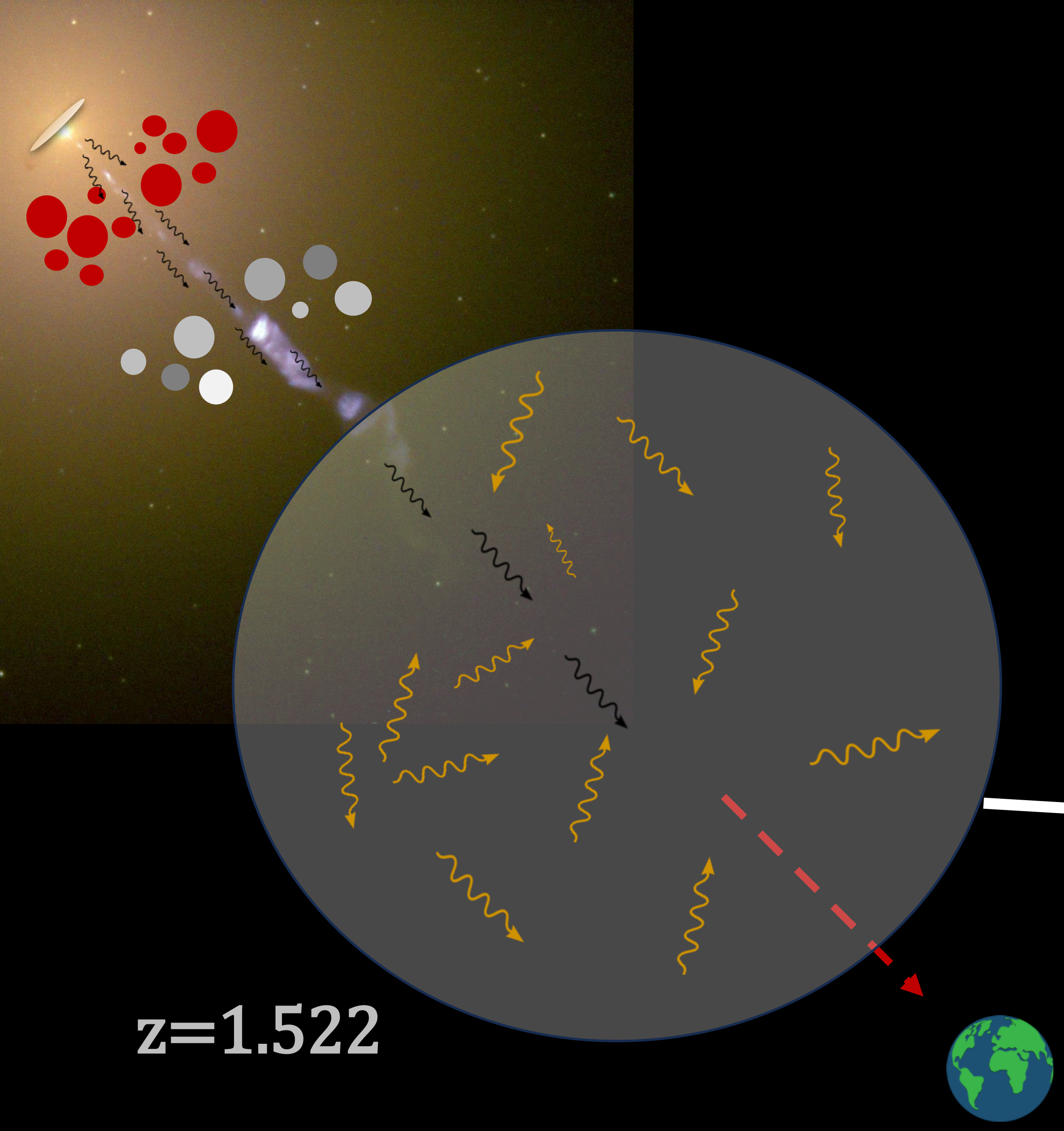
+

Possibily flaring for a fairly long time

+

Improve photon statistics

PKS 1424-418 | z=1.522 | $M_{BH} = 4.5 \times 10^{9} M_{\odot}$



M87 emitting a relativistic jet [Credits: Nasa]

More Massive Black hole → More disk Luminosity → More BLR Luminosity → More γ-ray Absorption??

Influence of Extragalactic background light (EBL) → More γ-ray Absorption??

PKS 1424-418 (z=1.522)

Absorption signature at E = 40 – 95 GeV

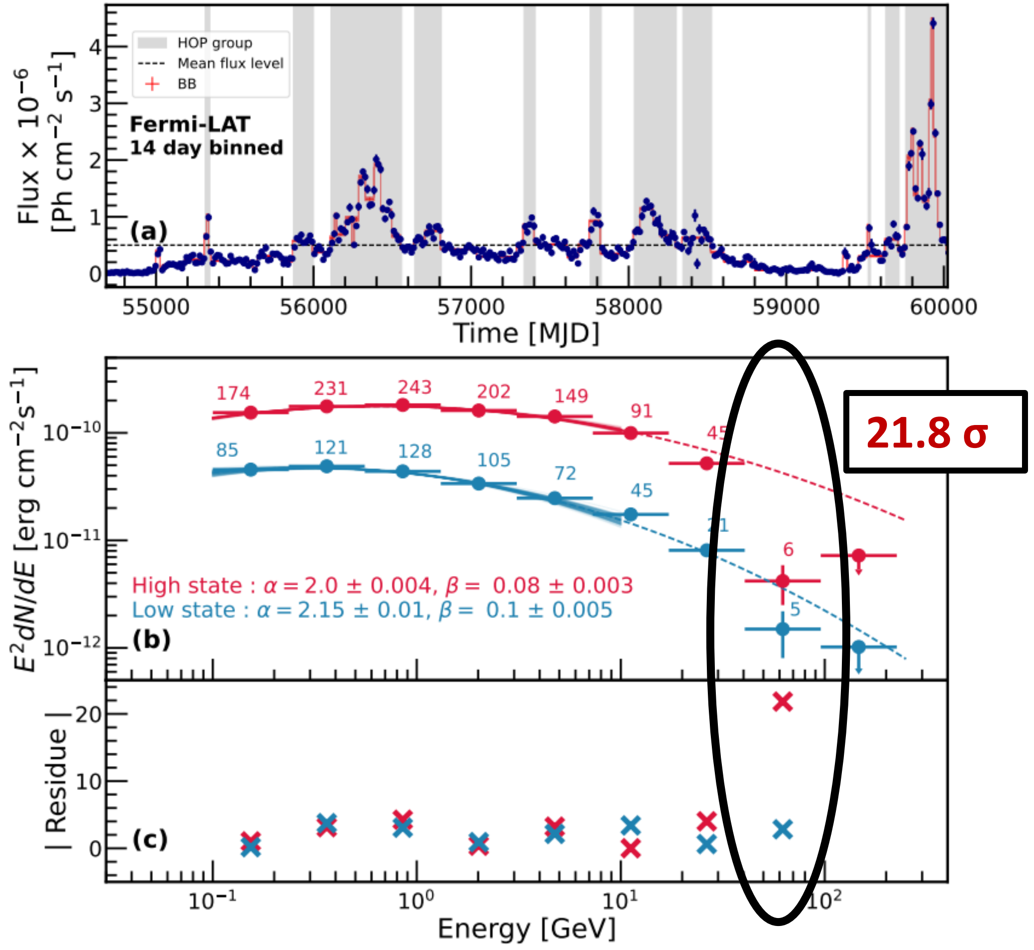


Fig: (a) Fermi-LAT LC of PKS 1424-418 for 16 years of Fermi era (MJD 54683-60024). (b) The combined spectrum for all photons in high state (grey patches (a)) and low state (white patches in (a)). (c) Residual for each energy bin

Exploring the Origins of absorption feature

1. EBL absorption

Gamma ray photons are optical thin to EBL upto

$$E_{crit} = 170\,(1+z)^{-2.38}\text{GeV} = \mathbf{18.8\ GeV}$$

2. BLR absorption

Lyα influence spectrum beyond **10 GeV.**

Gamma ray spectrum from 100MeV – 10 GeV

↓

TRUE INTRINSIC SPECTRUM OF THE SOURCE

Exploring the Origins of absorption feature

EBL absorption

1. **Low state**
   EBL Models FIT well!

2. **High state**
   Extra absorption feature beyond 10 GeV in addition to EBL model

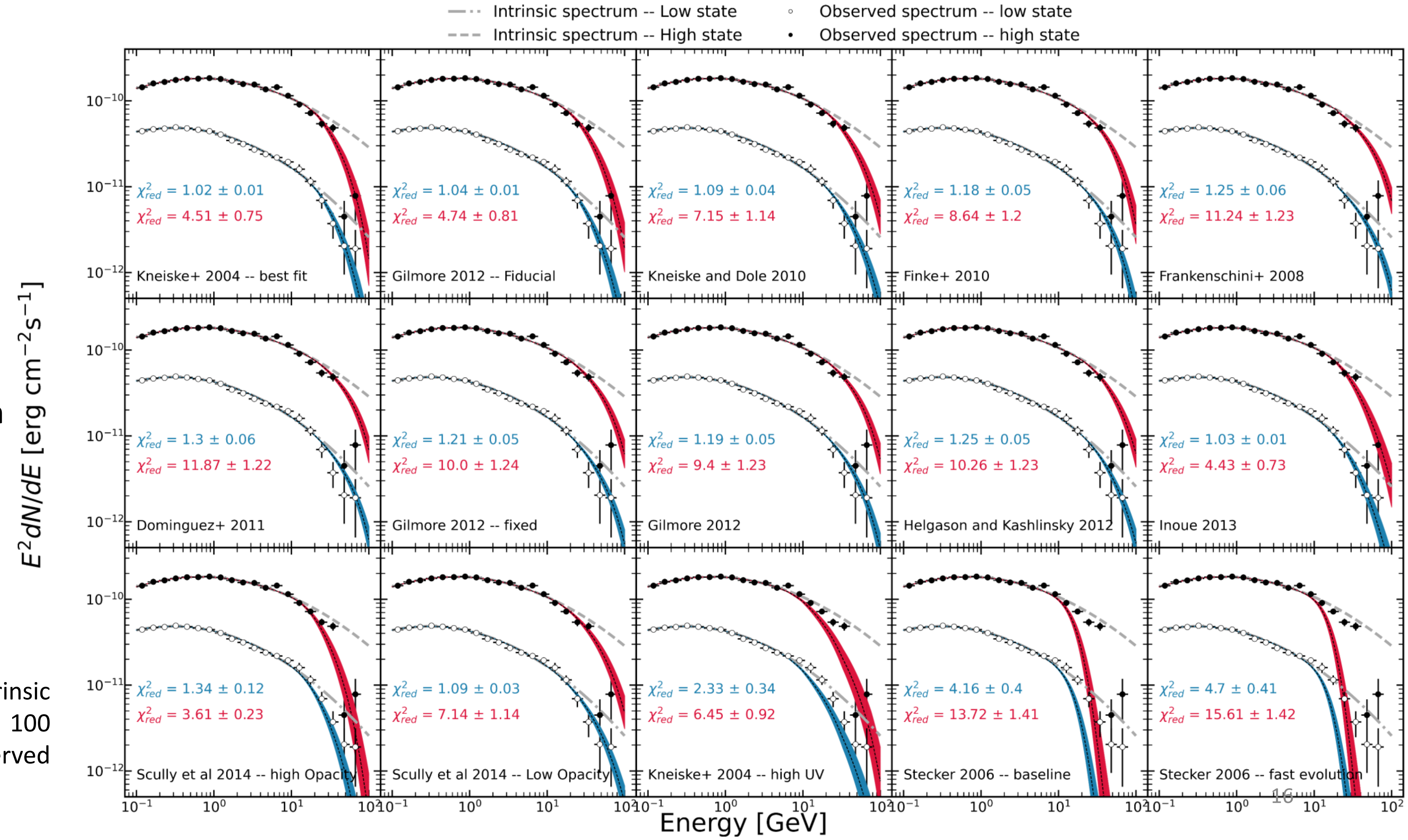
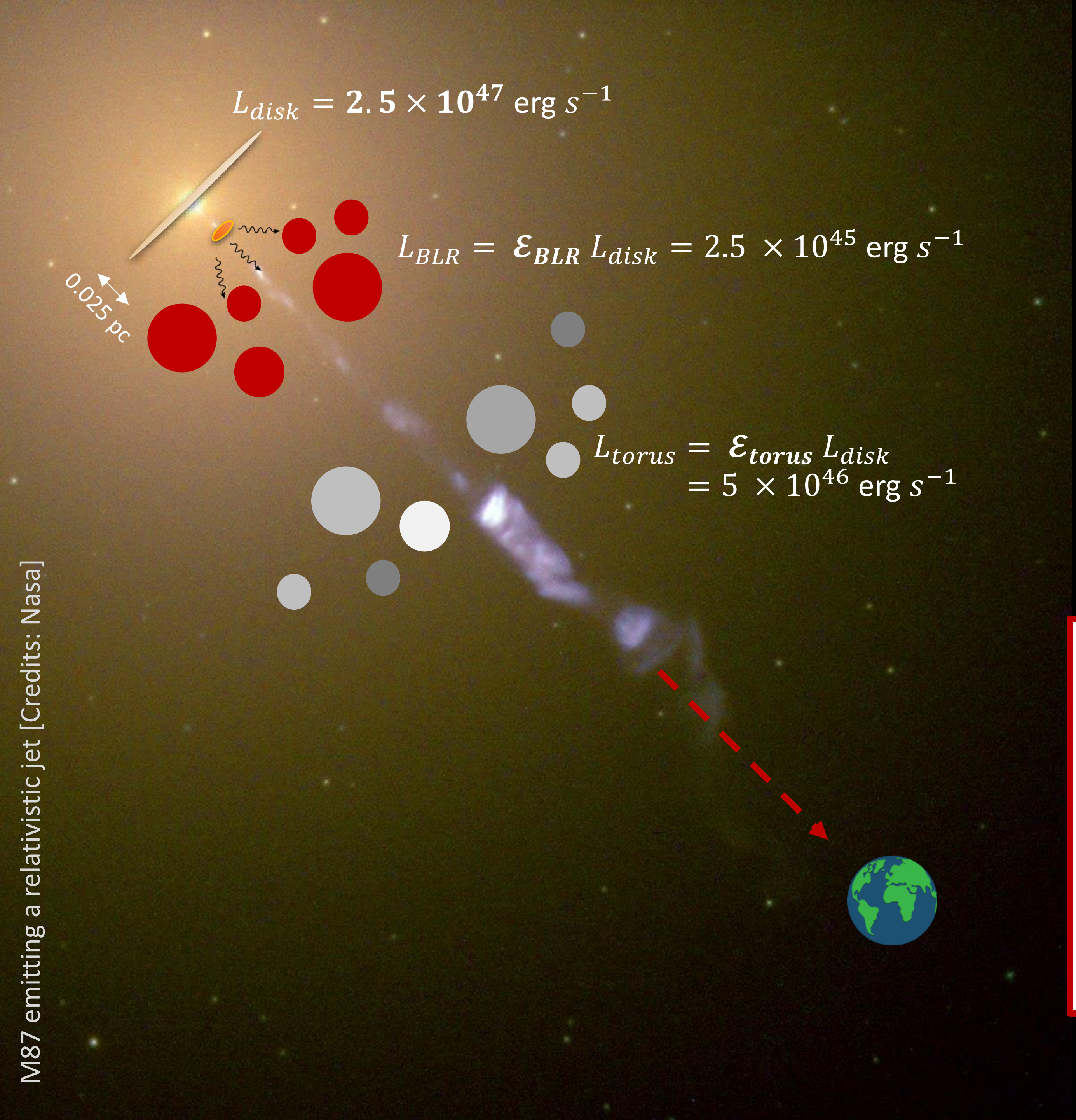


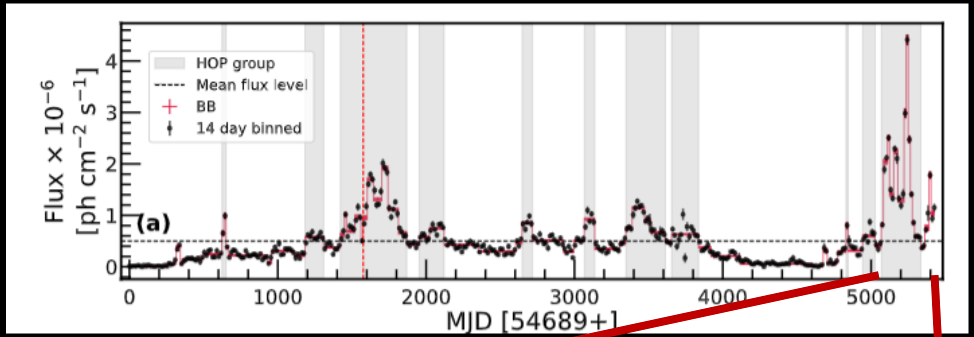
Fig: EBL absorption on intrinsic spectrum extrapolated upto 100 GeV and compared with observed spectrum for 15 EBL models



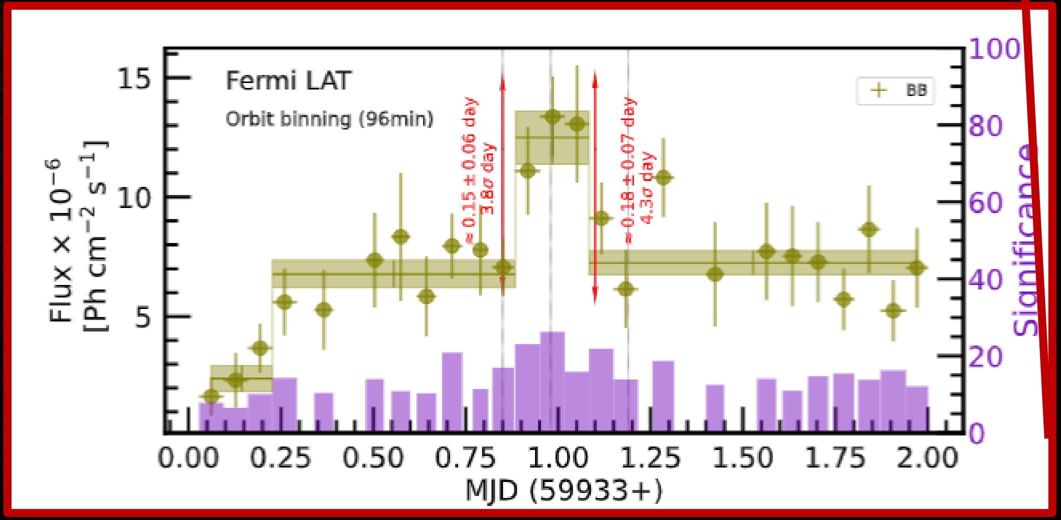
M87 emitting a relativistic jet [Credits: Nasa]

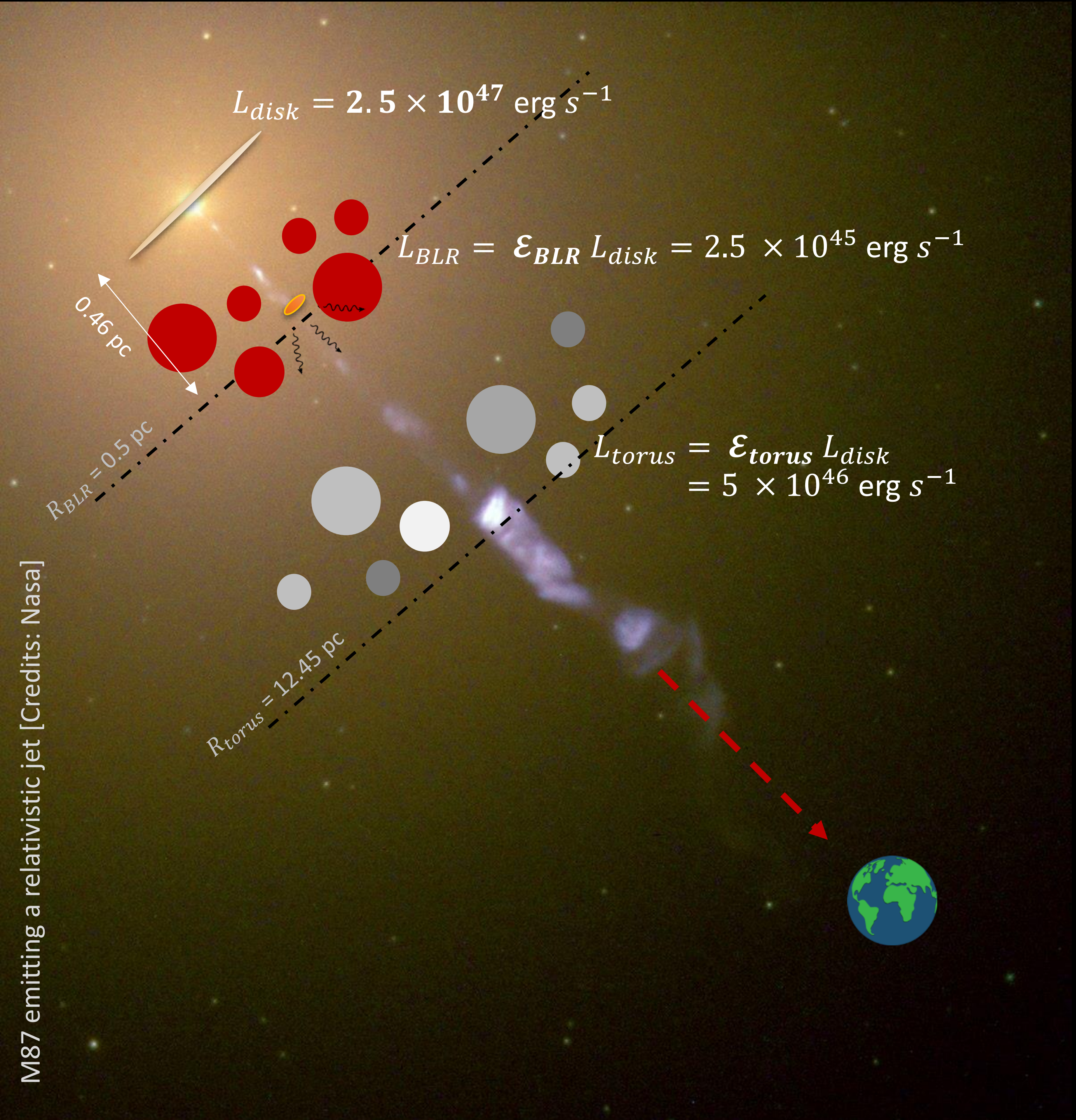
PKS 1424-418 (z=1.522)

Observational constraints



$t_{var} = 0.15 \pm 0.06$ day





PKS 1424-418 (z=1.522)

Observational constraints

1. BLR is optical thick to photons E > 10 GeV
2. Torus is optical thick to photons with E> 345 GeV

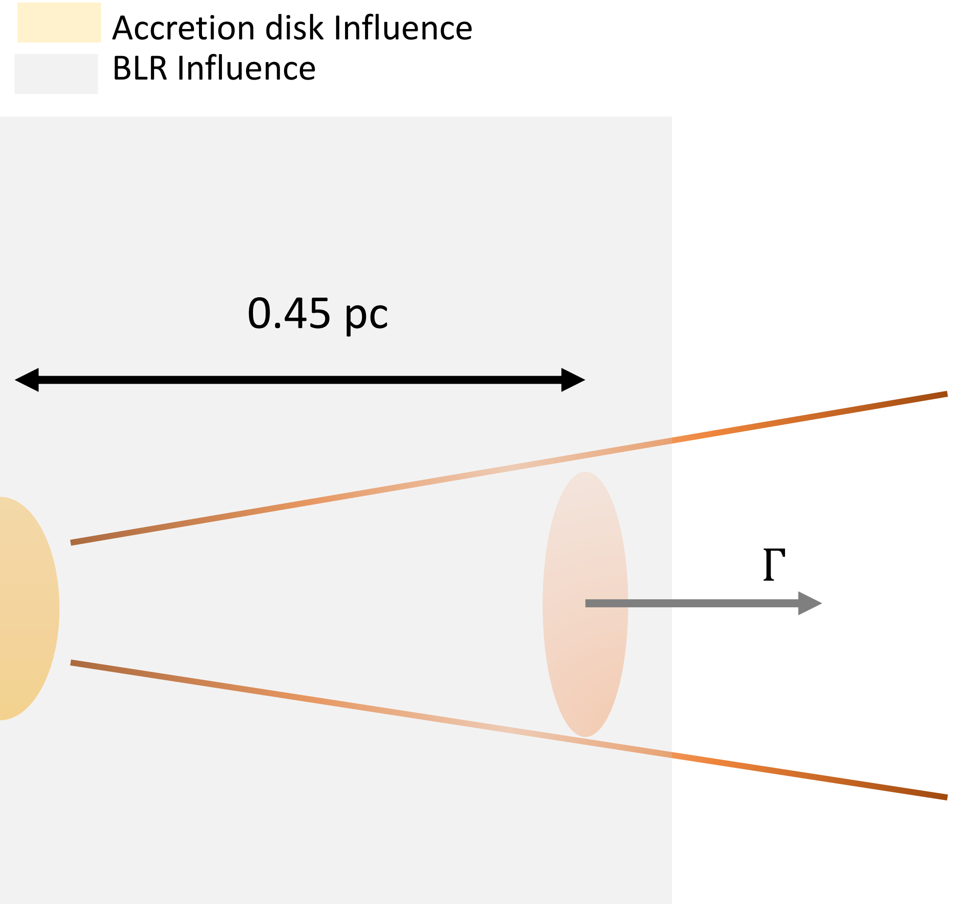
Several photons with E > 15 GeV detected

Highest energy photon = 65 GeV

Other possible origin

Fast variability

- **Observed variability:** 0.15 days
- **Dissipation distance >** 0.025 pc
- **Observed highest energy photon** = 65 GeV
- Location of emission zone at R > 0.45 pc



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- **Observed variability:** 0.15 days
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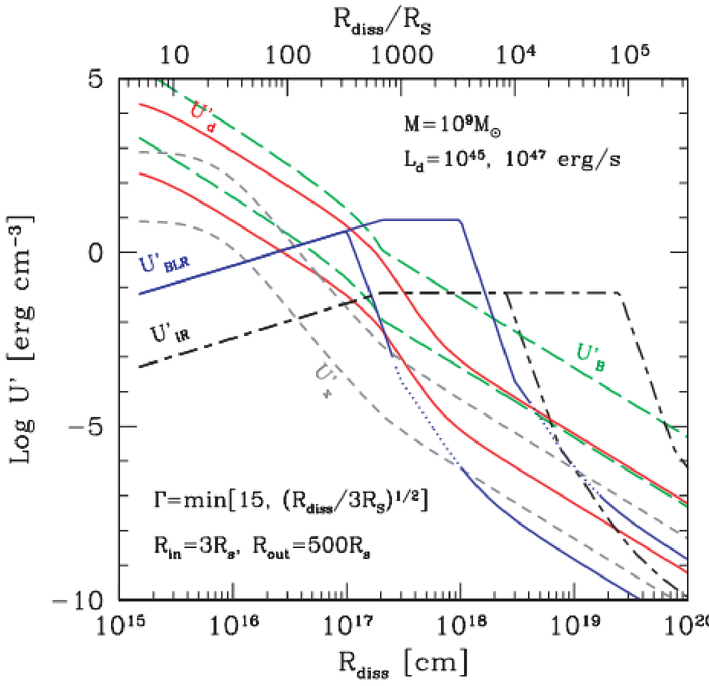
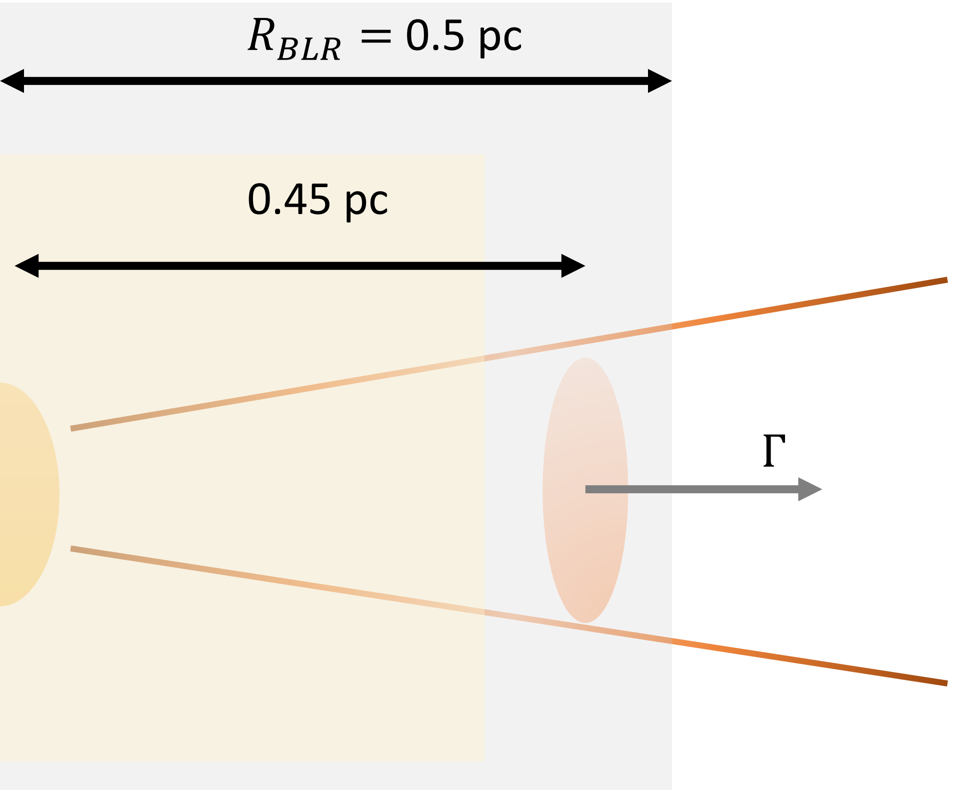
- Location of emission zone at **R > 0.45 pc** ← **Edge of BLR**



Ghisellini 2015

Accretion disk Influence

BLR Influence



$$s = \frac{\varepsilon_{soft}\varepsilon_\gamma\,(1+z)(1-\cos\theta)}{2\,(\,m_e\,c^2\,)^2}$$

For Pair production: s < 1

$$E_{th} = \frac{2\,(\,m_e\,c^2\,)^2}{\varepsilon_{soft}(1+z)(1-\cos\theta)}$$

Other possible origin

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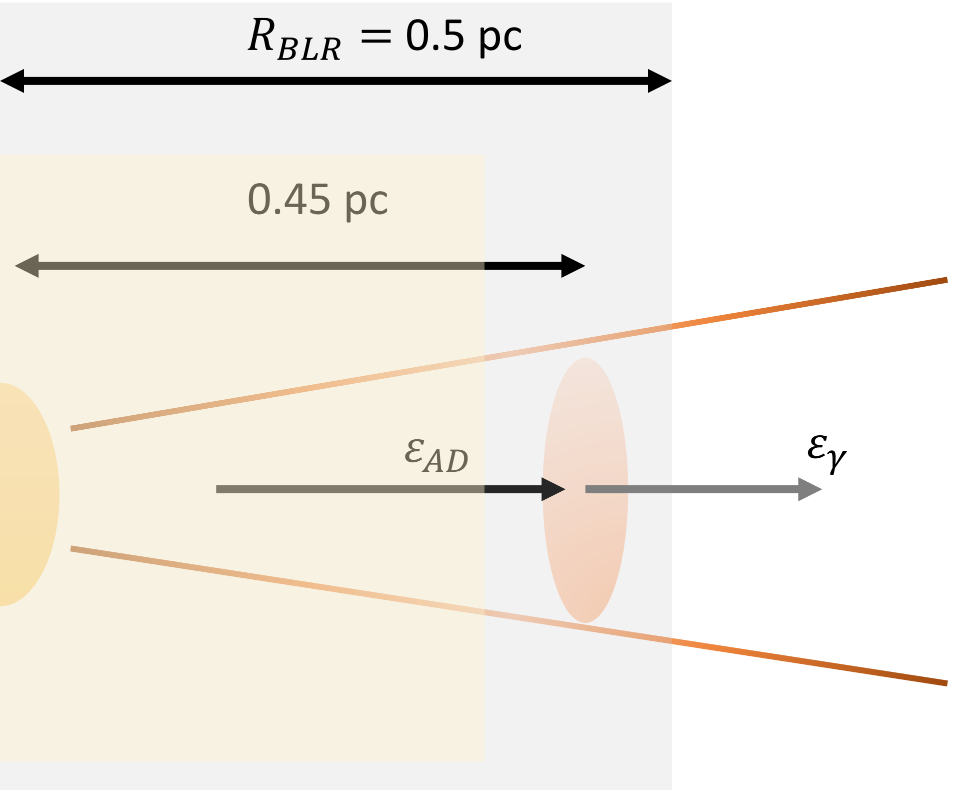

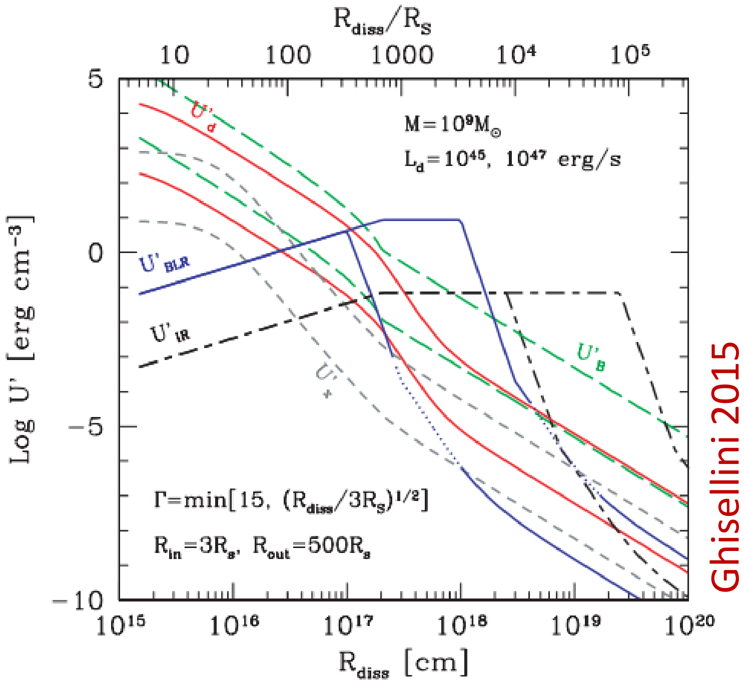

Ghisellini 2015

Contribution from accretion disk?

More chances of tail on collision from accretion disk photon.

Pair absorption extremely unlikely

Other possible origin

Fast variability

- **Observed variability:** 0.15 days
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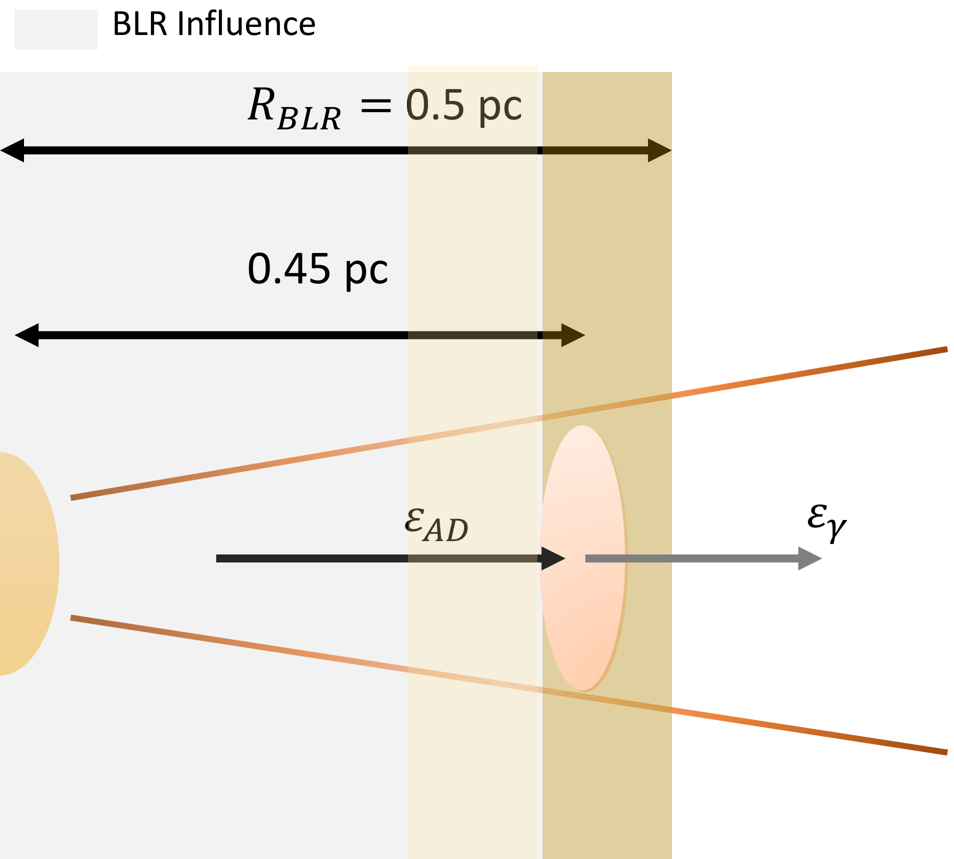


Contribution from BLR?

1. The blob lies towards the edge of BLR
2. Low ionized molecular clouds reside at the edge of BLR
3. **Absorption from 40 – 70 GeV** could be from low ionization **Hα or $H\beta$** at outer edge of BLR.
4. **Absoprtion from 10 – 30 GeV** could be from low ionization **hydrogen Lyα or Ly continumm**.

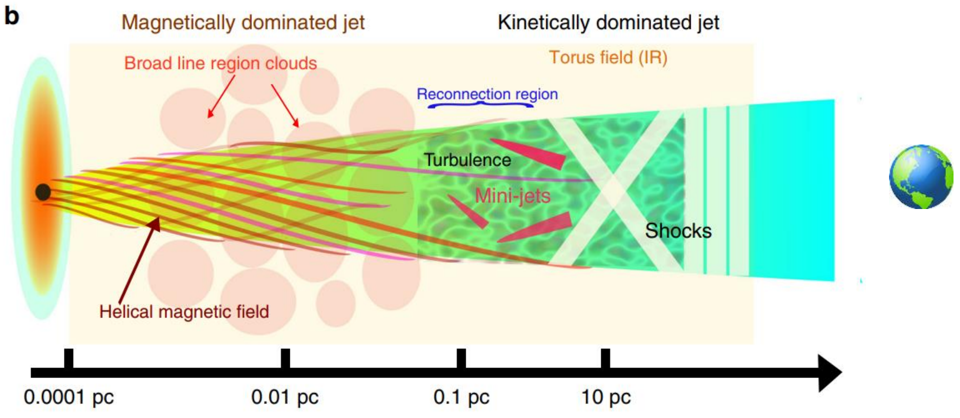
Takeaways

Possible contribution from outer edge of BLR

- **Emission region located at the edge of BLR** as also observed by Stern and Poutanen 2014.
- The observed absorption at E > 10 GeV possibly because of low ionization lines located at the edge of BLR.
- **Prominent absorption feature present specifically during the high state of the source in contrast to its absence in low flux states**
- **Powerful dissipation events within or at the edge of the BLR evolve into fainter gamma-ray emitting zones outside the BLR.**
- Similar flux resolved searches with improved photon statistics needed for other high mass Black hole FSRQs.

Bl laceratae (Agarwal et al 2023, MNRASl)

Shift in broadband spectrum



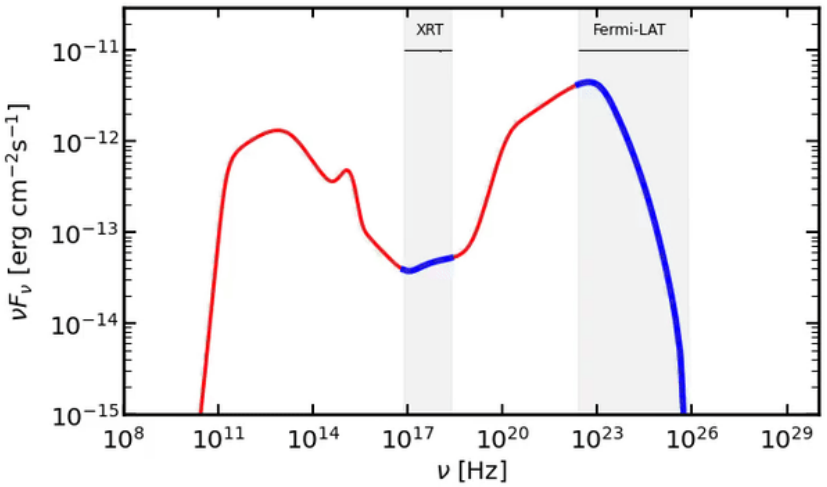


Fig: (Top) A representation of site of magnetic reconnection [Shukla et al 2020]. (Bottom) Representation of the shift in SED due to specific alignment of jets

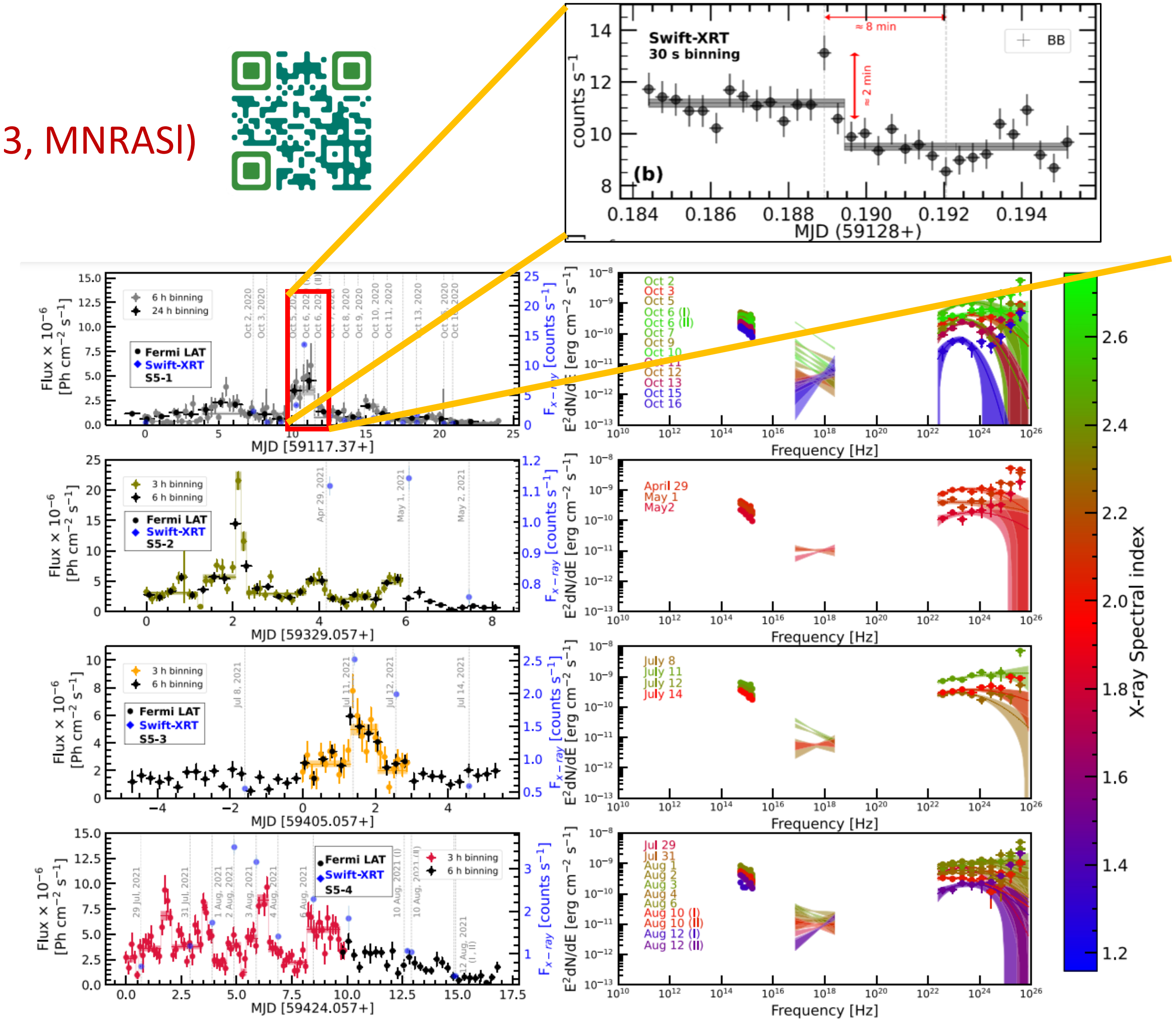
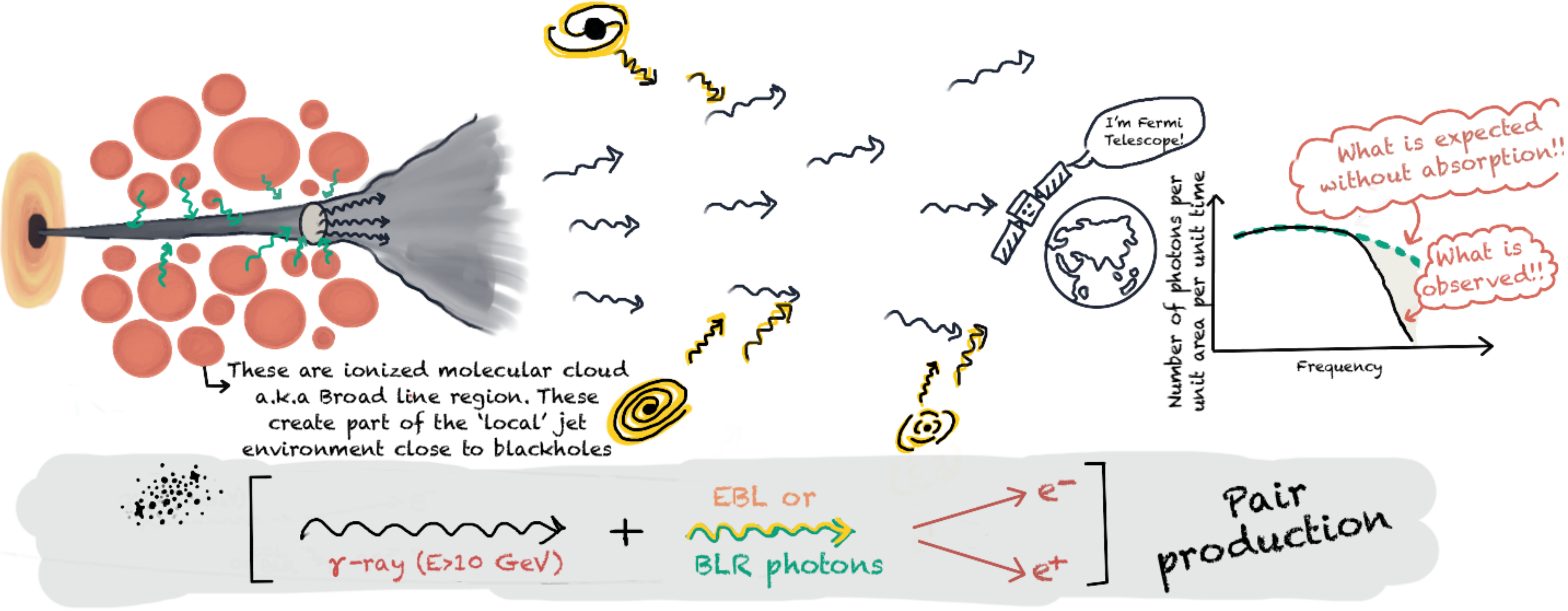


Fig: The multiwavelength spectral energy distribution (SED) for the four activity state studied in the work : S51, S52, S53, S54. The flux evolution (left) and corresponding SED for selected epochs (Right)

Thank you!!



This work

Other work

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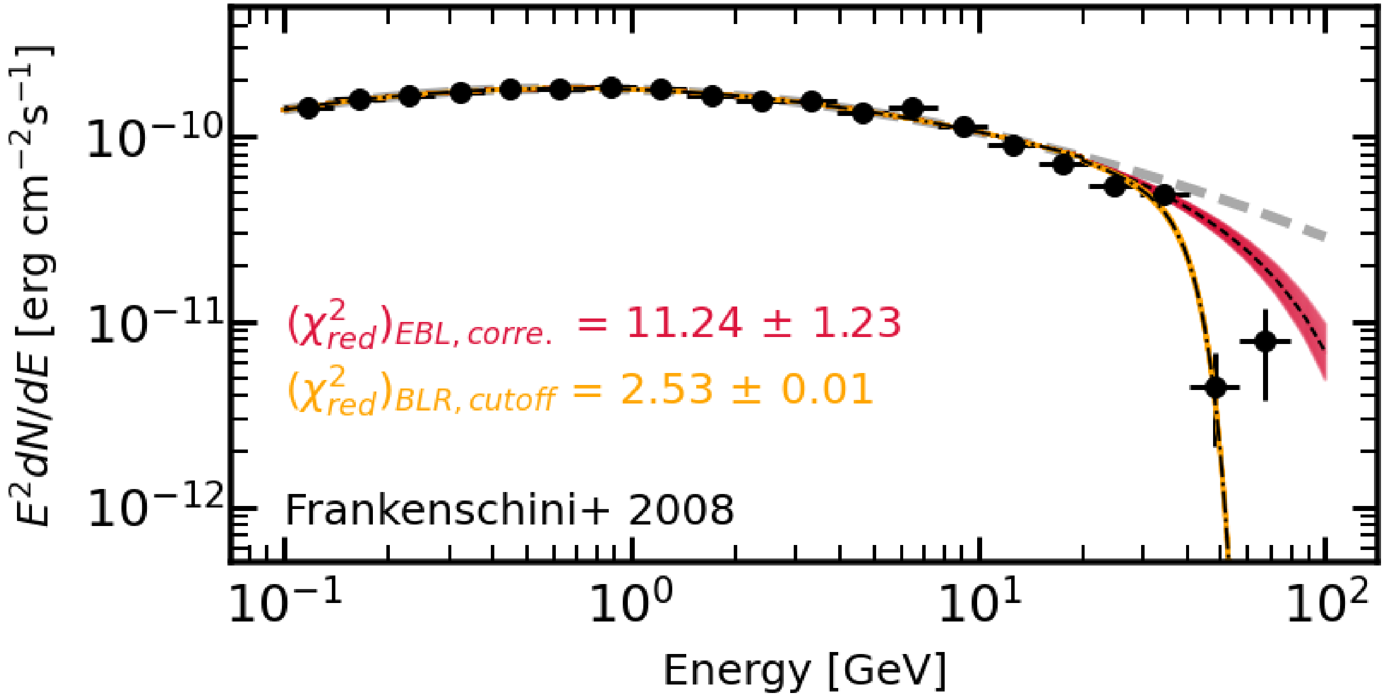
Backup

BLR cutoff + EBL absorption

$$\frac{dN}{dE} = EBL\, absorbed\, spectrum \;*\; exp\left(- \left(\frac{E}{E_o}\right)^{\beta_c} \right)$$



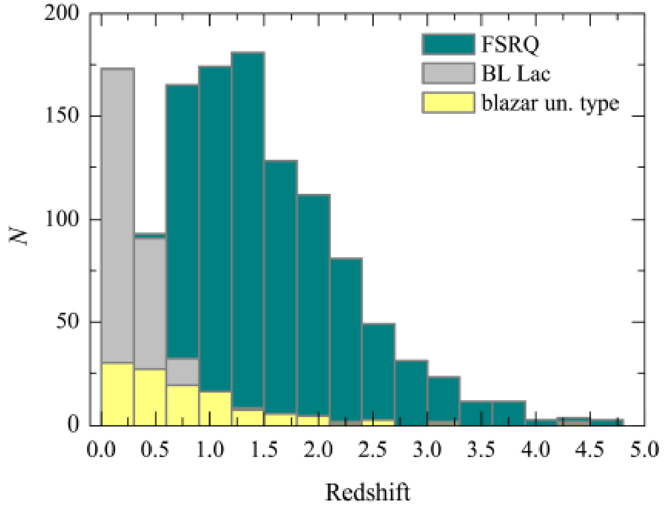
$\mathbf{E_o}$ = 43 GeV

$\boldsymbol{\beta_c}$ = 6.9

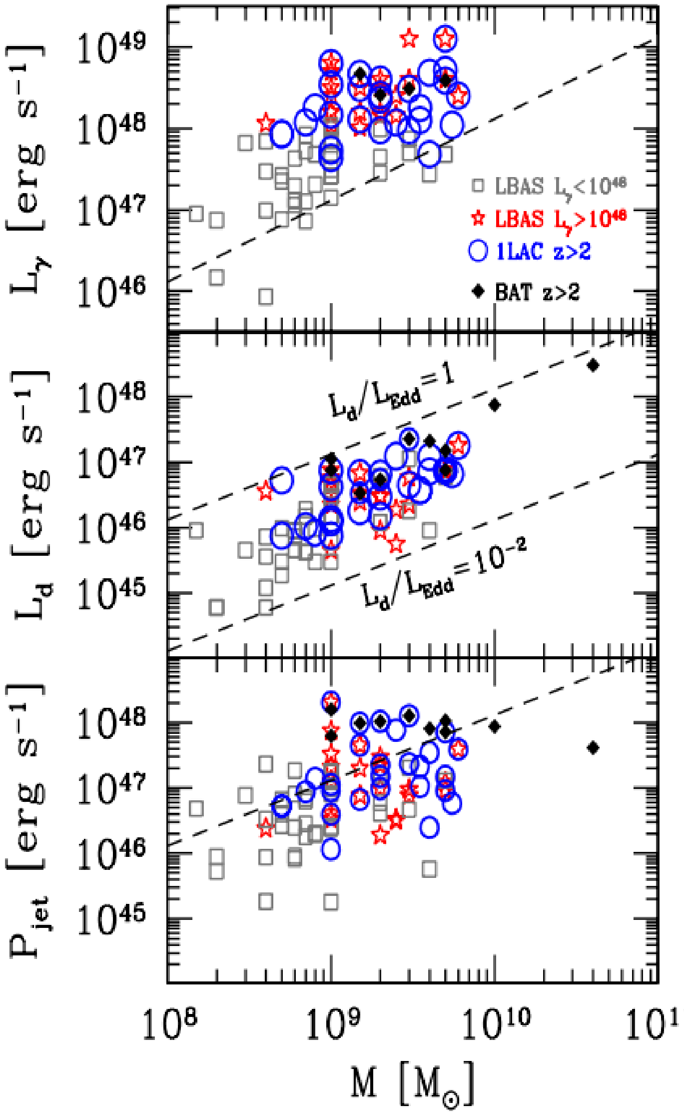
PKS 1424-418

FSRQ | z=1.522 | $M_{BH} = 4.5 \times 10^9 M_\odot$

- FSRQ are the most luminous blazars
- Mostly constrained at high redshift.
- **Linear relation between Black hole mass (M_{BH}) and disk luminosity (L_d).**
- Disk luminosity is reprocessed into BLR luminosity hence**, luminous disk means luminous BLR**.
- Emission within luminous BLR should result in **cutoff in high energy spectrum**.



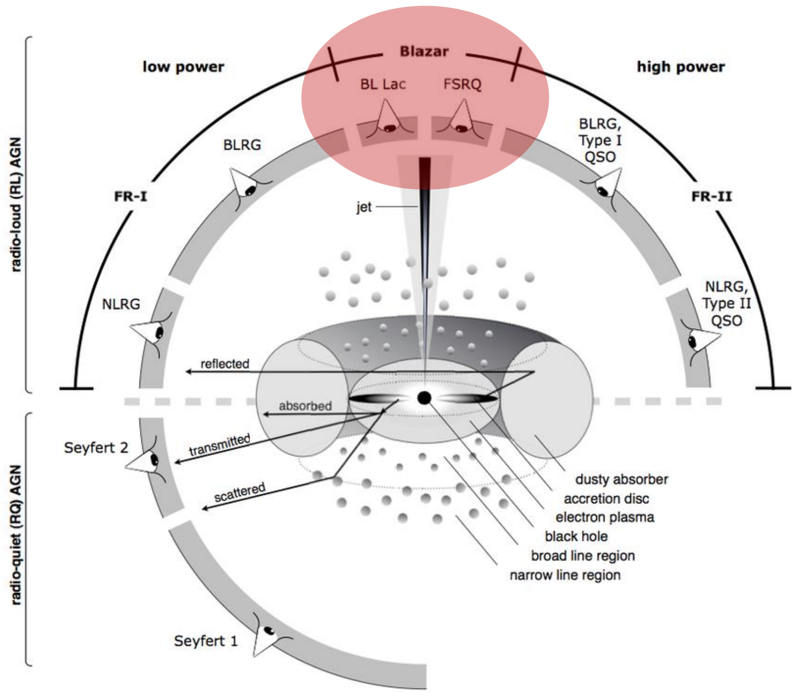
Kerby & Falcone 2023

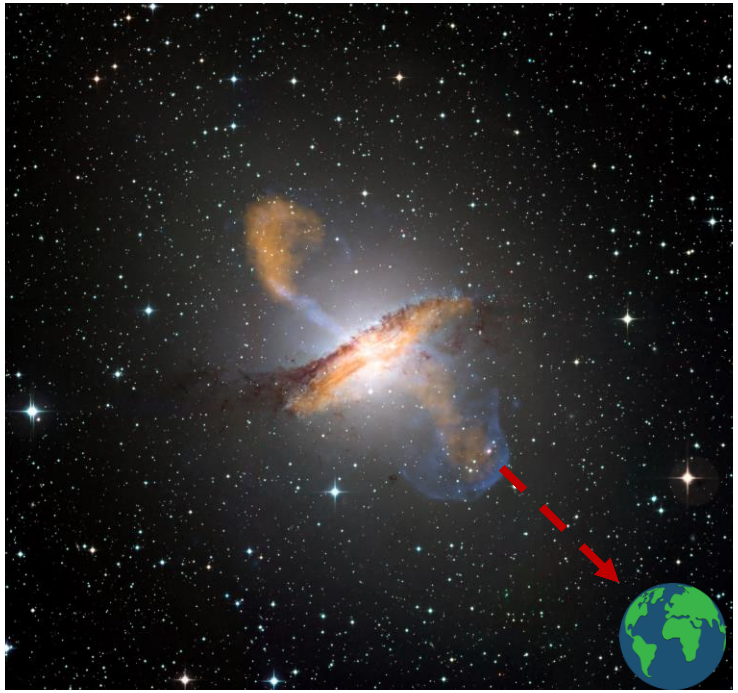


Ghisellini et al. 2011

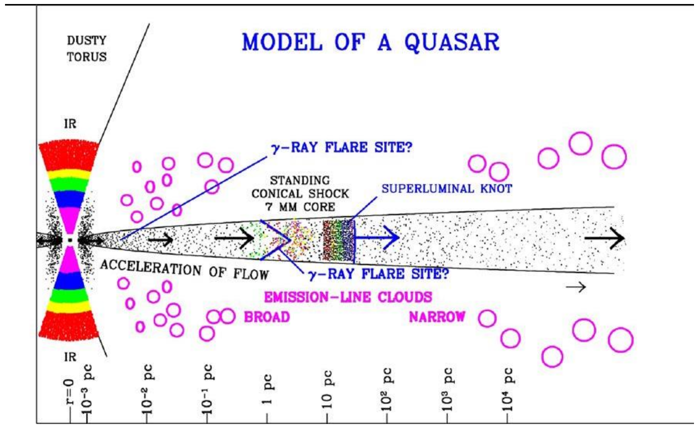
Active galactic nuclie & Blazars

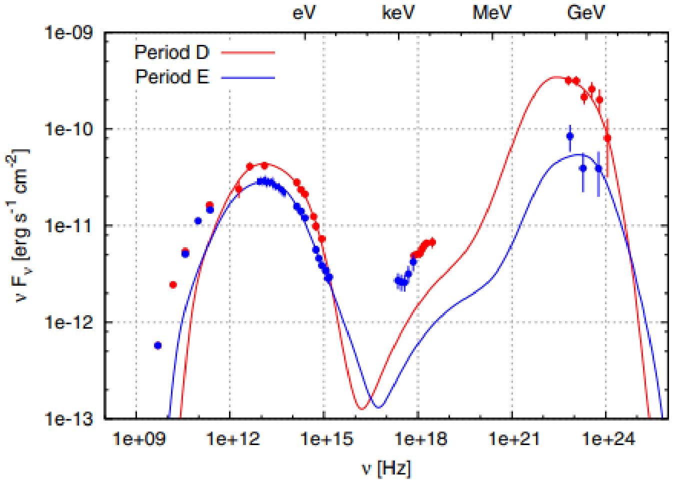
1. **Active galactic nuclie have a luminous core. Emission from core dominate the emission from galaxy.**
2. **Blazars – Specifically aligned AGNs with jet pointing towards observer.**





Location of γ-ray emission region in FSRQ?





Large Compton dominance in FSRQ

- <u>Variability estimate of size of emission</u>: Detection of **fast variability constrains emission region within BLR** (in **Bl lacerate, 3C 279, PKS 1222+216, CTA 102, PKS 2155−304**) [**Agarwal et al 2023, Shukla et al 2020, Nalewajko et al 2012, Hayashida et al. 2012**]

- **Detection of TeV photons** along with fast variability requires **emission region outside BLR** to escape photon-photon absorption [**Ton 599, PKS 1222+216, 3C279, PKS 1510-089, PKS 1441+25 +**] [**VERITAS collaboration 2011**]

- **However, Large Compton dominance** in FSRQ necessitates **proximity to region of seed photons**.

- Origin of gamma-rays in Fermi blazars found beyond Broad line region [106 Blazars] [**Costamante et al 2018**]

Result

Possible contribution from outer edge of BLR

- **Emission region located at the edge of BLR as also observed by Stern and Poutanen 2014**
- **The observed absorption at E > 10 GeV possibly because of low ionization lines located at the edge of BLR.**
- **The presence of emission region towards the edge provides ample amount of H_α and H_β lines which have energy threshold of 40 - 60 GeV.**
- **High ionization lines, forming smaller angles at large distance have very little contribution to observed absorption in contrast to the low ionization lines.**
- **Powerful dissipation events within or at the edge of the BLR evolve into fainter gamma-ray emitting zones outside the BLR.**
- **Similar flux resolved searches with improved photon statistics needed for other high mass Black hole object.**

Thank you!!

This work

Other work

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Infrared image of Herbig-Haro 212 (HH 212)
European Southern Observatory's Very Large Telescope

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