Fermi Gamma-ray Space Telescope

High-z Blazar SEDs Clues to Evolution in the Early Universe

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on behalf of the Fermi-LAT Collaboration

Outline

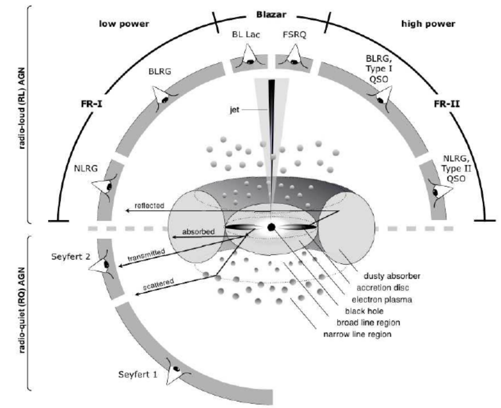
- **Blazars**

- **Blazar emission and spectral energy distribution (SED) models**

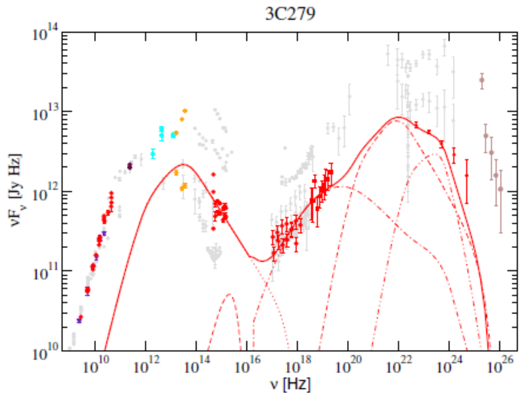
- **High-z blazars**

Extragalactic background light (EBL)

Early evolution of massive high-spin black holes



Beckmann & Schrader 2013



Boettcher 2013

Blazars are AGNs with the relativistic jets pointing towards Earth

Blazars: jet-emission dominating

Depending on the <u>optical line emission</u>

Flat-spectrum radio quasars (**FSRQs**): emission lines EW>5$\mathring{A}$

BL Lacs: weak emission lines (EW<5$\mathring{A}$) or featureless continuum

And BL Lacs:

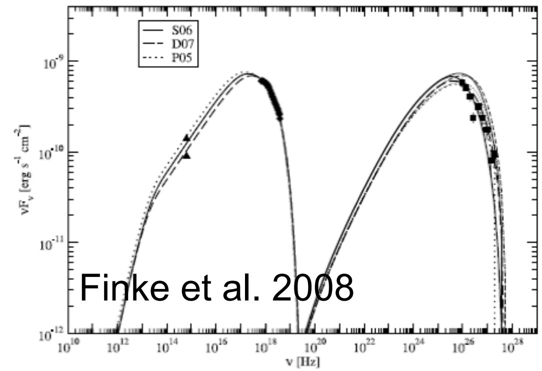
Depending on low-energy-emission <u>peak frequency</u>

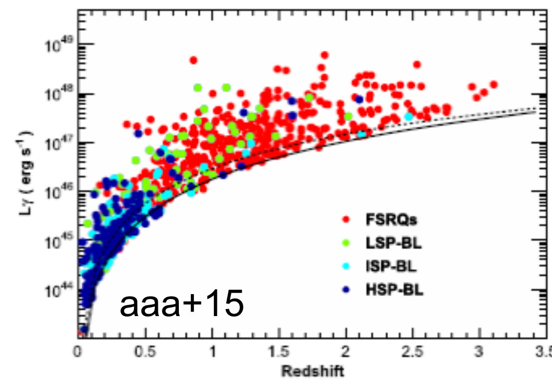
Low-synchrotron-peaked (**LSP**, $\nu_{sy} < 10^{14}$ Hz)

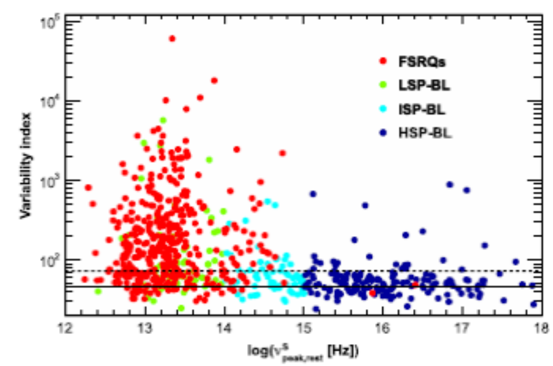
Intermediate-synchrotron-peaked (**ISP**, $10^{14} < \nu_{sy} < 10^{15}$ Hz)

High-synchrotron-peaked (**HSP**, $10^{15} < \nu_{sy}$ Hz)

Fermi 3LAC (aaa+15): 1563 AGNs (98% are blazars)







Blazars emit across the EM wavebands

- **Highly variable emission on almost all time scales**

- **Characteristic double hump SED**

Low energy hump:

Electron synchrotron (+disk, torus…)

High energy one (X-rays to TeV gamma rays):

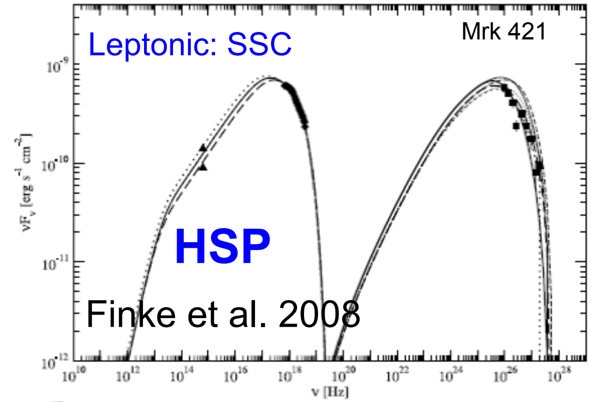
Self- or External Compton (**Leptonic**)

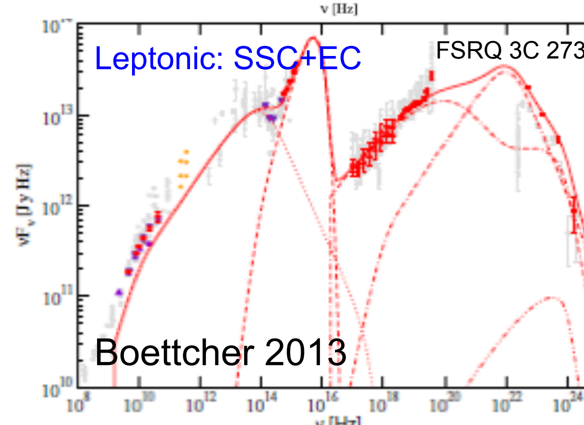
Proton synchrotron or photo-pion production (**Hadronic**)

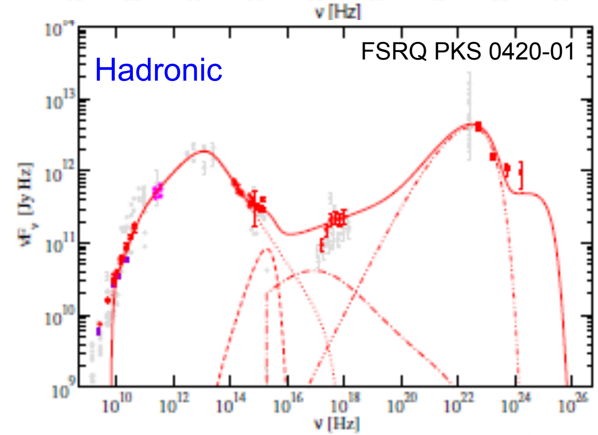
One zone vs. evolution

Spine-sheath structure (e.g., TC08)

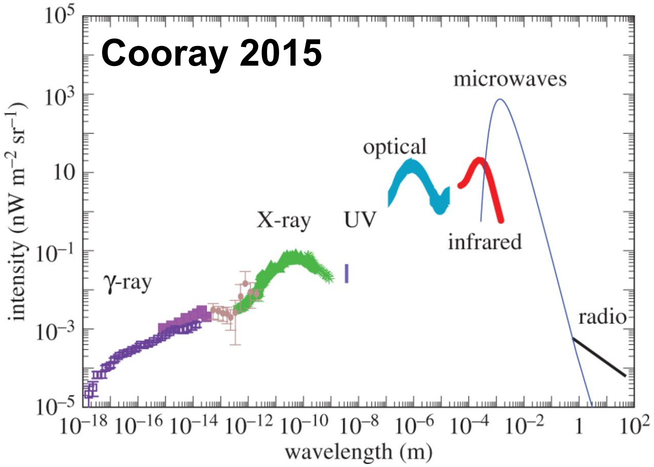
Internal shocks (e.g., MG85)

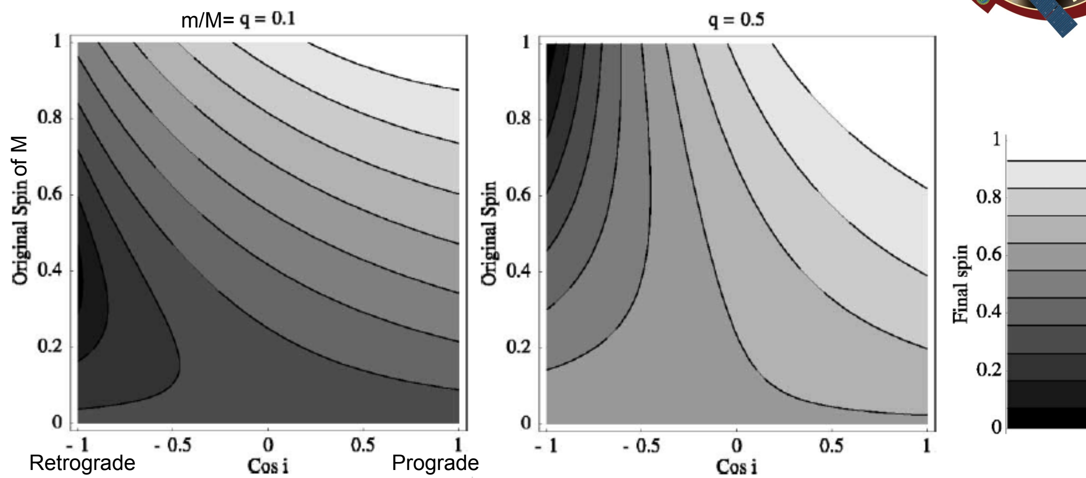






Environment and Evolution in the Early Universe probed using high-z blazars

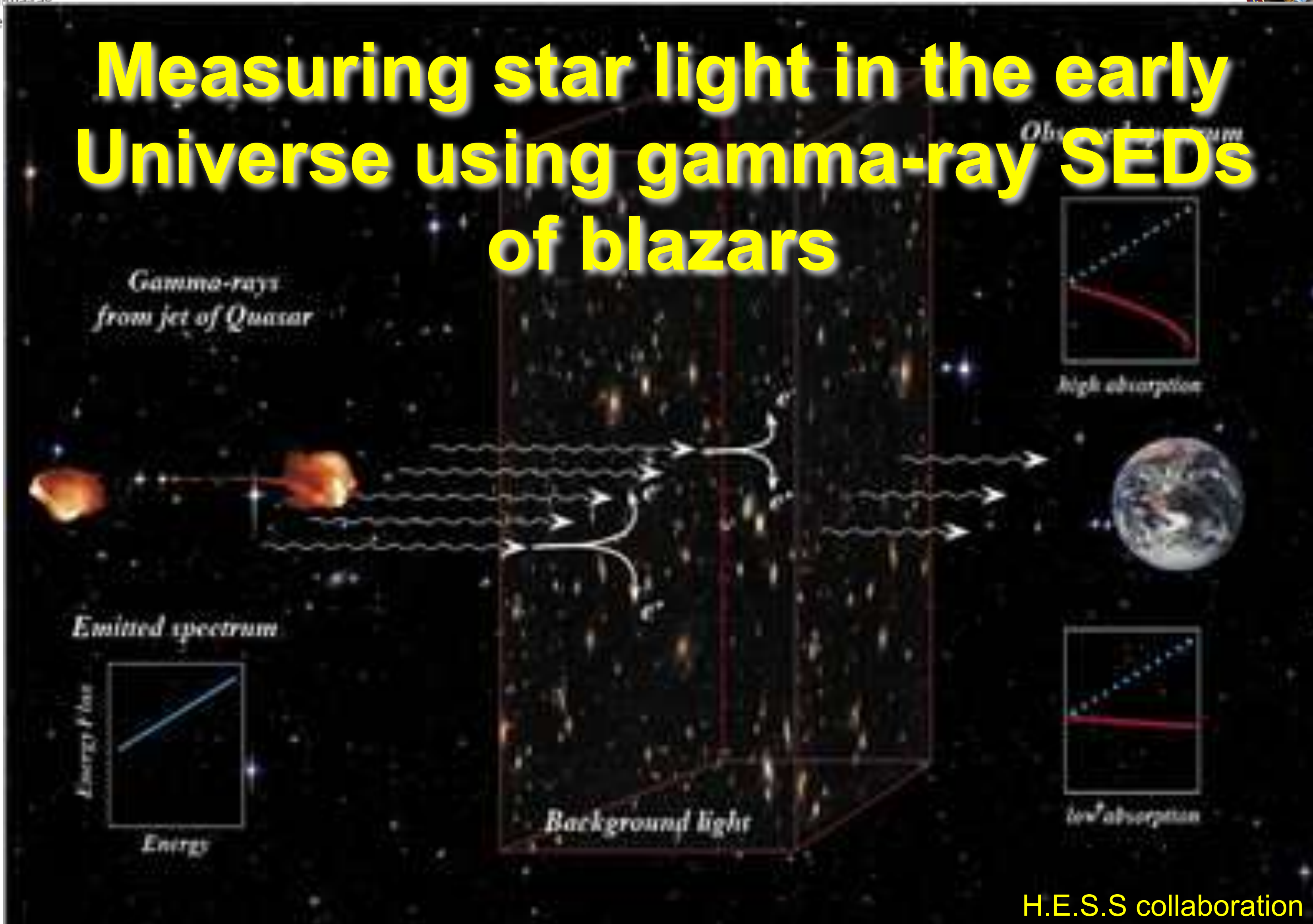




Spin evolution of binary mergers (Hughes & Blandford 2003)

- **IR-Optical Star light (Pop III) in the early Universe (high z) can tell us about the star formation and cosmic evolution**
- **Formation/growth of rapidly spinning massive black holes in the Early Universe is challenging**
- **High-z blazars allow us to study these**

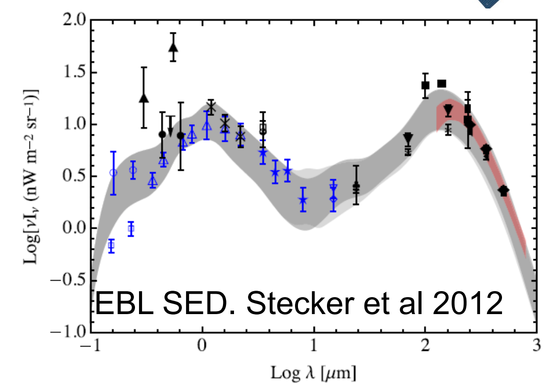
Measuring star light in the early Universe using gamma-ray SEDs of blazars



H.E.S.S collaboration

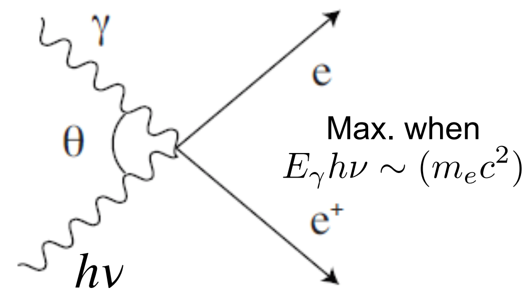
Extragalactic background light (EBL) can be best measured with gamma-ray data

- Extragalactic background light (EBL) in the IR to UV band is an important probe to cosmic evolution (e.g., star-formation history; Abdollahi et al. 2018 in press)



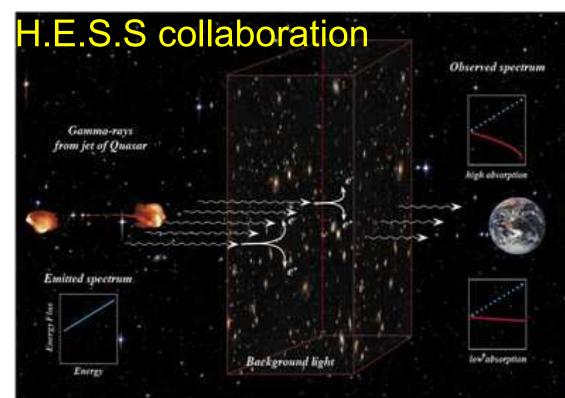
- Direct measurements are limited by foreground emission

- High-energy gamma rays interact with the optical/IR background (0.1—1000) via the pair production process (best with TeV)

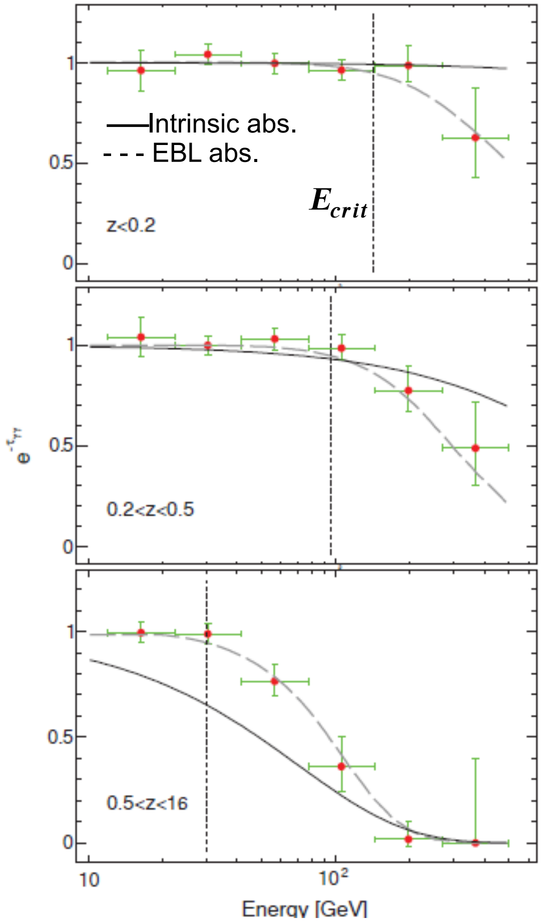


- Gamma-ray emissions from distant sources (blazars) are attenuated by the gamma-gamma pair-production process

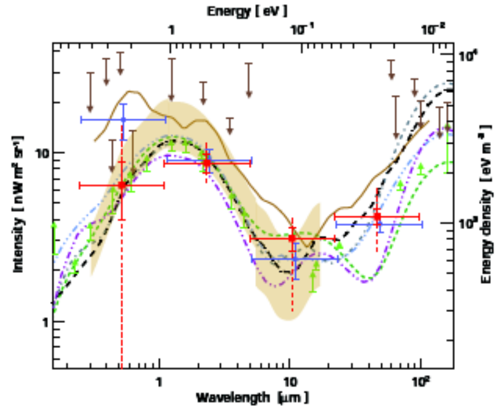
- Knowing the intrinsic SED of a blazar, we can measure the EBL in the IR-Optical band



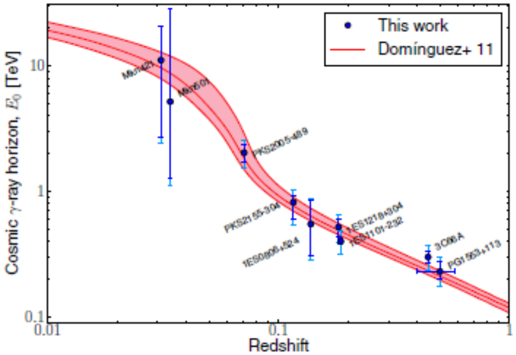
IR-Optical EBL has been measured with gamma-ray SEDs



Gamma-ray attenuation
Ackermann et al. 2012



IR-Optical EBL SED
H.E.S.S 2017



Cosmic gamma-ray horizon
Dominguez 2013

- Stacked blazar SEDs are used to measure the attenuation strength with z
- TeV attenuation data are useful to measure low-frequency EBL
- The EBL models are used to derive the Cosmic gamma-ray horizon (gamma-ray energy for which EBL attenuation optical depth is 1)
- See also Abdollahi et al. 2018 (in press)

We attempt to test EBL models with LAT data of individual blazars at high z

As we do with the low-energy data (e.g., X-rays), the gamma-ray attenuation models may be tested for individual blazars

Targets:

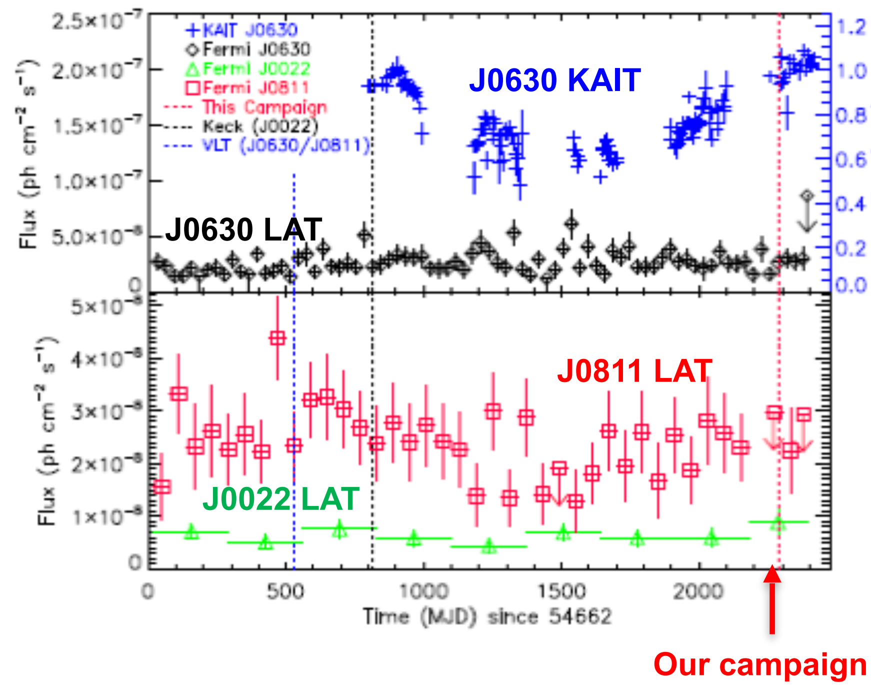
- **Bright in the X-ray and the LAT bands**
- **Good X-ray and LAT measurements of the SED**
- **ISP/HSP BL Lacs: particularly useful with no significant external Compton and so simple SSC emission in the gamma-ray band**
- **At a reasonable range of redshift**

(e.g., ; $E_{crit}(z) \approx 170(1+z)^{-2.38} GeV$ **; Ackermann et al. 2012)**

Sample exercise: SEDs of three high-z BL Lacs

- **Targets: ISP—HSP BL Lacs**
  J0022.1-1855 (z=0.774)
  J0630.9-2406 (z>=1.24)
  J0811.2-7529 (z=0.689)

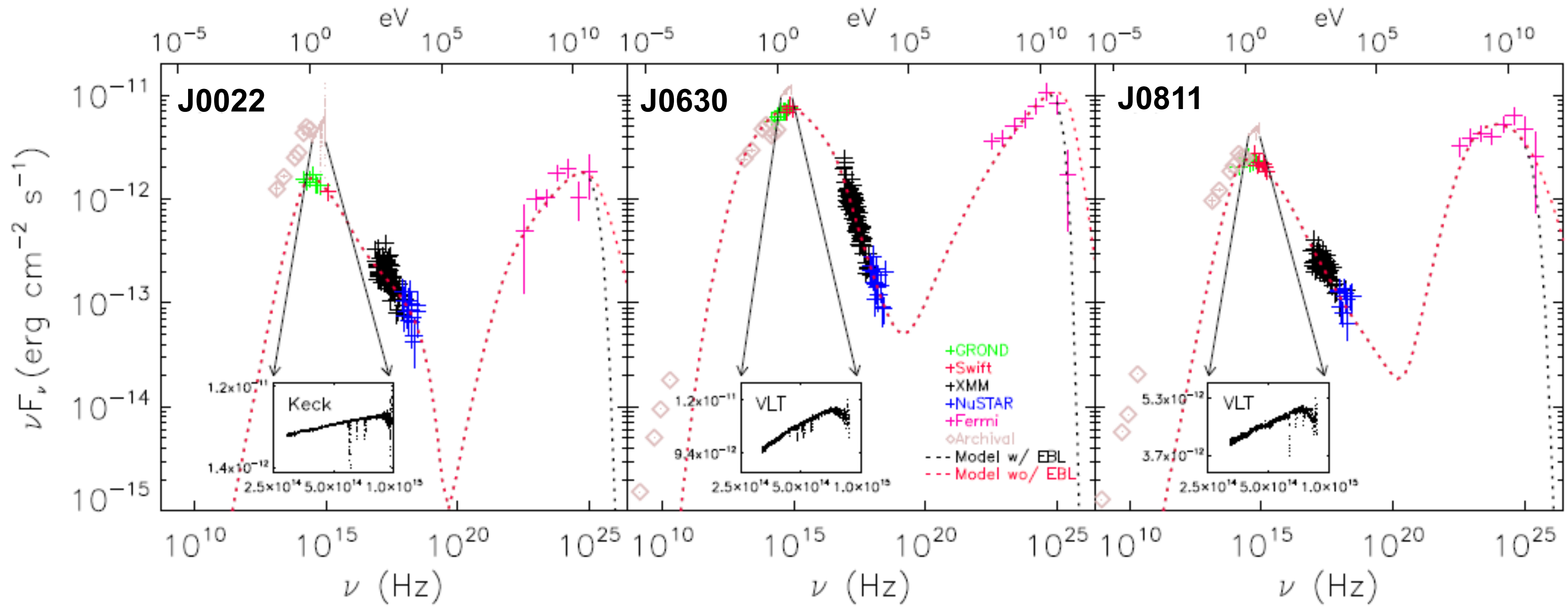
- **~60% variability is seen in the optical monitoring data of J0630**



- **No statistically significant (3 sigma) variability is seen in the LAT band for any source**

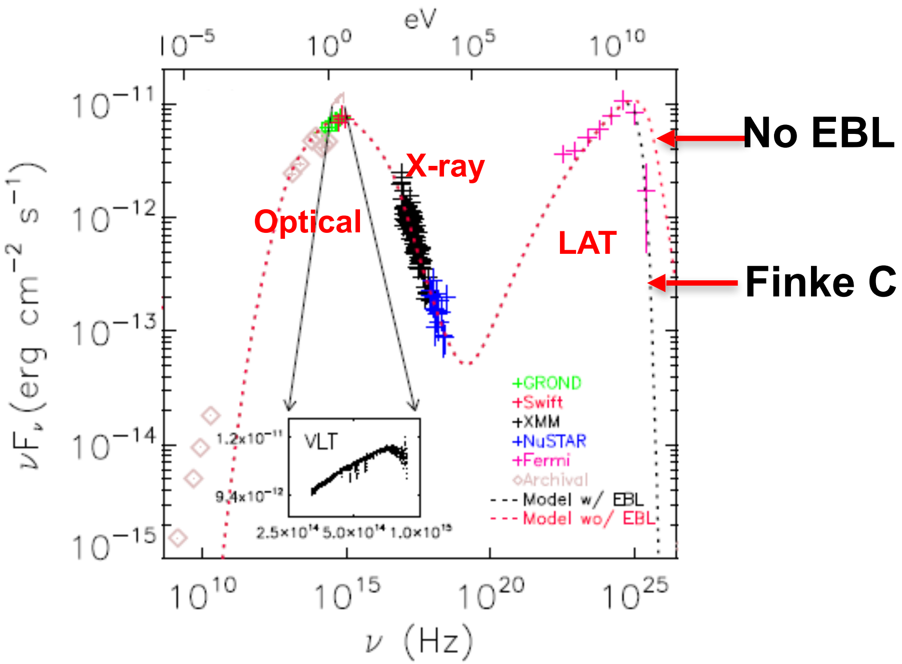
- **The LAT data can be combined with the contemporaneous optical to X-ray data**

We modeled the SEDs using a synchro-Compton (SSC) model



- **High-quality Optical/X-ray data are obtained with GROND, Swift, XMM-Newton and NuSTAR**
- **The Optical-to-X-ray data constrain the shape of the Sy/SSC humps**
- **PASS 8 LAT data are used to test EBL models**

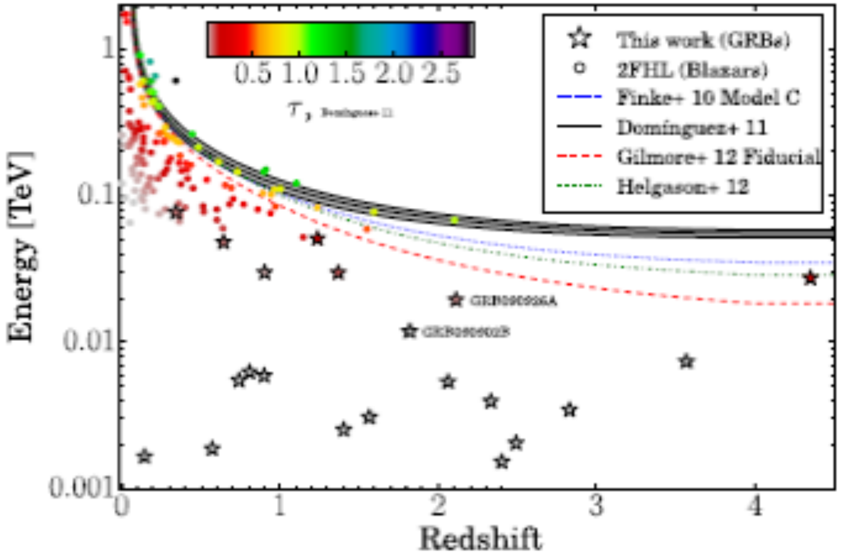
Some EBL models are ruled out by the highest-z blazar (J0630) SED



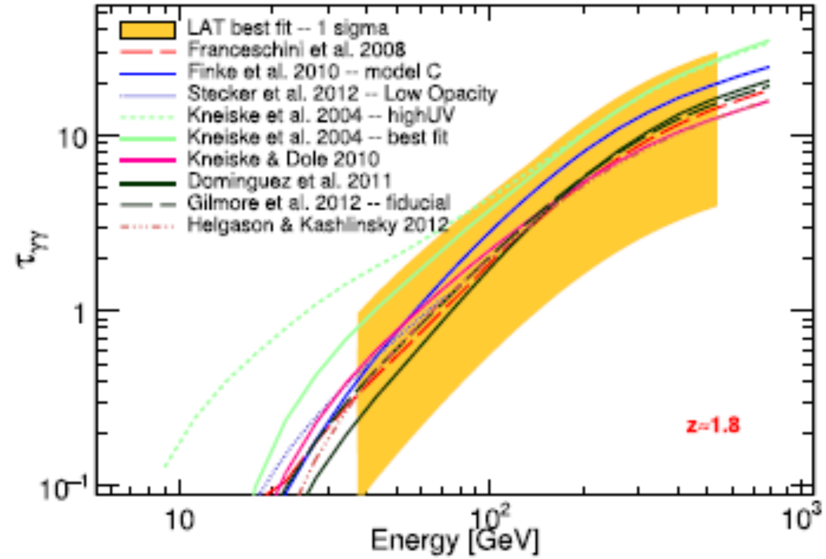
Model	J0022	J0630 (χ^2)	J0811
No EBL	151.1	197.4	128.9
Domínguez	151.1	186.2	129.6
Franceshini	151.1	186.2	129.6
Gilmore Fiducial	151.0	189.2	130.0
Gilmore Fixed	151.1	186.5	129.6
Helgason	151.1	186.3	129.5
Kneiske04 best fit	151.1	191.4	130.6
Kneiske & Dole	151.1	187.4	129.8
Kneiske high UV	150.3	205.1	132.8
Stecker high opac.	151.0	194.0	131.6
Stecker low opac.	151.0	187.4	130.2
Finke 'C'	151.1	187.0	129.7

- **Clear signatures of EBL is visible at high energies of the LAT band for the highest-z target J0630-2406**
- **With this, we can rule out some EBL models (e.g., high-UV model)**

GRB constraints also agree with our results



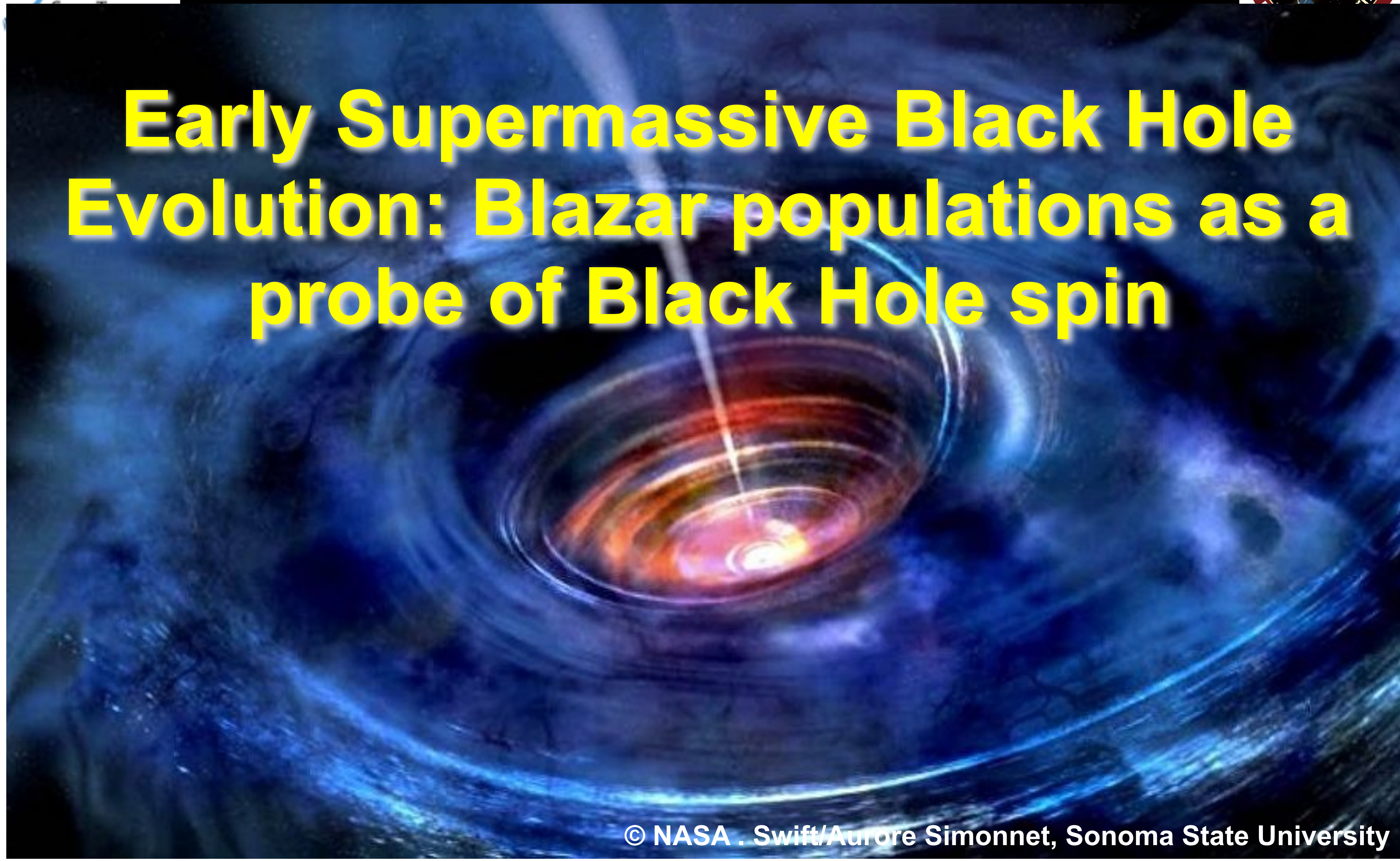
Cosmic gamma-ray horizon
Desai et al 2018.



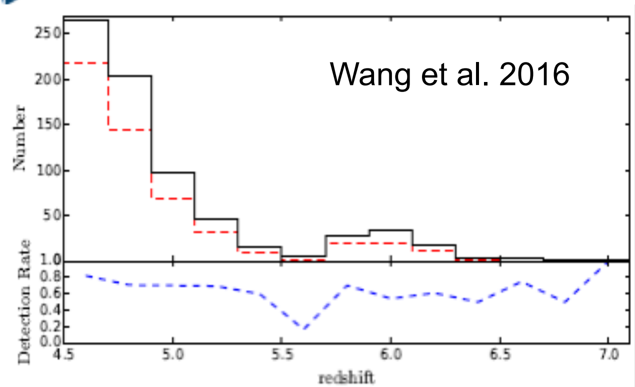
Optical depth for gamma-ray photons
Desai et al 2018.

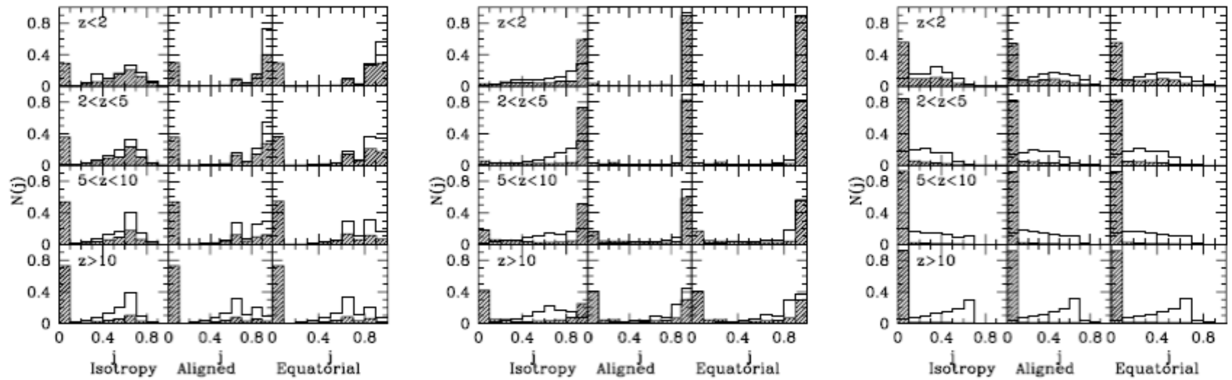
- **Fermi-LAT GRB data were used for EBL studies**
- **Intriguingly, the LAT blazar SED data (Ackermann et al. 2012) + GRB data also rule out the EBL models that are incompatible with our J0630 SED**

Early Supermassive Black Hole Evolution: Blazar populations as a probe of Black Hole spin



There exist massive high-spin black holes in the early Universe





Berti and Volonteri (2008)

Before
After

- **There exist massive black holes >$10^9 M_\odot$ at z>5 (e.g., Fan et al. 2001, Mortlock et al. 2011)**

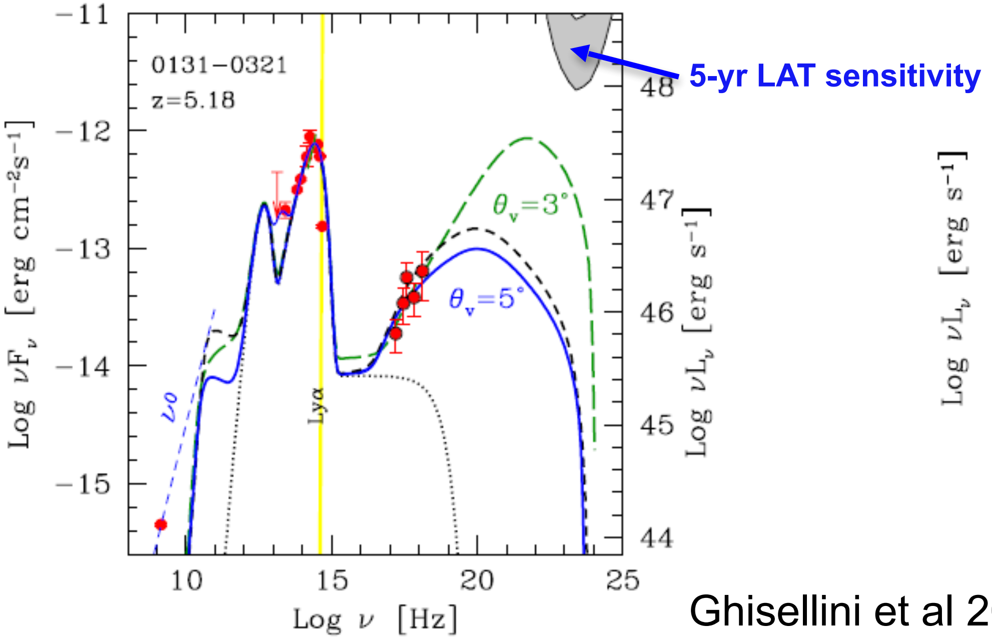
- **Four of them are known to be blazars (Romani 2006, Ghisellini et al. 2015)**

- **It is challenging to grow a seed black hole to $10^9 M_\odot$ levels in the limited age (high z): mergers and/or accretion**

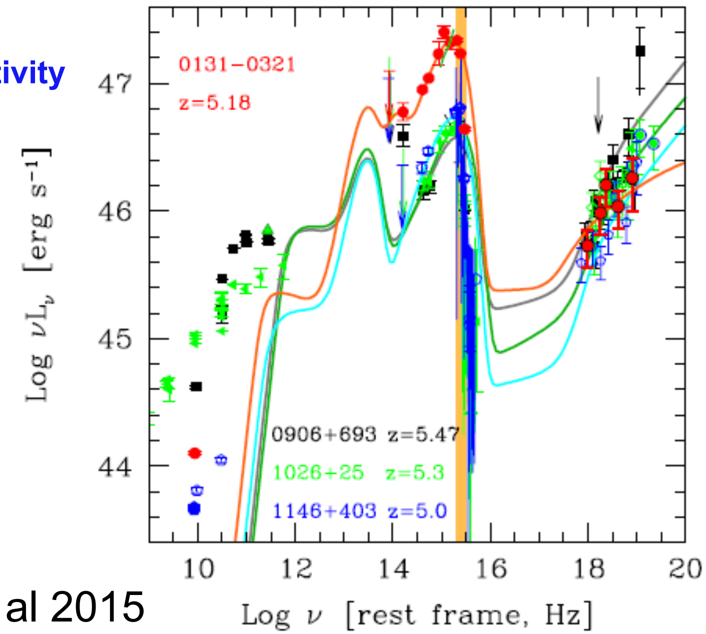
- **Depending on the growth scenarios, the final spin distribution differs (Berti & Volonteri 2008)**

- **Need to estimate the high-z blazar (high spin) population carefully**

It has been suggested that the bulk Lorentz factors of the four blazars are >10



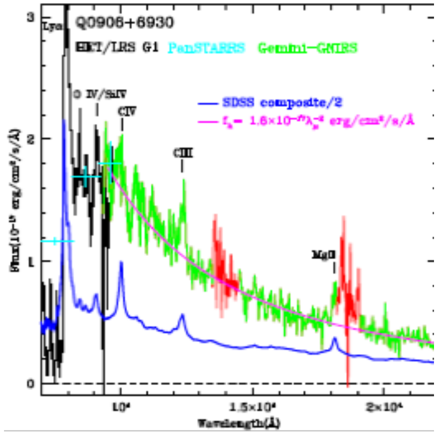
Ghisellini et al 2015



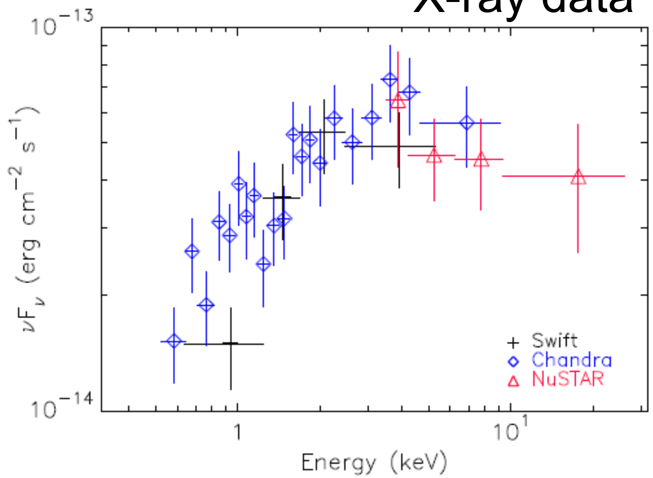
- **Because of beaming every observed source represents ~ $2\Gamma^2$ others not seen, so good constraints on Γ are important for population estimates**
- **In the previous SED studies, the bulk Lorentz factors Γs for these z>5 blazars are estimated to be ~10 without any upper or lower bound**
- **With better X-ray and LAT measurements we can improve the population estimate**

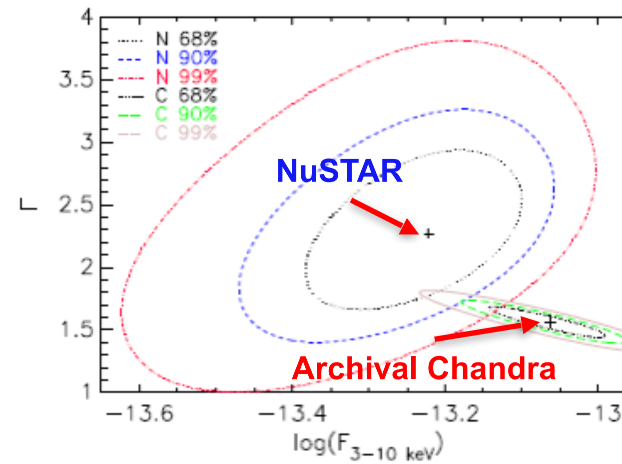
We collected high-quality IR/X-ray data for the highest-z blazar QSO J0906+6930

IR data



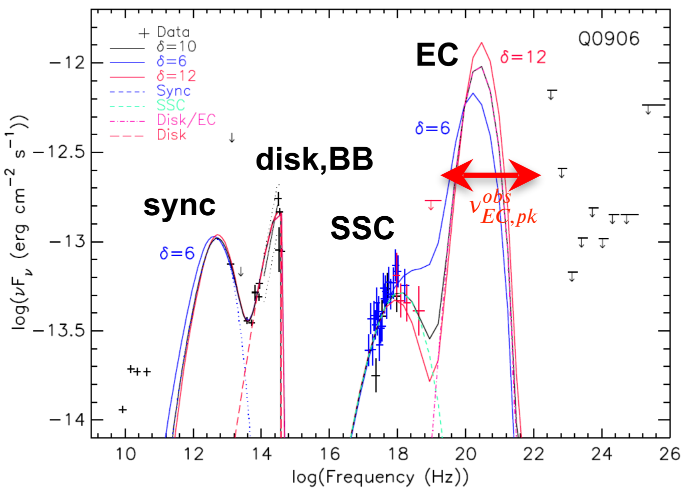
X-ray data

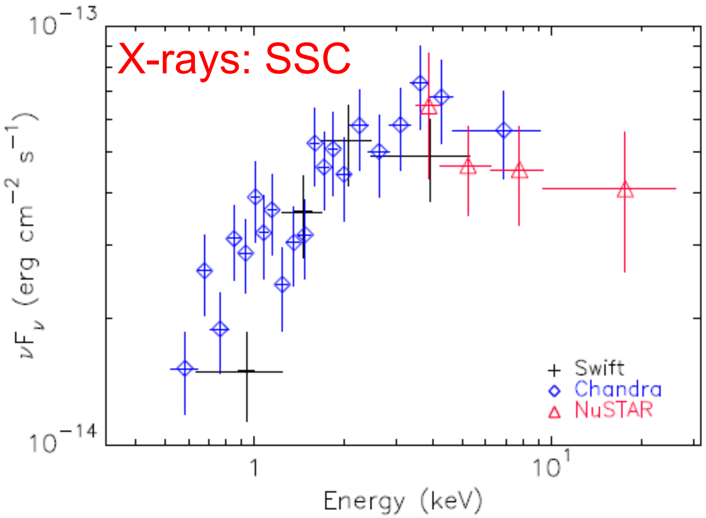




- The IR data obtained with Gemini provide the black-hole mass ($M_{\rm BH} \sim 4 \times 10^9 M_\odot$, so the disk temperature) and the flux of the accretion disk (seed for the EC hump in the gamma-ray band)
- The X-ray SED shows a break and constrains the SSC emission strongly (F_{swift}=$F_{chandra}$: no variability between the two epochs)
- No LAT (upper limit measurements) variability is seen, but a historical EGRET detection may suggest variability

We constrained for the highest-z blazar Q0906 using the SED





- **We obtained high-quality IR/X-ray data and stringent LAT upper limits for the Q0906 SED**

- **The peak of each SED component has different dependence on :**

$\delta \; (= \left[\Gamma\left(1-\beta\cos\theta_v\right)\right]^{-1})$

$$\nu_{sy,pk} \approx 4\times10^6\,\gamma_e^2 B\ Hz \qquad \nu^{obs}_{sy,pk} = \frac{\nu_{sy,pk}\delta}{1+z} \qquad \nu^{obs}_{ssc,\,pk} = \gamma_e^2 \nu^{obs}_{sy,pk} \qquad \nu^{obs}_{EC,\,pk} \approx \delta^2\gamma_e^2\nu^{obs}_{BB,pk}$$

- **Peak positions alone suggest** $0.6 < \delta < 13$

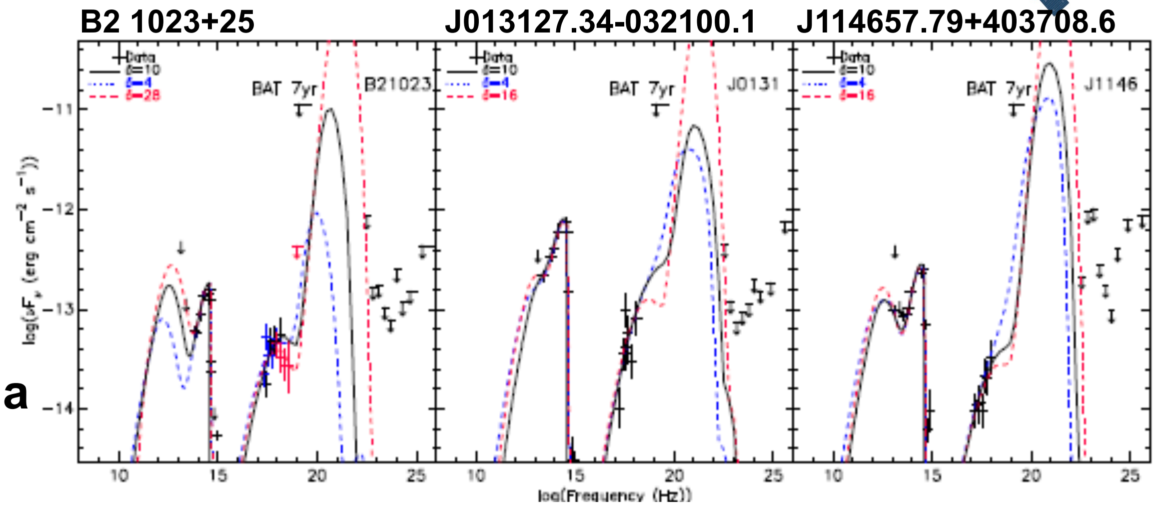
- **Detailed SED fitting determines** $6 < \delta < 11.5$

We also estimate s for the other z>5 blazars for a population study

- The SEDs for the other blazars are not very well measured but the general structure is all similar

- The second highest-z blazar B2 1023 also seems to show a spectral break in the X-ray band, but the confidence is not very high

- Improved LAT SEDs help but we could make only weak constraints on δs for these sources

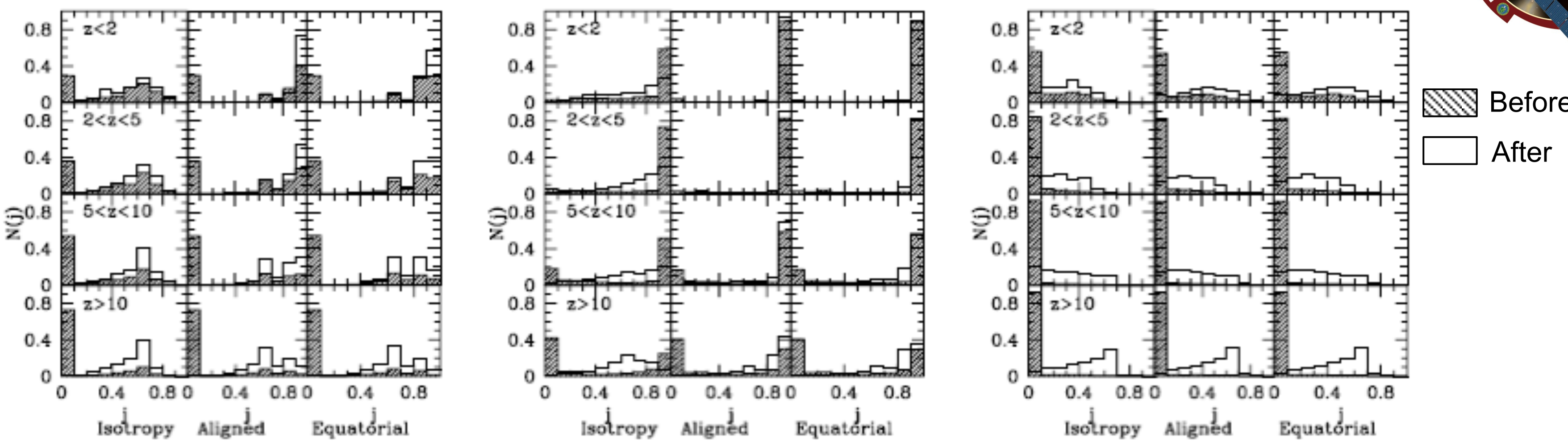


Parameter	Symbol	Value			
Target		Q0906	B2 1023	J0131	J1146
Redshift[a]	z	5.48	5.28	5.18	5.00
Black Hole mass ($M_\odot^a$)	$M_\bullet$	4.2×10^9	4×10^9	1.5×10^{10}	8×10^9
Disk Luminosity (erg/s)	L_{disk}	2.4×10^{47}	2.7×10^{47}	1.1×10^{48}	3.5×10^{47}
Doppler factor	δ^b	6–11.5	4–28	4–16	4–16
Magnetic field (G)	B	6.9	2.9	11	2.1
Comoving radius of blob (cm)	R'_b	8.8×10^{14}	2.6×10^{15}	1×10^{15}	4.1×10^{15}
Effective radius of blob (cm)[c]	R'_E	5.5×10^{15}	1.1×10^{16}	6×10^{15}	1.6×10^{16}
Electron density (cm^{-3})	n_e	6.1×10^3	7×10^2	7×10^3	3×10^2
Initial electron spectral index	p_1	1.8	2.1	1.7	1.6
Initial min. electron Lorentz factor	γ_{min}	2.2×10^2	4×10^2	4.5×10^2	4.5×10^2
Initial max. electron Lorentz factor	γ_{max}	7.2×10^2	10^3	1.4×10^3	1.2×10^3
Injected particle luminosity (erg s^{-1})[d]	L_{inj}	5.4×10^{45}	2×10^{46}	2×10^{46}	5×10^{46}

- Each source represents $\approx 2\delta^2 \sim 200$ similar sources at the redshifts

- MeV telescopes (e.g., AMEGO, e-ASTROGAM) can help constrain the EC peak

Using the inferred ranges we estimate that ~10—20% of massive AGNs are blazars



Black spin distribution for several growth scenarios. Berti and Volonteri (2008)

- **Assuming a δ^{-s} distribution for a population estimate, we infer**
  s=0 (uniform prior) : ~620 similar blazars
  s=2 (Ajello et al. 2012 for z~<3 FSRQs) : ~350 similar blazars

- **These imply that ~10—20 % of massive AGNs (~3200 at z=5—5.5 with $> 10^9 M_\odot$; Vestergaard & Osmer 2009) may harbor a rapidly spinning massive black hole**

- **This fraction is likely conservative: sky survey incompleteness and additional selection effects on follow-up limit the high-z blazar census**

Summary

- Blazars at high redshifts can be used to study early Universe
- We presented that EBL models can be tested with individual blazars. The EBL SED may be measured with improved SED data and models; Fermi will keep collecting data and future CTA data will greatly help
- Highest-z blazars can help understand the growth of massive black holes in the very early Universe; finding more z>5 blazars will be particularly useful, and future MeV telescopes such as AMEGO, e-ASTROGAM and COSI will help to measure the EC peak precisely