High energy emission from blazars

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On behalf of the Fermi-LAT Collaboration

Extragalactic Relativistic Jets: Cause and Effect

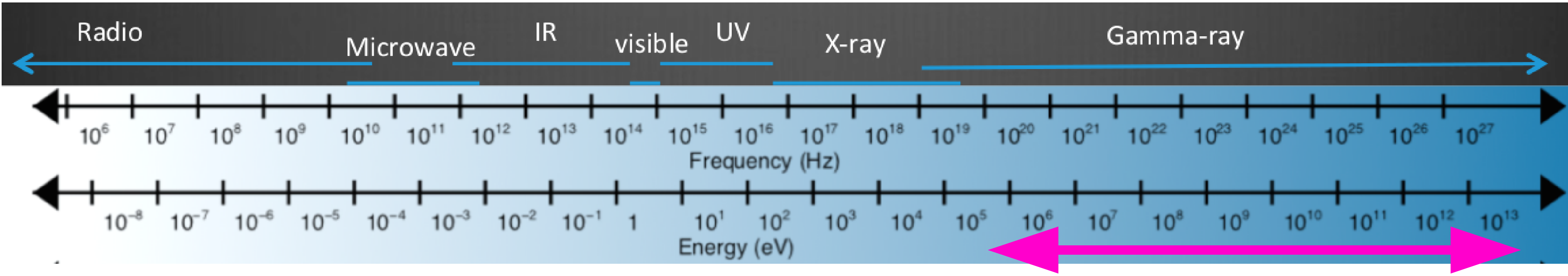
Outline

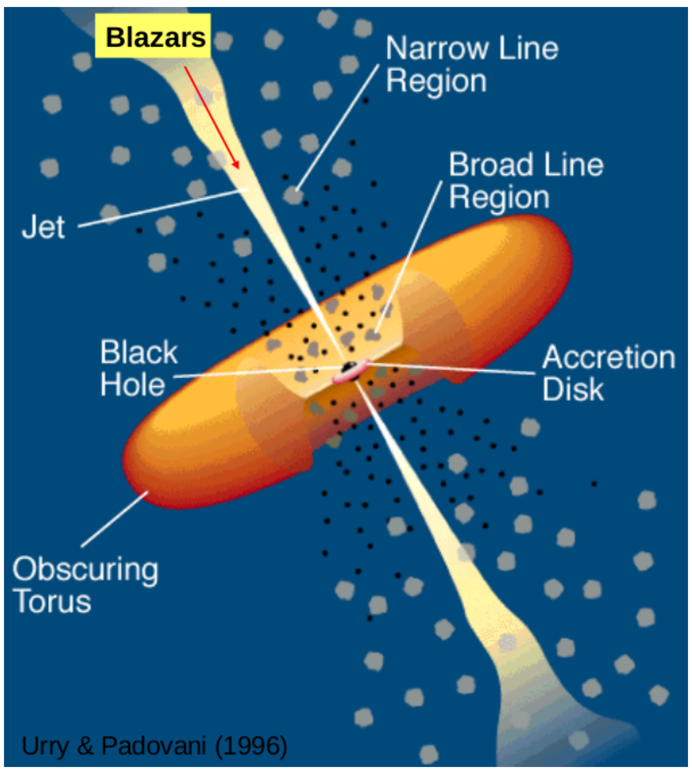
High-energy emission from blazars

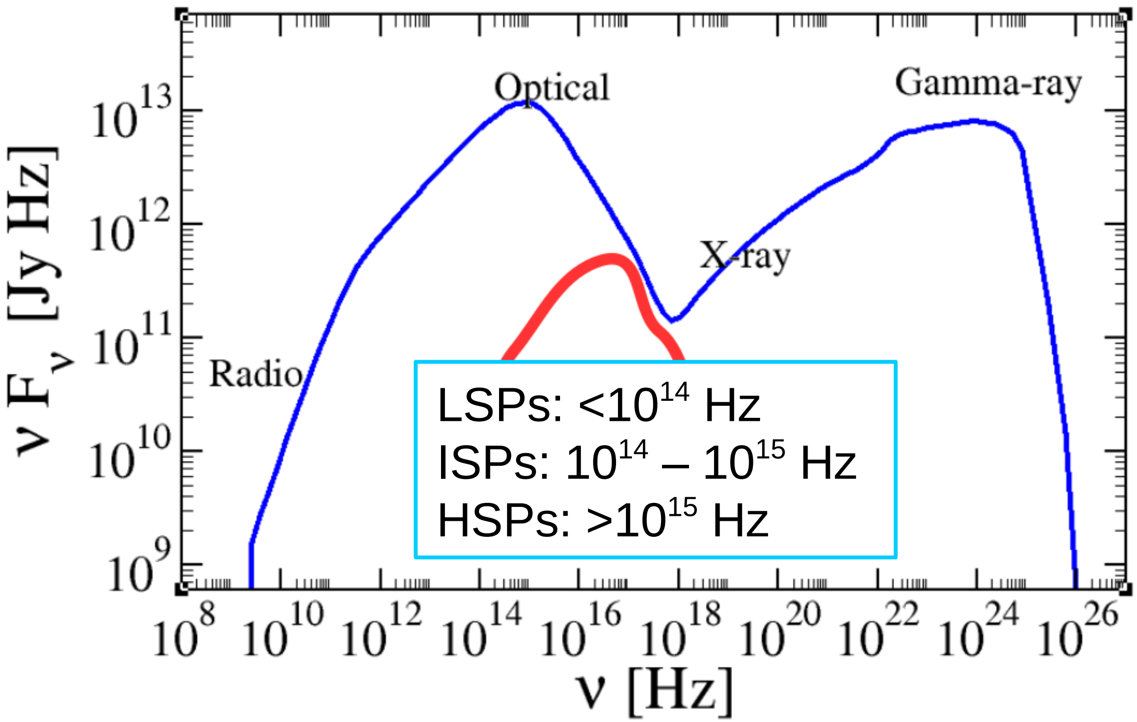
Where and how gamma-rays are produced

Future perspectives

Before we start

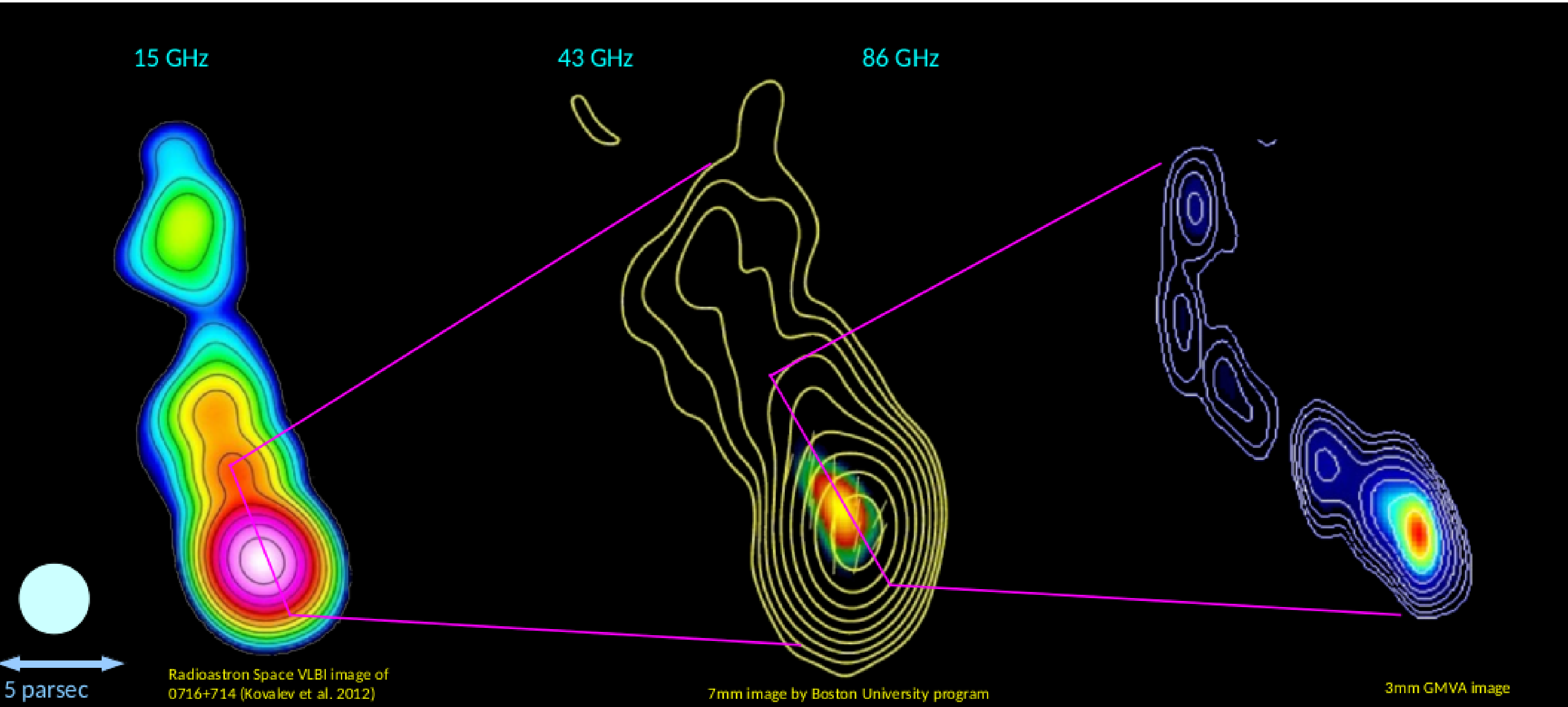






Broadband spectral energy distribution

Before we start

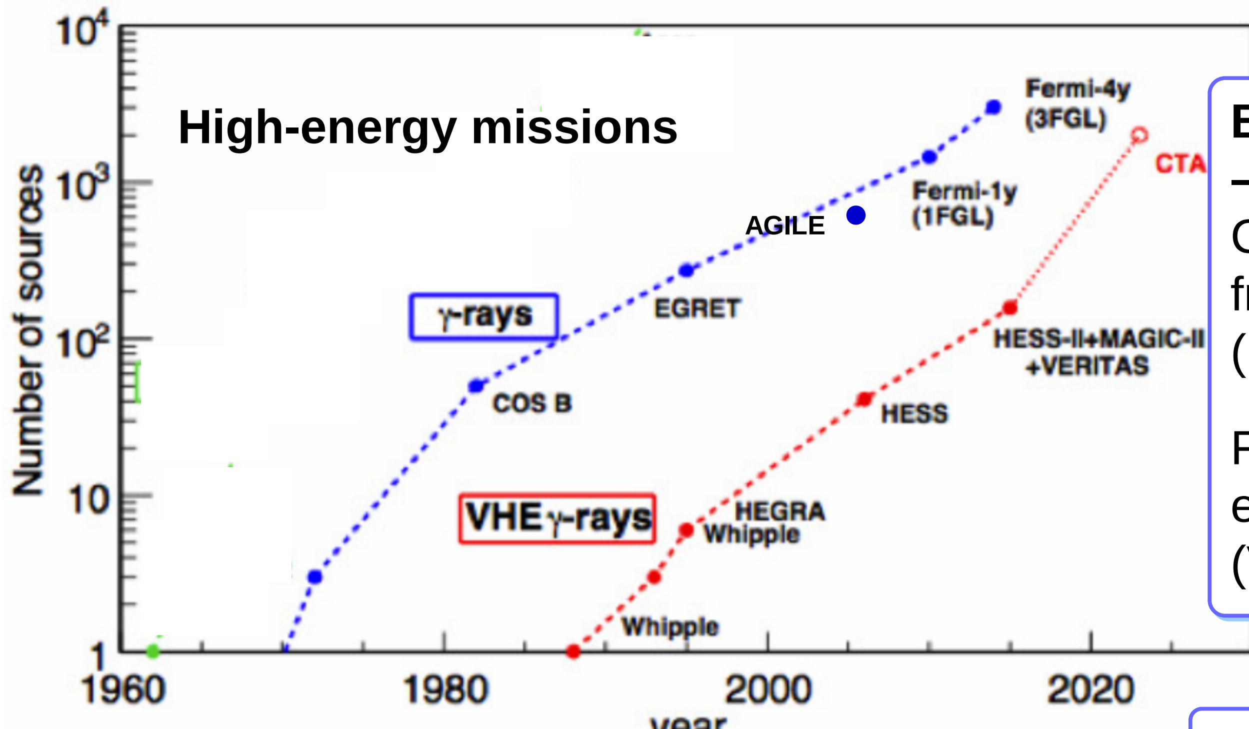


At arcsecond scales, S5 0716+714 has a core-dominated jet pointing towards the North (15 GHz image) and is pointed at θ≤5° to our line-of-sight. A bent jet structure is observed at milli-arcsecond scales (43 GHz image). The jet bending is even more pronounced at micro-arcsecond scales (86 GHz image).

With an angular resolution of ~50μas mas, we can reach scales down to ~700 R_s (for a 10^9 solar mass black hole) at z~0.1

High-energy emission from blazars

Before Fermi – EGRET and others



Balloon-based experiments – 1970s :
Confirmed bright emission from the Galactic plane (Kniffen & Fichtel 1970)

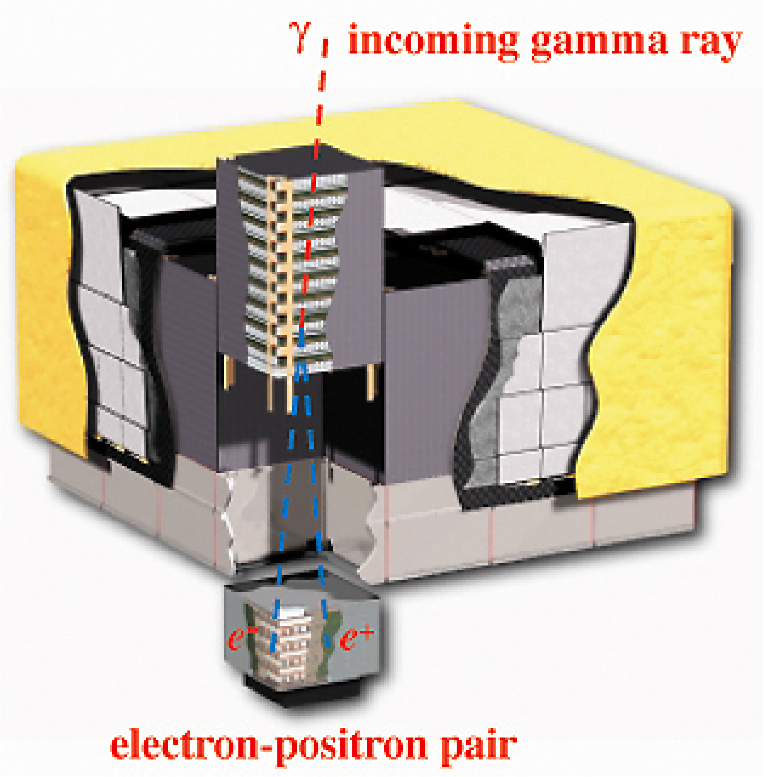
Found evidence for pulsed emission from Crab pulsar (Vasseur et al. 1970)

Small missions:
Second small astronomy satellite (SAS-2: 1972-73) –20 MeV to 1 GeV : Mapped the Galactic mission (Thompson et al. 1975) and discovered gamma-rays from Vela pulsar (Fichtel et al. 1975)

COS-B (1975-82) – 2 KeV to 5 GeV: first detection of **extragalactic emission from 3C 273** (Bignami et al. 1981)

Major/Big missions :
Energetic gamma-ray experiment telescope (EGRET on board CGRO – 1991-2000) – 20 MeV to >10 GeV: detected more than 250 sources at E>100 MeV (Hartman et al. 1999)

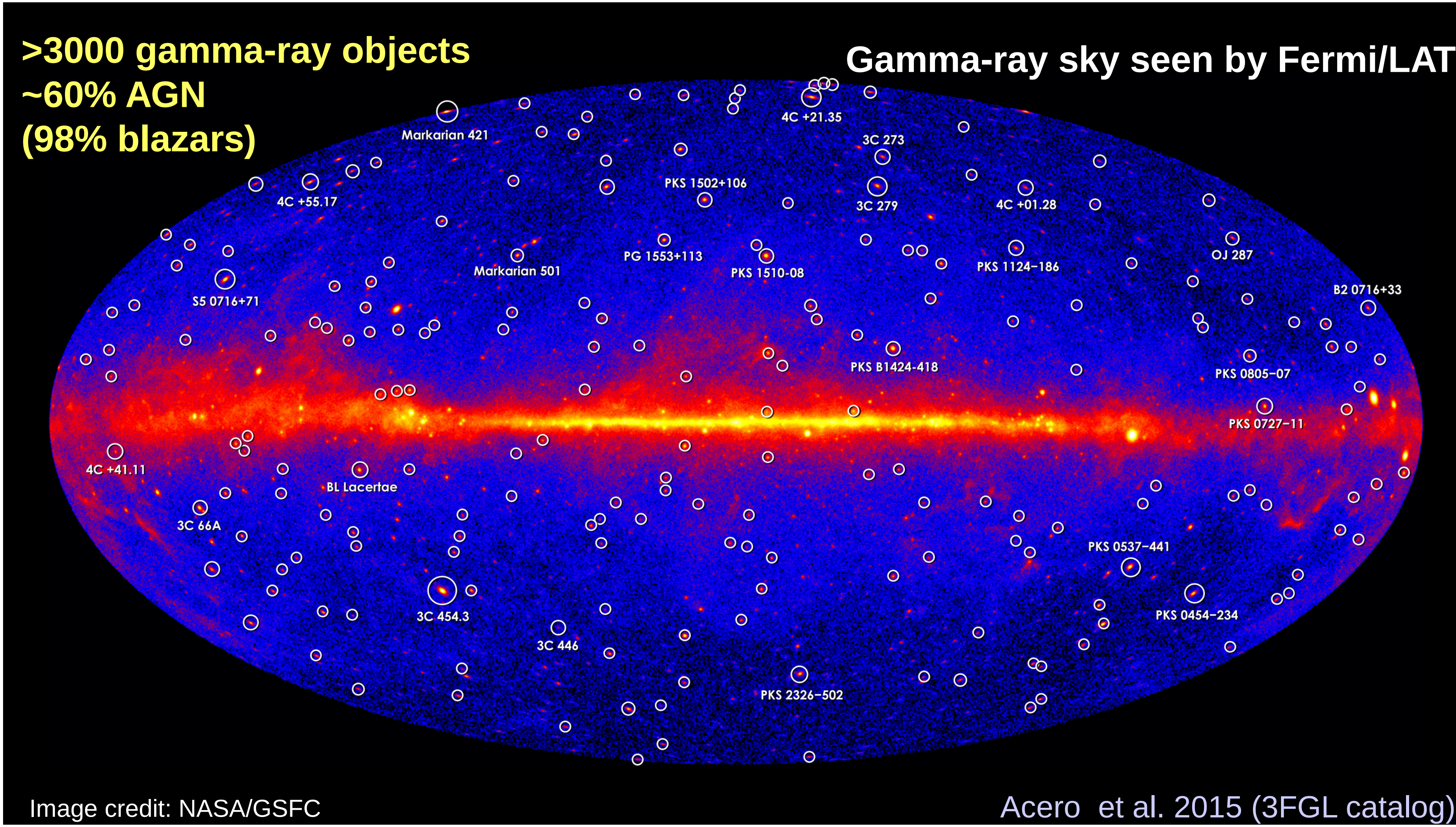
The Fermi mission



- energy range: 30 MeV - 300 GeV
- large FOV: 2.4 sr
- A_{eff}:~8000 cm^2 at 1 GeV
- PSF: $\theta_{68\%}$~0.8° at 1 GeV
- altitude: 565 km
- inclination: 25.6°
- orbital period: 91 min
- whole sky covered in 2 orbits in survey mode (rocking angle 50°)
- public data, available within 12 h
- operation guaranteed until 2018

http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm

The Fermi era

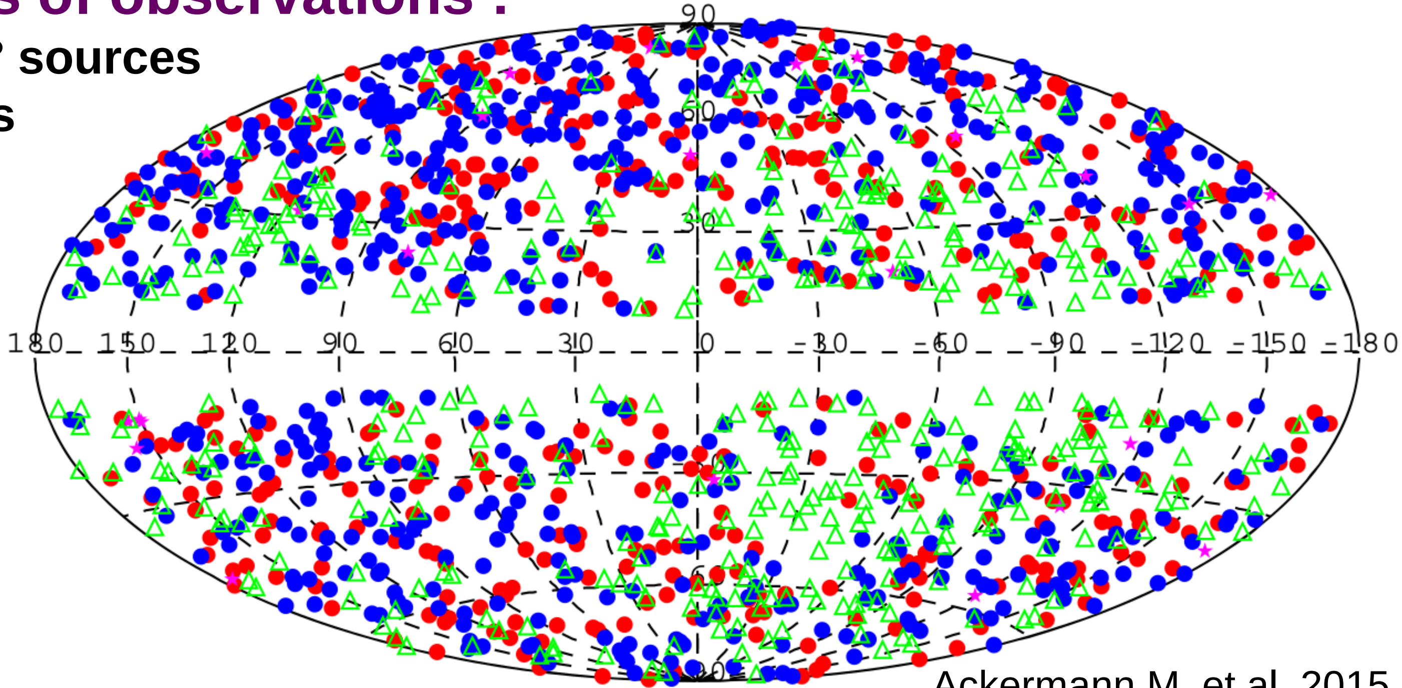


Since its launch in 2008, the **Fermi-LAT (Large Area Telescope)** has revolutionized our knowledge of gamma-ray sky with a combination of **high sensitivity, wide field-of-view, and large energy range (about 20 MeV to more than 300 GeV)**.

The Fermi era – 3rd AGN catalog (3LAC)

Using 48 months of observations :

- 2192 TS>25, |b|>10° sources
- 3LAC: 1563 sources



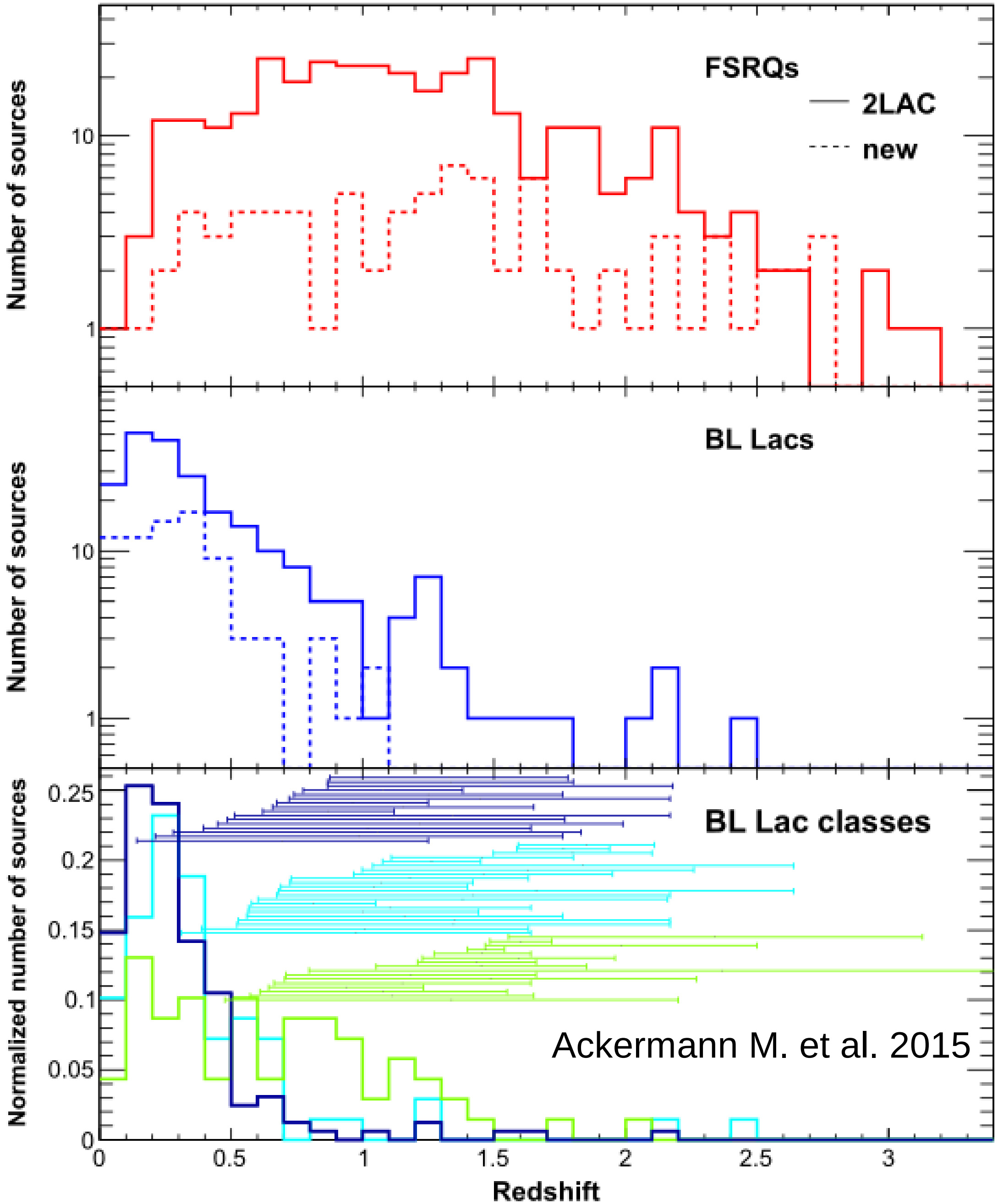
Ackermann M. et al. 2015

Census : 1444 AGNs in Clean sample

415 FSRQs
602 BL Lacs
413 of unknown type (BCUs)
23 other AGNs

Non-Blazar/Misaligned AGNs (~2%)
11 FRI
3 FRII
7 SSRQ or CSS
5 Radio-loud NLSyl
6 Other AGNs

Redshift distribution

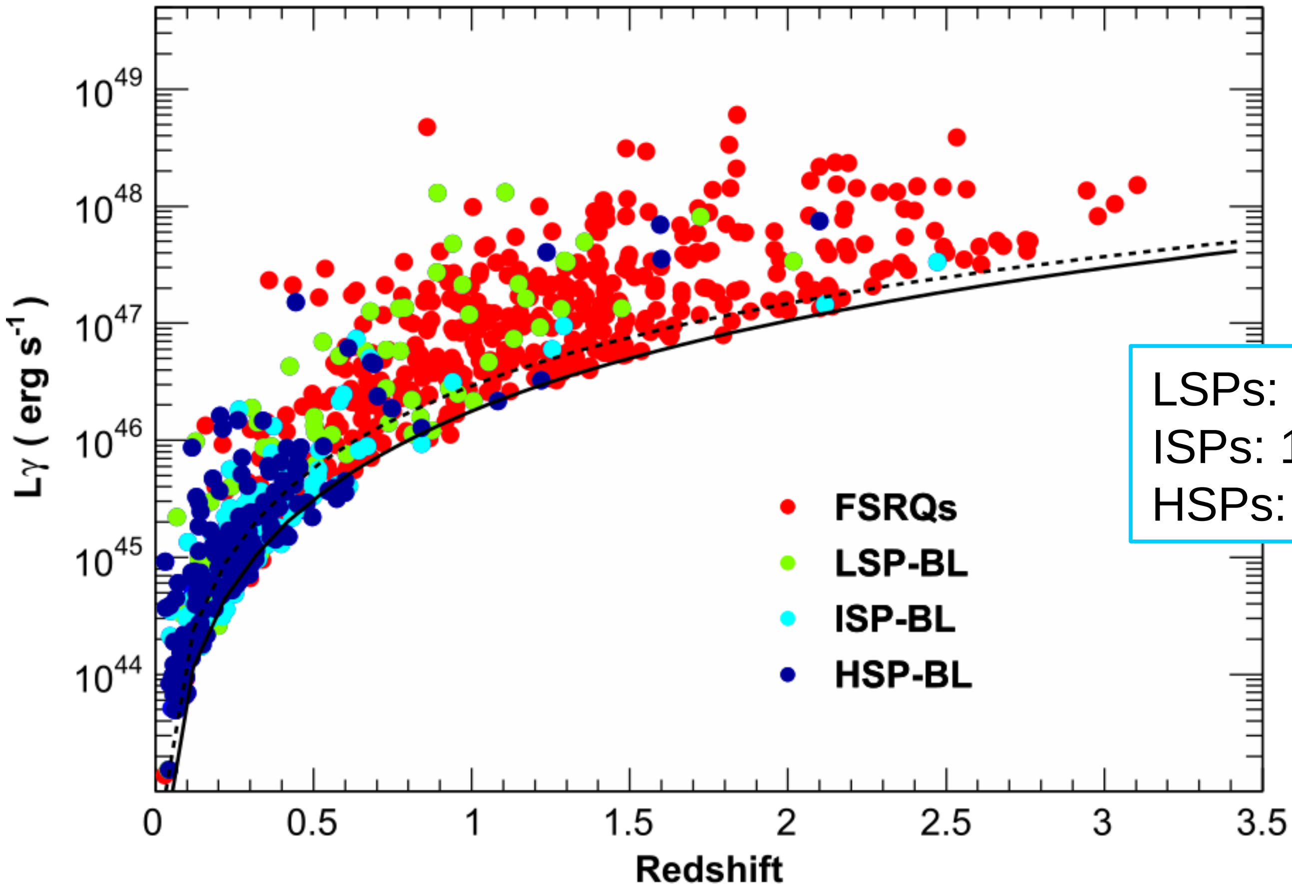


Slightly higher z for new FSRQs relative to 2LAC ones <z> = 1.33 vs. 1.17

maximum redshift still z=3.1 (maximum z=6.8 in BZCAT list)

~50 % (295/604) BL Lacs have no measured redshifts

Luminosity vs. redshift



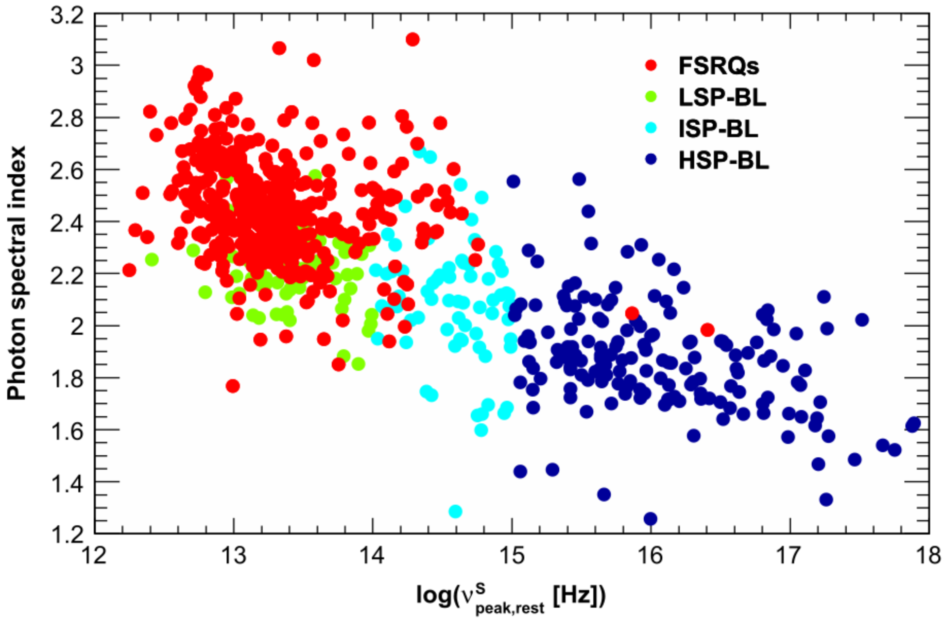
LSPs: <10^{14} Hz
ISPs: 10^{14} – 10^{15} Hz
HSPs: >10^{15} Hz

The Malmquist bias is clearly visible.

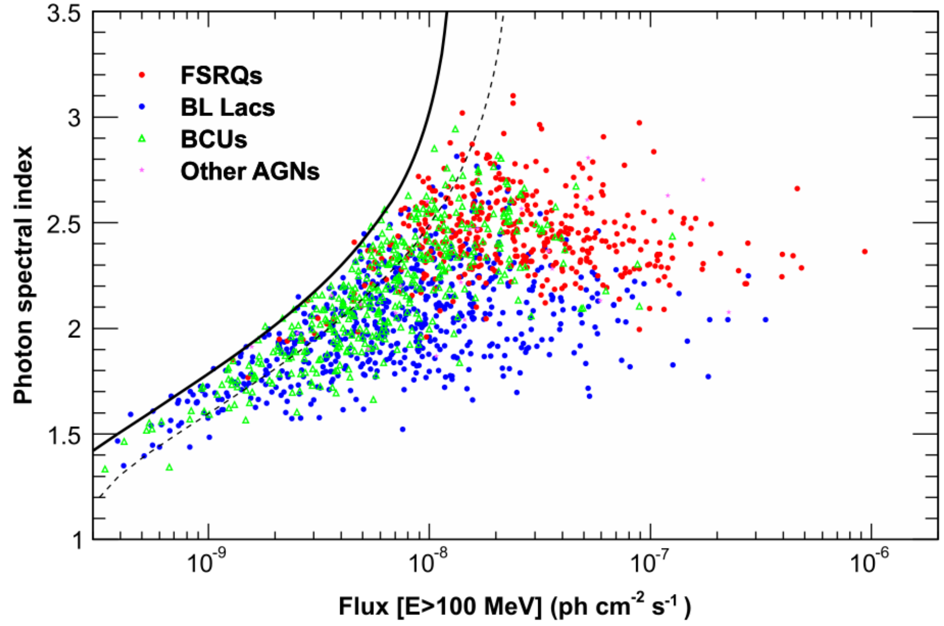
Low-luminosity BL Lacs (<10^{45} erg s^{-1}) cannot be detected at z > 0.4 .

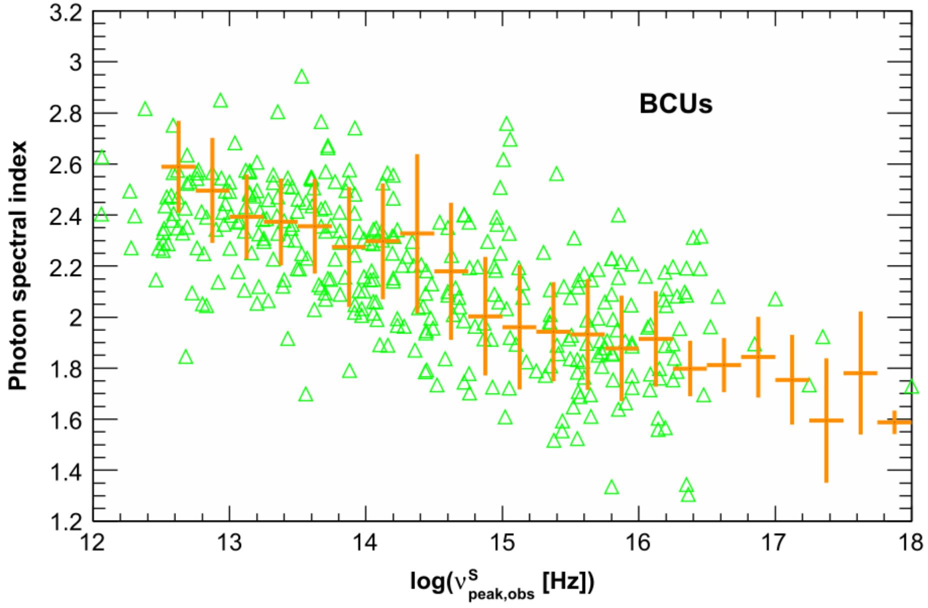
Sources with a luminosity greater than 5*10^{47} erg s^{-1} (64 are in 3LAC) could still be detected at z > 3.2

Gamma-ray flux and spectral index

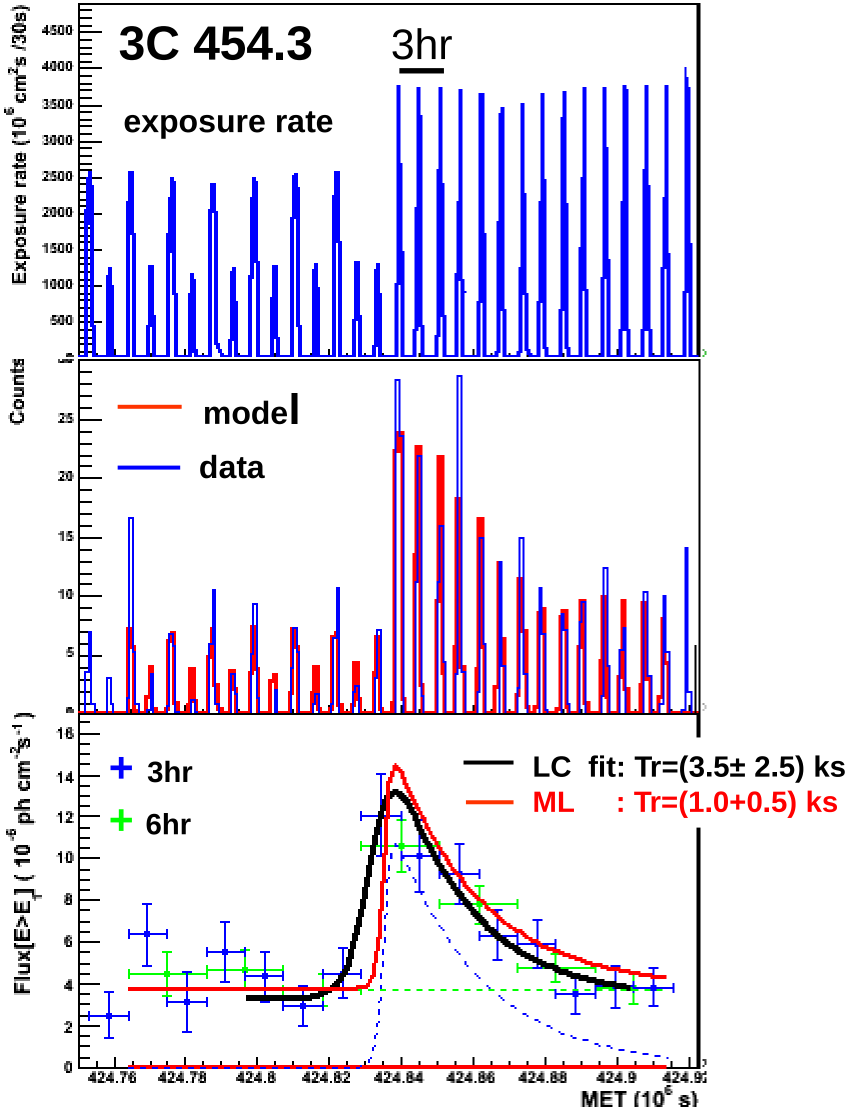


- Correlation between spectral hardness and ν_{peak} confirmed
- Lowest index~1.5, as predicted by shock-acceleration models
- Same correlation applies to BCUs





Flux and Spectral variations



Abdo et al. 2010

Constraints on size and location of emitting zone

4 sources show T_{min} close to 3 hr:
3C 454.3, 3C 273, 4C+21.35, PKS 1510-089
$R_S/c \sim 10^4 M_9$ s

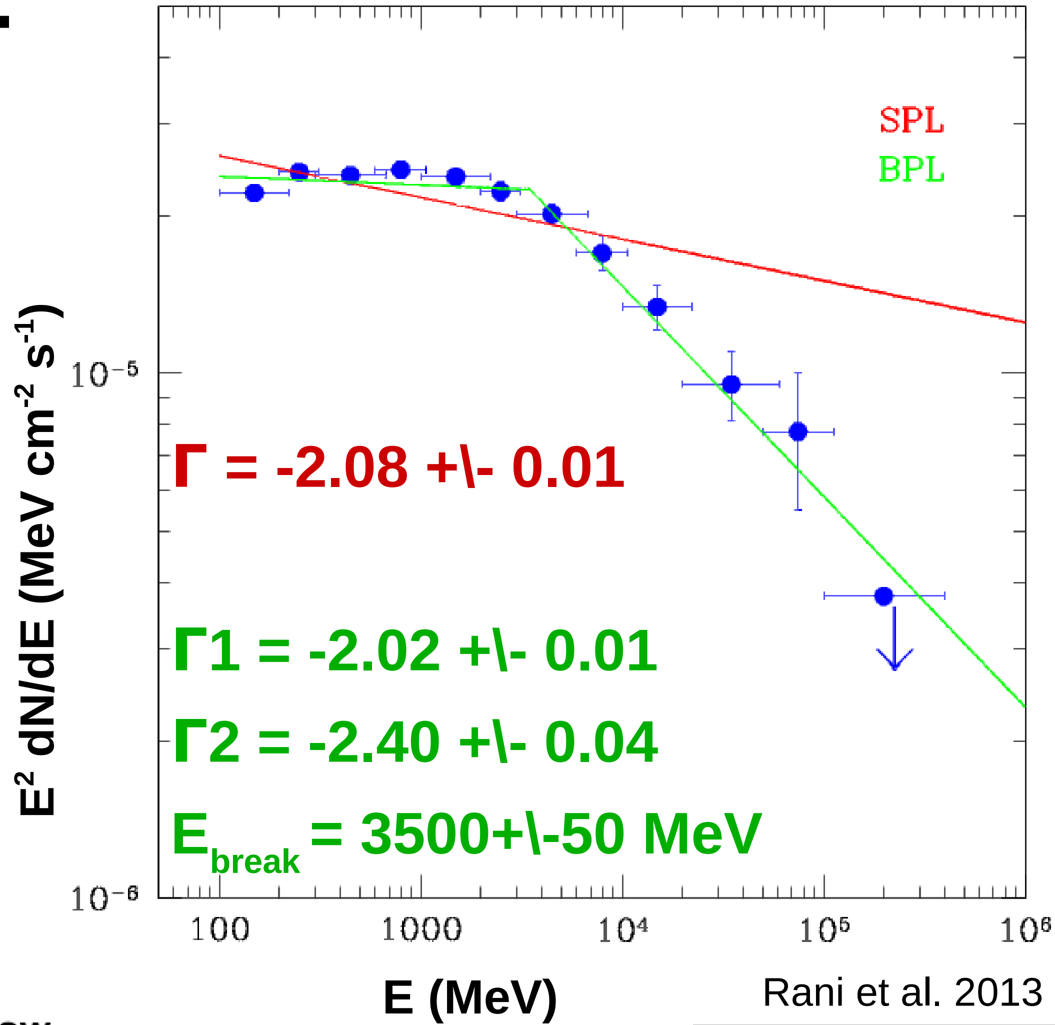
Binned light curves unsuitable to derive T_{min} accurately

Unbinned maximum-likelihood method

Sub-hour variability is found for 3C454.3 and PKS 1510-089, 3C 279

Flux and Spectral variations

Origin of spectral breaks is still an open question



Rani et al. 2013

PowerLaw simple power law

$N(E) = N_0 (E/E_0)^{\Gamma}$

N_0 :Prefactor, Γ:spectral index

E_0:energy scale

BrokenPowerLaw two component power law

$N(E) = N_0 (E/E_b)^{\Gamma 1+1}$ E<Eb

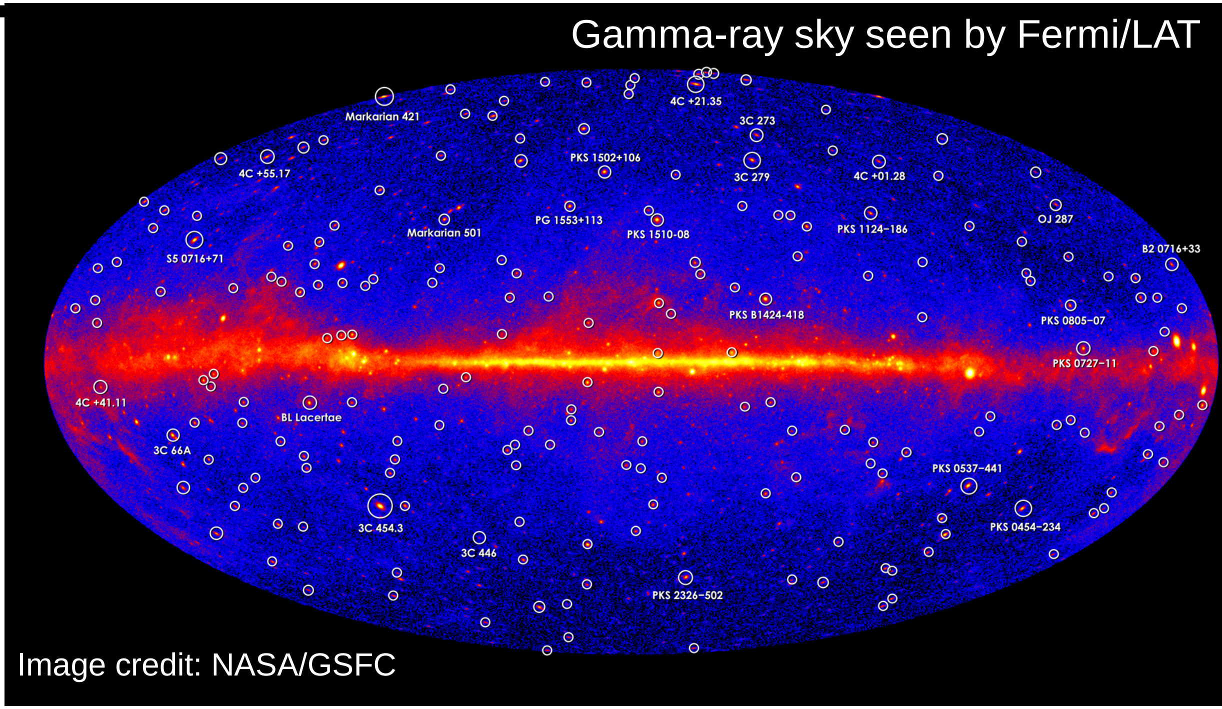
$= N_0 (E/Eb)^{\Gamma 2+1}$ E>Eb

N_0 :Prefactor Γ1:low energy spectral index Γ2:high energy spectral index

Eb:break energy

The Fermi era

>3000 gamma-ray objects
~60% AGN
(98% blazars)



Since its launch in 2008, the **Fermi-LAT (Large Area Telescope)** has revolutionized our knowledge of gamma-ray sky with a combination of high sensitivity, wide field-of-view, and large energy range (**about 20 MeV to more than 300 GeV**).

Blazars are considered as the prime candidates for the emission of Ultra High Energy Cosmic Rays (UHECRs).

High-energy radiation seems to be related to relativistic particles accelerated in jets

Where and how gamma-rays are produced?

High-energy radiation seems to be related to relativistic particles accelerated in jets.

1. Observed radio-gamma-ray correlations

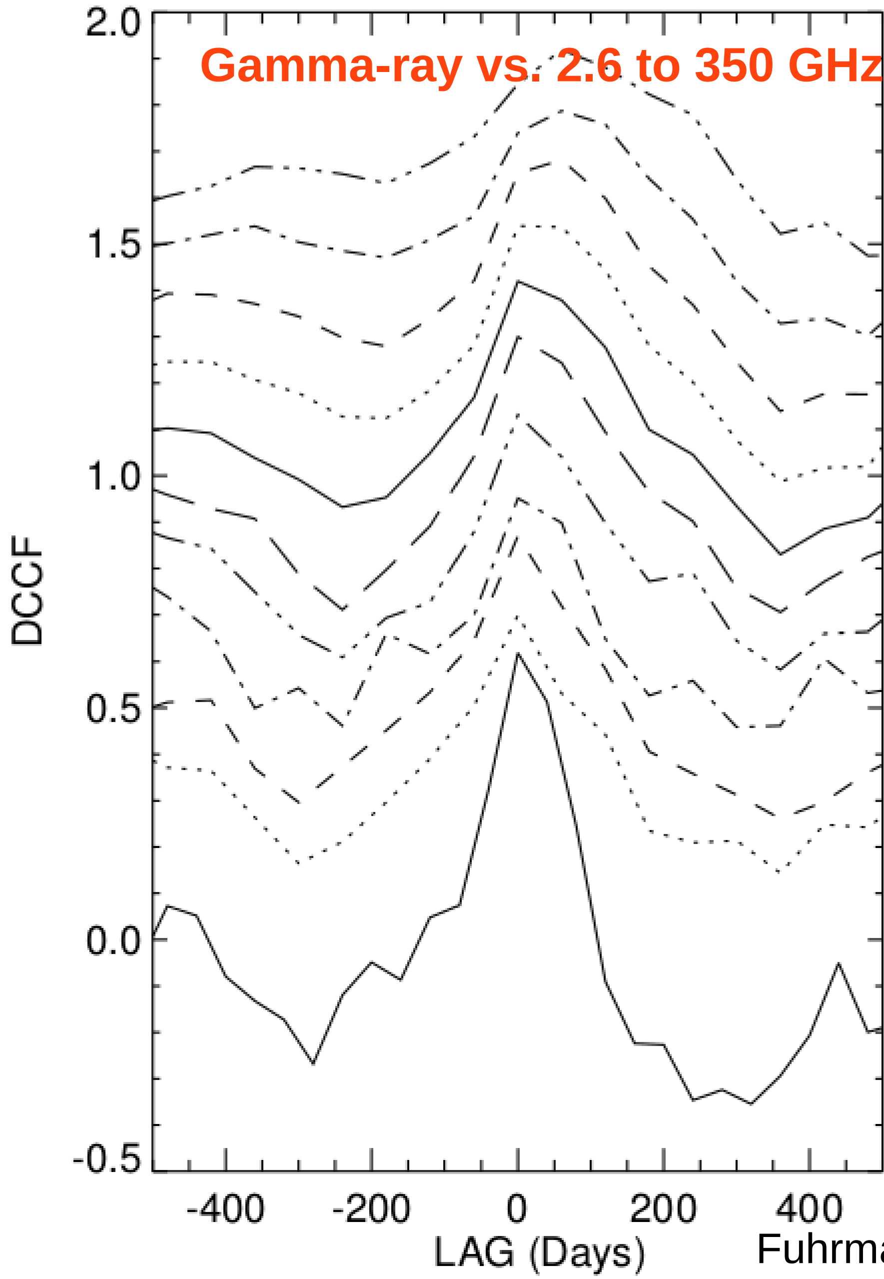
2. Jet morphology and gamma-ray correlations

3. Coincidence of gamma-ray flare with appearance of new jet components

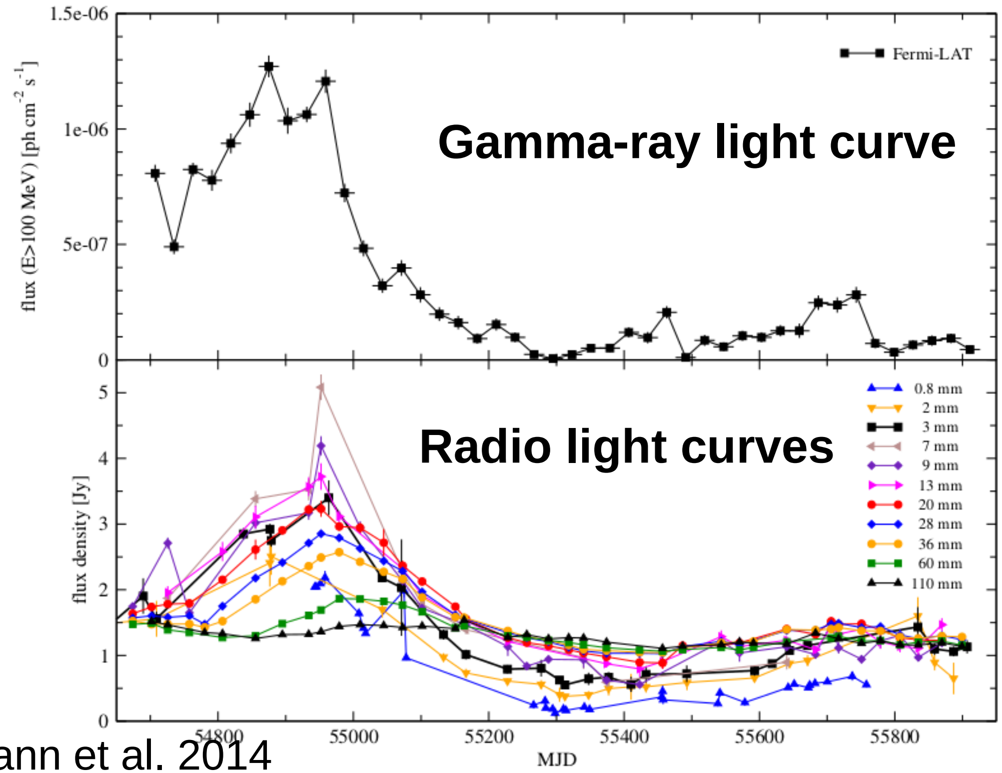
4. Coincidence of gamma-ray flare with the interaction of moving features with stationary features

5. Polarization angle swings during gamma-ray flares

Radio – gamma-ray correlations

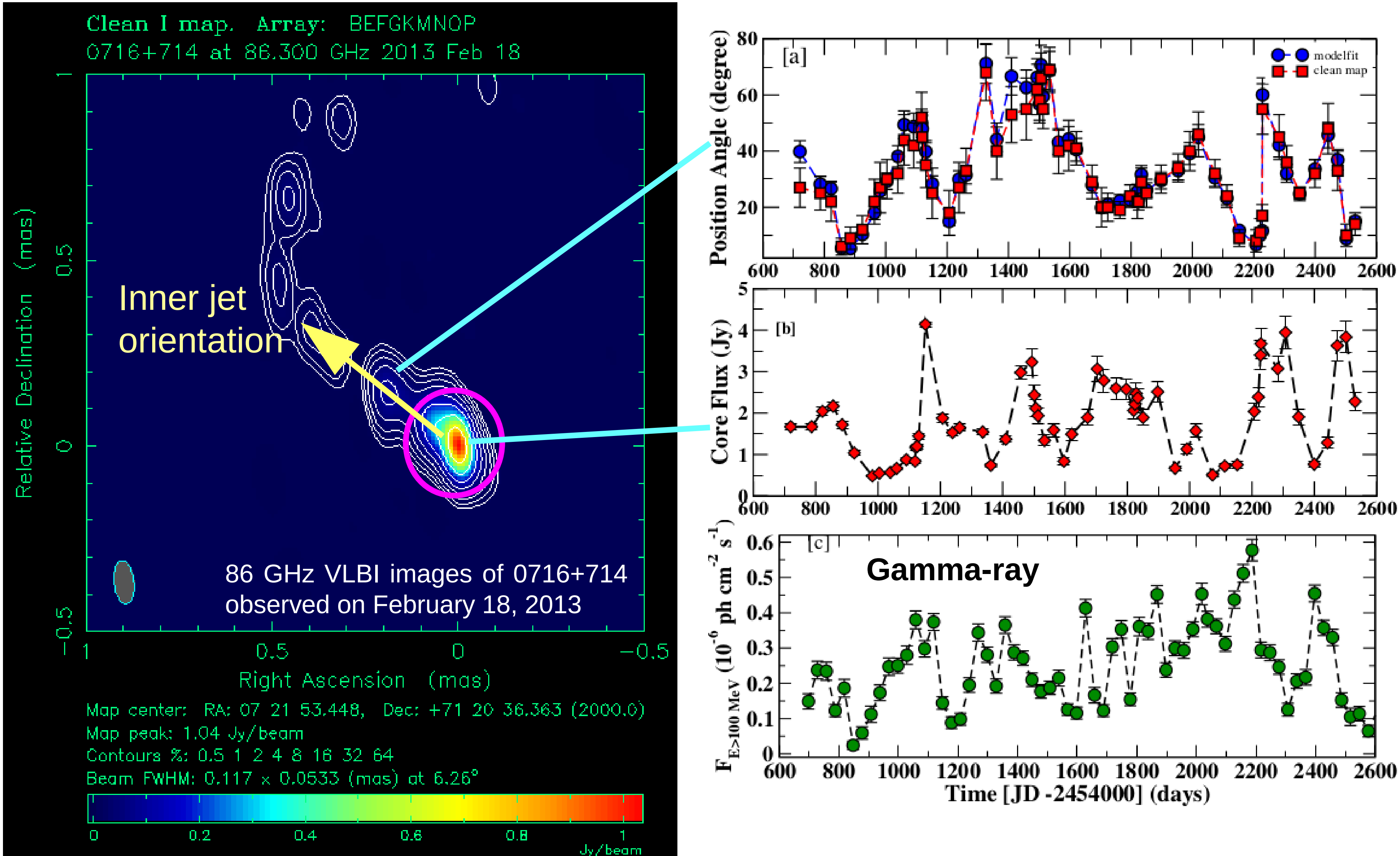


Observed gamma-ray – radio correlation (Agudo et al. 2010, 2011, Jorstad et al. 2010, 2013, Marscher et al. 2008,2010, Fuhrmann et al. 2014, Rani et al. 2013,2014, Max-Moerbeck et al. 2014)



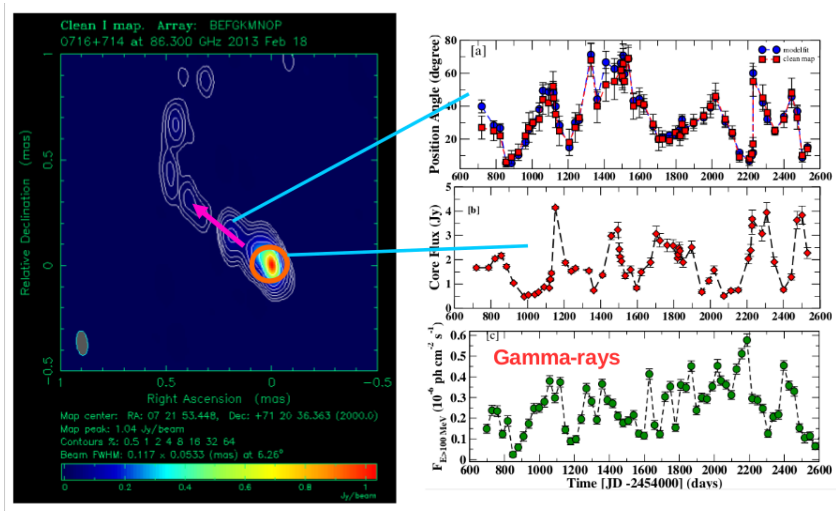
Fuhrmann et al. 2014

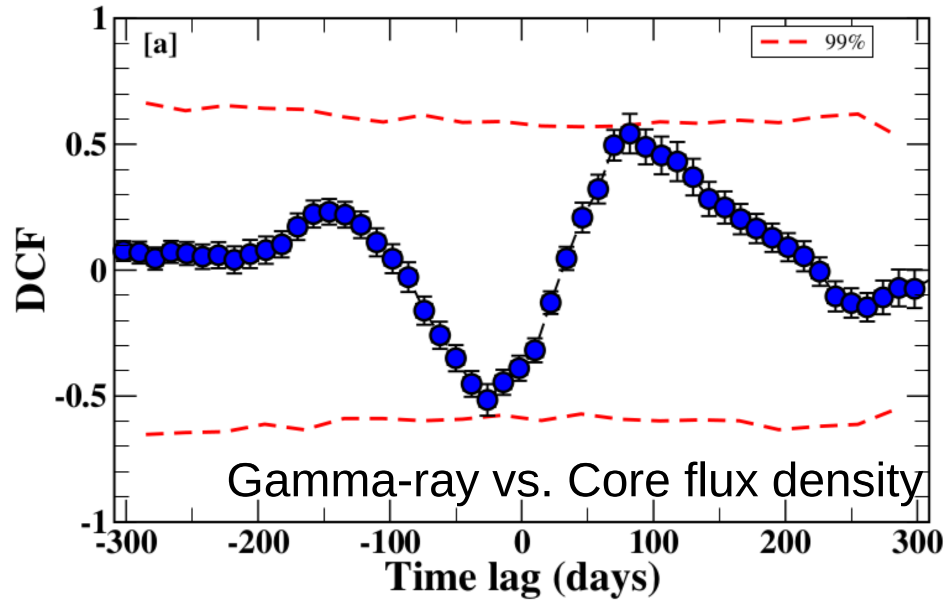
Jet outflow and gamma-ray emission correlations



Rani et al. 2014

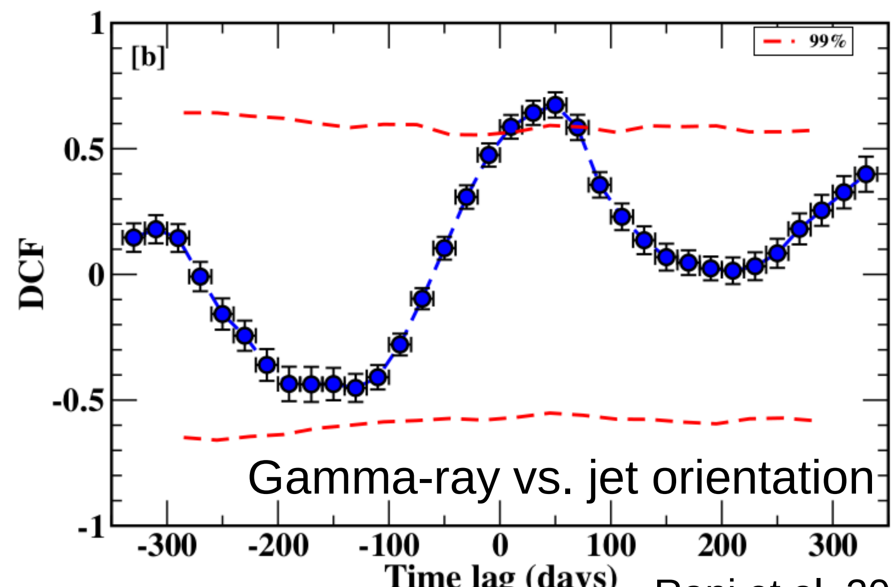
Jet outflow and gamma-ray emission correlations





The analysis suggests a strong correlation between high-energy emission and inner jet morphology.

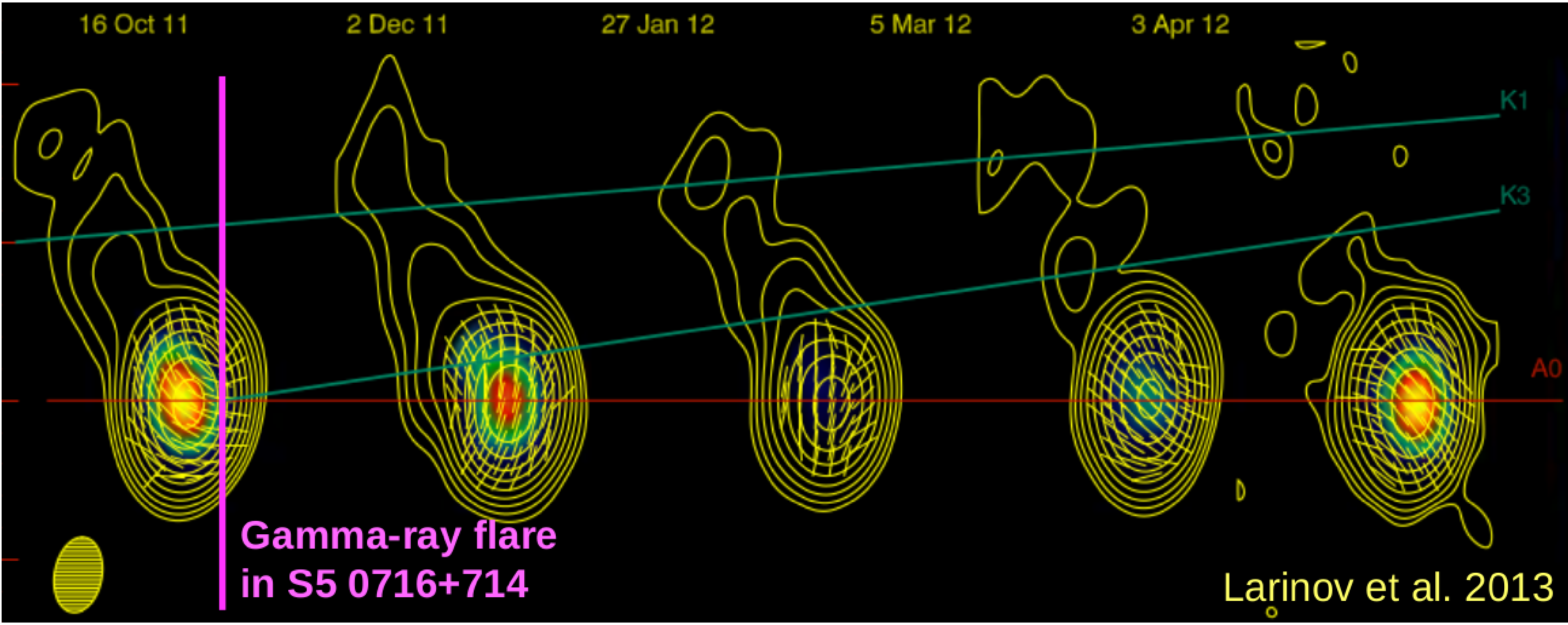
The results imply a strong physical and causal connection between gamma-ray emission and the inner jet morphology in the source.



Rani et al. 2014

Coincidence of gamma-ray flares often with appearance of new jet components

Coincidence of gamma-ray flares often with appearance of new jet components has been reported for several blazars (Jorstad et al. 2010, 2013, Marscher et al. 2011, Larinov et al. 2013, Rani et al. 2015)



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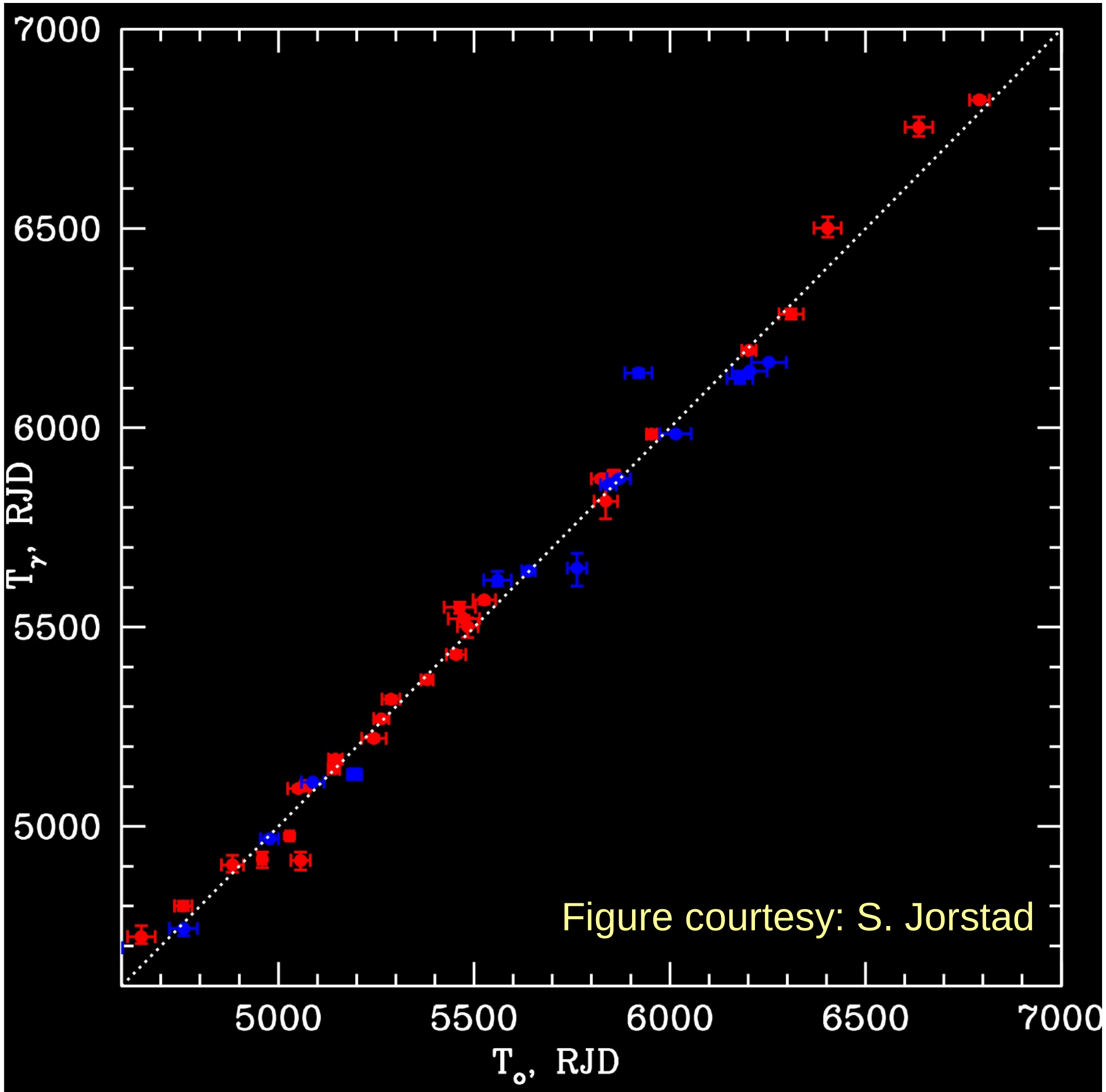
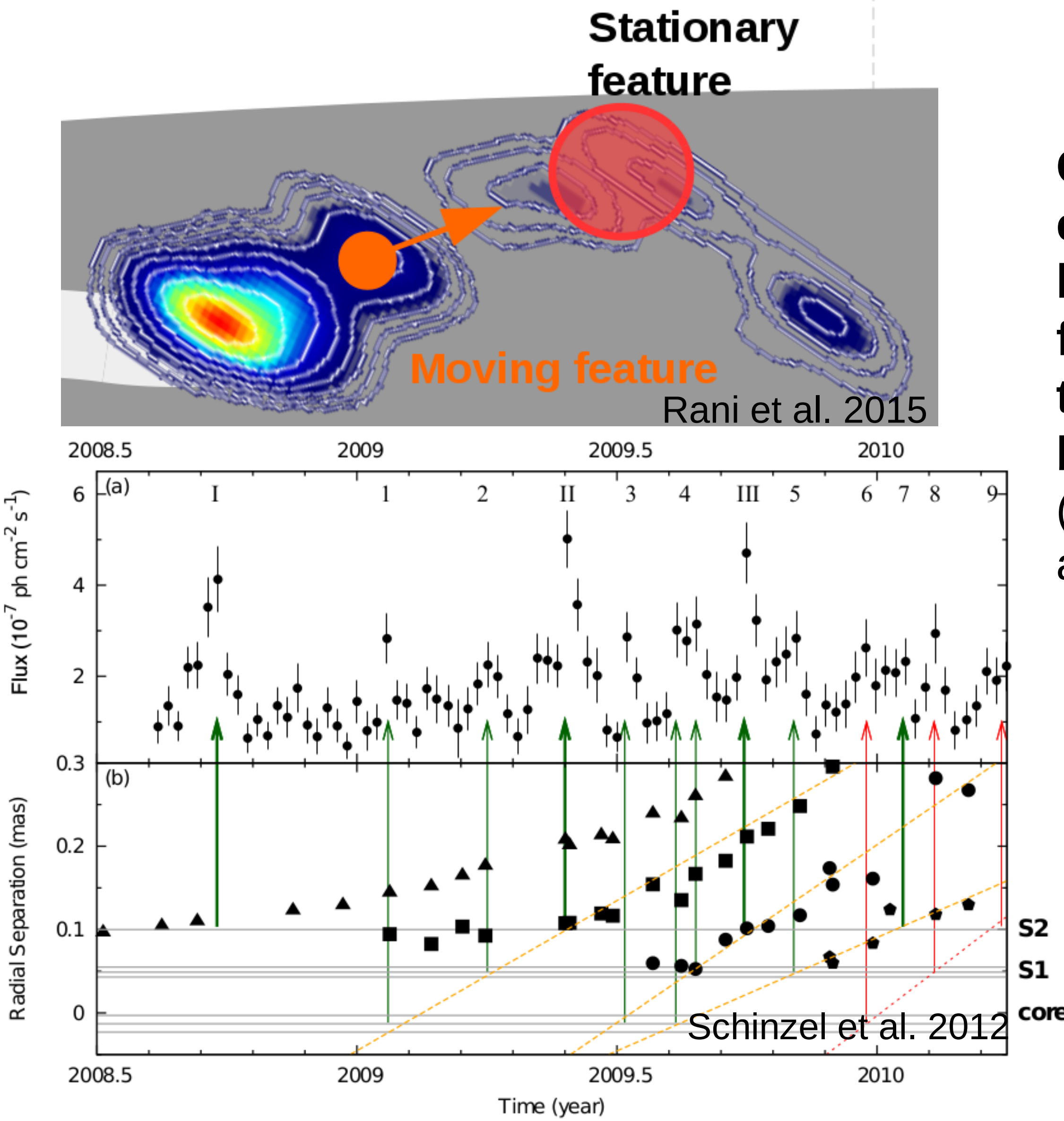


During 2008-2013 we detected in 18 quasars and 12 BLLacs:

100% of the gamma-ray events are accompanied by brightening of the 43 GHz VLBI core

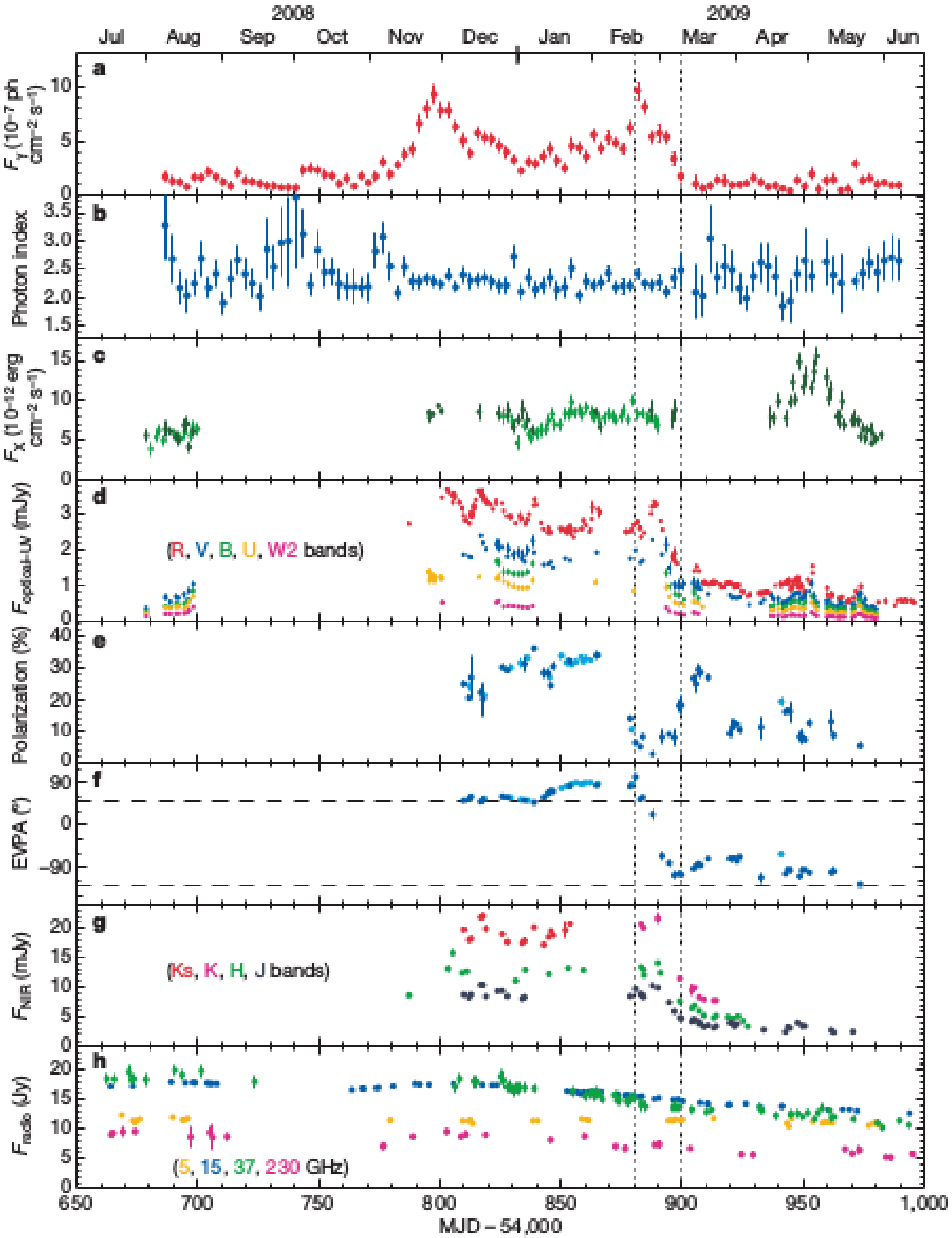
90% of the gamma-ray events are associated with the ejection of a super-luminal knot within the flare duration

Passage of moving features through stationary features



Good agreement between epochs of passage of moving knots through stationary features in the jet and peaks in the gamma-ray light curve has been found for many sources (Hodgson et al. 2014, Schinzel et al. 2012, Marscher et al. 2013)

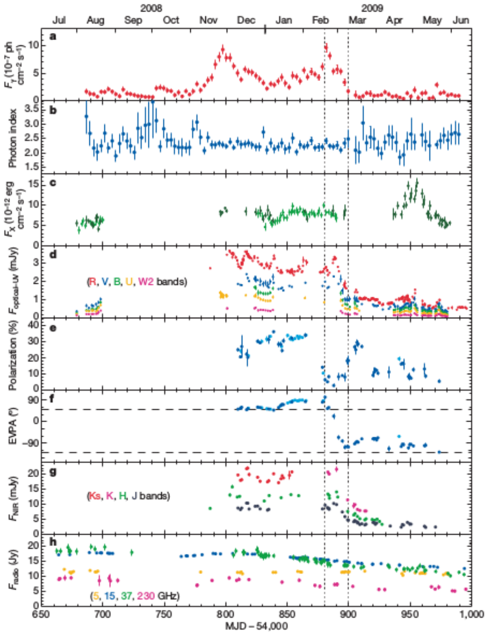
Polarization angle swings during gamma-ray flares



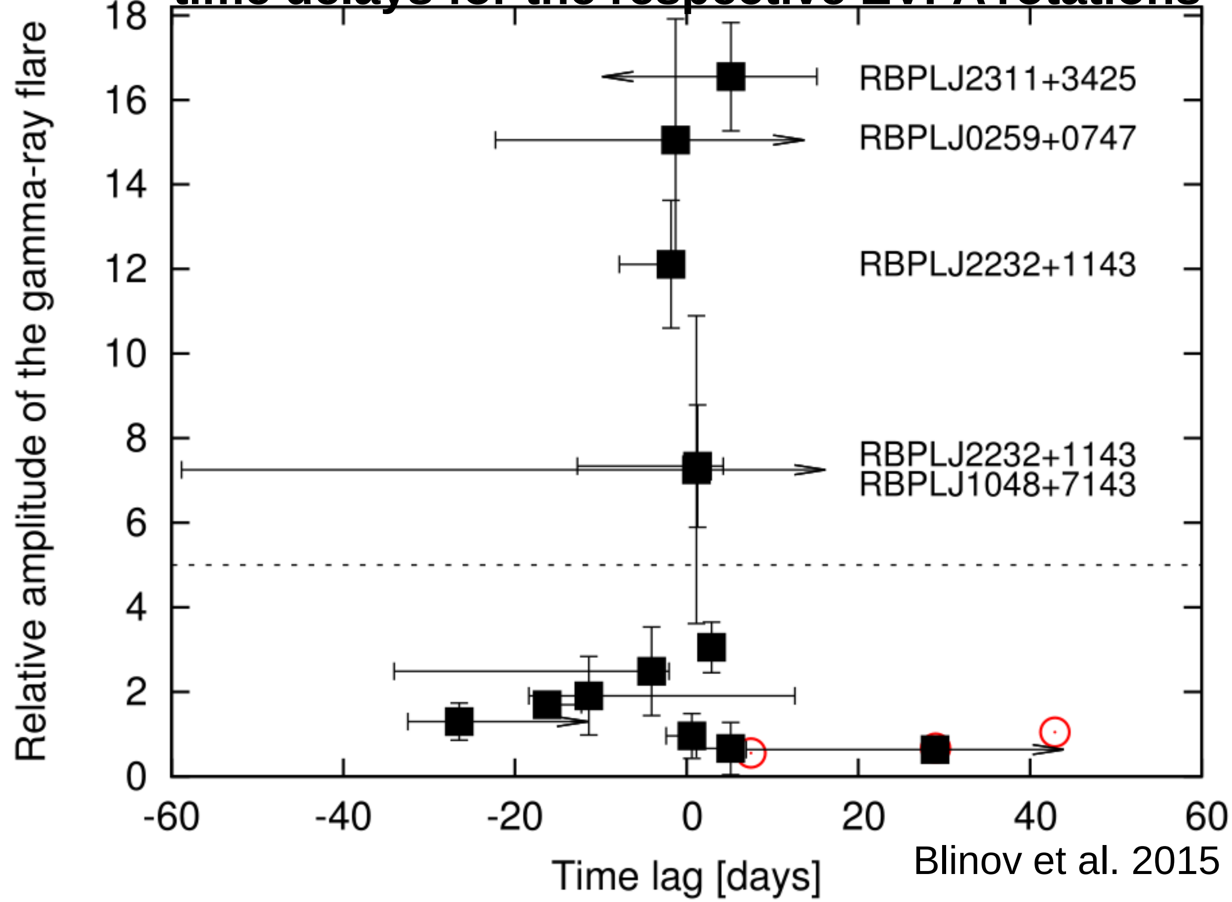
Coincidence of a smooth rotation of EVPA (>180 degree) with a gamma-ray flare in 3C 279

Abdo et al. 2010

Polarization angle swings during gamma-ray flares



Relative brightness of gamma-ray flares w.r.t. time delays for the respective EVPA rotations

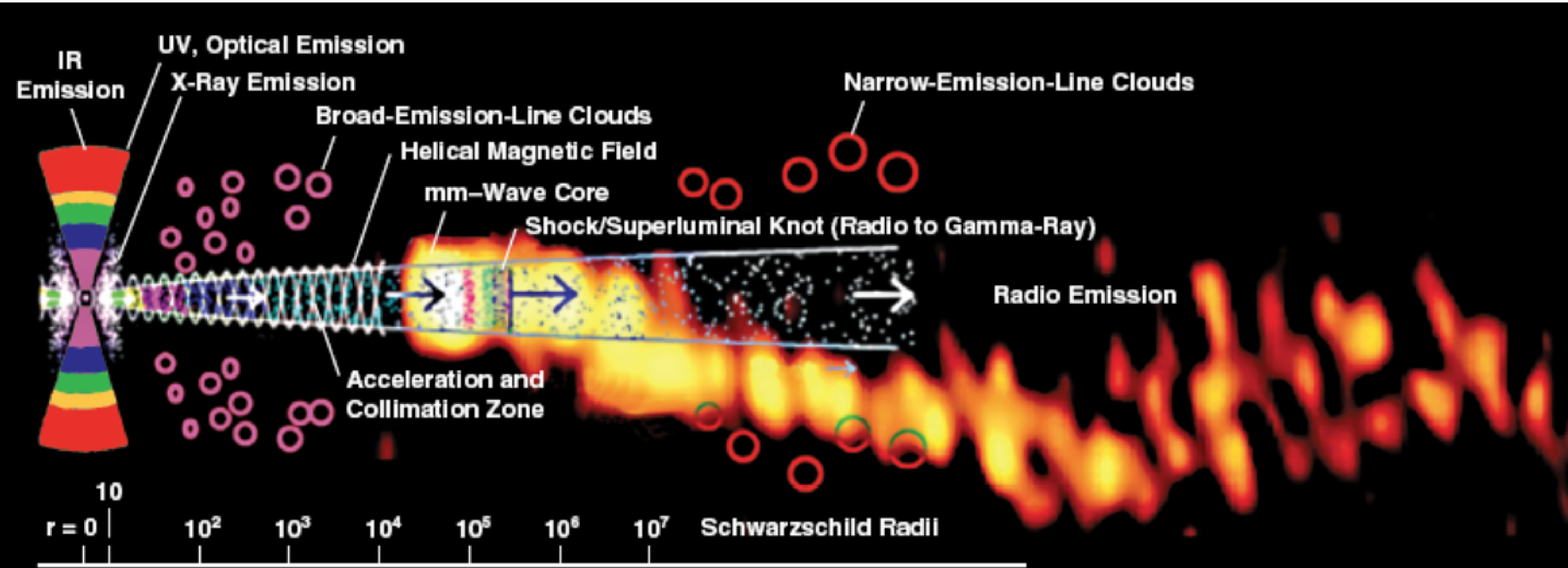


Blinov et al. 2015

The close association of the gamma-ray flare with the smooth, continuous change of the optical polarization angle provides evidence for the presence of highly ordered magnetic fields in the regions of gamma-ray production.

High-energy radiation seems to be related to relativistic particles accelerated in jets.

Where?



Where

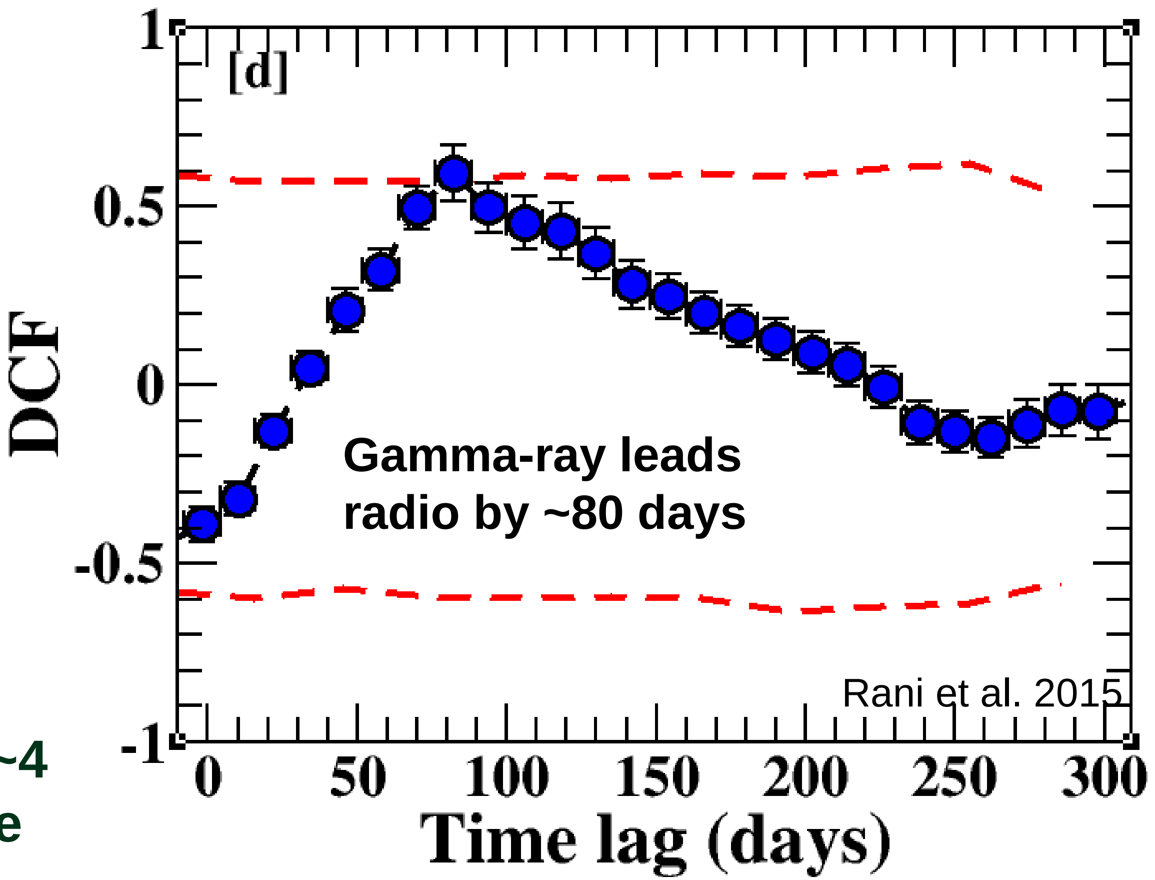
- **Within the broad-line region**
- **On sub-parsec scales (100-1000 R_s)**

-- Observed gamma-ray -- radio correlations (Marscher et al. 2008,2010, Rani et al. 2013, Fuhrmann et al. 2014)

$$\Delta r_{\mathrm{r},\gamma} = \frac{\beta_{\mathrm{app}}\, c\, \tau^{\mathrm{source}}_{\mathrm{r},\gamma}}{\sin\theta}$$

β_{app} : apparent speed

Θ : viewing angle

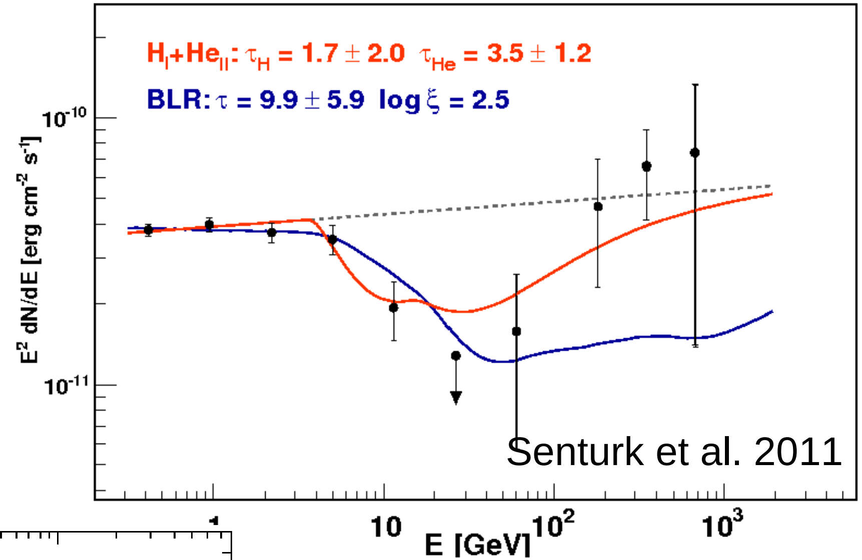


e.g. a time lag of 80 days translates to a distance of ~4 parsecs in the source frame

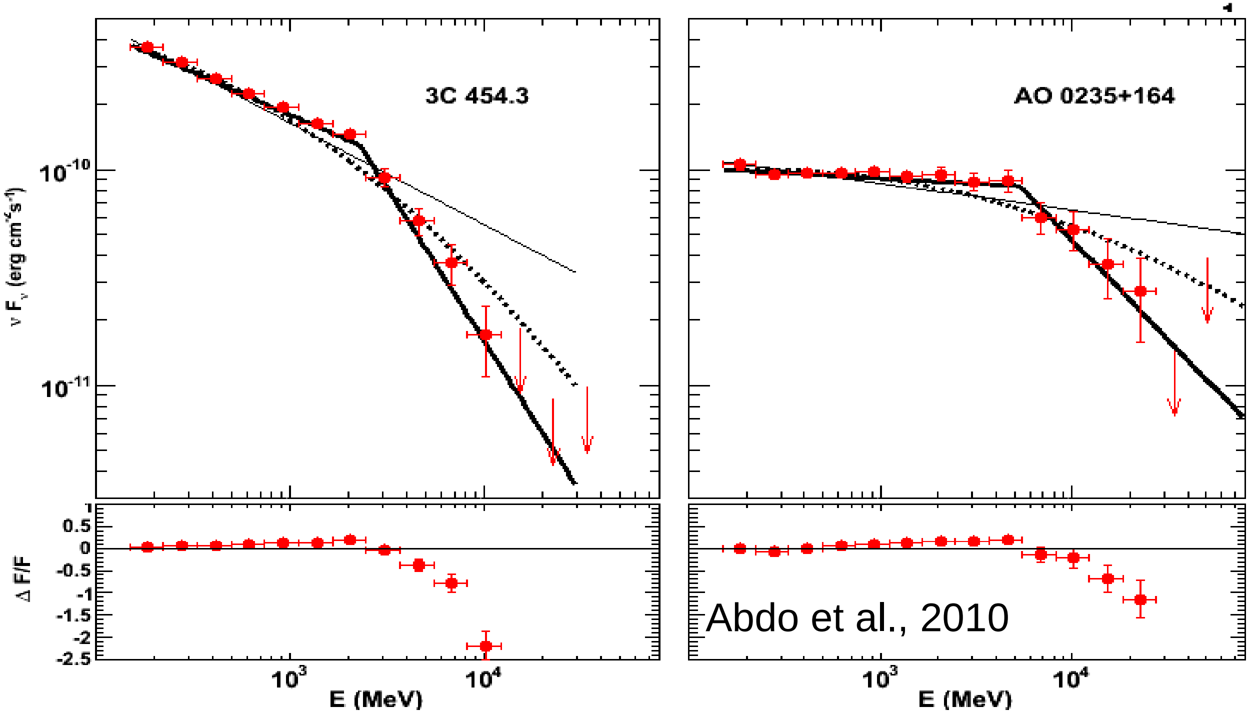
Where

- Within the broad-line region
- On sub-parsec scales (100-1000 R_s)

-- Observed gamma-ray spectral break at few GeVs (Abdo et al. 2009, Finke & Dermer 2010, Rani et al. 2013a,b, Tanaka et al. 2011)

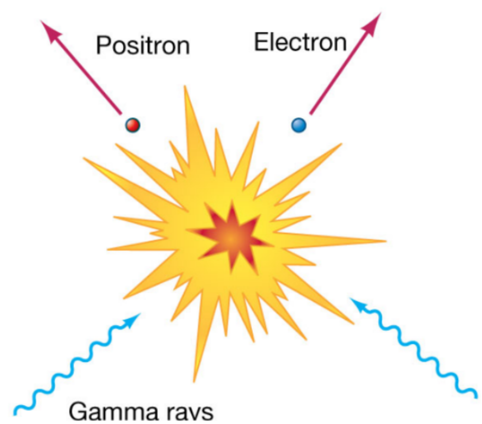


Senturk et al. 2011

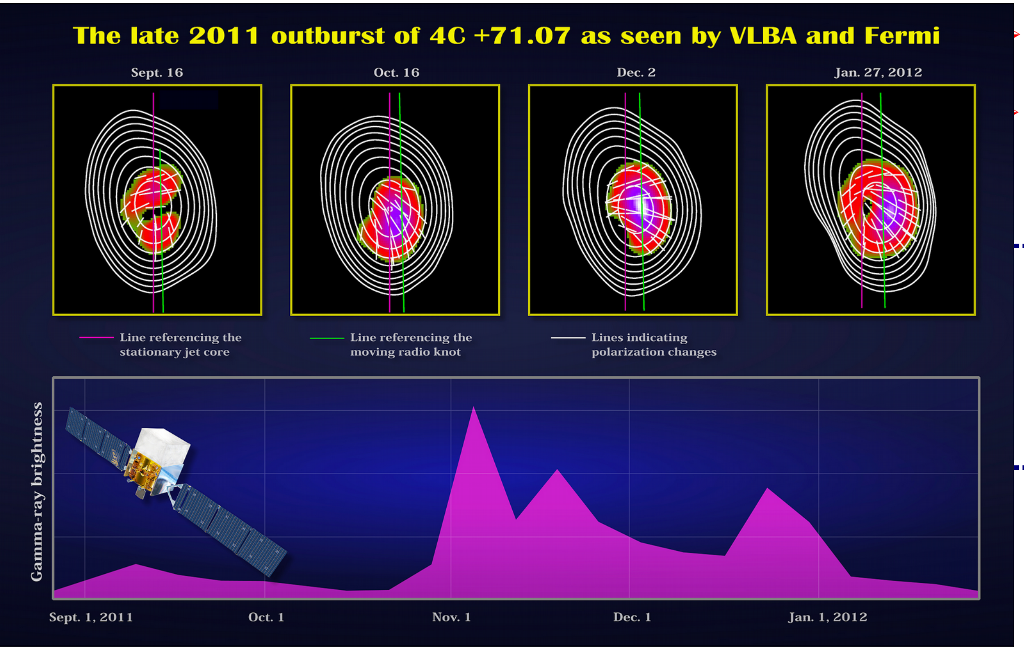


Abdo et al., 2010

Absorption via pair production



Where



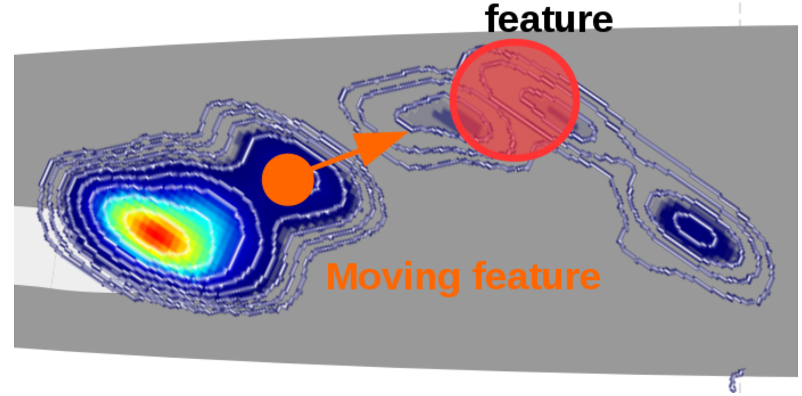
Credit: NASA's Goddard Space Flight Center/A. Marscher and S.Jorstad (BU)

Outside the Broad-line Region

Down stream from the core

Coincidence of gamma-ray flares with

- **Appearance of new jet components (Jorstad et al. 2010, 2013, Marscher et al. 2011)**
- **Passage of moving components through stationary features in jets (Hodgson et al. 2014, Schinzel et al. 2012, Marscher et al. 2013)**



Coincidence of the enhanced gamma-ray emission with the superluminal knot propagating from the mm-wave core down the jet and places the emission region of the highest gamma-ray flux at **~35 pc from the BH in a distant (z=2.17) blazar 4C+71.07** (Jorstad et al. 2013).

Where

- **Within the broad-line region**
- **On sub-parsec scales (100-1000 R_s)**

-- **Observed gamma-ray -- radio correlations (Marscher et al. 2008,2010, Rani et al. 2013, Fuhrmann et al. 2014)**

-- **Observed gamma-ray spectral break at few GeVs (Abdo et al. 2009, Finke & Dermer 2010, Rani et al. 2013a,b, Tanaka et al. 2011)**

- **Outside the Broad-line Region**
- **Down stream from the core**

Coincidence of gamma-ray flares with

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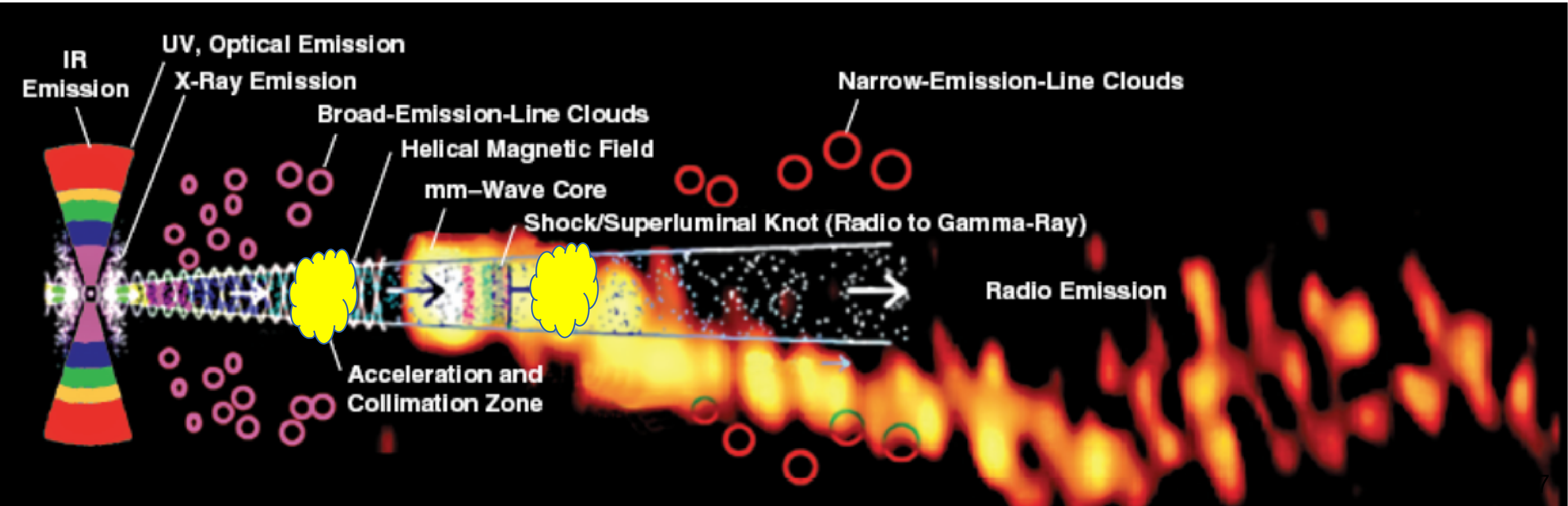
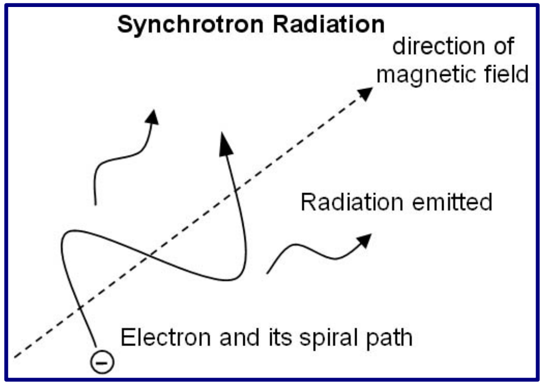
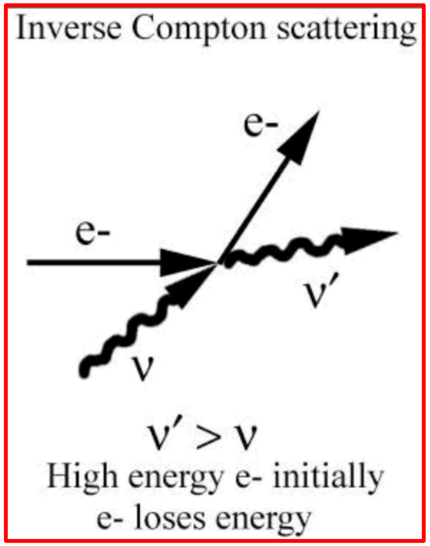
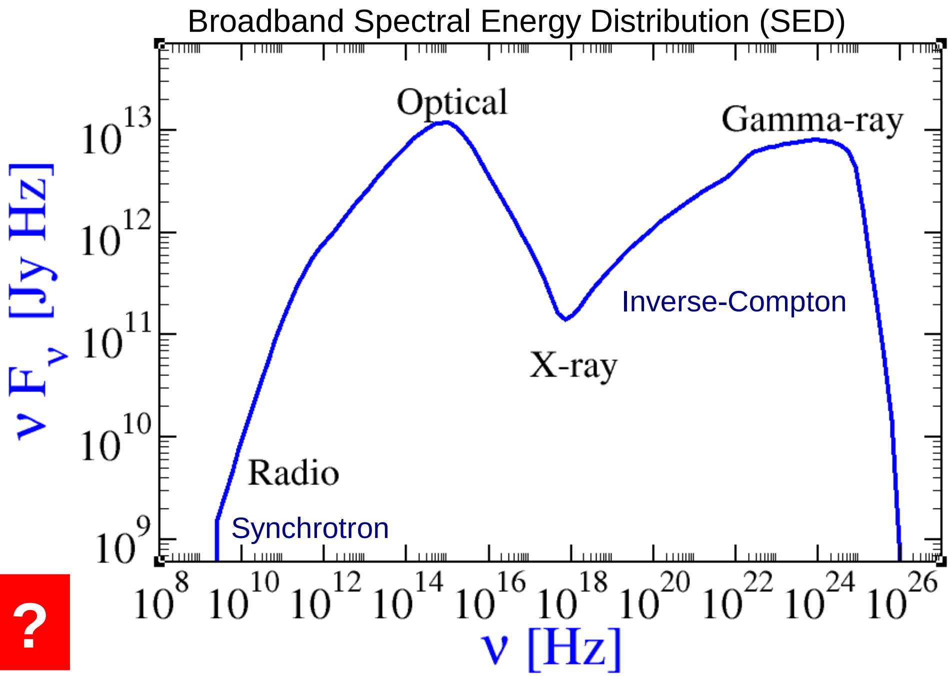


How : Leptonic Models





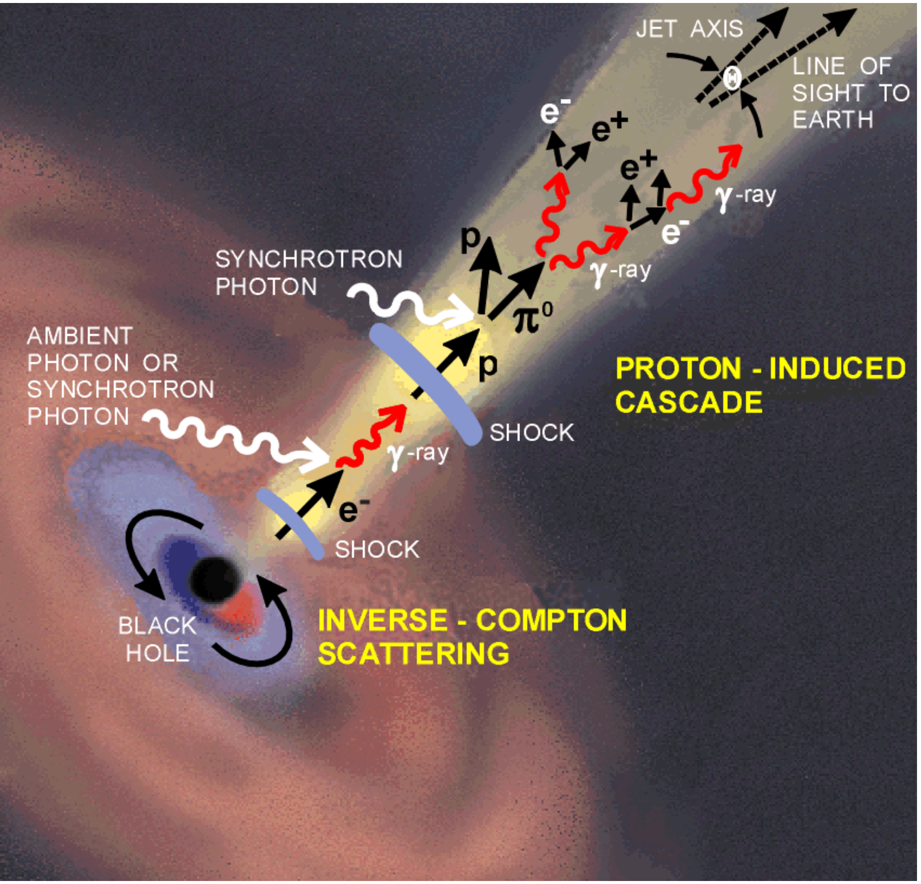
SSC and/or EC ?

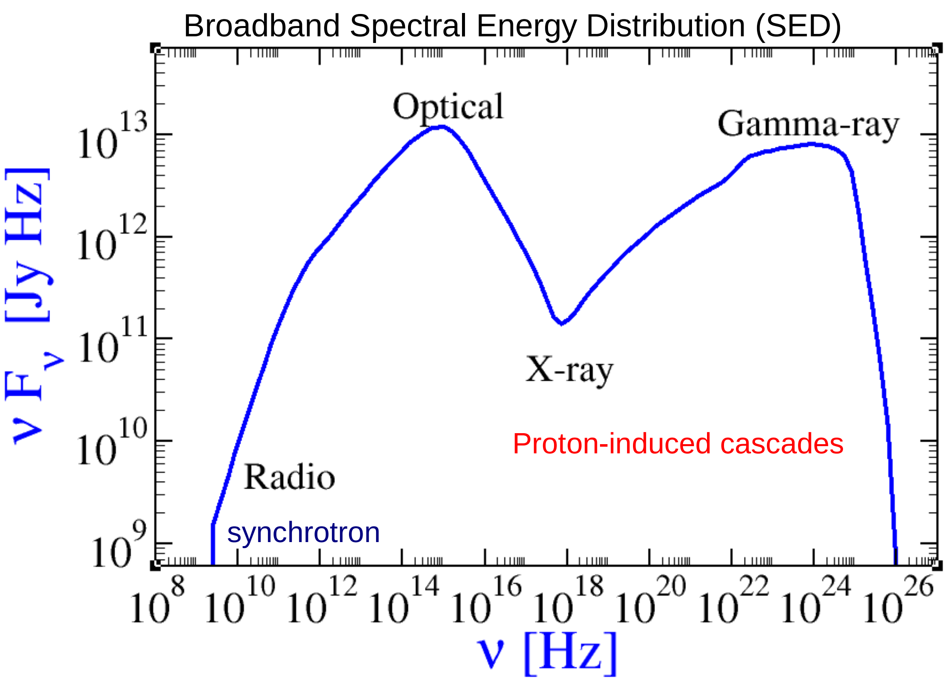


Böttcher at al. 2002, 2012

	Seed photons
Synchrotron Self-Compton	: synchrotron photons from the jet
External Compton	: thermal photons from accretion disk, broad-line region, and/or molecular torus

How : Hadronic Models

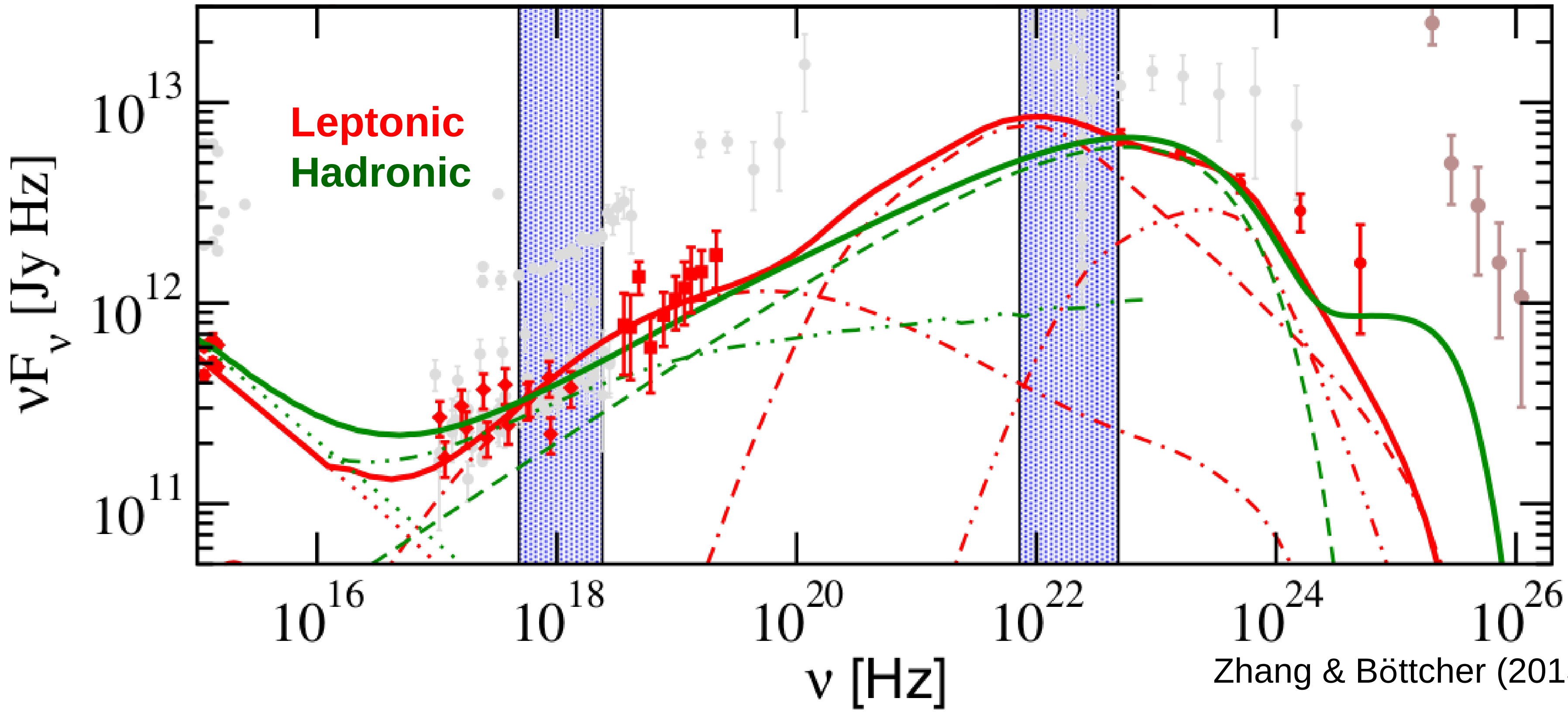




Böttcher at al. 2002, 2012

Significant fraction of jet power converted into acceleration of protons in strongly magnetized (B ~ several tens of Gauss) environments reaching the threshold for pγ-pion production ($E_p \geq 10^{19}$ eV).

How – Leptonic vs. Hadronic models



Zhang & Böttcher (2013)

Broadband SEDs of blazars can be well explained via both leptonic and hadronic models; literature is however more biased towards leptonic models.

Near Future Outlook

Leptonic vs. Hadronic models

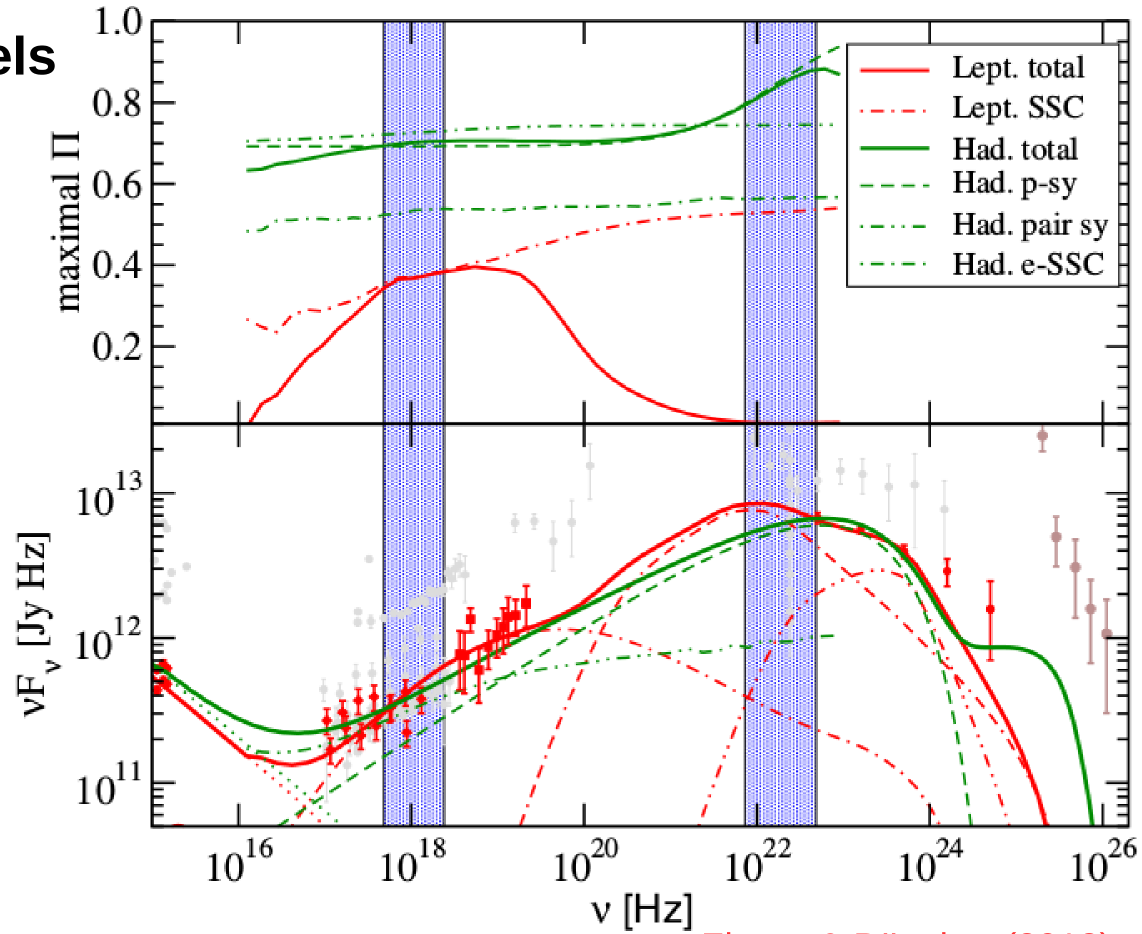
High polarization is expected in Hadronic models compared to Leptonic ones.

Leptonic ≤ 30 – 40 %

Hadronic ≤ 70 – 75 %

X-ray polarization observations :

GEMS, POLAR, ASTRO-H



Zhang & Böttcher (2013)

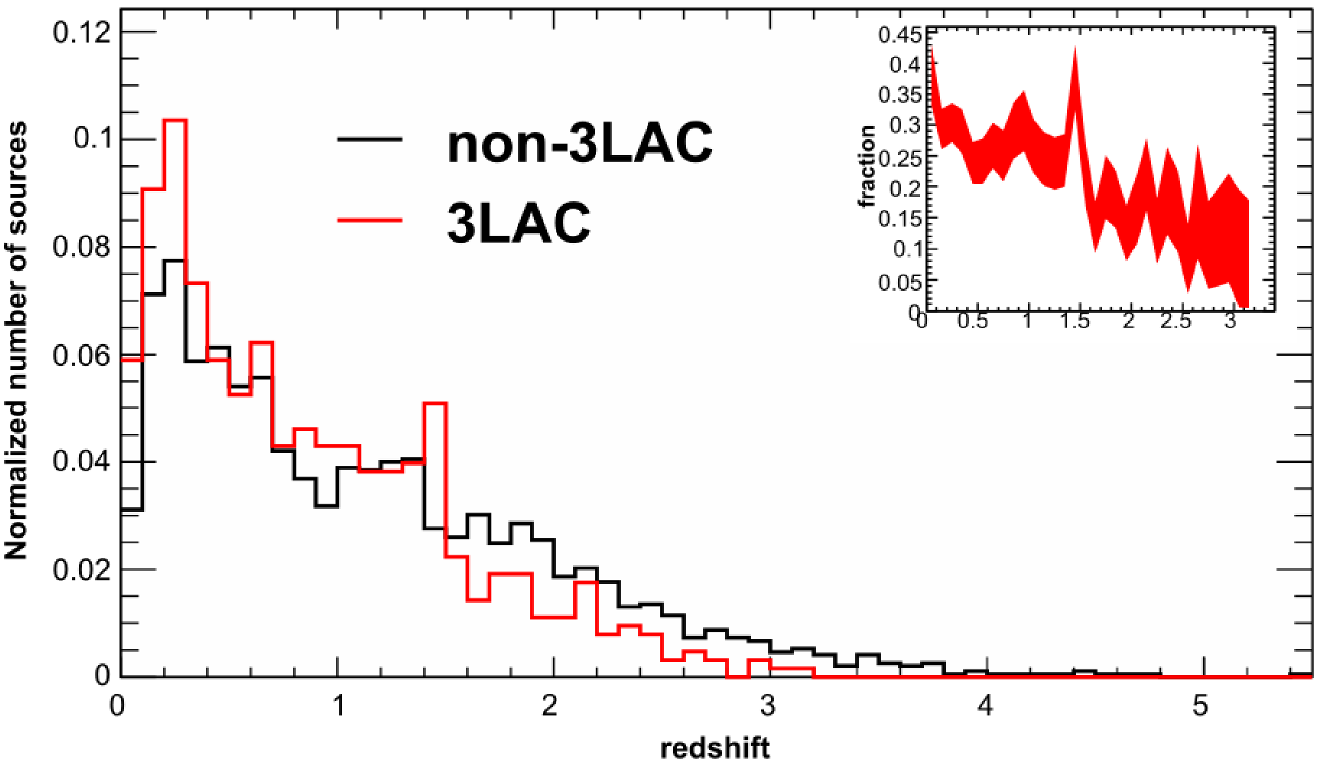
Coincidence of extraterrestrial neutrinos detected by the IceCube collaboration (Science, Nov. 2013) with high-energy flares

Near Future Outlook

- **Gamma-ray loud vs. Gamma-ray quiet blazars**

  -- A large fraction of known blazars (>60%) are still missing their gamma-ray counterpart

  -- This leads to an evolving dichotomy of gamma-ray loud (or gamma-ray detected) blazars and gamma-ray quiet (or gamma-ray non-detected) blazars.

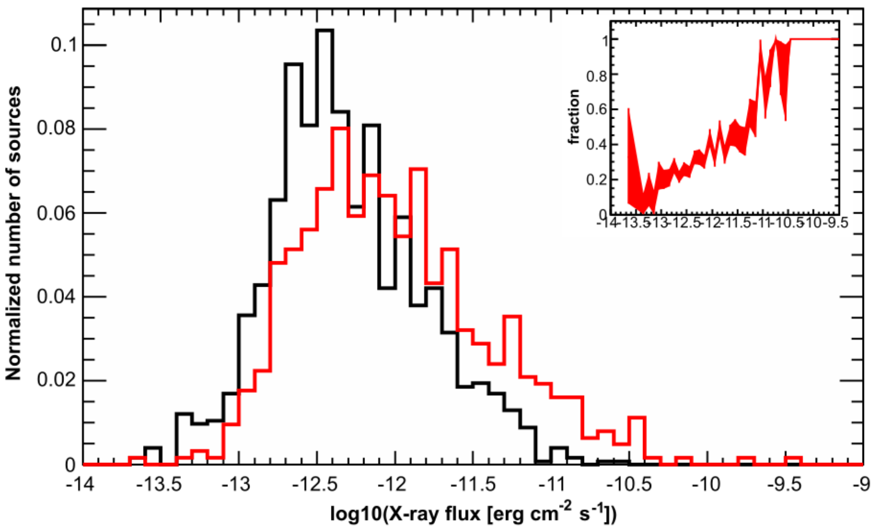


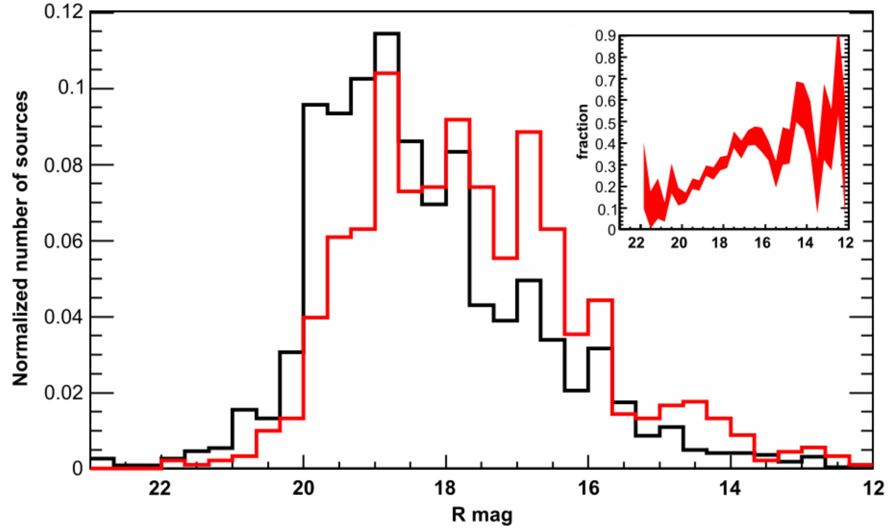
Redshift distribution of LAT detected and non-detected blazars

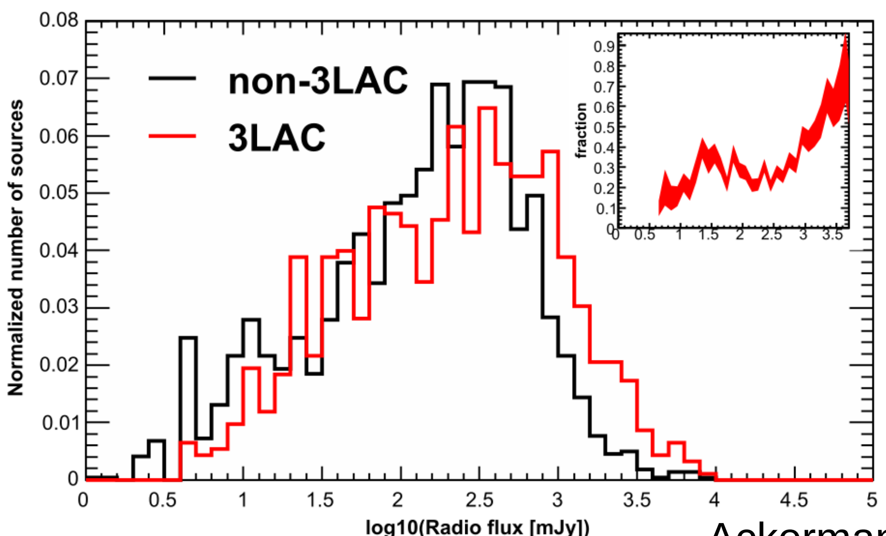
Ackermann M. et al. 2015

Near Future Outlook

- **Gamma-ray loud vs. Gamma-ray quiet blazars**







gamma-ray sources slightly brighter than average in other bands

large overlap in distributions between gamma-ray loud and quiet blazars

Ackermann M. et al. 2015

In near future...

Fermi is doing great –

>3000 Fermi-LAT sources (c.f. ~300 GeV sources prior to Fermi)

Many discoveries, many new source classes, many surprises

Pass8 data release June 2015– improved systematics, a significant reduction in background contamination coupled with an increased effective area, a better point-spread function, a better understanding of the systematic uncertainties, and an extension of the energy reach for the photon analysis below 100 MeV and above a few hundred GeV (Atwood et al. 2013)

The future of high-resolution VLBI is also very bright and rich –

The event horizon telescope (EHT) will offer an angular resolution of ~10 micro arcseconds

Participation of ALMA will probably bring a new era

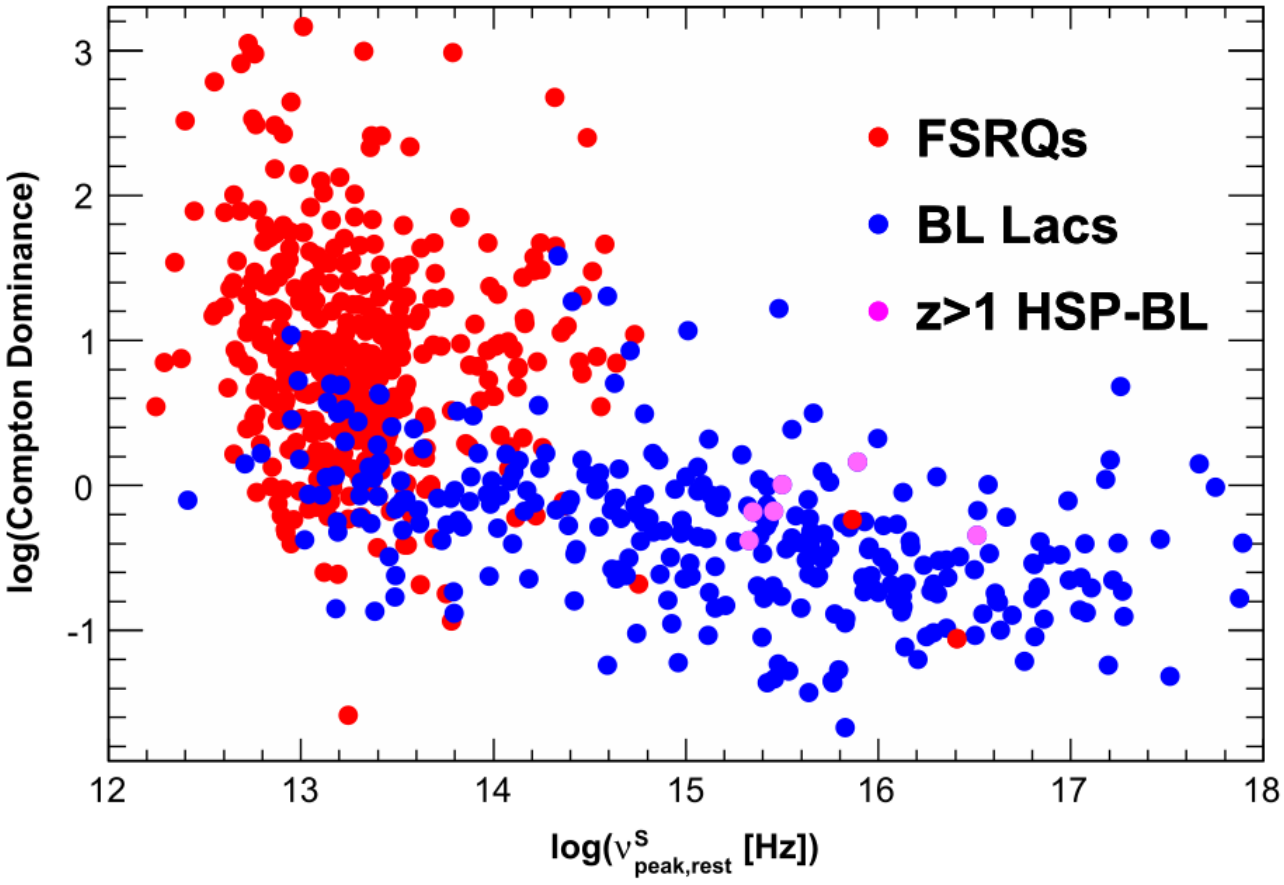
The high-energy polarization missions are also on their way –

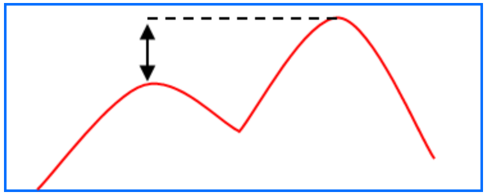
Astro-H, GEMS, X-calibur, PoGOLite, Polar, Harpo, and many more

We certainly have promising tools to solve the mysteries

Thanks for your attention

Compton dominance



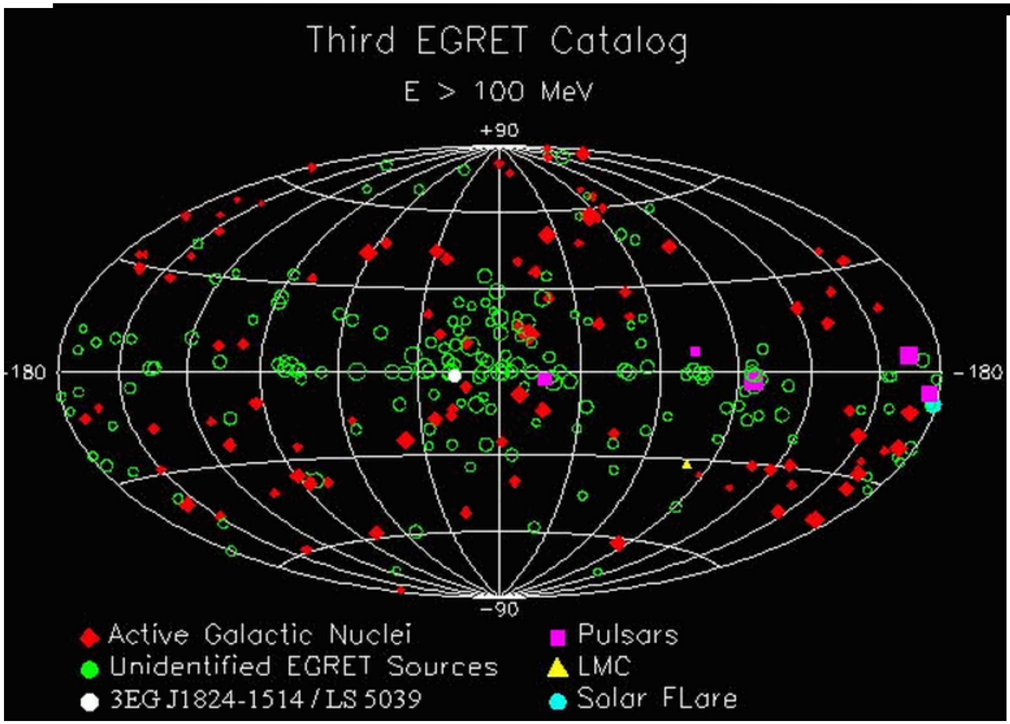


Compton dominance = ratio of the two SED hump peaks

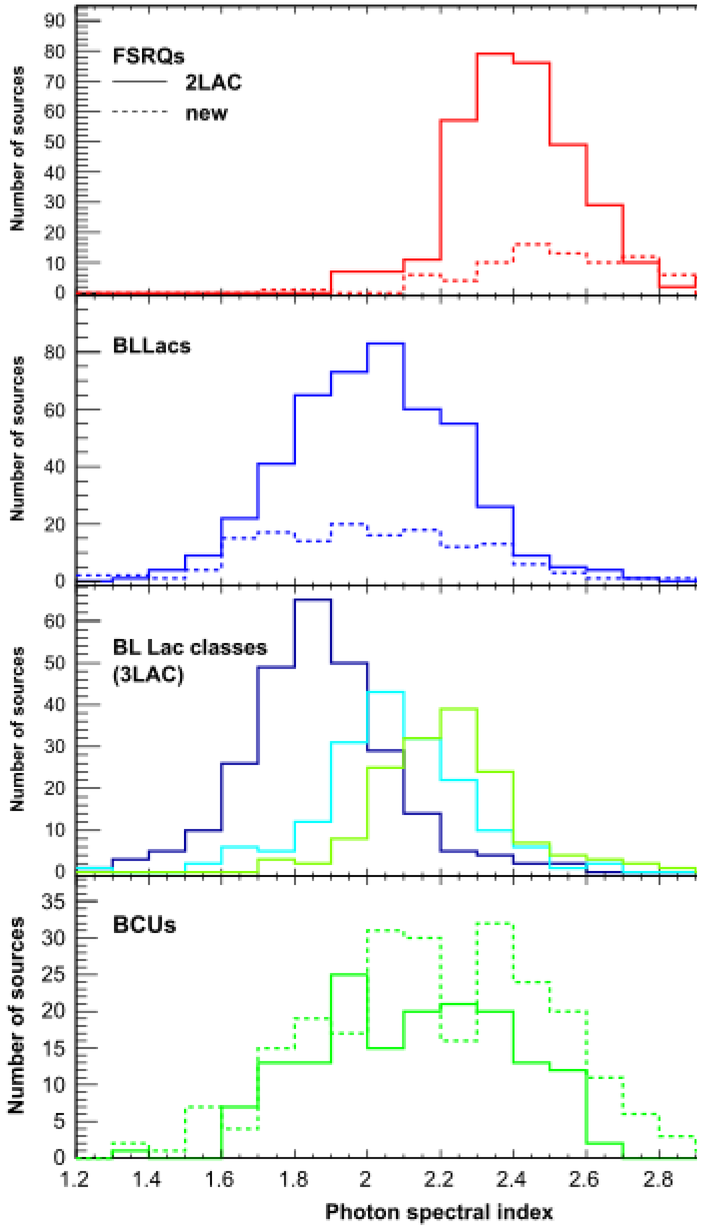
Independent of z

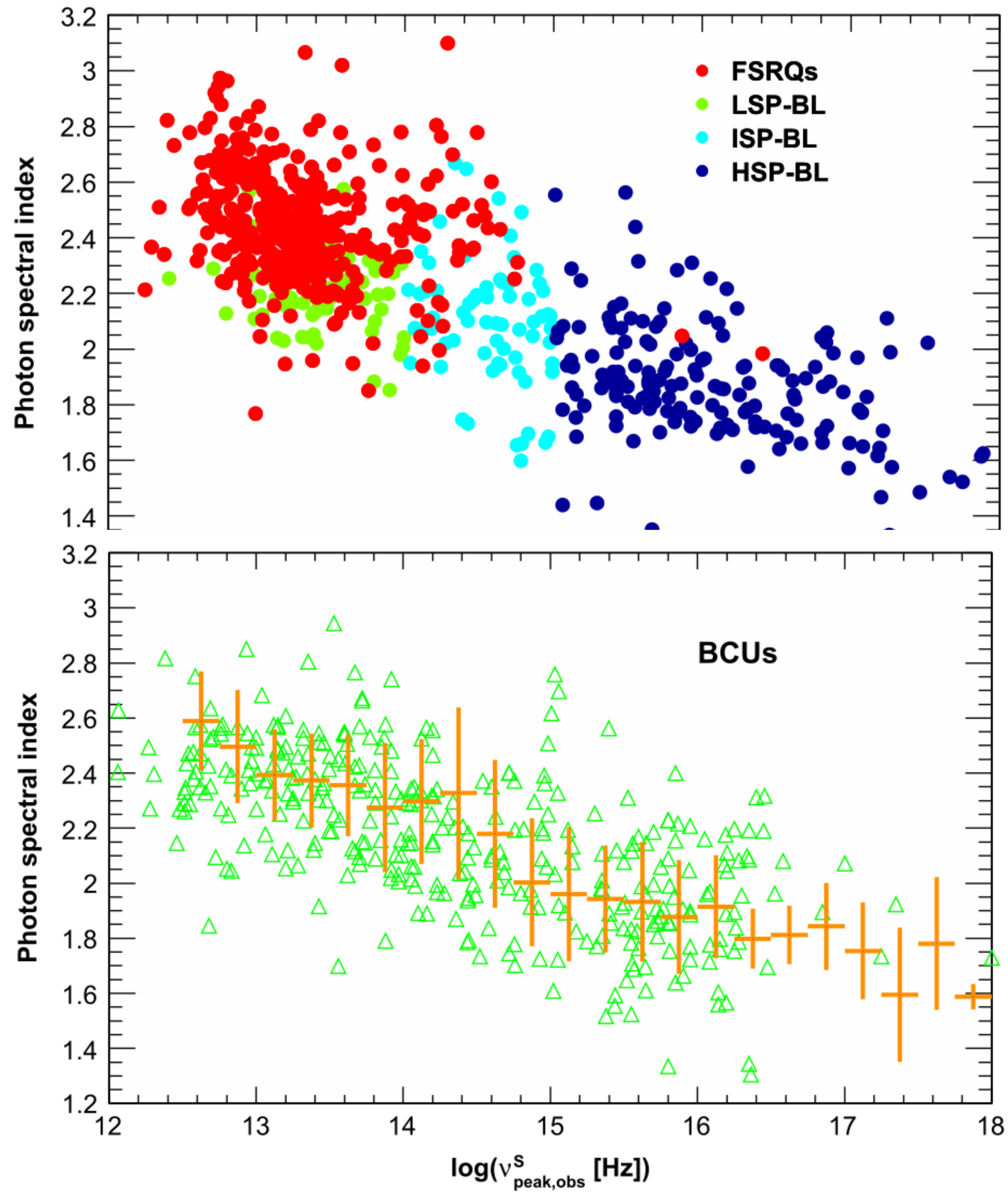
FSRQs have higher Compton dominance than BL Lac objects

LSP BL Lacs have similar


Third EGRET Catalog
E > 100 MeV
+90
-180
-180
-90
Active Galactic Nuclei
Unidentified EGRET Sources
3EG J1824-1514 / LS 5039
Pulsars
LMC
Solar FLare

The


FSRQs
2LAC
new
BLLacs
BL Lac classes
(3LAC)
BCUs
Number of sources
Photon spectral index


FSRQs
LSP-BL
ISP-BL
HSP-BL
BCUs
Photon spectral index
log(ν^S_peak,obs [Hz])