Radio-Loud AGN: An Introduction + Results from Fermi/LAT

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What is an AGN?

Super-Massive Black Hole (SMBH)

10^6 – 10^{10} solar masses!!

What is an AGN?

Accretion Disk!

Accretion + **SMBH** = Active Galaxy or Active Galactic Nucleus or ***AGN***

Note: not actually necessarily a "disk" per se

Two main models:

(1) Shakura-Sunyaev (1973)

- aka "Standard Thin Disk"
- aka "Geometrically Thin, Optically Thick"
- gives you a *modified black body* that peaks in the optical/UV, sometimes known as the "big blue bump"

What is an AGN?

Accretion Disk!

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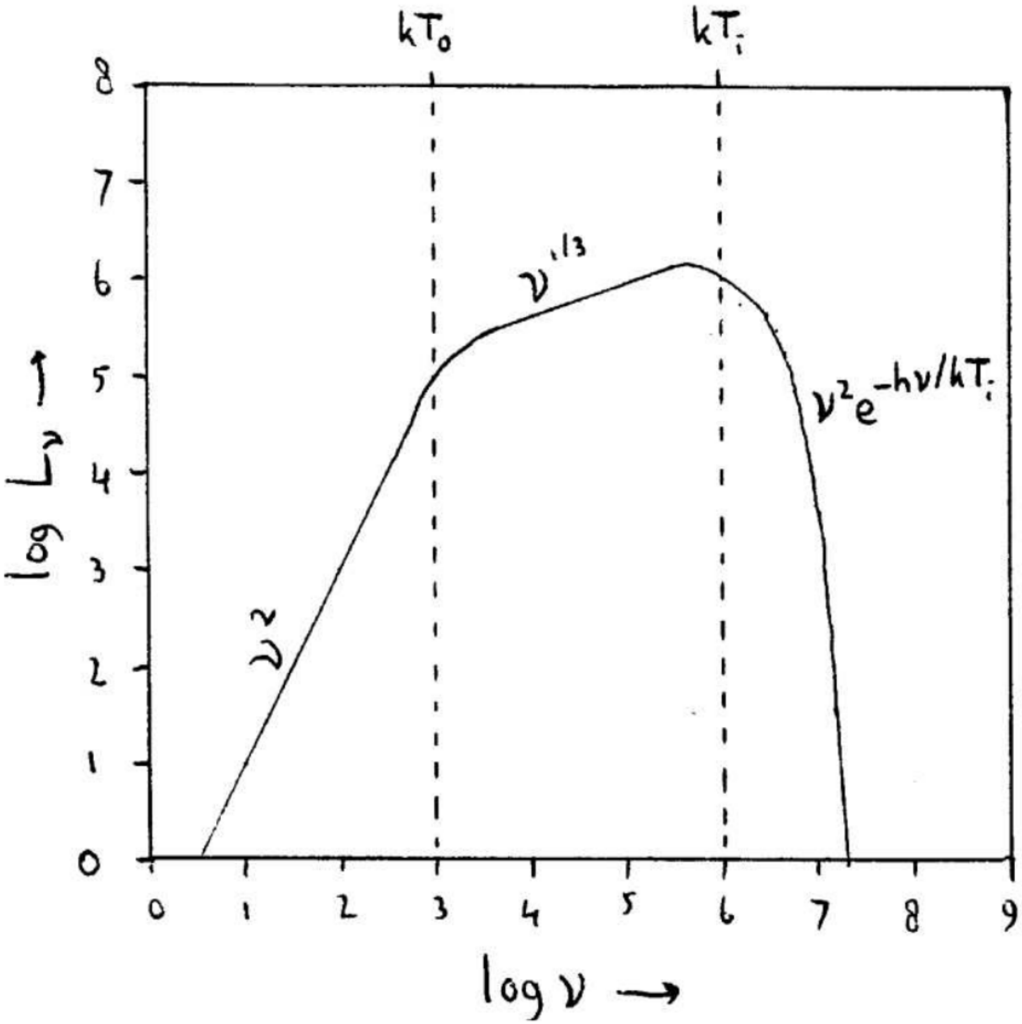
Two main models:

(2) ADAF

- aka "Advection-Dominated Accretion Flow"
- can be optically thin or thick, puffy
- does **not** give you a modified black body.
- spectrum is rather complex & varies by model parameters

Shakura-Sunyaev Disk

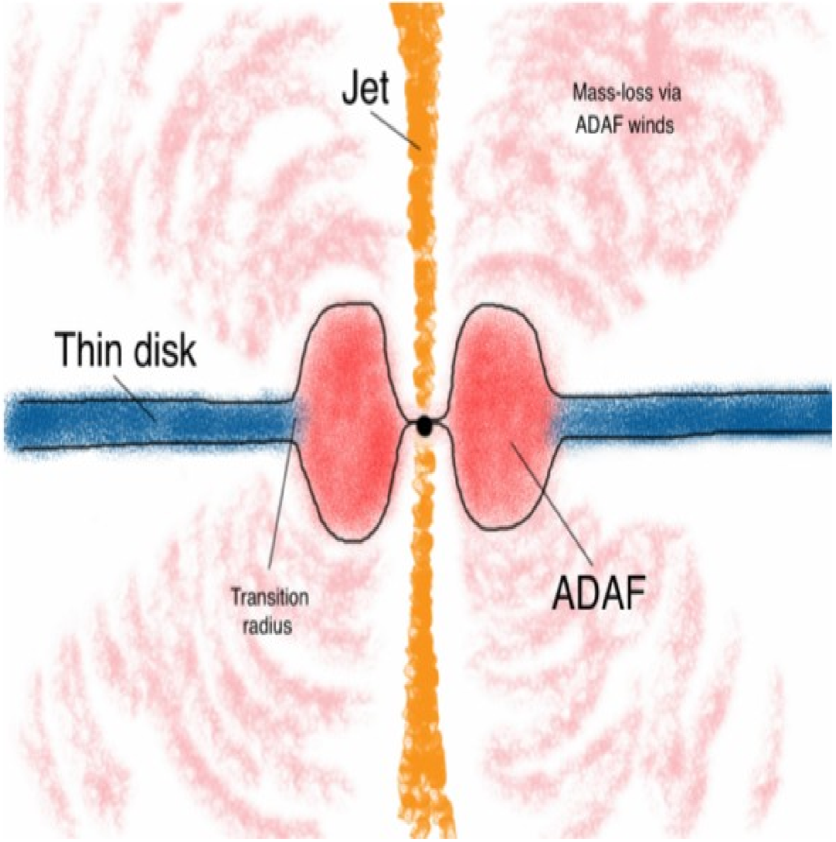


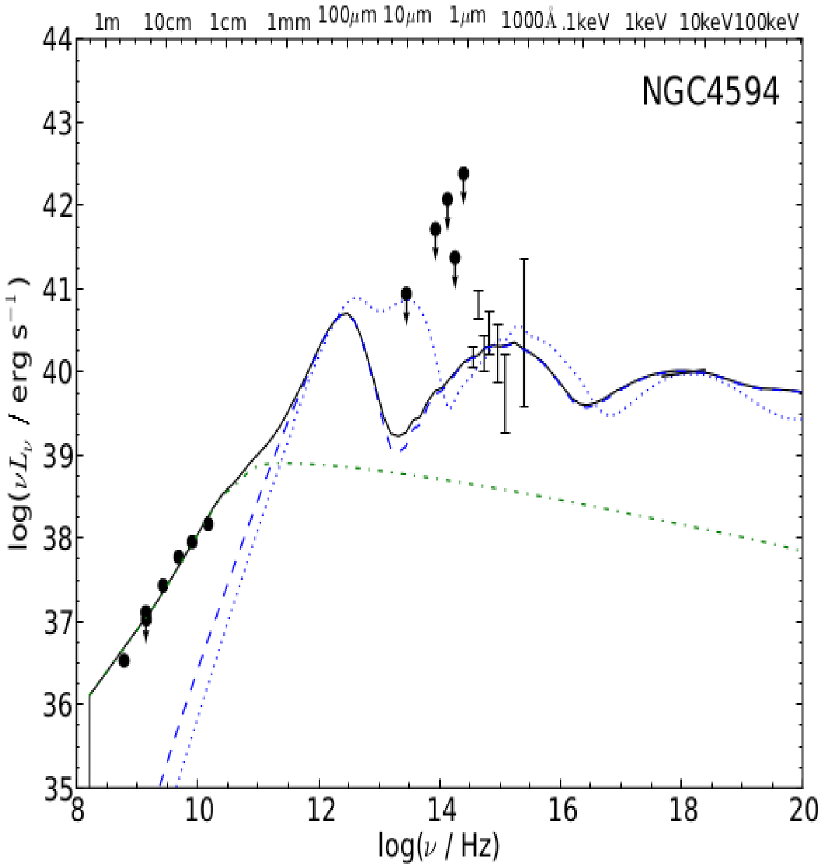
Classic "**modified black body**" - i.e., more or less what you get by integrating over concentric rings of black body emission which gets hotter with decreasing radius.

Shakura & Sunyaev showed that Temperature ~ $R^{-3/4}$ regardless of how gas loses angular momentum in the disk

*In AGN, such a disk produces the "**big blue bump**" in the optical/UV*

ADAFs





Model developed for LLAGN (Nemmen+ 2014). Inner “puffy” ADAF disk transitions to thin disk on large scales. Jet may or may not be present (or dominant) but outflows are ubiquitous.

ADAFs

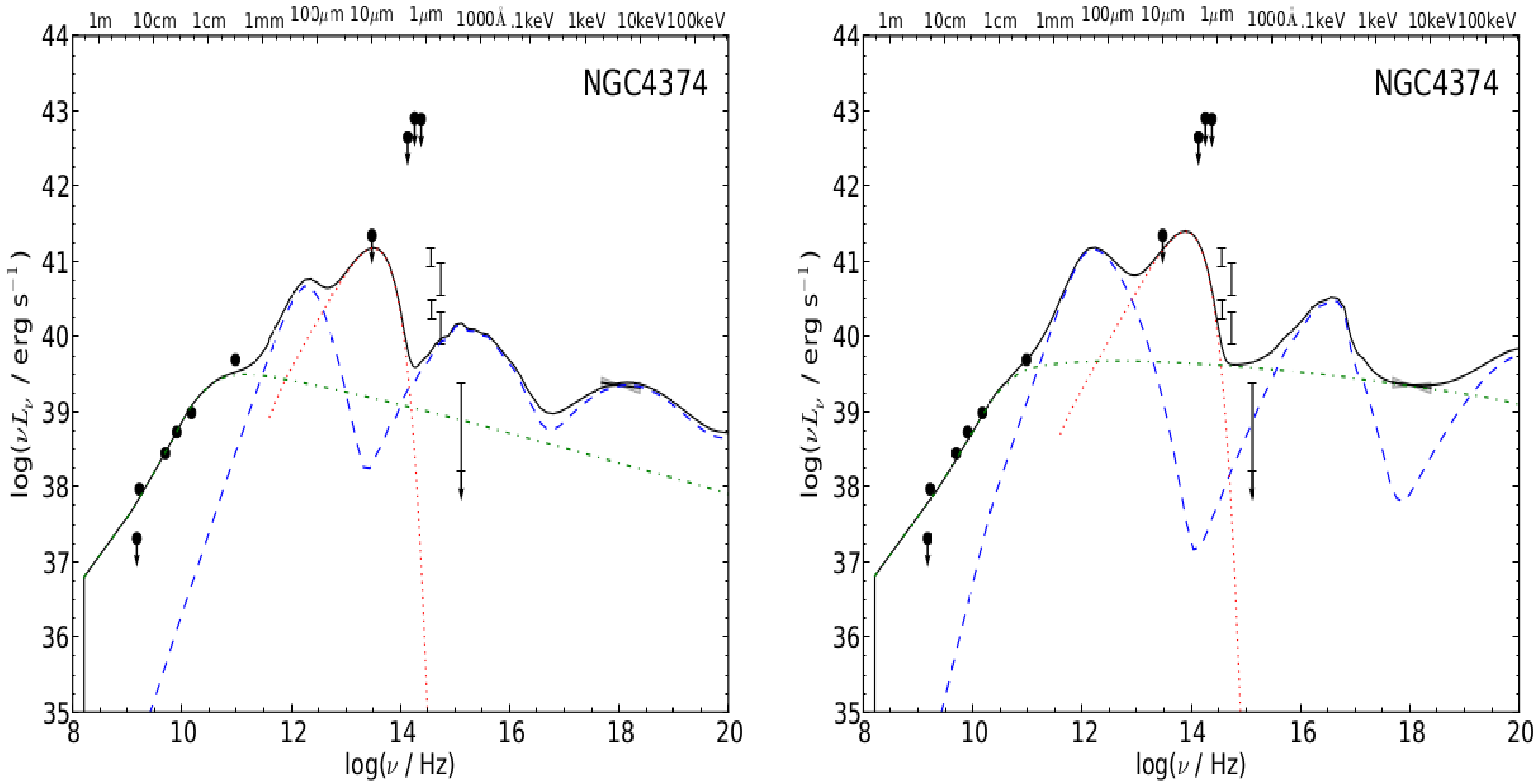
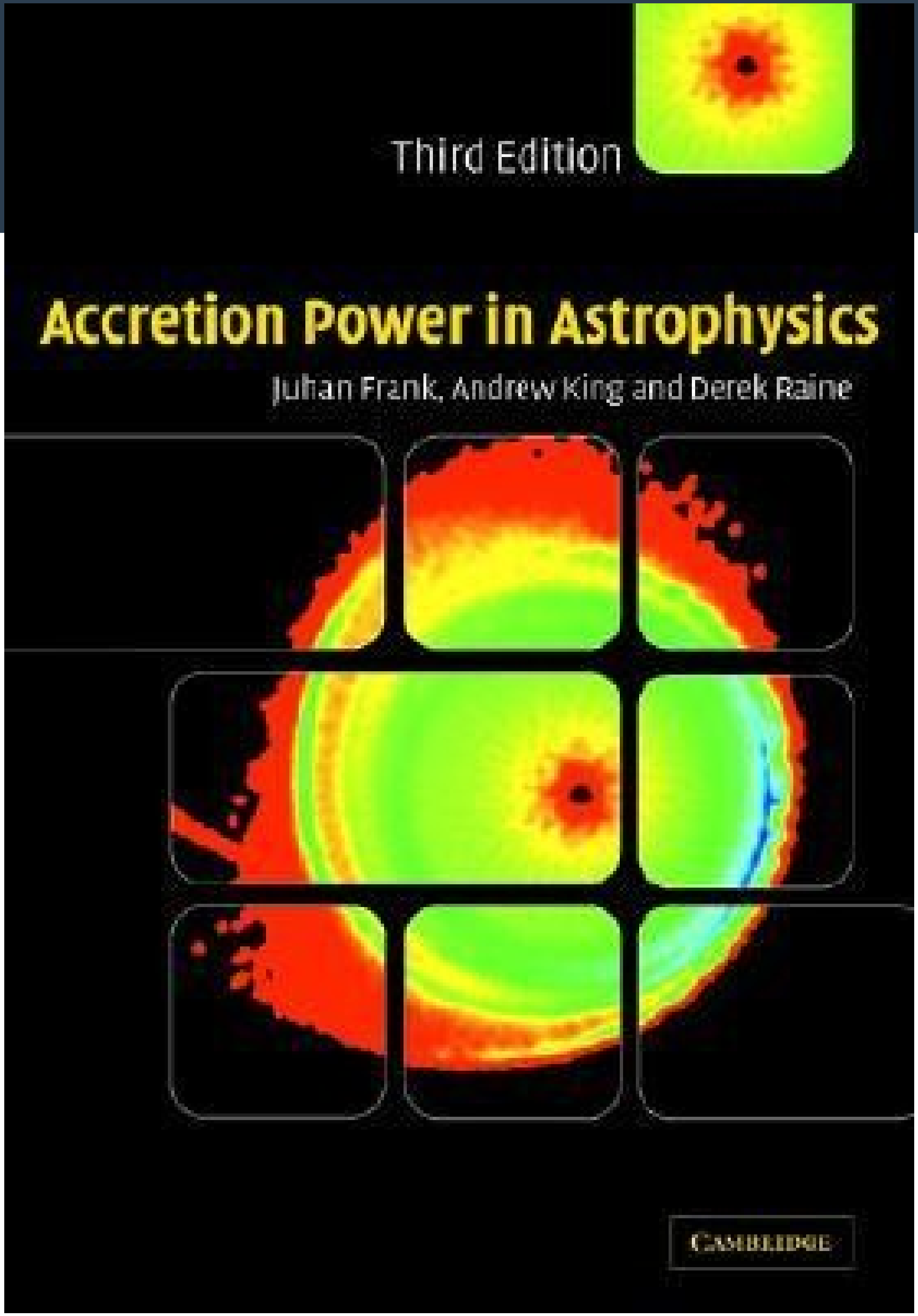


Figure 3. Models for the SED of NGC 4374/M84 showing the emission of the ADAF (*dashed*), jet (*dot-dashed*), truncated thin disk (*dotted*) and the total emission (*solid*). **Left:** model in which the ADAF dominates the observed X-ray emission ("AD model"). **Right:** model in which the jet dominates the X-ray output ("JD model").

MeV can break the degeneracy between jet and accretion-disk dominated models for the X-rays, as shown above. This is a long-term project for AMEGO or similar missions (fluxes are likely just below the 3-year sensitivity). Assuming a long-lived mission, nearby LLAGN are a likely source population.


Third Edition
Accretion Power in Astrophysics
Juhan Frank, Andrew King and Derek Raine
CAMBRIDGE

How Big is the Black Hole?

- **What is the inner-most stable orbit of a black hole (ISCO)?**

$$r_{isco} = \frac{6\,GM}{c^2} = 3R_S$$

For 10^6 $M_\odot$, r_{isco} = 0.05 AU* (10x sun radius or 8x closer than mercury)
For 10^9 $M_\odot$, r_{isco} = 50 AU (A bit beyond the Kuiper Belt)

In theorist units:
For 10^6 $M_\odot$ → $7.5\text{x}10^{11}$ cm and for 10^9 $M_\odot$ → $7.5\text{x}10^{14}$ cm

However:

A *maximally* spinning (Kerr) black hole has r_{isco} = $9R_s$ if the disk is retrograde and $1R_s$ if it is prograde.

**Google makes this easy: [6*G*(mass of the sun)*1e6/c^2 in AU]*

How Big is the Accretion Disk?

2 Suzy Collin and Jean-Marc Huré: The Size-Mass-Luminosity Relations in AGN.

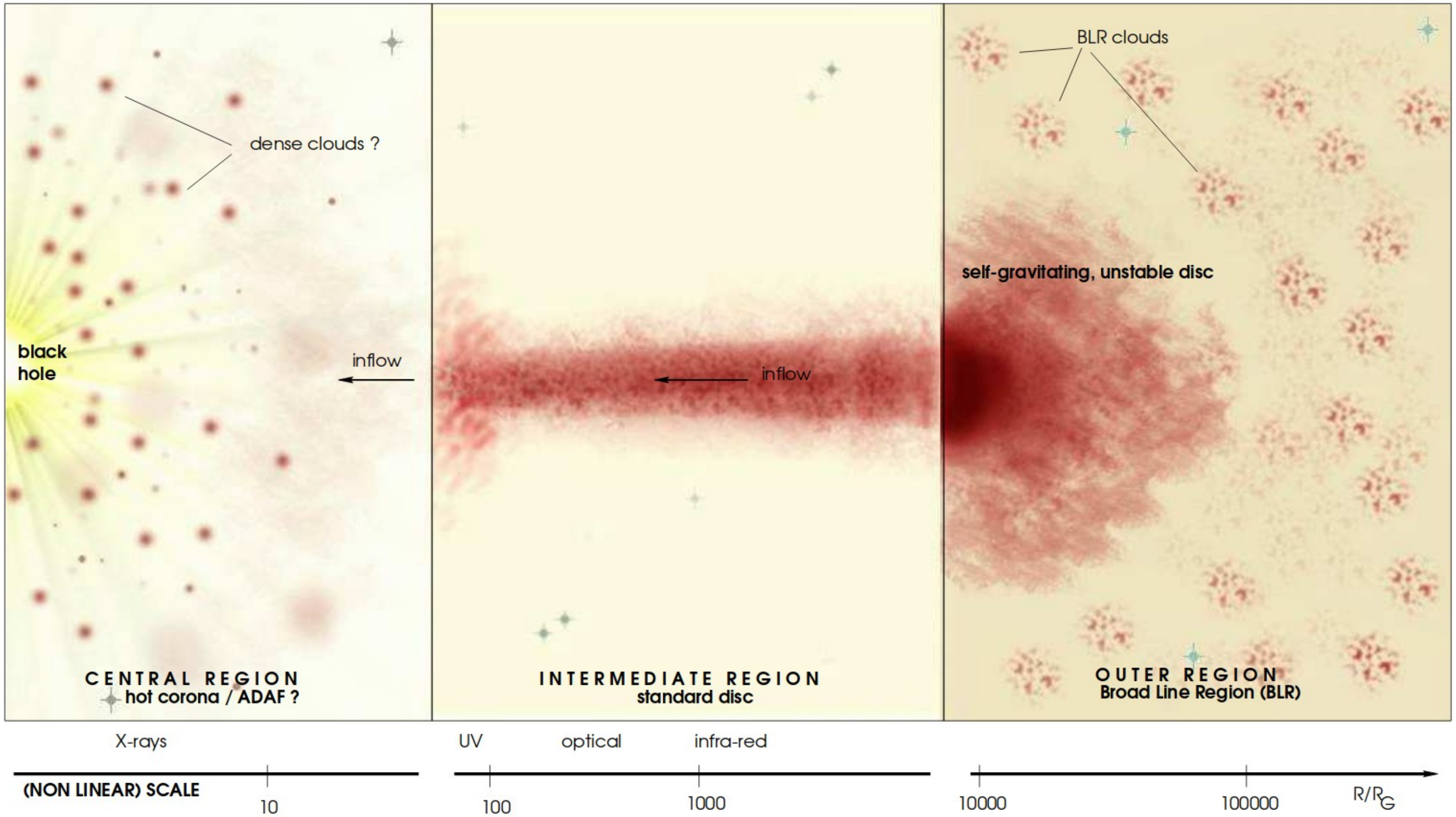


Fig. 1. Schematic view of the most central region of an AGN. The scaling depends slightly on the mass and on the accretion rate, and is appropriate for a 10^8 $M_\odot$ black hole ($R_G \simeq 1.5 \times 10^{13}$ cm) accreting at $\dot{m} \sim 0.1$ in Eddington units.

(1 AU)

Inner (hot) disk is on the order of 100s to 1000s of AU.
Typical Star Separations in the solar neighborhood are around 500k AU

The 'Central Engine'

- *Accretion can be very efficient at turning GPE into radiation*

Gravitational potential energy released for an object with mass M and radius R when mass m is accreted:

$E_{acc} = GMm/R = (R_s/R)mc^2$

In reality there is an efficiency parameter:

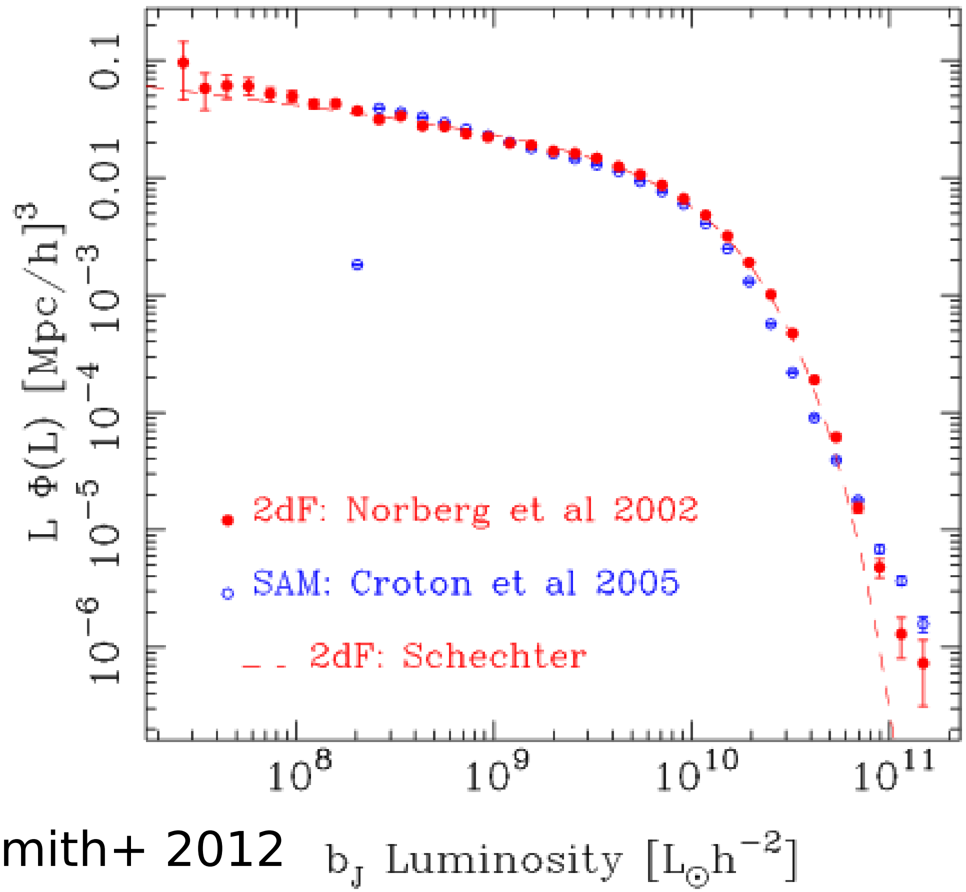
$Eacc = \eta * mc^2 \quad \eta \sim 0.1$

Far more efficient than nuclear fusion:
(H => He) ~ $0.007mc^2$

AGN Luminosities can reach up to 10^{46} erg/s!!

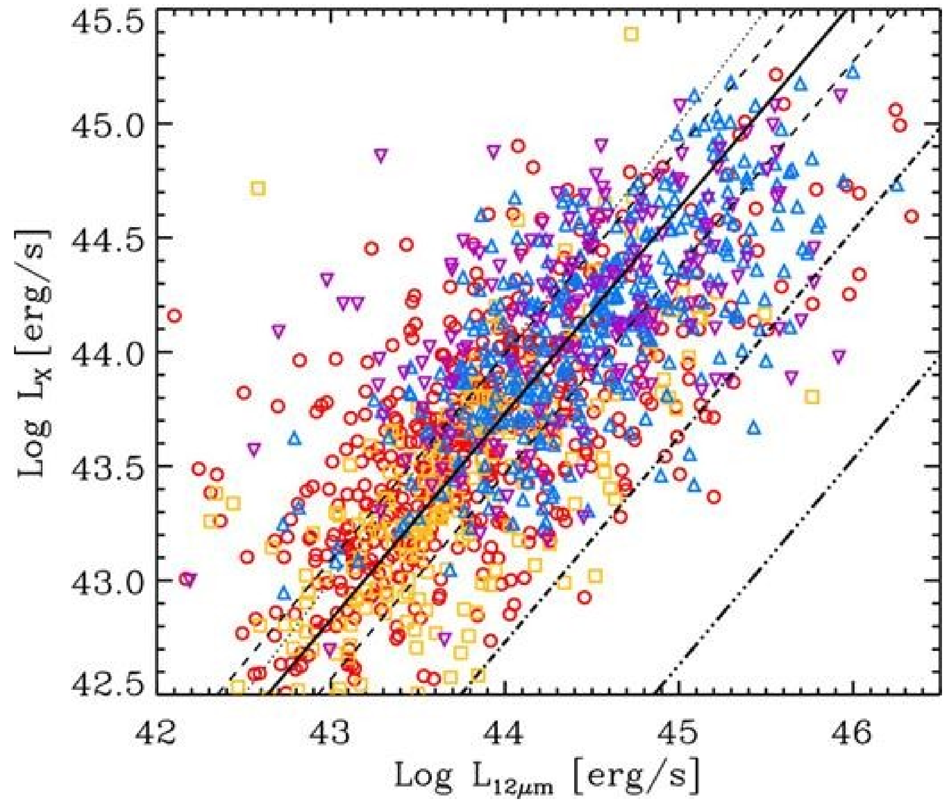
The ‘Central Engine’

Galaxy lum. Fn.



Smith+ 2012

Sample of SDSS AGN



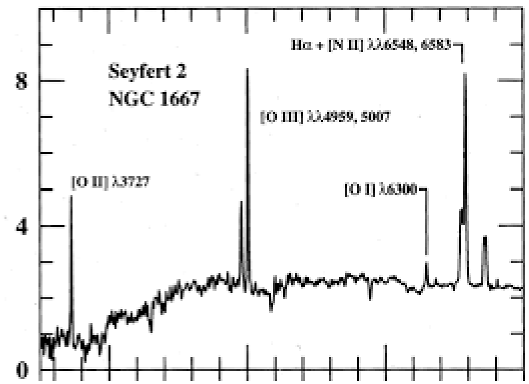
Merloni+ 2013

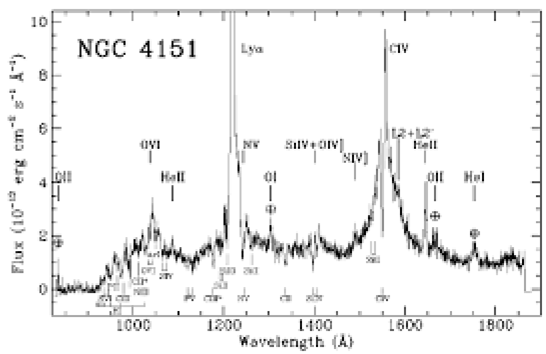
AGN can easily outshine the host galaxy of billions of stars!

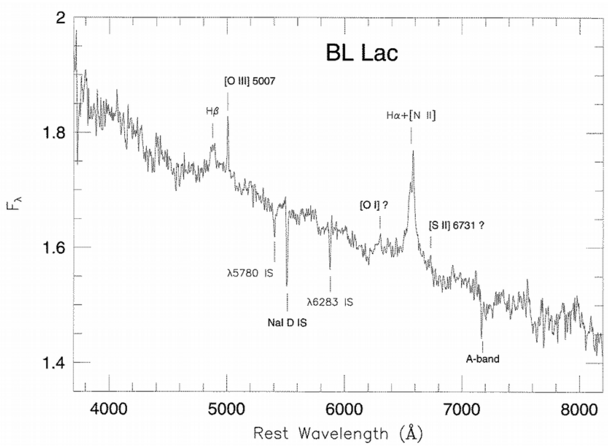
But there are also a large population of low-luminosity (LL) AGN

Why “active”?

- **Emission Lines!**





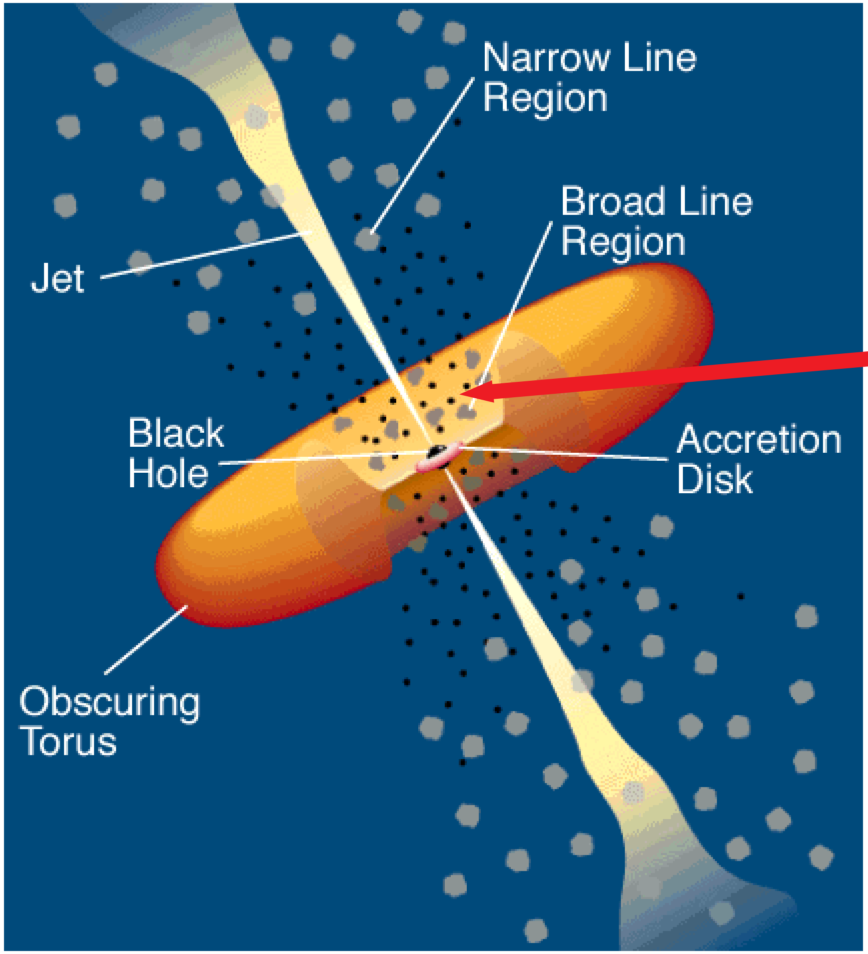


Earliest ‘active galaxies’ were identified in the 1940s by ground-based spectroscopy – had “very unusual” spectra

Lines can be **narrow** (~300-1000 km/s) or **broad** (3000-10,000 km/s!)

These lines come from gas clouds ionized by the central AGN disk – strong lines imply strong continuum!

The Standard Model



The Standard Model also posits an obscuring **molecular torus (MT)** of dust

Explains why we only see narrow lines in some AGN (known as “type 2” AGN)

BLR – Broad Line Region:

very close to the black hole (10^{16} cm)

probed by *reverberation mapping*

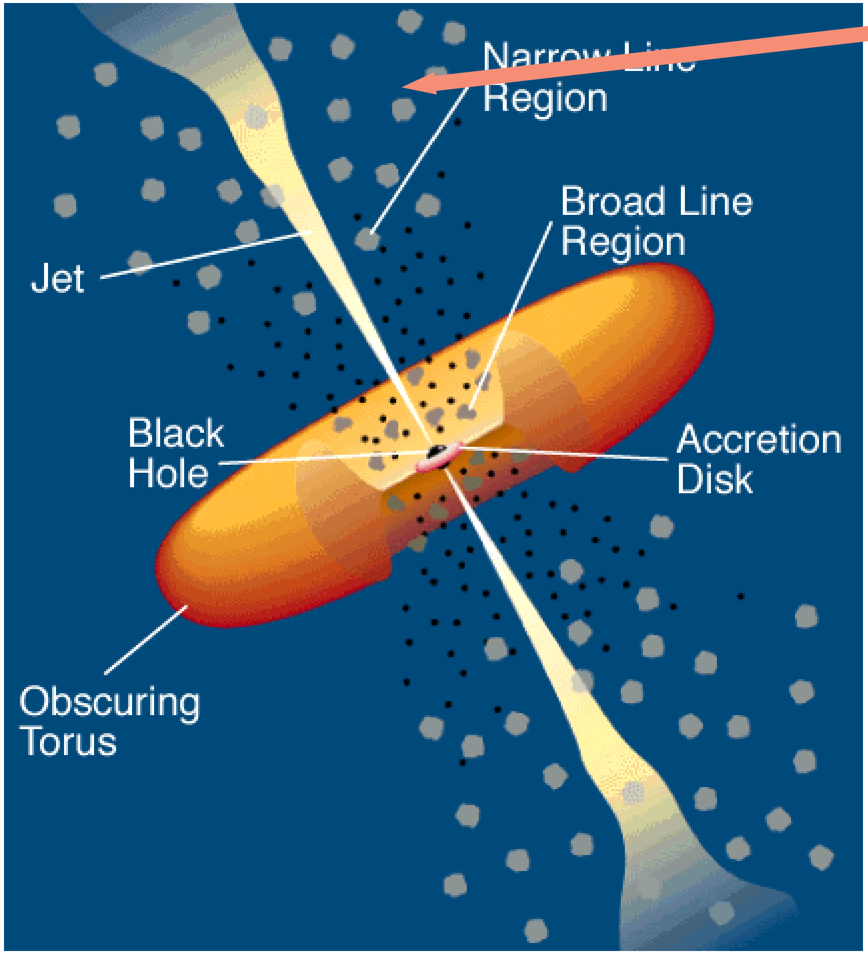
Doppler broadened due to fast motions of gas

dense (lack of forbidden lines):

$n_e >\sim 10^8$ cm^{-3}

blocked by MT at large viewing angles

The Standard Model



Grossly out of scale!

NLR – Narrow Line Region:

Gas clouds *far* from the black hole
100s to 1000s of parsecs = 10^{21}-10^{23} cm!

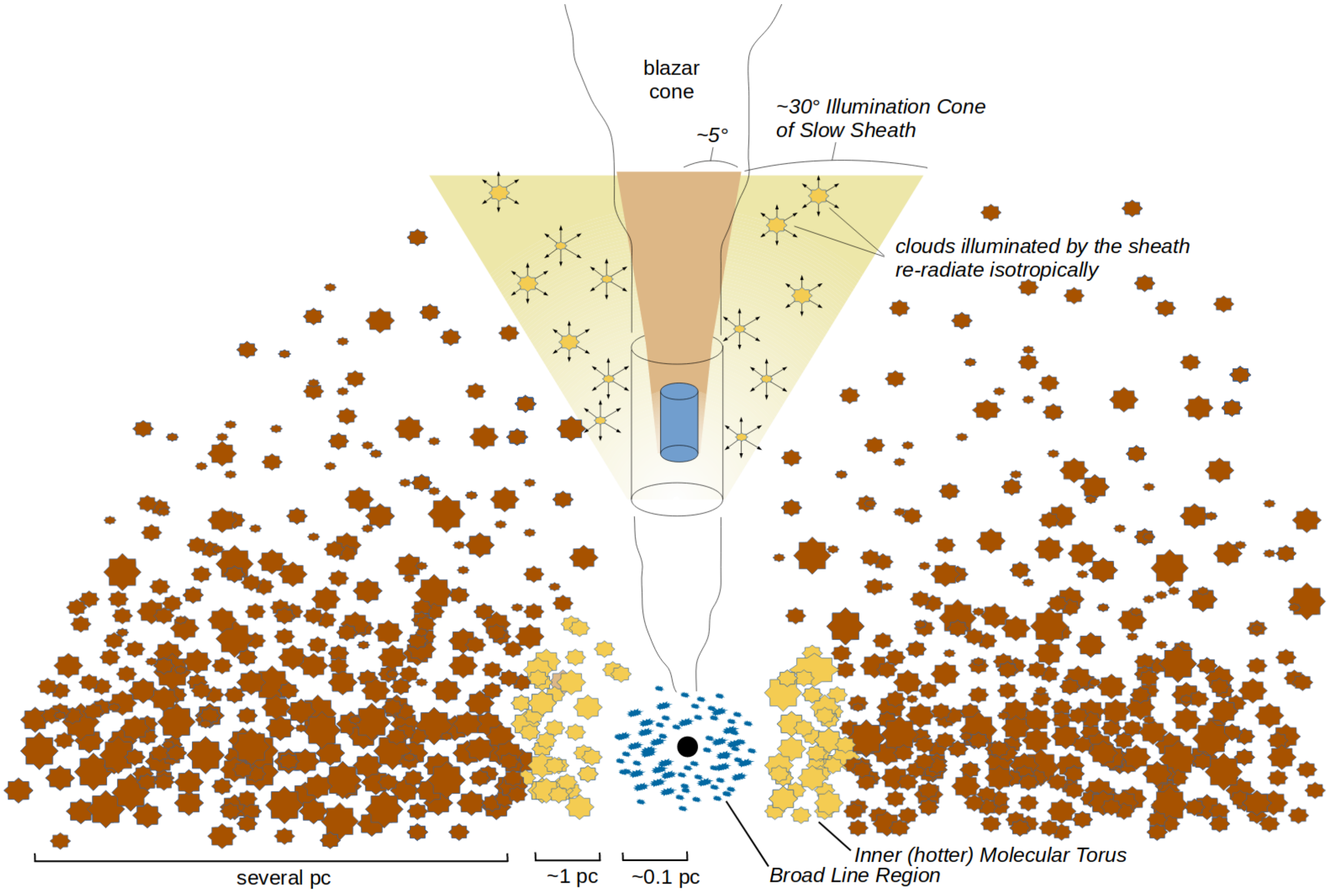
Does *not* obviously respond to the central continuum

Further out = less gravitational potential = slower motions

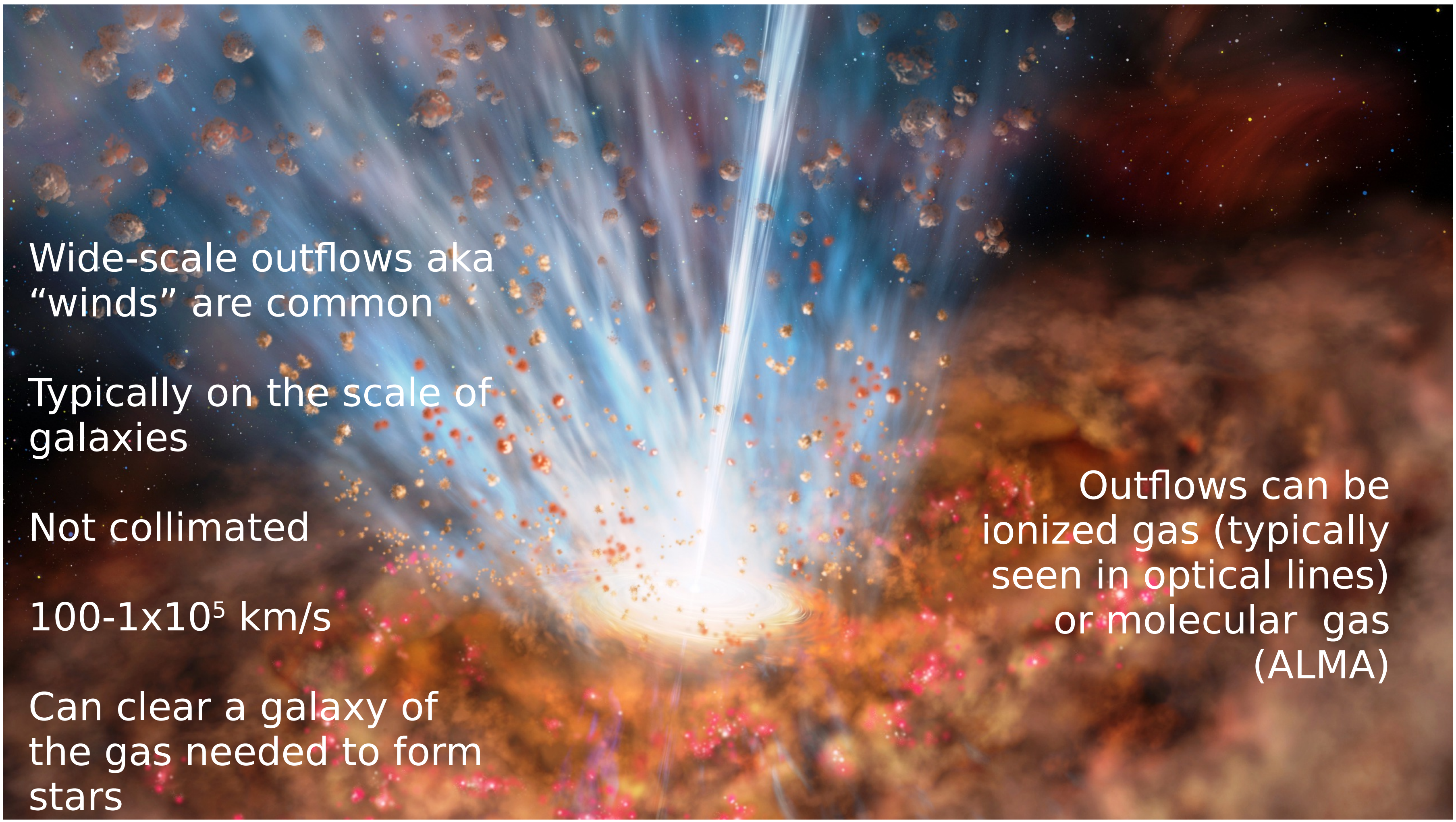
Less dense:
$n_e \sim 10^3 – 10^6 \text{ cm}^{-3}$

Not blocked by MT
(except for "changing look" AGN?)

The Standard Model



Outflows



Wide-scale outflows aka "winds" are common

Typically on the scale of galaxies

Not collimated

100-1x10^5 km/s

Can clear a galaxy of the gas needed to form stars

Outflows can be ionized gas (typically seen in optical lines) or molecular gas (ALMA)

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Nature Astronomy PERSPECTIVE

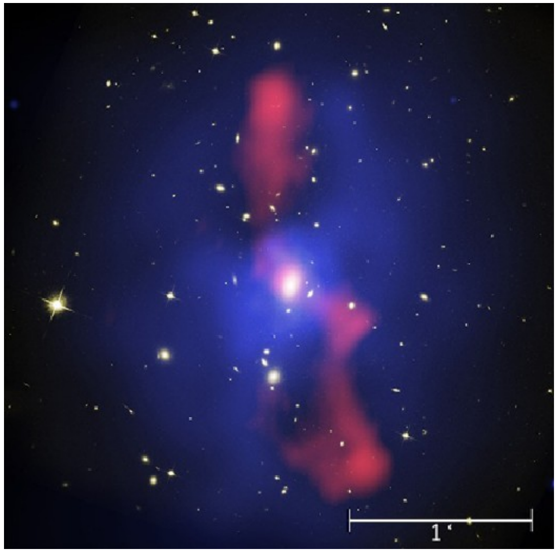
AGN outflows and feedback twenty years on

C.M. Harrison[1*], T. Costa[2], C.N. Tadhunter[3], A. Flütsch[4,5], D. Kakkad[6], M. Perna[7], G. Vietri[8,9,1]

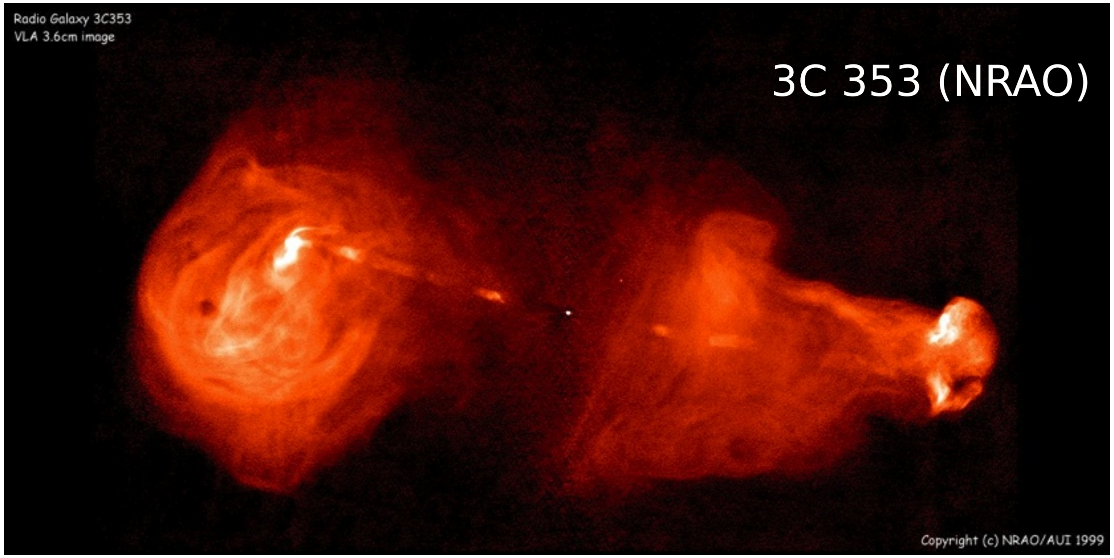
Relativistic Jets!

About 10% of AGN have Jets of relativistic, fully ionized plasma

Emit **synchrotron radiation**
from radio to X-rays
Thus, “radio-loud” AGN



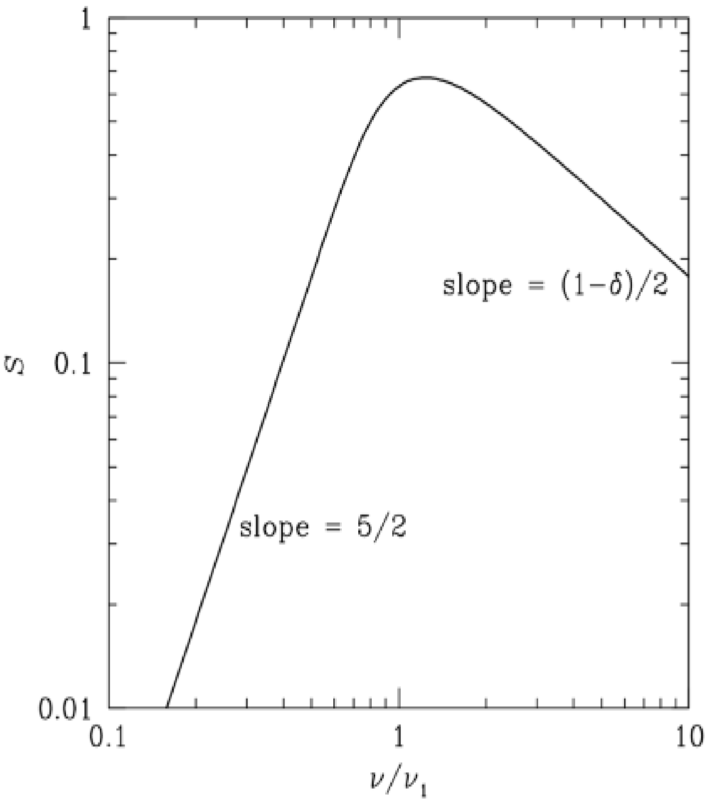
MS0735.6
(McNamara et al 2009)



Kinetic Powers up to 10^{46} erg s
Lifetimes ~ 10^7 yr (?)
Jet lengths can reach several Mpc (10^{25} cm!)
→ up to 1 billion times the scale of the SMBH
Heating of the galaxy-scale gas
and cluster medium

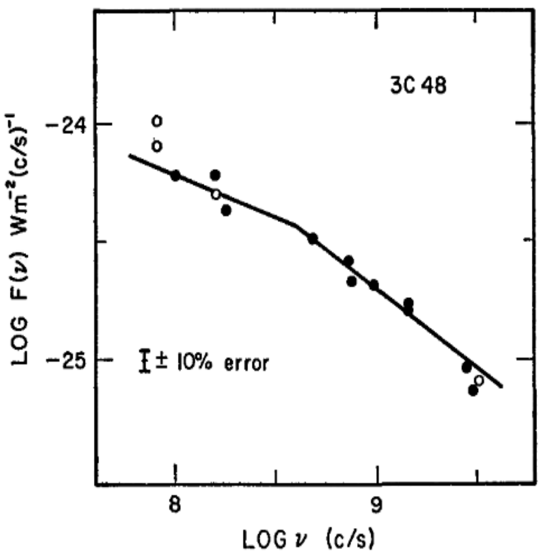
The SED of a jetted AGN

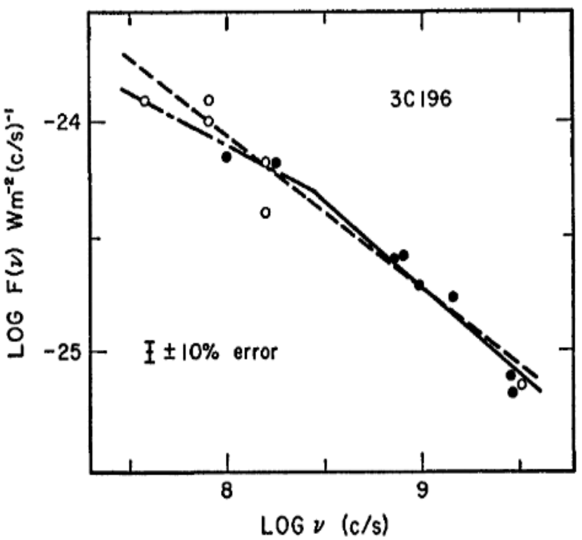
Radio Emission is Synchrotron Emission from a Relativistic Plasma



Generally assume a power-law distribution of electrons:
$n(\gamma) = \gamma^{-p}$

For a peak (in νF_ν) in the optical: max $\gamma \sim 10^6$



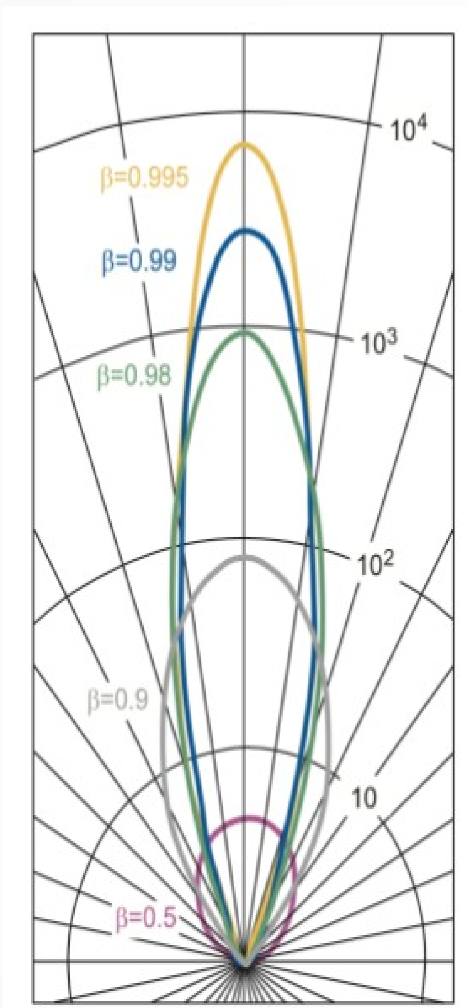


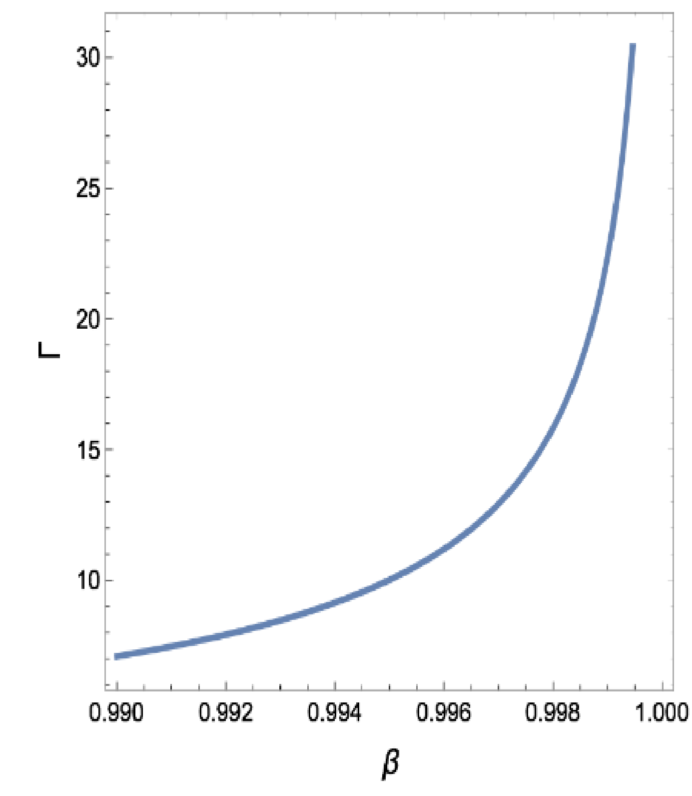
Emission is strongly beamed!   Bulk Lorentz factors Γ ~ 2-50 (0.87-0.9998 c)

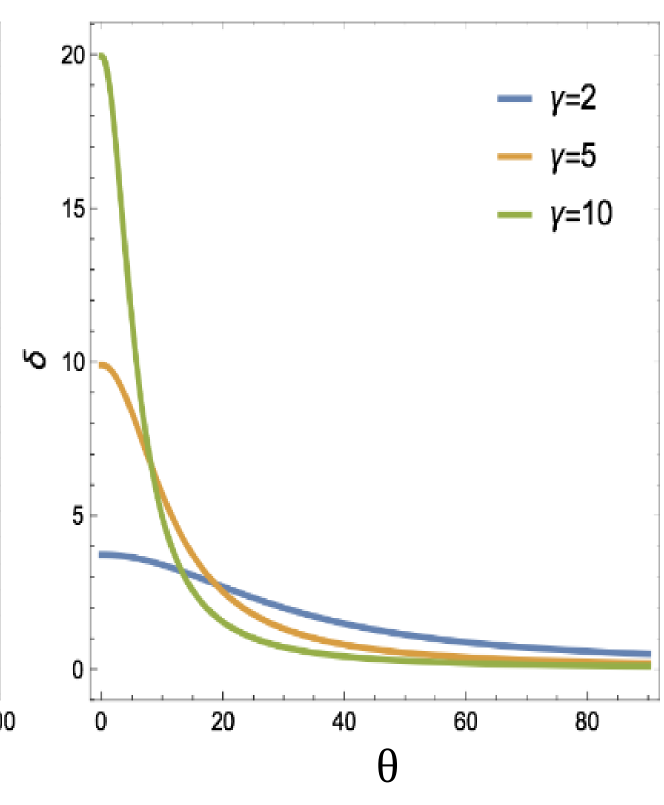
(Compare to GRB: 50-500, or X-ray binaries, Γ <~2)

$$\Gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$\delta = \frac{1}{\Gamma(1-\beta\cos\theta)}.$$



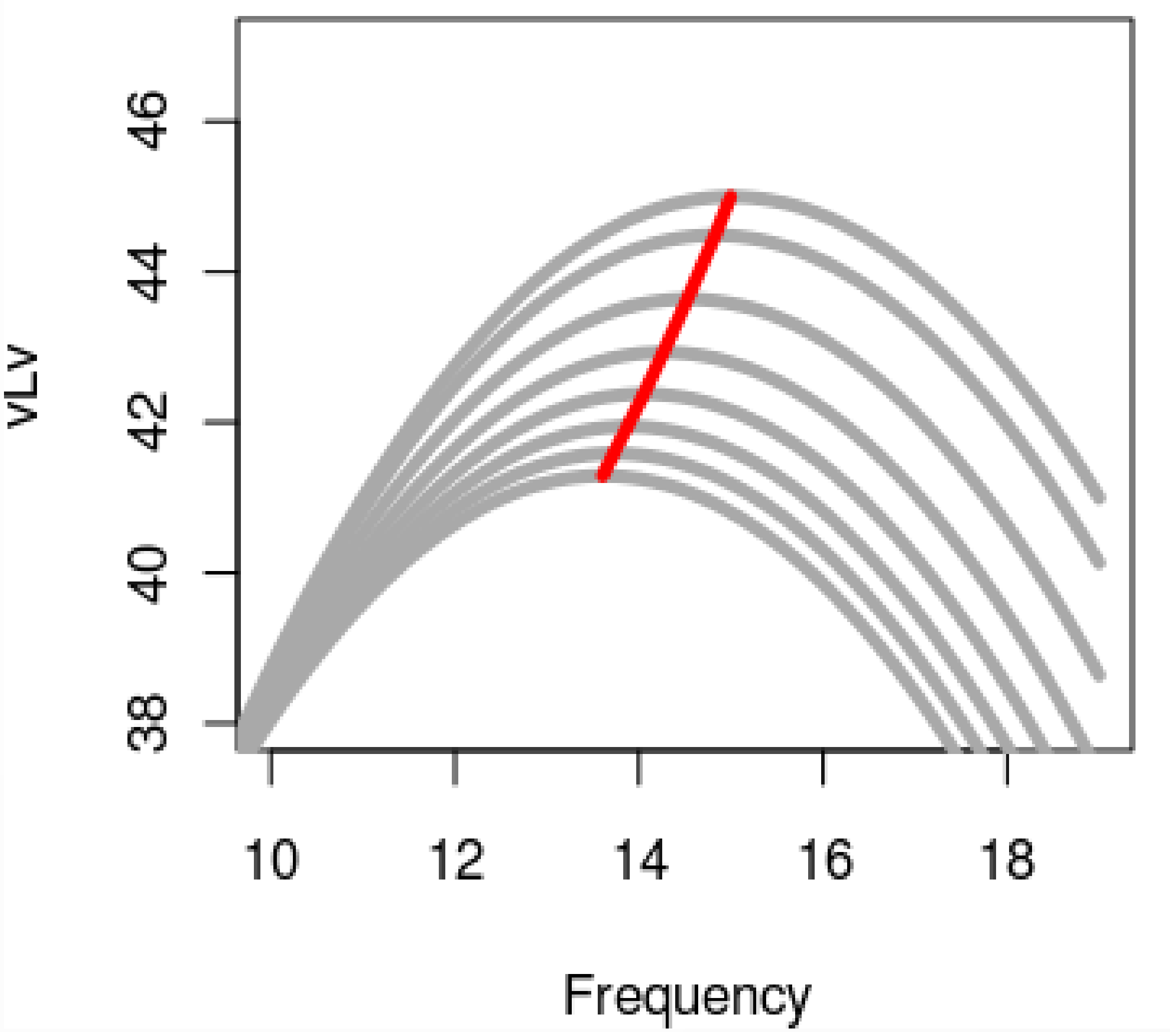




- Doppler Boosting of the Apparent Luminosity and Peak Frequency (Cartoon)

$$F_\nu = \delta^{3+\alpha} F'_\nu$$

$$\nu = \delta\nu'$$



Inverse Compton Emission

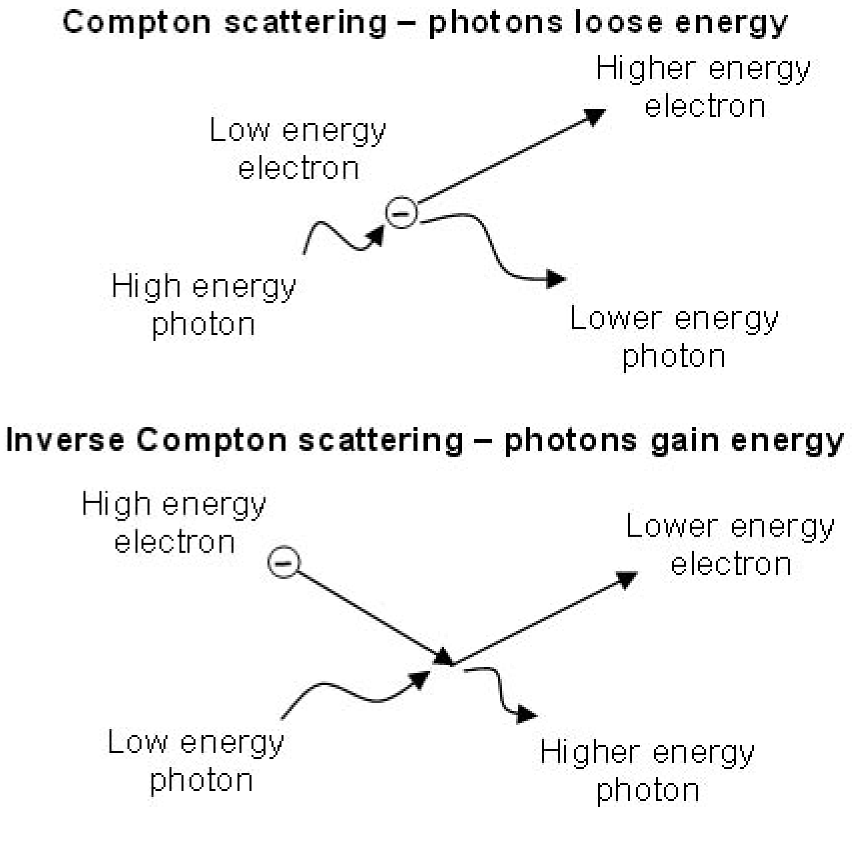
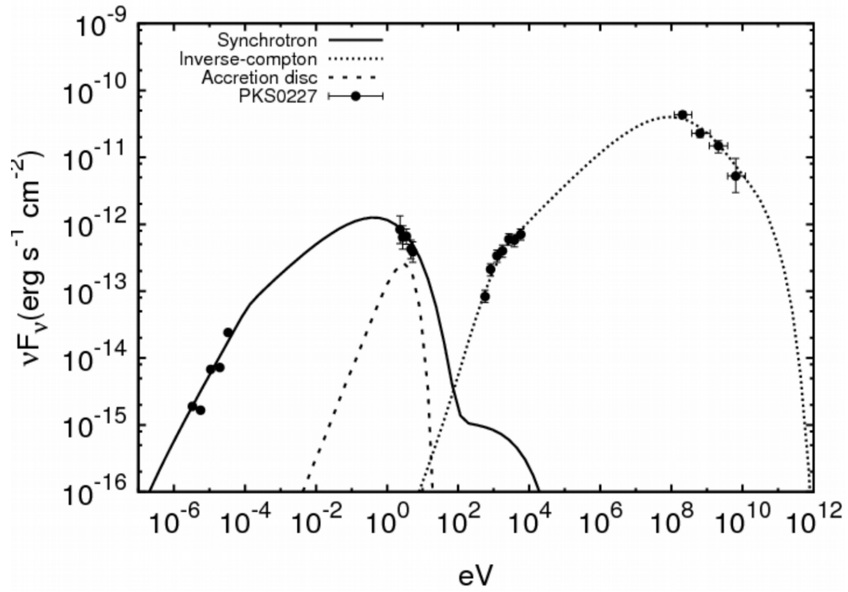


Figure 6: The two Compton scattering processes result in radiation being shifted to lower energies (Compton scattering) or higher energies (inverse Compton scattering). The essential factor differentiating these two processes is the kinetic energy of the electron involved.

Roughly, scattered photon has frequency $\nu \approx \gamma^2 \nu_0$



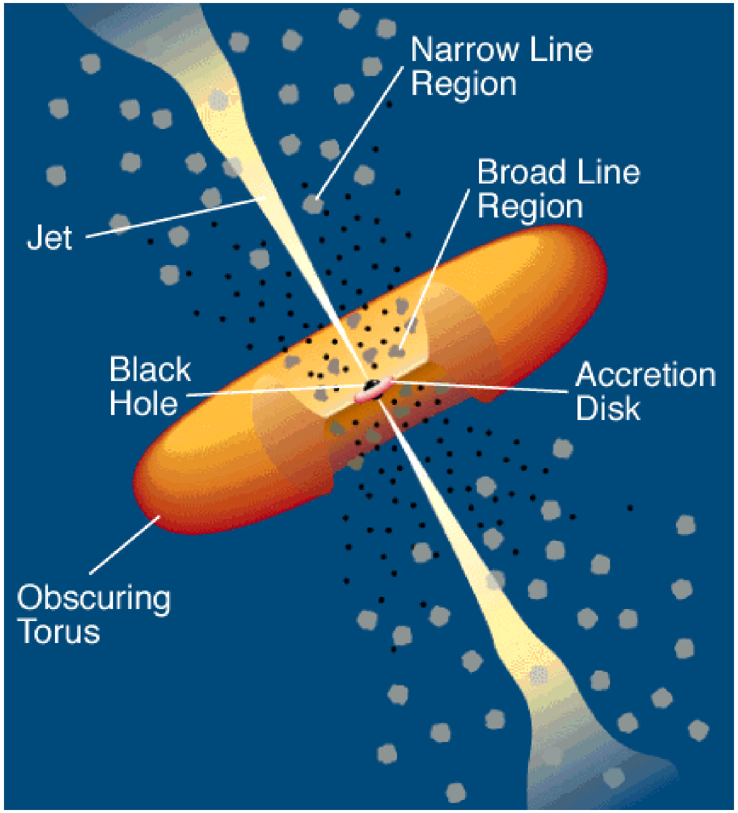
Energy loss rates:

iC: $-dE/dt = (4/3)\sigma_T c u_{rad} \beta^2 \gamma^2$

Sync: $-dE/dt = (4/3)\sigma_T c u_{mag} \beta^2 \gamma^2$

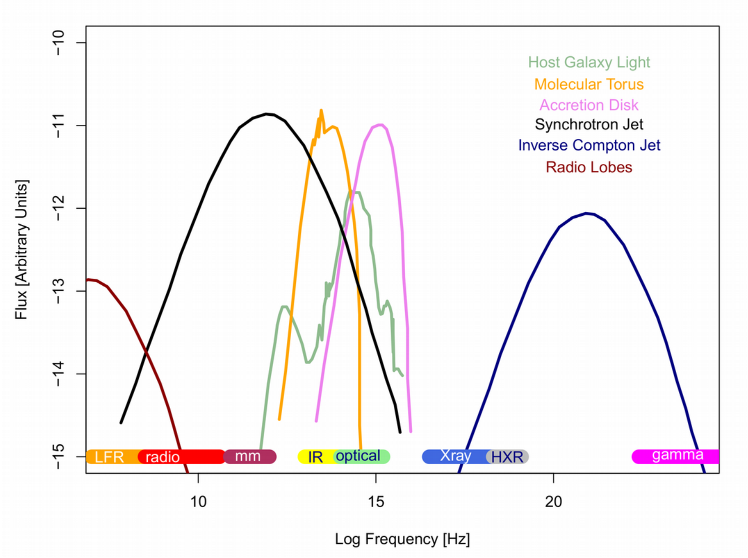
Inverse Compton Emission

- **Requires a source of external photons**

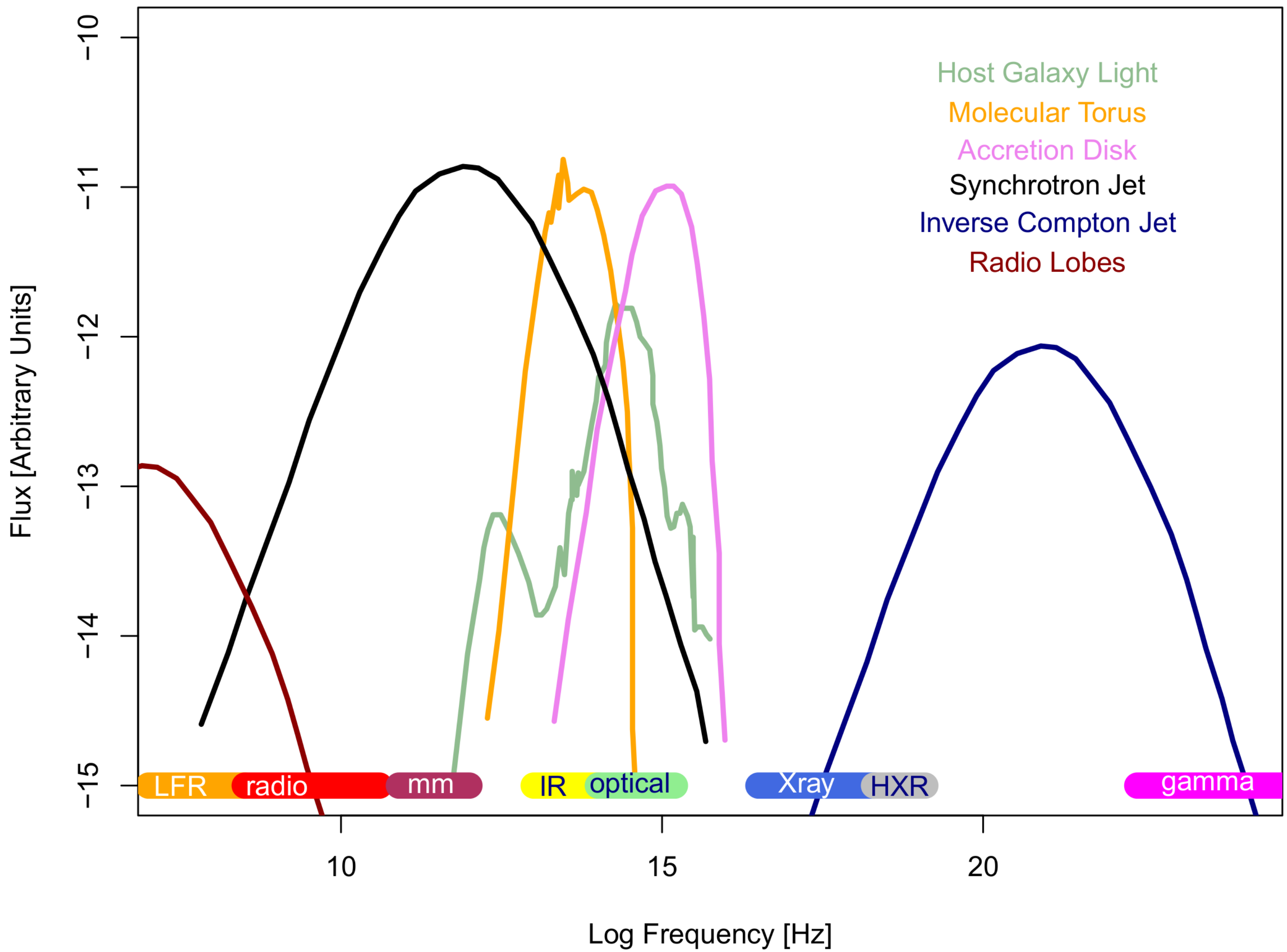


"External Compton" (EC) – accretion disk, BLR, molecular torus, in special cases the CMB or EBL

"Synchrotron Self-Compton" (SSC) - photons from the jet itself



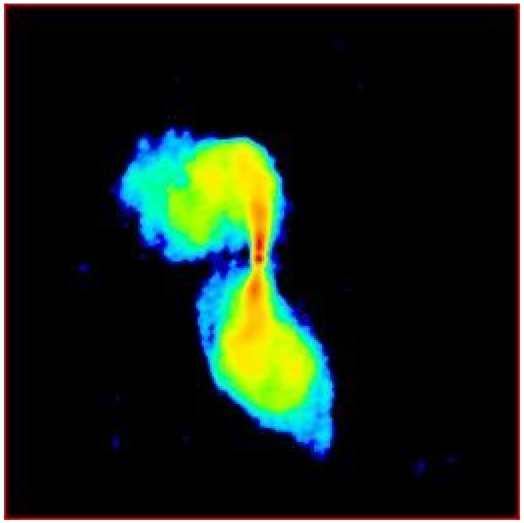
The SED of a jetted AGN



Radio Loud AGN Unification

(beyond orientation)

Blazar Spectral Type

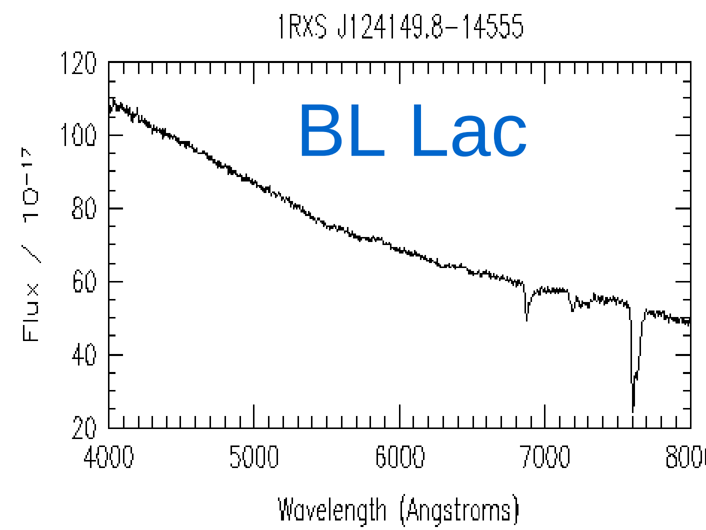


Radio Galaxy Morphology

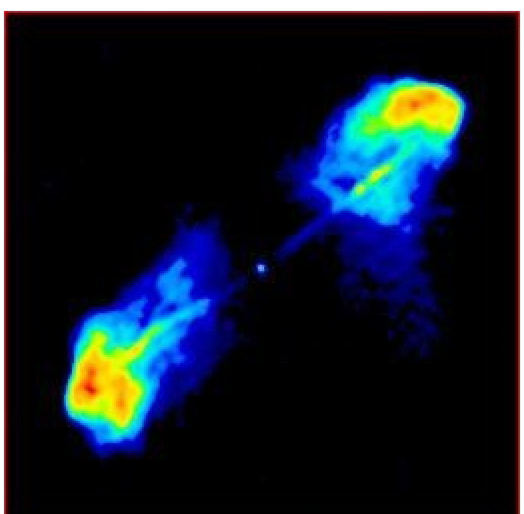
FR I

Low power, weak lines)

ADAF



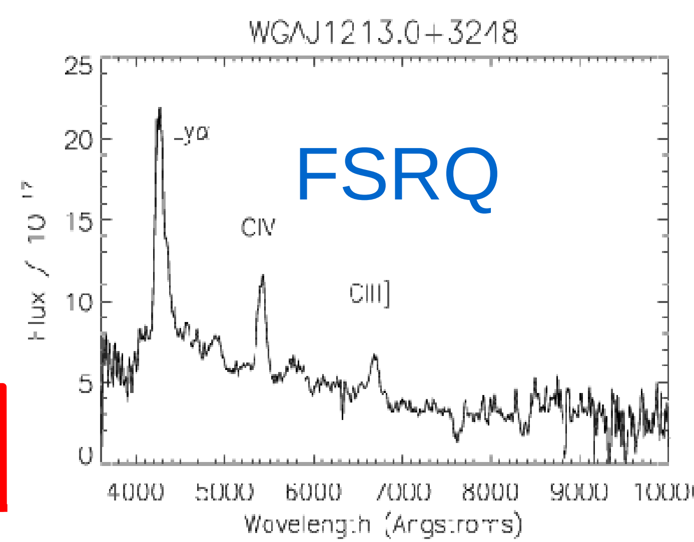
(Many notable exceptions!)



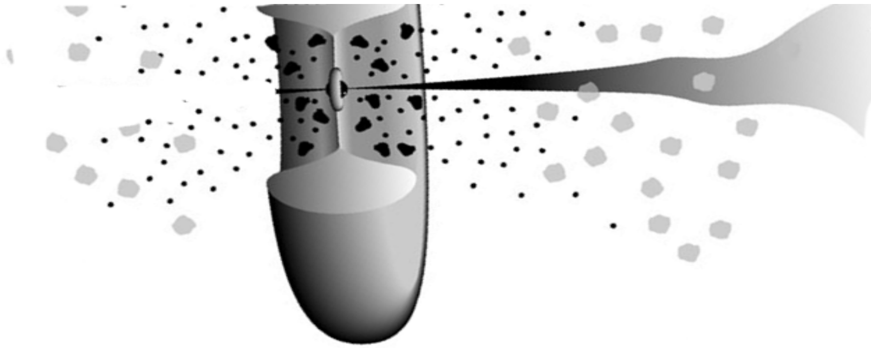
FR II

High power, high excitation spectra

Thin disk



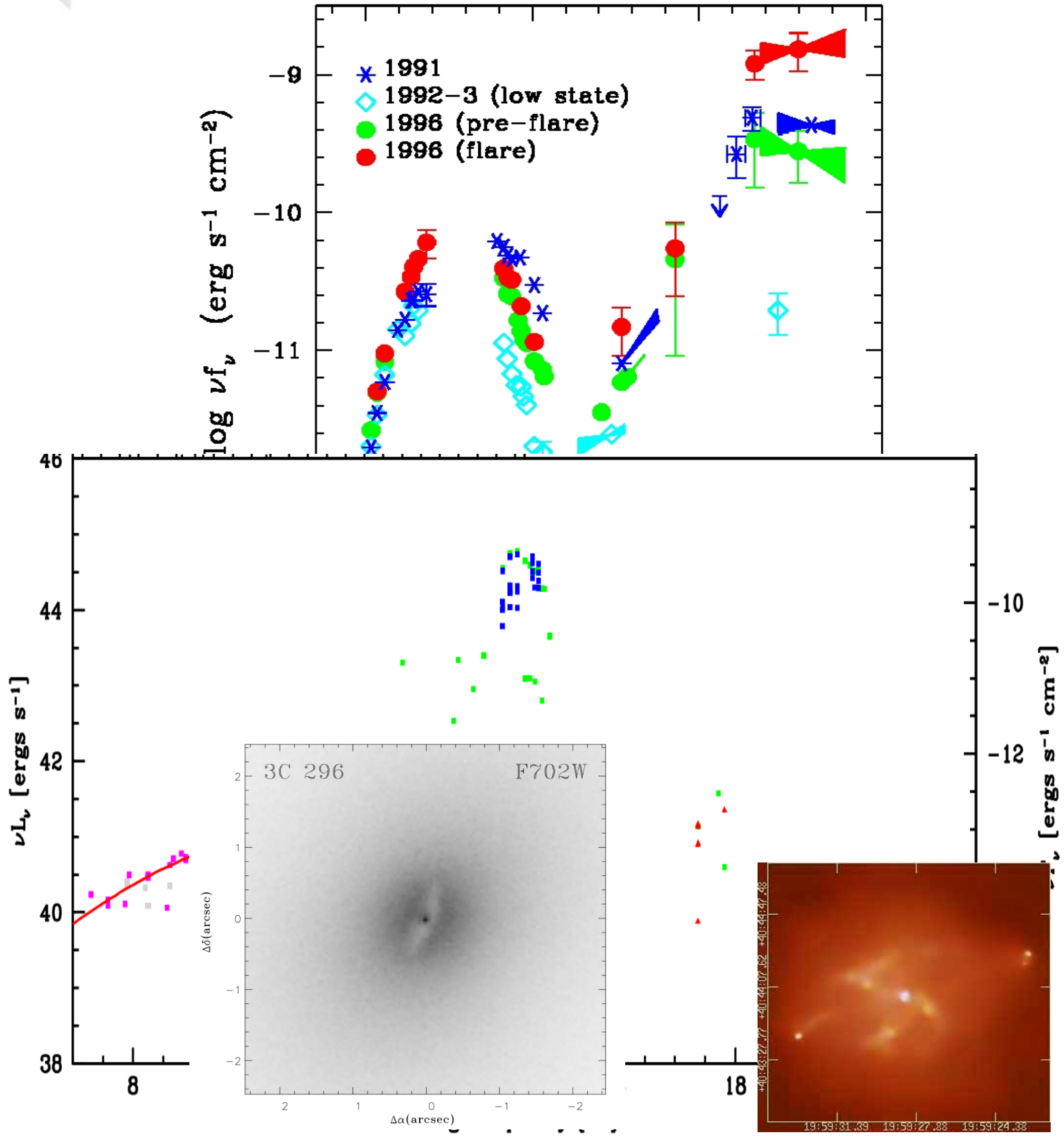
AGN Unification: Zeroth Order

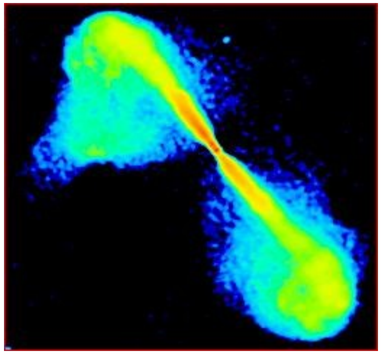


Blazars

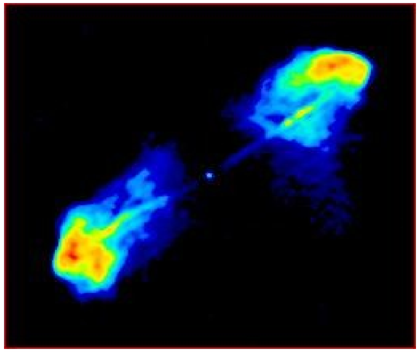
Direct view of the jet!

Radio Galaxy

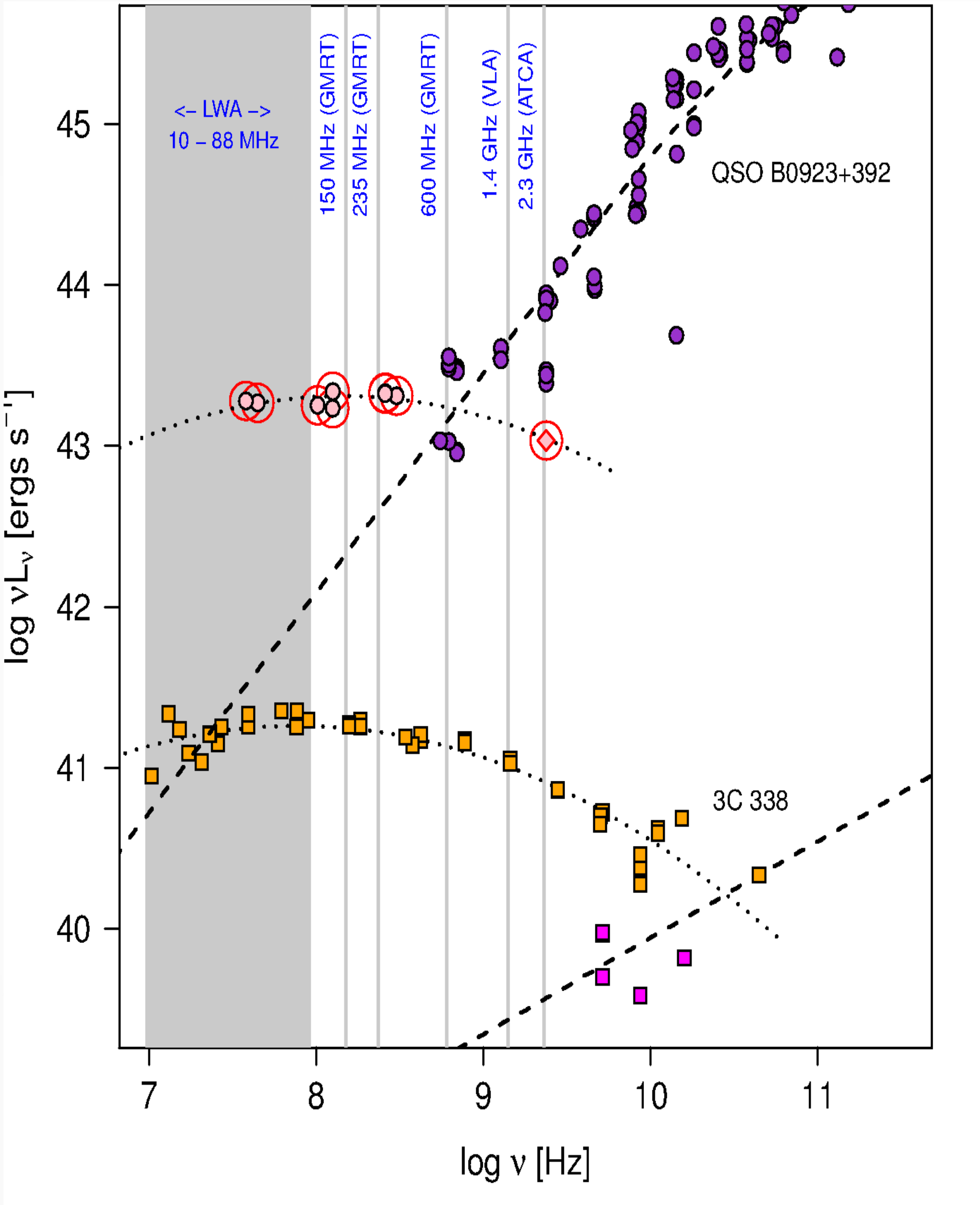




FR I: brightest at the center, “plumey jets”



FR II: brightest in the lobes, collimated jets



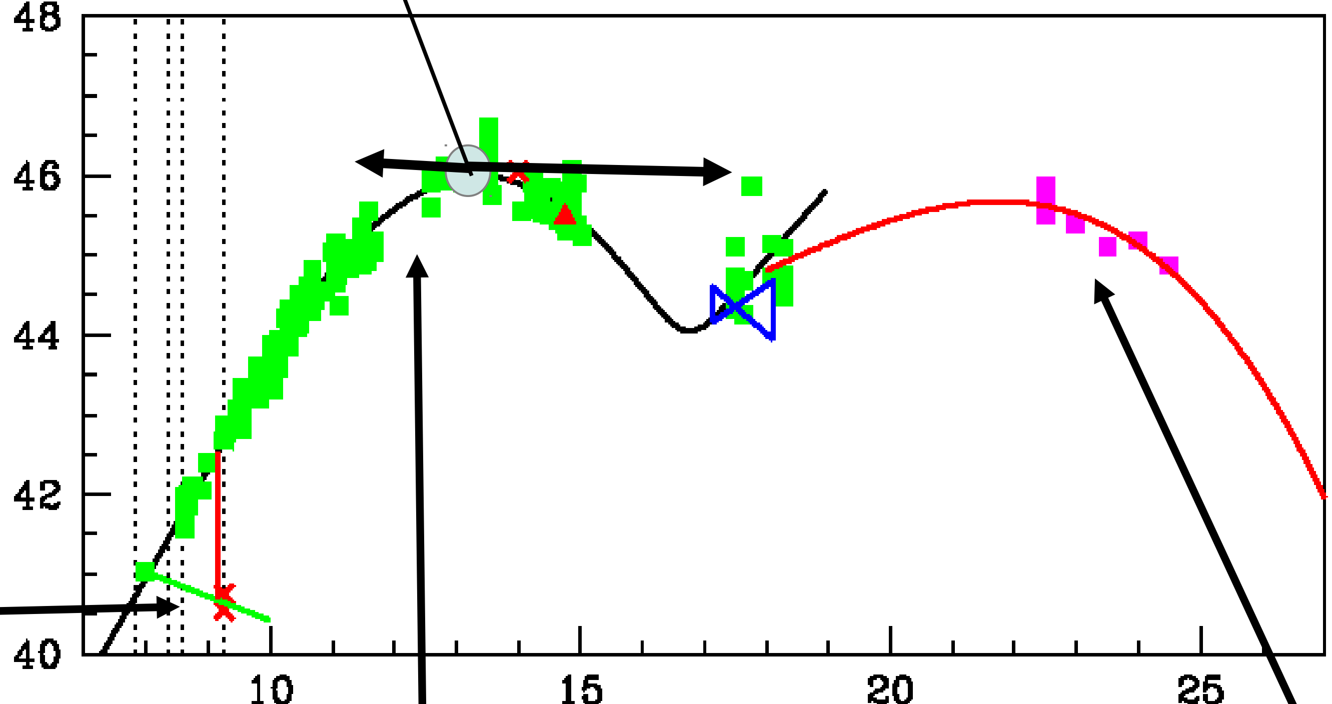
The Radio SED (real life)

← Synchrotron emission comes from all along the jet, but what tends to dominate is the lobe (unbeamed) at low frequencies, and the core (beamed, variable) at higher frequencies.

Here are shown to sources with very different lobe luminosities, indicating jets with *intrinsically different time-averaged power output.*

The Blazar SED

Peak frequency,
wide range

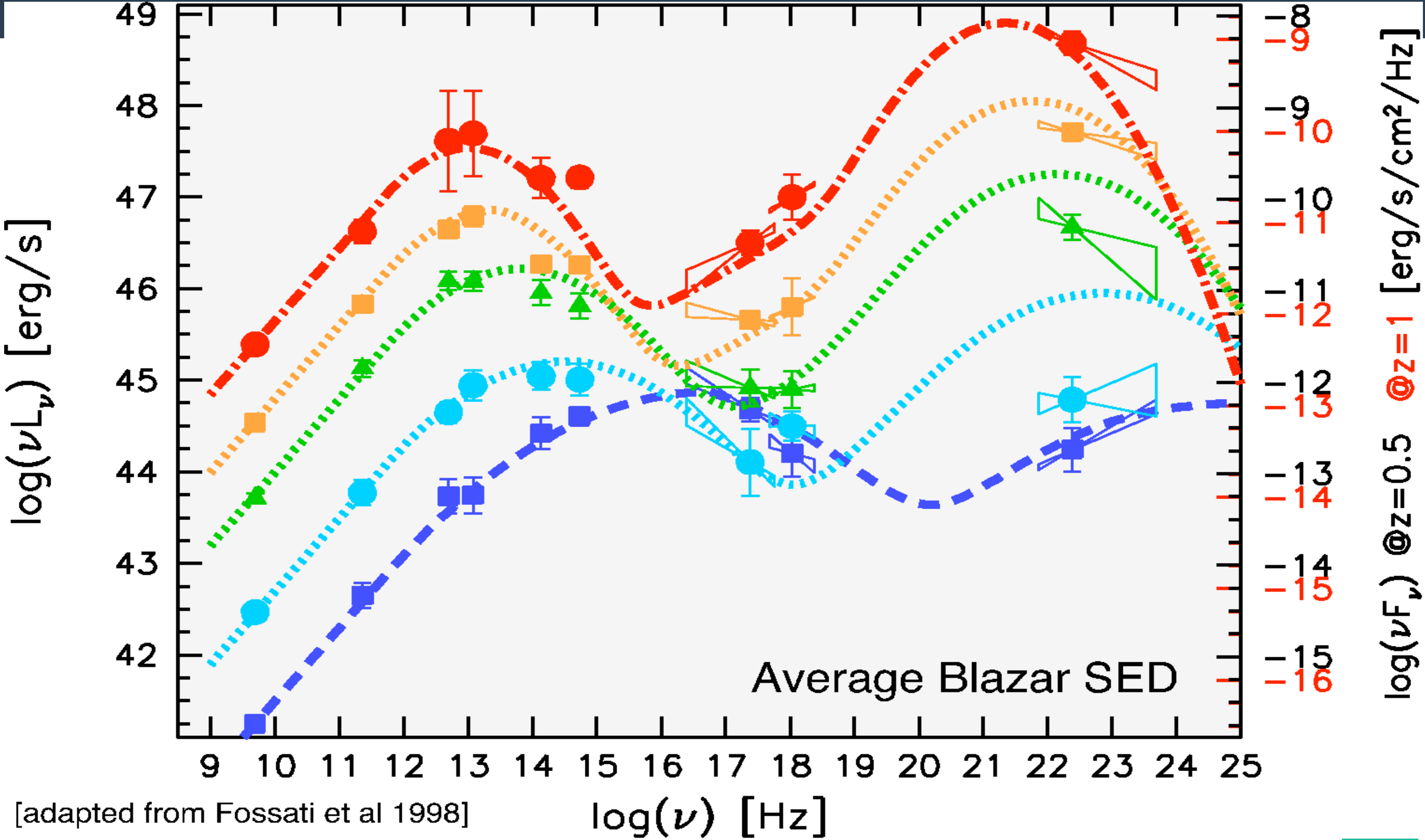


Isotropic Radio Emission from Slowed Plasma in the Lobes

Synchrotron emission

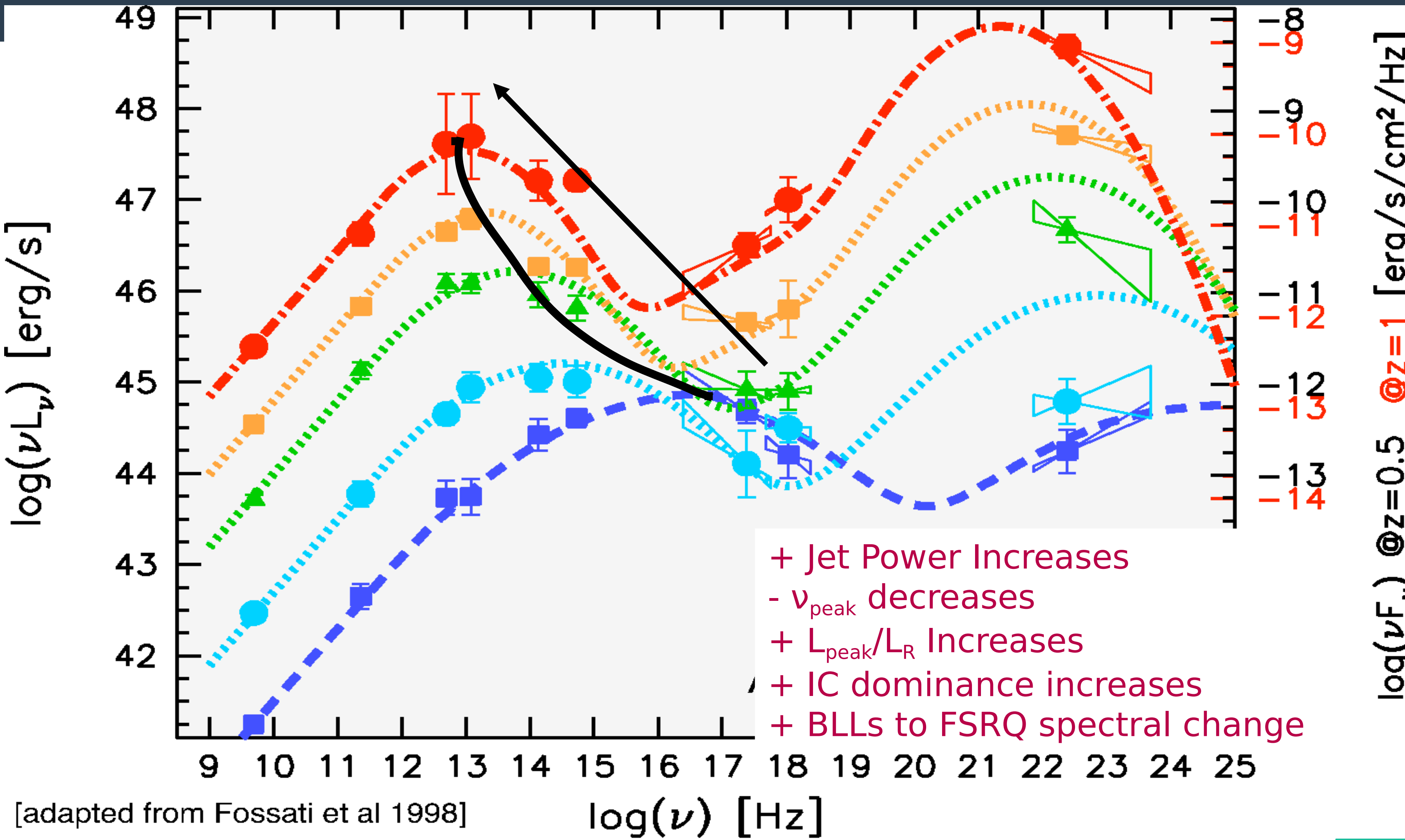
Inverse Compton
(source of upscattered photons not well understood)

The Blazar Sequence



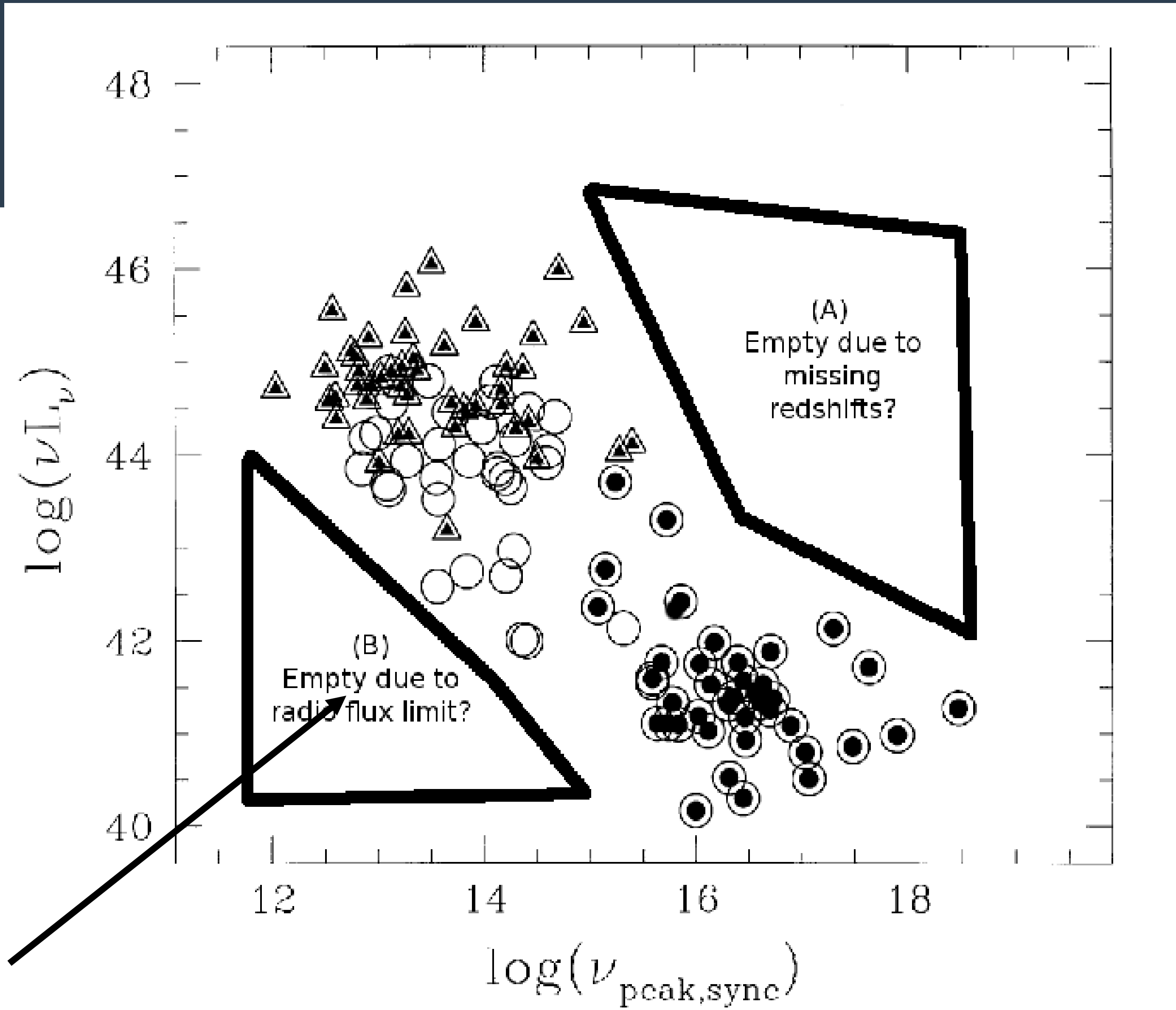
[adapted from Fossati et al 1998]

The Blazar Sequence



+ Jet Power Increases
- ν_{peak} decreases
+ L_{peak}/L_R Increases
+ IC dominance increases
+ BLLs to FSRQ spectral change

[adapted from Fossati et al 1998]

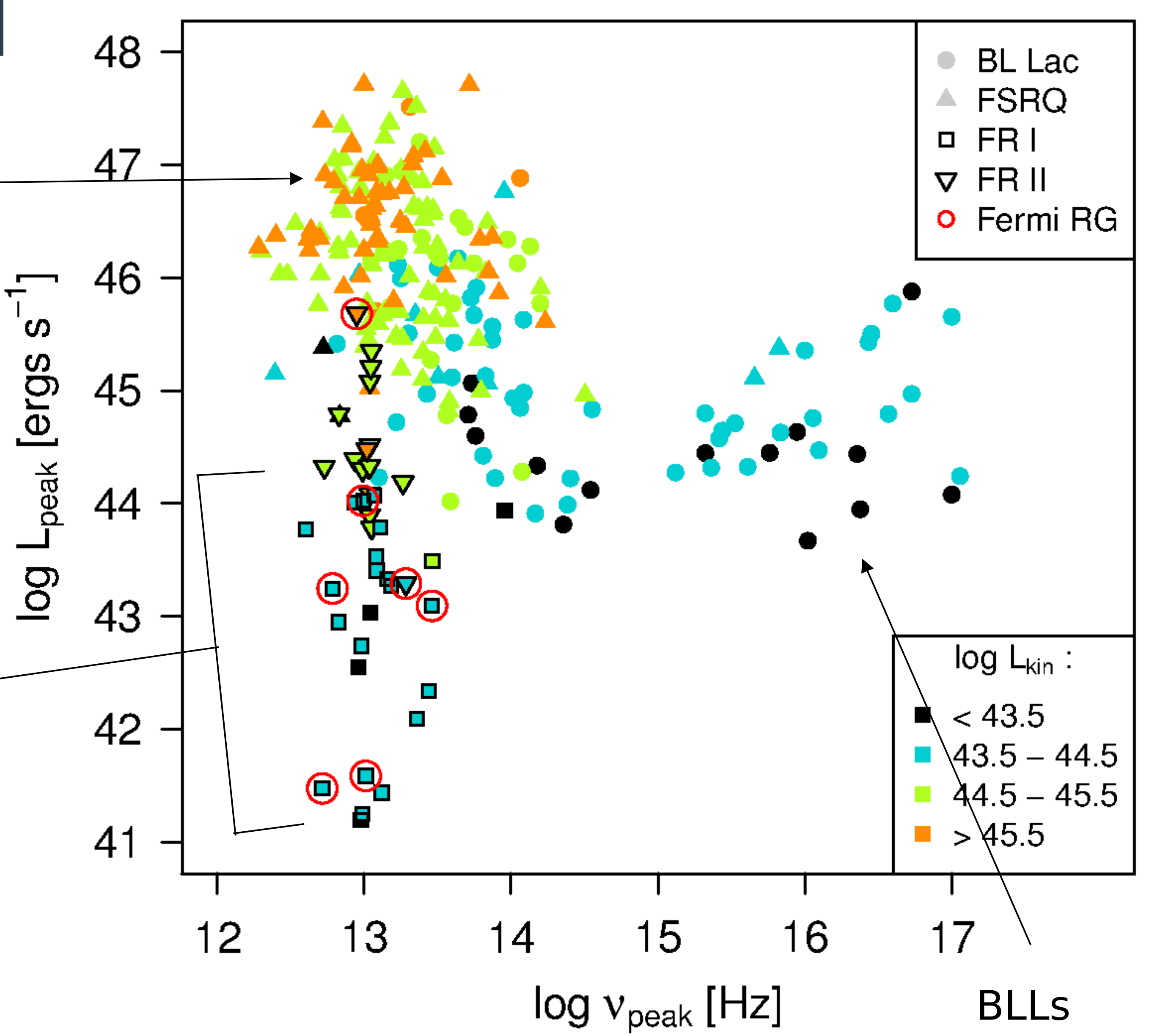


Sources here were found (Nieppola 2006, Landt 2006, Caccianiga 2004)

BL Lacs: Jet Power uncorrelated with ν_p

The Blazar ‘Envelope’

FSRQ & BLLs

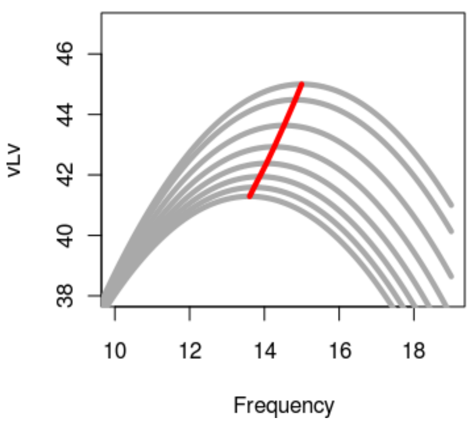


Radio Galaxies

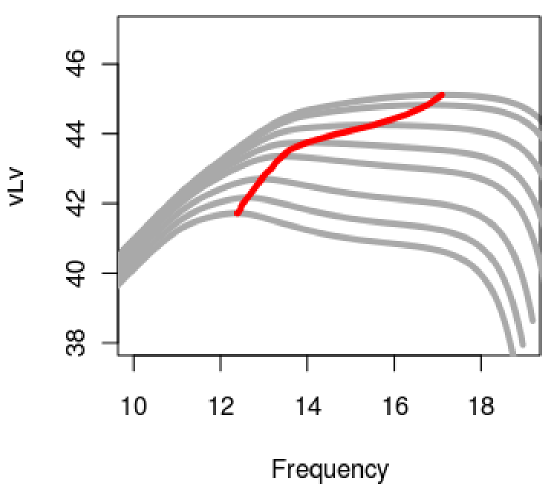
Meyer+ 2011

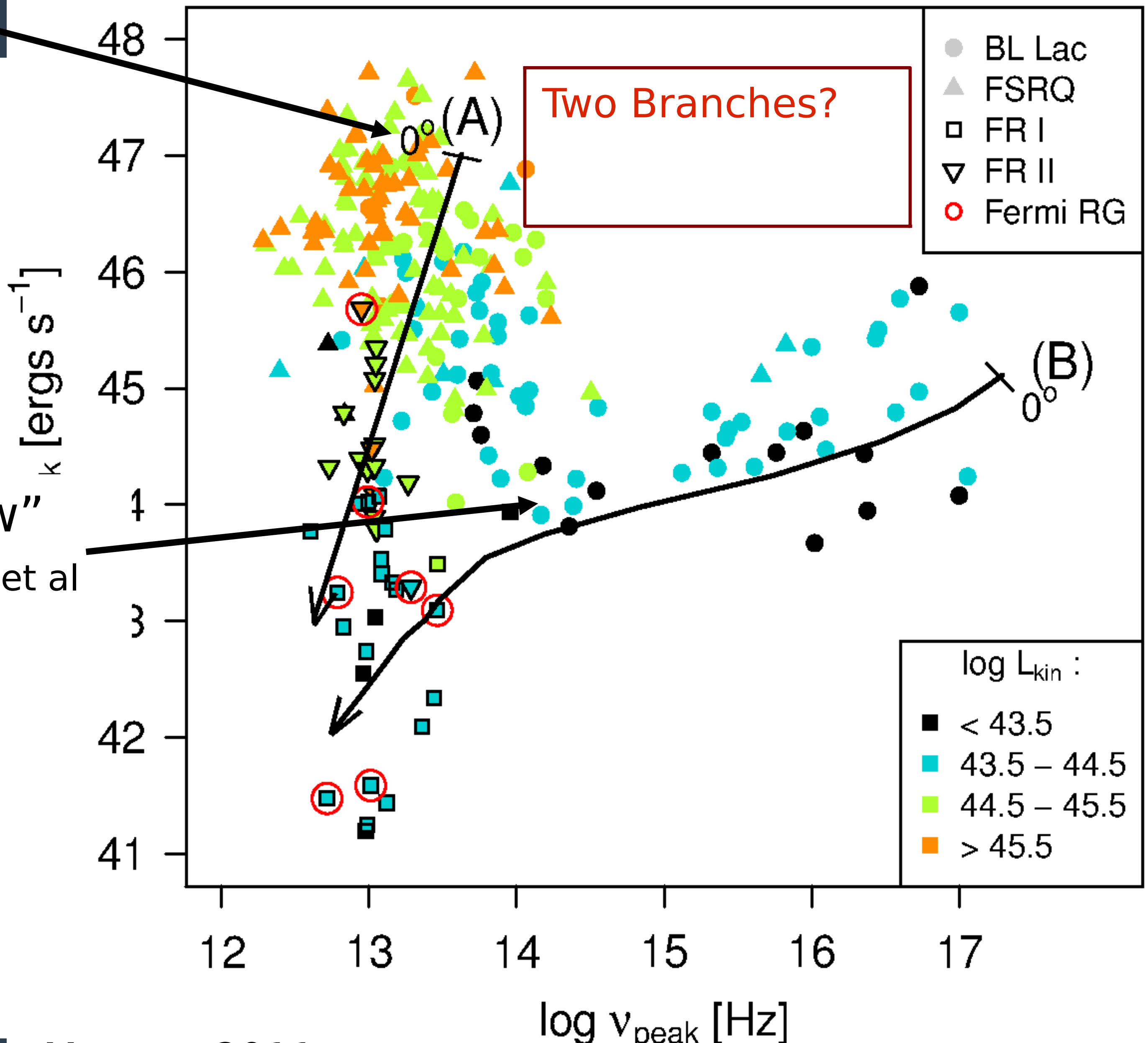
BLLs

“Simple jet”
(single Γ)



“Decelerating Flow” model (Georganopoulos et al



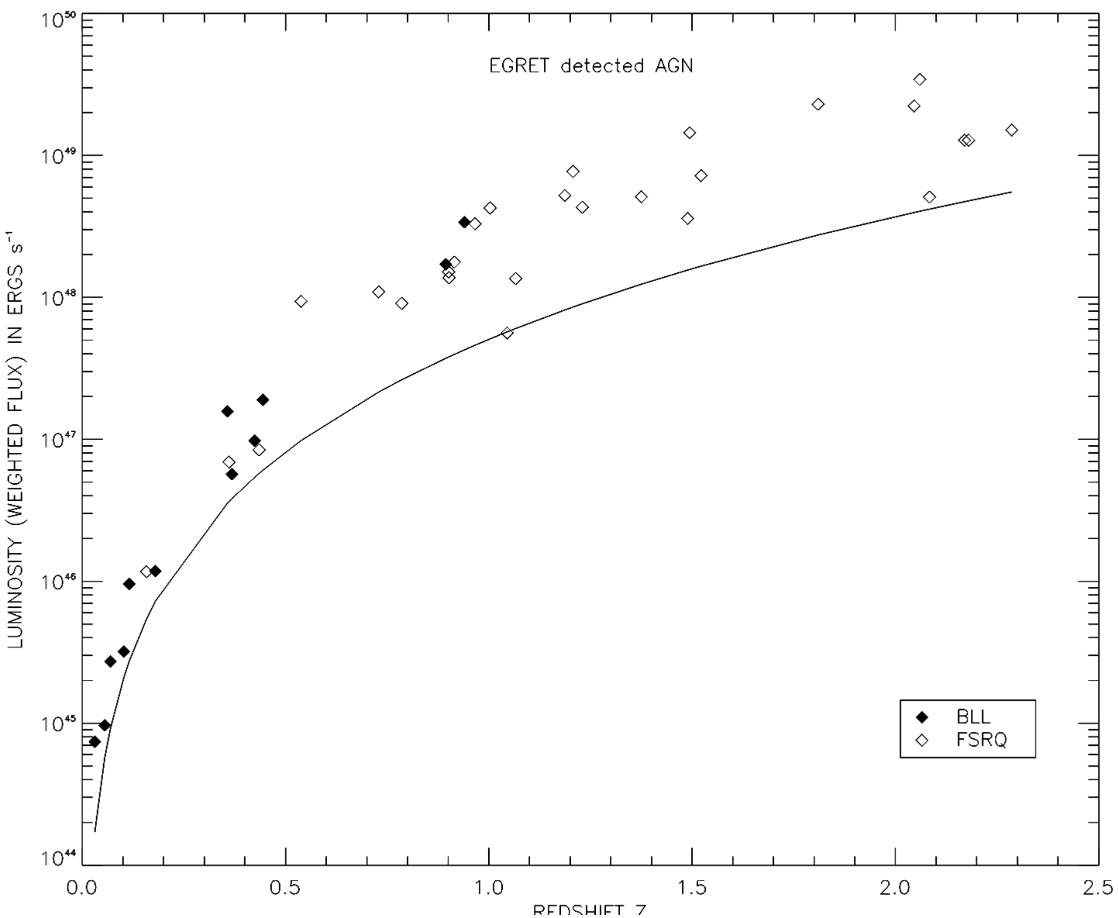


Meyer+ 2011

What are we working on now?

- How are these jets created? Why only 10%?
- How are different kinds of AGN related in the bigger picture?
- What are the jets made of?
- How much energy do they carry, and how long do they live?
- How important are they to the host galaxy & the evolution of galaxies and clusters?
- Do all galaxies have a jet phase? How do we grow black holes?

The Era of EGRET (1991-2000)



At the time EGRET was launched in 1991, 3C 273 was the only extragalactic source known to emit γ-rays (Mukherjee 2001)

EGRET detected ~ 70 blazars, mostly FSRQs

The famous 'Blazar Sequence' (Fossati+ 1998) was based on EGRET data

Sensitive from 20 MeV-30 GeV

The Fermi Era (2008 - present)

1 FGL Catalog (11 Months): ~ 1500 sources, ~ 680 associated to blazars
2 FGL Catalog (24 Months): ~ 1900 sources, ~ 830 RL AGN (mostly assoc.)

3 FGL Catalog (48 Months): 3033 sources! 1162 RL AGN

"Relative to the 2FGL catalog, the 3FGL catalog incorporates twice as much data as well as a number of analysis improvements, including improved calibrations at the event reconstruction level, an updated model for Galactic diffuse γ-ray emission, a refined procedure for source detection, and improved methods for associating LAT sources with potential counterparts at other wavelengths"

4FGL Catalog will contain 8 years of data, 5523 sources

Preliminary Source list available here:
https://fermi.gsfc.nasa.gov/ssc/data/access/lat/fl8y/

Multi-wavelength Support & Campaigns

Multiwavelength Observing - Support Programs

A number of observing programs have been established to provide either regular monitoring or targeted observations specifically designed to help support the *Fermi* science effort. Many of the programs listed below provide their datasets publicly as a service to the science community. These data are not part of the *Fermi* public dataset, so their use should be coordinated directly with the project leads. Please refer to each site for data usage and/or attribution information. For more information on coordinated observations with the LAT, please contact the LAT Multiwavelength Coordinating Group.

Blazar Monitoring

The Radio/Gamma-ray AGN Working Group Home Page provides more information on ongoing science and data acquisition activities in support of *Fermi* AGN Science.

- Blazar Monitoring List
  This page contains all blazars known to be regularly monitored at optical wavelengths, plus all the MOJAVE and Boston University monitored sources and known TeV blazars. (Courtesy of the Mojave group).
- Owens Valley Radio Observatory (OVRO) Monitoring of *Fermi* Blazars
  40M Radio telescope (15 GHz) monitoring more than 1200 blazars about twice per week.
- MOJAVE/2cm Survey Data Archive
  An imaging survey of compact radio sources at 15 GHz. Many sources are from the *Fermi*-LAT First Point Source Catalog
- University of Michigan Radio Astronomy Observatory
  Tabulated daily averages for flaring gamma-ray blazars.
- TANAMI (Tracking Active Galactic Nuclei with Austral Milliarcsecond Interferometry)
  Tracking the jets of flaring *Fermi* blazars south of -30 degrees declination at 8.4GHz and 22GHz
- Boston University Blazar Group
  Provides monthly Images of gamma-ray blazars with the VLBA at 43 GHz
- SMARTS Optical/IR Observationsof LAT Monitored Blazars
  Uses three telescopes at CTIO to monitor all blazars on the LAT Monitored Sources List that are viewable from Chile
- Optical Linear Polarization Monitoring of Bright Fermi Blazars
  Regular monitoring of gamma-ray bright blazars from University of Arizona's Steward Observatory
- *Swift*-XRT Monitoring of *Fermi*-LAT Sources of Interest
  Near-real time monitoring of sources on the LAT Monitored Sources List from the *Swift* XRT instrument
- VIPS (The VLBA Imaging and Polarimetry Survey)
  A combined 5 GHz and 15 GHz survey with the Very Long Baseline Array of ~1100 active galactic nuclei (AGN) with full polarization and high dynamic range
- Goddard Robotic Telescope (GRT)
  A 14" robotic telescope project whise goal is to understand the jet physics through the muti-wavelength observations of the Gamma-ray Bursts (GRBs) and the Active Galactic Nuclei (AGNs).
- KAIT Fermi AGN Light-curve Reservoir
  This web page shows the light curves of AGNs that are monitored by KAIT with average cadence of 3 days
- VLA observations of Fermi unassociated sources
  Has an aim to undertake a detailed examination of every Fermi detected object in the northern sky with declination > +10 deg not yet associated with a known source type (blazar, pulsar, etc.).
- VLBA Observations of TeV Blazars
  This is an archive of all of the VLBA data they have obtained on TeV-emitting HBLs during the course of their research program. This archive contains data beginning with observations of Markarian 421 in 1994, and continuing to the present.

Source (link to more information)	Time Interval
Mrk501: Multi-frequency campaign	2018 April - 2018 Sept. **- Current**
Mrk421: Multi-frequency campaign	2017 Dec. - 2018 May **- Current**
Mrk501: Multi-frequency campaign	2017 April - 2017 Aug
Mrk421: Multi-frequency campaign	2016 Nov - 2017 May
Mrk501: Multi-frequency campaign	2016 March - 2016 September
Mrk421: Multi-frequency campaign	2015 Dec - 2016 May
1H 0323+342: Multi-frequency campaign	2015 August - 2015 December
Mrk421: Multi-frequency campaign	2015 January - 2015 May
Mrk501: Multi-frequency campaign	2014 March - 2014 August
Mrk421: Multi-frequency campaign	2013 Dec - 2014 May
Mrk501: Multi-frequency campaign	2013 April - 2013 August
Mrk421: Multi-frequency campaign	2012 Dec - 2013 June
Mrk501: Multi-frequency campaign	2012 Feb - 2012 July
Mrk421: Multi-frequency campaign	2011 Dec - 2012 June
Mrk501: Multi-frequency campaign	2011 March - 2011 Sep.
Mrk421: Multi-frequency campaign	2010 Dec - 2011 Dec
PSRB1259-63/SS2883 2010/2011 MW Campaign	2010 Nov. -2011 Feb.
Mrk421: Multi-frequency campaign	2009 Dec - 2010 Dec
PMN J0948+0022: Multiwavelength campaign	2009 Mar (end) - June (end)
Mrk501: Multiwavelength campaign	2009 Mar (mid) - July (end)
3C279: Planned Intensive campaign	2009 Jan (end) - Mar (mid)

https://confluence.slac.stanford.edu/display/GLAMCOG/Fermi+LAT+Multiwavelength+Coordinating+Group

Results: The Markarians

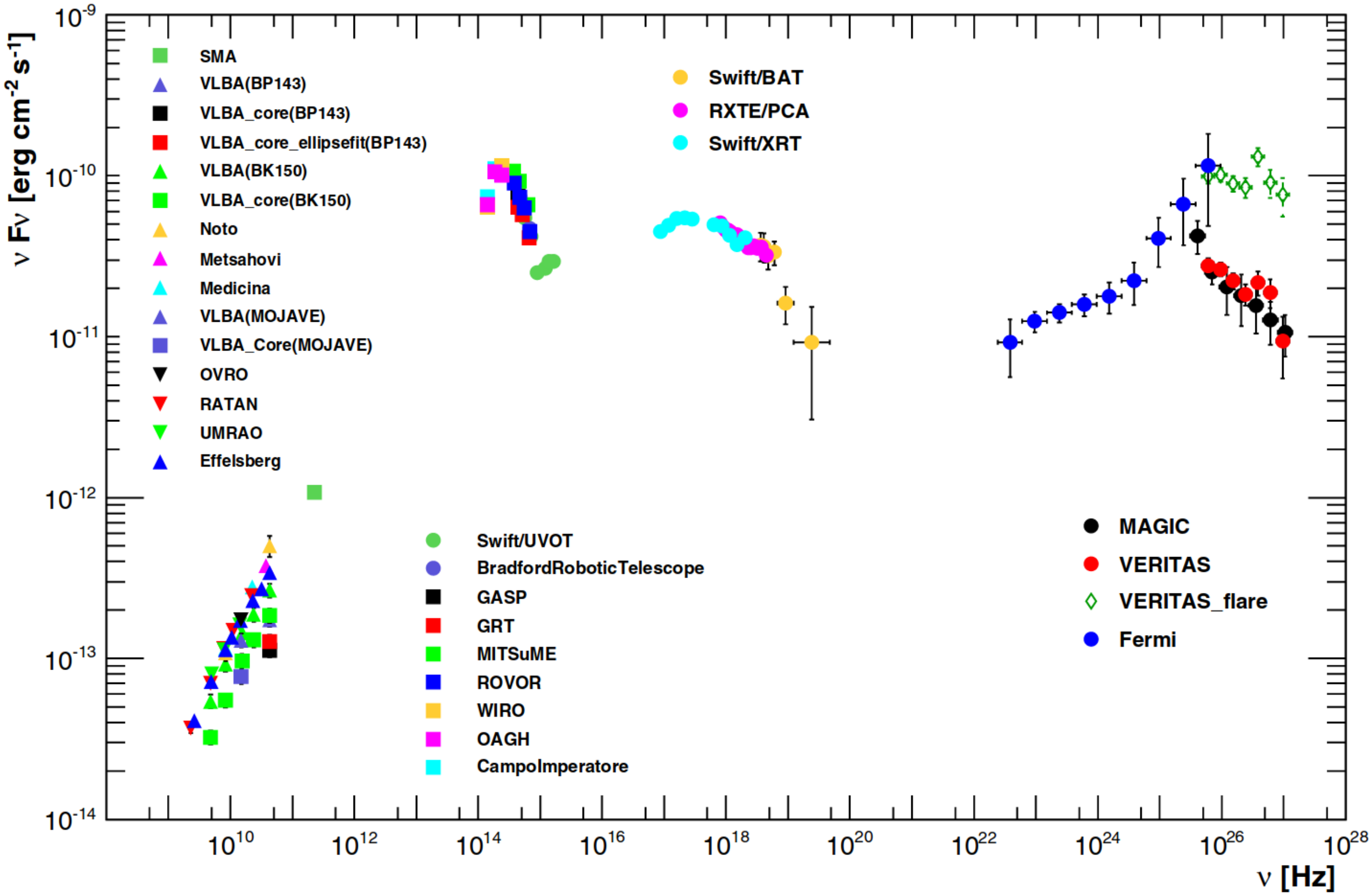
Mkn 501 (shown here) and Mkn 421 are very low-power blazars.

Synchrotron peak at 10^{17} Hz!

Note the unusual spectral shape during the flare.

Low Compton Dominance (SSC Source).

[Abdo+ 2011]



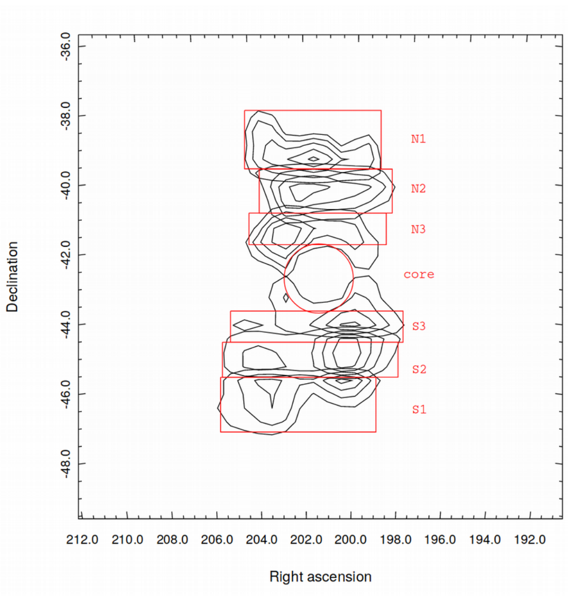
Results: The Lobes of Cen A

Centaurus A – one of the nearest radio galaxies

Lobes are 10 degrees across (600 kpc)

“Purple Glow” at left is a resolved detection from Fermi/LAT (Sun+ 2016)

Results: The Lobes of Cen A



Pure Leptonic Model fits at left (require B-field enhancement at edge of south lobe) – lepto-hadronic models also considered.

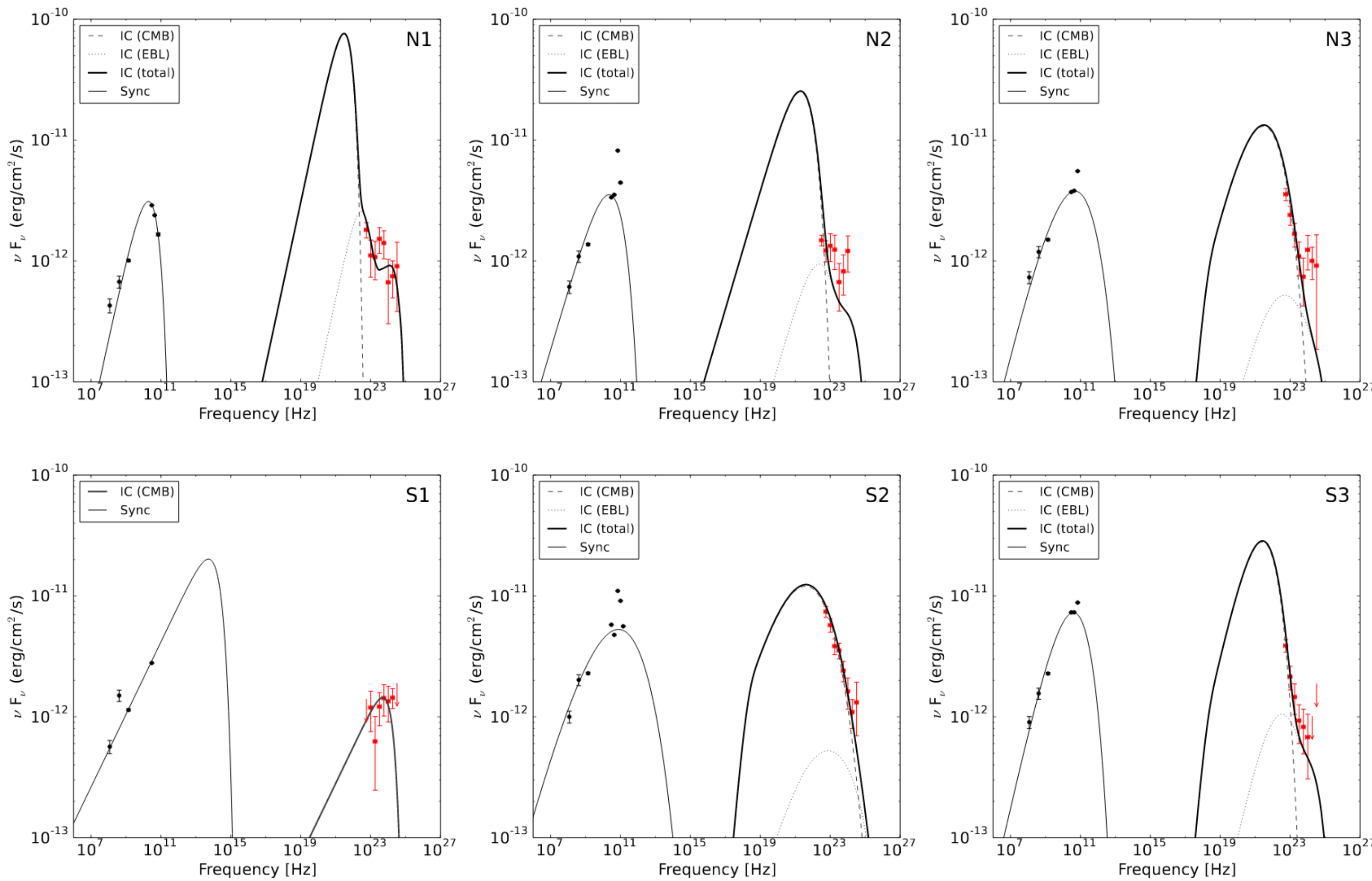


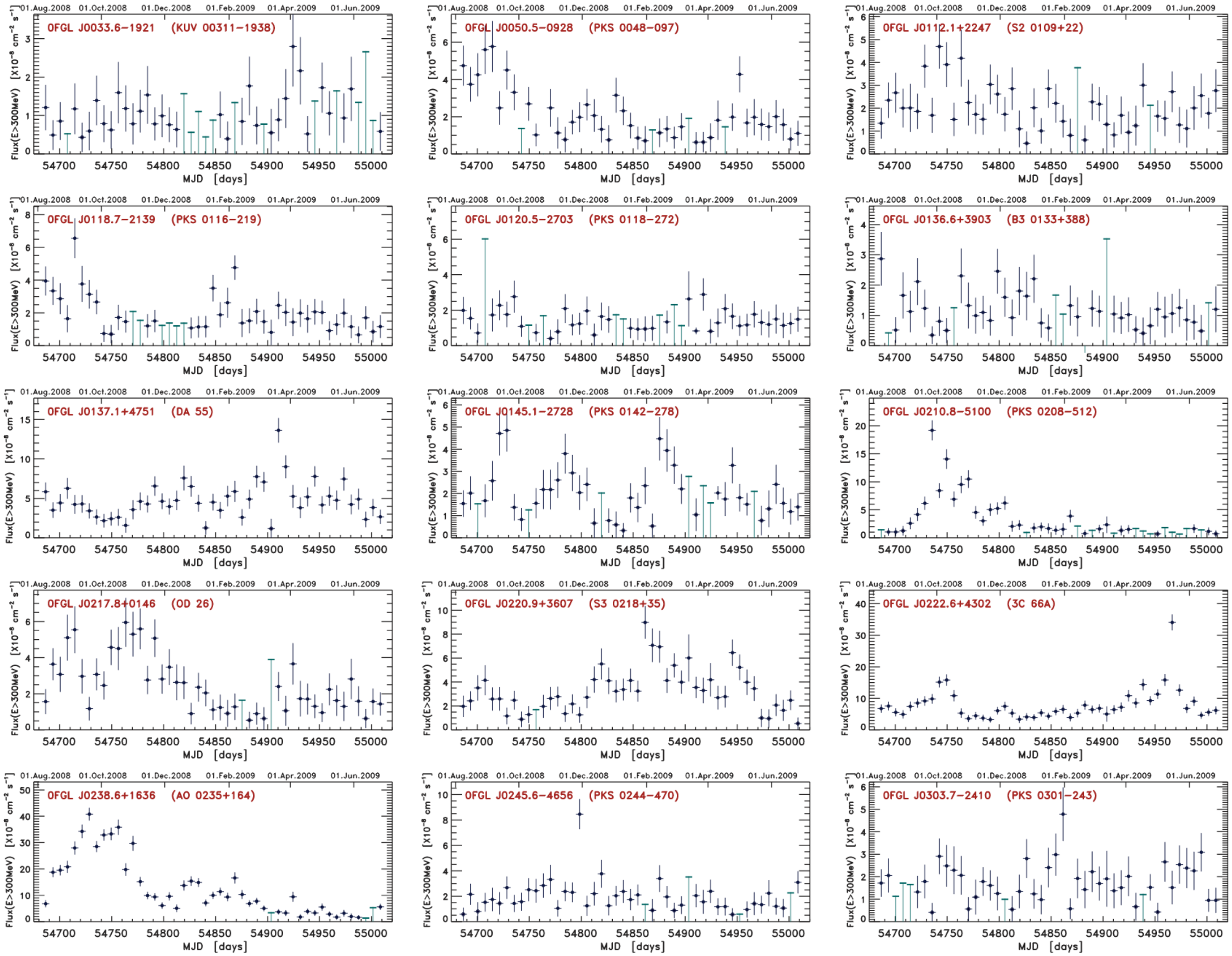
Fig. 7. Broadband SEDs for each region shown in Figure 3. Observed radio and *Planck* data (black dots with error bars) are fitted with a synchrotron model. Observed *Fermi*-LAT data (red dots with error bars) are fitted with the inverse-Compton (IC) scatterings of the CMB and EBL photon fields except for S1, which only requires the seed photon contribution from the CMB. The upper limits are calculated within a 3σ confidence level.

Results: Variability

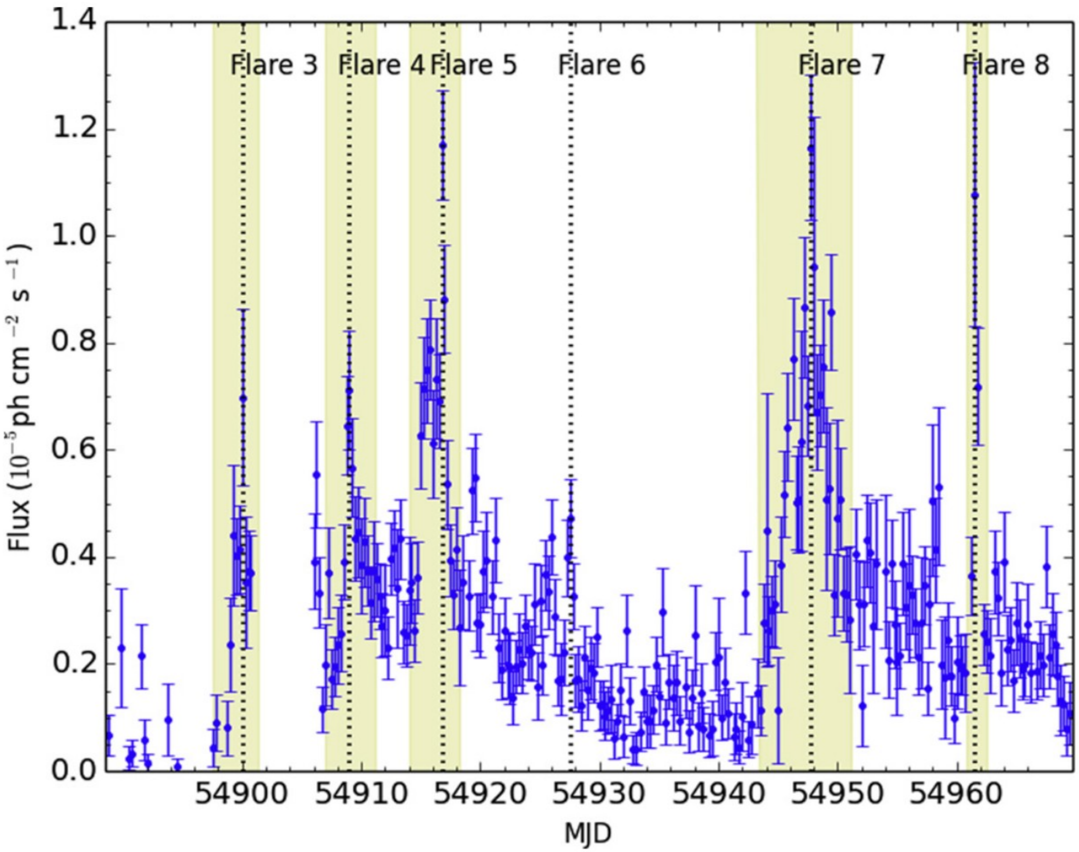
Blazars are extremely Variable!

> 50% of sources in the initial 11-month sample [Abdo+ 2010]

This number is now higher: far more unusual to find a non-variable blazar. These are usually faint sources with insufficient statistics to build a lightcurve.)



Results: Fast Variability



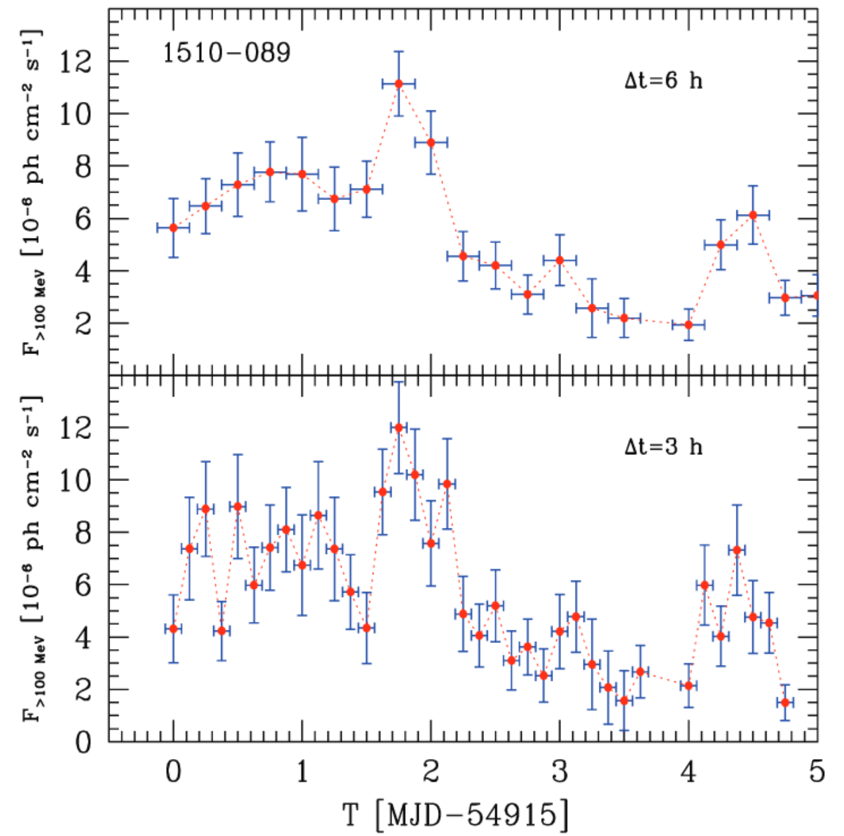


Figure 3. Light curve of PKS 1510−089 with bin sizes of 6 h (upper pan and 3 h (lower panel) starting on MJD 54915 (2009 March 25). Significa variations with time-scales of 6 h (and marginally also of 3 h) are clear visible.

Rise and Fall times of tens of hours – comparing low and high-energy decay timescales can suggest the location of the emission (Dotson+ 2015)

Tavecchio+ 2010

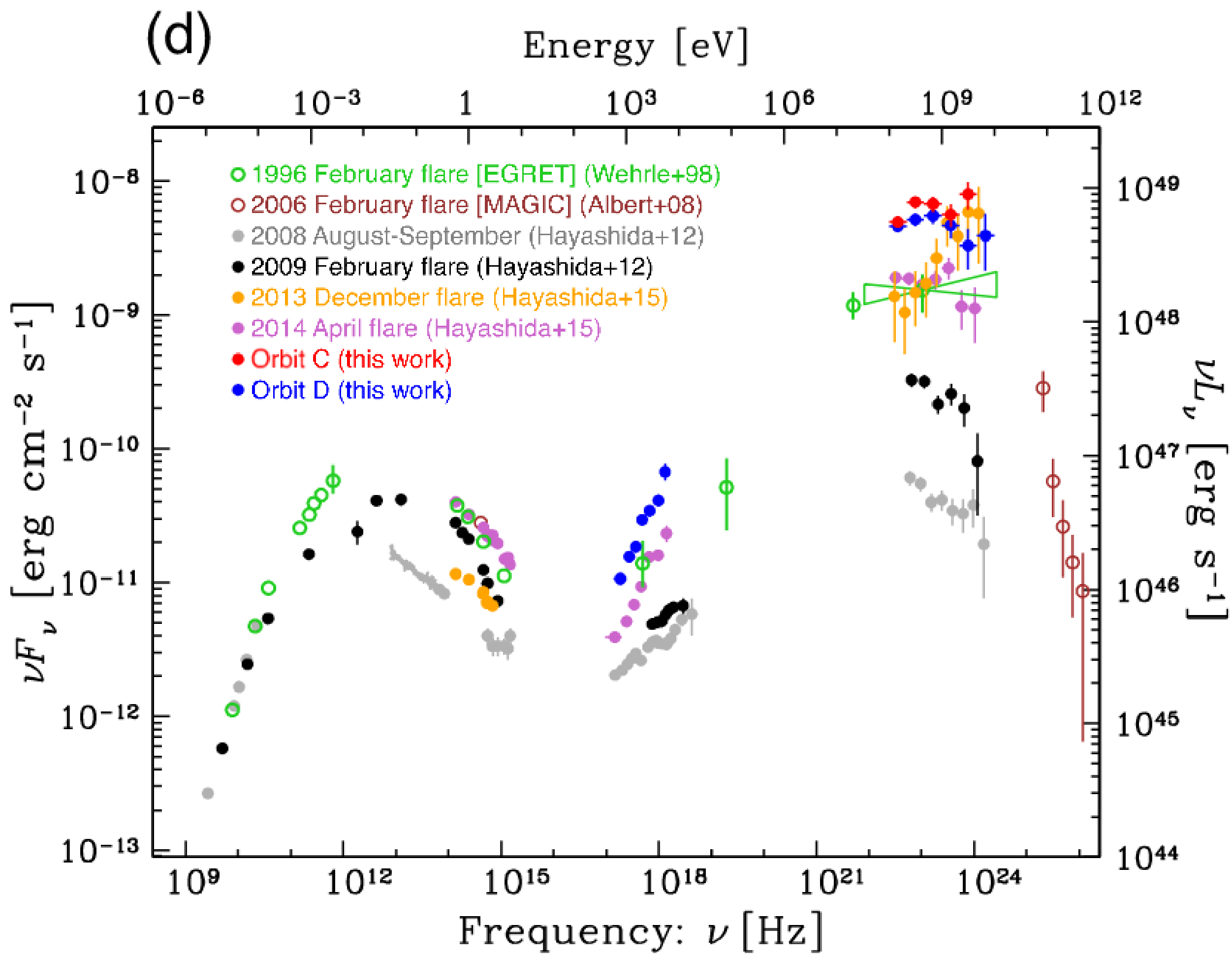
Results: MINUTE-timescale Variability

3C 279
One of the brightest powerful blazars

Went into outburst in 2015 June (red and blue points)

Note the extreme Compton Dominance!

[Ackermann+ 2016]



Results: MINUTE-timescale Variability

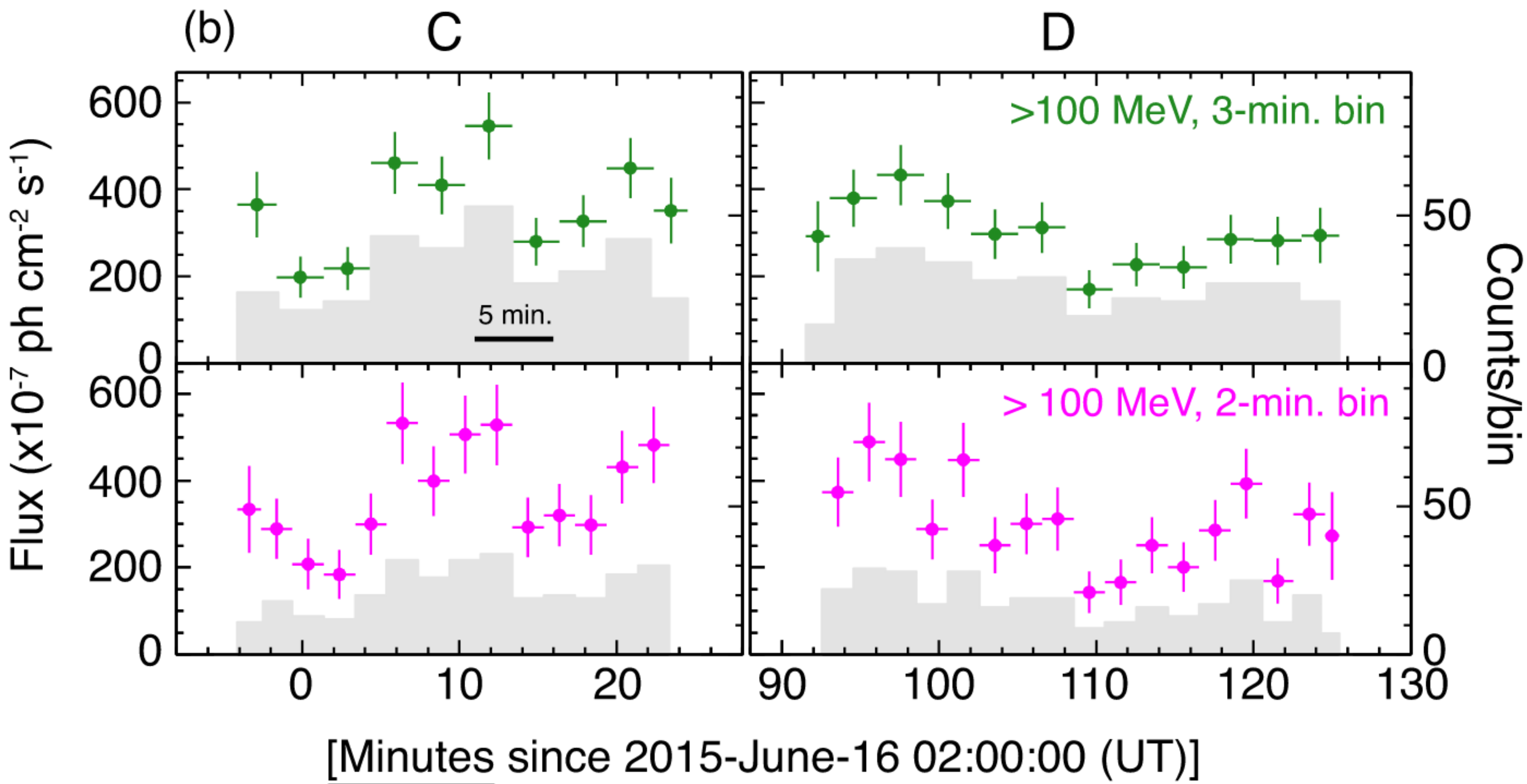
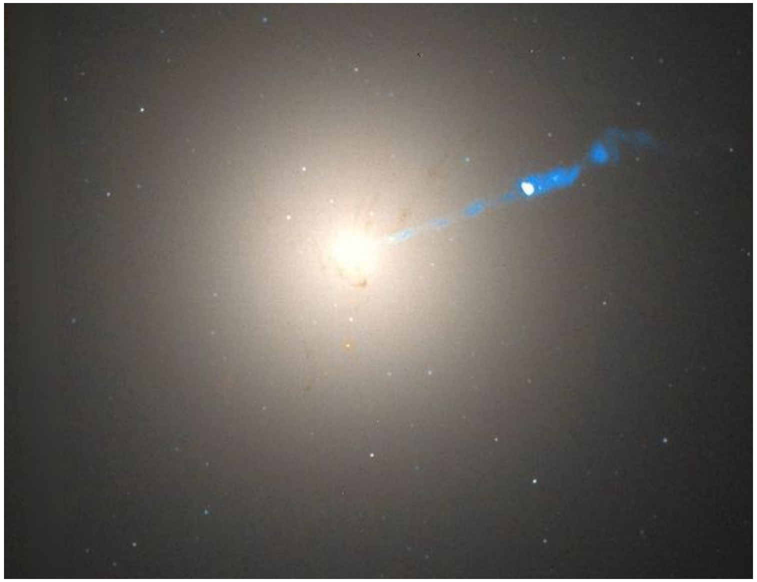


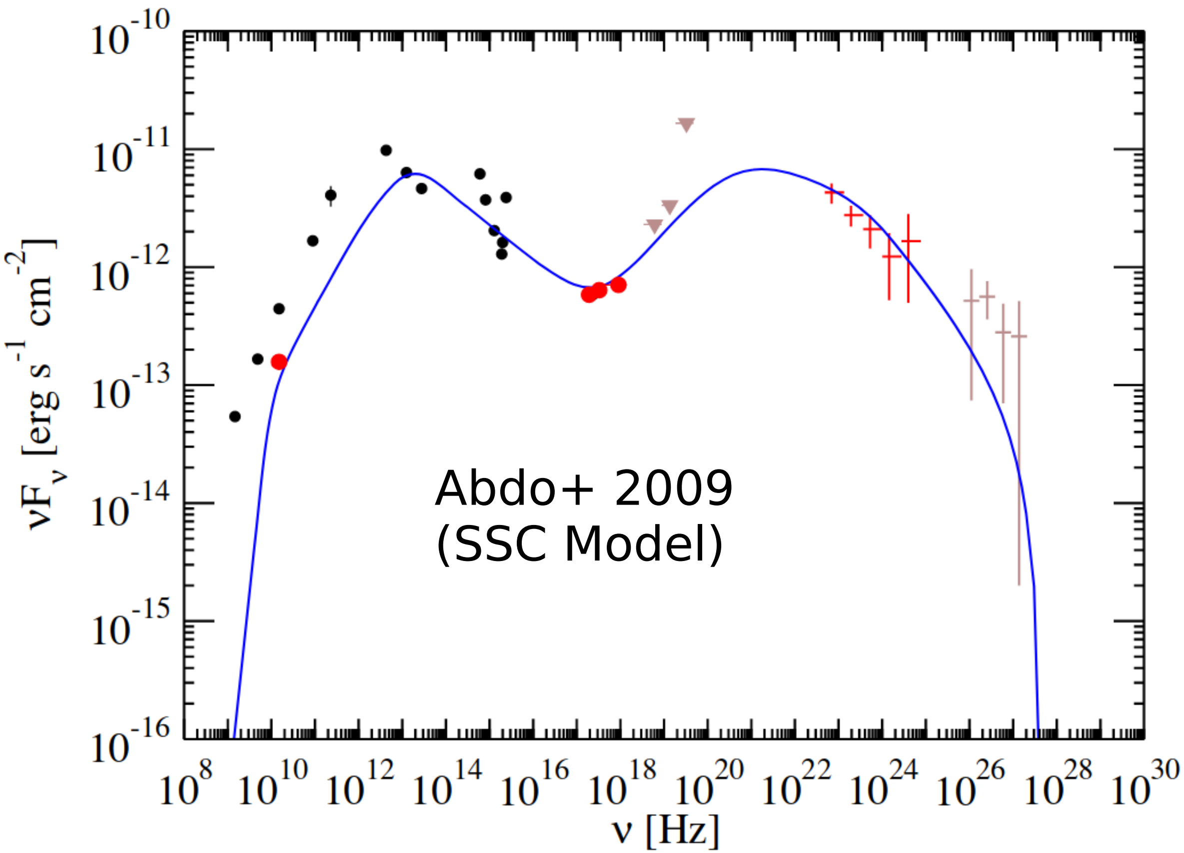
Figure 2. Light curves of 3C 279 above 100 MeV with minute-timescale intervals. (a): Intervals of 5 min (red) and 3 min (green) during the outburst phase from Orbits B–J. (b): Enlarged view during Orbits C and D. Each range is indicated with dotted vertical lines in (a). The points denote the fluxes (left axis), and the gray shaded histograms represent numbers of events (right axis) detected within 8° radius centered at 3C 279 for each bin. Contamination from both diffuse components were estimated as ∼ 1 photon for each 3-min bin.

Results: Gamma-Rays from RG

THE ASTROPHYSICAL JOURNAL, 707:55–60, 2009 December 10 doi:10.1088/0004-637X/707/1/55

FERMI LARGE AREA TELESCOPE GAMMA-RAY DETECTION OF THE RADIO GALAXY M87





Results: Gamma-Rays from RG

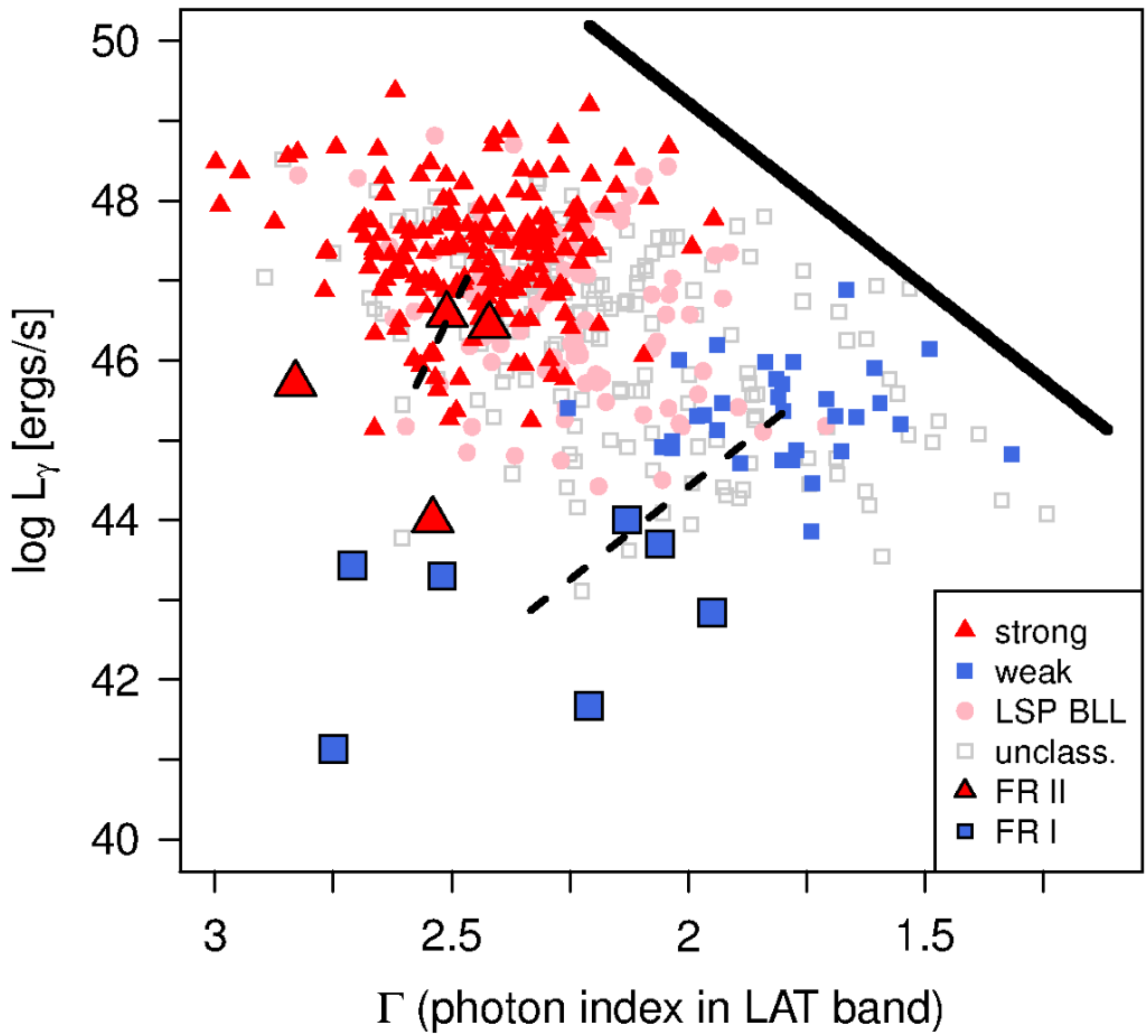
Meyer+ 2012

“The Compton Envelope”

Most aligned sources near the black line.

Strong/Weak sources are separated.

Radio Galaxies lie farthest from the black line.



Results: Monster Black Holes

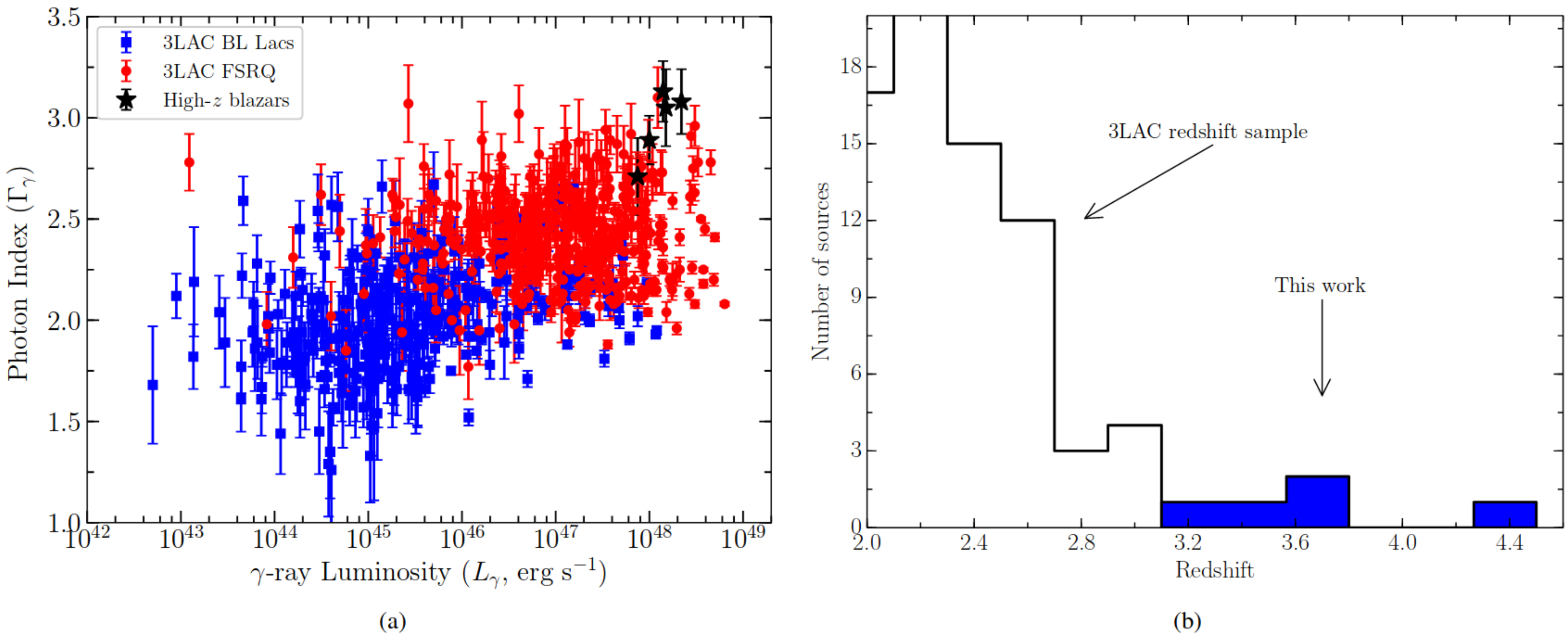
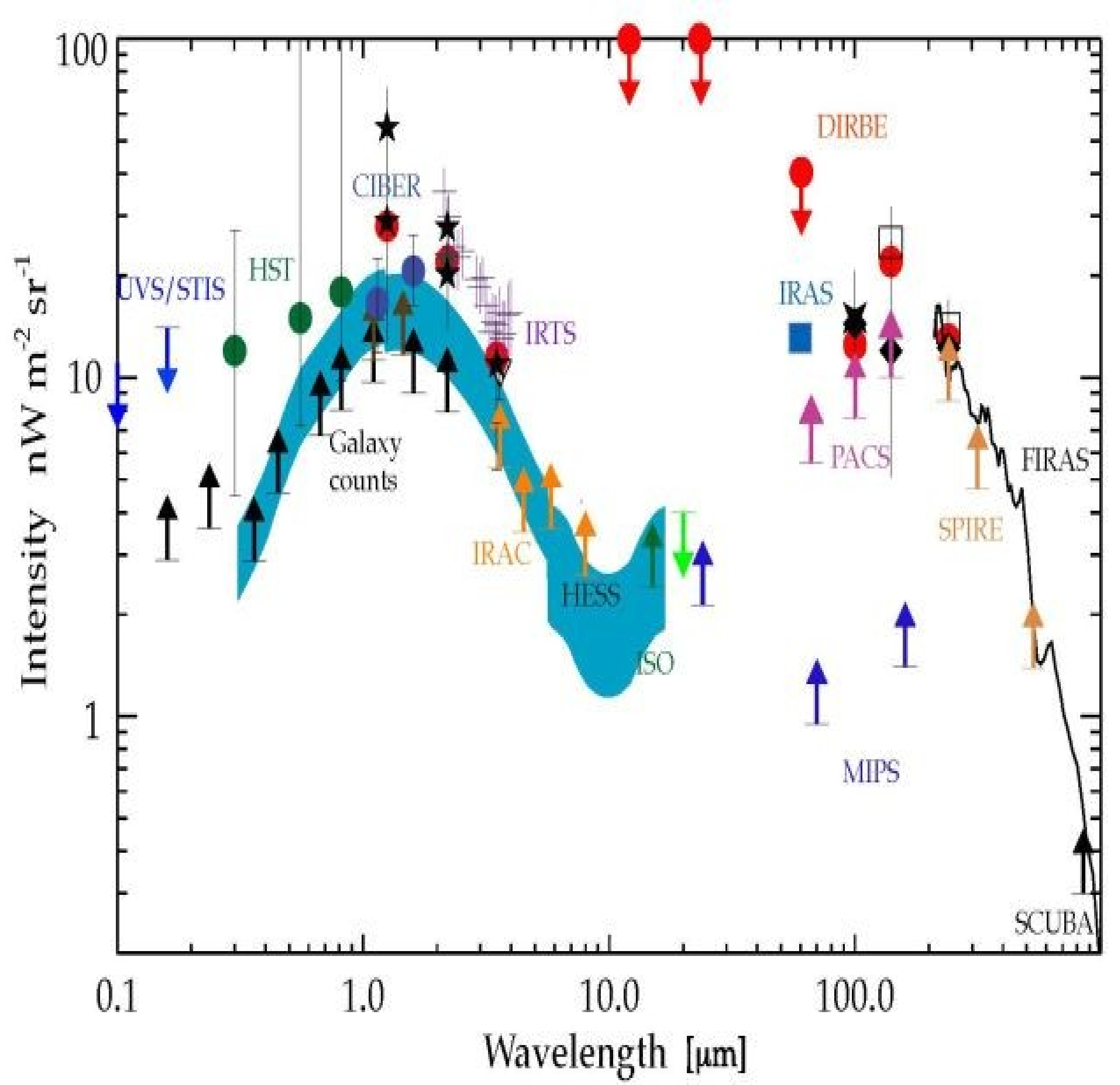


Figure 2. Comparison of new γ-ray detected high-z blazars with 3LAC objects in, left: γ-ray luminosity vs. photon index plane, and right: the redshift histogram. The plotted L_γ and Γ_γ are derived for the 0.1−300 GeV energy band, both for 3LAC and high-z blazars newly detected in γ-rays, for an equal comparison.

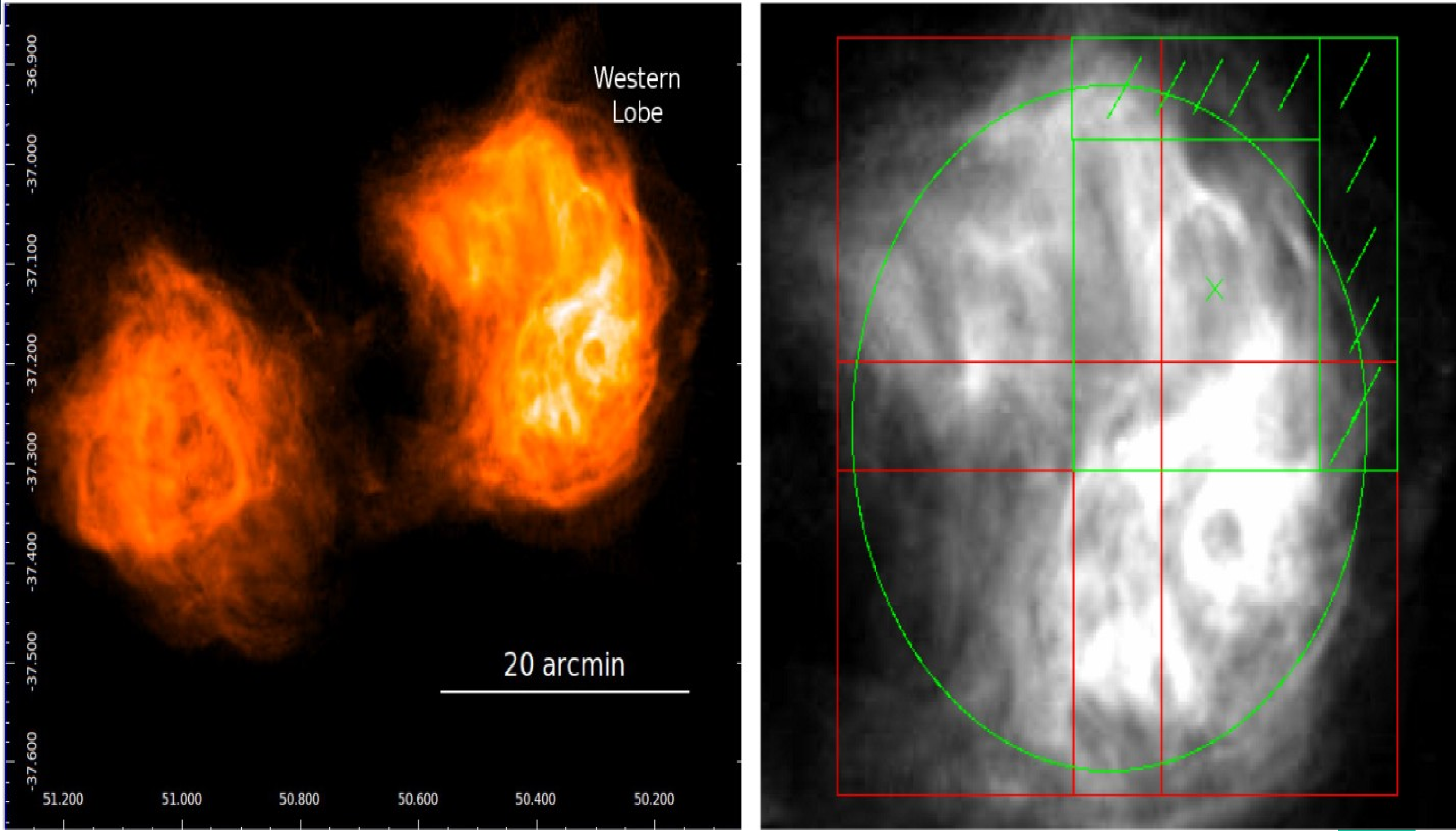
These blazars have SMBH on the order of 10^9-10^{10} when the Universe is only 2 Billion years old! [Ackermann+ 2017]

Radio Lobes can measure the EBL

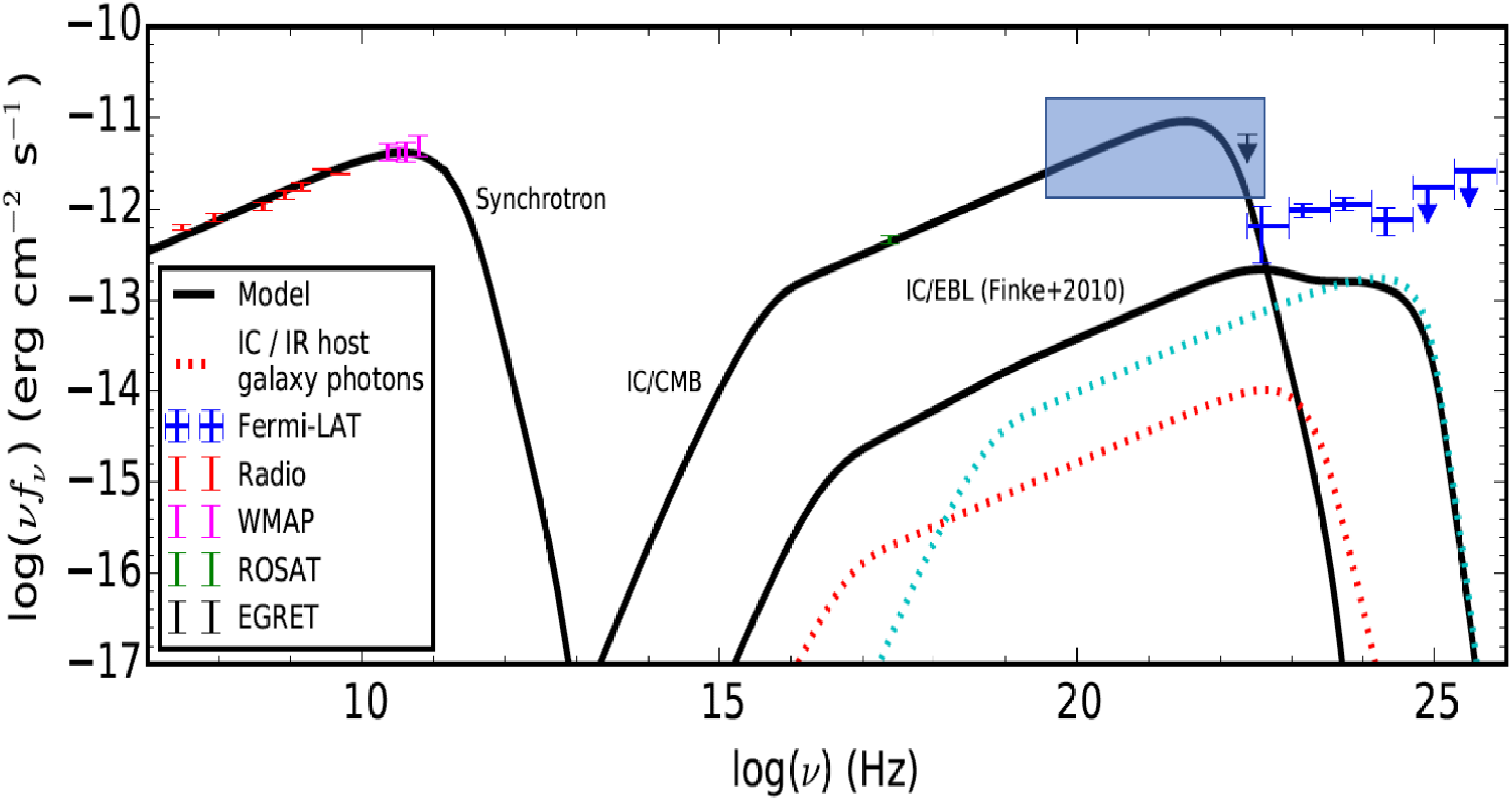
(Georganopoulos+ 2008)



Results: Fornax A

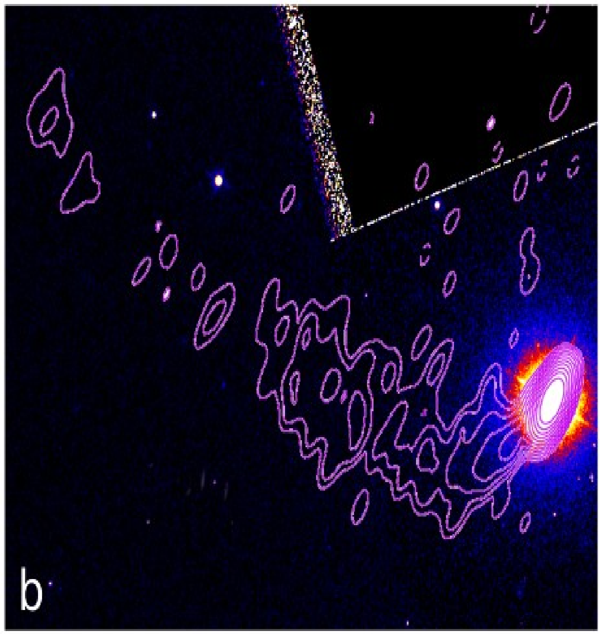


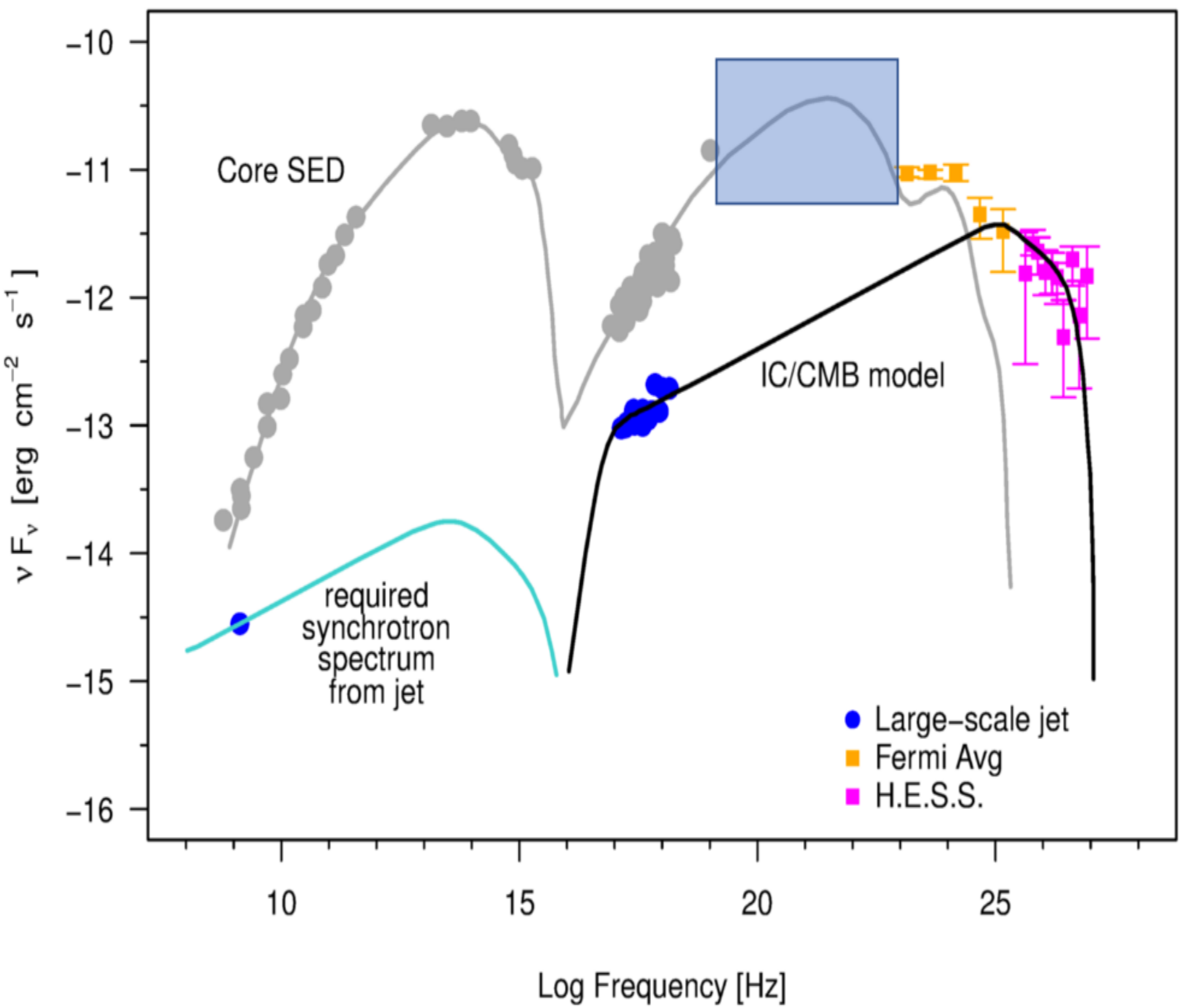
Results: Fornax A



Ackermann+ 2016 (Fermi Collaboration)

Aside: The Need for an 'MeV Fermi'





AP Librae
Complex "extremely broad" Compton component. No MeV constraints.