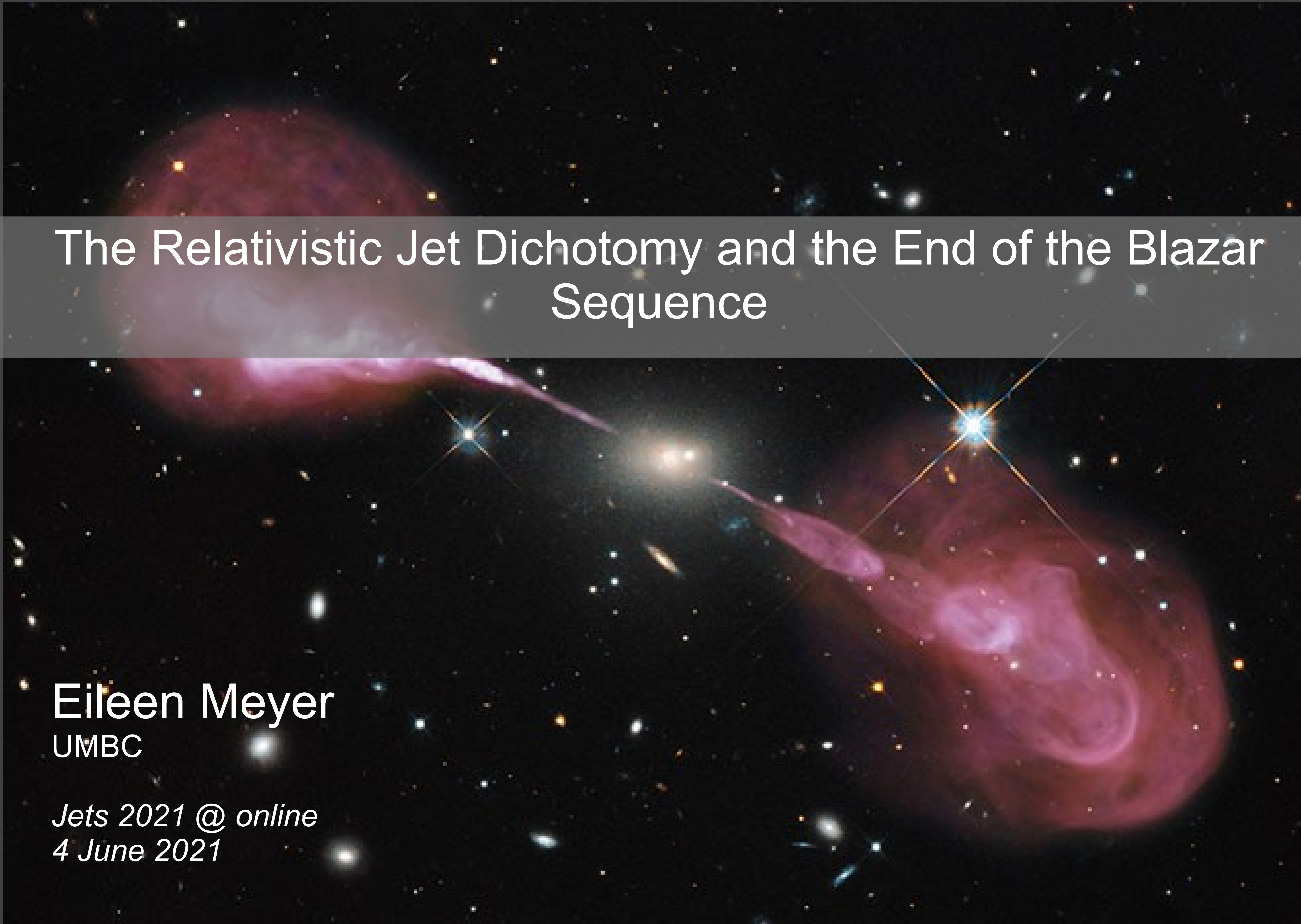
The Relativistic Jet Dichotomy and the End of the Blazar Sequence



Eileen Meyer
UMBC

Jets 2021 @ online
4 June 2021

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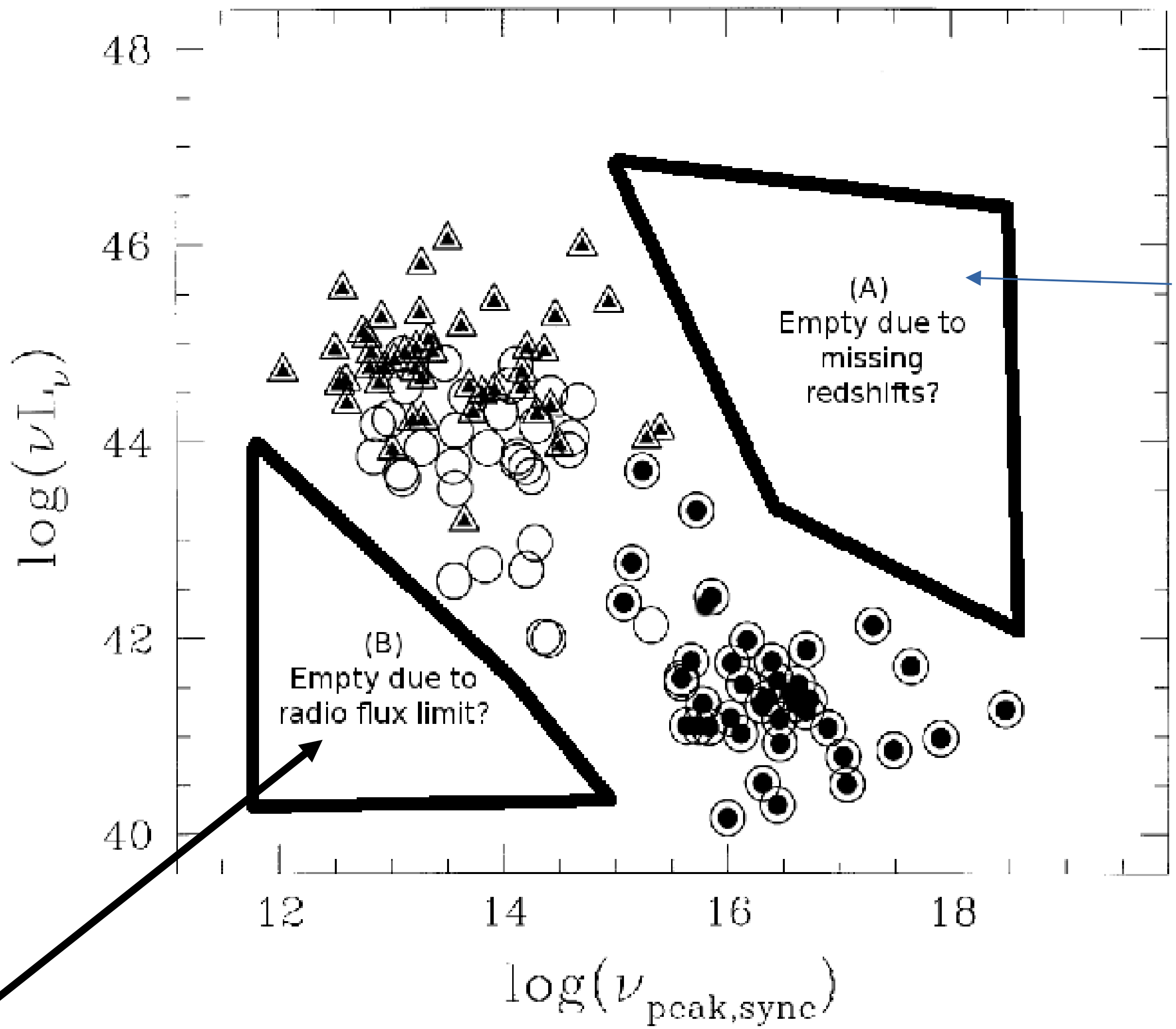
Mary Keenan
PhD UMBC 2020

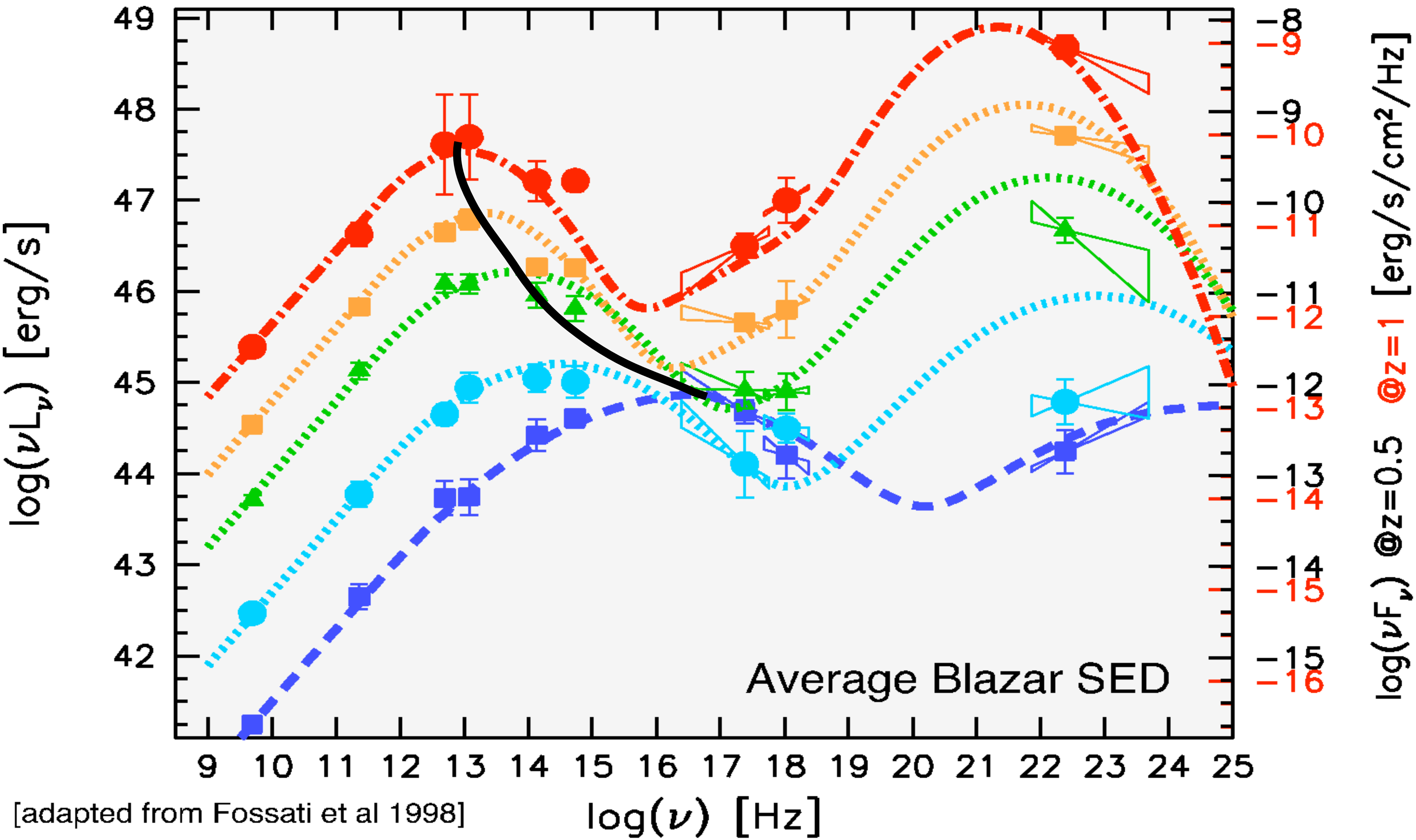
Fossati 1998: The Blazar Sequence



Sources also found here (Padovani 2003, 2012, Cerutti 2017)

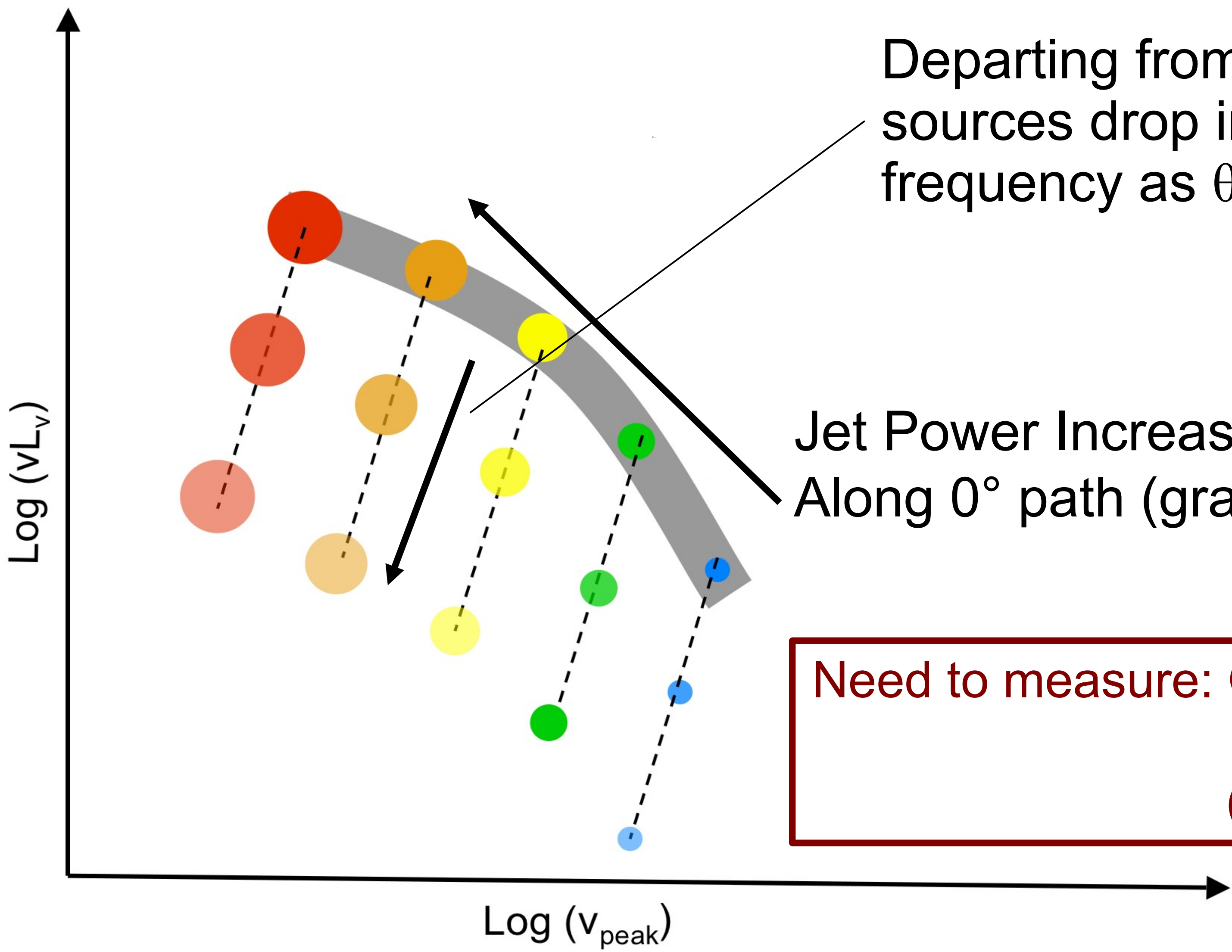
Sources were found here (Nieppola 2006, Landt 2006, Caccianiga 2004)

1998: The Blazar Sequence



[adapted from Fossati et al 1998]

Hypothesis: The Blazar Sequence
Envelope



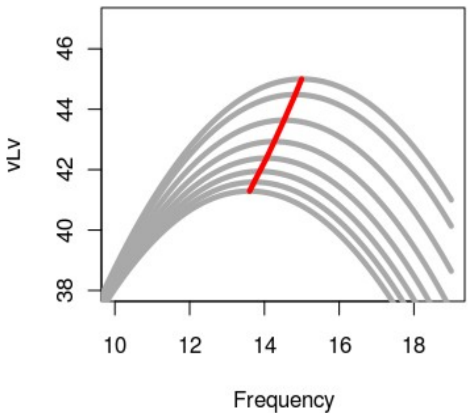
Departing from the sequence, sources drop in Luminosity and frequency as θ increases

Jet Power Increases (blue → red)
Along 0° path (gray): L_p increases
ν_p decreases

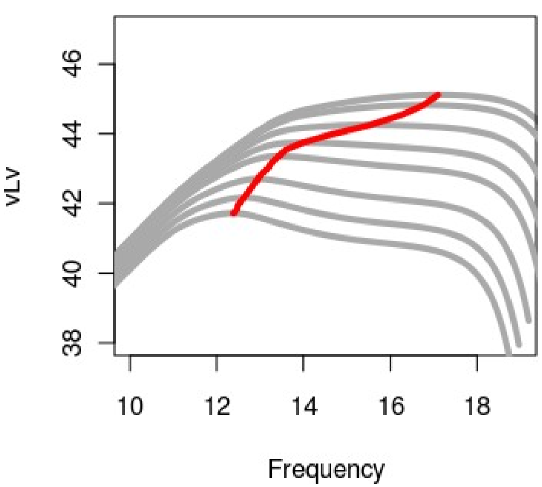
Need to measure: Orientation (θ)
Intrinsic Jet Power
(good $L_{p,}$ ν_p)

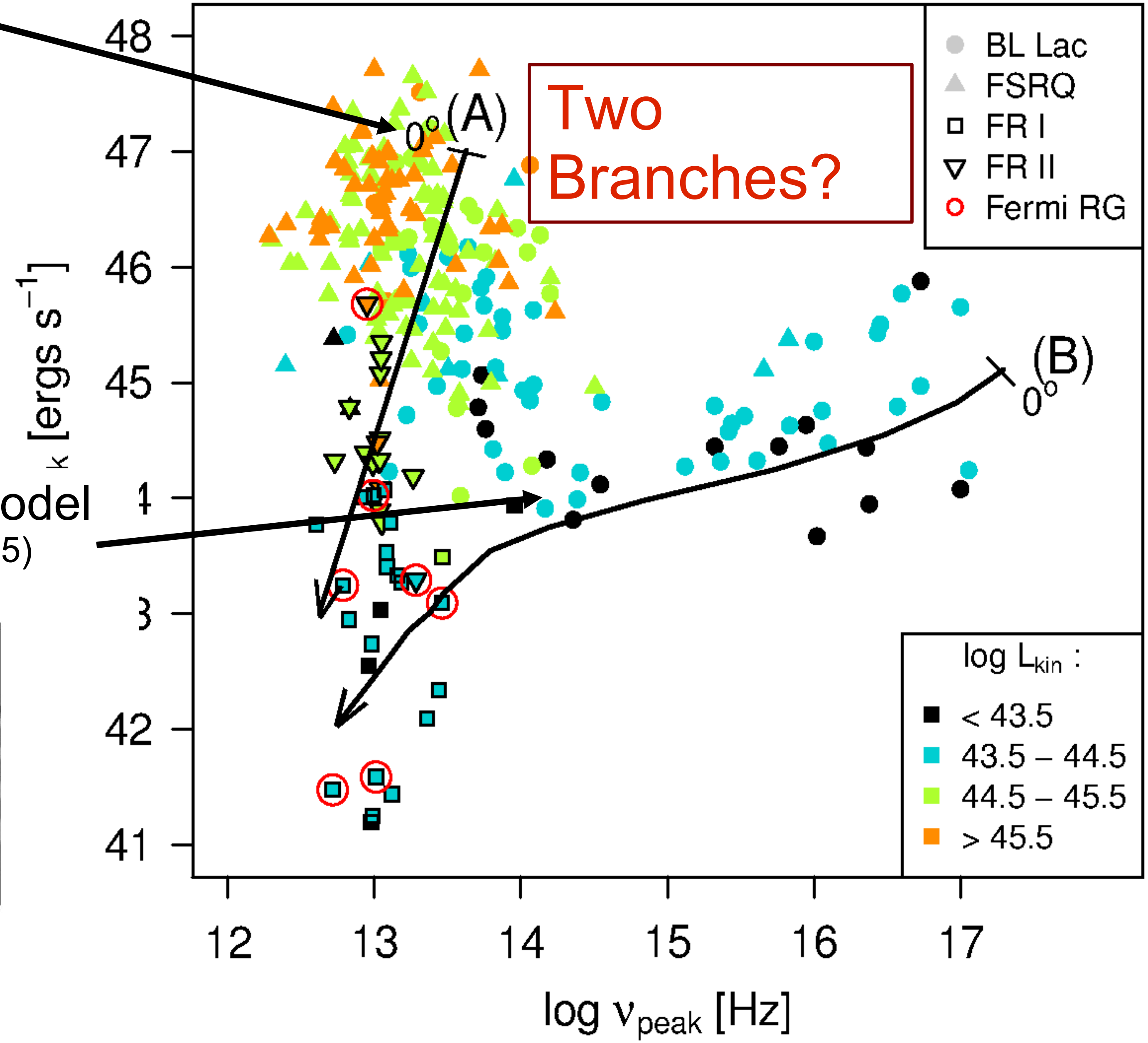
Meyer 2011: The “Blazar Envelope”

“Simple jet”
(single Γ)

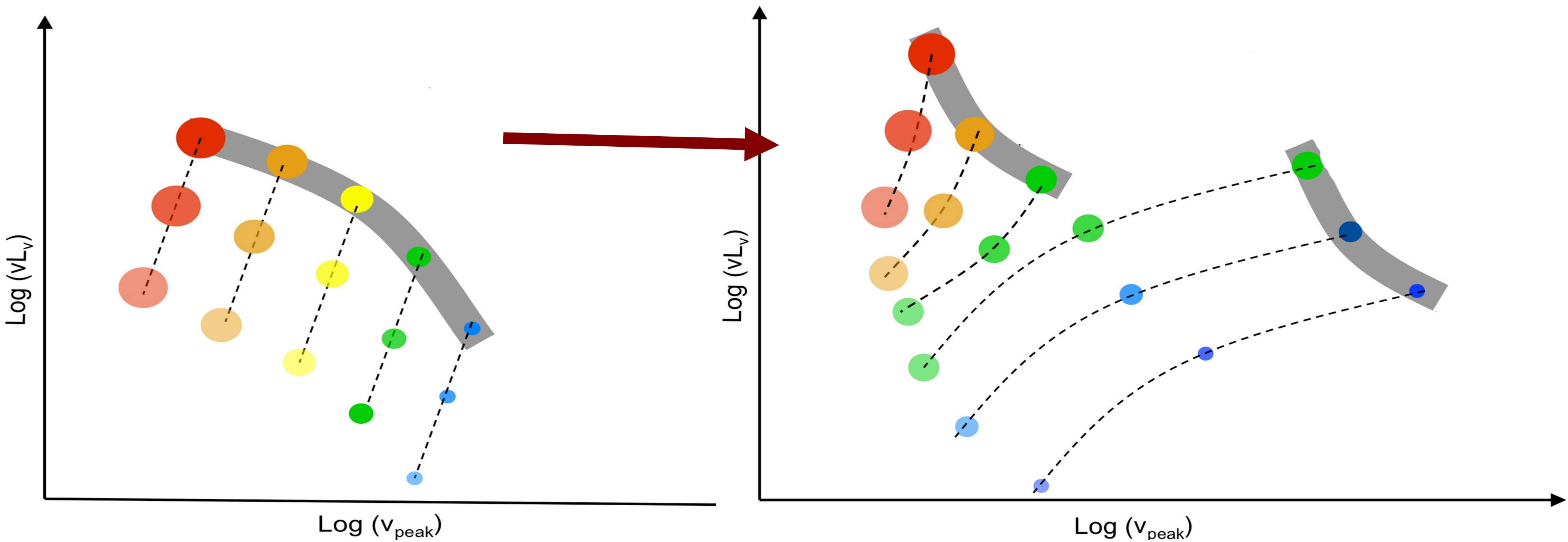


“Decelerating Flow” model
(Georganopoulos et al 2005)





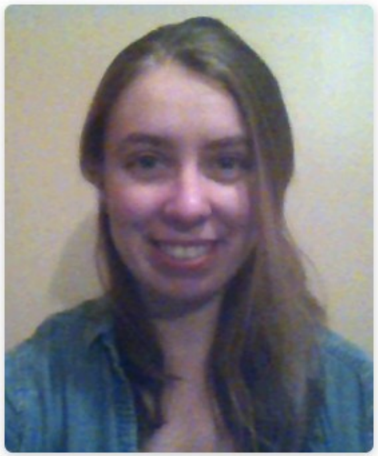
Meyer 2011: The "Blazar Envelope"



New Hypothesis: a "broken" sequence?
Need better statistics!

New Decade, New Study

Mary Keenan



ArXiv:
2007.12661

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The Relativistic Jet Dichotomy and the End of the Blazar Sequence

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ABSTRACT
Our understanding of the unification of jetted AGN has evolved greatly as jet samples have increased in size. Here, based on the largest-ever sample of over 2000 well-sampled jet spectral energy distributions, we examine the synchrotron peak frequency – peak luminosity plane, and find little evidence for the anti-correlation known as the blazar sequence. Instead, we find strong evidence for a dichotomy in jets, between those associated with efficient or 'quasar-mode' accretion (strong/type II jets) and those associated with inefficient accretion (weak/type I jets). Type II jets include those hosted by high-excitation radio galaxies, flat-spectrum radio quasars (FSRQ), and most low-frequency-peaked BL Lac objects. Type I jets include those hosted by low-excitation radio galaxies and blazars with synchrotron peak frequency above 10^{15} Hz (nearly all BL Lac objects). We have derived estimates of the total jet power for over 1000 of our sources from low-frequency radio observations, and find that the jet dichotomy does *not* correspond to a division in jet power. Rather, type II jets are produced at *all* observed jet powers, down to the lowest levels in our sample, while type I jets range from very low to moderately high jet powers, with a clear upper bound at $\sim 10^{43}$ erg s^{-1}. The range of jet power in each class matches exactly what is expected for efficient (i.e., a few to 100% Eddington) or inefficient (< 0.5% Eddington) accretion onto black holes ranging in mass from $10^7 - 10^{9.5}\ M_\odot$.

Key words: galaxies: active; galaxies: jets; catalogs; BL Lacertae objects: general

1 INTRODUCTION

Radio-Loud Active Galactic Nuclei (RL AGN) exhibit highly collimated relativistic jets of non-thermal plasma originating very near the central super-massive black hole (of $10^6 - 10^{10} M_\odot$) and propagating out to kpc - Mpc scales (see, e.g. Blandford et al. 2019, for a recent review). They can have a major impact on their host galaxy and surrounding environment, heating the intercluster medium (McNamara & Nulsen 2007; Chang et al. 2012) and halting or (more rarely)

Historically, a large number of sub-classes of radio-loud AGN have been defined, usually based on observational properties in the band in which they were discovered – e.g. steep-spectrum radio quasars, optically violent variable sources, X-ray selected BL Lacertae objects, broad-line radio galaxies, and many more (see Urry & Padovani 1995). Part of the extreme variety of appearance is clearly due to differences in viewing angle, as the radiation from the jet comes to dominate the spectral energy distribution (SED) when oriented at

New Decade, New Study

Starting sample of **6585** radio-loud AGN

Table 1. Radio-Loud AGN Samples

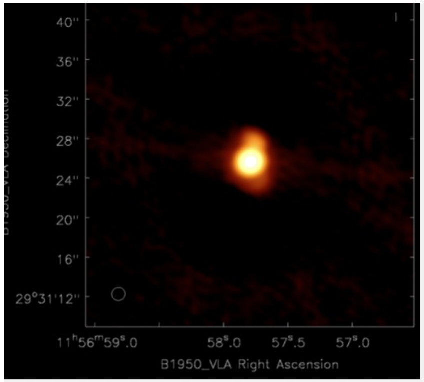
Sample (1)	Abbr. (2)	N_{init} (3)	N_{final} (4)	N_{unique} (5)	Reference (6)	Ref. Let. (7)
1 Jansky Blazar Sample	1Jy	34	34	0	Stickel et al. (1991)	a
2 Jansky Survey of Flat-Spectrum Sources	2Jy	232	129	5	Wall & Peacock (1985)	b
2-degree field (2dF) QSO survey	2QZ	26	1	0	Londish et al. (2002, 2007)	c
Third Cambridge Catalogue of Radio Sources	3CRR	173	68	2	Laing et al. (1983)	d
The 3rd Catalog of Hard Fermi-LAT Sources	3FHL	1553	446	1	Ajello et al. (2017)	e
The 3rd Catalog of AGN Detected by the Fermi/LAT	3LAC	1894	838	100	Ackermann et al. (2015)	f
Molonglo Equatorial Radio Galaxies	...	178	49	8	Best et al. (1999)	g
The Candidate Gamma-Ray Blazar Survey	CGRaBs	1625	1154	467	Healey et al. (2008)	h
Cosmic Lens All-Sky Survey	CLASS	232	79	23	Caccianiga & Marcha (2004)	i
Deep X-Ray Radio Blazar Survey	DXRBS	283	151	47	Landt et al. (2001)	j
Einstein Slew Survey Sample of BL Lac Objects	...	66	14	0	Perlman et al. (1996)	k
Hamburg-RASS Bright X-ray AGN Sample	HRX	172	42	2	Beckmann et al. (2003)	l
The MOJAVE Sample of VLBI Monitored Jets	...	512	456	21	Lister et al. (2018)[2]	m
Metsahovi Radio Observatory BL Lacertae sample	...	393	168	3	Nieppola et al. (2006b)	n
Parkes Quarter-Jansky Flat-Spectrum Sample	...	878	524	155	Jackson et al. (2002)	o
Radio-Emitting X-ray Source Survey	REX	143	32	9	Caccianiga et al. (1999)	p
Radio-Optical-X-ray Catalog	ROXA	801	234	101	Turriziani et al. (2007)	q
RASS - Green Bank BL Lac sample	RGB	127	72	1	Laurent-Muehleisen et al. (1999)	r
Einstein Medium-Sensitivity Survey of BL Lacs	EMSS	52	6	0	Rector et al. (2000)	s
RASS - SDSS Flat-Spectrum Sample	...	501	96	21	Plotkin et al. (2008)	t
Sedentary Survey of High-Peak BL Lacs	...	150	27	1	Giommi et al. (1999b)	u
Ultra Steep Spectrum Radio Sources	...	668	2	0	De Breuck et al. (2000)	v
The X-Jet Online Database	...	117	96	10	[2]	w

[1]http://www.physics.purdue.edu/astro/MOJAVE/allsources.html
[2]https://hea-www.harvard.edu/XJET/

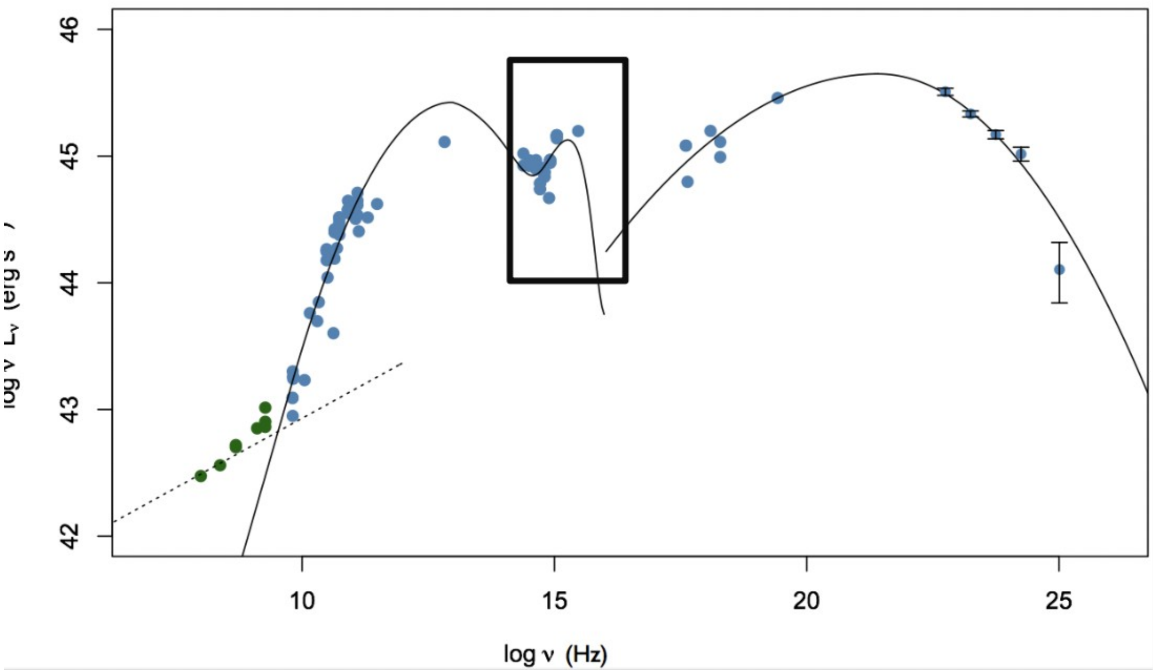
New Decade, New Study

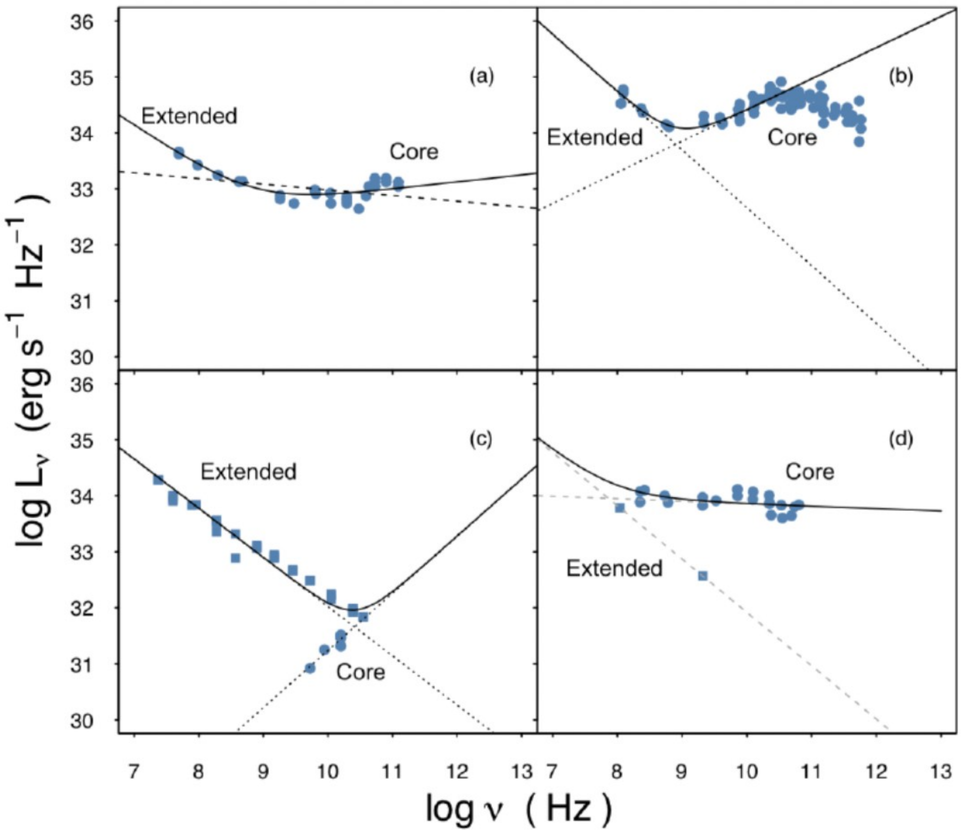
Starting sample of **6585** radio-loud AGN

Analyzed 460 VLA observations, 169 ALMA observations, 2 SMA and 1 VLA program, 17 archival HST observations



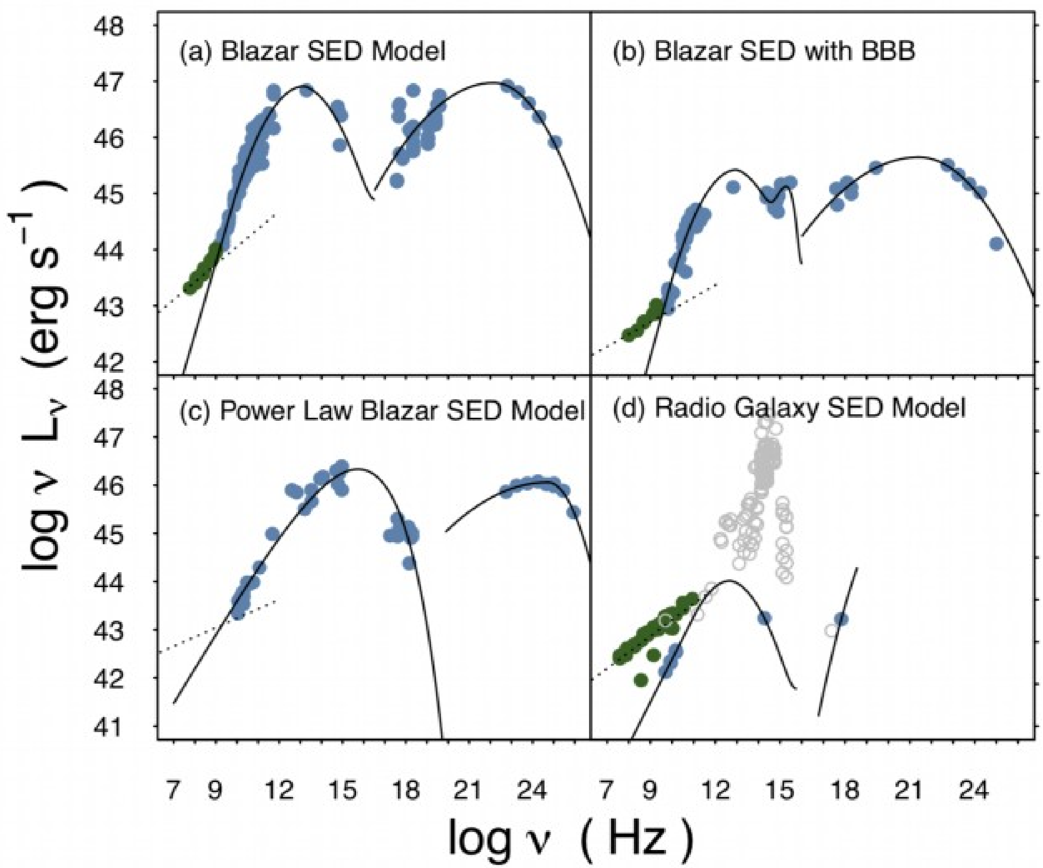
2124 sources had “good” SEDs:



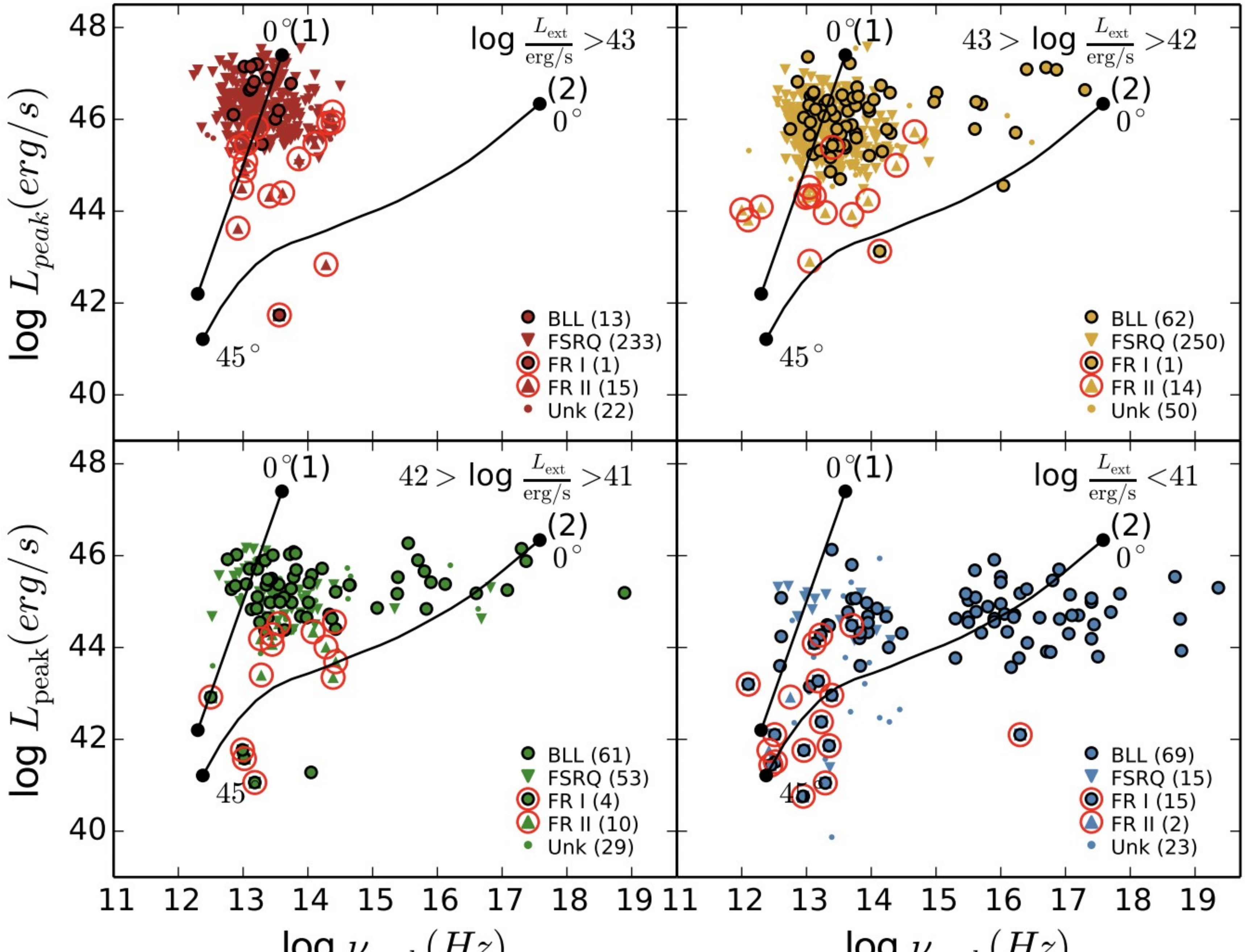


← examples of jet/lobe decompositions

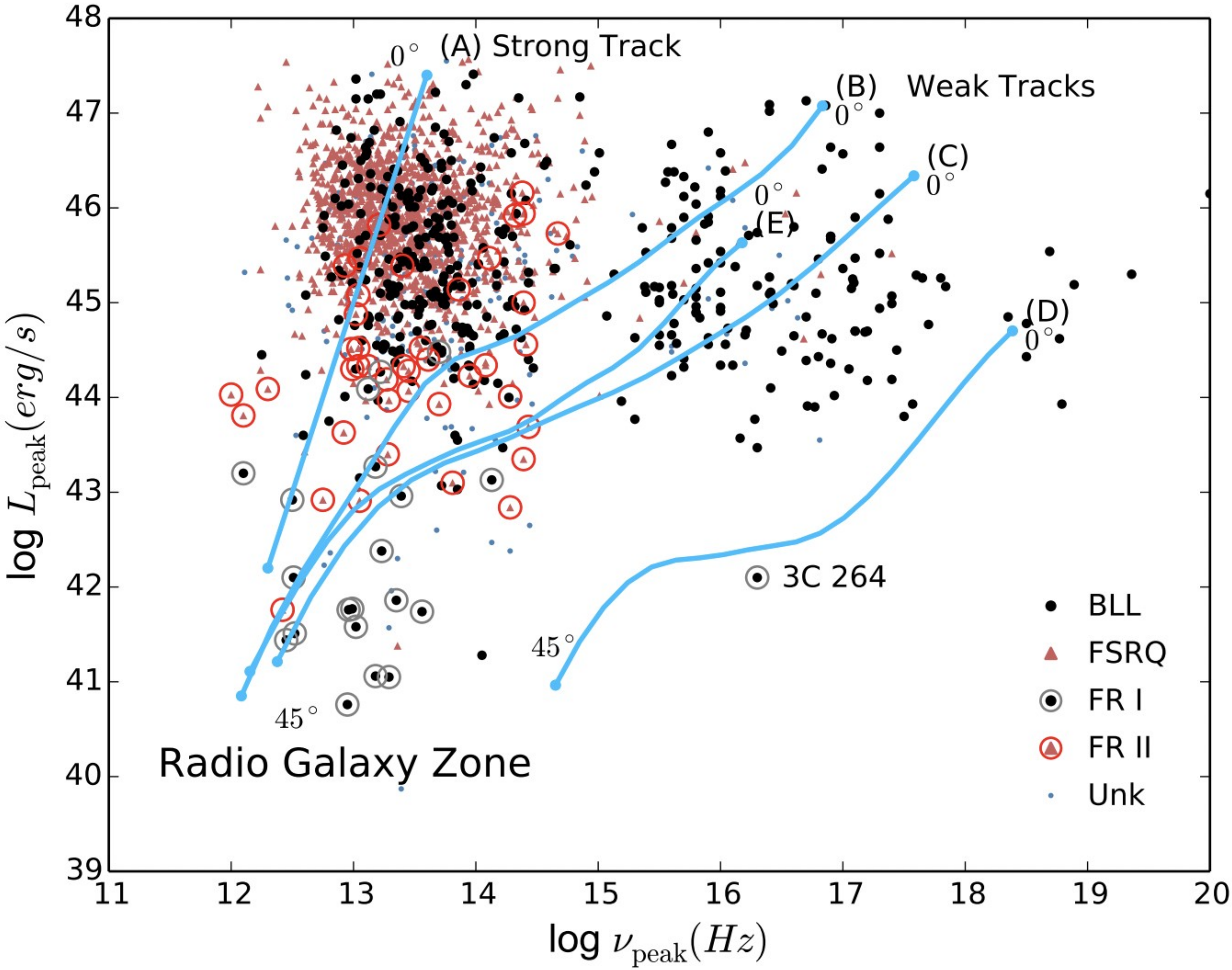
examples of SED fitting →



Results

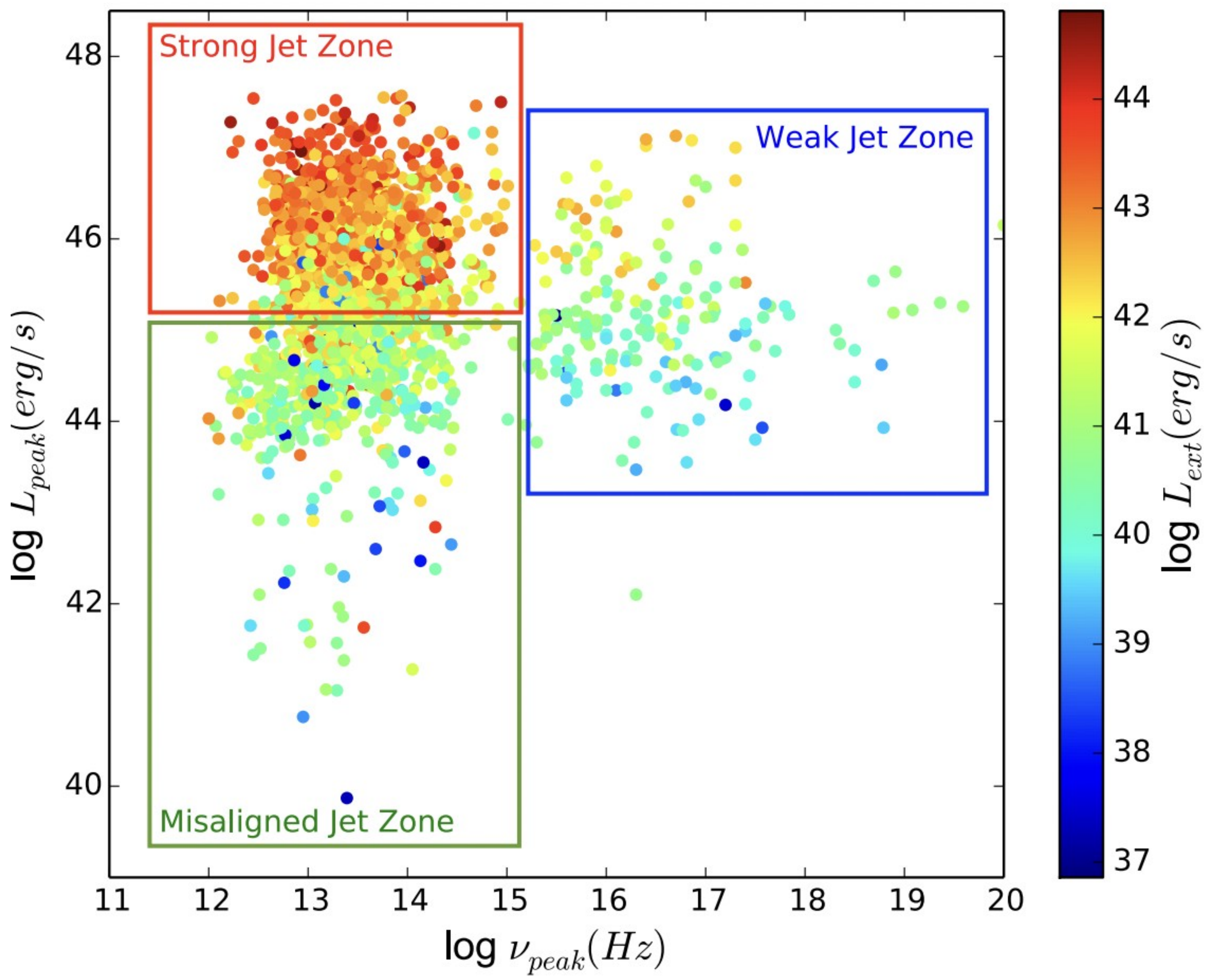


0°(1)
$\log \frac{L_{ext}}{erg/s} > 43$
(2)
0°
45°
BLL (13)
FSRQ (233)
FR I (1)
FR II (15)
Unk (22)
$43 > \log \frac{L_{ext}}{erg/s} > 42$
BLL (62)
FSRQ (250)
FR I (1)
FR II (14)
Unk (50)
$42 > \log \frac{L_{ext}}{erg/s} > 41$
BLL (61)
FSRQ (53)
FR I (4)
FR II (10)
Unk (29)
$\log \frac{L_{ext}}{erg/s} < 41$
BLL (69)
FSRQ (15)
FR I (15)
FR II (2)
Unk (23)
$\log L_{peak}(erg/s)$
$\log \nu_{peak}(Hz)$
40
42
44
46
48
11
12
13
14
15
16
17
18
19

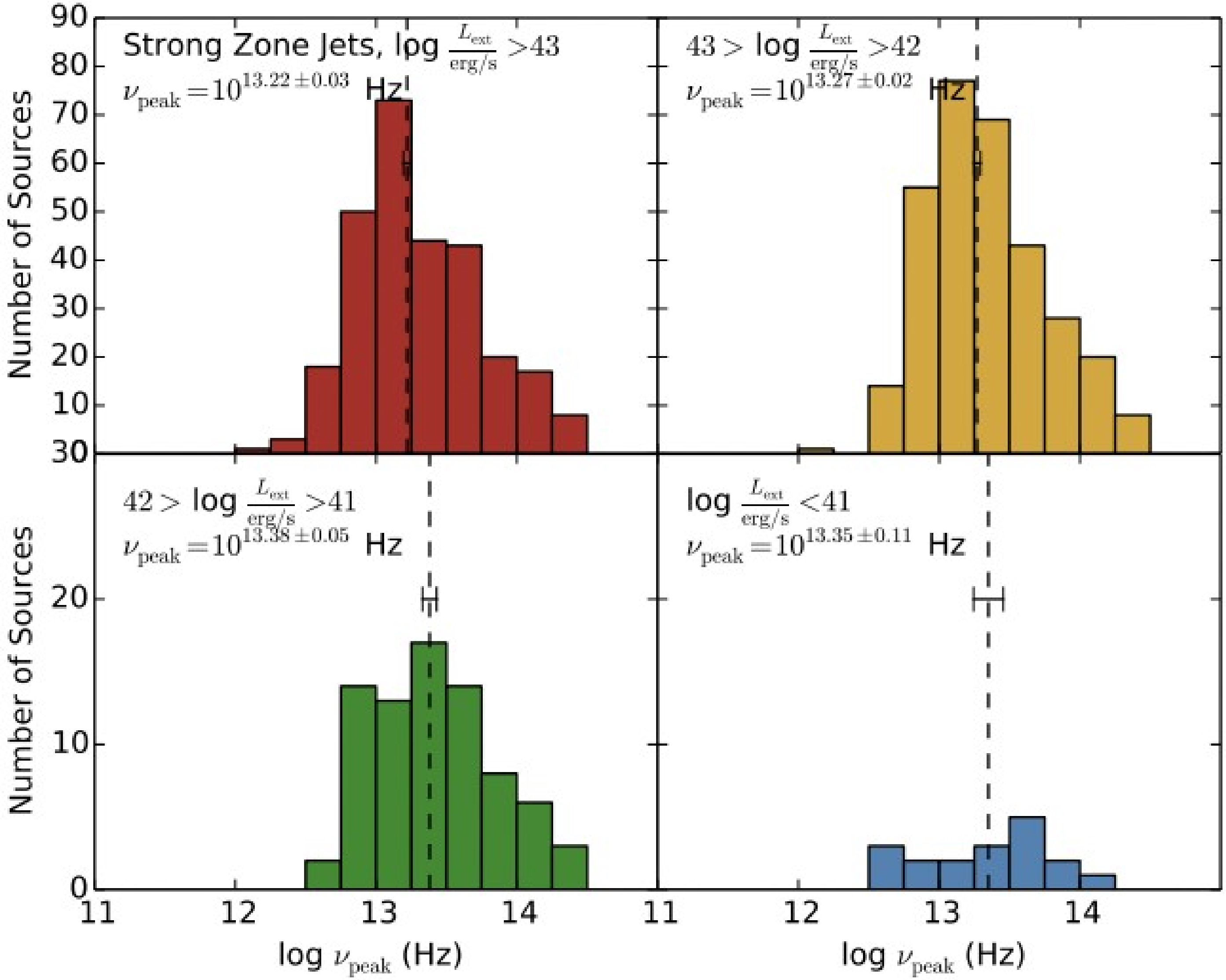


(A) Strong Track
(B) Weak Tracks
(C)
(D)
(E)
0°
45°
3C 264
Radio Galaxy Zone
BLL
FSRQ
FR I
FR II
Unk
log $L_{\rm peak}(erg/s)$
log $\nu_{\rm peak}(Hz)$

Return to a dichotomy?



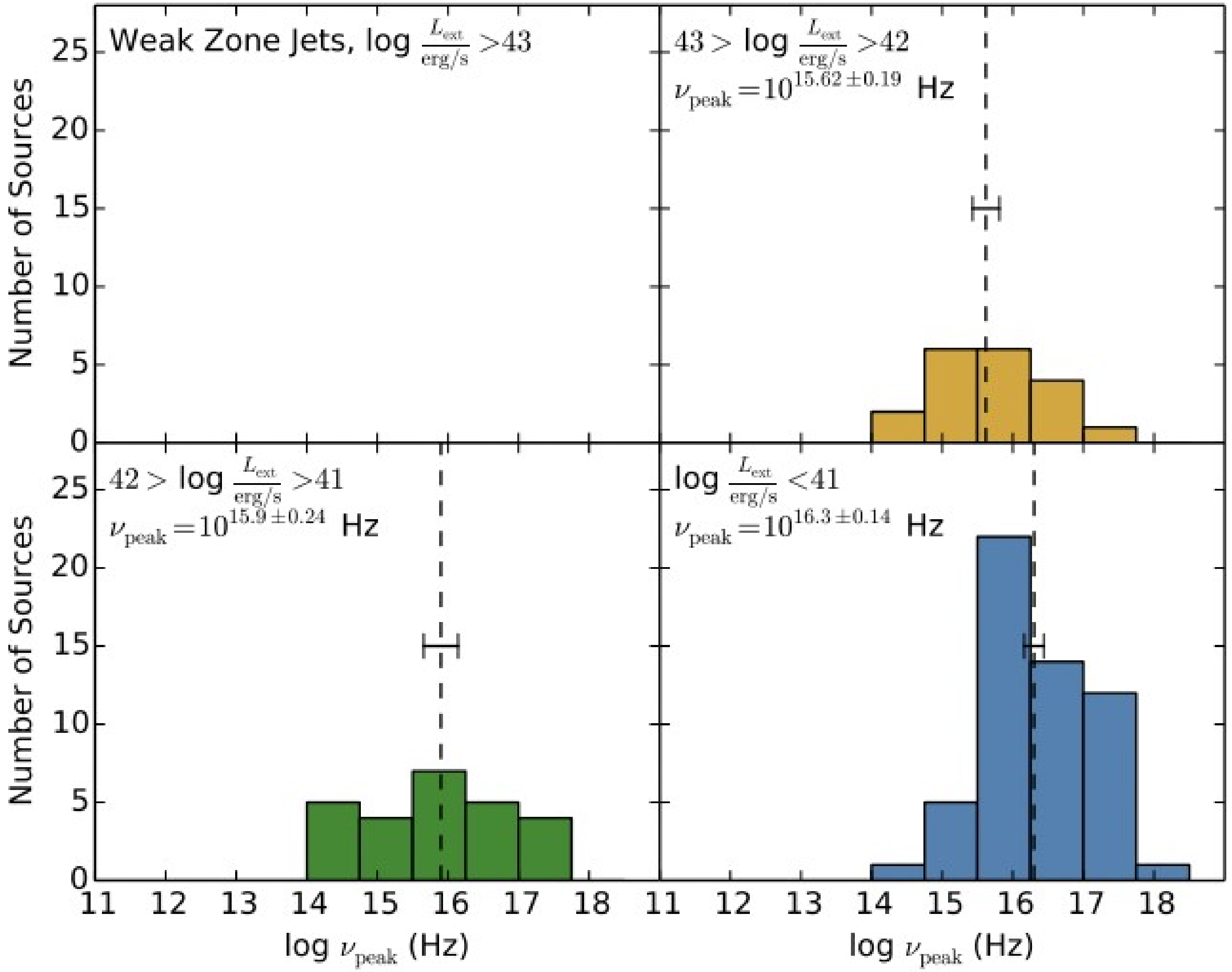
Results



No evidence of "sequence-like" behavior for type II jets

Average peak frequency does not change with jet power over >4 OOM.

Results



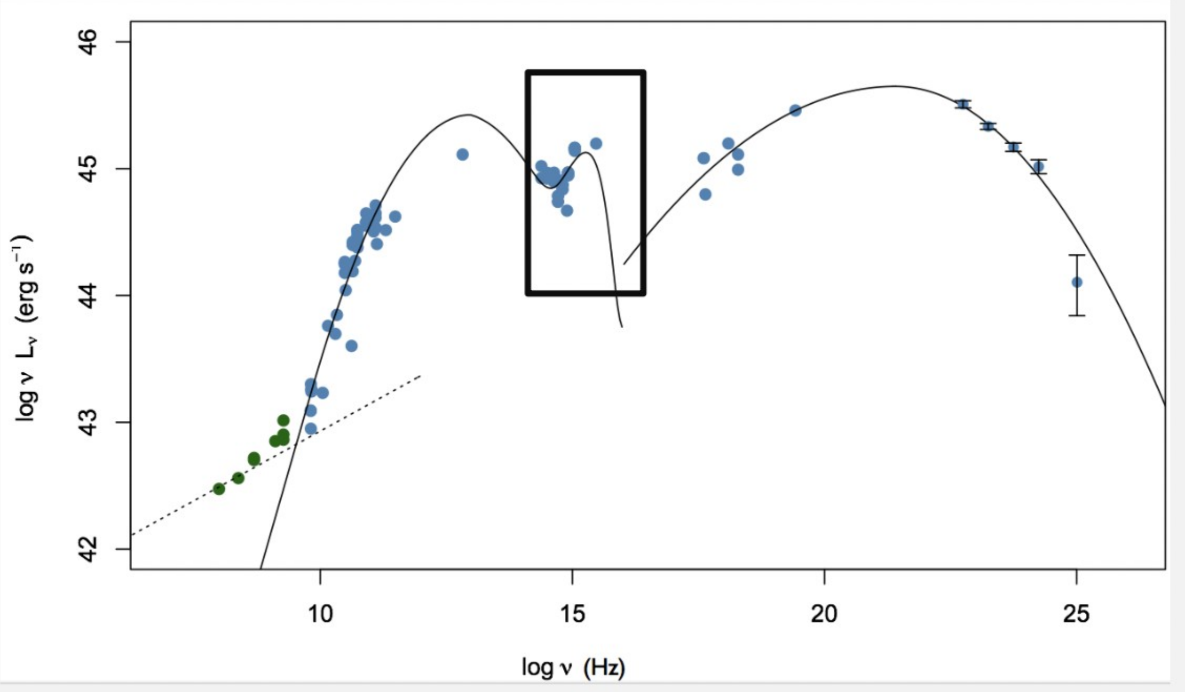
Similar findings for weak jets, though with weaker statistics

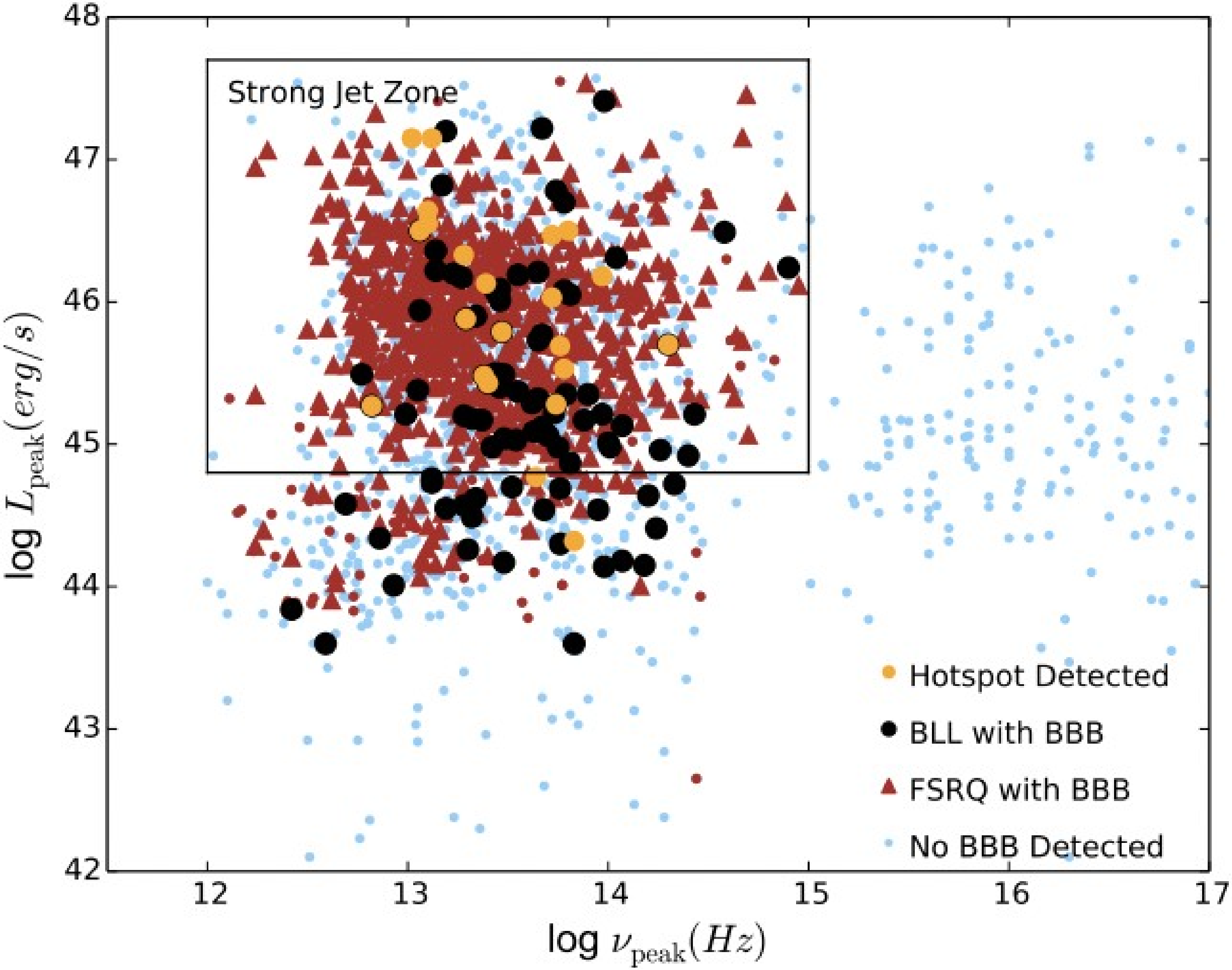
Conclusions

- ***The Blazar Sequence does not exist***
  - No monoparametric mapping between jet power and spectral type
  - Type II (FSRQ/FR II) jets exist from highest to lowest jet powers

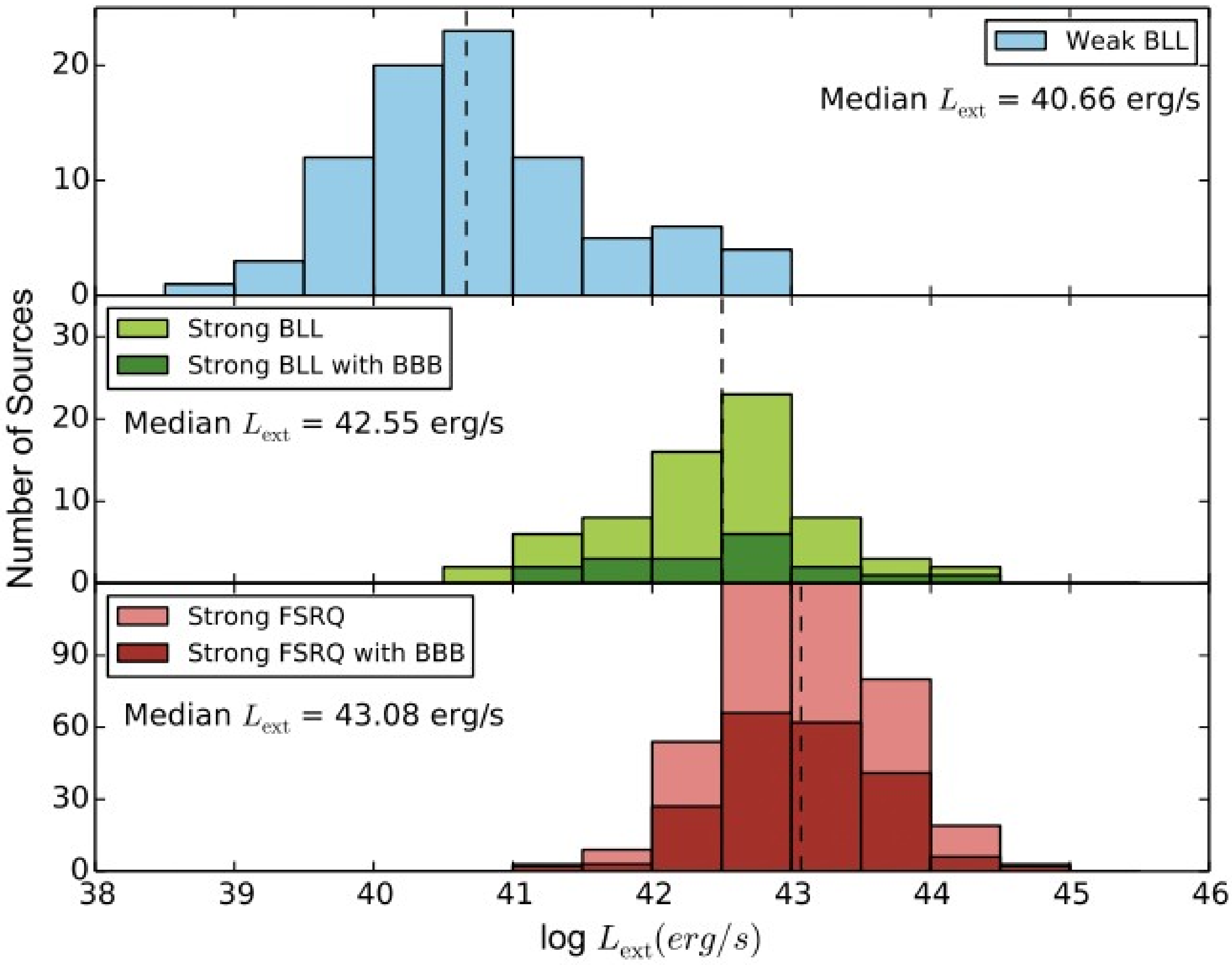
REMINDER: BIG BLUE BUMP

- The thermal emission from the accretion disk is a sign of a powerful accretion disk, thought to be characteristic of strong jets
- Can look at where these sources live in the $\nu_{peak} - L_{peak}$ plane




Strong Jet Zone
Hotspot Detected
BLL with BBB
FSRQ with BBB
No BBB Detected
log $L_{\rm peak}(erg/s)$
log $\nu_{\rm peak}(Hz)$
48
47
46
45
44
43
42
12
13
14
15
16
17

Jet Power in Different Zones

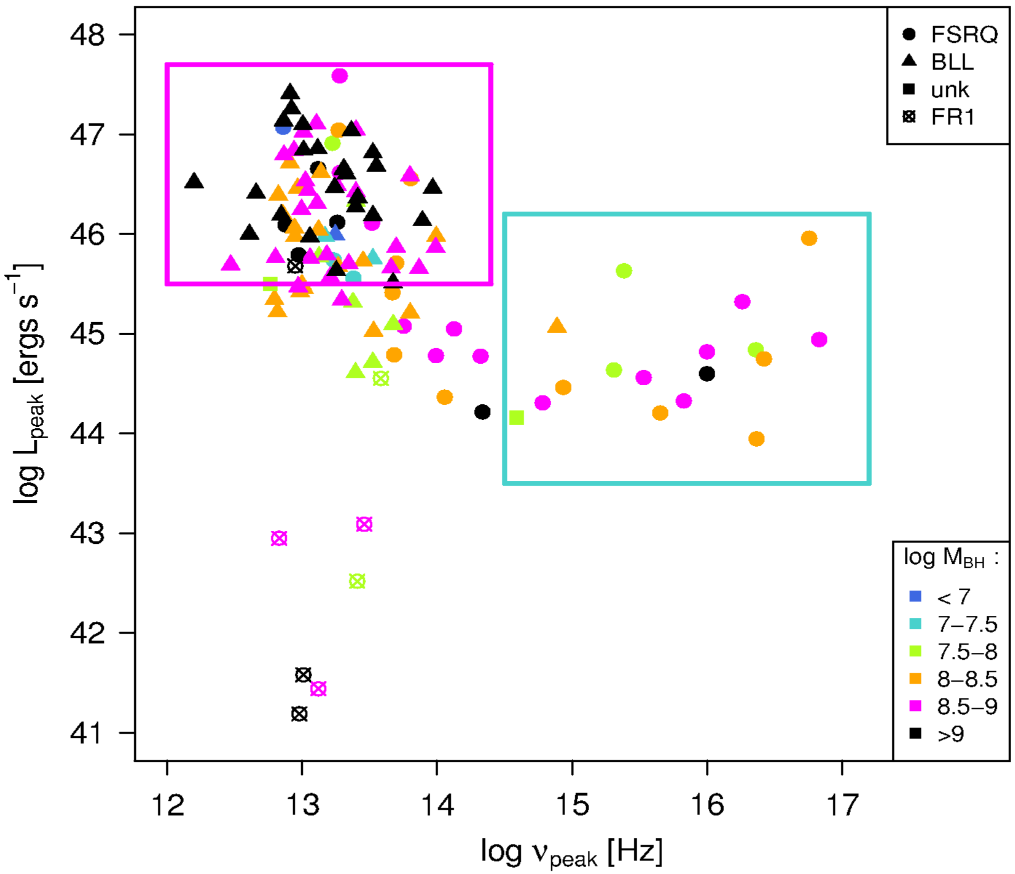


BL lacs in the "strong jet" zone are much more like FSRQs in power

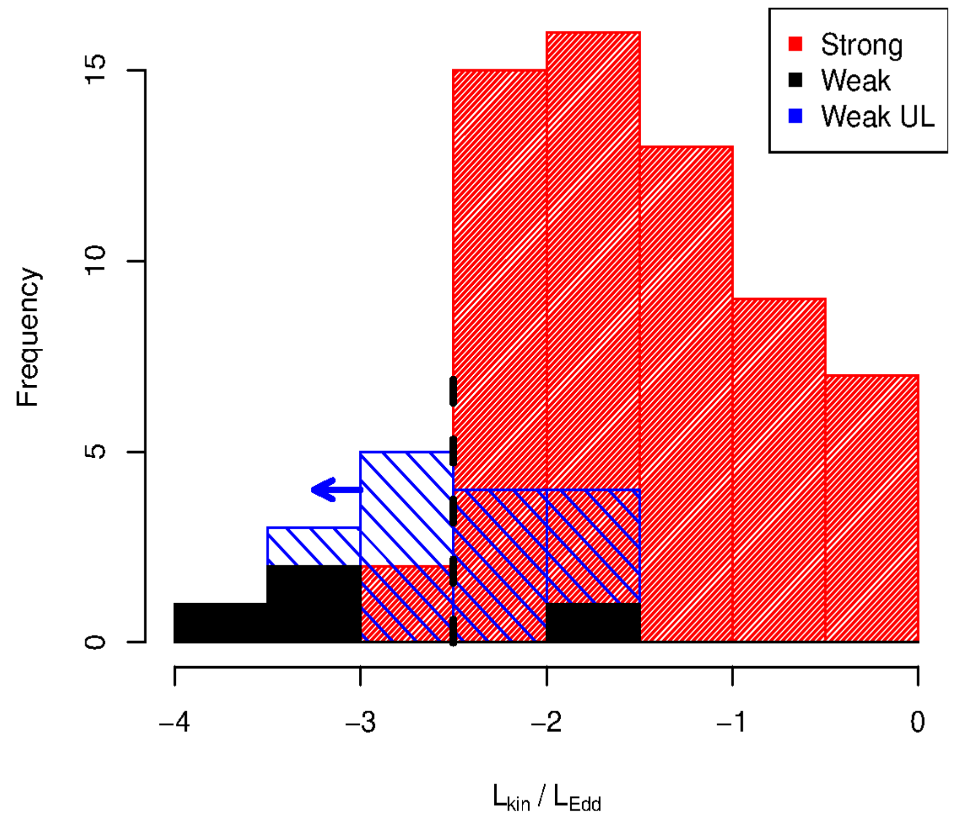
Conclusions

- ***The Blazar Sequence does not exist***
  - No monoparametric mapping between jet power and spectral type
  - Type II (FSRQ/FR II) jets exist from highest to lowest jet powers
- ***Not all BL Lacs are equal***
  - LBLs (low-peaking, vp < 1015 Hz) are mostly type II jets

Meyer 2011: Eddington Ratio



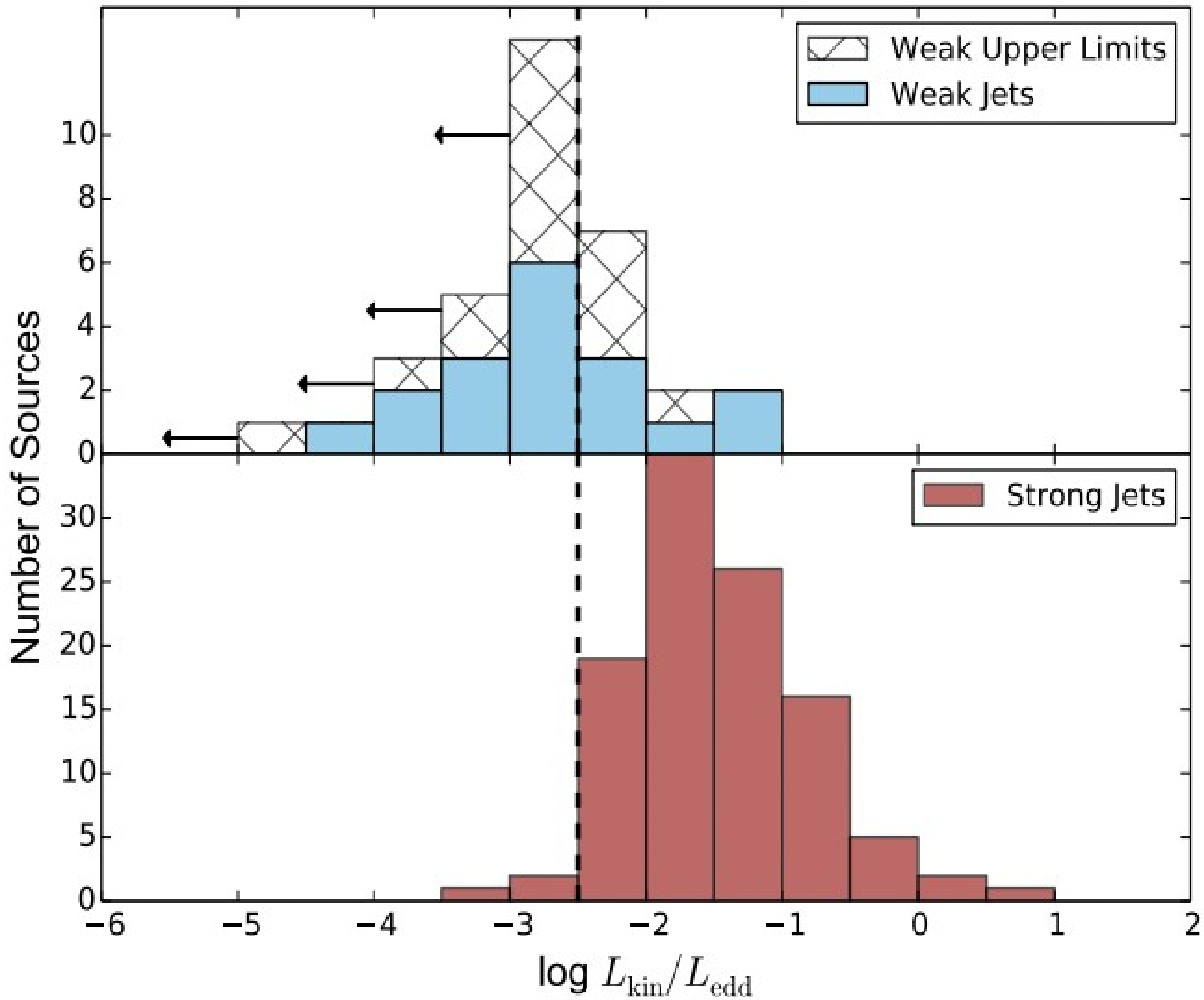
(Mass estimates from reverberation mapping, velocity dispersions, mass-luminosity scalings)



Weak Jets = Inefficient

Strong Jets = Efficient

Keenan 2021: Eddington Ratio



Separation of strong/weak based on location in v_p-L_p plane

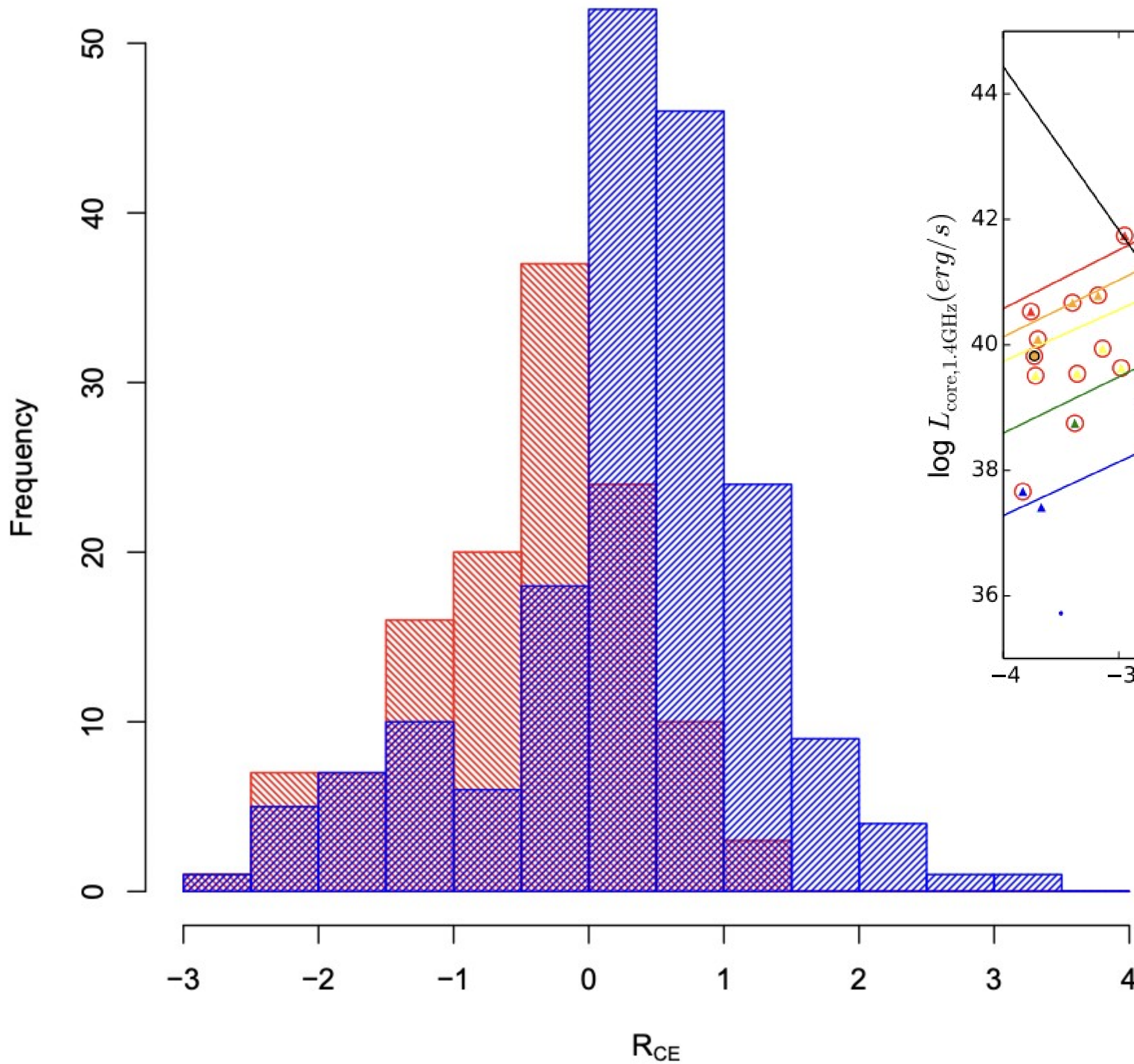
Eddington fraction estimated from radio lobe power (L_{kin}) in comparison to the Eddington limit implied by black hole mass, where known.

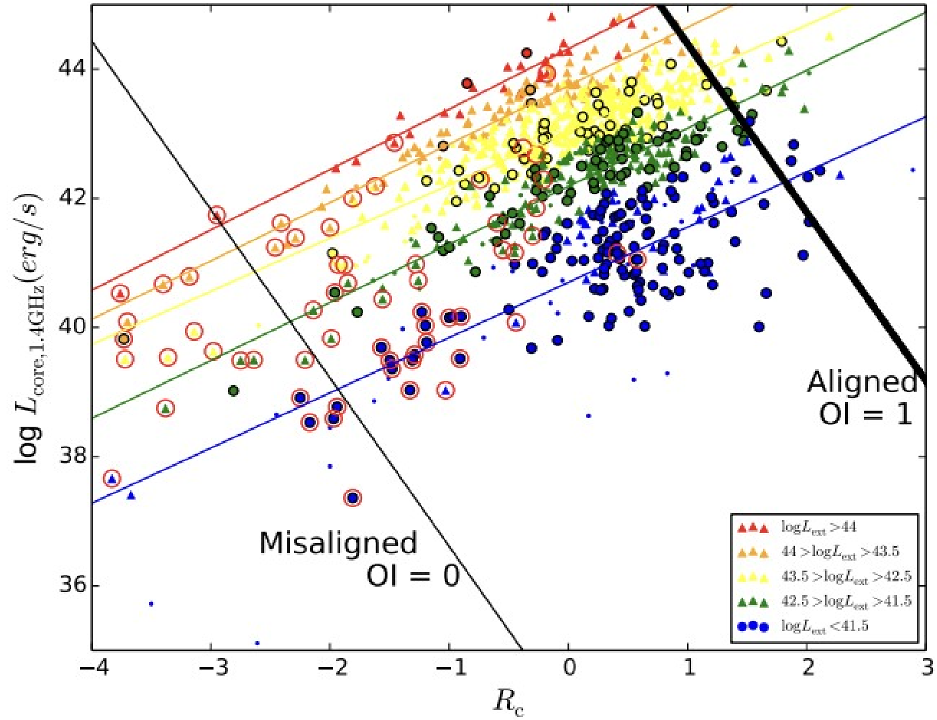
Clear divide at $\log(L_{kin}/L_{edd}) = -2.5$

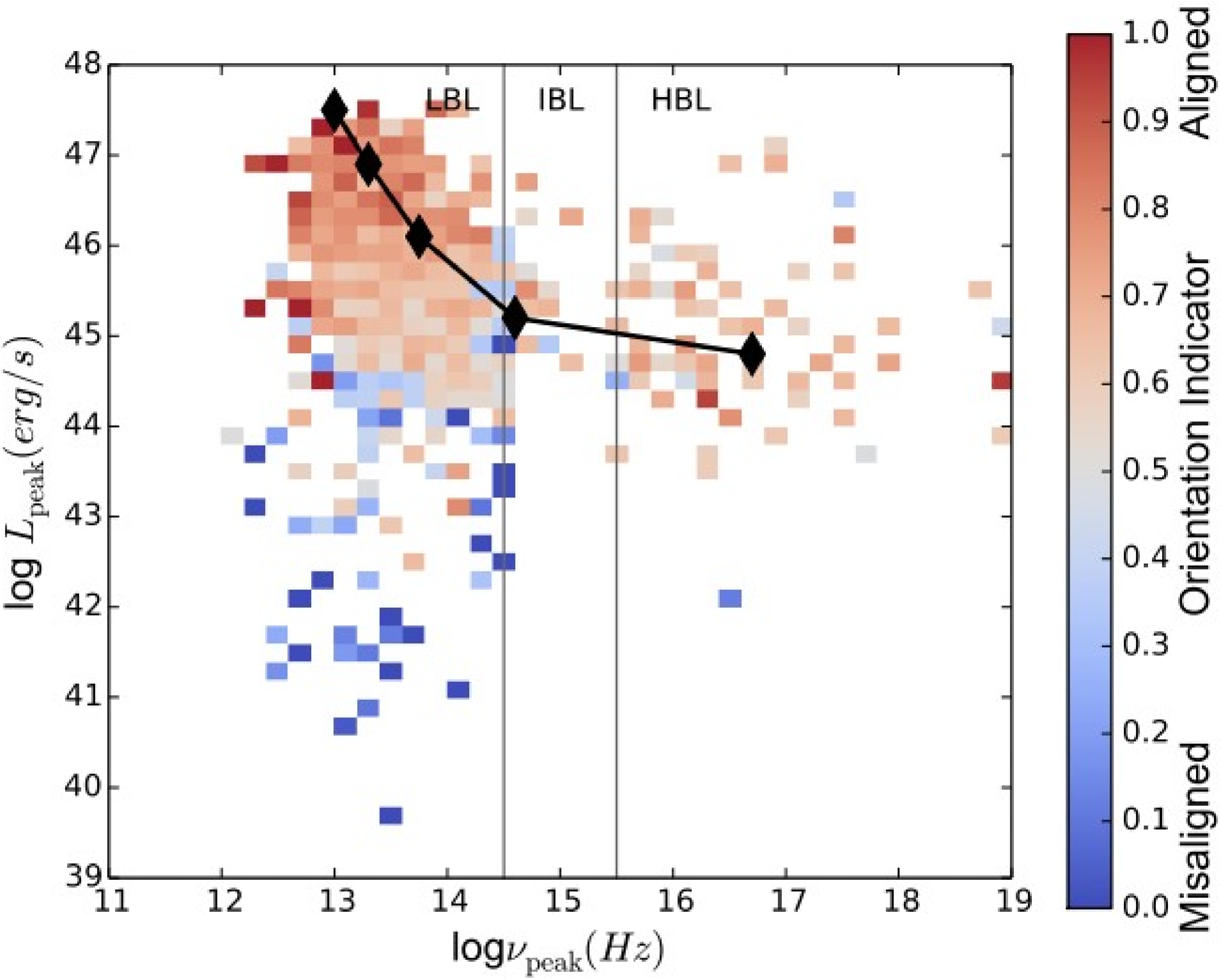
Conclusions/Observations

- ***The Blazar Sequence does not exist***
  - No monoparametric mapping between jet power and spectral type
  - Type II (FSRQ/FR II) jets exist from highest to lowest jet powers
- ***Not all BL Lacs are equal***
  - LBLs (low-peaking, $\nu_p < 10^{15}$ Hz) are mostly type II jets
- ***There is a Jet Dichotomy which is apparent in the ν_p-L_p plane***
  - Strong/type-II jets have high-efficiency accretion
  - Strong/type-II jets are not "allowed" to have $\nu_p > 10^{15}$ Hz
  - Weak/type-I jets are inefficient accretors, matching spectral type
  - Weak/type-I jets have higher ν_p
  - Weak/type-I jets have a maximum power of 10^{43} erg/s

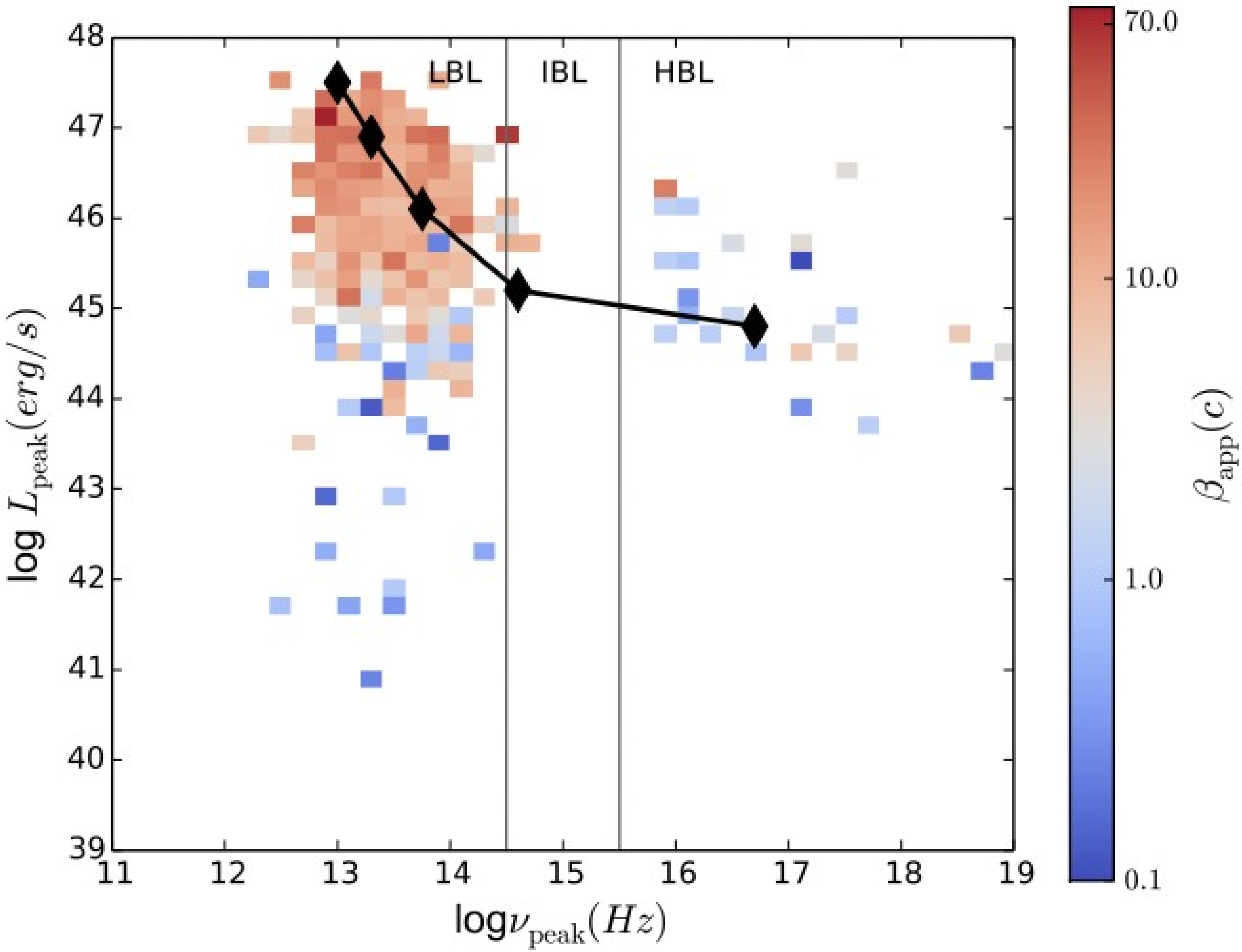
Radio Core Dominance is not Universal







LBL
IBL
HBL
log $L_{\mathrm{peak}}(erg/s)$
log$\nu_{\mathrm{peak}}(Hz)$
48
47
46
45
44
43
42
41
40
39
11
12
13
14
15
16
17
18
19
Aligned
Orientation Indicator
Misaligned
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0



IBL population remains poorly understood

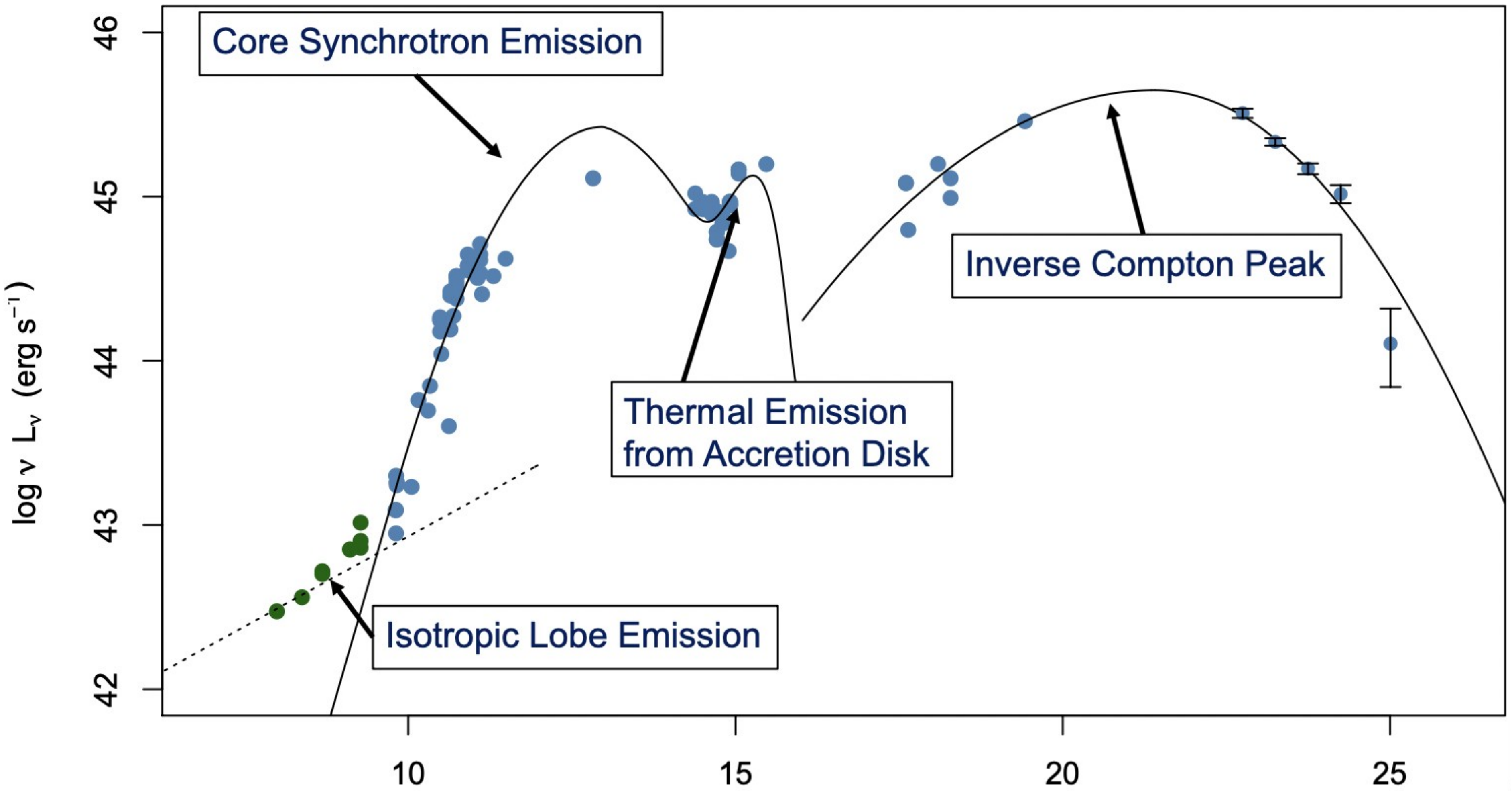
We need more VLBI speed studies of weak jets

Future work/what remains

- While the ν_p divide at 10^{15} Hz seems clear, not apparent what makes the difference between a source at 10^{16} Hz and 10^{19} Hz.
- Other types of jets/more LL AGN need to be studied (especially misaligned jets)
- Some regions of the ν_p-L_p plane are still poorly populated (IBLs are rare).
- Statistically Complete Samples?

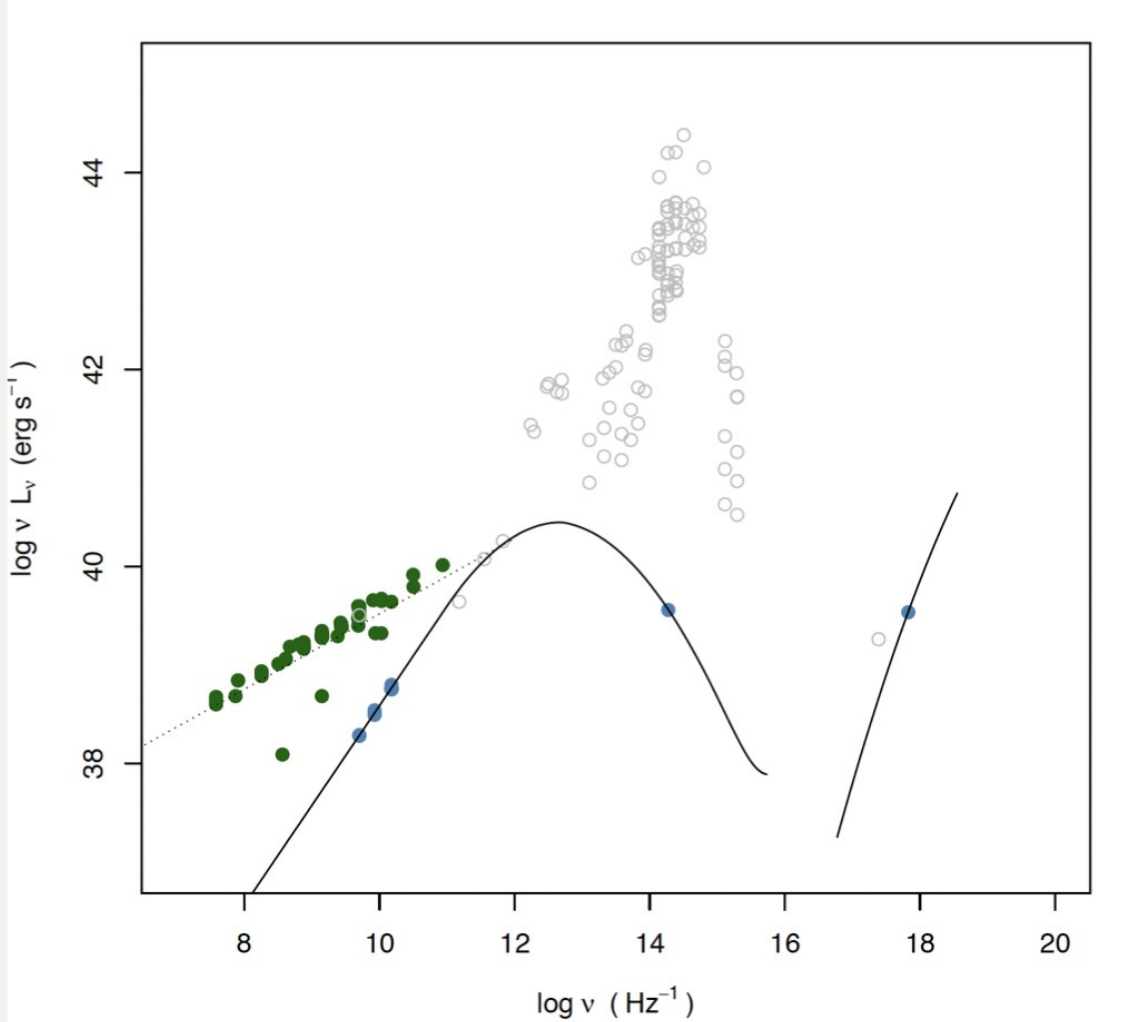
Thank you!

Blazars: Looking down the throat of a jet



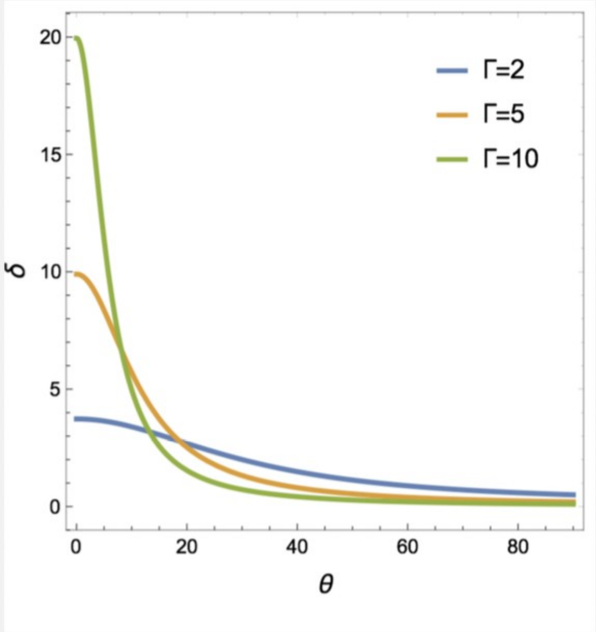
RADIO GALAXY SED

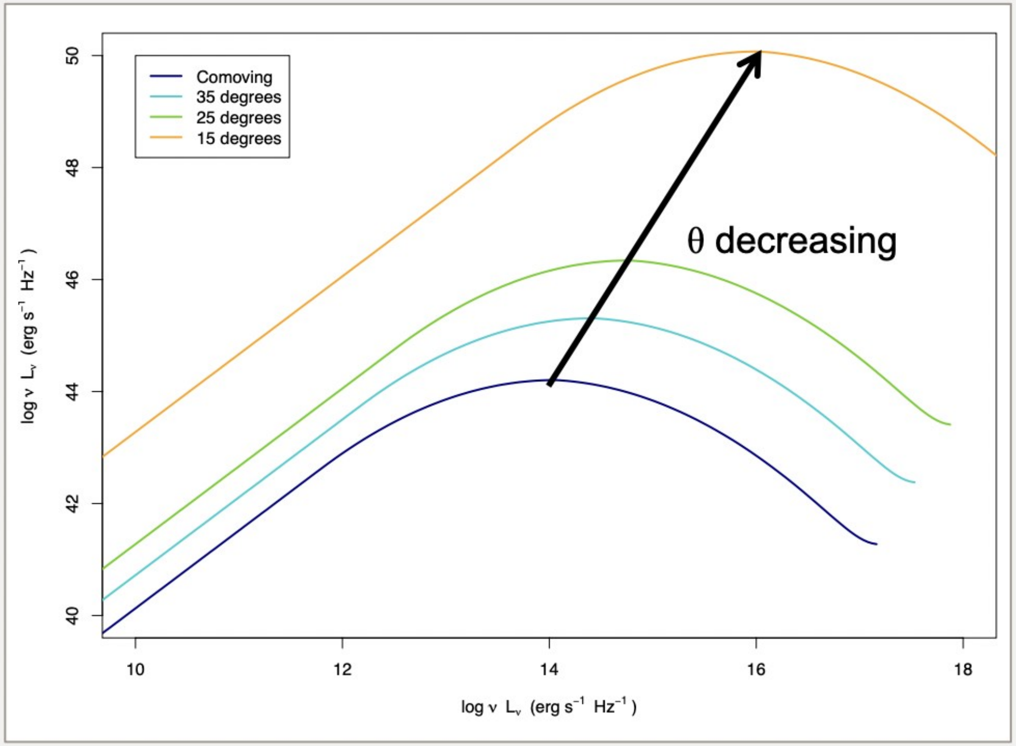
- Extended Emission (green) now dominates over the de-beamed core emission (blue)
- Open gray circles are dominated by non-jet sources



DOPPLER BOOSTING

When the plasma is relativistic, the Apparent Luminosity/Frequency is dependent on θ, Γ





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

$$L_{observed} = L_{intrinsic}\, \delta^{3+\alpha}$$

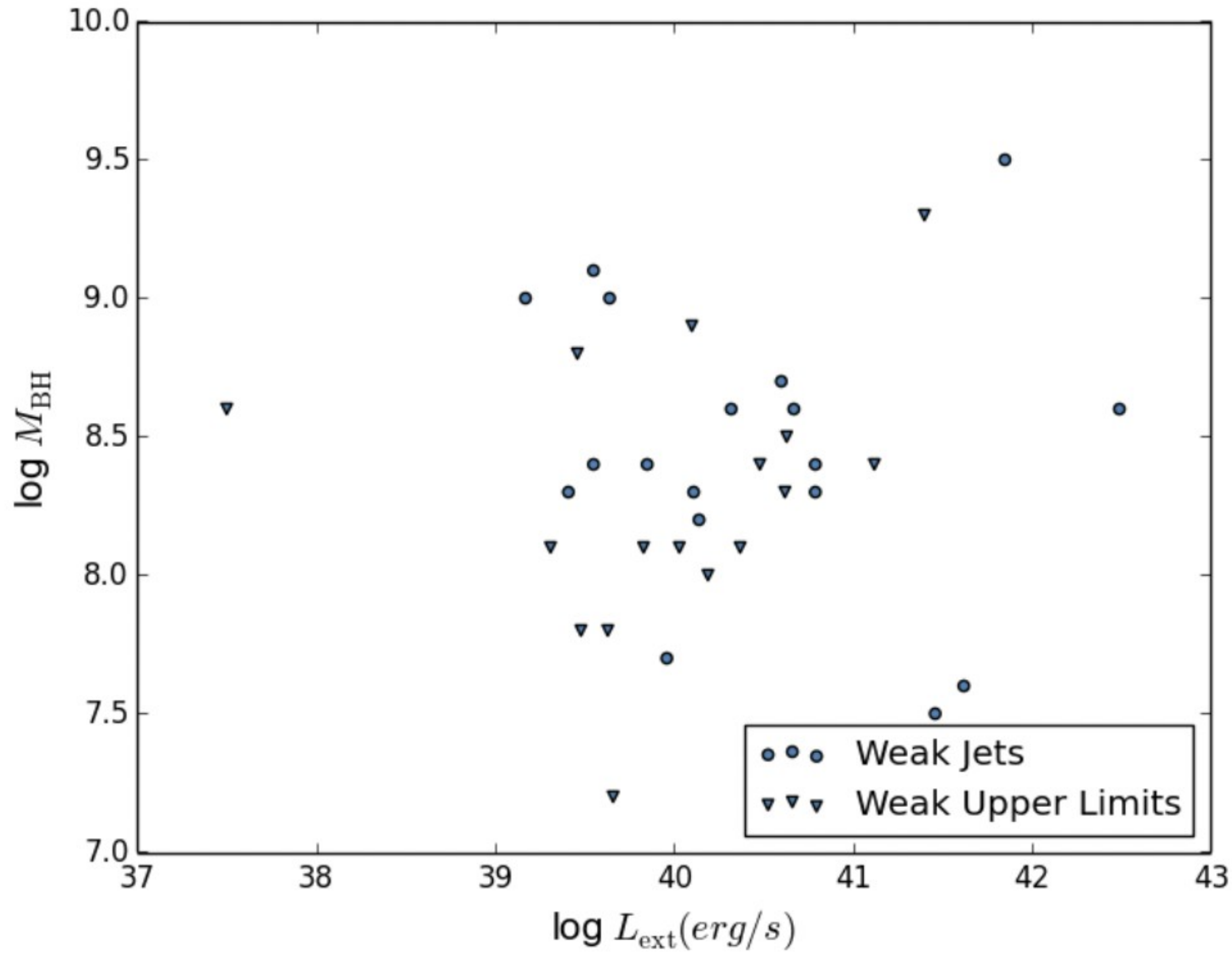
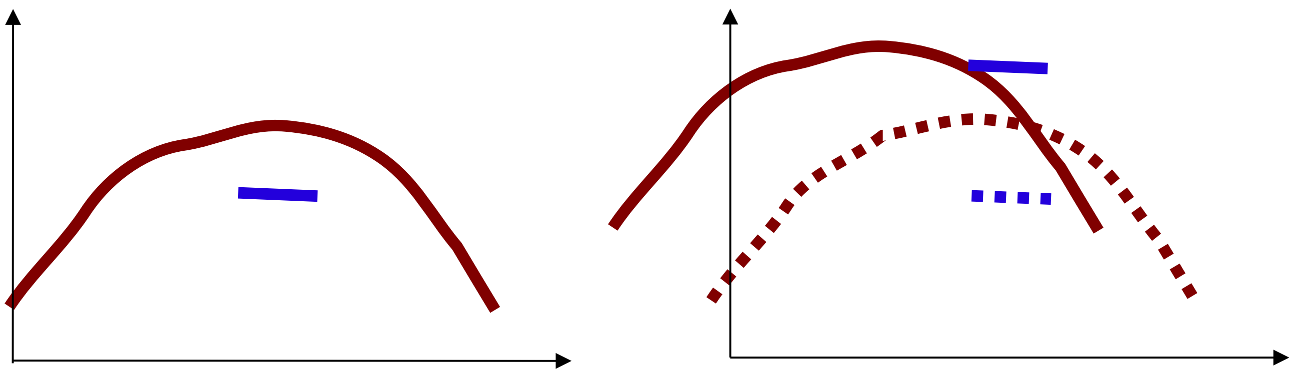


Figure B6. A plot of $M_{\rm BH}$ versus $L_{\rm ext}$ for weak jets.

What if we can’t see the emission lines?



= Doppler-boosted jet

= emission lines

Increasing L_{kin} → Line & Jet Luminosity Increases

→ Cooling Increases, v_p shifts out of optical