AGN1

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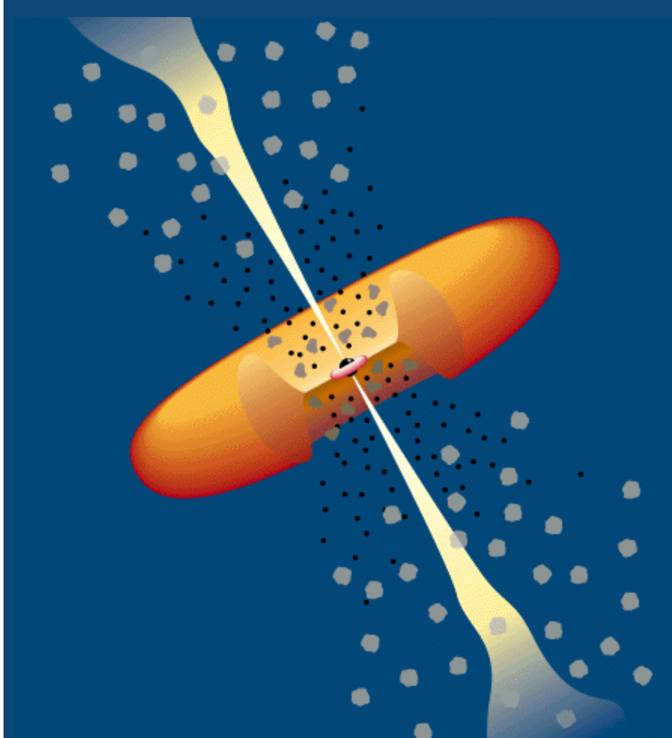
AGN1: Introduction

AGN Unification, radio galaxies, radio loudness, jets, blazars

Topics for AGN Part I

- Introduction to AGN
  - Unification ingredients: BH, disk, BLR, NLR, torus/obscuration, jets
  - Radio-loud v. radio-quiet
  - Blazars as beamed radio galaxies
- Multiwavelength emission from blazars
  - Relativistic beaming
  - Parent population (radio galaxies) and the effect of beaming on luminosity functions
  - Time variability (& polarization?)
  - Spectral energy distributions and the Fossati scheme



AGN ingredients:

Black hole

Accretion disk

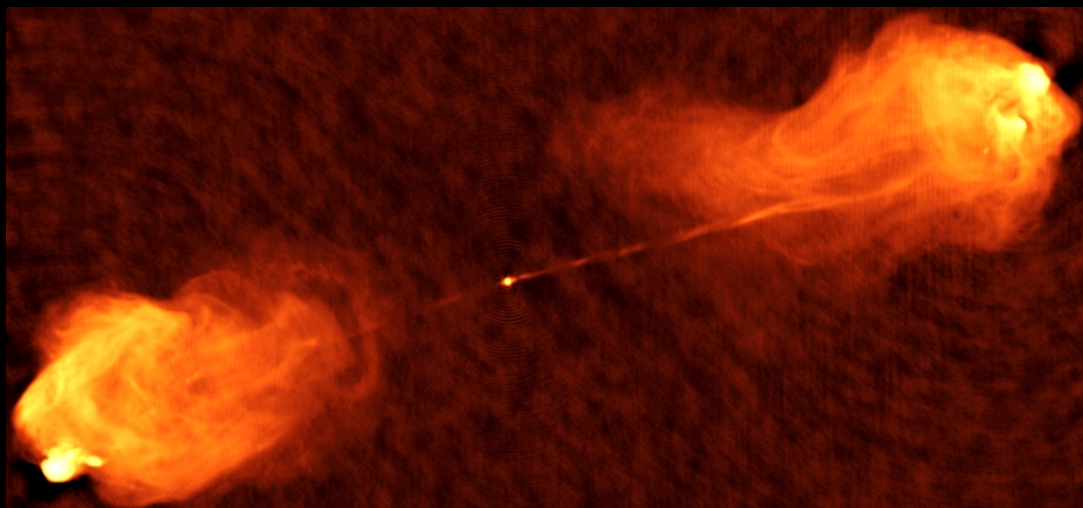
Broad & narrow emission line clouds

Ionized plasma

Obscuring torus (or warped disk)

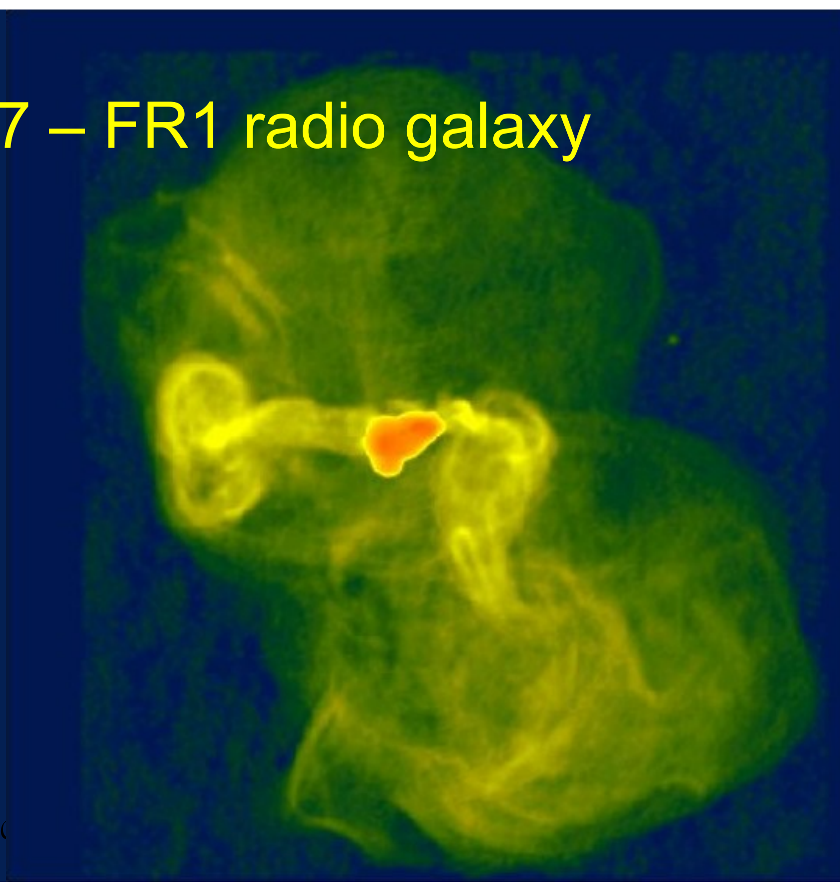
Jets (optional?)

Cygnus A – FR2 radio galaxy



Carilli et al.

M87 – FR1 radio galaxy



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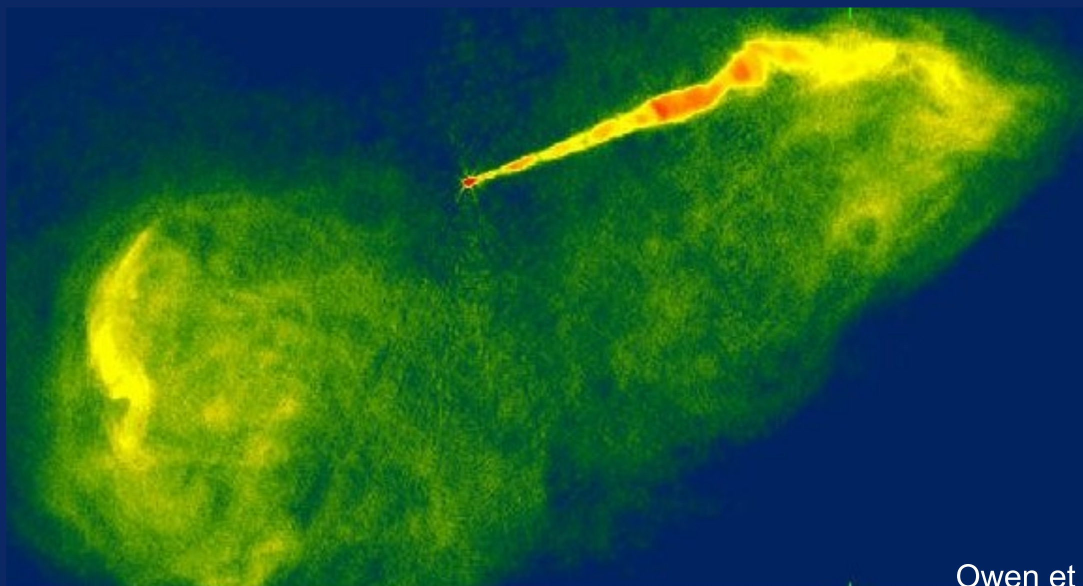
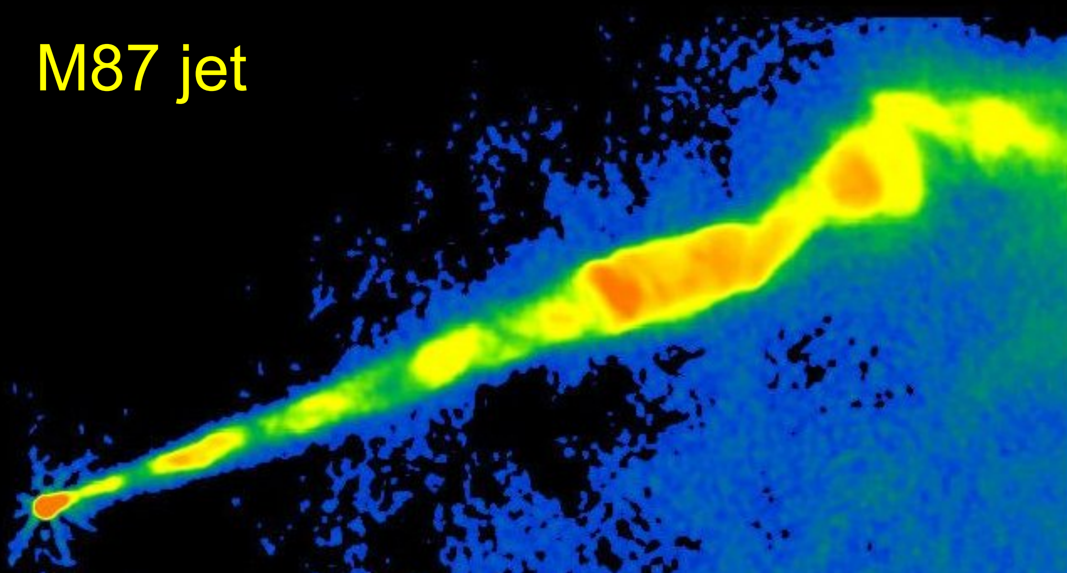
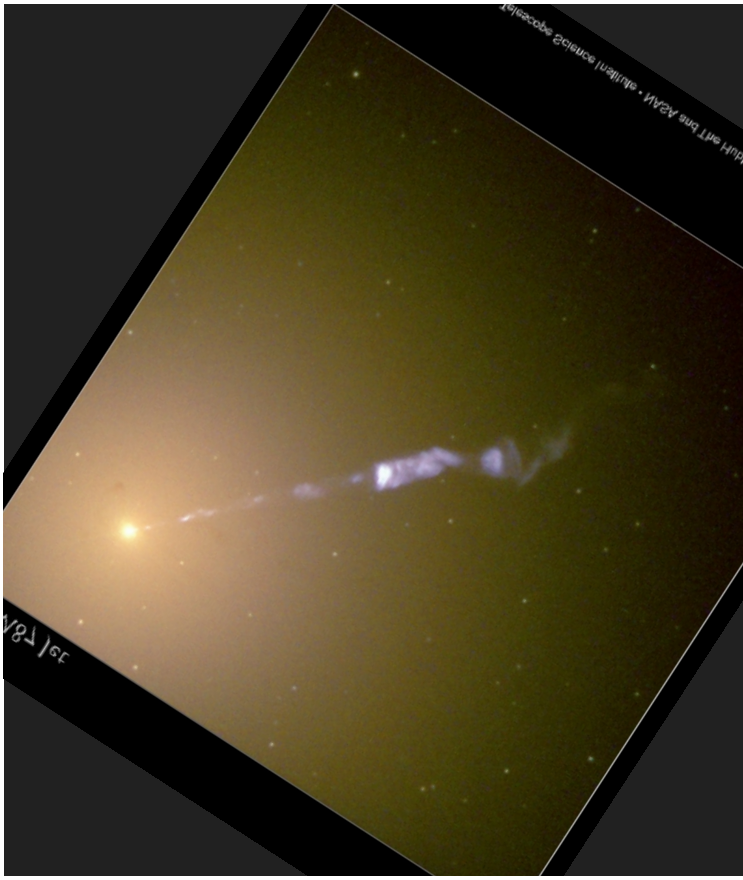


Owen et al.

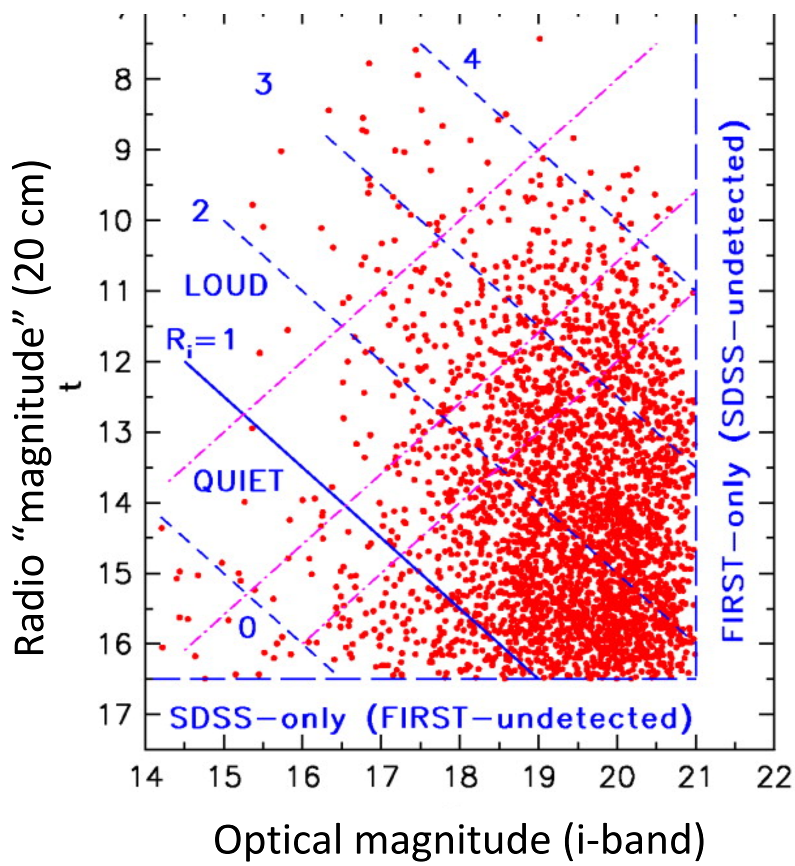
M87 jet





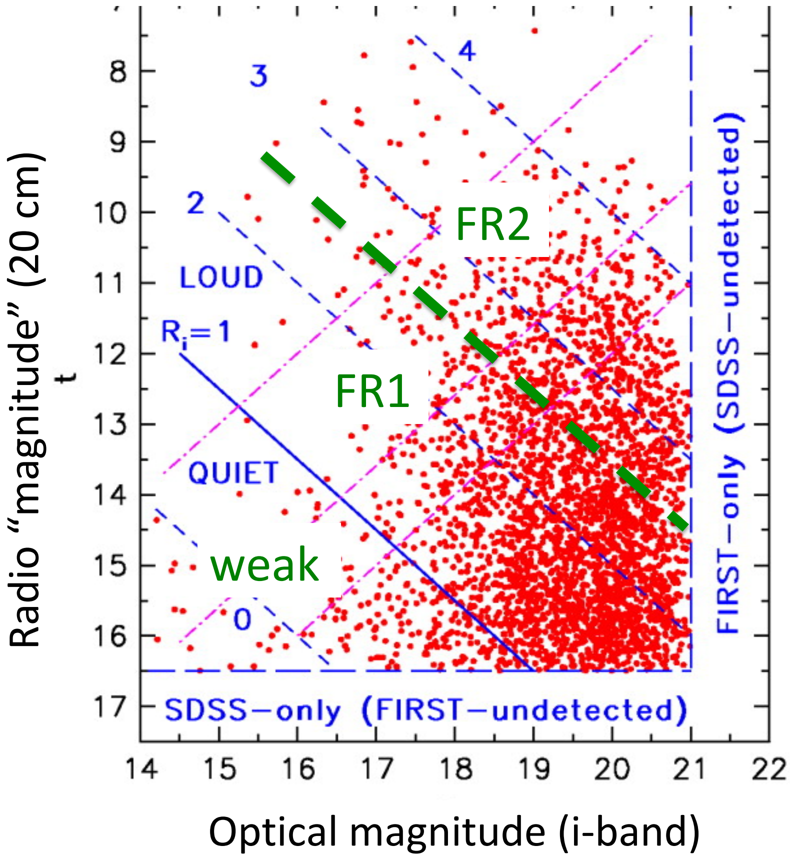
Why do active galaxies have jets (or not)?

Radio-loud v. radio-quiet

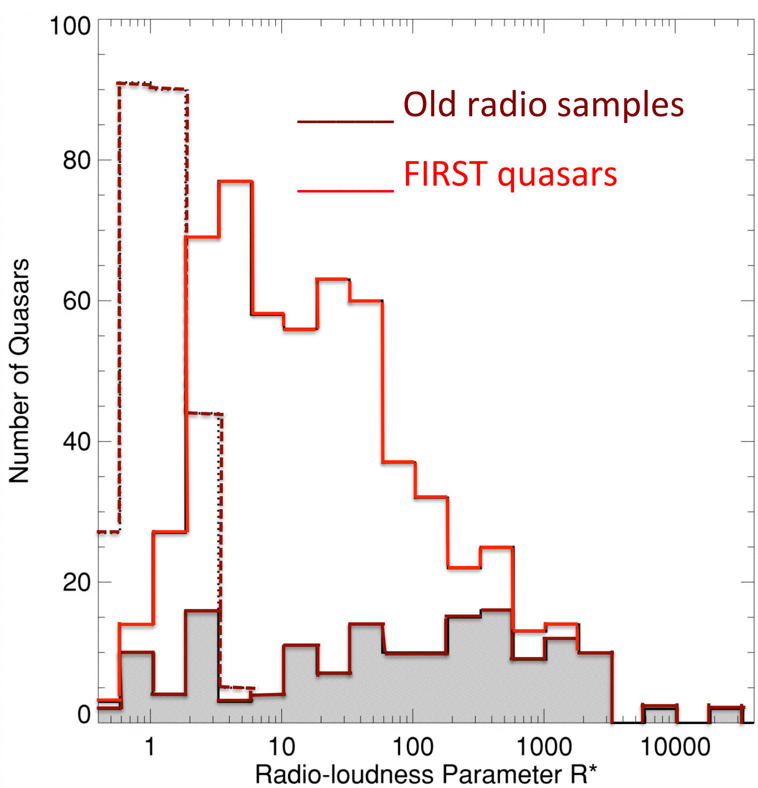


Ivezić et al. 2004

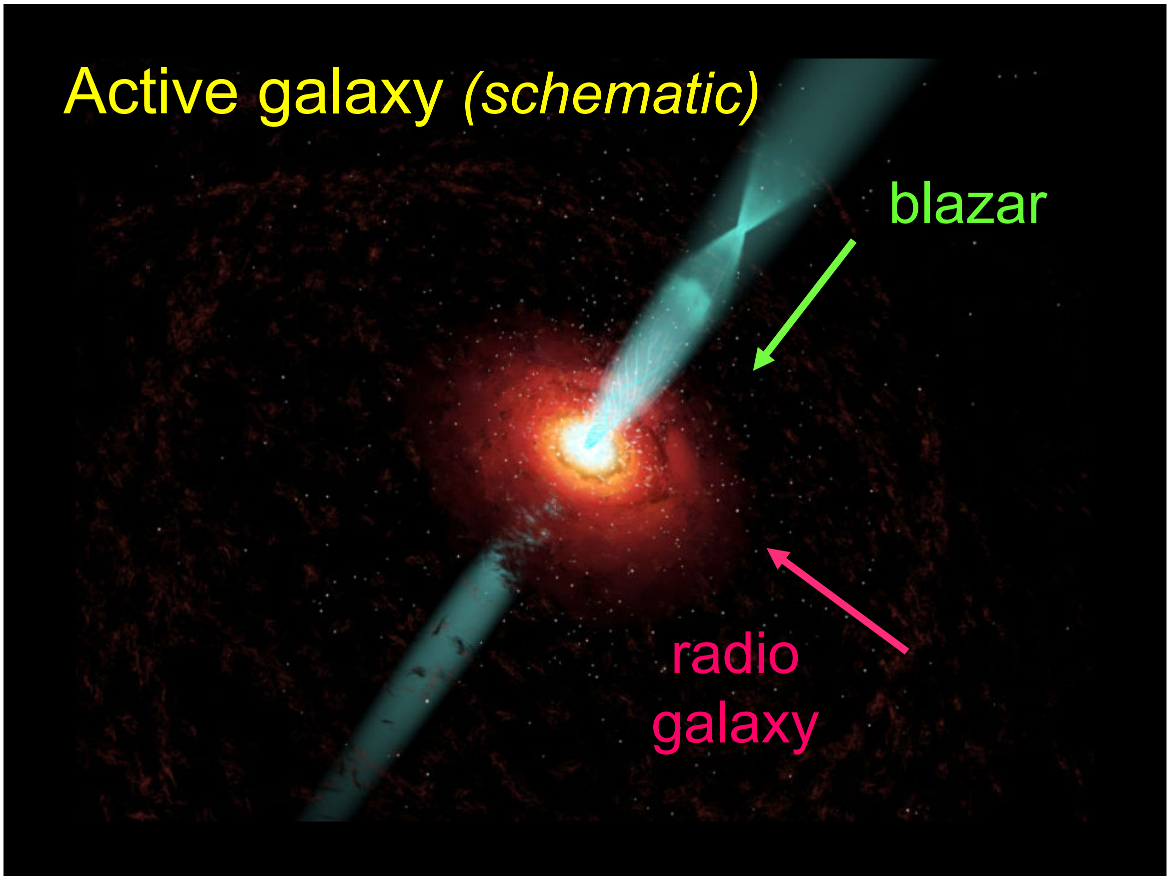
Radio-loud v. radio-quiet

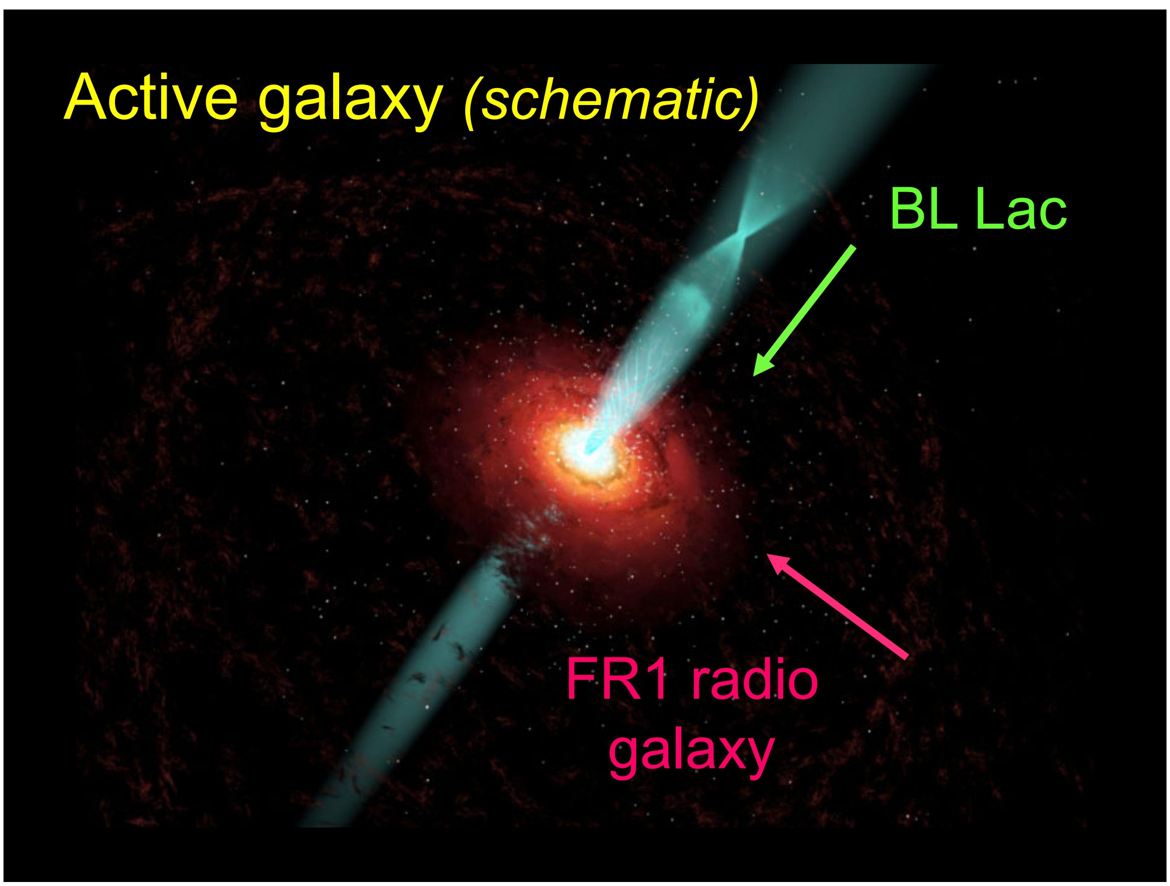


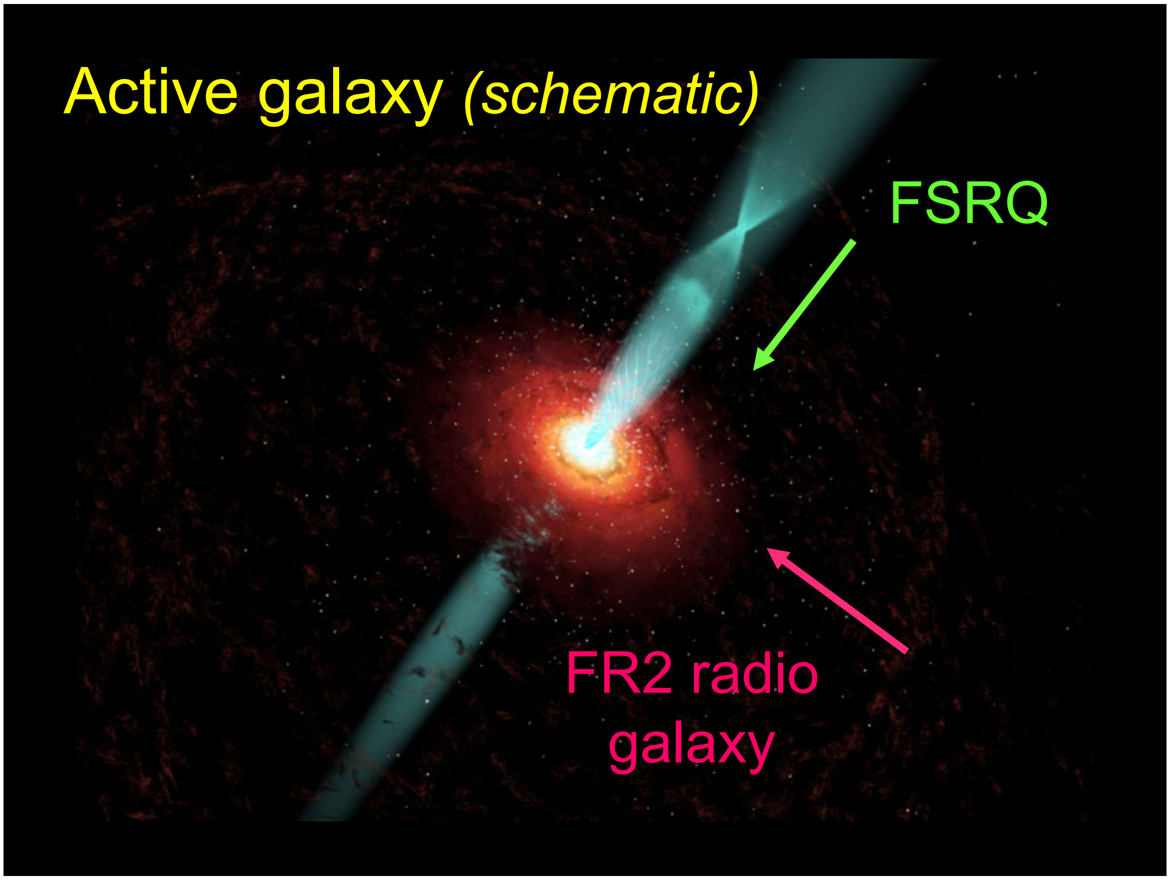
Ivezić et al. 2004



Maybe all AGN make jets


Active galaxy (schematic)
blazar
radio
galaxy


Active galaxy (schematic)
BL Lac
FR1 radio
galaxy



“Relativistic” Jets

- Seen in some *active galaxies* or *quasars* (*galaxies with fast-growing supermassive black holes*)
- Jets form near black hole
- Inner jets are *relativistic* (*jet material flows outward at nearly the speed of light*)
- Relativistic speeds to kpc scales
- Implies huge kinetic energy
- Clues from *blazars*

AGN1: Blazars & Relativistic Beaming

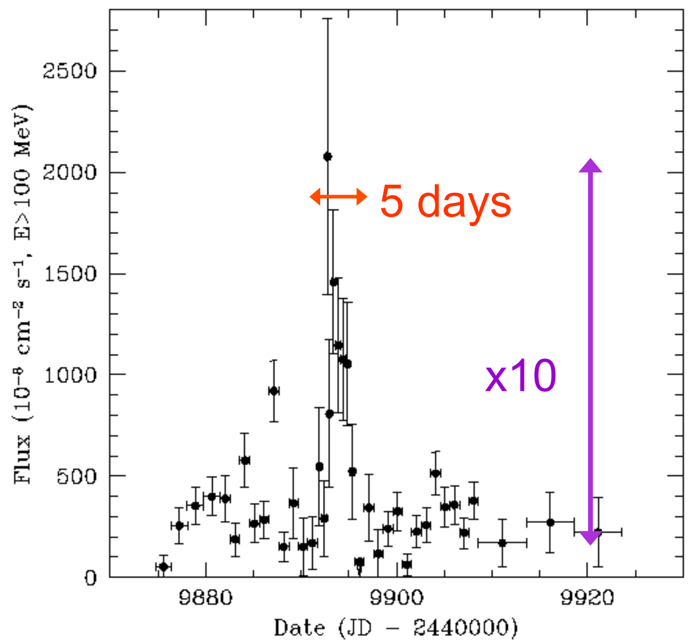
Special relativity, superluminal motion, Doppler factor, beaming

Blazars are extreme quasars

- Optically point-like (like a star)
- Rapidly variable

  ➡ must be compact
- Superluminal (*faster than light*)
- Very luminous!

Rapid Variability (gamma rays)



Mattox et al.

… implies blazars are compact

If much brighter in 1 day,

must be <1 light-day across.

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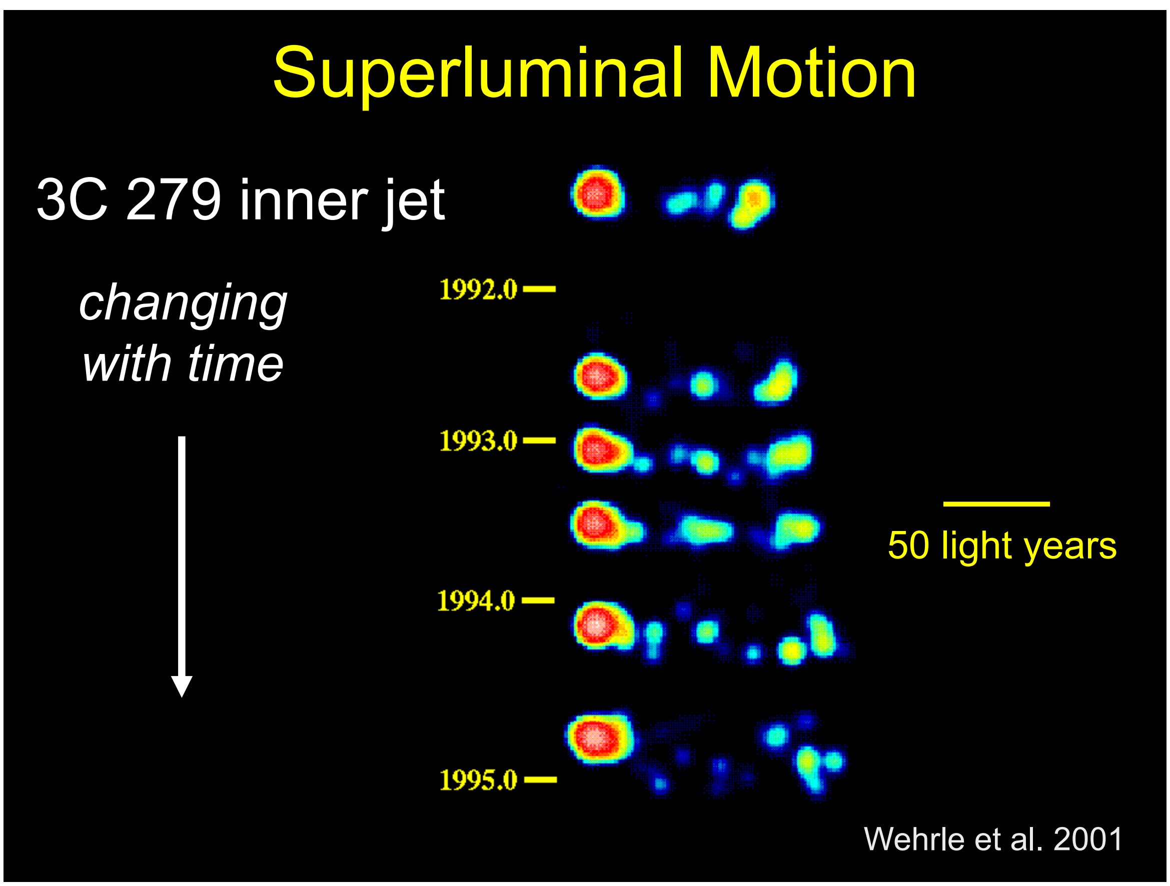

Blazars are extreme quasars

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Special Relativity

Finite speed of light

+ relativistic outflows in jets $\Rightarrow$

– Appearance of superluminal motion

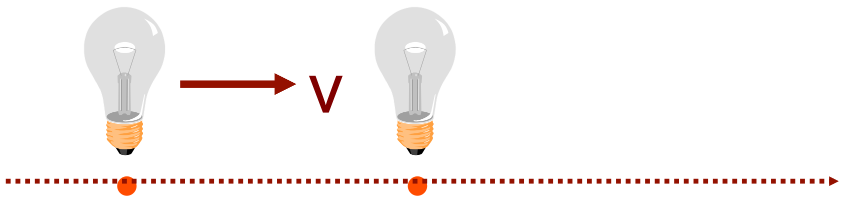
– Appearance of rapid variability

– Apparently high luminosity

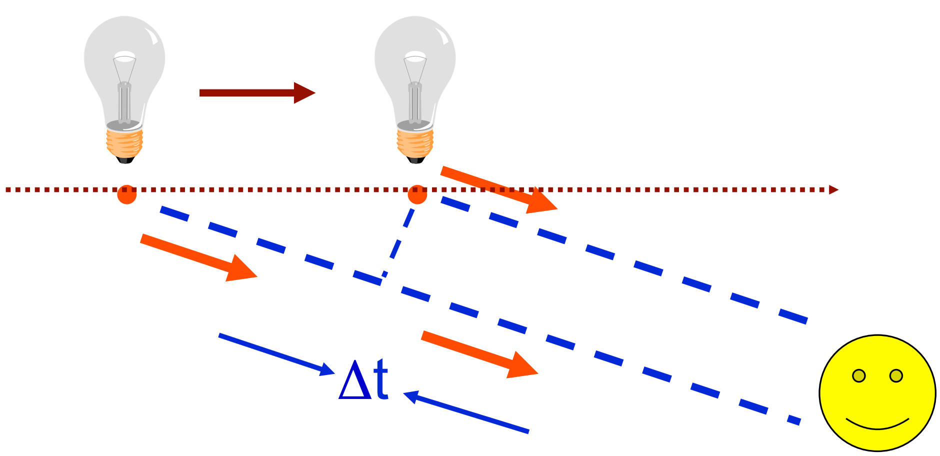
– Copious production of X- and γ-rays

i.e., blazars

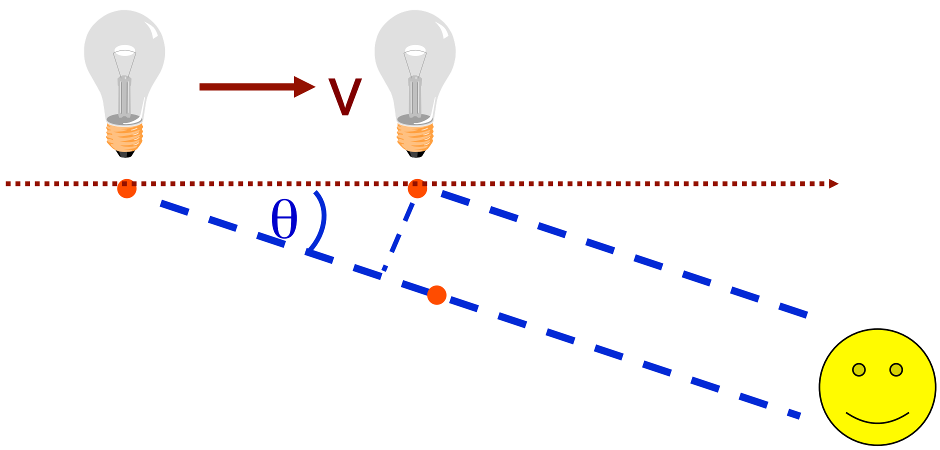
Superluminal motion

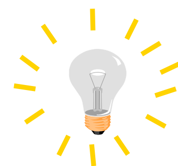


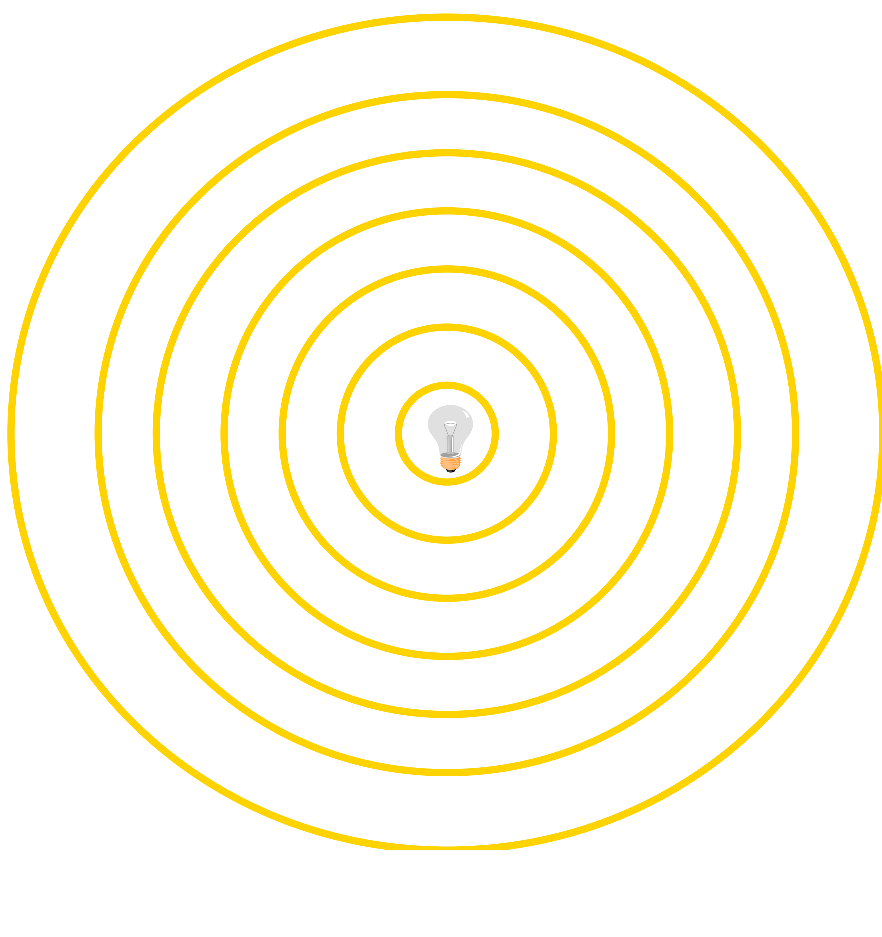
Superluminal motion

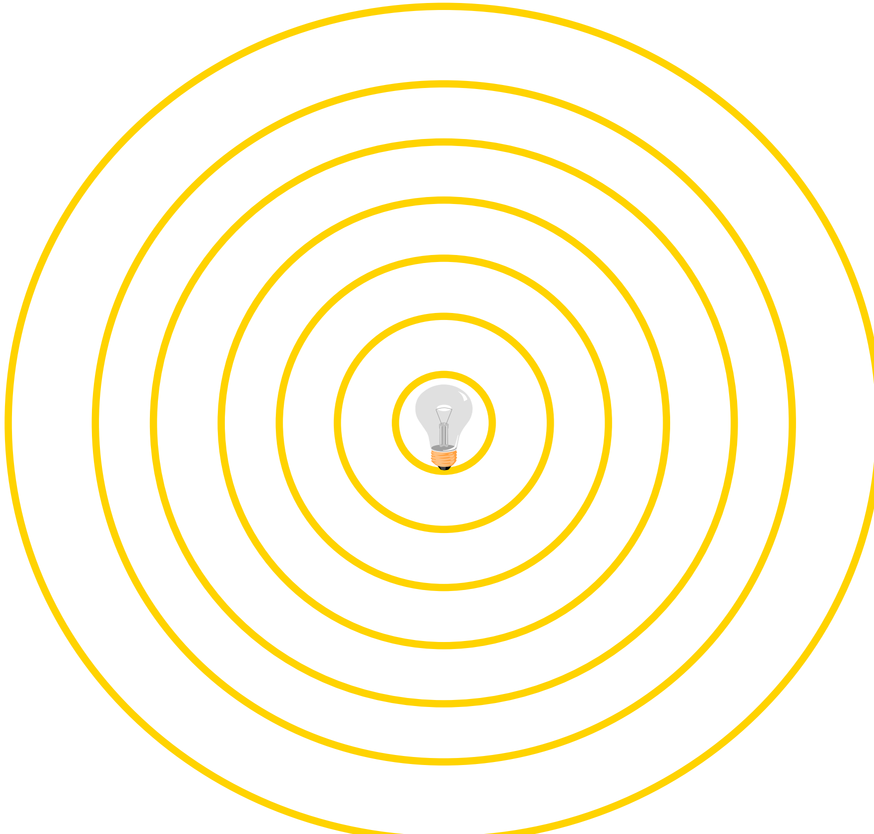


$$\text{apparent speed} = \frac{v \sin\theta}{(1 - v/c \cos\theta)}$$

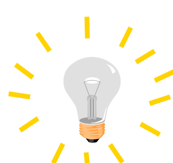


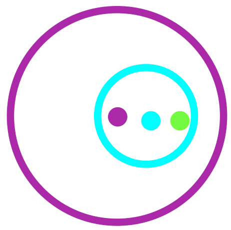


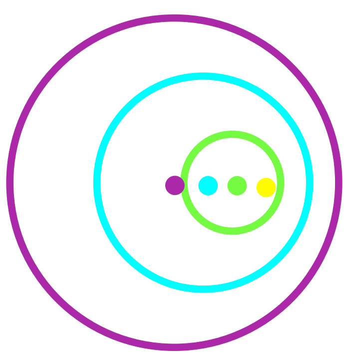


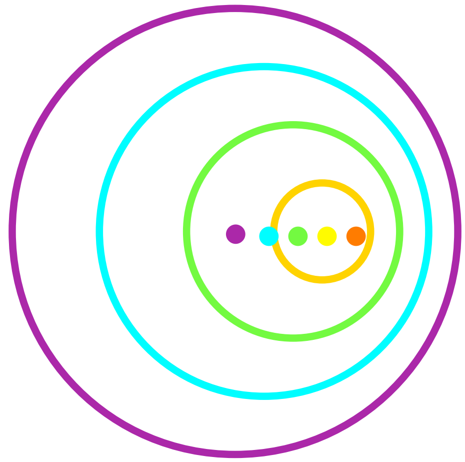


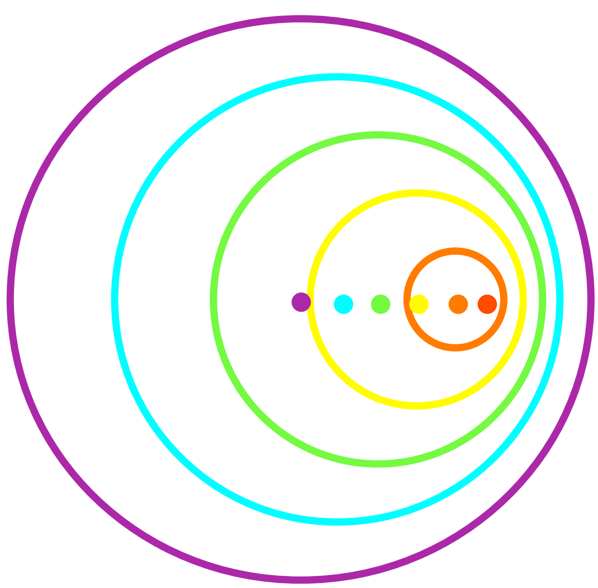
$v \sim c$

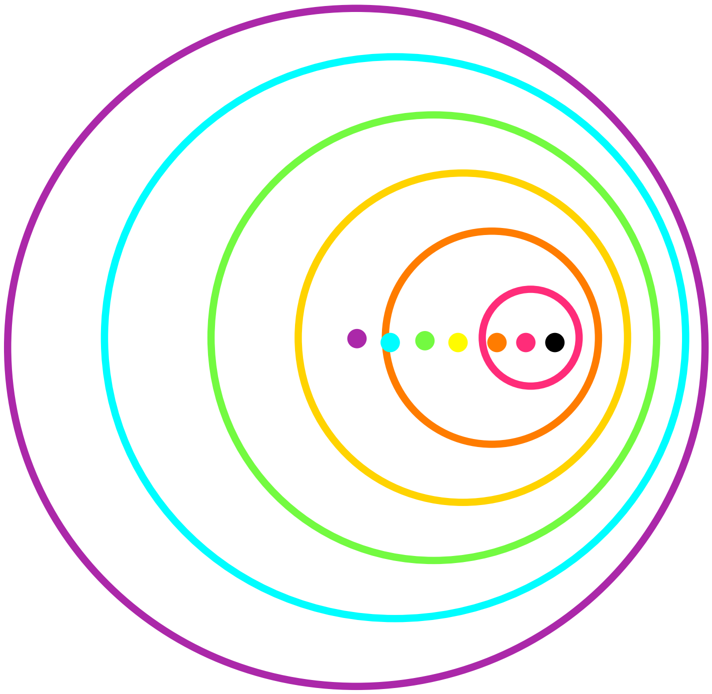


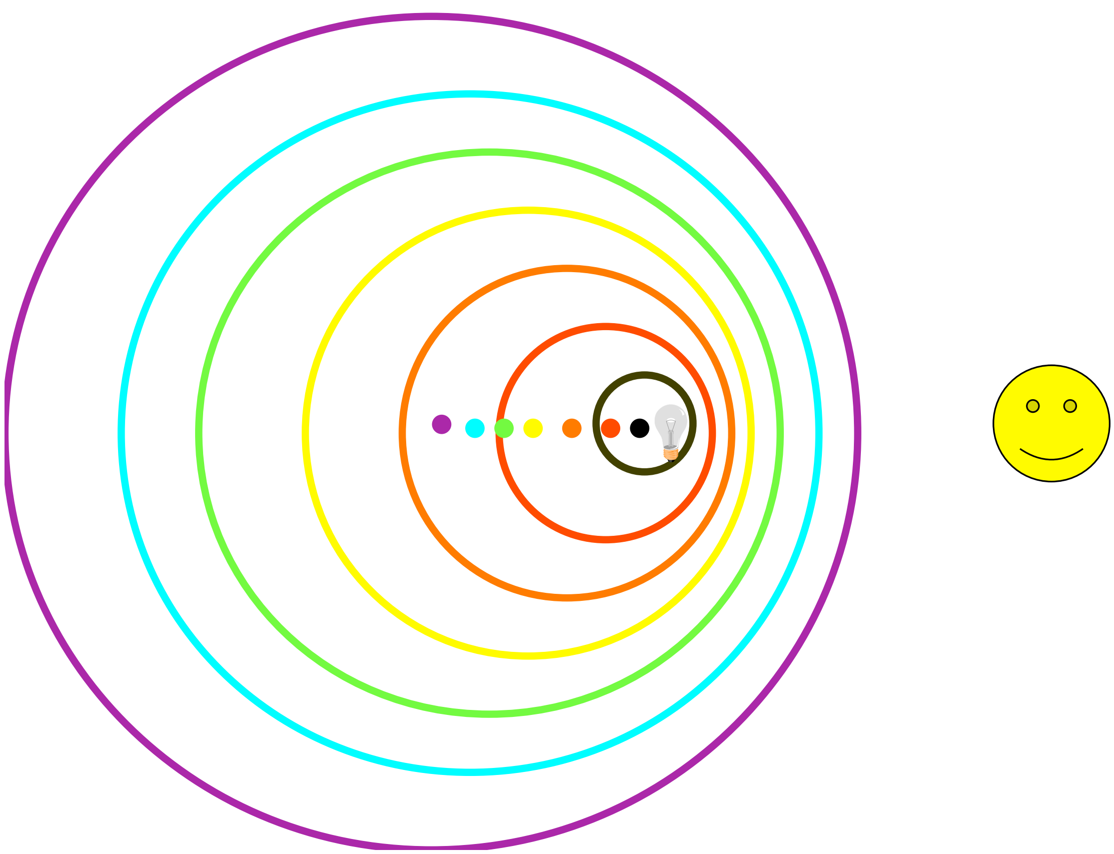








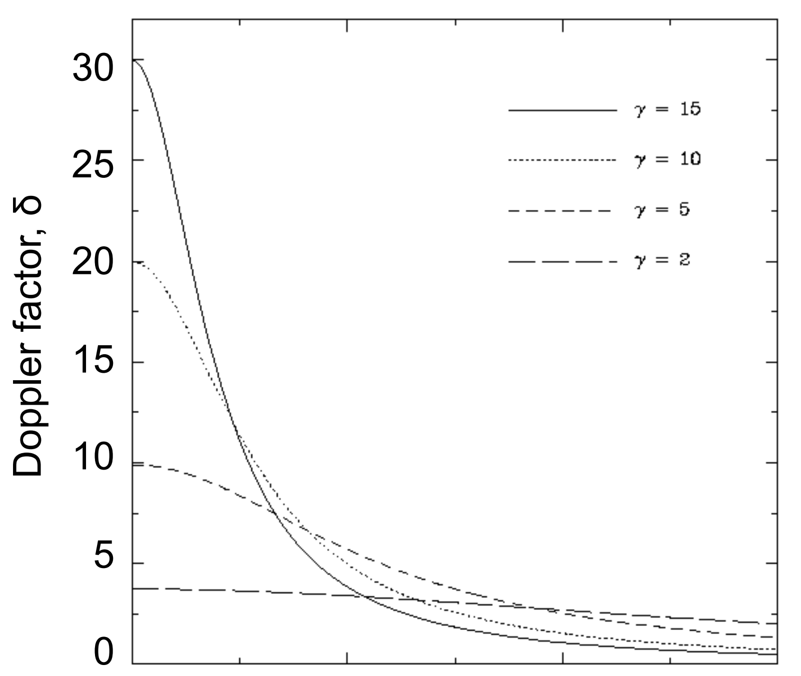




Doppler beaming

$$\delta = [\, \gamma\, (1 - \beta \cos\theta)\,]^{-1}$$

where $\gamma = (1 - \beta^2)^{-1/2}$ and $\beta = v/c$



Doppler beaming effects

Appearances:

- Events happen faster: $\Delta t_{obs} = \delta^{-1} \Delta t_{em}$
- Radiation is blue-shifted: $\nu_{em} = \delta \nu_{em}$
- Superluminal velcty: $v_{obs} = v \sin\theta/(1-\beta\cos\theta)$

$$= v \gamma\delta \sin\theta$$

- Intensity is much higher: $I_{obs} = \delta^3 I_{em}$

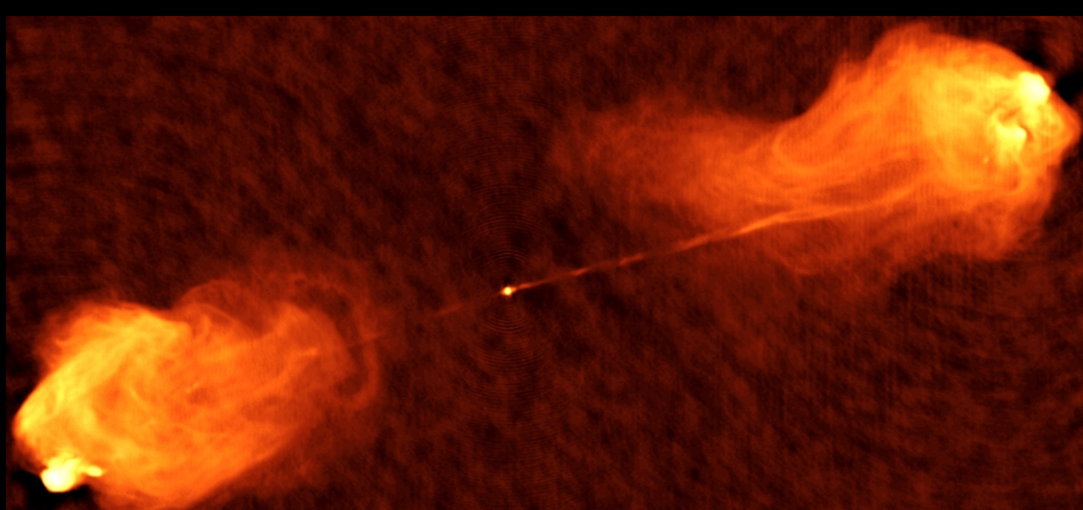
Homework: Limits near θ~0

- Maximum v_{app}? [$v_{app} < \gamma v$]
- Maximum value of δ? [$\delta < 2\gamma$]
- Angle at which v_{app} is maximum? [$\theta \sim 1/\gamma$]
- Value of δ at that angle? [$\delta \sim 2\gamma$]
- Approximate ratio beamed ($\theta < 1/\gamma$) objects to unbeamed objects (the rest)? [γ^2]

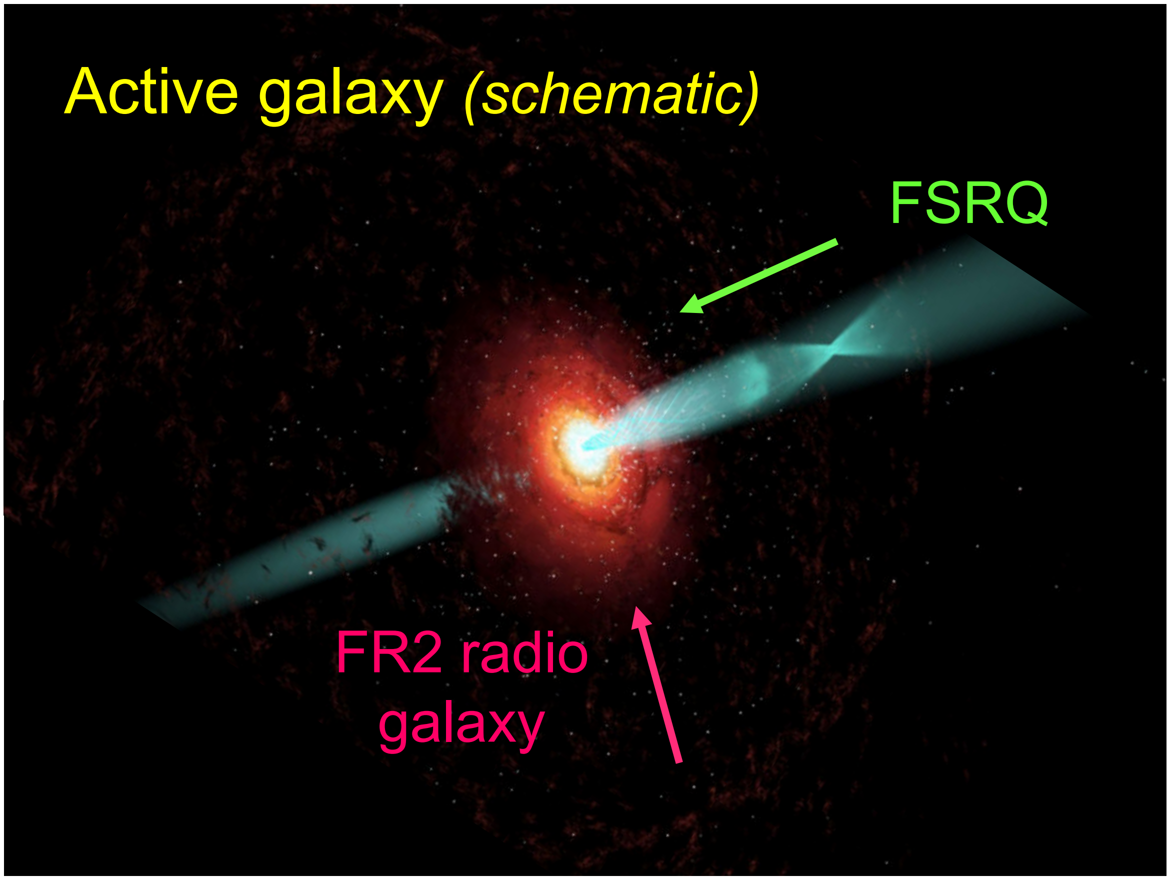
Blazars are Nature's demonstration of Special Relativity

- Jets pointing at us!
  - Many more must point elsewhere
  - these are "radio galaxies"
- Outflow speeds v~c

Cygnus A – FR2 radio galaxy



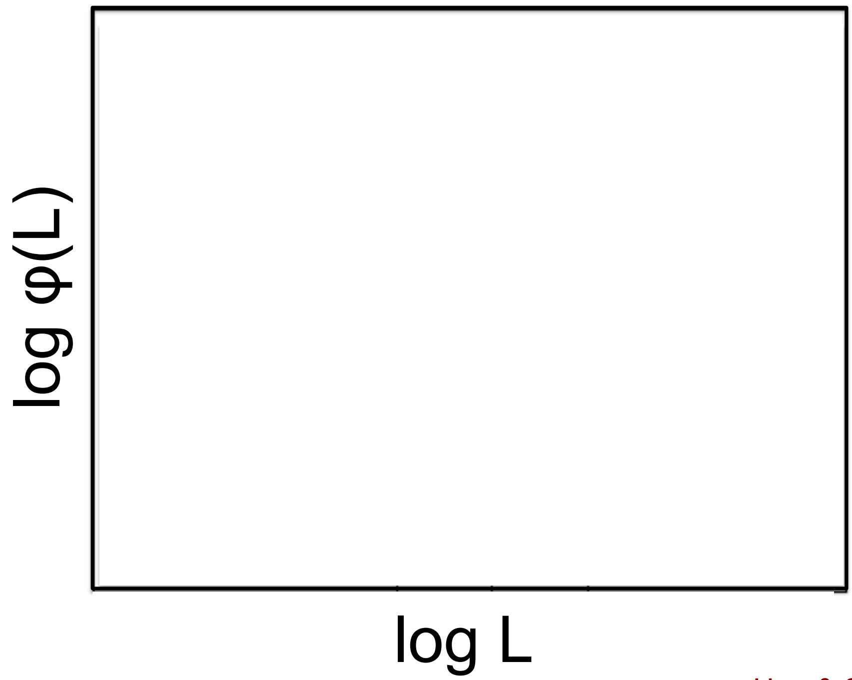
Carilli et al.



Beamed luminosity functions

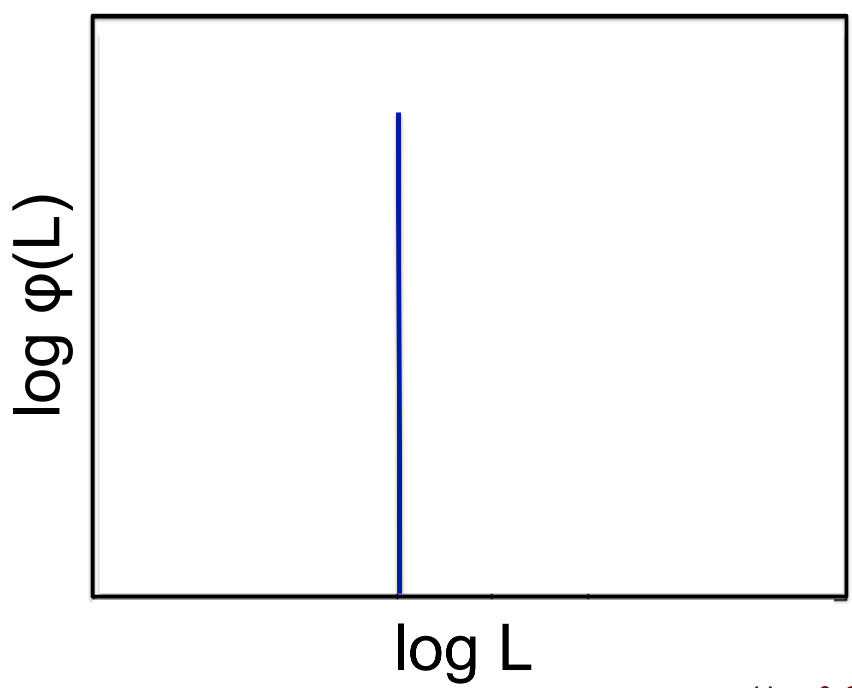
parent (radio galaxy) and beamed
(blazar) populations

Relativistically beamed LF



Urry & Shafer 1984

Relativistically beamed LF



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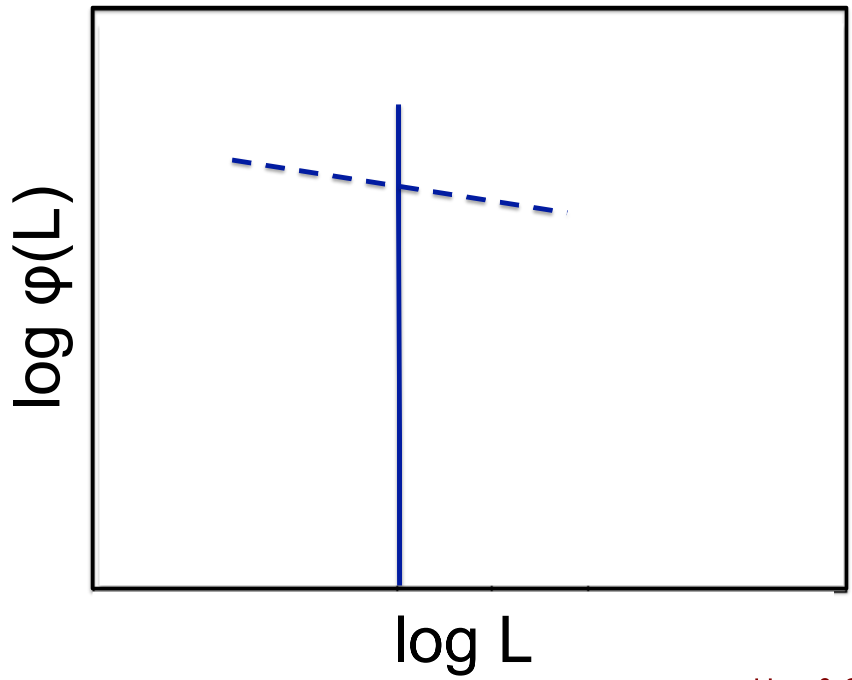

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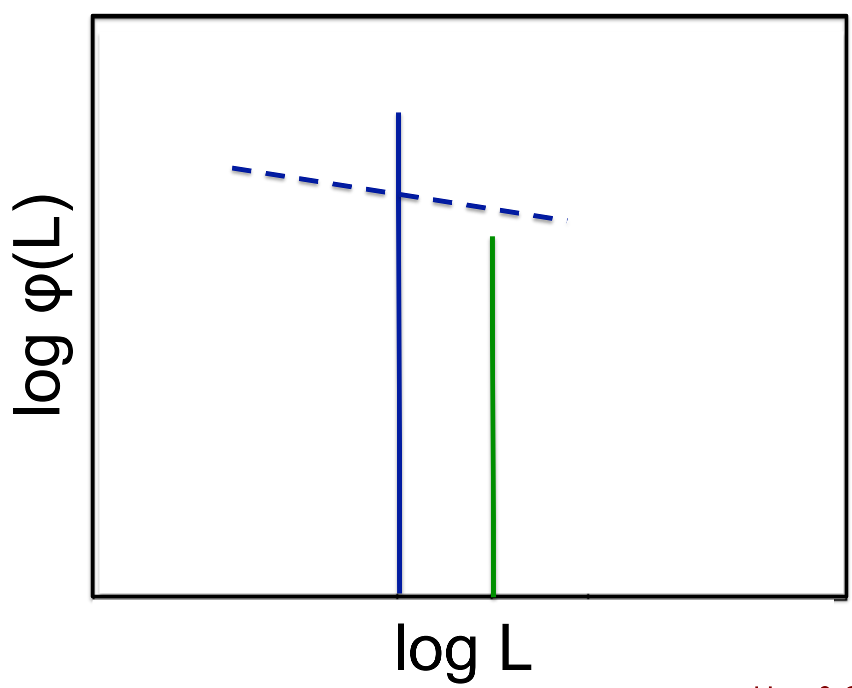

Urry & Shafer 1984

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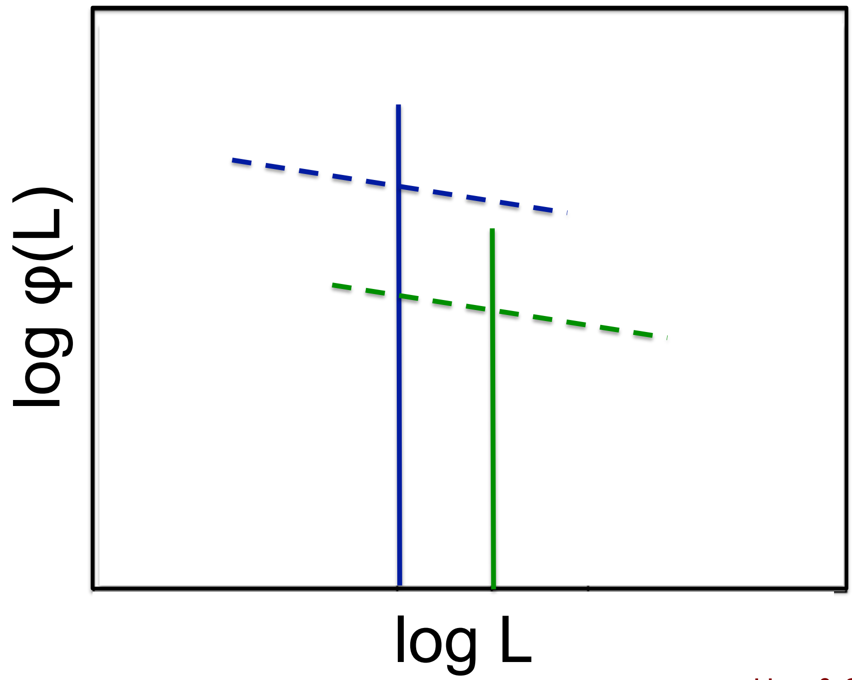

Urry & Shafer 1984

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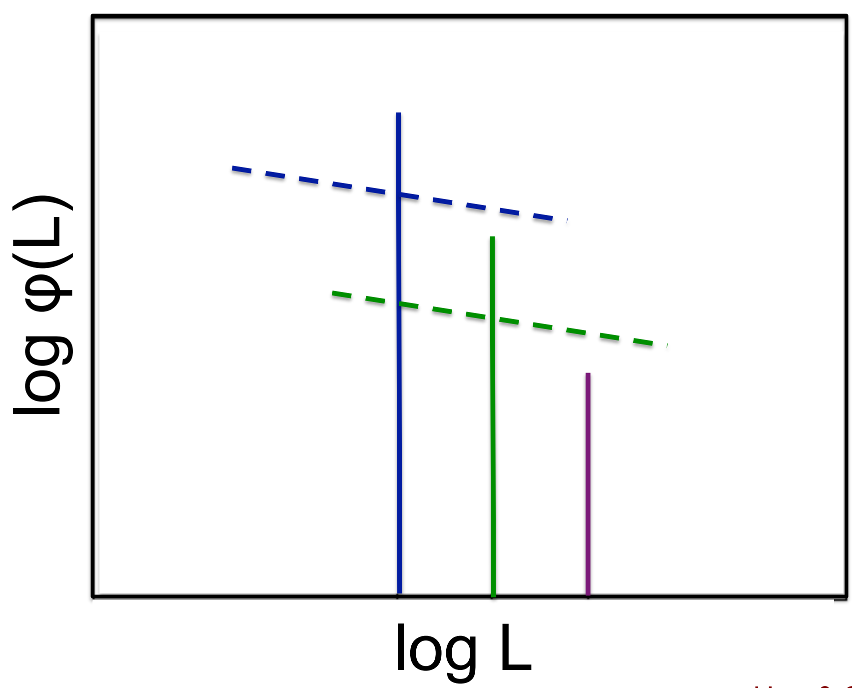

Urry & Shafer 1984

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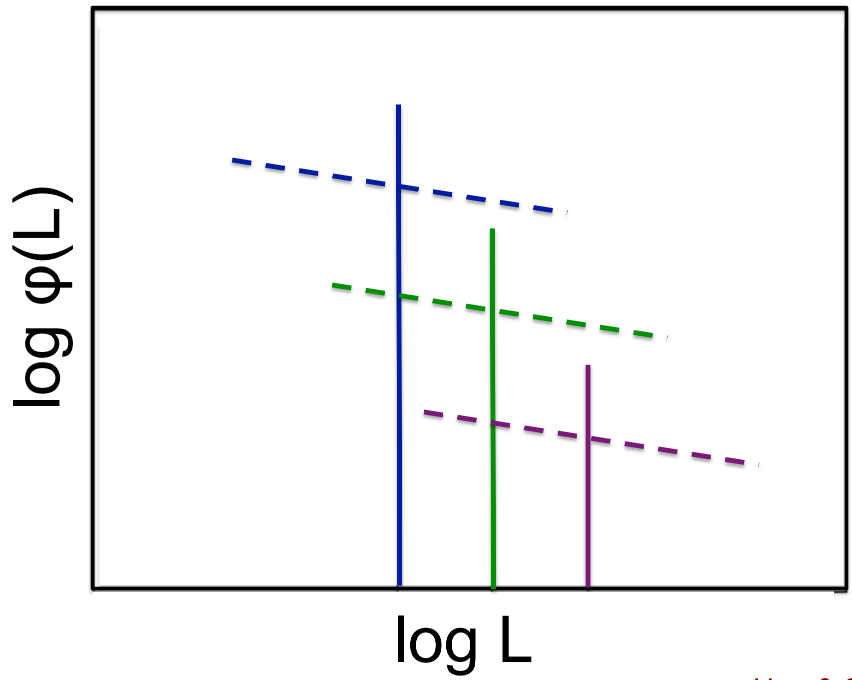

Urry & Shafer 1984

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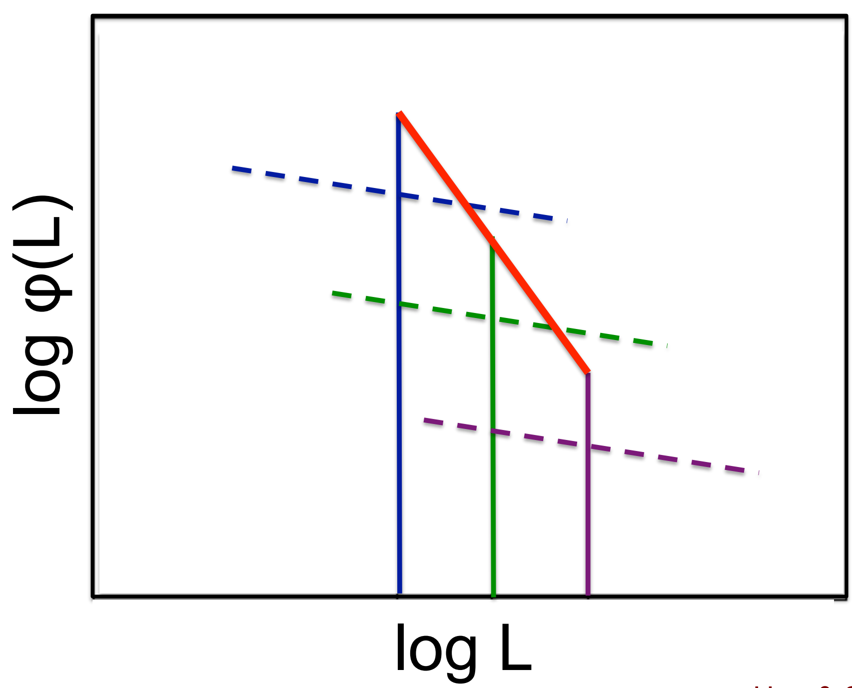

Urry & Shafer 1984

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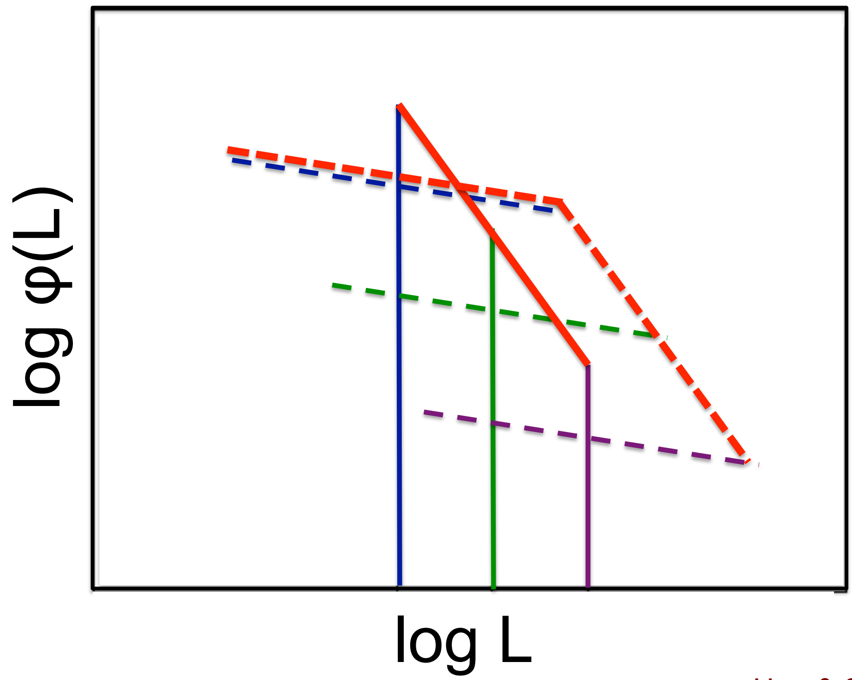

Urry & Shafer 1984

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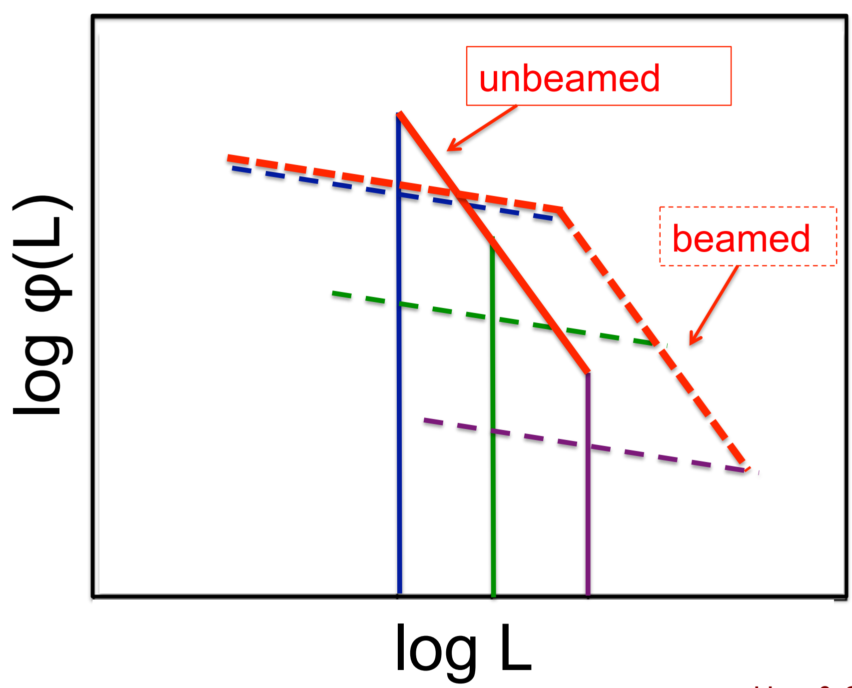

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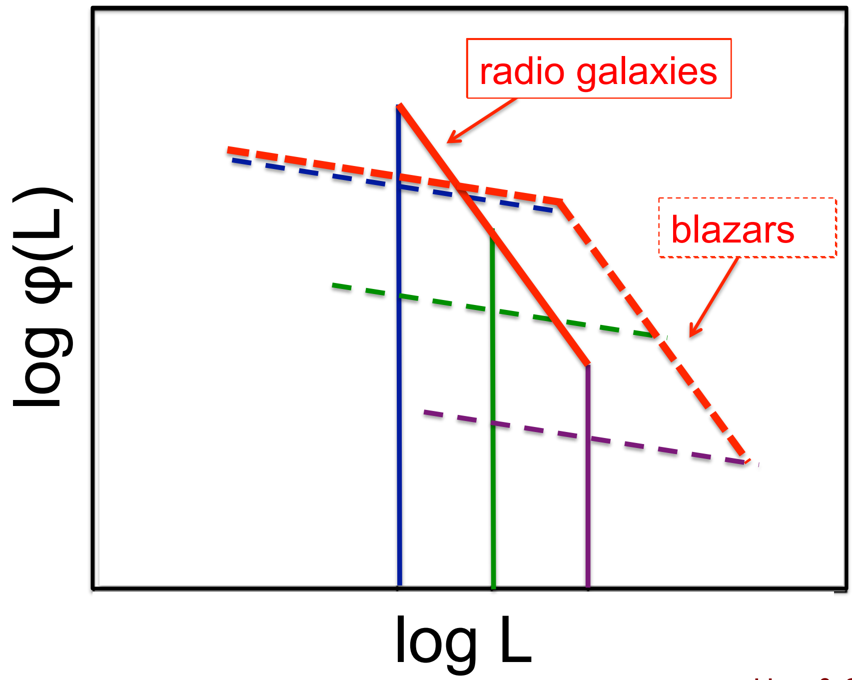
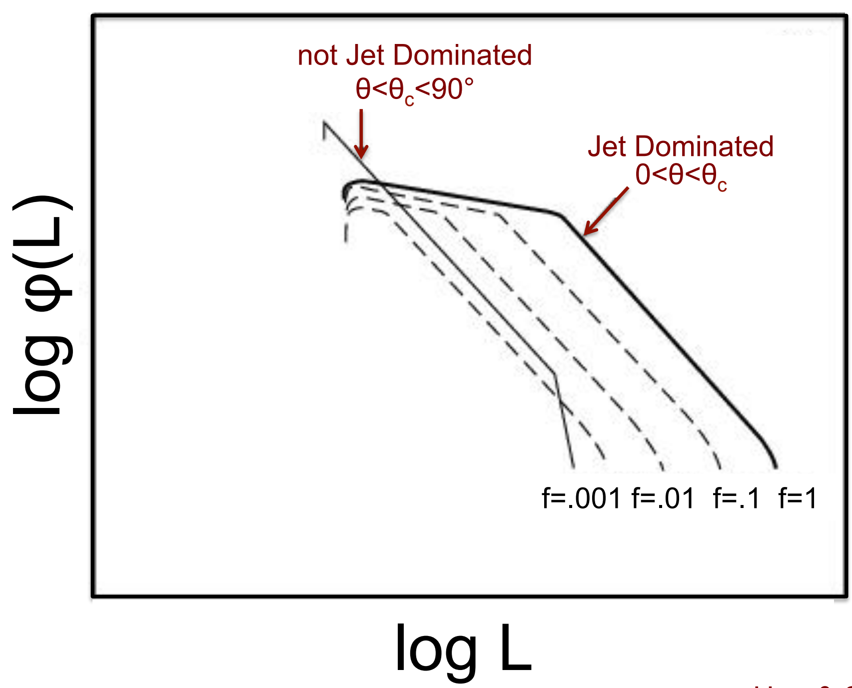


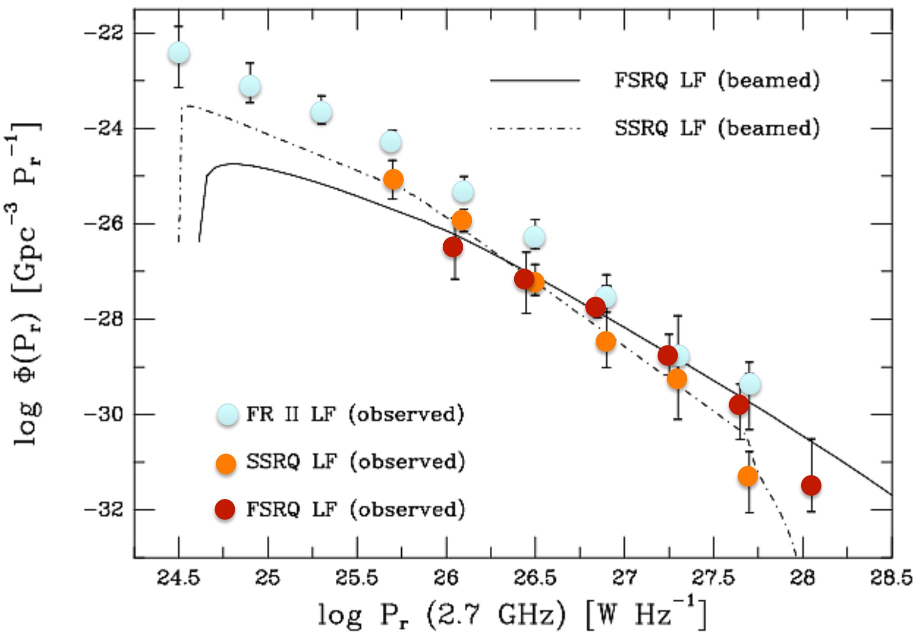
Urry & Shafer 1984

Relativistically beamed LF



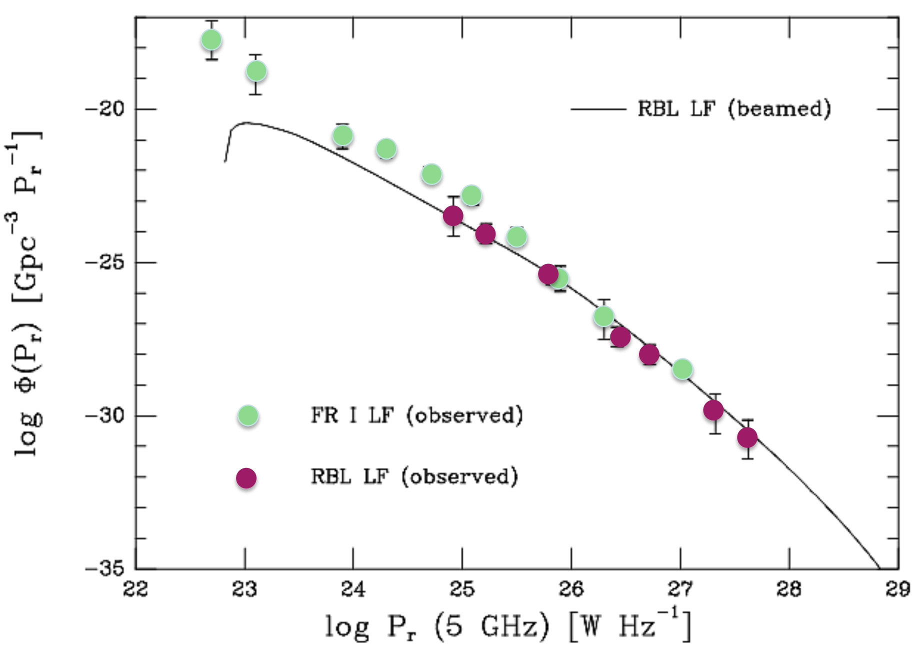
Urry & Shafer 1984

Quasar/FRII radio LFs



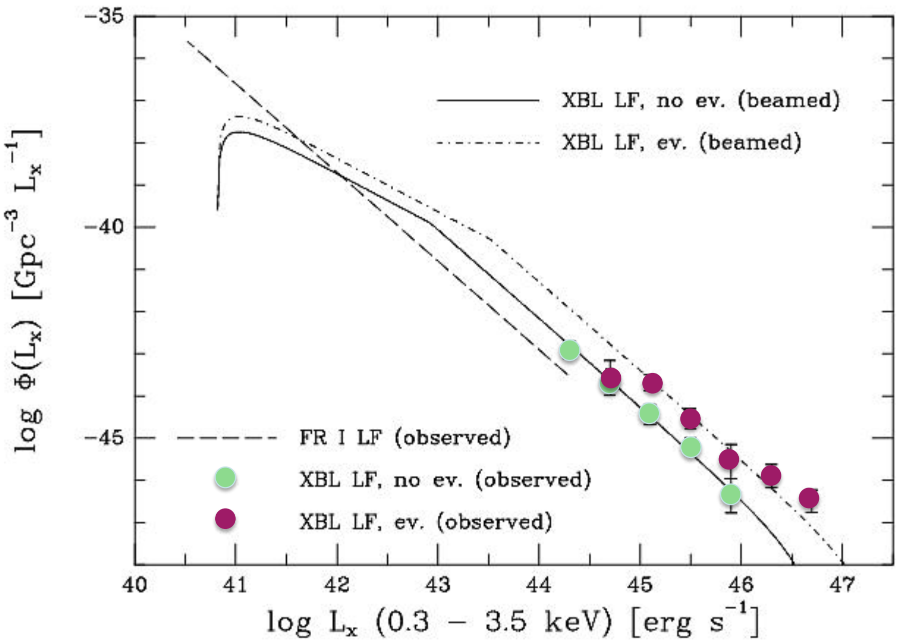
Padovani & Urry 1992

BL Lac/FRI radio LFs



Padovani & Urry 1991

BLL/FRI X-ray LFs



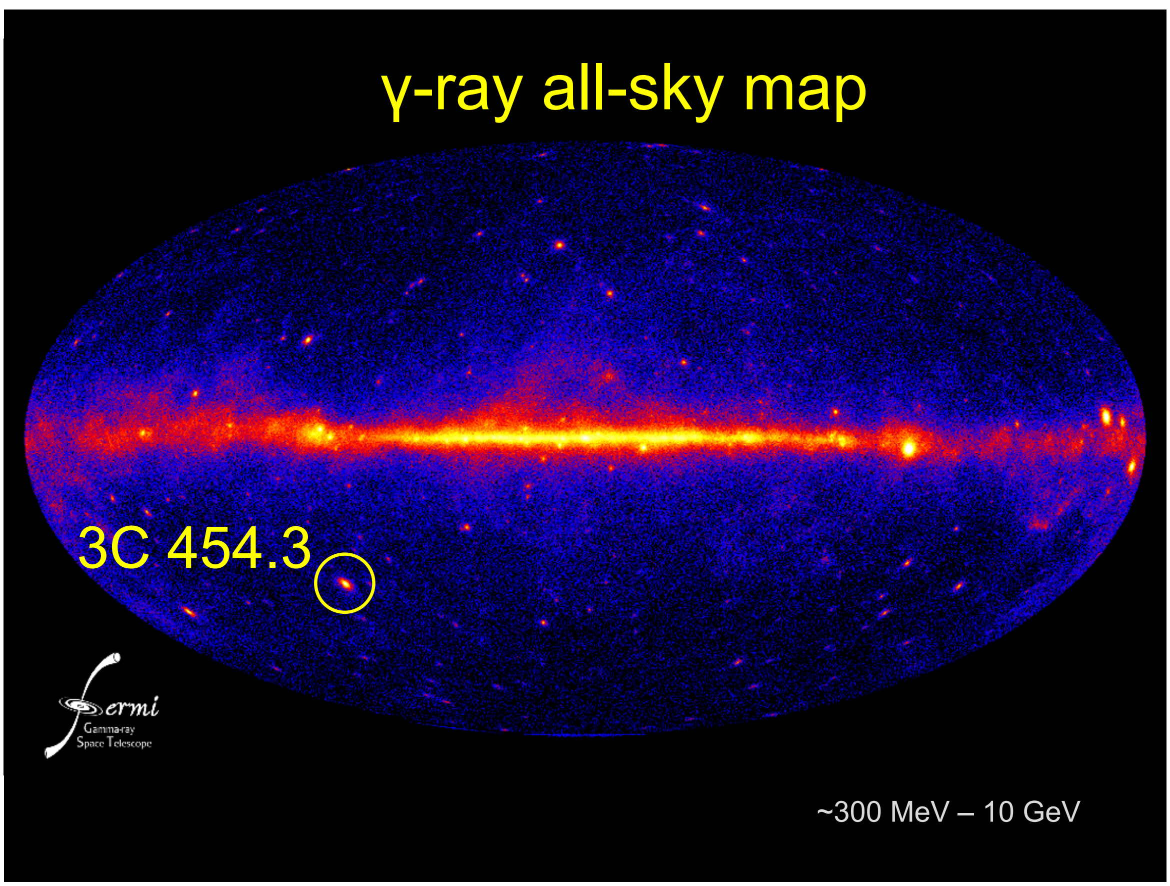
Urry & Padovani 1991

Blazars + radio galaxies = Unification

- Parent populations identified
  - BL Lacs = FR1s
  - FSRQs = FR2s
  - Lots of transitional objects
  - γ, δ, θ, β vary
- $\gamma \sim$ 5-10 for LFs to match
- γ up to 100 seen (300 in GRBs), from time variability, superluminal motion, Compton catastrophe,..

Time variability

Multiwavelength light curves,
emission models



High-energy blazar observations

- Fermi Gamma-ray space telescope
- 100 MeV - 300 GeV
- High energy peak of most luminous blazars

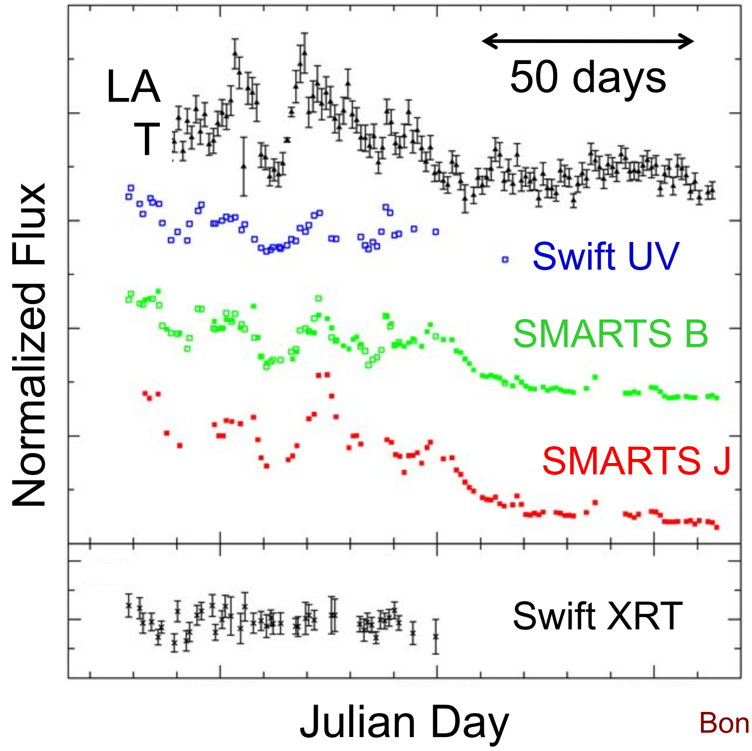
- Atmospheric Cerenkov telescopes (VERITAS, MAGIC, H.E.S.S.)
- VHE gamma-rays up to several TeV
- Peak of less luminous blazars

Yale/SMARTS multiwavelength campaign

- SMARTS: Small and Moderate Aperture Telescope System
  Cerro Tololo, Chile
- SMARTS 1.3m + ANDICAM: simultaneous 0.4-2.2 μm images
  BVRJK every 1-3 days
- Optical spectra of bright blazars once per month per object
- Data online
- ~1 day response time for flaring sources

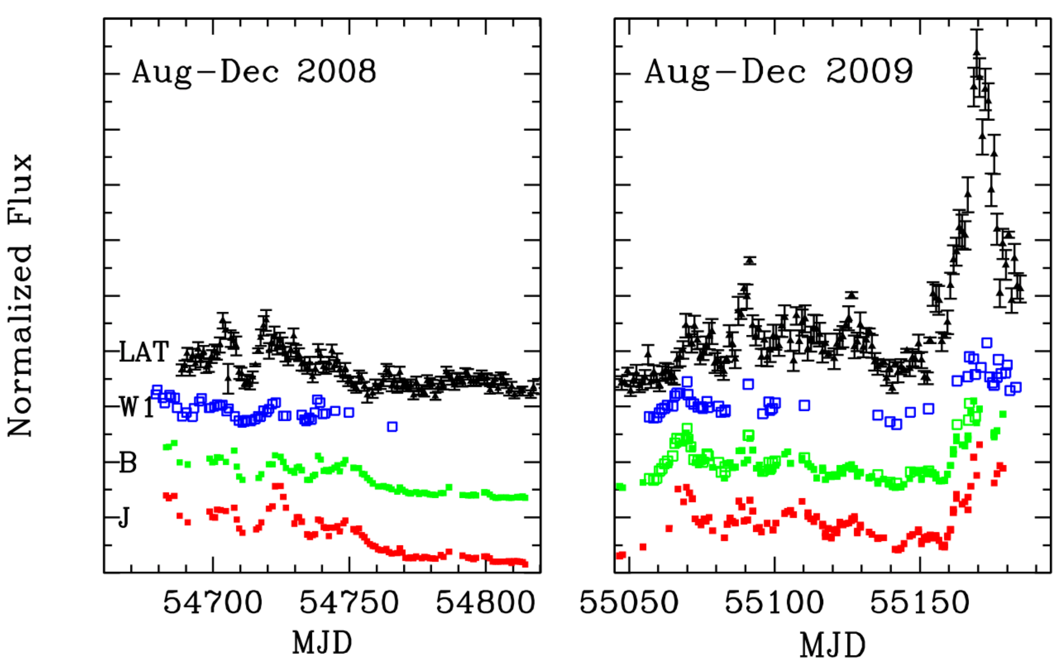
www.astro.yale.edu/smarts/fermi/

3C 454.3 Multiwavelength Data

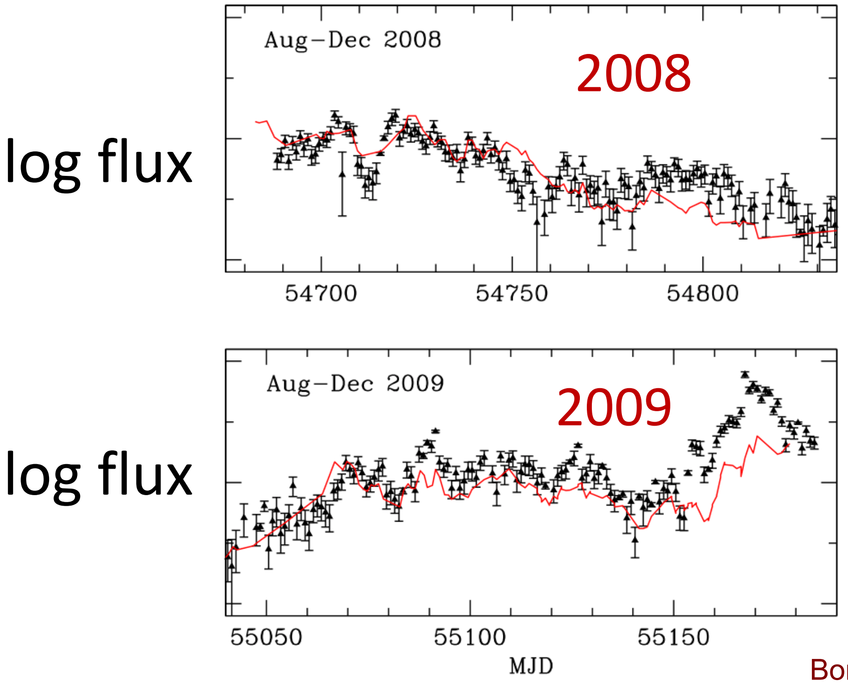


Bonning et al. 2009

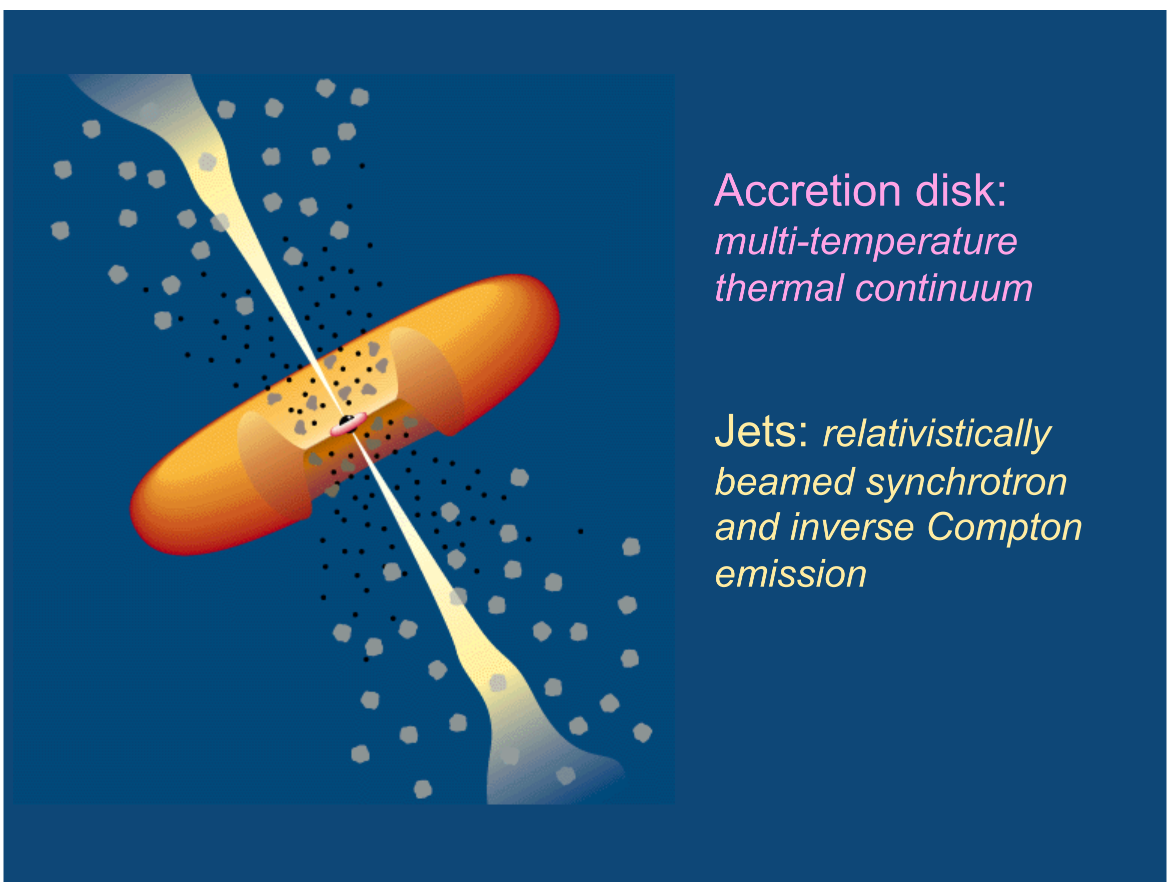
3C454.3: 2008-2009



3C454.3: IR - γ-ray correlation



Bonning et al. 2012



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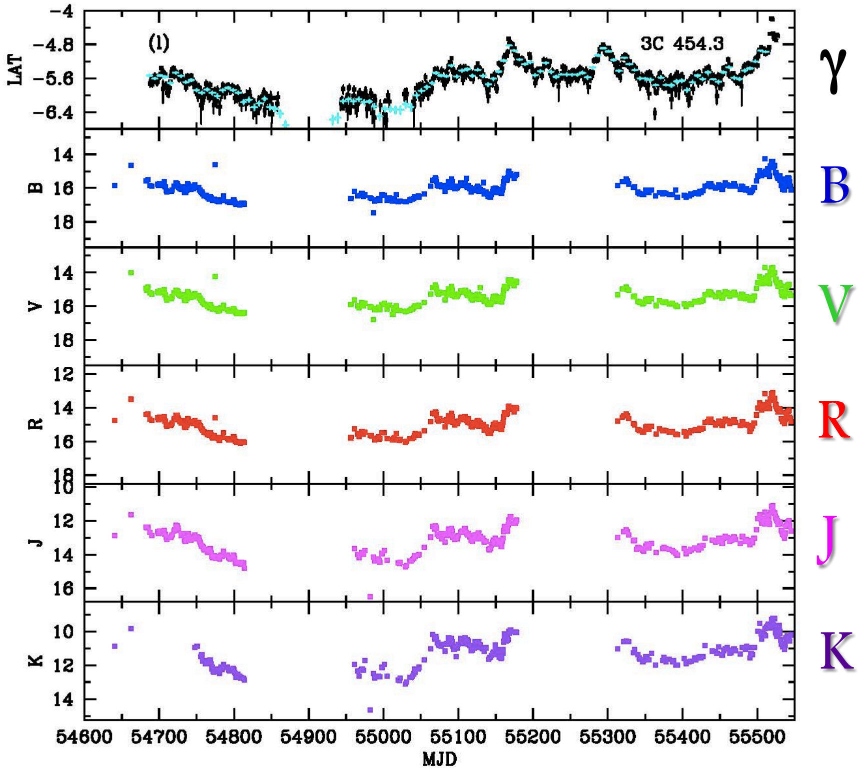
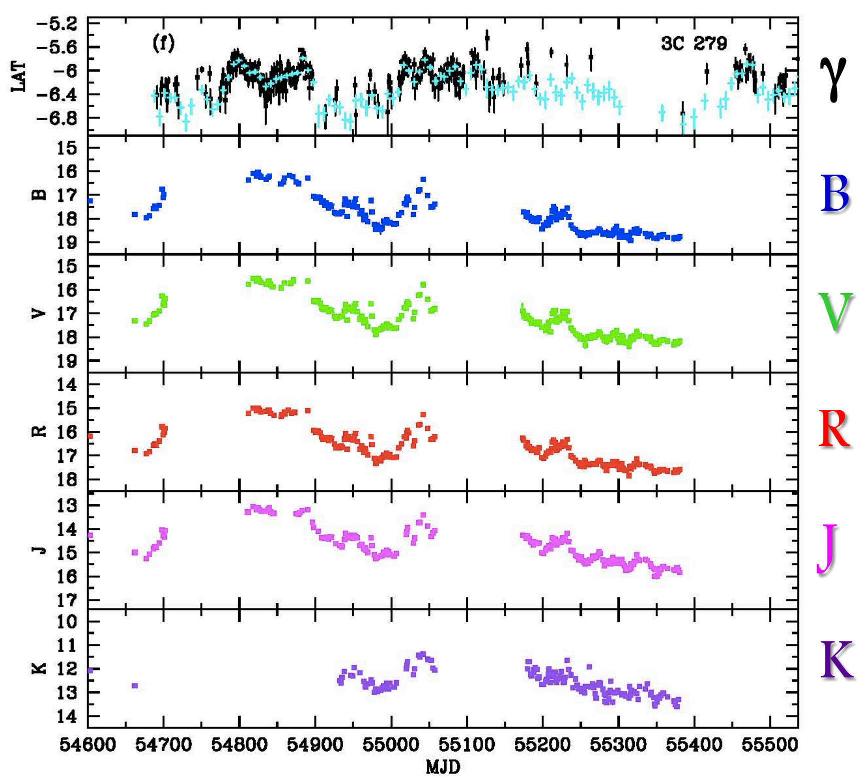


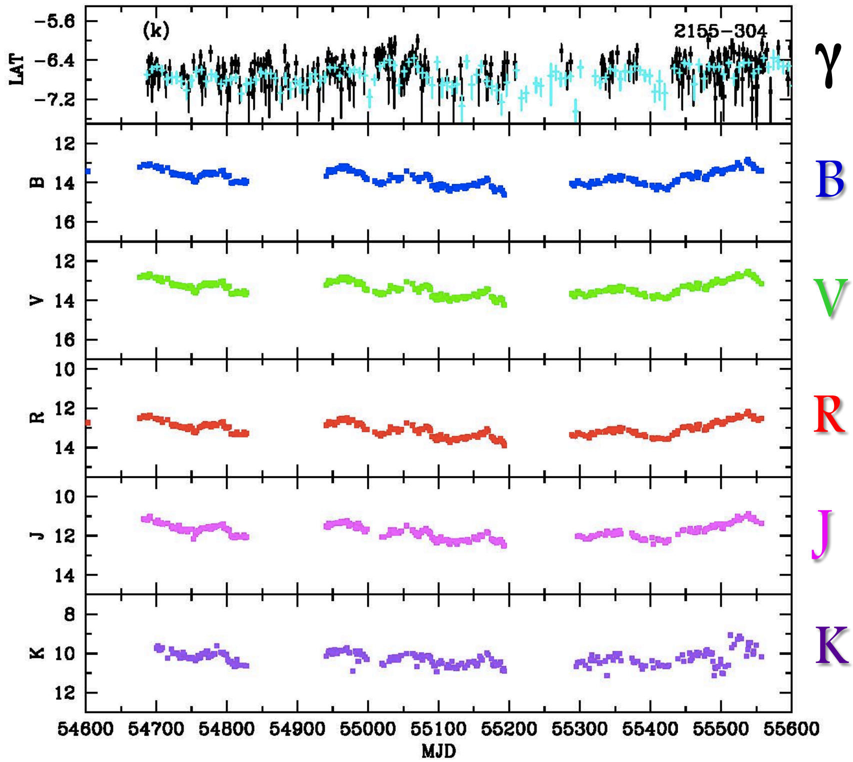
Bonning et al. 2012

3C279



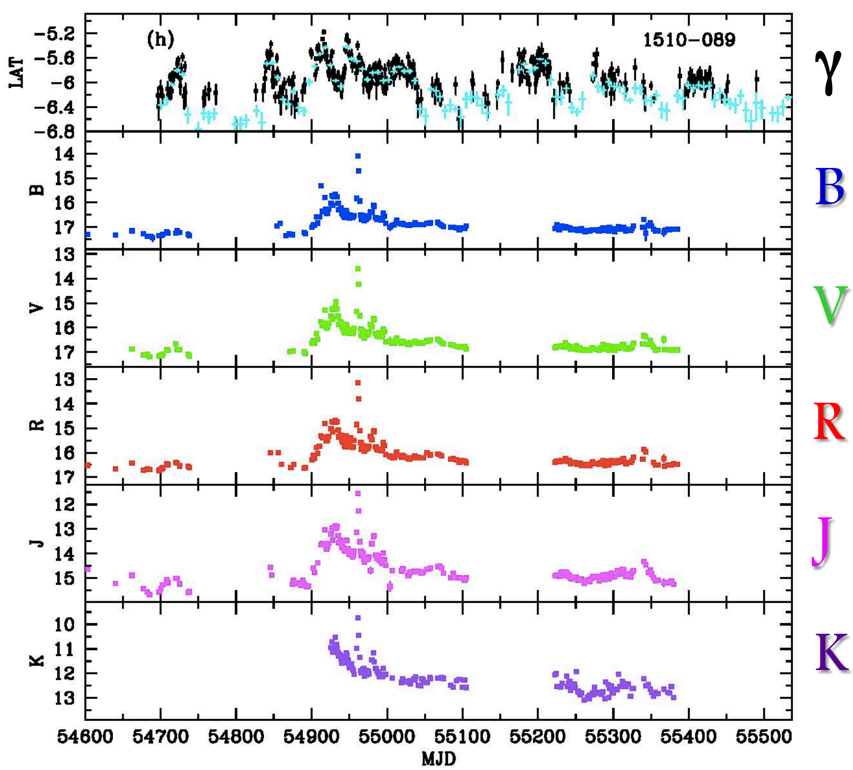
Bonning et al. 2012

2155-304

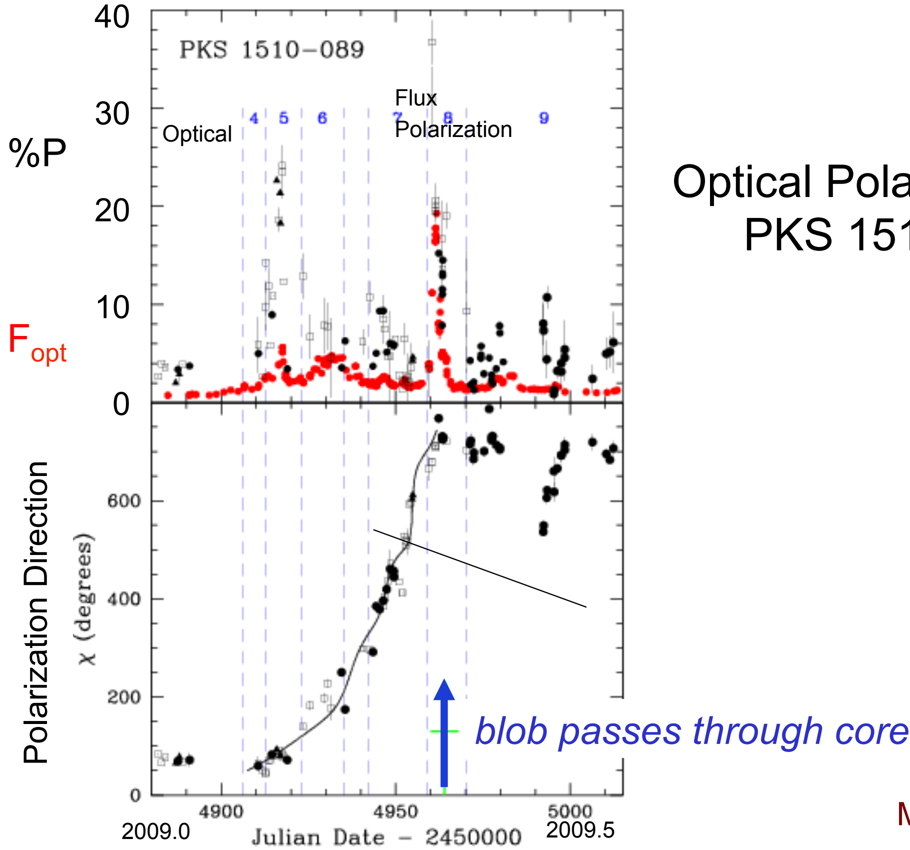


Bonning et al. 2012

1510-089



Bonning et al. 2012

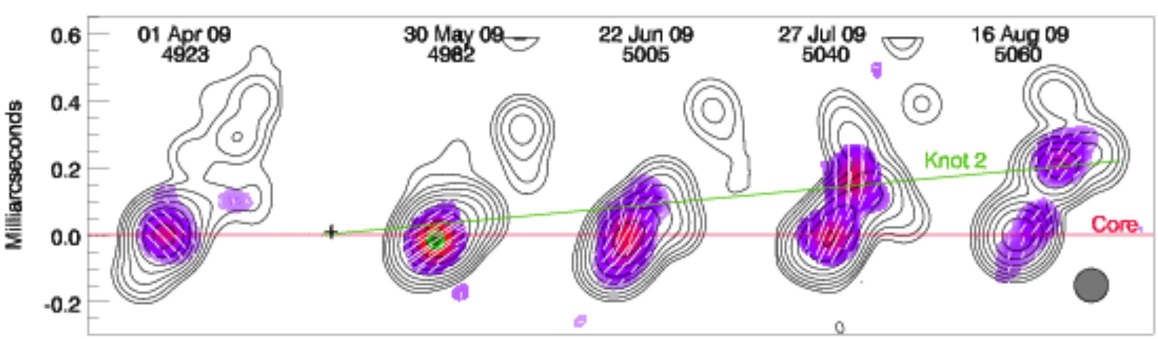


Optical Polarization in PKS 1510-089

Marscher group

Superluminal knot emerges in PKS 1510-089

(May 2009, ~MJD 4960)



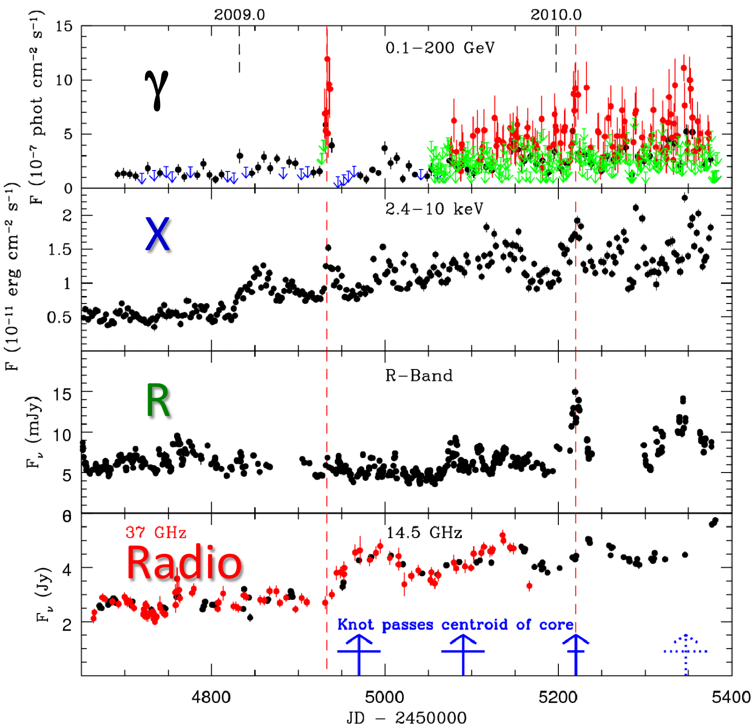
VLBA images at 43 GHz

Contours=intensity, Colors=polarization

Bright superluminal blob passed “core” in early May 2009

Apparent speed = 21c

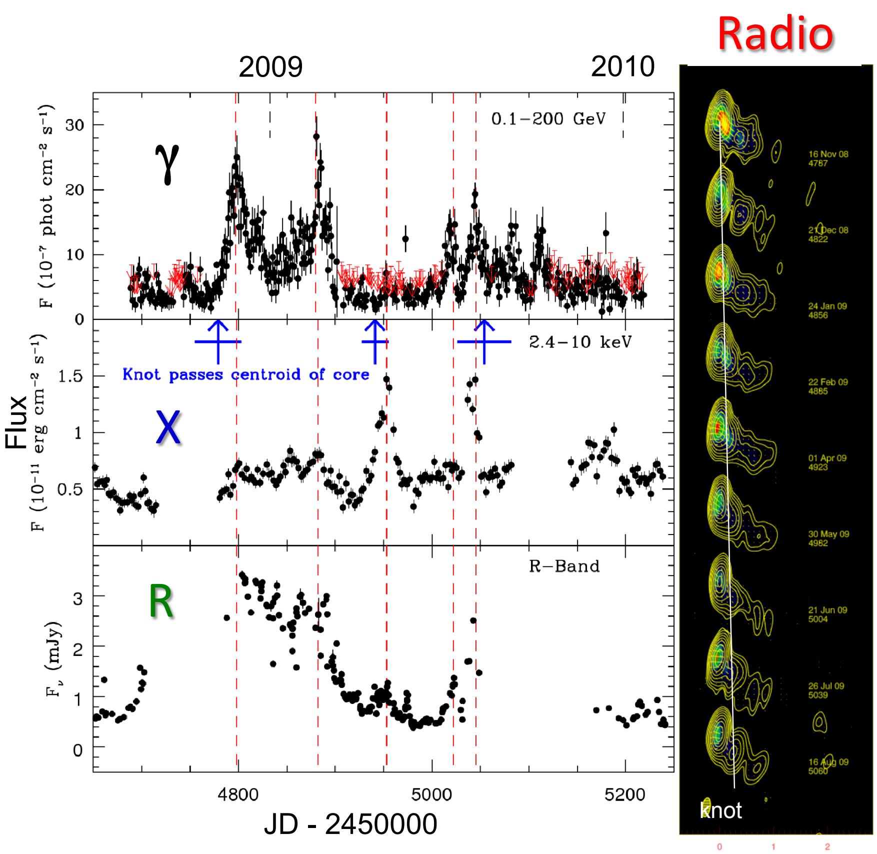
Marscher et al. (2010)



BL Lac

Prominent γ-ray flares when knot passes through 43GHz core

Marscher group



3C 279

Marscher group

Trends in λλλ variability for FSRQs

- Gamma-ray + optical/IR variations correlate
  → Same electrons (External Compton or Synchrotron Self-Compton)
- γ, opt usually faster than X-ray, IR, mm
  → smaller volume and/or more severe radiative losses
- γ-ray flares coincide with events in radio jet
  → Standing shocks in jet?
- γ-rays should produce e^+e^- pairs
  → Low photon/particle density → γ-rays produced far from BH?
- Related to direction of magnetic field?

Spectral energy distributions

SED shape, trends, Fossati scheme

Blazar Spectral Energy Distributions (SED)

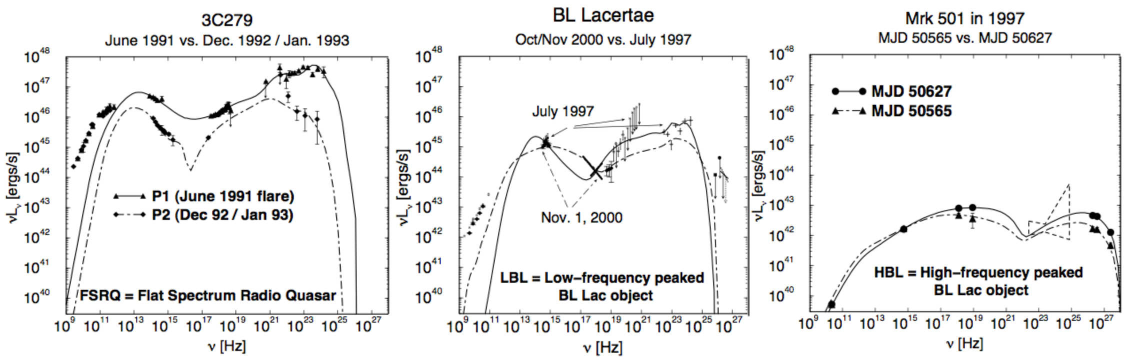
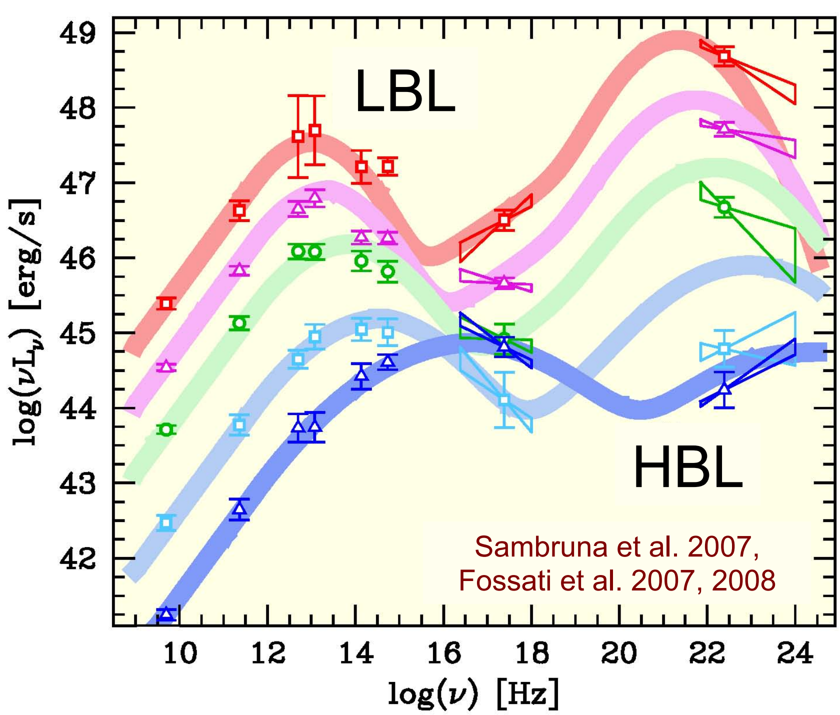


Fig. from Boettcher, Astro. Space Sci. (2007)

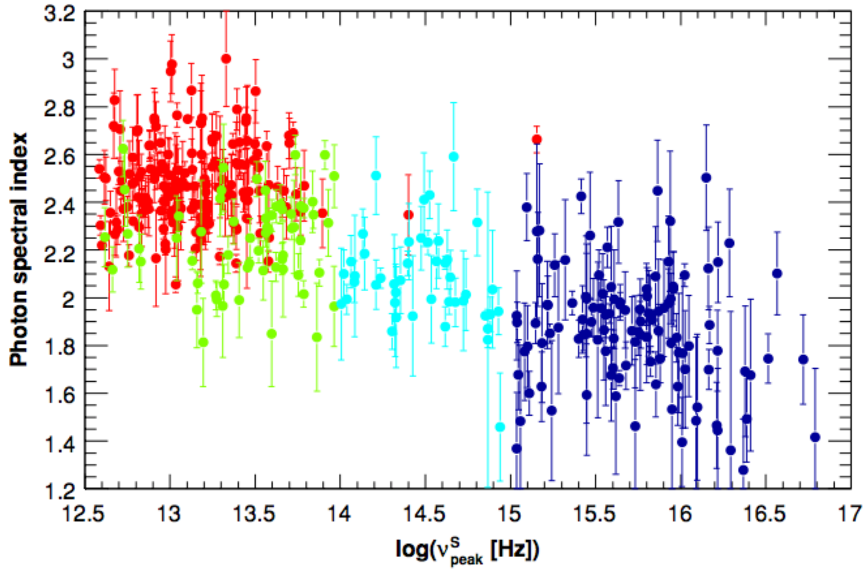
- SED has two peaks
- Peak energy decreases with increasing peaks luminosity

Fossati et al 1998

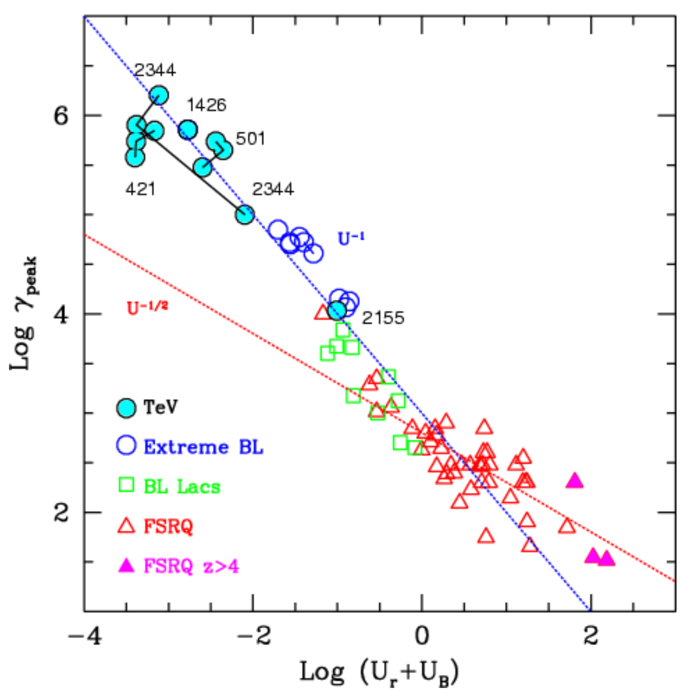


SED-luminosity trend required: *Urry, Brandt, Maraschi+*

1LAC: Blazars by synchrotron peak

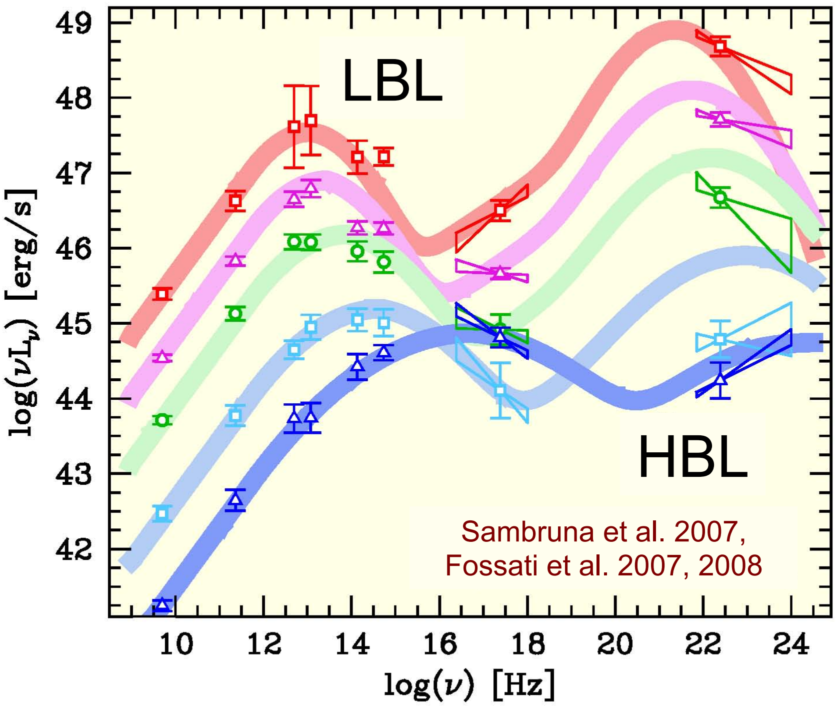


Physical Parameters along the SED Sequence



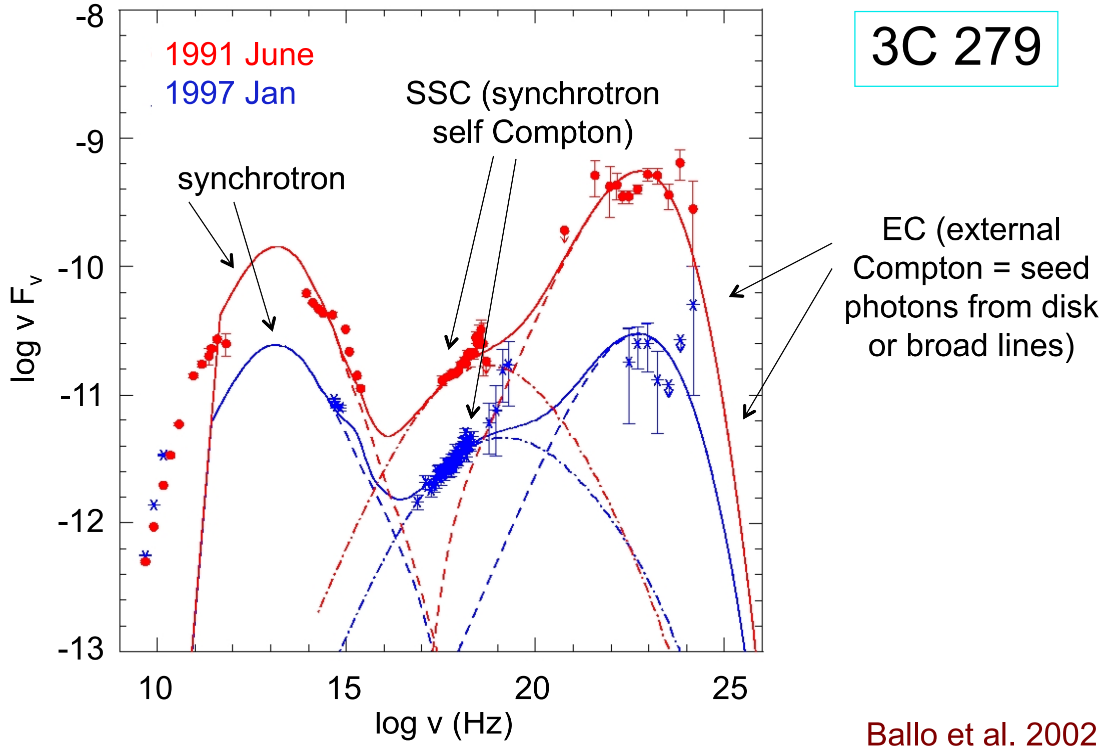
Ghisellini Celotti & Costamante 2002

more variability above peaks



Unresolved jets

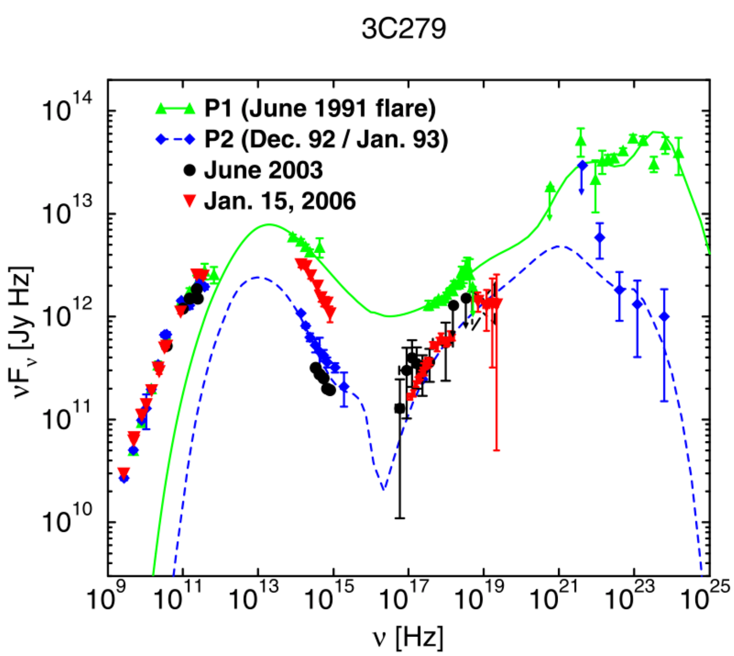
Use SED + variability to infer jet structure and physics



Ballo et al. 2002

Challenges for SED modeling

- Many models fit single-epoch SED
- Temporal variability adds constraints
- Requires simultaneous λλλ data (multiple observatories)



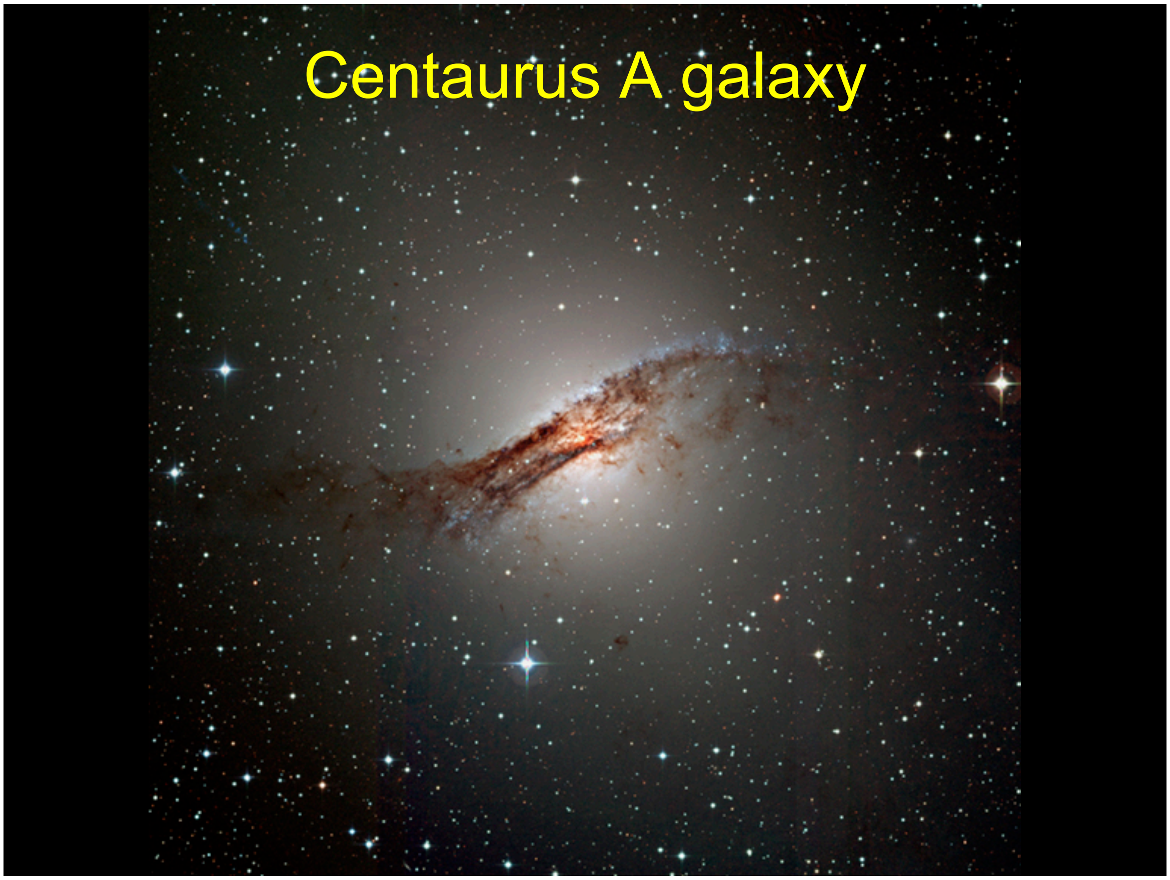
Boettcher et al. 2007

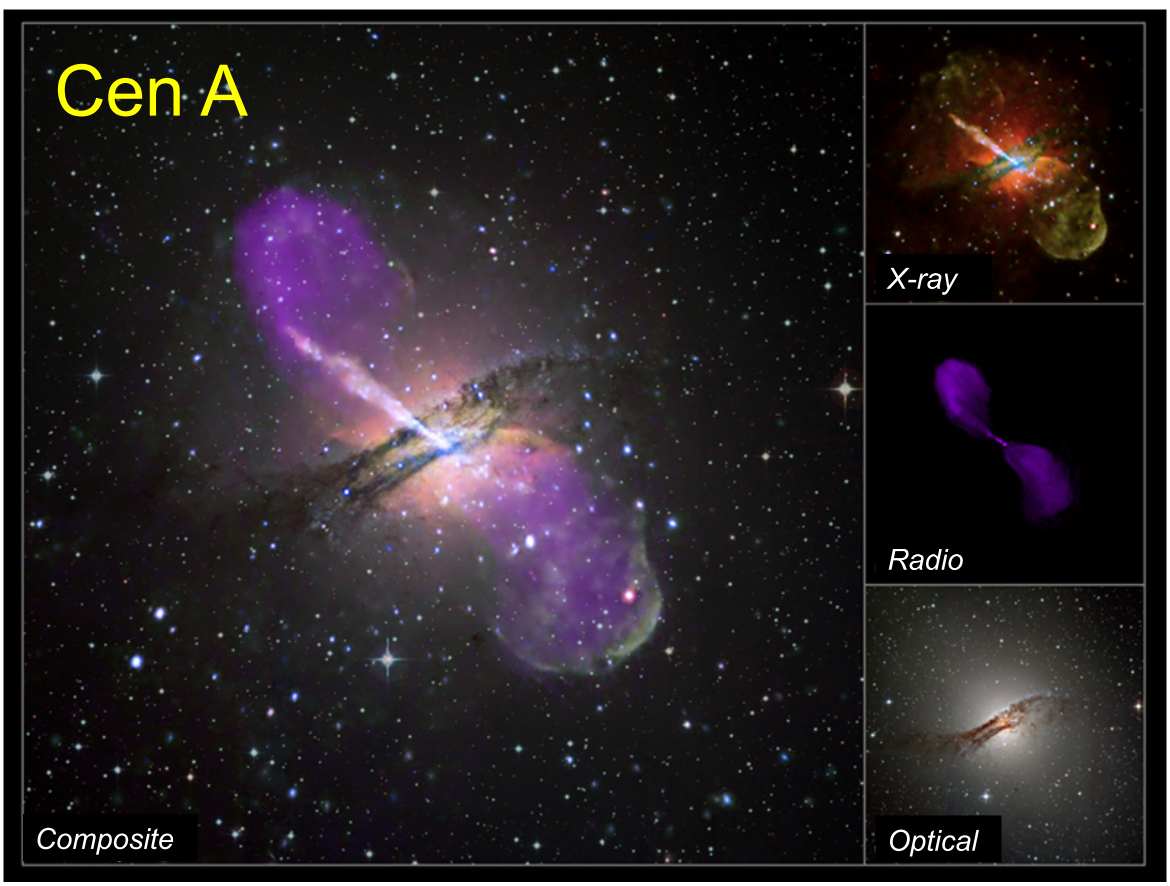
Classes of emission models

- Leptonic
  - Synchrotron radiation
  - Inverse Compton-scattered radiation
    - SSC = scattered synchrotron photons
    - EC = scattered ambient (thermal) photons
- Hadronic
  - Strong magnetic fields (10s G) accelerate protons
    - High-energy peak from proton synchrotron radiation and $\mu^+\mu$ cascades
    - Photo-pion production and pion decay
    - Low-energy peak from electron synchrotron

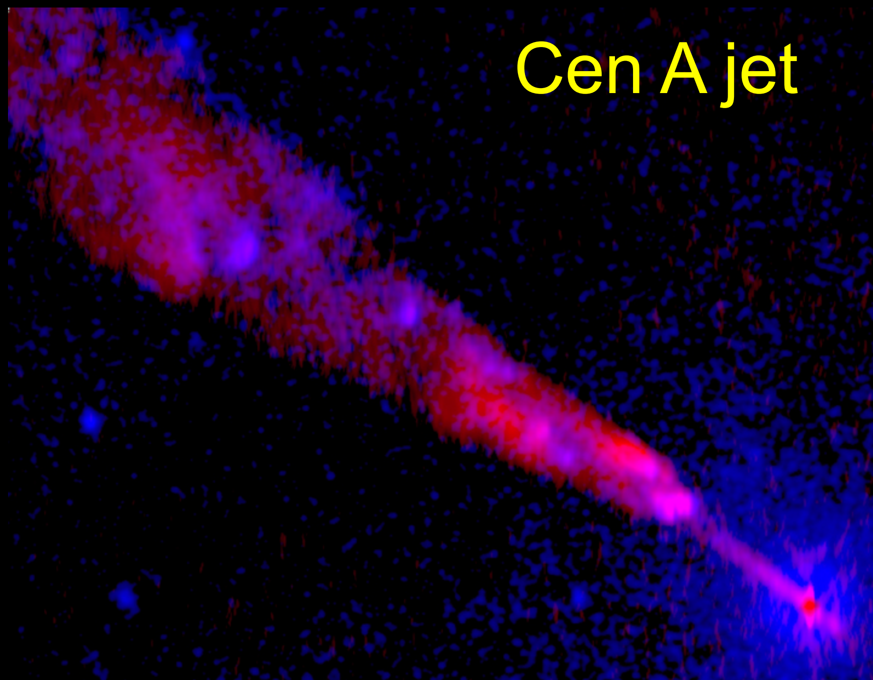
Coordinated variations predicted

Resolved jets (kpc scales)


Centaurus A galaxy


Cen A
X-ray
Radio
Composite
Optical

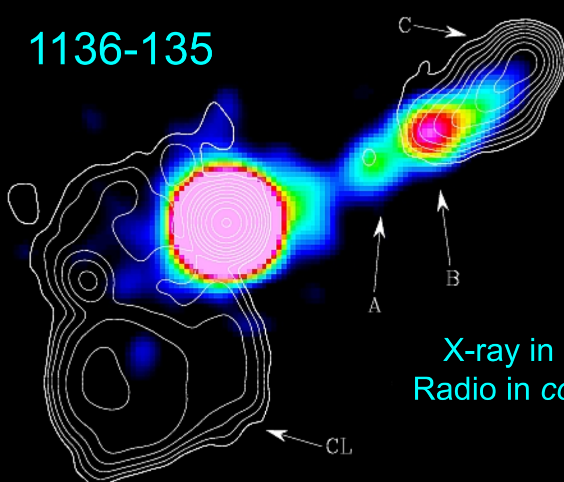
Cen A jet



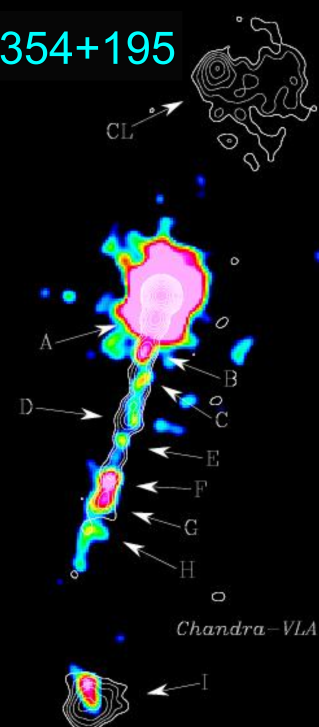
Optical, X-ray composite

kpc X-ray jets

1136-135



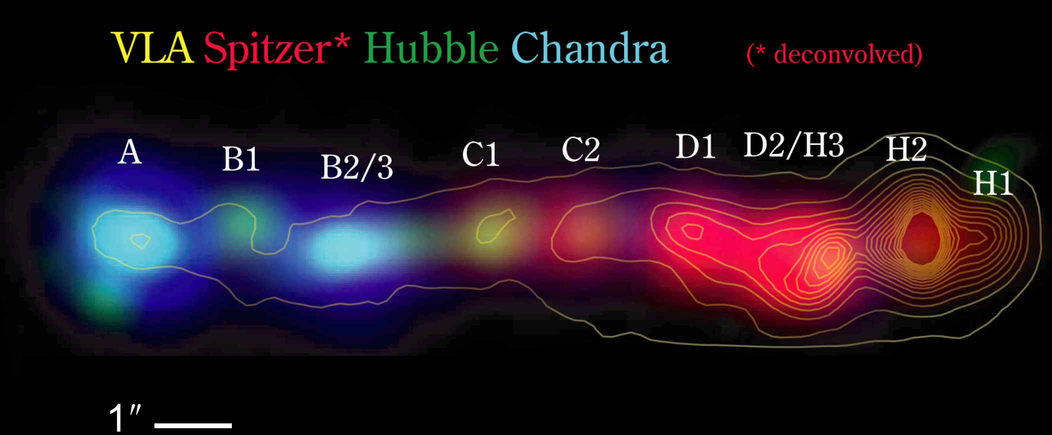
1354+195



X-ray in *color*
Radio in *contours*

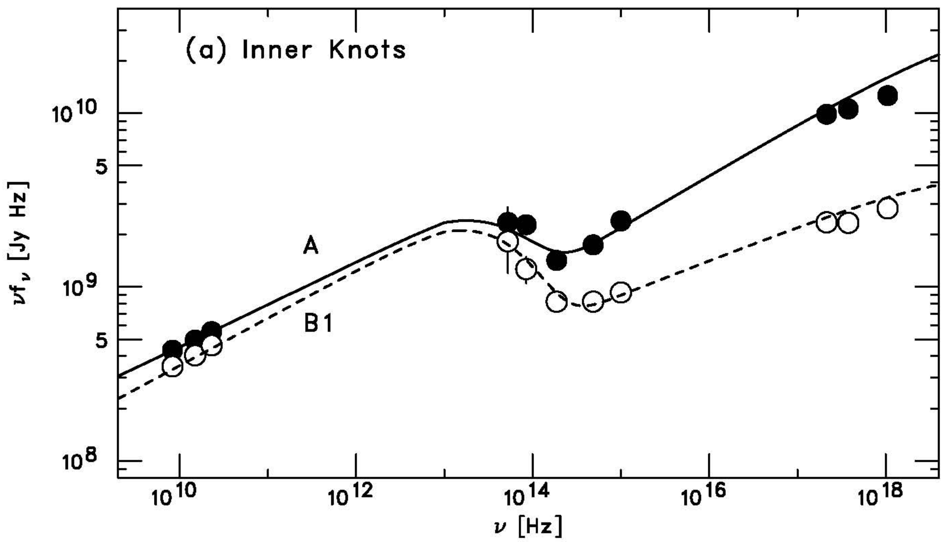
Sambruna et al. 2002, with Cheung, Maraschi, Scarpa, Tavecchio, CMU

3C 273 Outer Jet



Uchiyama et al. 2006, Jester et al. 2006

SEDs of 3C273 Jet Knots



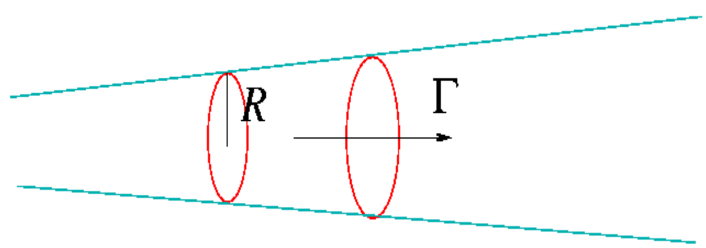
Resolved jets

- Inverse Compton scattering of CMB photons
  - – CMB photon density is strong function of redshift
- Requires *on large (kpc) scales*
  - – Relativistic electrons
  - – Relativistic bulk motion

Jet models

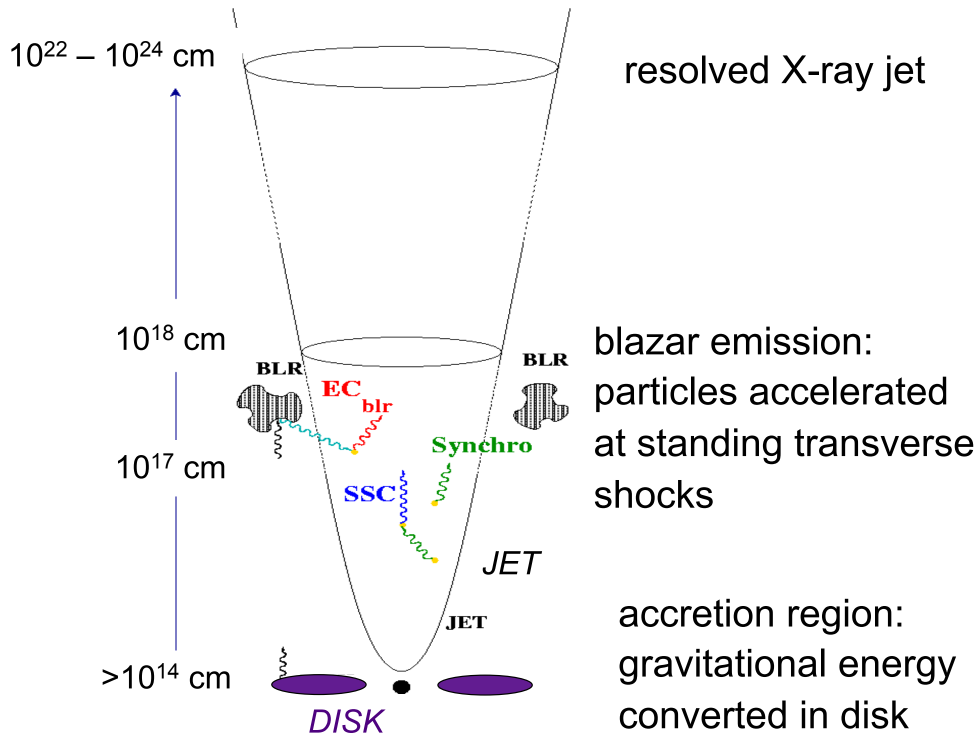
Shocks in jet

Jet Power



$P_{\rm jet} = \pi R^2 \Gamma^2 \beta c U$ *where* $U = U_B + U_e + U_p$

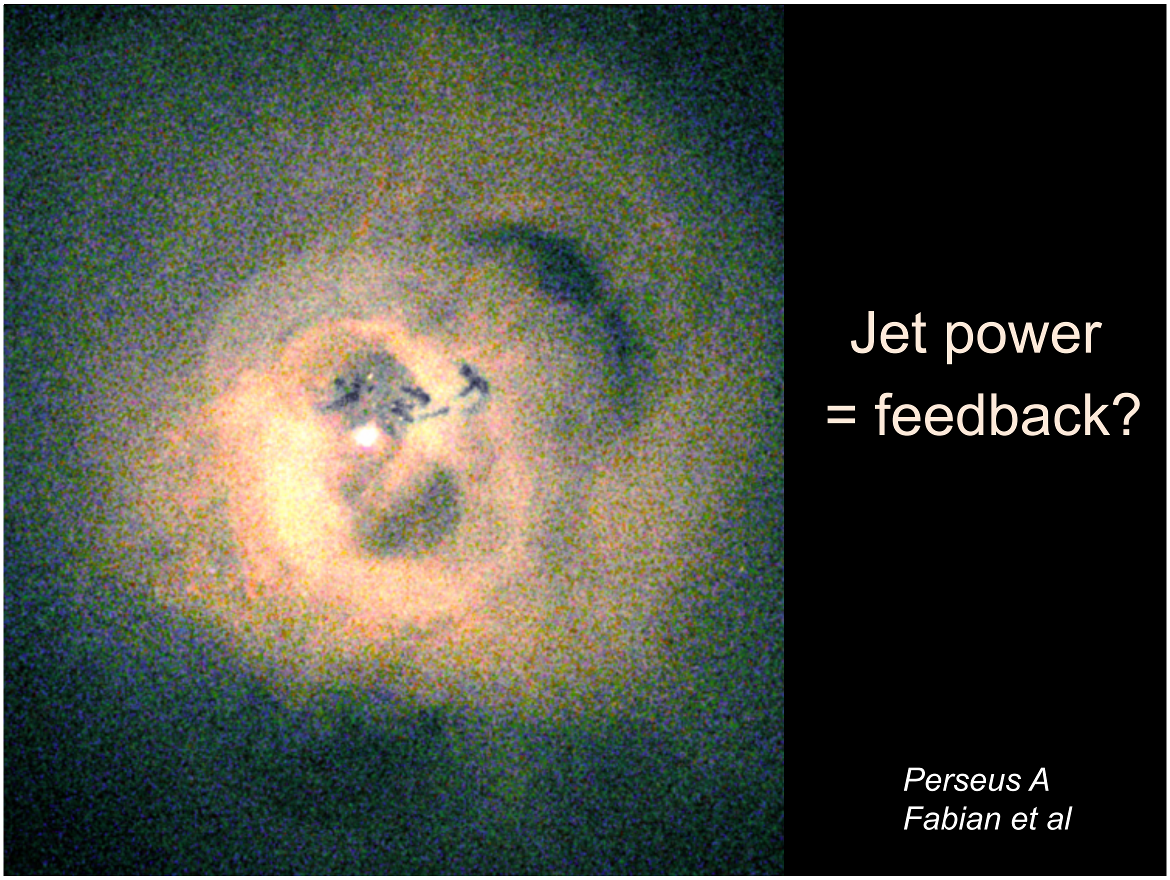
$$U_p + U_e = n m_e c^2 \left(< \gamma > + \frac{m_p}{m_e} \right)$$



Maraschi, Ghisellini & Celotti 1992; Sikora, Begelman & Rees 1994; Dermer & Schlickeiser 1993; Marscher et al. 2010, /Agudo et al. 2010 …

Accepted concepts:

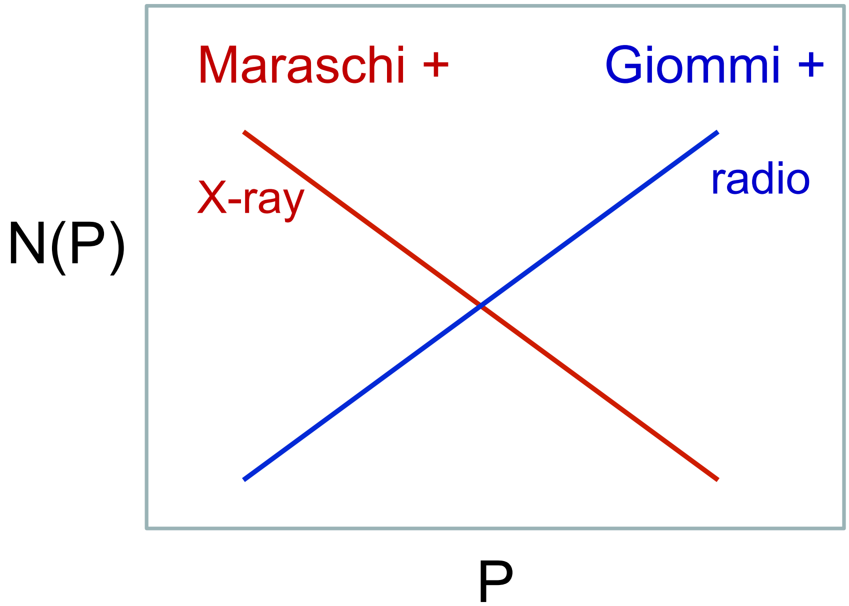
- Blazars = relativistic jets pointed at us
- Parent population = radio galaxies
  - FRI → BL Lacs (HBL)
  - Weak-lined FRII → BL Lacs (LBL)
  - FRII → FSRQ
- Range of intrinsic power. Linked to SED
  Fossati
- Particles accelerated by shocks in jet
- Blazars → jet physics



Observational results:

- Opt/IR well correlated with γ-rays *FSRQ, LBL*
- Lags < 1 day *SMARTS*
- Above peak: high variability *+ polarization*
- Correlation: same electron energy ***leptonic models***
- Polarization flips reported *Bjornsson et al. 1982a,b*
  - – "blob" on helical trajectory, or
  - – different regions light up ***multi-zone models***
- X-ray polarization coming *Astro-H!*

blazar demographics debate



New perspectives: demographics debate

- EGRET detected FSRQ, some LBL, few HBL
- Fermi detects more of each –
  - *But larger increase in HBL*
- That is, as flux limit ↓ ratio HBL:FSRQ ↑
- As predicted if HBL more numerous!
- This is logical: "Normal" luminosity function, with few high-luminosity blazars and many low-luminosity blazars

New perspectives: evolution

- Previously: $\langle V/V_m \rangle < 0.5$ for HBL, $\langle V/V_m \rangle > 0.5$ for FSRQ
- *Equivalently: few HBL at high z, few FSRQ at low z*
- Evolution FSRQ → BLL?

BUT

- Different evolution due to selection effect

  Brandt, Urry, Maraschi et al., in preparation

SO, do FSRQ evolve to BL Lacs?

- Not necessary

Open issues

- Ultra-high-speed outflows → $\Gamma \sim 100$
  PKS 2155-304
- Hadronic v. leptonic models
  - Variability favors SSC/EC models
  - Neutrino detection would be unambiguously in favor of hadronic models
- Big goal: jet kinetic energy
  - (Eddington limit should include total energy)

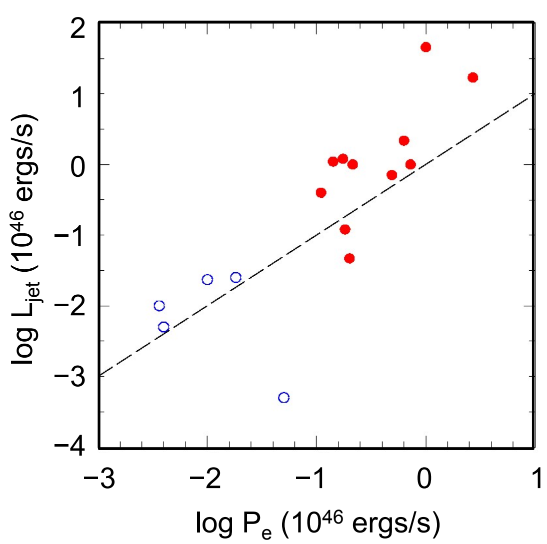
Open issues

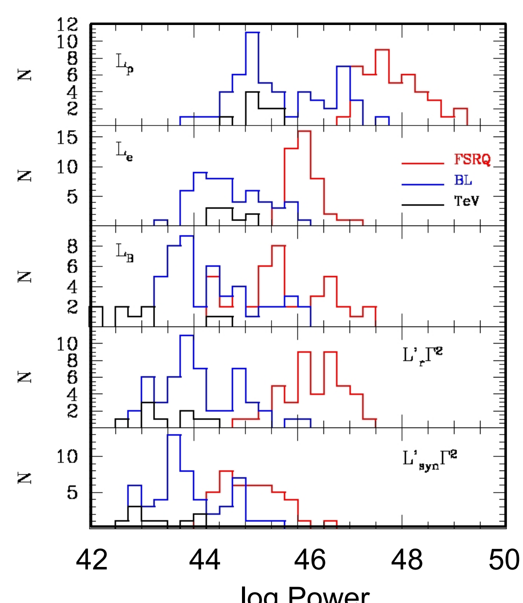
Intrinsic parameters + Doppler beaming

→ observed blazar properties … ***BUT***

- Doppler factor (*guess*) + emission mechanism (*debated*) → physical parameters (*very uncertain*)
- Particle composition uncertain (*x2000 in energy!*)
- $N(P_{kinetic})$ of jets hotly debated since 1990s

Jet power, matter content





If $P_e < L_{jet}$ → protons

Celotti & Ghisellini 2002, Maraschi & Tavecchio 2004, Wardle 1998, Hirotani et al. 2000