The Doppler Crisis of TeV Blazars

Fermi Summer School

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Julius-Maximilians-
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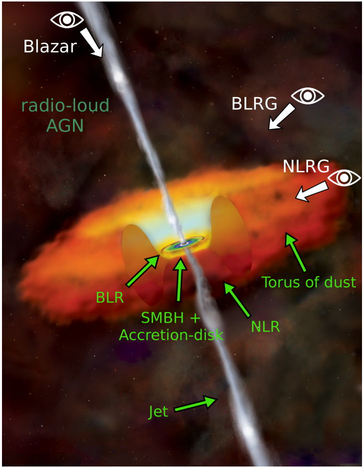
WÜRZBURG

Unification Scheme

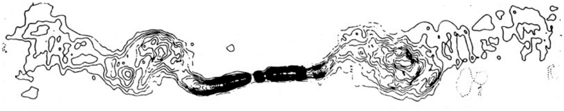


Adapted from: NASA/CXC/M.Weiss

- AGN classifications based on spectral lines, luminosity, morphology, etc.
- Unification: Only two parameters defining AGN types
  $\Rightarrow$ (radio-)luminosity
  $\Rightarrow$ inclination angle
- relativistic jet in radio-loud AGN
- Low inclination angle leads to Doppler boosting

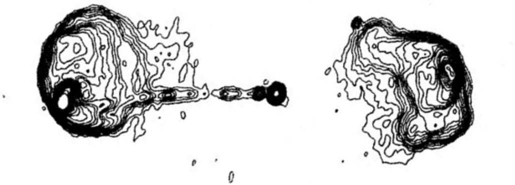
Morphological classification by Fanaroff and Riley

FR 1: $\log(L) < 24.5$



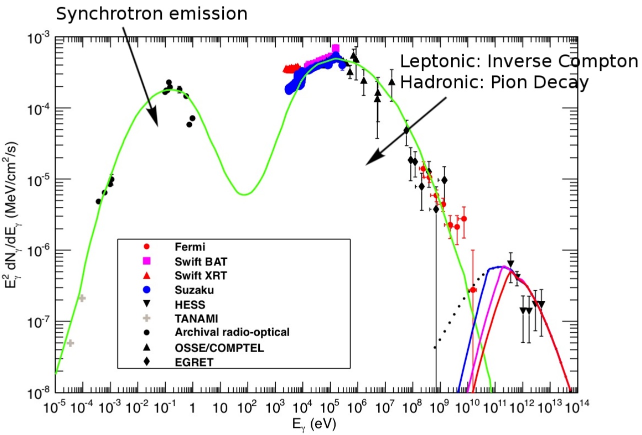
3C449 from Perley et al., 1979

FR 2: $\log(L) > 26$



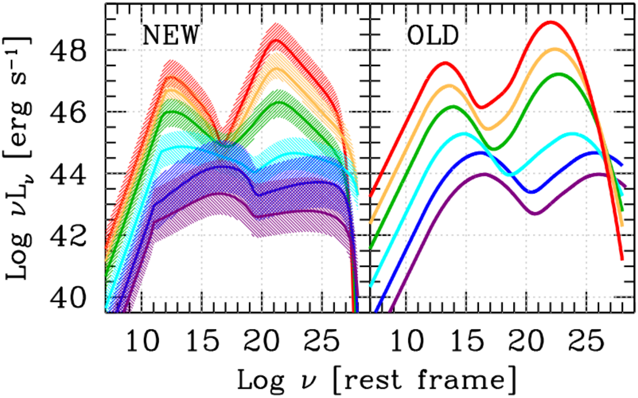
3C47 from Bridle et al., 1994

Blazars: Spectral Energy Distribution



Adapted from: Sahu et al., 2012

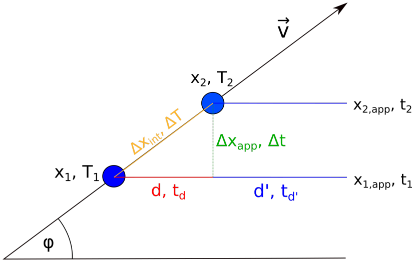
The Blazar Sequence

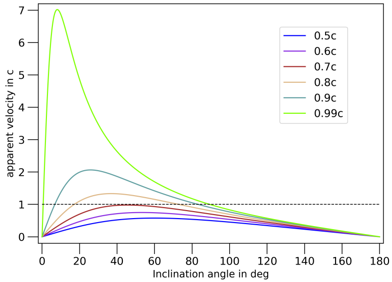


Credit: Ghisellini et al., 2017

- High-frequency-peaked BL Lac $\nu_{\rm sp} > 10^{15}\,\rm Hz$

Apparent Superluminal Motion





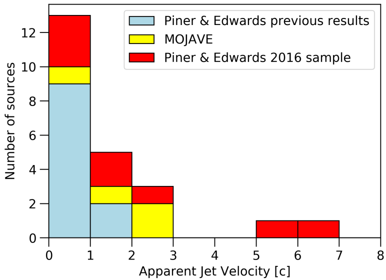
$$\beta_{\mathrm{app}} = \frac{\beta_{\mathrm{int}} \sin(\phi)}{1 - \beta_{\mathrm{int}} \cos(\phi)}$$

TeV blazars: Observations

- Ground based telescopes like H.E.S.S., MAGIC and VERITAS
- Over 200 sources listed at `tevcat.uchicago.edu`
- Majority of extragalactic objects are HBL
- Rapid and strong flares in several sources, e.g. PKS 2155−304, Mrk 501, Mrk 421
- Flux variability down to minutes ($\sim 600\,\mathrm{s}$)
- Very small emitting regions $\Rightarrow$ Heavily boosted with $\Gamma \sim 50$ and $\delta \sim 100$

Kinematic studies of HBLs

- Majority of kinematic studies by Piner and Edwards
- VLBA observations at $\sim 10\mathrm{s\,GHz}$
- Slow apparent motions in all sources
- e.g. 2155-304: $v_{\mathrm{app}} = (0.93 \pm 0.31)c$
- modest brightness temperatures

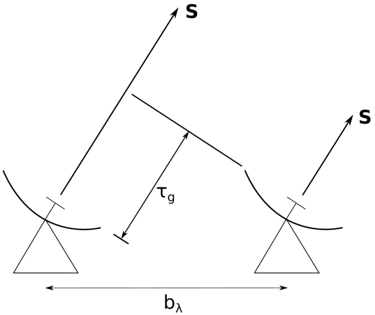


Reproduced from Piner and Edwards, 2016

- slow apparent speeds (radio) vs. high Lorentz factors (γ) $\Rightarrow$ Doppler Crisis

Two-Element Interferometer

Two antennas with geometrical delay τ_g and baseline b_λ



Interferometer measures the complex visibility:

$$V_{ij} = \int A(\sigma) B_\nu(\sigma) \exp\left(i2\pi b_{ij,\lambda} \times \sigma\right) \mathrm{d}\Omega$$

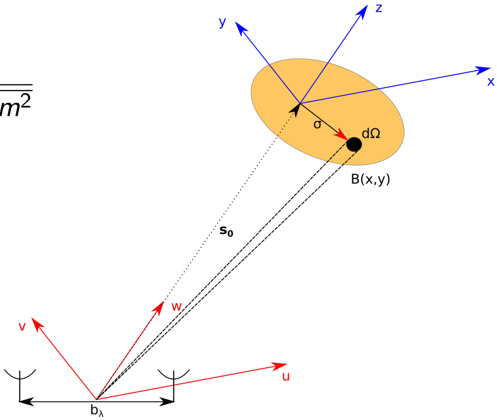
The (u, v)-plane

$$V_{ij} = \int A(l,m) B_\nu(l,m)$$
$$\exp\left[i 2\pi (ul + vm)\right] \frac{\mathrm{d}l \mathrm{d}m}{\sqrt{1 - l^2 - m^2}}$$

Small angle approximation:

$$V_{ij} \approx \int A(x,y) B(x,y)$$
$$\exp\left[i 2\pi (ux + vy)\right] \mathrm{d}x \mathrm{d}y$$

$$\Rightarrow B(x,y) \overset{\mathrm{FT}}{\rightleftarrows} V(u,v)$$



Aperture Synthesis with Arrays

- Earth rotation synthesis: δ-dependence
- Closure relations:
  - $\phi_{ijk} = \bar{\phi}_{ij} + \bar{\phi}_{jk} + \bar{\phi}_{ki}$
  - $A_{ijkl} = \frac{|\bar{V}_{ij}||\bar{V}_{kl}|}{|\bar{V}_{ik}||\bar{V}_{jl}|}$
- $V_{\text{measured}} = w(u, v)W(u, v)V(u, v)$

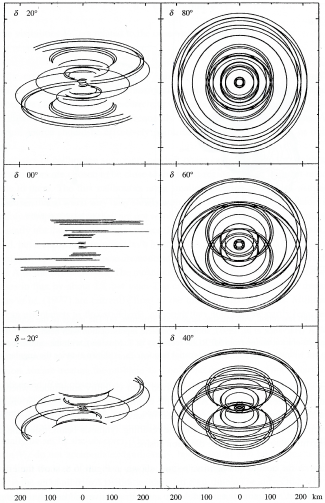
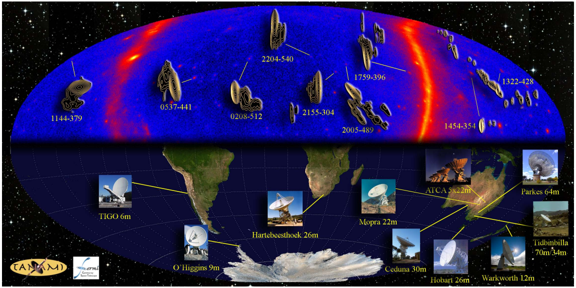


Figure: Credit: Burke and Graham-Smith, 2010

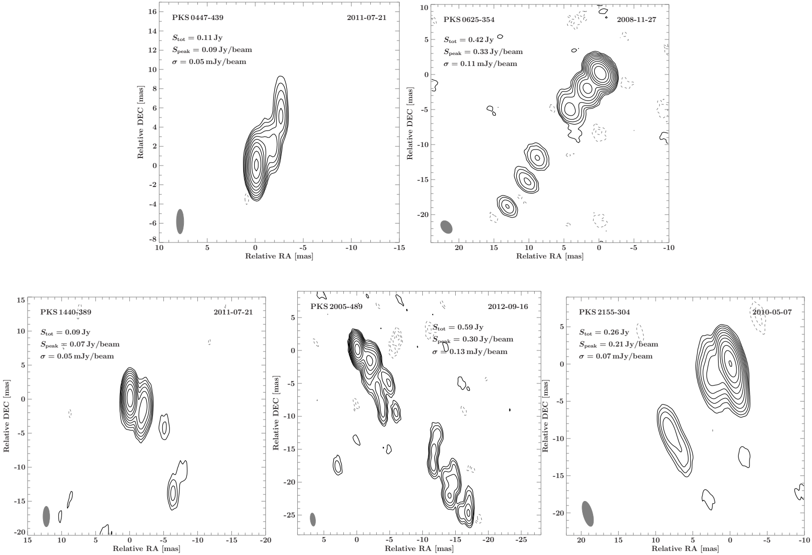
TANAMI



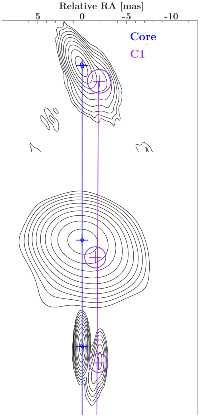
Credit: Matthias Kadler

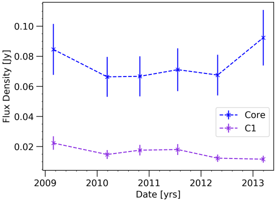
- Tracking Active Galactic Nuclei with Austral Milliarcsecond Interferometry
- multiwavelength program with VLBI at its core
- Sample of Southern sources $\delta < -30^\circ$

The Sample

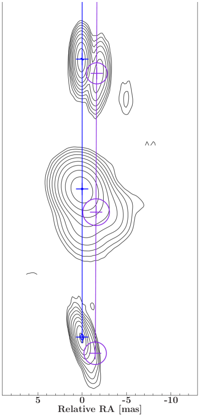

PKS 0447-439
2011-07-21
$S_{\rm tot}$ = 0.11 Jy
$S_{\rm peak}$ = 0.09 Jy/beam
σ = 0.05 mJy/beam
PKS 0625-354
2008-11-27
$S_{\rm tot}$ = 0.42 Jy
$S_{\rm peak}$ = 0.33 Jy/beam
σ = 0.11 mJy/beam
PKS 1440-389
2011-07-21
$S_{\rm tot}$ = 0.09 Jy
$S_{\rm peak}$ = 0.07 Jy/beam
σ = 0.05 mJy/beam
PKS 2005-489
2012-09-16
$S_{\rm tot}$ = 0.59 Jy
$S_{\rm peak}$ = 0.30 Jy/beam
σ = 0.13 mJy/beam
PKS 2155-304
2010-05-07
$S_{\rm tot}$ = 0.26 Jy
$S_{\rm peak}$ = 0.21 Jy/beam
σ = 0.07 mJy/beam
Relative DEC [mas]
Relative RA [mas]

PKS 1440−389: Kinematic analysis

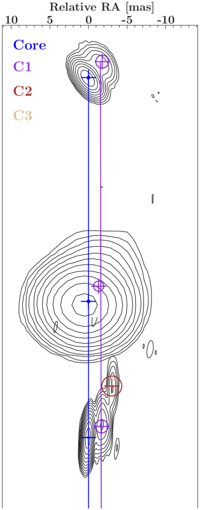


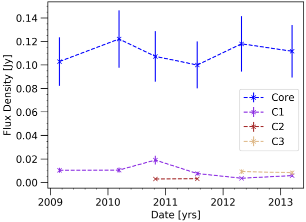


- HBL at $0.14 < z < 2.2$
- Compact jet to southwest
- one component with $\beta_{\text{app}} = 0.99 \pm 0.73$
- stable flux density

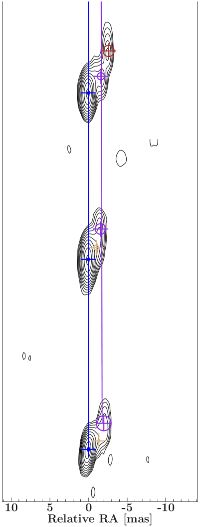


PKS 0447−439: Kinematic analysis

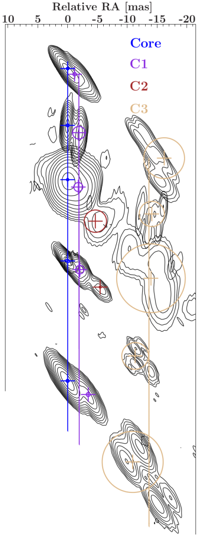


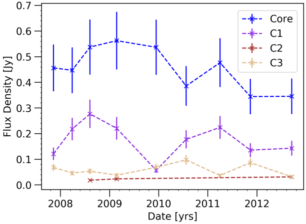


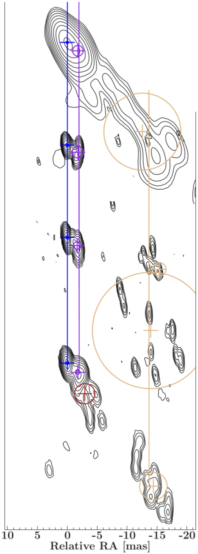
- HBL (initially Seyfert I), redshift ambiguous
- superluminal component with $\beta_{\mathrm{app}} = 5.4 \pm 2.5$
- stable flux density



PKS 2005−489: Kinematic Analysis

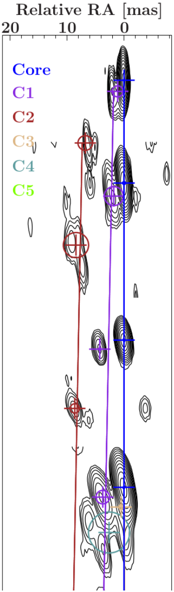


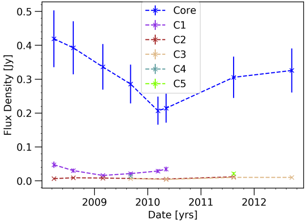




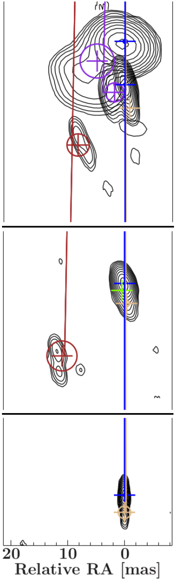
- radio flux density of $\sim 0.56 - 0.88\,\mathrm{Jy}$
- jet difficult to model
- inner component stationary

PKS 2155−304: Kinematic Analysis



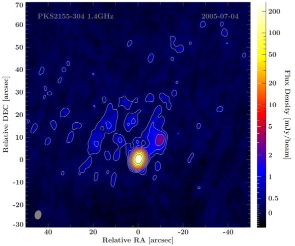


- huge flare in 2006
- variable flux density
- possible jet bending
- all comps. superluminal, fastest $\beta_{\mathrm{app}} = 7.8 \pm 2.5$

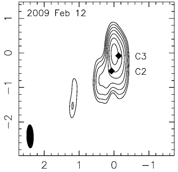


PKS 2155−304: Jet Bending

Small-scale bending ($\sim 75\,^{\circ}$) in Piner et al., 2010 and large scale bending proposed in Seeg, 2017:

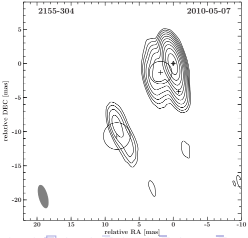


Credit: Seeg, 2017

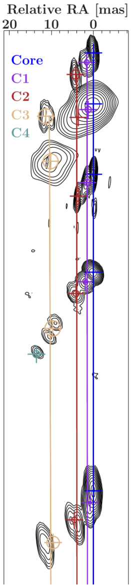


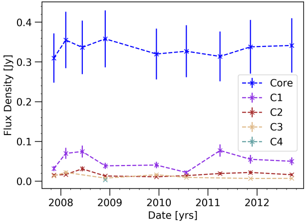
Credit: Piner et al., 2010

Small scale jet-bending at $8.4\,\mathrm{GHz}$
from C3 to C1 with bending of $\sim 47\,^{\circ}$

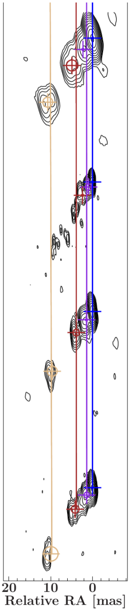


PKS 0625−354: Kinematic Analysis



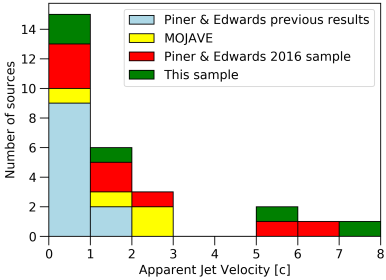


- fastest component at $\beta_{\mathrm{app}} = 1.07 \pm 0.89$
- morphology $\rightarrow$ FR I, spectrum $\rightarrow$ BL Lac
- computed inclination angle as $\phi < 59^\circ$



Implications for the Doppler Crisis

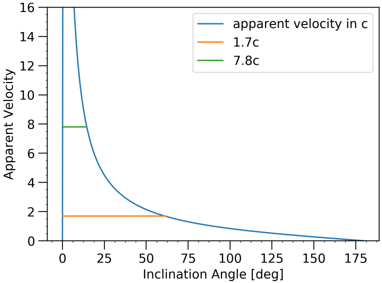
- Previous kinematic studies on HBLs done by only one group
- Goal: independent study of Southern TeV Blazars
- Result: Mostly slow and stationary, but also superluminal components
- Distribution requires more statistical analysis
- If Doppler Crisis true: How to explain the discrepancy?



Adapted from Piner and Edwards, 2016

Problems and Models

- PKS 2155−304: $\Gamma \sim 50$ or $\beta_{\mathrm{int}} \sim 0.9998$
- Plotting $\beta_{\mathrm{app}} = \frac{\beta_{\mathrm{int}} \sin(\phi)}{1-\beta_{\mathrm{int}} \cos(\phi)}$ for two speeds of PKS 2155−304
- $\phi \ll 1^\circ \Rightarrow$ Huge linear sizes $\sim 220\,\mathrm{Mpc}$ for $\phi \sim 0.01^\circ$ $\Rightarrow \phi = 10.9^\circ$ (Seeg, 2017)
- Tiny jet opening angles ζ $\Rightarrow$ Seeg, 2017: $\zeta = 3.4^\circ$
- Single-zone model insufficient
  - Deceleration along jet axis (Georganopoulos and Kazanas, 2003)
  - Spine-Sheath model (Ghisellini et al., 2005)



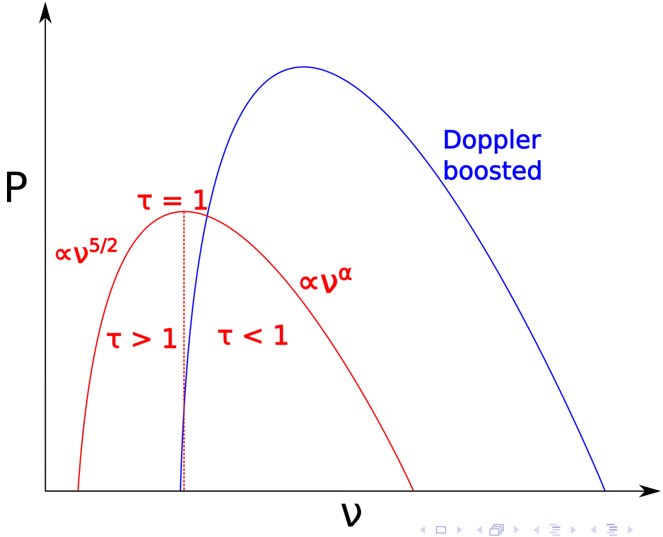
Summary

- Doppler Crisis: Discrepancy of derived intrinsic Lorentz factors in the γ-rays and the small apparent speeds from kinematic anylsis in the radio-frequencies
- Aim is to perform an independent kinematic analysis for TeV blazars from the TANAMI sample
- Extended results to Piner & Edwards gained:
  - Many components stationary or subluminal
  - But: peak velocities at $\sim 8c$ and $\sim 6c$
- Further research on Doppler Crisis required
- Inclination of PKS 0625−354 restricted to be between BL Lac and FR 1
- More jet-bending in PKS 2155−304 proposed

Backup Slides

Doppler Beaming

Cone-shaped emission of relativistic particles with opening $\sim \Gamma^{-1}$
$D = \nu_{\rm obs}/\nu_{\rm emit}$ and $S(\nu_{\rm obs}) = D^{3-\alpha} S(\nu_{\rm emit})$



Resolution

Smallest resolvable angle is given by Rayleigh criterion

$$\theta \sim \frac{\lambda}{D}, \quad [\theta] = 1\,\mathrm{rad}$$

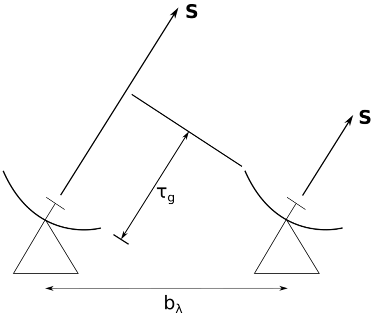
Consider $\lambda = 3.5\,\mathrm{cm}$ (radio frequencies)
and $D = 100\,\mathrm{m}$ (Effelsberg)

$$\Rightarrow \theta \approx 1.2\,\mathrm{arcmin}$$

But we need $\theta \lesssim 1\,\mathrm{mas}$ for kinematics!
$\Rightarrow$ Very Long Baseline Interferometry

Two-Element Interferometer

Two antennas with geometrical delay τ_g and baseline b_λ



Interferometer measures the complex visibility:

$$V_{ij} = \int A(\sigma) B_\nu(\sigma) \exp\left(i 2\pi b_{ij,\lambda} \times \sigma\right) \mathrm{d}\Omega$$

The (u, v)-plane

$$V_{ij} = \int A(l, m) B_\nu(l, m)$$

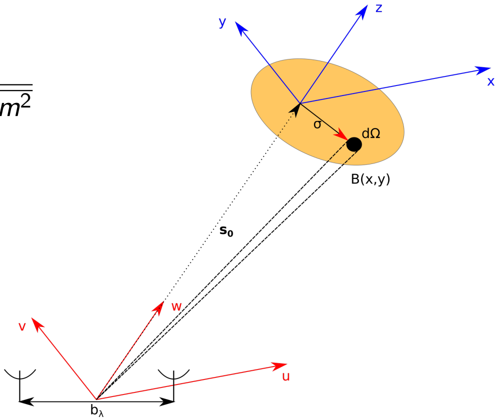
$$\exp\left[i2\pi(ul + vm)\right] \frac{\mathrm{d}l\mathrm{d}m}{\sqrt{1 - l^2 - m^2}}$$

Small angle approximation:

$$V_{ij} \approx \int A(x, y) B(x, y)$$

$$\exp\left[i2\pi(ux + vy)\right] \mathrm{d}x\mathrm{d}y$$

$$\Rightarrow B(x, y) \overset{\mathrm{FT}}{\rightleftarrows} V(u, v)$$



Imaging with CLEAN and SELFCAL

Task: Deconvolution of complex visibility with dirty beam and inverse Fourer transform
Method: Hybrid Imaging
CLEAN algorithm from Högbom, 1974

- Place windows over brightest peaks in dirty image
- Subtraction from dirty image with gain $\gamma \leq 1$
- repeat until coherent model is found

Reduction of Errors with SELFCAL

$$S = \sum_k \sum_{ij} w_{ij}(t_k) \left| V_{ij}^{\mathrm{cal}} - g_i(t_k) g_j^*(t_k) V_{ij}^{\mathrm{mod}}(t_k) \right|^2$$

Usage of several phase and amplitude selfcals during imaging

Inclination of PKS 0625−354

Inclination angle given by flux ratio:

$$\phi = \arccos\left[\frac{1}{\beta}\frac{\left(\frac{S_{\rm jet}}{S_{\rm counter}}\right)^{\frac{1}{3-\alpha}} - 1}{\left(\frac{S_{\rm jet}}{S_{\rm counter}}\right)^{\frac{1}{3-\alpha}} + 1}\right]$$

Venturi et al., 2000 computes $\phi < 61^\circ$ and $\phi < 43^\circ$ with another method

Use flux of inner two components and approximate counter-jet with 5σ
$\Rightarrow$ average over all epochs

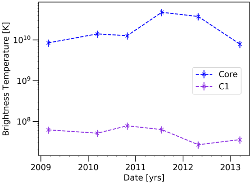
$$\phi < 59^\circ$$

$\Rightarrow$ intermediate object, neither FR 1 nor BL Lac

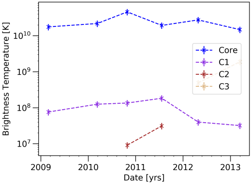
Brightness Temperatures

$$T_b = \frac{2\ln 2}{\pi k_B}\frac{S_c \lambda^2 (1+z)}{\theta_{\mathrm{maj}}\theta_{\mathrm{min}}}$$

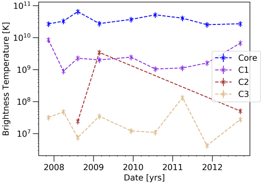
(Kovalev, 2005)



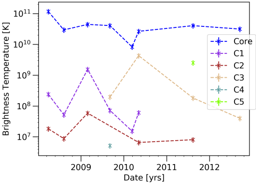
PKS 1440−389



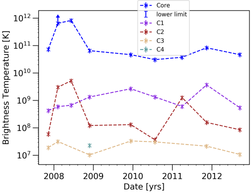
PKS 0447−439



PKS 2005−489



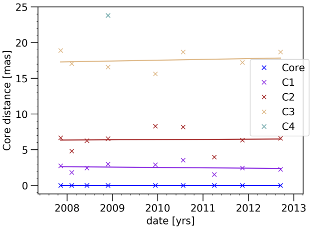
PKS 2155−304

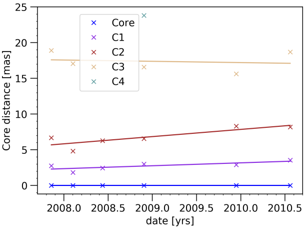


PKS 0625−354

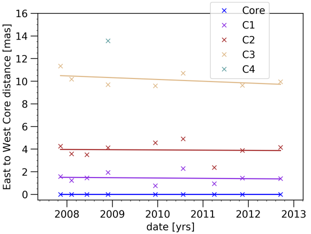
Fitting with Linear Regression

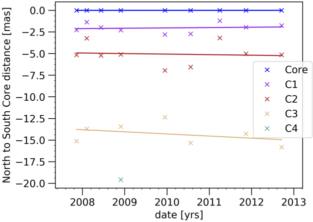
Radial method and comparison with Trüstedt, 2013:





Separate *x*- and *y*- fits with subsequent norm computation:





Apparent Velocities

Two Methods: Radial velocity or vectorial method, i.e. separate x- and y-velocites

Source Name	Label	$\beta_{\rm app,rad}$	$\beta_{\rm app,vec}$
PKS 1440−389	C1	-0.03 ± 0.87	0.99 ± 0.73
PKS 0447−439	C1	4.9 ± 2.2	5.4 ± 2.5
PKS 2005−489	C1	0.26 ± 0.74	0.31 ± 0.41
	C3	3.2 ± 2.6	4.3 ± 2.2
PKS 2155−304	C1	5.7 ± 6.0	7.4 ± 6.0
	C2	6.6 ± 3.1	7.8 ± 2.5
	C3	-1.8 ± 1.4	1.7 ± 1.4
PKS 0625−354	C1	-0.18 ± 0.49	0.18 ± 0.41
	C2	0.11 ± 1.1	0.24 ± 0.96
	C3	0.4 ± 1.1	1.07 ± 0.89