VLBI and γ-ray studies of TANAMI radio galaxies

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collaborators:
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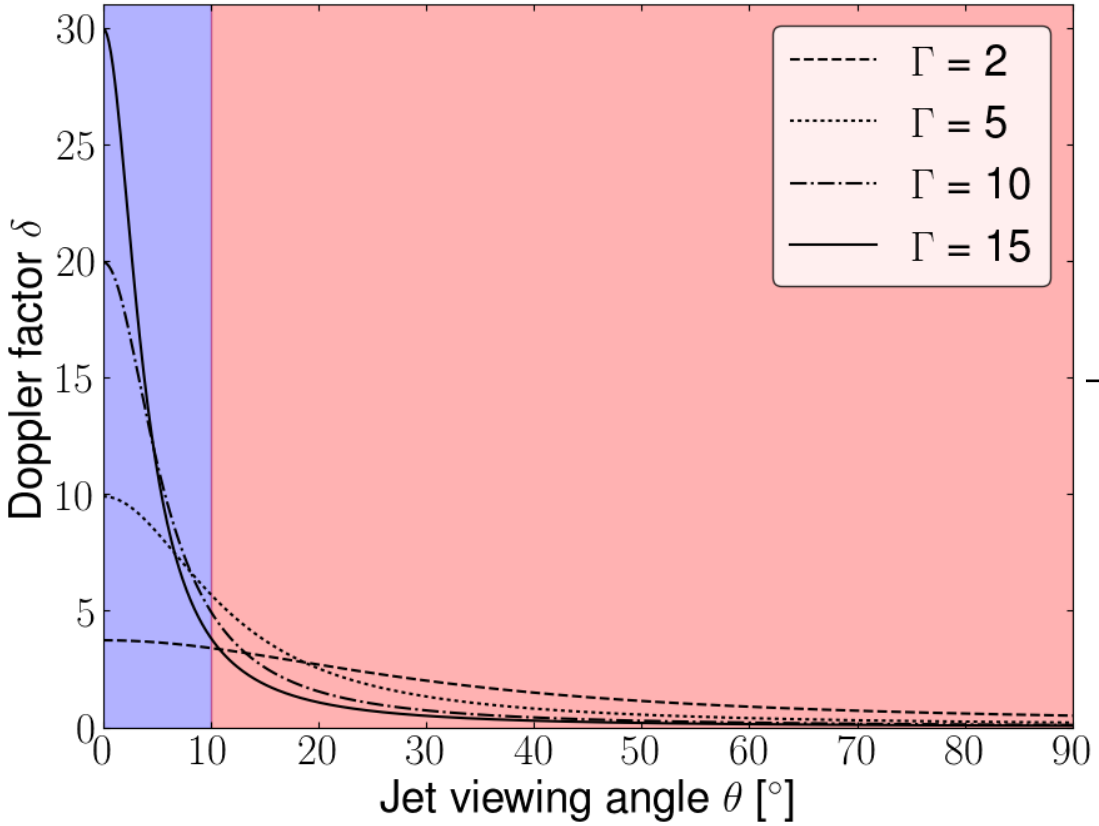
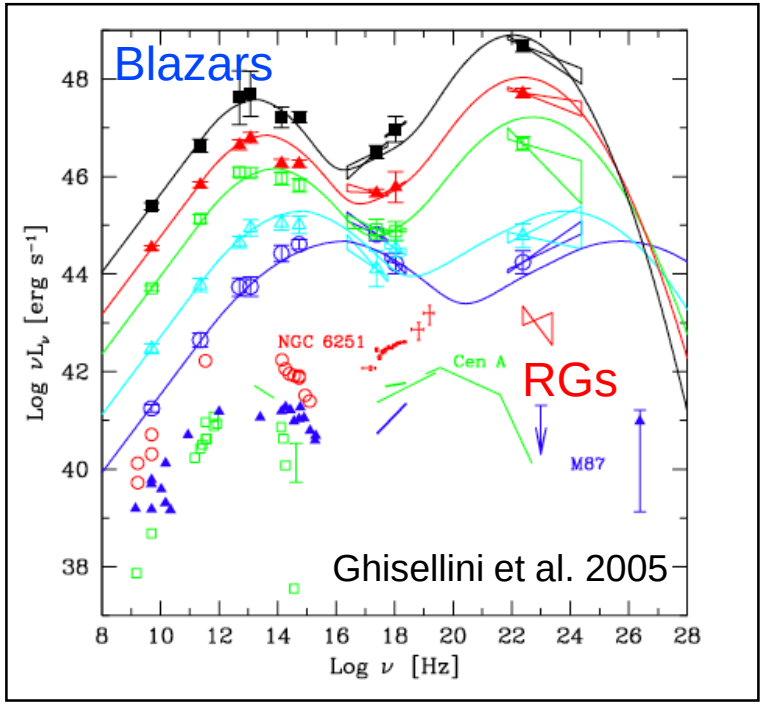
BACKGROUND

Radio galaxies

Radio galaxies: misaligned jets

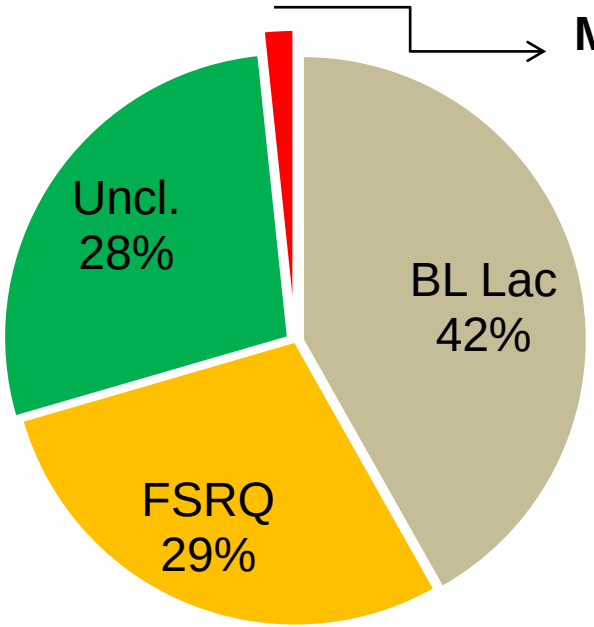
- The γ-ray sky is dominated by blazars → Doppler boosting dominated
- Radio galaxies are the misaligned parent population of blazars
  - Much less prominent jet Doppler boosting
  - Less jet-dominated SED
  - Much fainter at all wavelengths



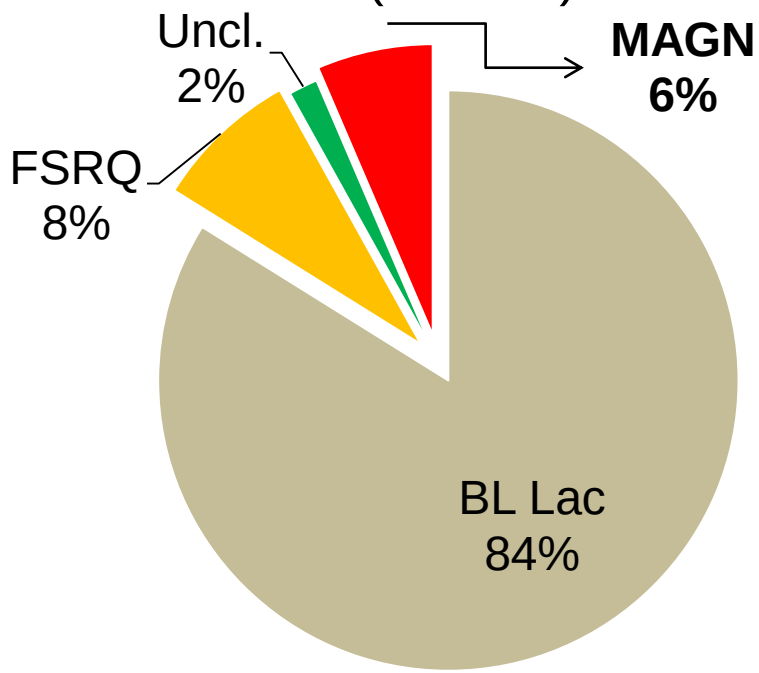


RGs as "disfavoured" high-energy sources

24 Misaligned AGN observed at HE (0.1-100 GeV) by ***Fermi*-LAT** 3LAC (Ackermann et al. 2015):



5 RGs observed at VHE (>100 GeV) by **IACTs** (TeVCat):



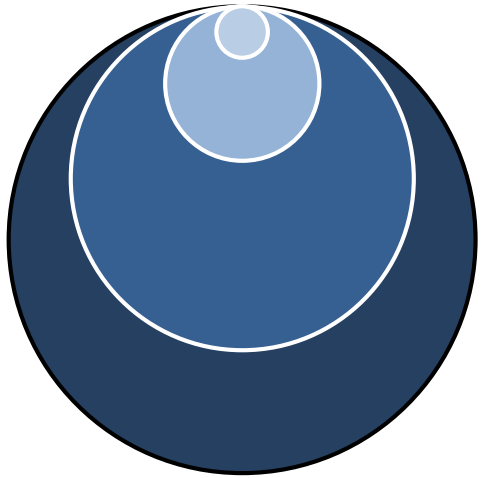
γ-ray RGs provide crucial information, but we have only few sources, particularly at Very-High Energies (VHE): **NGC 1275, Cen A, M 87, IC 310, PKS 0625-35**

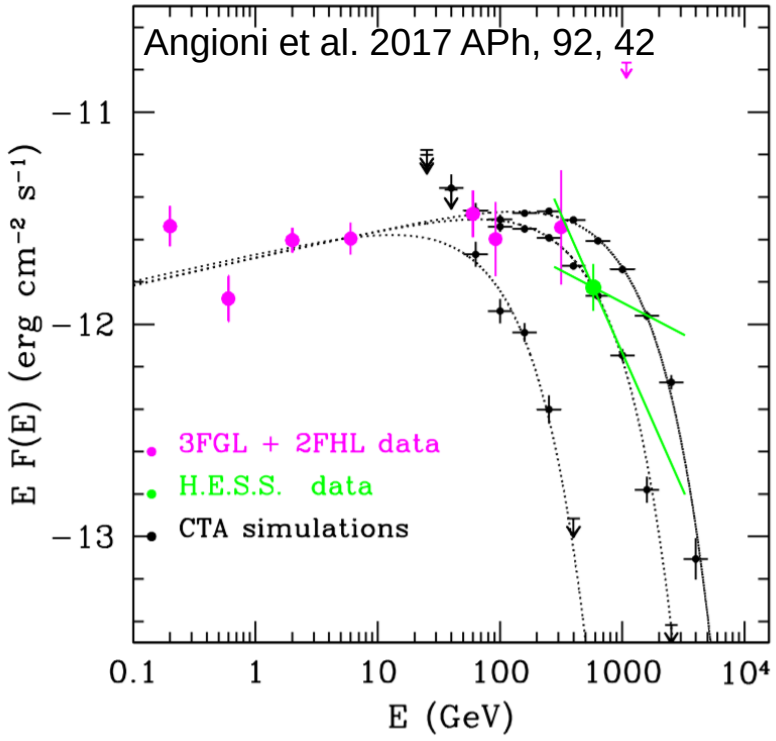
Can the upcoming **Cherenkov Telescope Array** increase the number of TeV detected RGs?

Discovery of new RGs with CTA

ctools: 50 h simulated CTA observations for all RG candidates

- All *Fermi* Misaligned AGN (24)
- TeV Misaligned AGN candidates (20)
- New detections with PL model (9)
- New detections with PL+cutoff model (3)





Best MAGN candidates for TeV detection:

- Local ($z < 0.1$)
- Flat spectrum ($\Gamma \leq 2.3$)

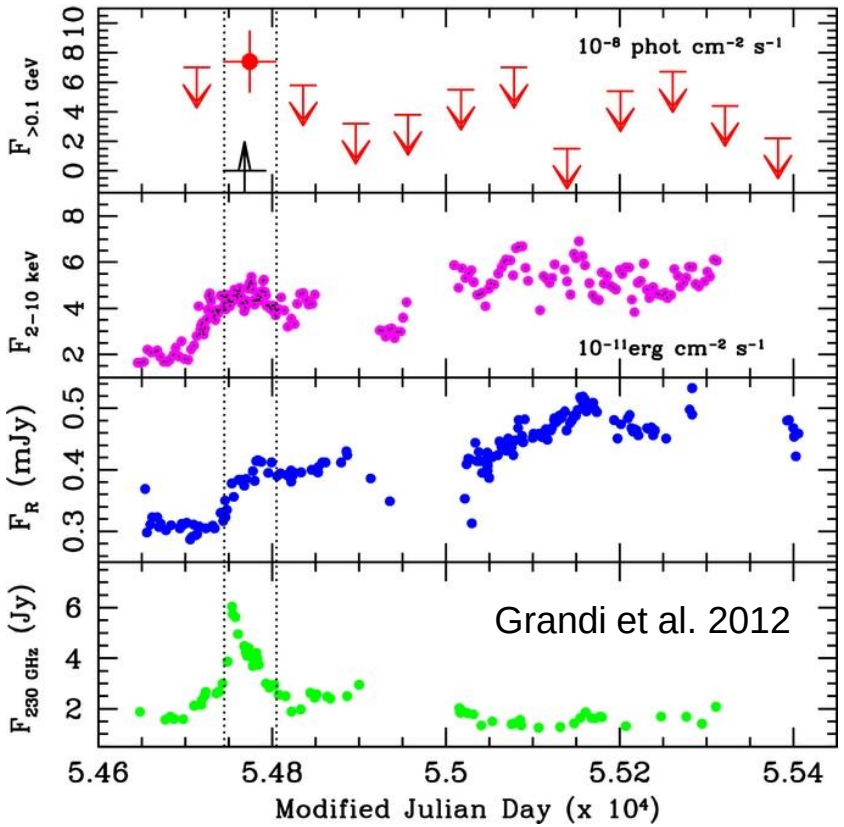
Note (Jul15): PKS 0625-35 probably already detectable

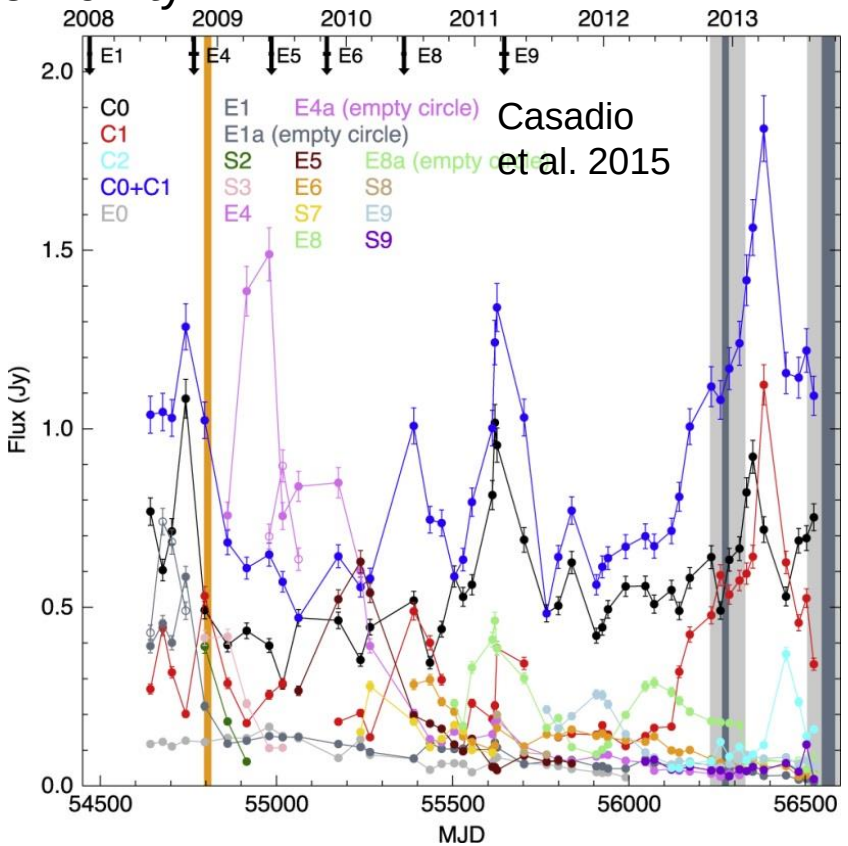
⬇

Detected by H.E.S.S.
(Dyrda+15, 34th ICRC proc.)

Fermi-LAT – VLBI connection in RGs

- Location of γ-ray emission region:
  - Upstream or downstream of radio VLBI core?
    - 3C 111 (Grandi+12) & 3C 120 (Casadio+15): γ-ray detections correspond to VLBI comp.ejection/core brightening
    - γ-rays come from upstream/core vicinity





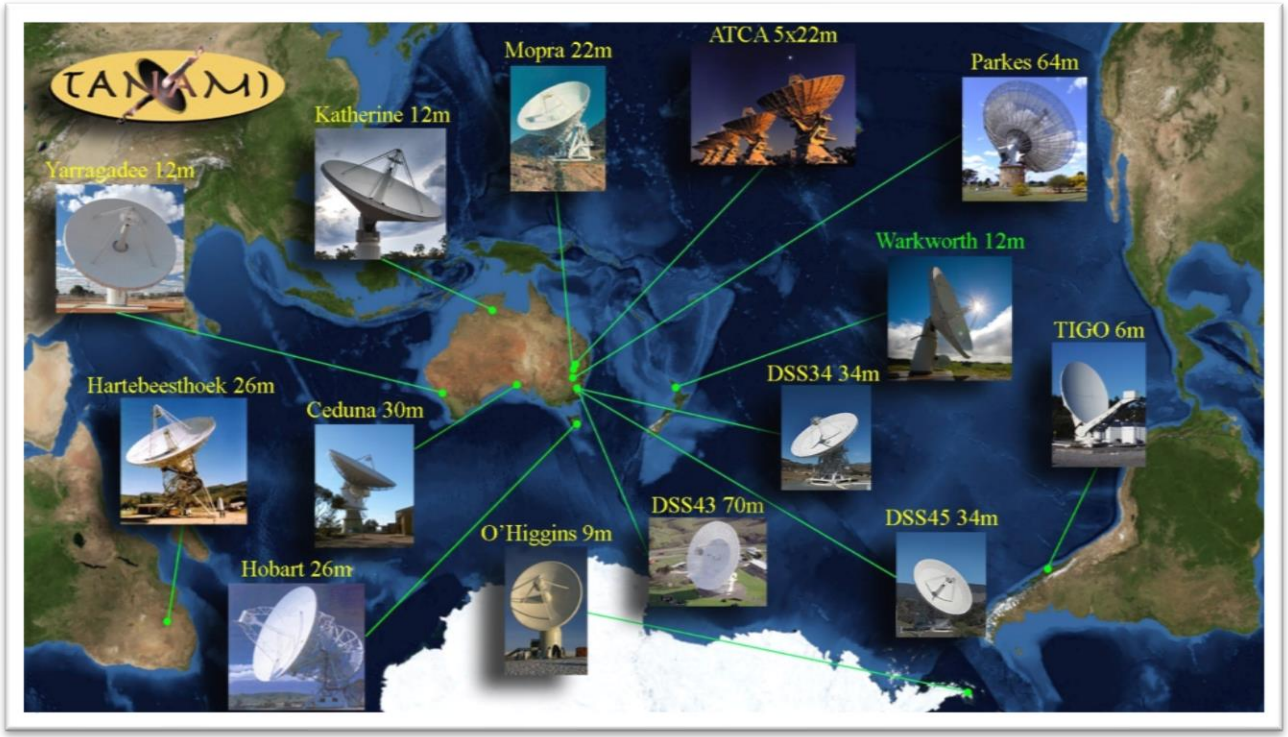
THE TANAMI PROGRAM

Multi-wavelength monitoring for the southern sky

The TANAMI program

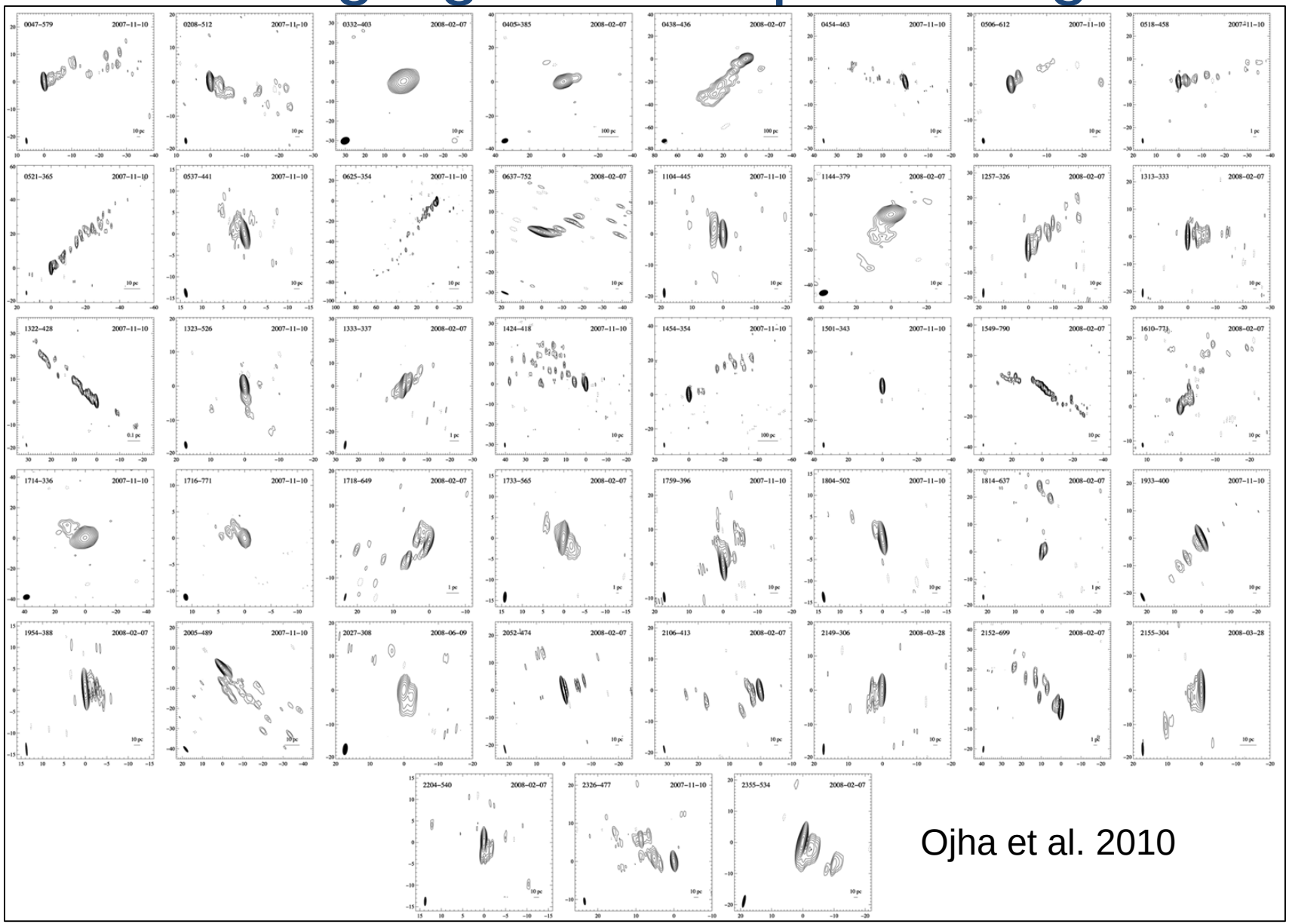
Tracking **A**ctive **N**uclei with **A**ustral **M**illiarcsecond **I**nterferometry

- ~90 jets at $\theta < -30^{\circ}$ declination at mas resolution since 2007
- Dual frequency 8.4 GHz and 22.3 GHz, 3-4 epochs/yr



Ojha+10 (First epoch maps)
Müller+11,14 (In depth study of CenA)
Krauss+16 (Dynamic blazar SEDs)
Kadler+16 (Neutrino-LAT flare coincidence)
Müller+17 (new sources maps, accepted)

TANAMI highlights: first-epoch images



Ojha et al. 2010

TANAMI highlights: new sources

New sources
Müller et al.
A&A accepted
arXiv:1709.03091

TANAMI RADIO GALAXIES

A multi-wavelength sample study

TANAMI radio galaxy sample

Table 1. TANAMI radio galaxies.

Source	Catalog	Class	z	RA(J2000)	Dec(J2000)	γ-ray det.
0518−458	Pictor A	FR II	0.035	79.957	−45.779	yes
0521−365	PKS 0521−36	RG/SSRQ	0.055	80.742	−36.459	yes
0625−354	PKS 0625−35	FR I/BLL	0.055	96.778	−35.487	yes
1258−321	PKS 1258−321	FR I	0.0170	195.253	−32.441	no
1322−428	Centaurus A	FR I	0.0018	201.365	−43.019	yes
1333−337	IC 4296	FR I	0.0125	204.162	−33.966	no
1343−601	Centaurus B	FR I	0.0129	206.704	−60.408	yes
1549−790	PKS 1549−79	RG/CFS	0.150	239.245	−79.234	no
1600−489	PMN J1603−4904	MSO[a]	0.18	240.961	−49.068	yes
1718−649	PKS 1718−649	GPS/CSO	0.0144	260.921	−65.010	yes[b]
1733−565	PKS 1733−56	FR II	0.098	264.399	−56.567	no
1814−637	PKS 1814−63	CSS/CSO	0.0627	274.896	−63.763	no
1934−638	PKS 1934−63	GPS	0.18	294.854	−63.713	no
2027−308	PKS 2027−308	RG	0.539	307.741	−30.657	no
2152−699	PKS 2153−69	FR II	0.0283	329.275	−69.690	no

[a] Classified as a young radio galaxy based on multi-wavelength studies (Müller et al. 2014, 2015, 2016).
[b] Migliori et al. (2016).

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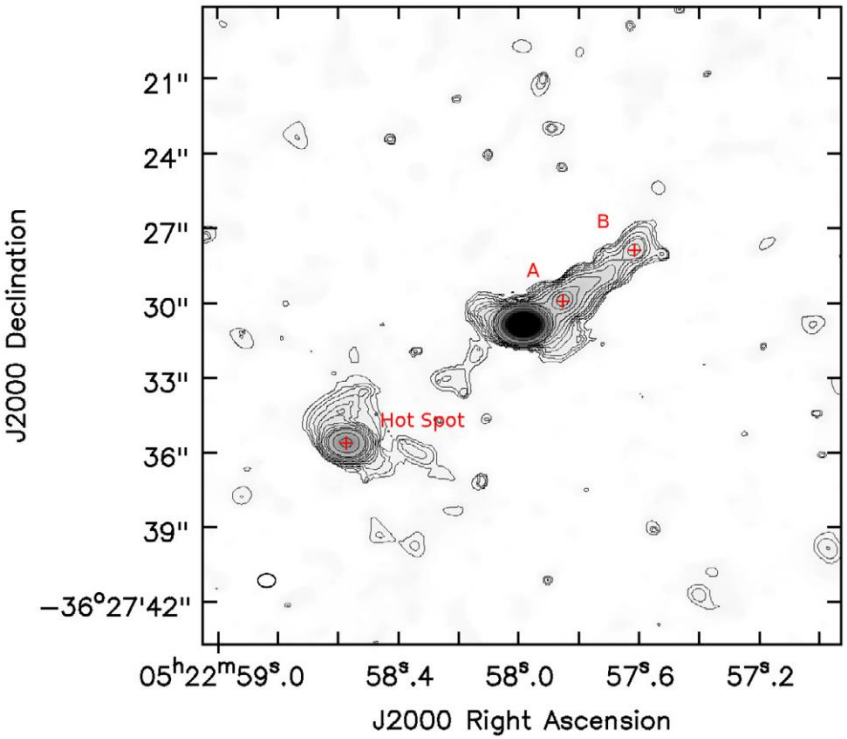
Pictor A

Image credit:
X-ray: NASA/CXC/Univ. of Hertfordshire/M. Hardcastle et al.
Radio: CSIRO/ATNF/ATCA

Classic FR II, $z = 0.035$

- Earlier VLBI study found jet viewing angle $\theta < 51°$ (Tingay+00)
- Detected by *Fermi*-LAT in 2012 (Brown+12) flux underestimated by SED model of western hot-spot, probably jet origin/contribution

PKS 0521−36



Miscl. BLL, likely RG-SSRQ, $z = 0.055$

- Small core dominance suggests weak boosting (Pian+96)
- SED spine-sheath model suggests viewing angles $6° < \theta < 15°$ (D'Ammando+15)
- ALMA view of large-scale structure supports small beaming and large angle (Leon+16)

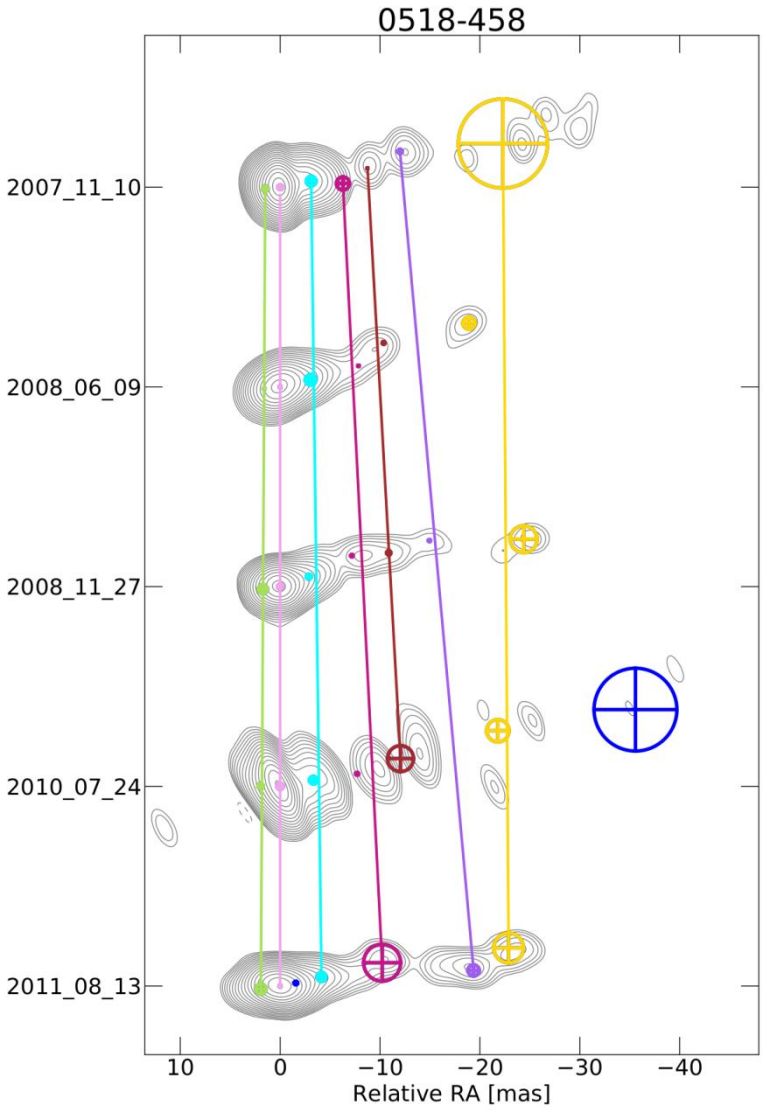
Image credit:
ALMA Band 3,6,7: Leon et al. 2016, A&A 586,70

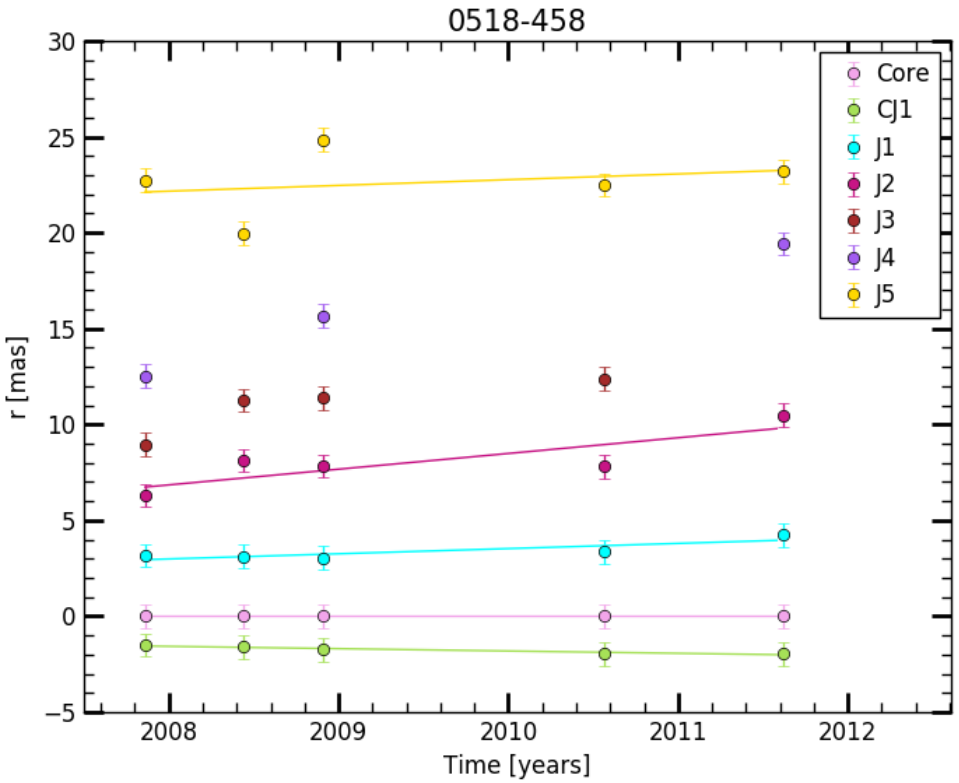
RESULTS

VLBI kinematics

Kinematic analysis: Pictor A

Angioni+ in prep.

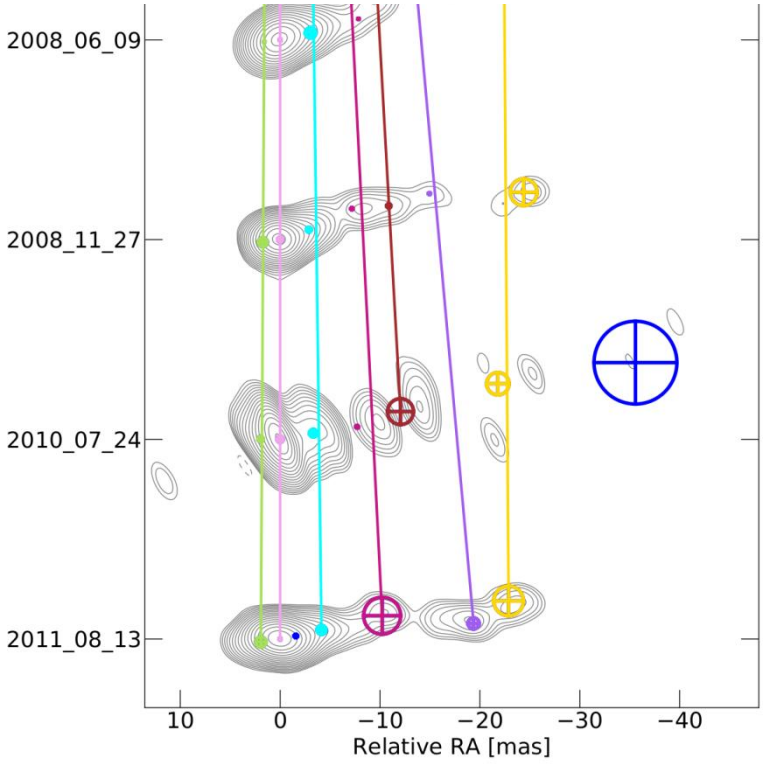


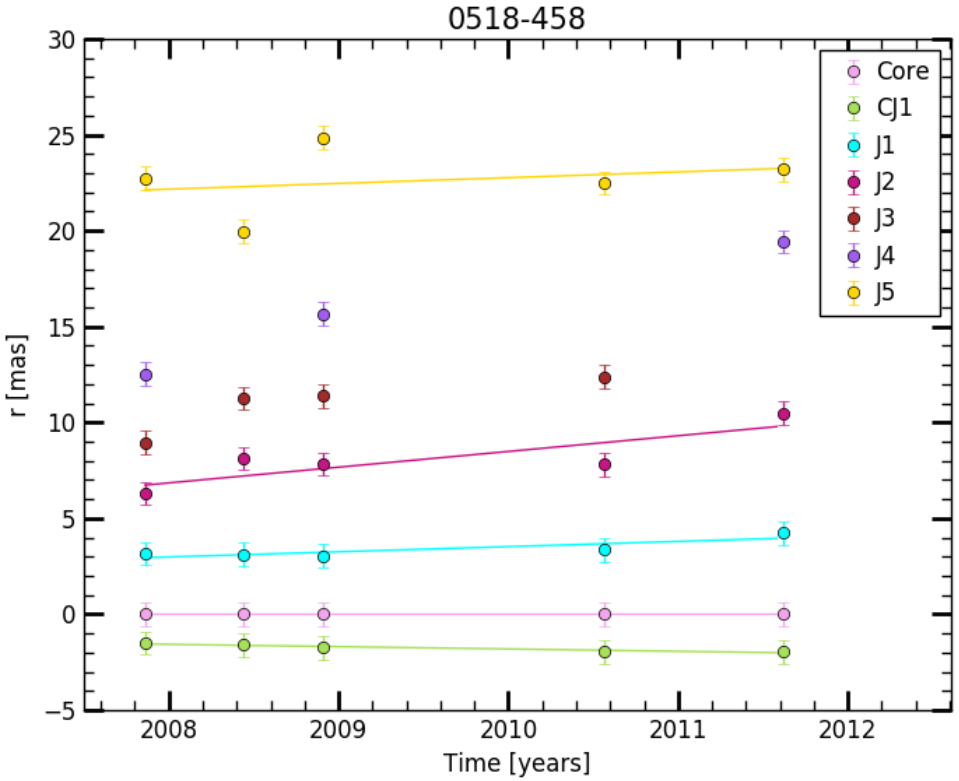


Kinematic analysis: Pictor A

Component ID	μ (mas/yr)	β_{app}	Epochs
CJ1	0.12±0.20	0.28±0.44	5
J1	0.27±0.21	0.62±0.48	5
J2	0.82±0.27	1.87±0.62	5
J5	0.31±0.10	0.70±0.22	5

Angioni+ in prep.





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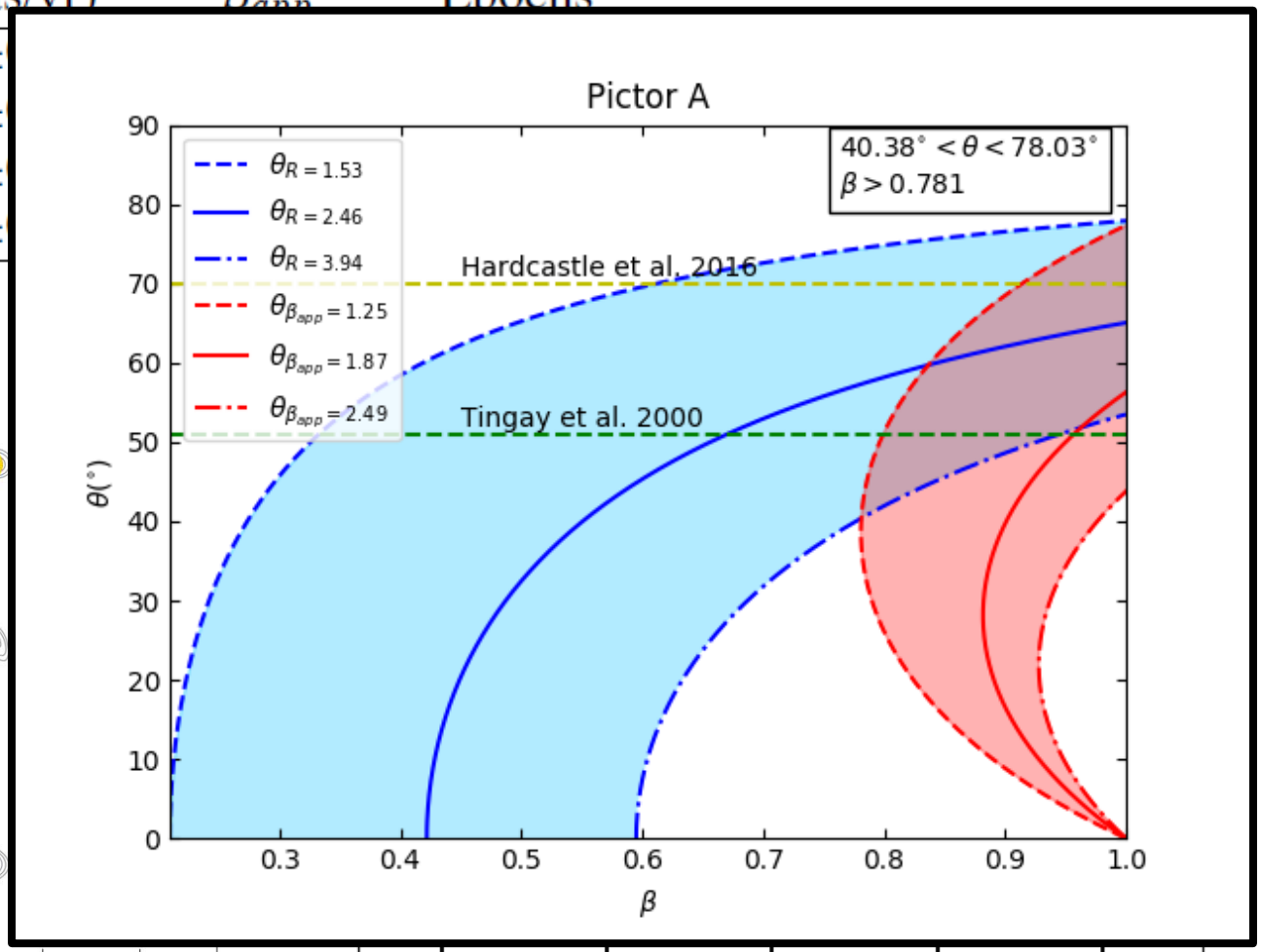
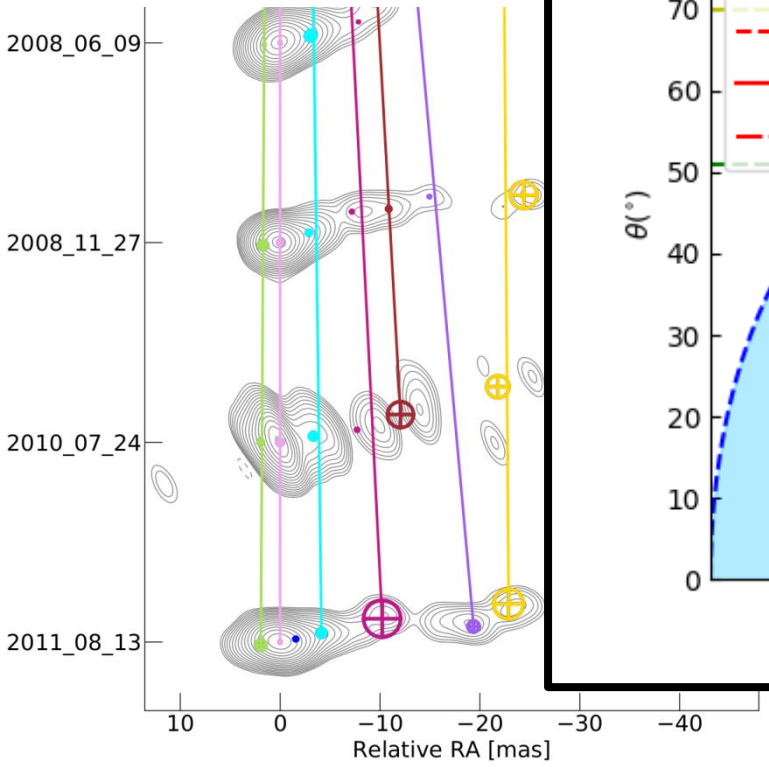
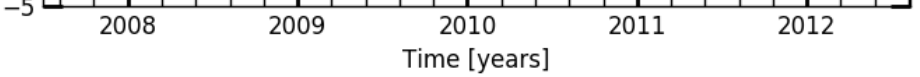
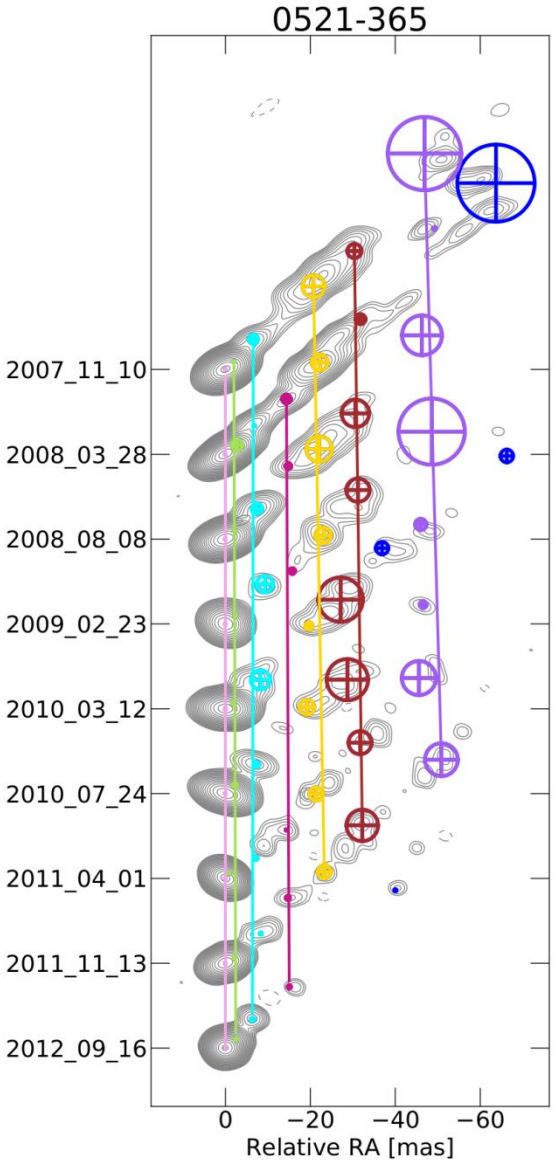


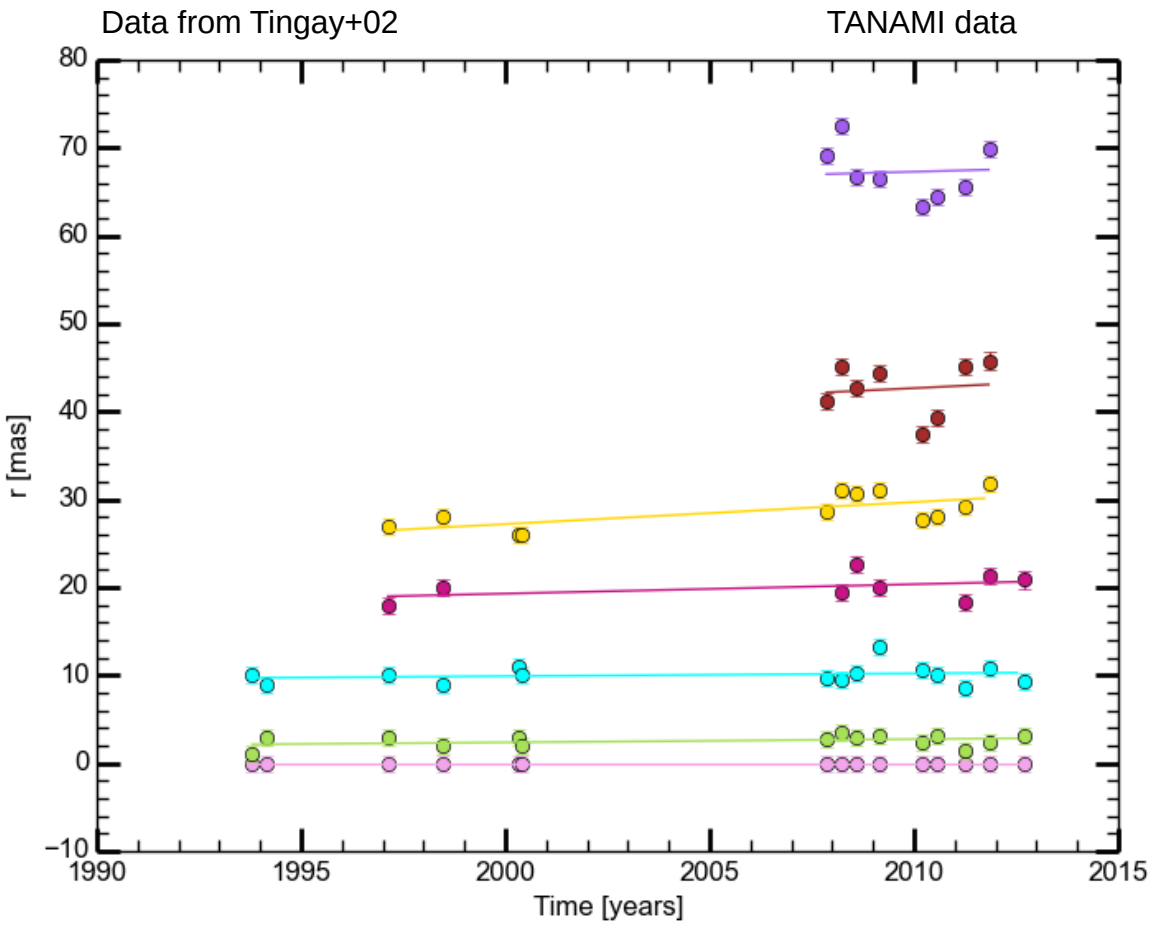




Kinematic analysis: PKS 0521−36

Angioni+ in prep.

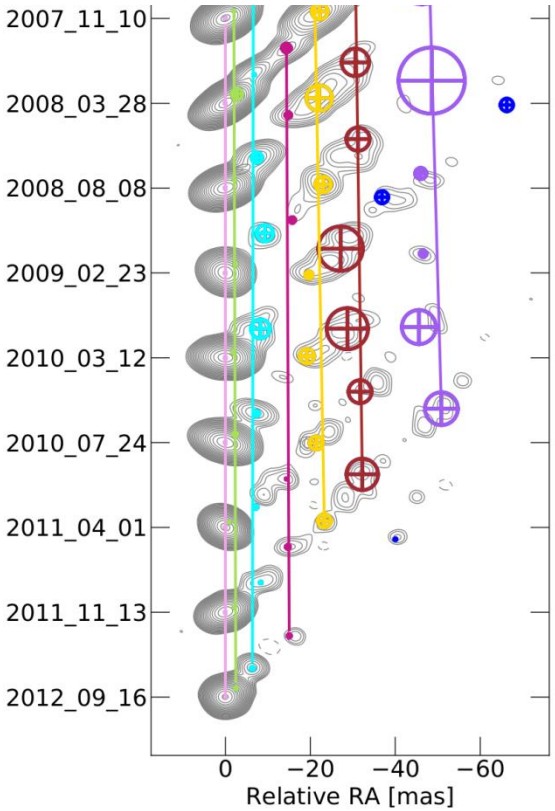




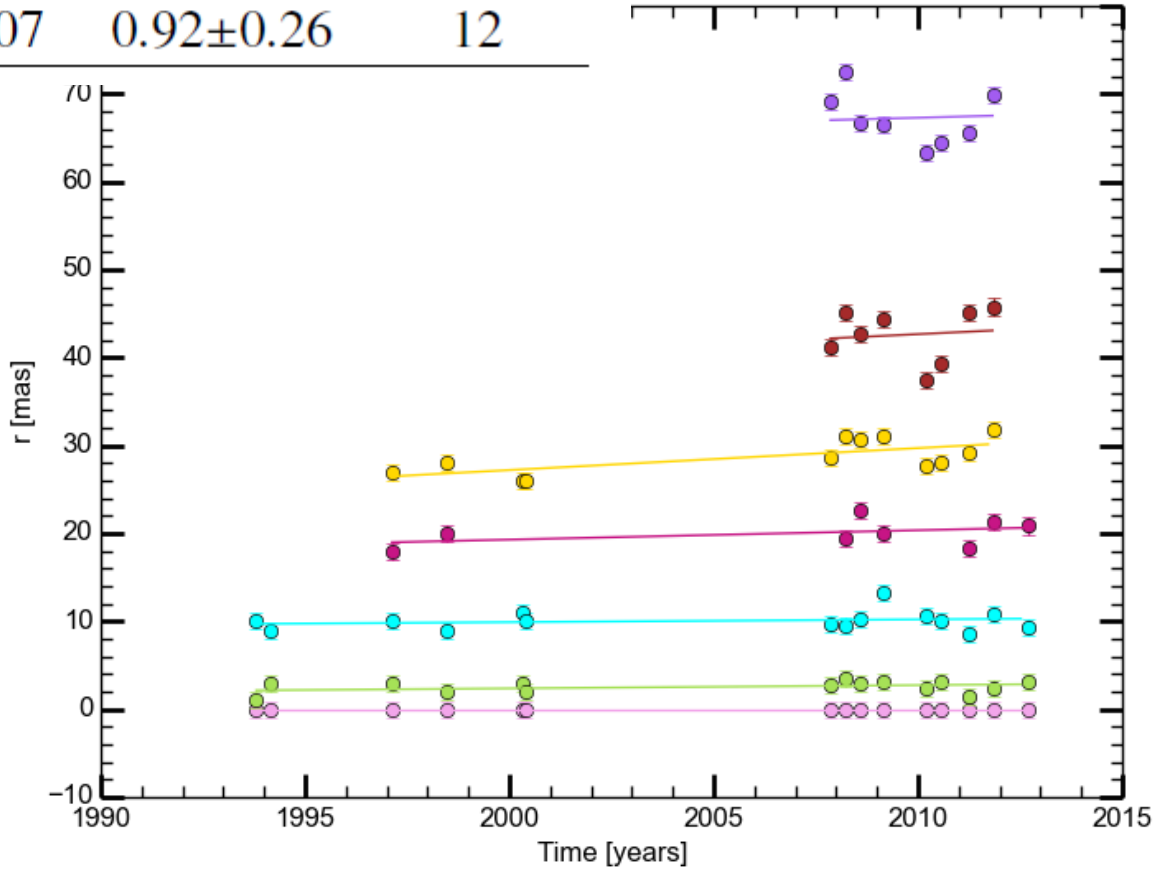
Kinematic analysis: PKS 0521−36

Component ID	μ (mas/yr)	β_{app}	Epochs
J1	0.04±0.05	0.16±0.16	15
J2	0.03±0.04	0.13±0.16	15
J3	0.11±0.07	0.39±0.26	8
J4	0.25±0.07	0.92±0.26	12

Angioni+ in prep.



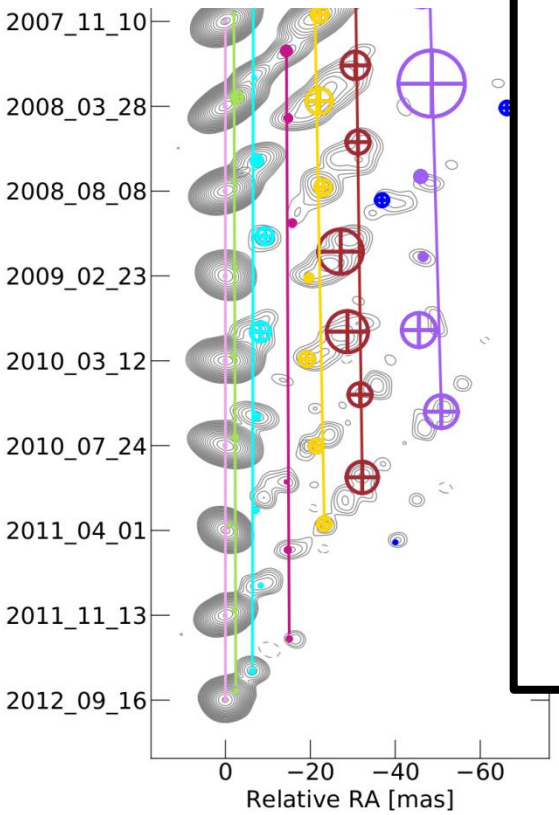
TANAMI data

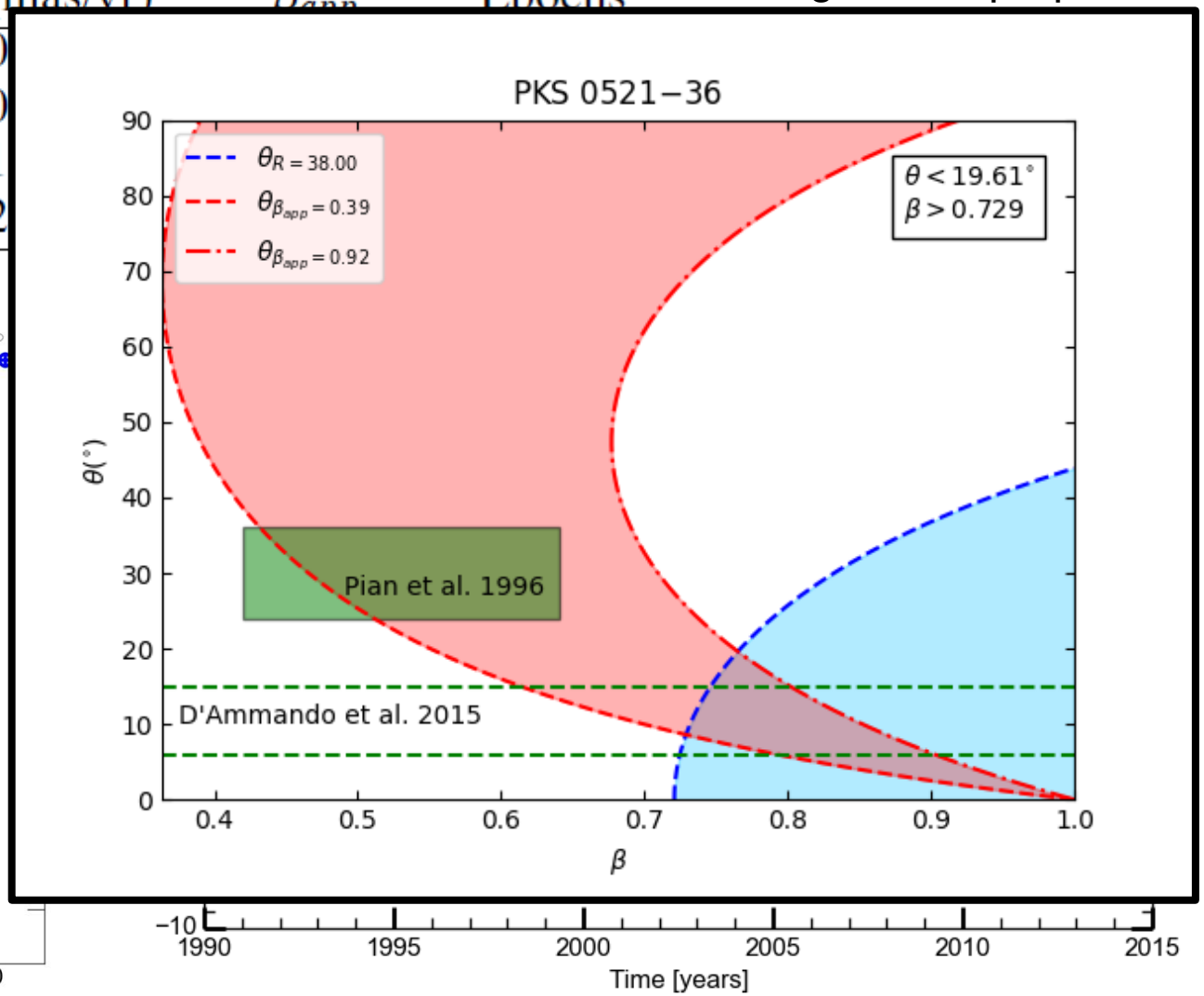


Kinematic analysis: PKS 0521−36

Component ID	μ (mas/yr)	β_{app}	Epochs
J1	0.0		
J2	0.0		
J3	0.1		
J4	0.2		

Angioni+ in prep.

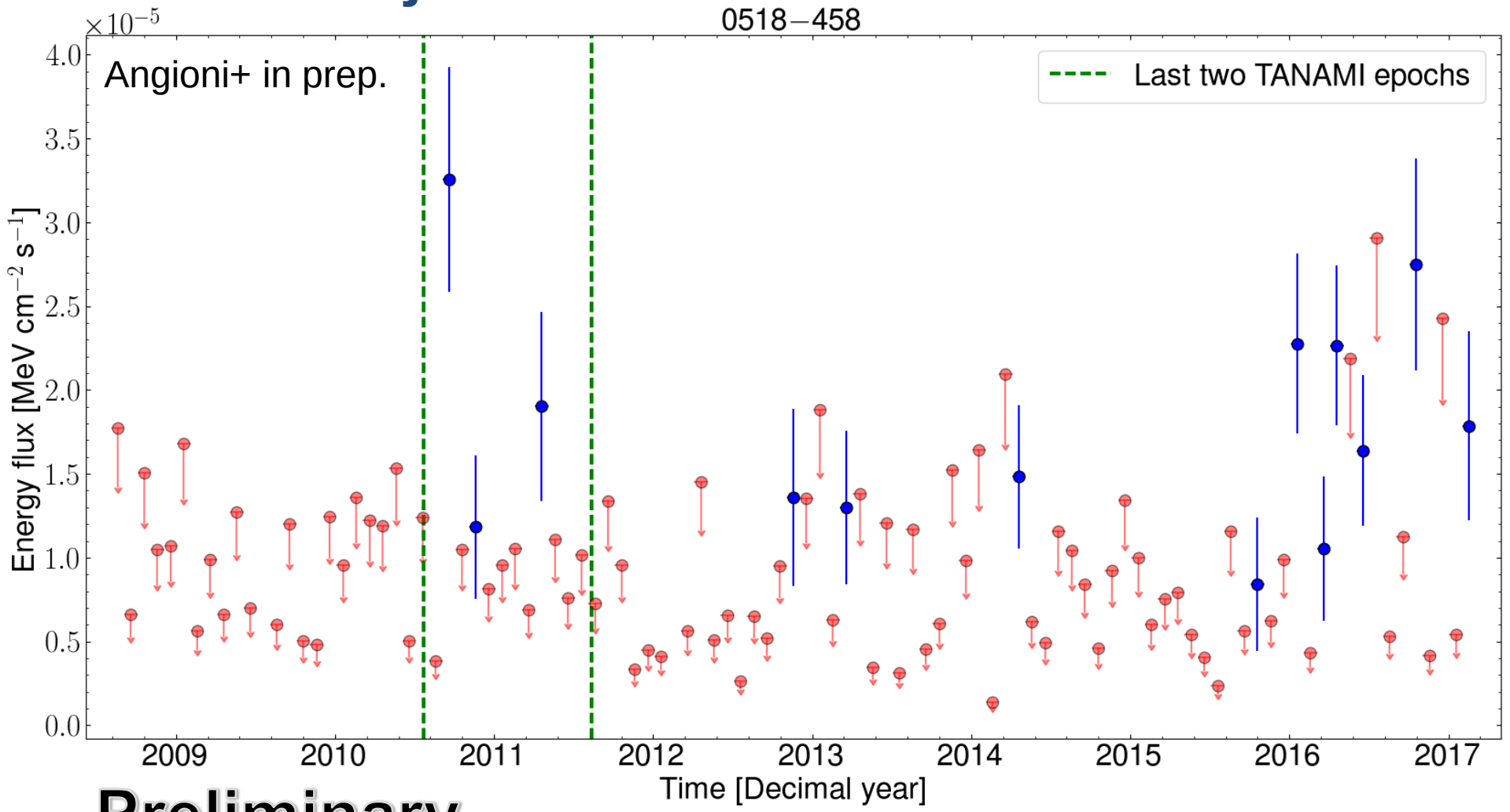




RESULTS

Fermi-LAT analysis

Pictor A: jet emission confirmed?



Preliminary

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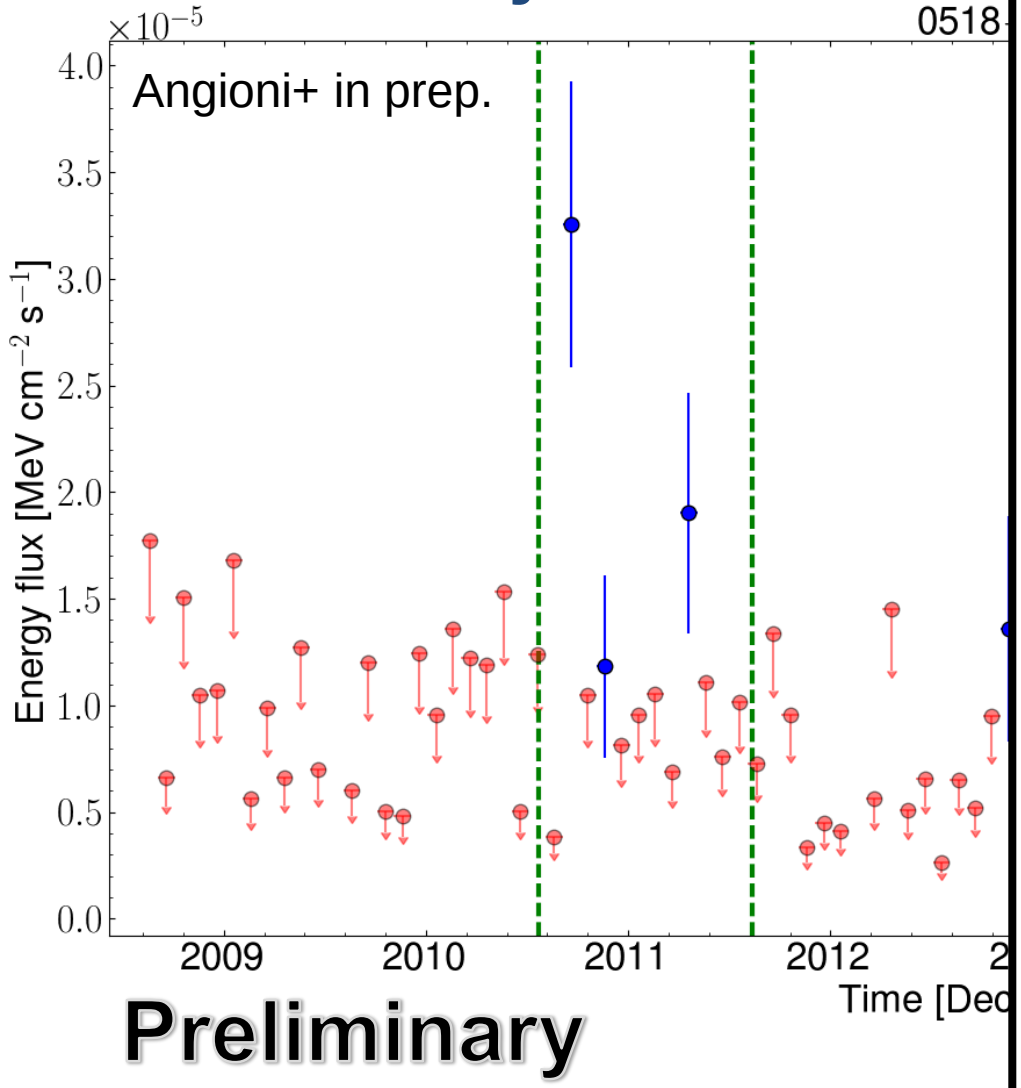

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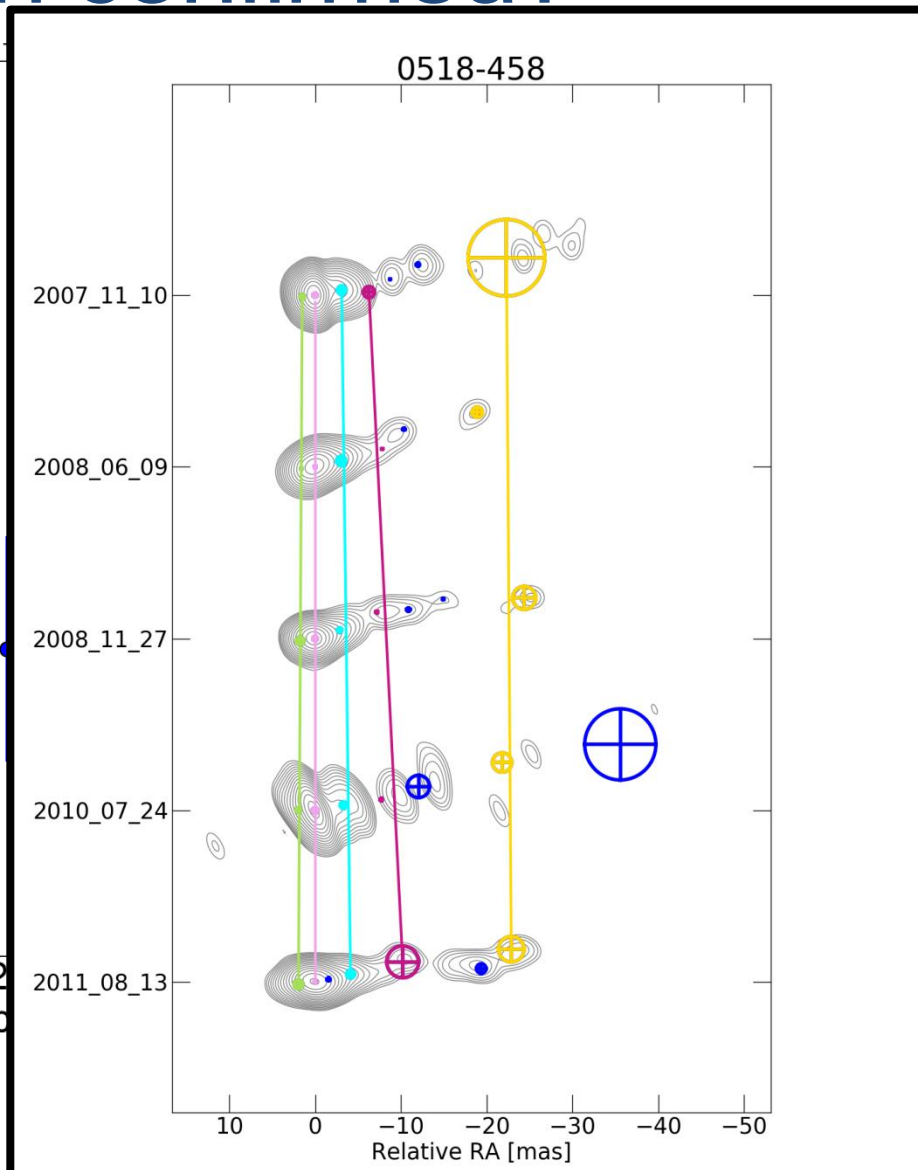
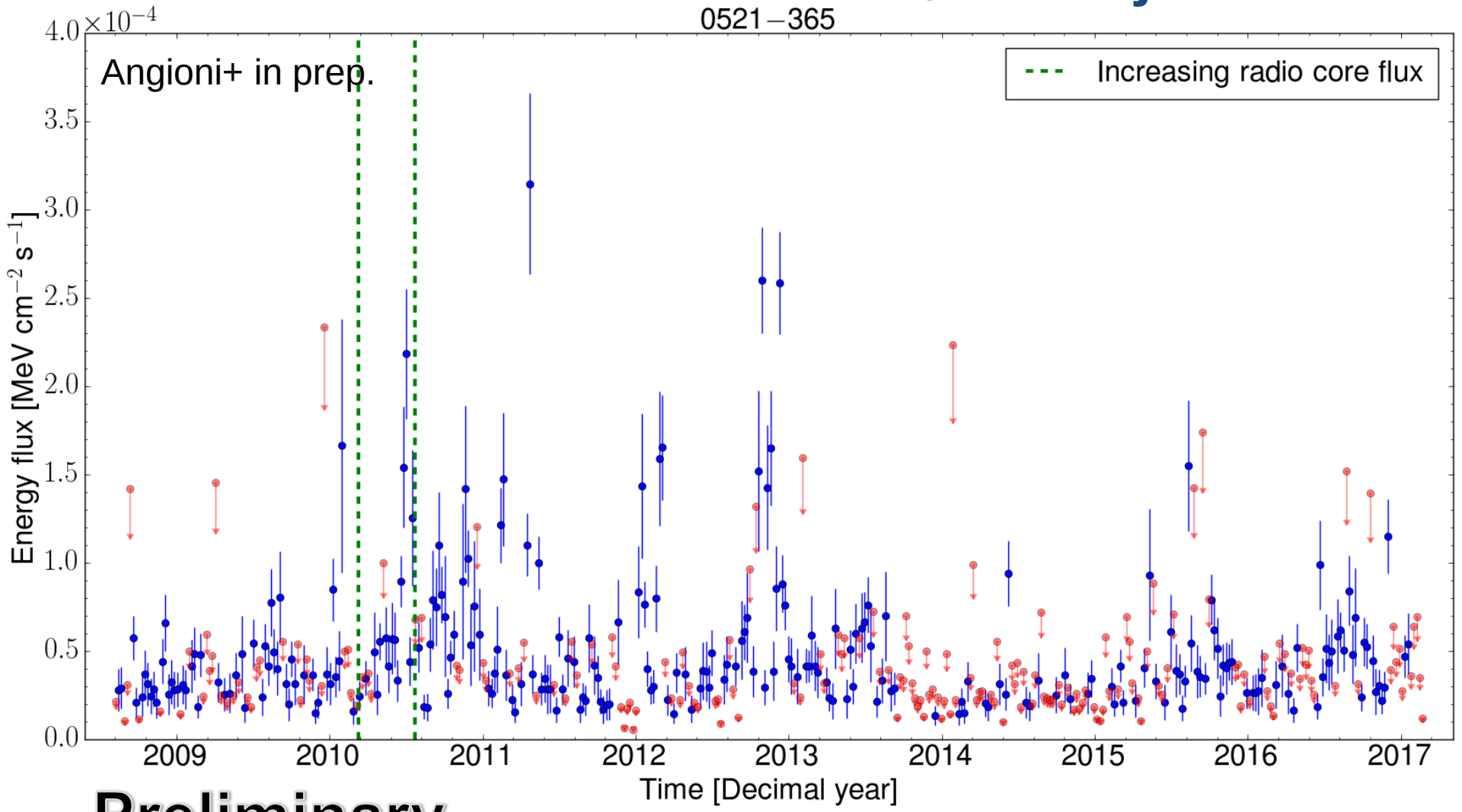


PKS 0521-36: fast flares, slow jet



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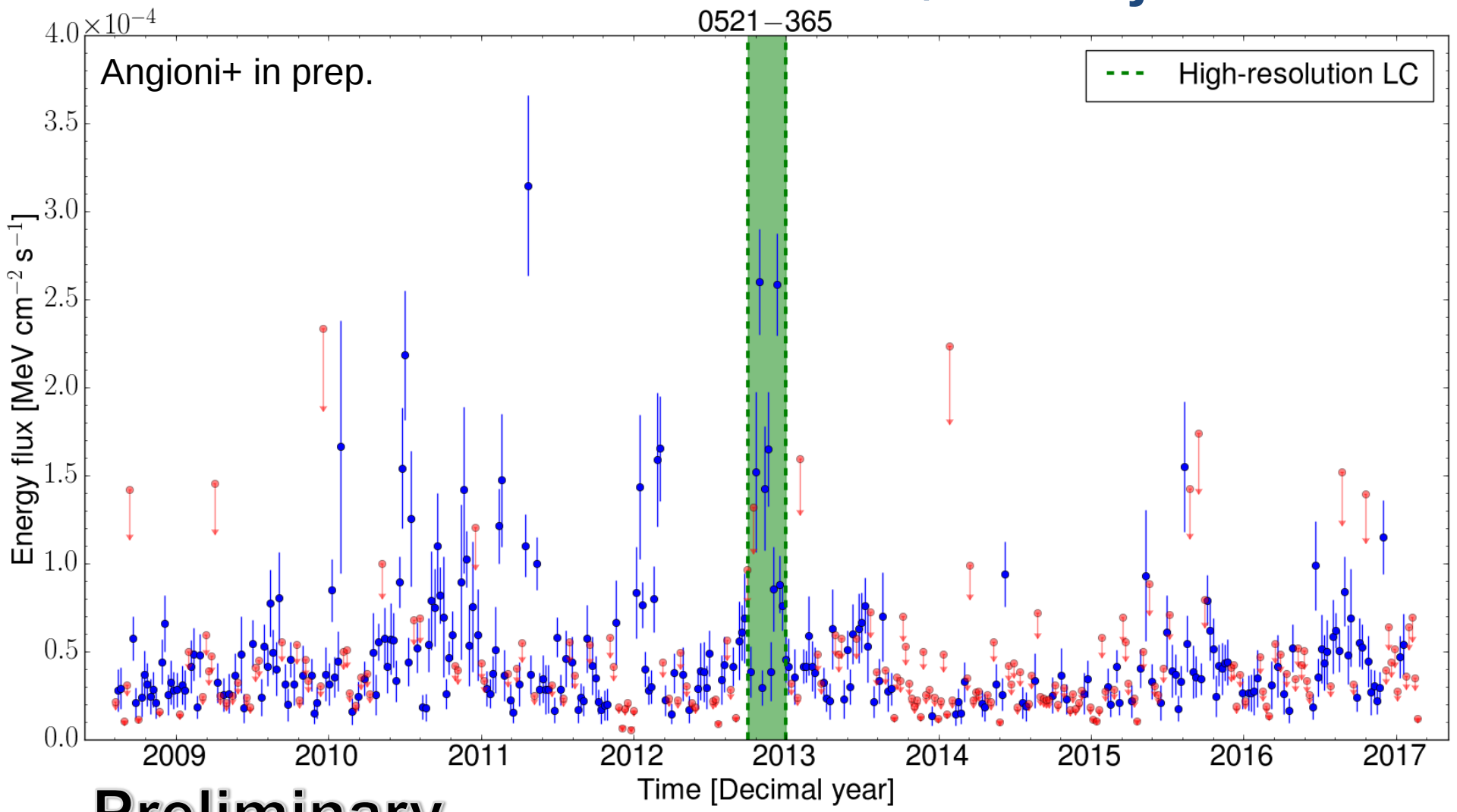

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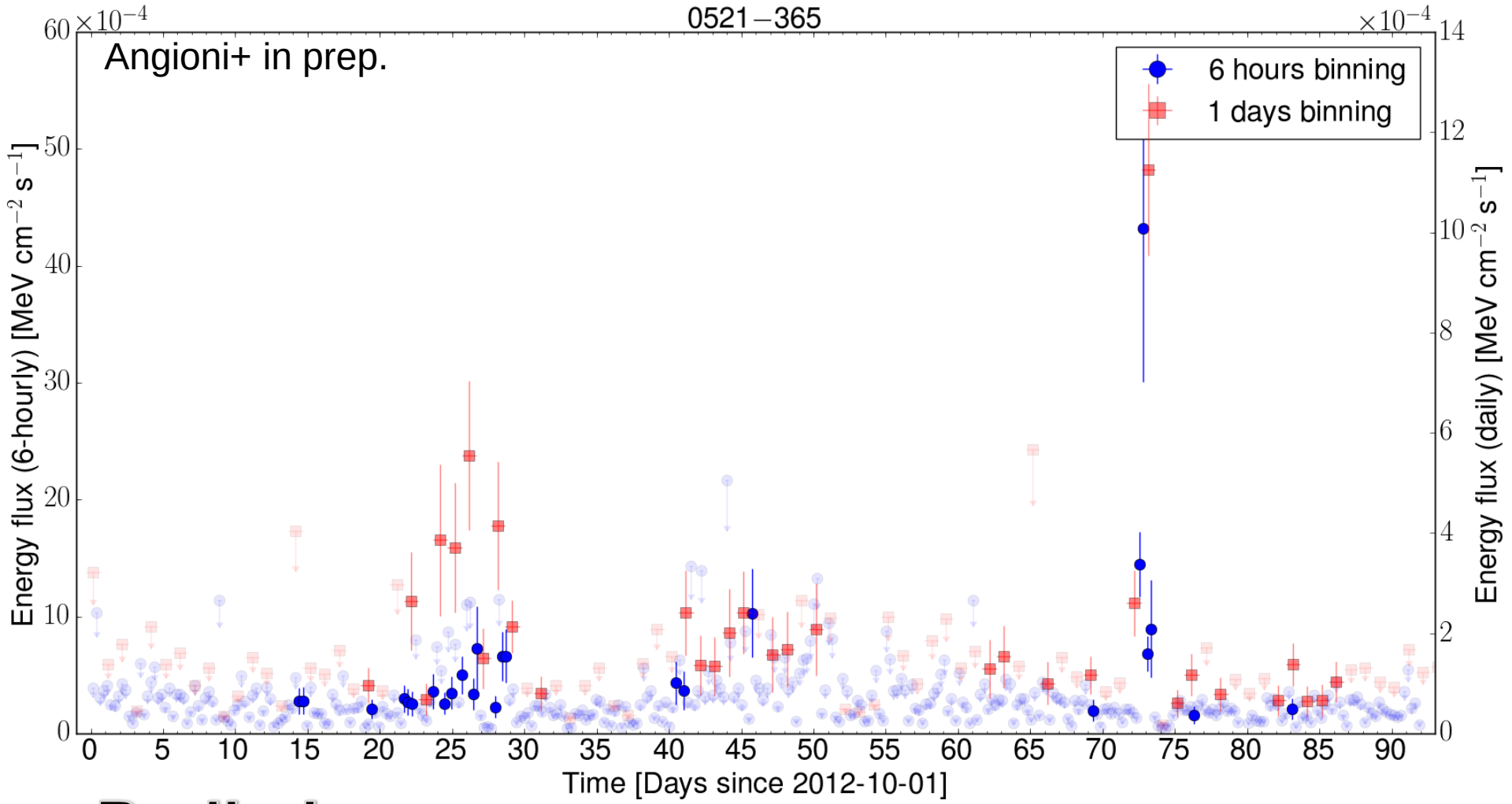

Preliminary

CONCLUSIONS

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- Combined VLBI-LAT analysis of well-known southern γ-ray radio galaxies
- Selected results on two sources:

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    - Subluminal jet speed
    - Intermediate viewing angle
    - Fast γ-ray variability
    - How to reconcile?

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    - How to reconcile?
- Paper(s) coming soon(ish)…stay tuned!

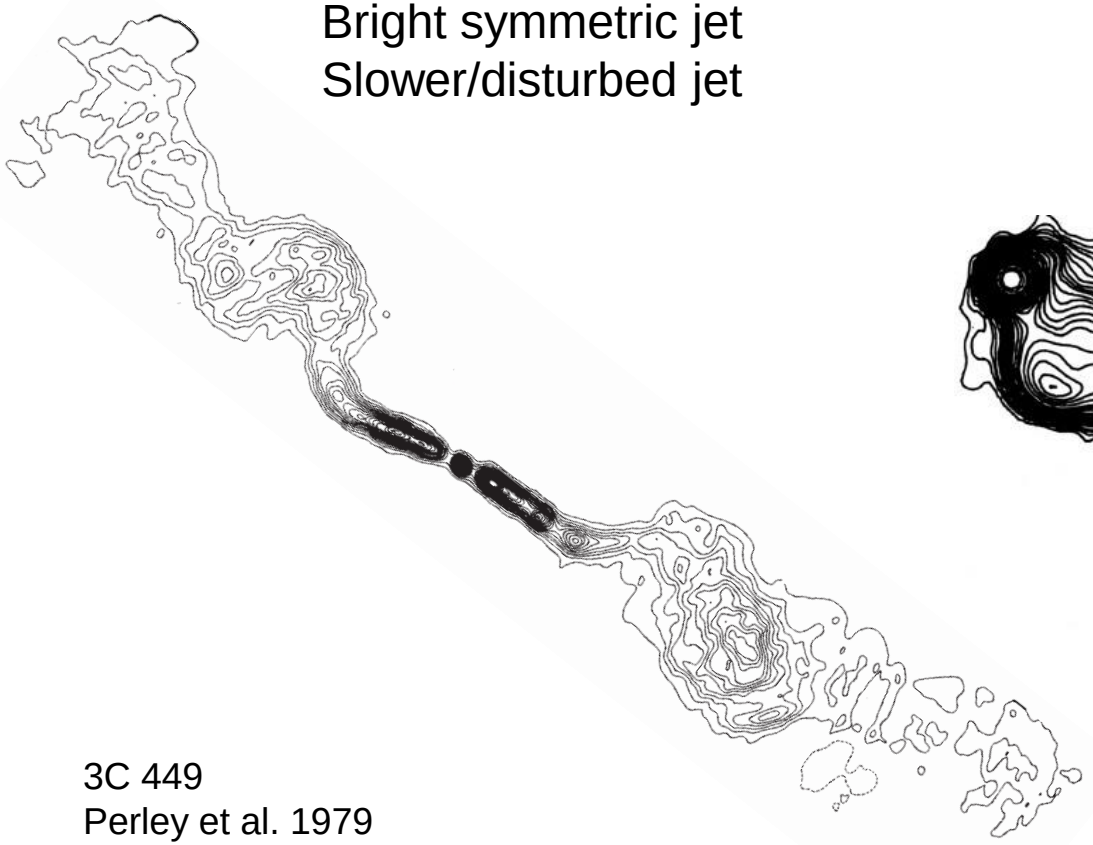
Thank you for your attention!

BACKUP SLIDES

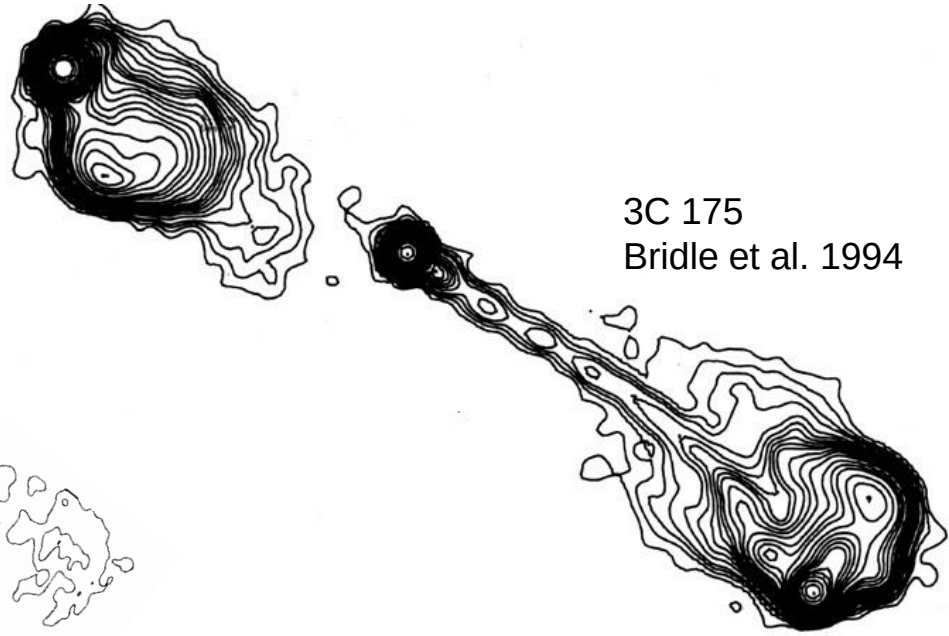
Radio galaxies: a bimodal population

FR I
Low power
Edge-darkened
Bright symmetric jet
Slower/disturbed jet

FR II
High power
Edge-brightened
Weak one sided jet
Faster/collimated jet



3C 449
Perley et al. 1979



3C 175
Bridle et al. 1994

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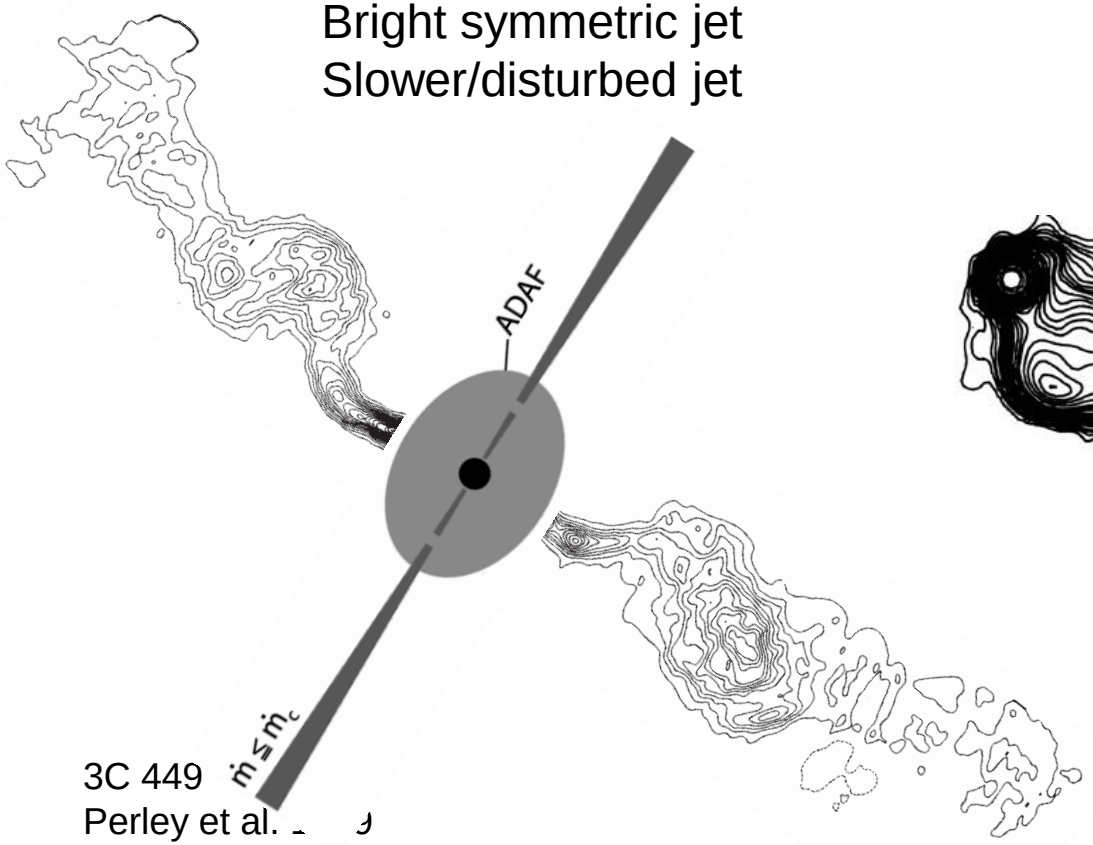
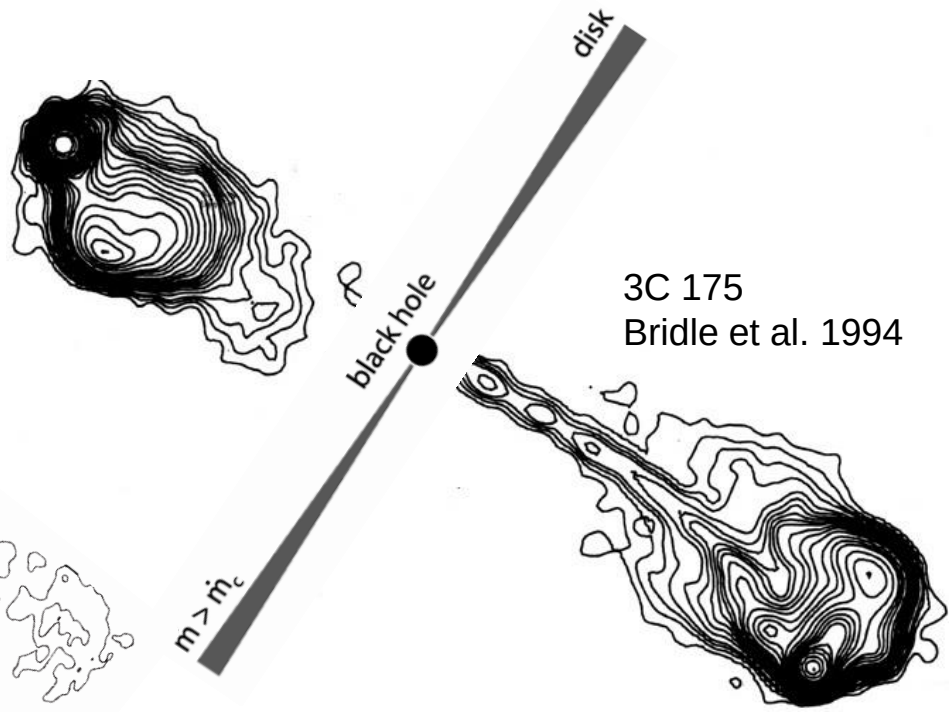


3C 449
Perley et al. [illegible]



3C 175
Bridle et al. 1994

Some formulas

Doppler factor	$\delta = [\Gamma(1 - \beta\cos\theta)]^{-1}$
Lorentz factor	$\Gamma = [1 - \beta^2]^{-1/2}$
Apparent jet speed	$\beta_{app} = \frac{\beta \sin\theta}{1 - \beta\cos\theta}$
Jet to counter-jet ratio	$R = \left(\frac{1 + \beta\cos\theta}{1 - \beta\cos\theta}\right)^{c+\alpha}$

The TANAMI sample

First epoch images presented in Ojha+10

Müller+ A&A accepted

Radio selected subsample

Stickel+94* (527)

$\mathrm{Dec} < -30°$
$S_{5\,\mathrm{GHz}} > 2\ \mathrm{Jy}$
$\alpha_{2.7,5} > -0.5$

↓

21 sources

γ-ray selected subsample

All EGRET sources at $\mathrm{Dec} < -30°$

↓

11 sources

Manually selected subsample

Known IDV sources
+
Noteworthy sources

↓

12 sources

New sources subsample

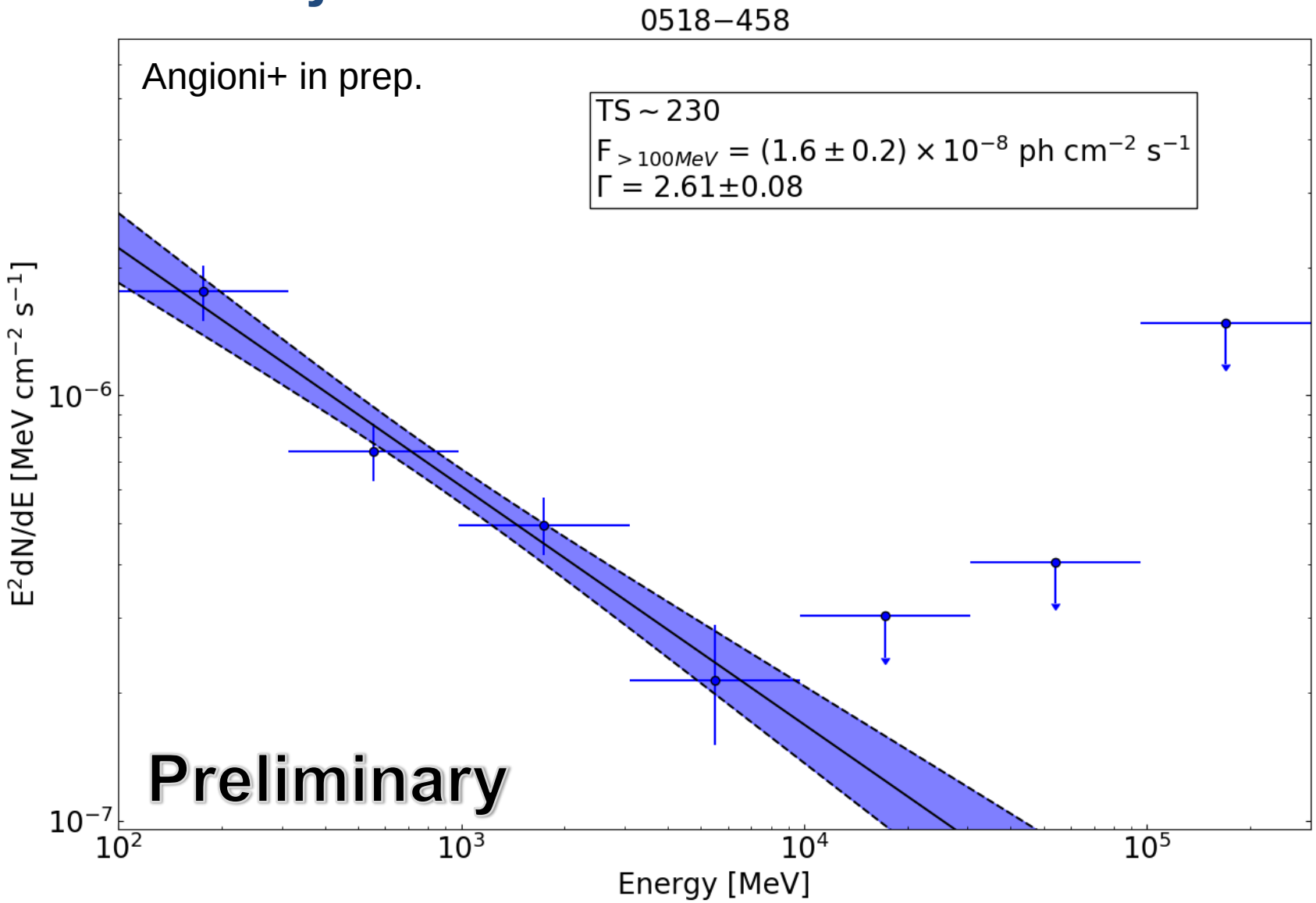
New γ-ray sources
+
New noteworthy sources

↓

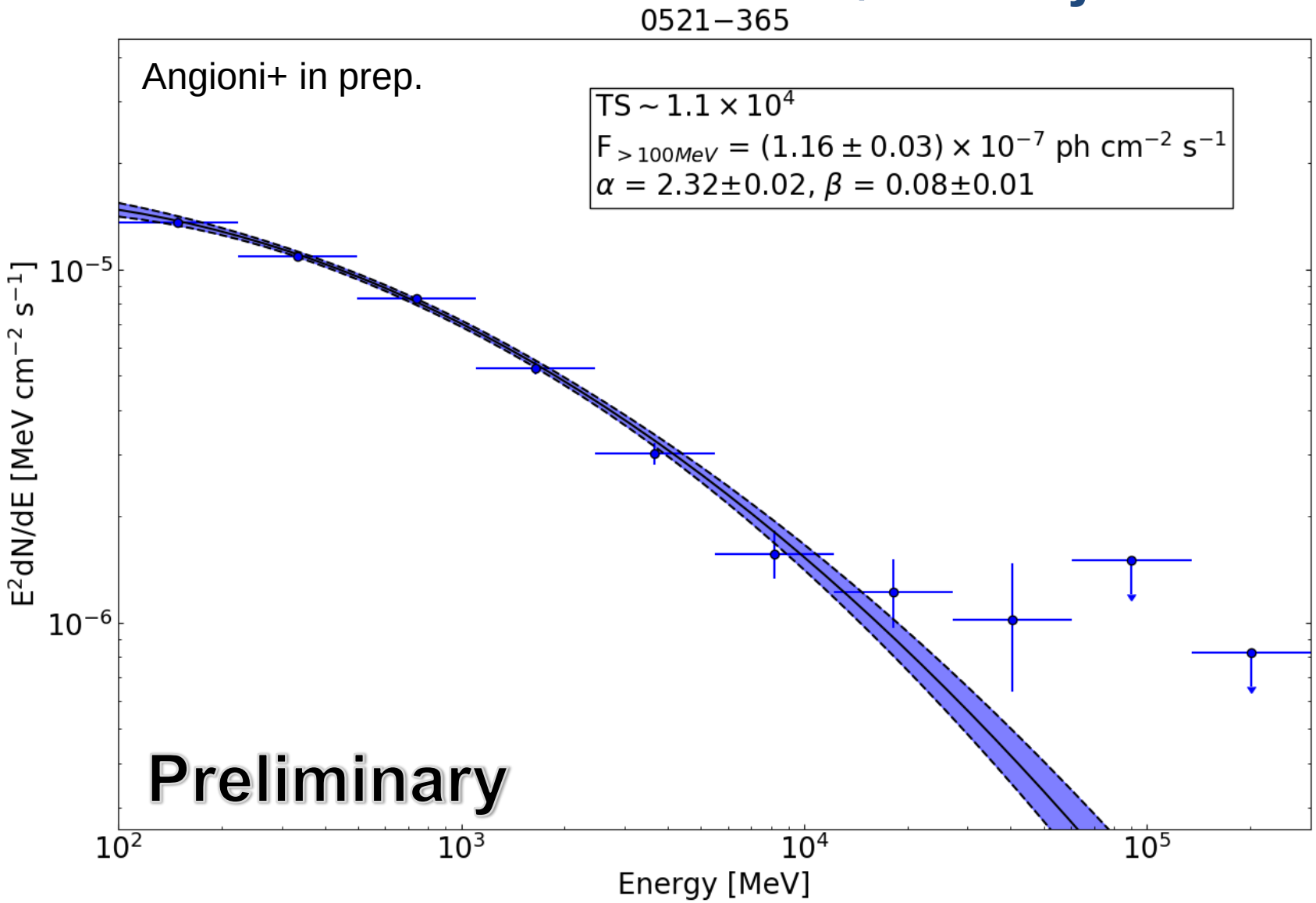
39 sources

*based on Kühr+81

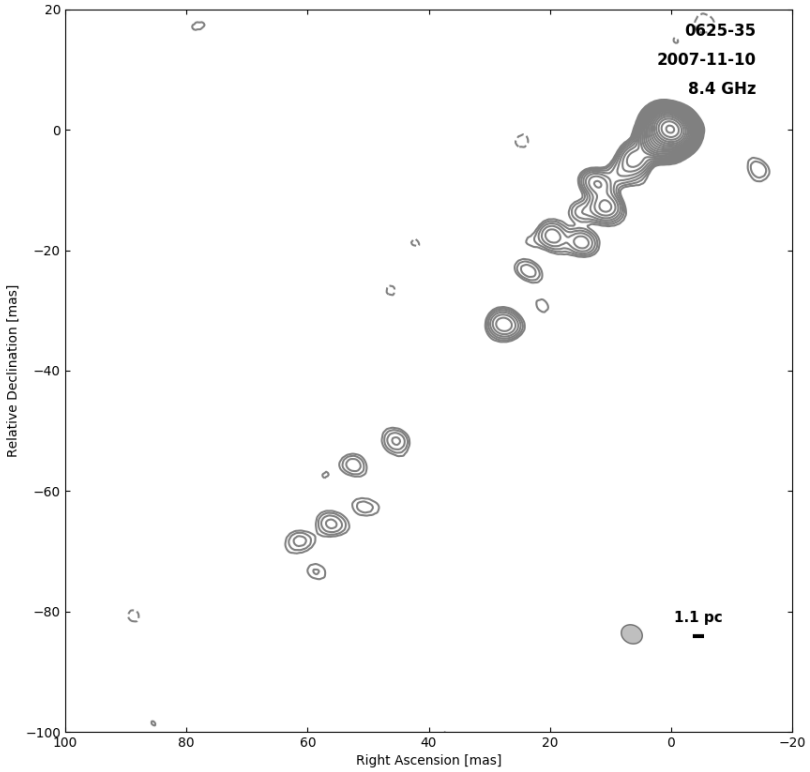
Pictor A: jet emission confirmed?



PKS 0521-36: fast flares, slow jet



PKS 0625−35



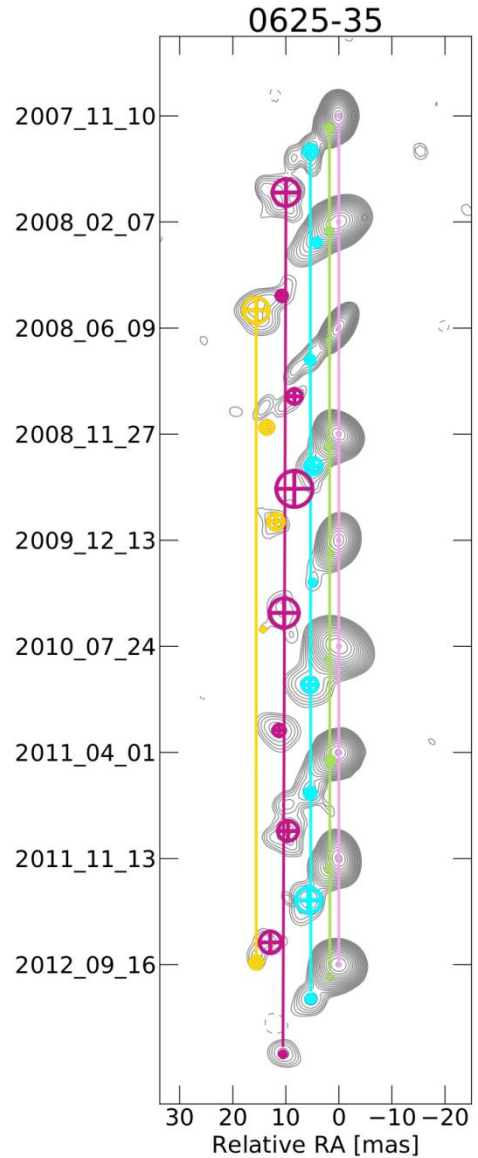
Angioni+ in prep.

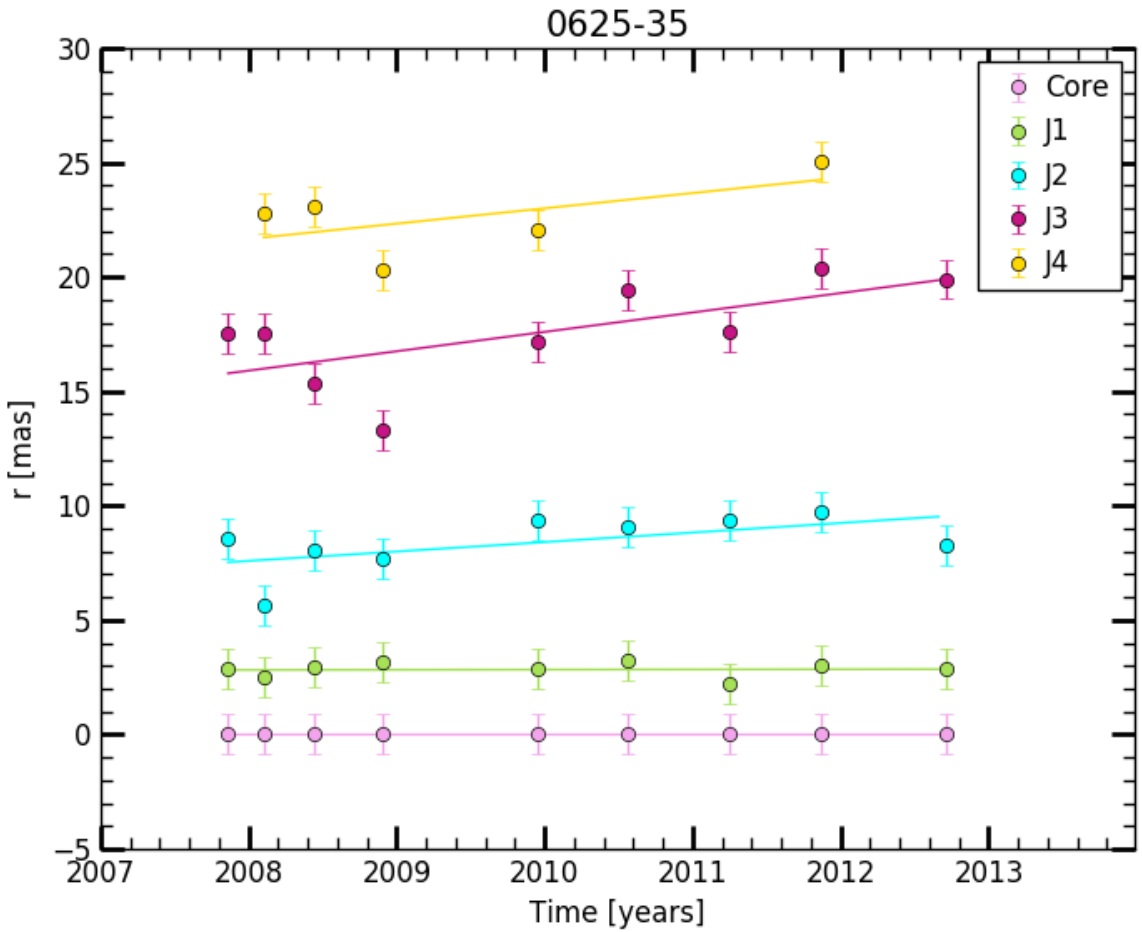
FR I – BLL transitional, $z = 0.035$

- Most recently detected TeV radio galaxy (Dyrda+15)
- Earlier VLBI study found viewing angle $\theta < 30°$ (Venturi+00)
- Preliminary analysis of early TANAMI epochs suggests superluminal motion (Müller+12, EVN proc.)

Kinematic analysis: PKS 0625−35

Angioni+ in prep.

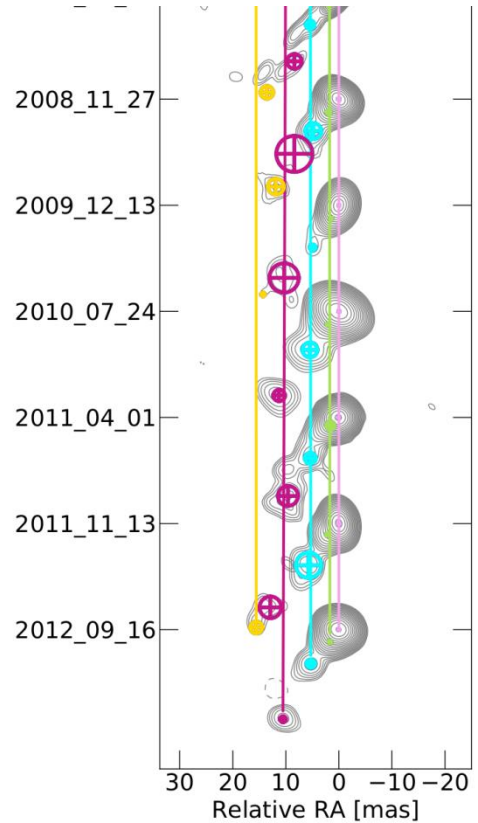


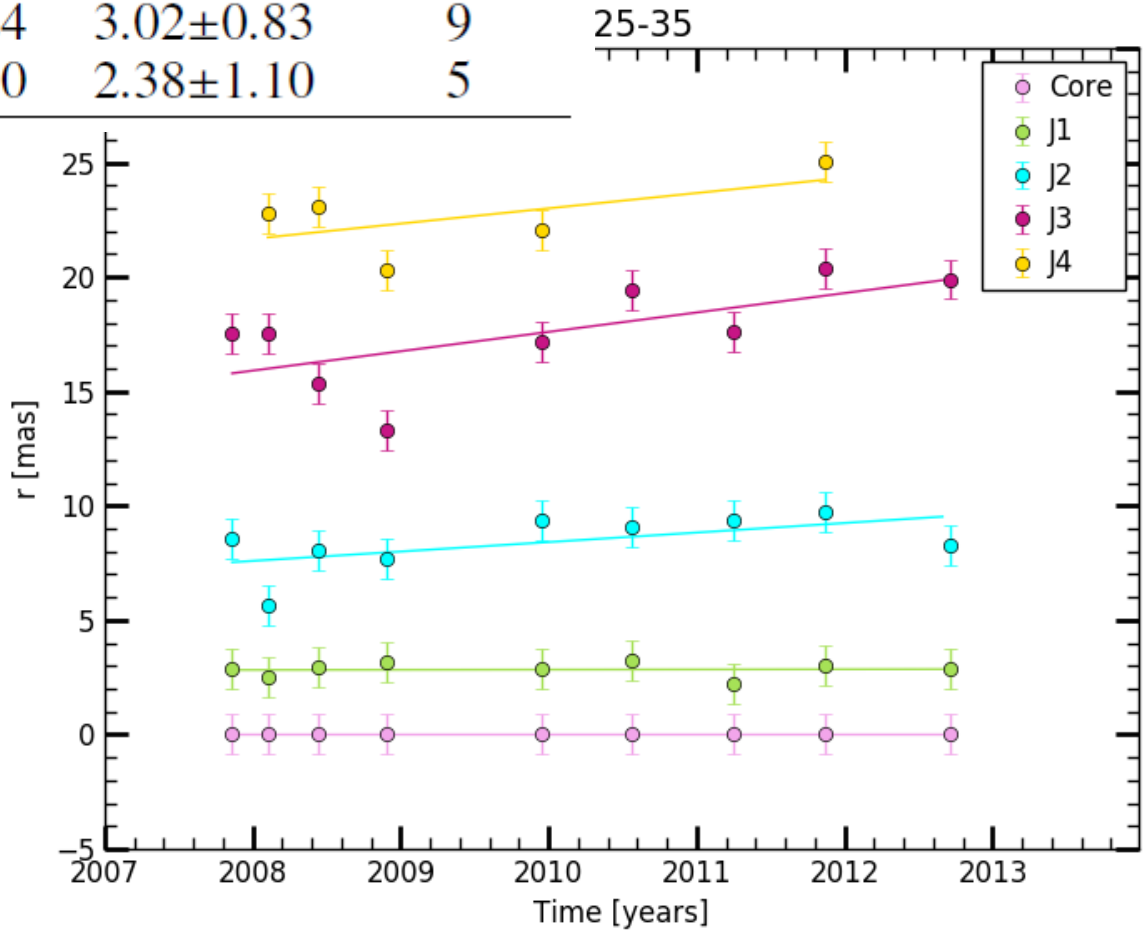


Kinematic analysis: PKS 0625−35

Component ID	μ (mas/yr)	β_{app}	Epochs
J1	0.01±0.24	0.04±0.86	9
J2	0.44±0.21	1.56±0.73	9
J3	0.85±0.24	3.02±0.83	9
J4	0.67±0.30	2.38±1.10	5

Angioni+ in prep.





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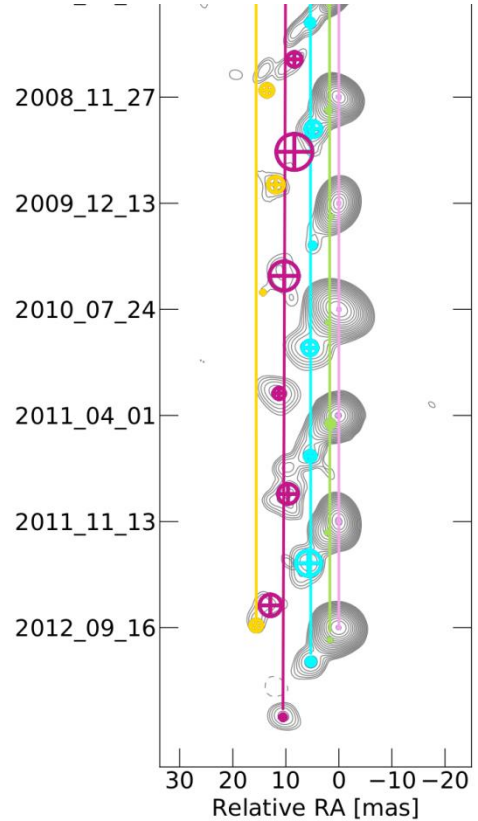
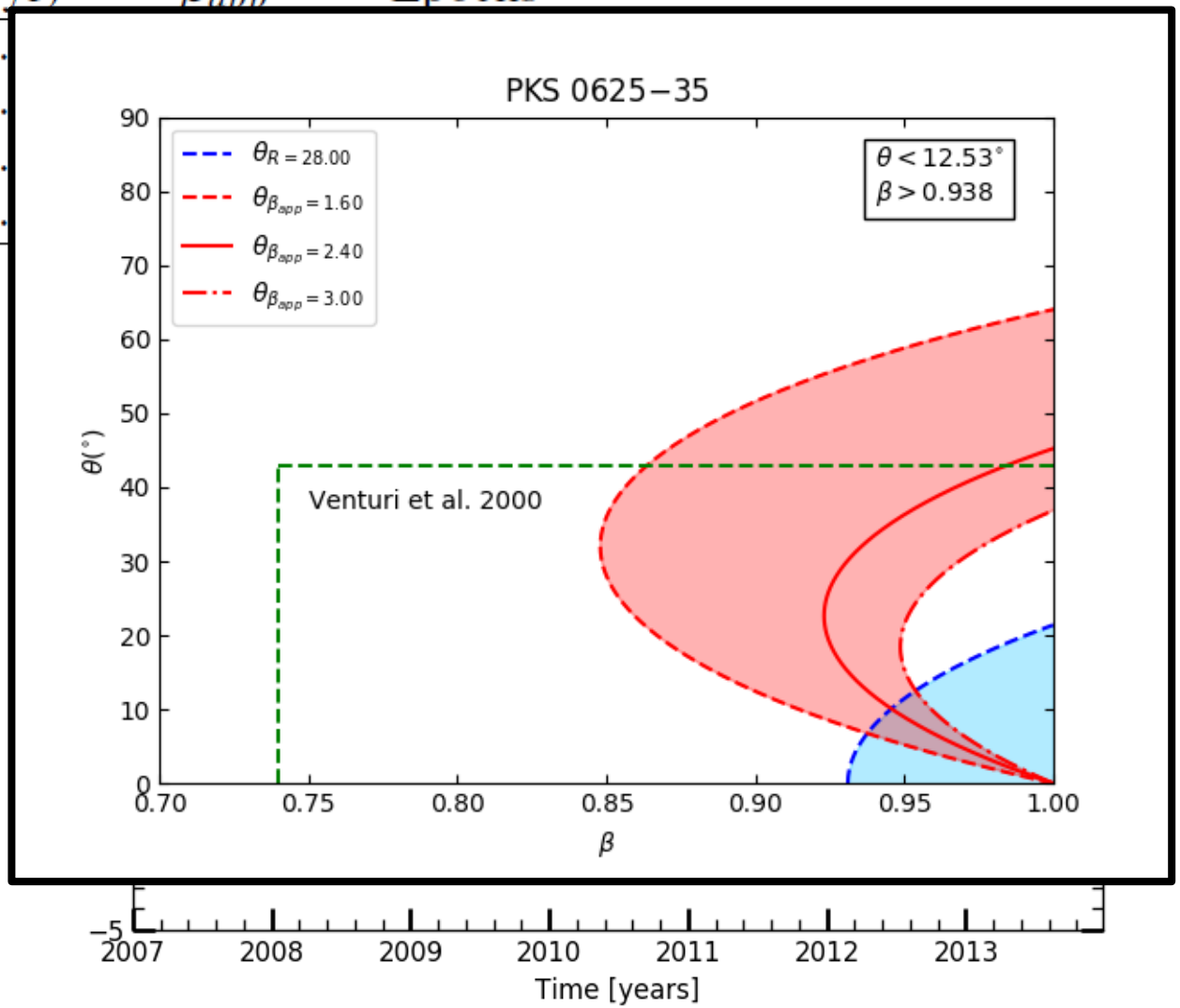
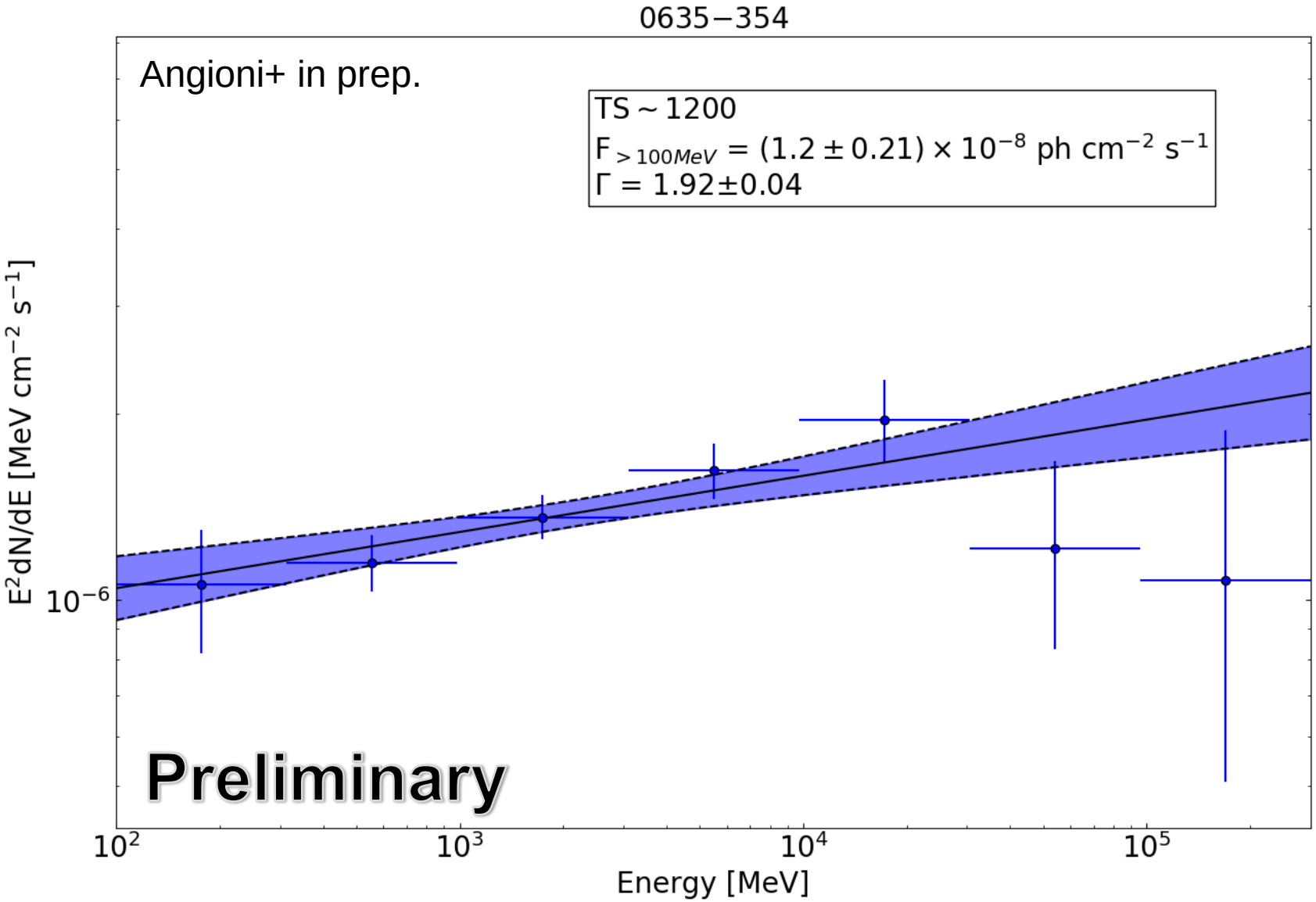
Angioni+ in prep.

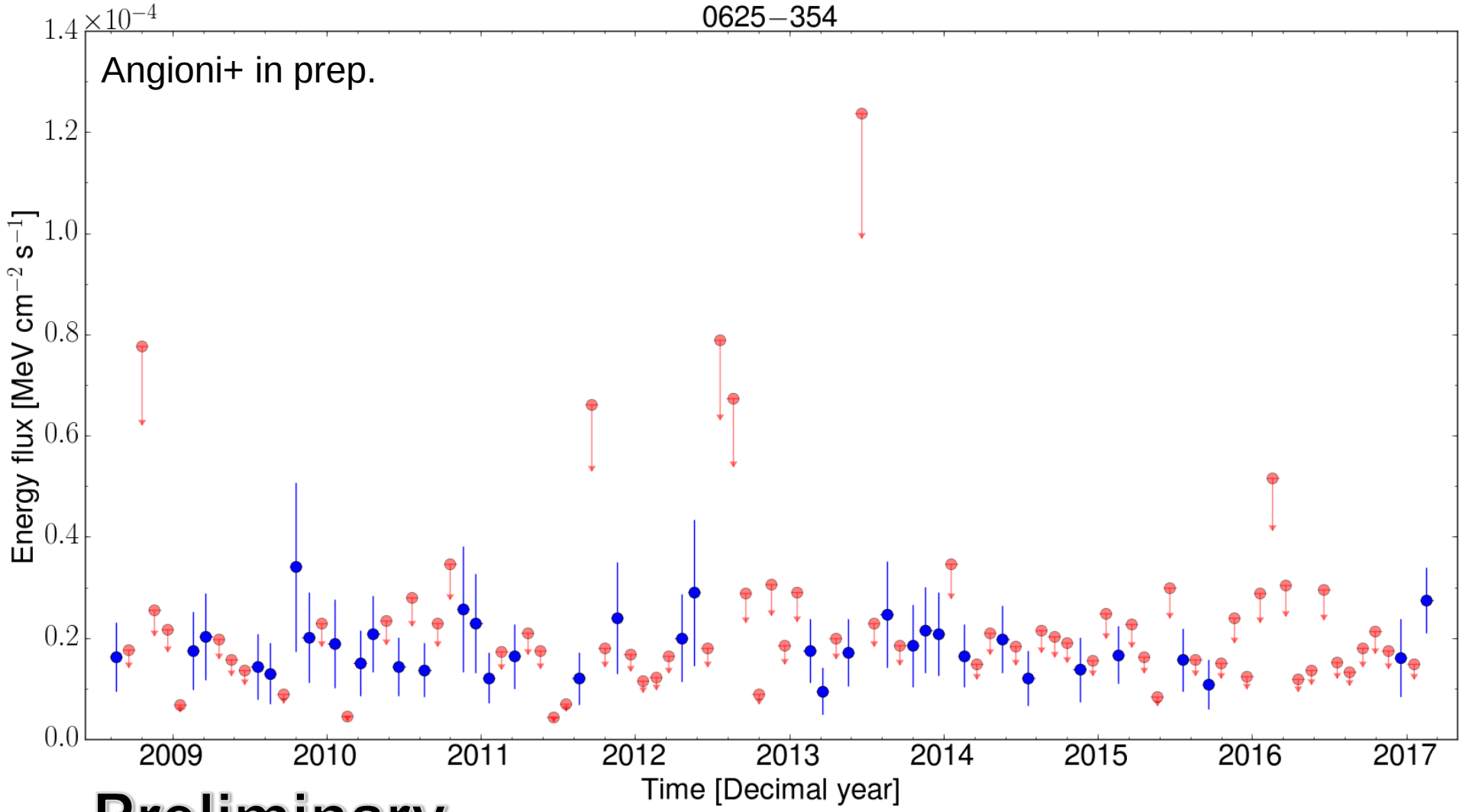




PKS 0625−35: the hardest spectrum



PKS 0625−35: the hardest spectrum



Preliminary