EHT observations and imaging of 3C 279 at 20 *μ*as

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with the EHT collaboration and EHT AGN & MWL WGs

Event Horizon Telescope

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MAX-PLANCK-GESELLSCHAFT

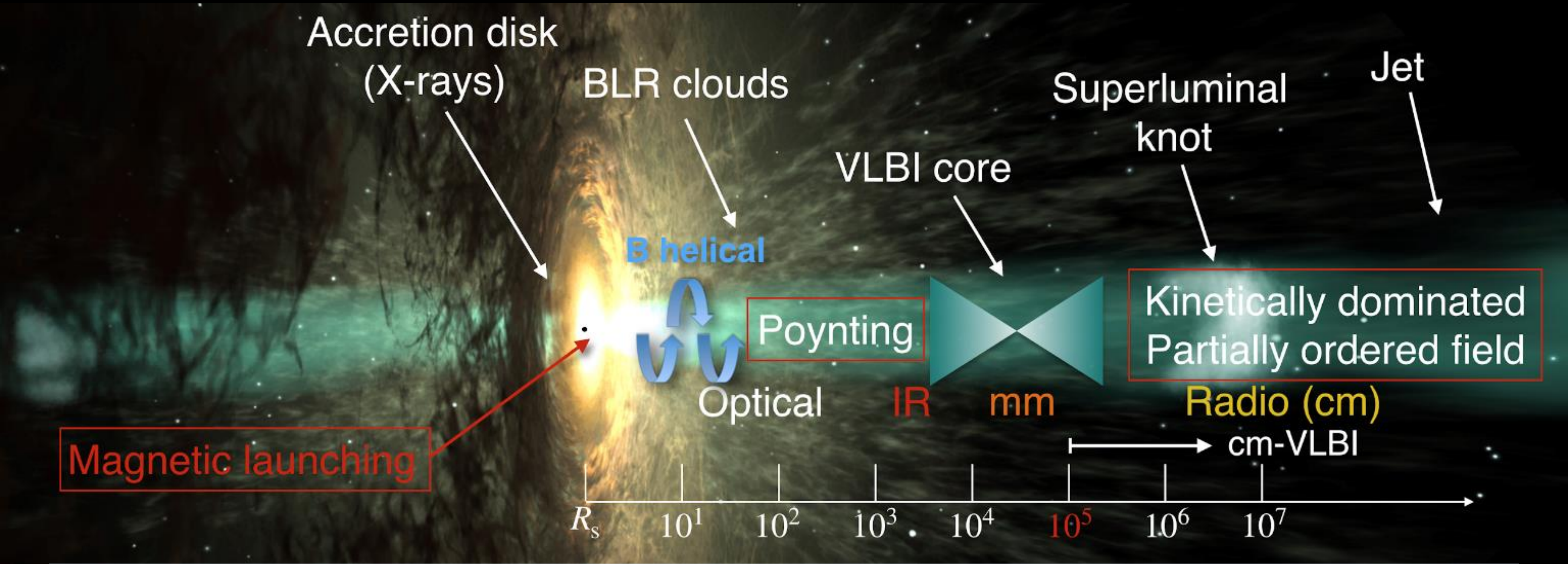
Max-Planck-Institut für Radioastronomie

Layout

- Background
- EHT observations
- Key results – images, rapid variability
- Analysis – imaging, dynamic model-fitting
- Discussions, interpretations
- Conclusions & outlook

Introduction

AGN jet physics on various scales



Key questions to address

- Magnetic launching: Blandford & Znajek (black hole) vs. Blandford & Payne (disk)
- Magnetic field, velocity stratification, and collimation profile in the acceleration and collimation zone
- Transition between the Poynting (ordered B, accelerating) to kinetically-flux (partially disordered B, conical) regimes.

Polarimetric VLBI imaging at resolution ≲50 μas (≲10^4 R_s) is required

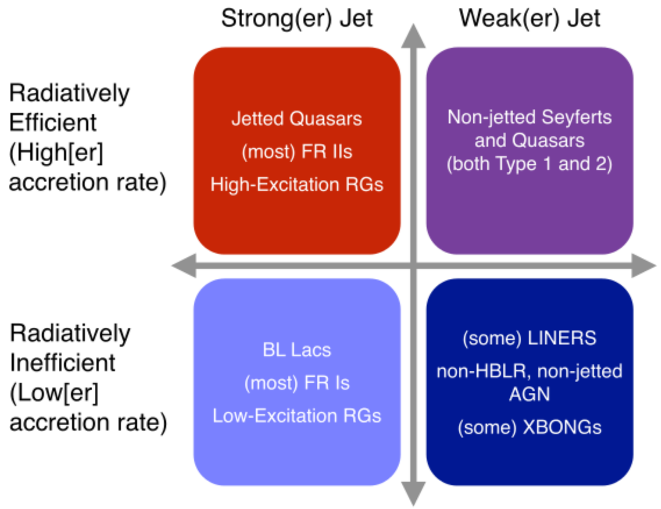
Slide from
EHT AGN WG

High resolution imaging of various AGN jets

Major science motivations:

1. study jet formation for different source classes (FRI/FRII, FSRQ/BLLac), luminosities, BH masses
2. test specific models, BP vs. BZ, magnetic vs. kinetic, etc.
3. compare hot accretion, thick disk (SgrA*, RIAF), vs. cold accretion, thin disk (FSRQs)
4. location of γ-ray emission, SSC vs ECs; seed photons?
5. AGN often highly polarized → B-field in jet launching region
6. RM studies → densities and matter composition (internal & ambient)
7. Address differences in B-field topology and jet speed between source classes (SgrA*, LLAGN, RGs, BLLacs, FSRQs)

A simple AGN Unification model

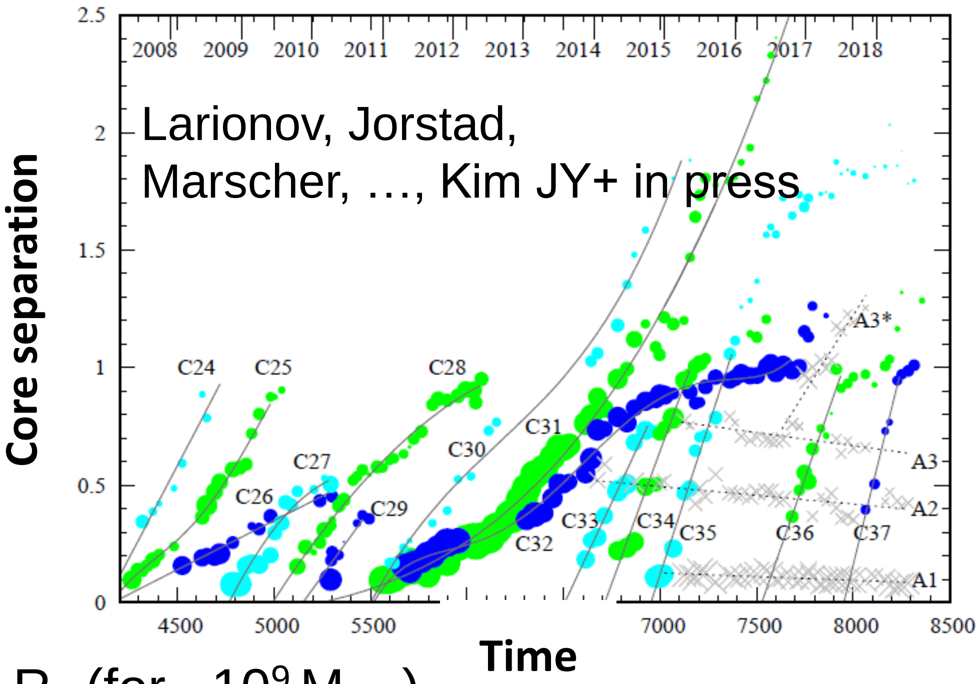


Padovani+2017 (AARev)

Slide from EHT AGN WG

3C 279: an archetypal blazar

- One of fastest AGN jets observed by VLBI (γ ~ 10-40)
  - First AGN jet showing apparent superluminal motions on monthly timescale (Whitney+71, Cohen+71)
  - Many speeds seen in the jet (~10*c* - 40*c*) with acceleration, deceleration, and curvatures



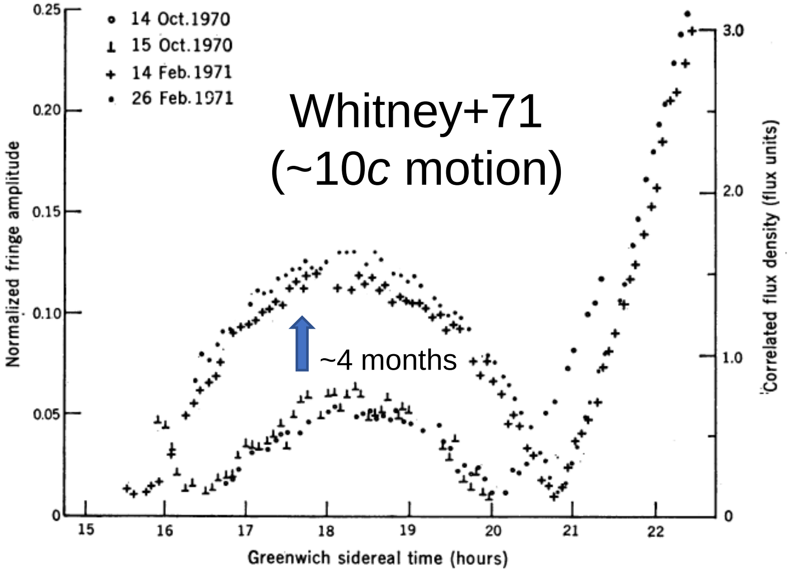
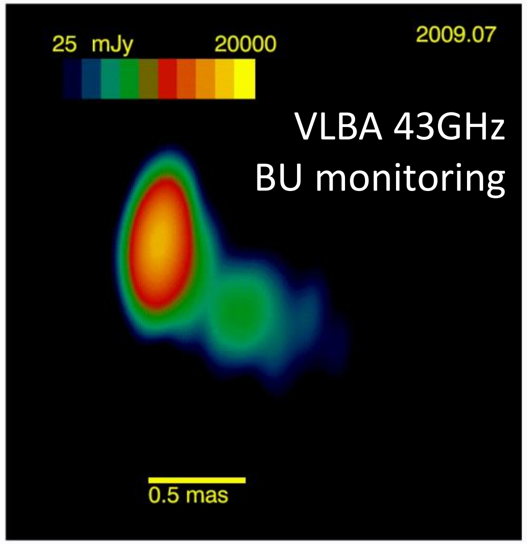


Fig. 1. Fringe-amplitude data from observations of 3C 279 with the Goldstone-Haystack interferometer. Each point is based on 110 seconds of integration.

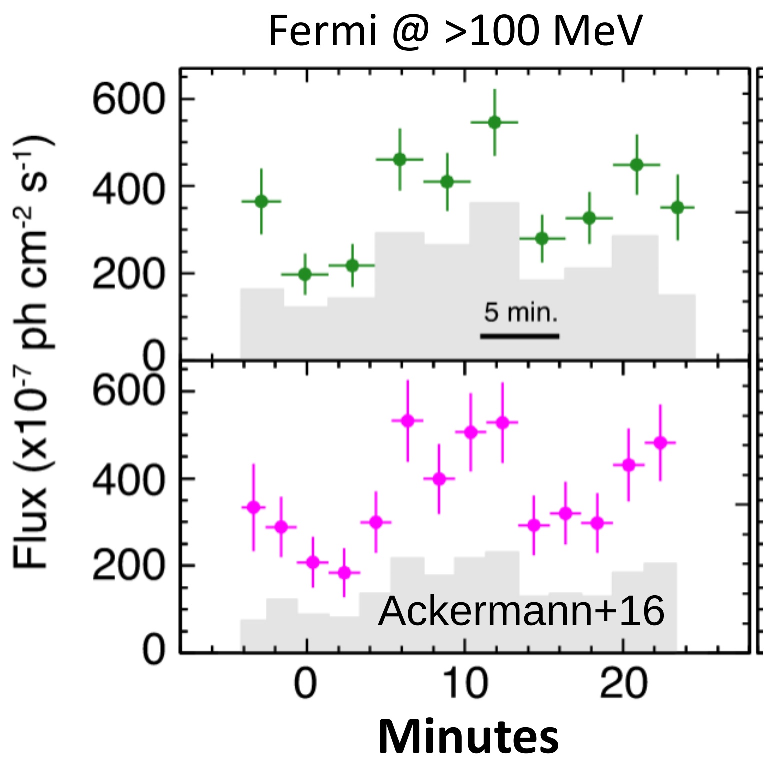


z=0.536

20 μas ~ 1700 R_S (for ~10^9 M_{sun})

3C 279: an archetypal blazar

- Bright and highly variable gamma-ray emission
  - One of first EGRET sources (Fichtel+ 1994), arguably the most studied gamma-ray AGN
  - Rapid gamma-ray variabilities (record holder: 5 min!)
    - Often requires jet γ >100 (how to achieve?)
    - Invoke various models (turbulences, jet-in-jet, hadronic plasma etc)
  - Important to identify and determine by VLBI technique:
    - jet acceleration & collimation zone
    - most variable regions
    - jet composition

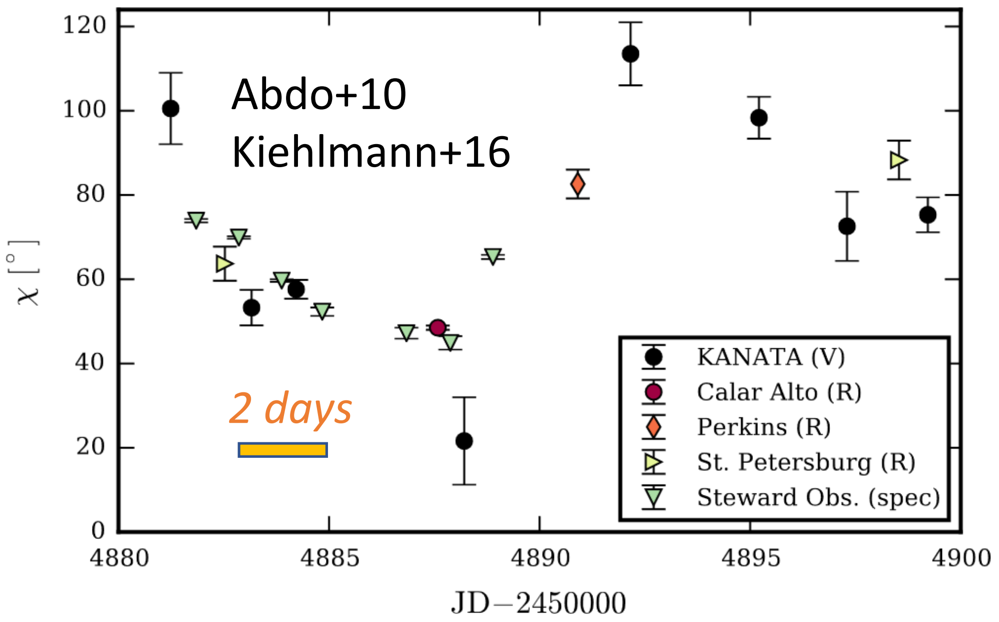


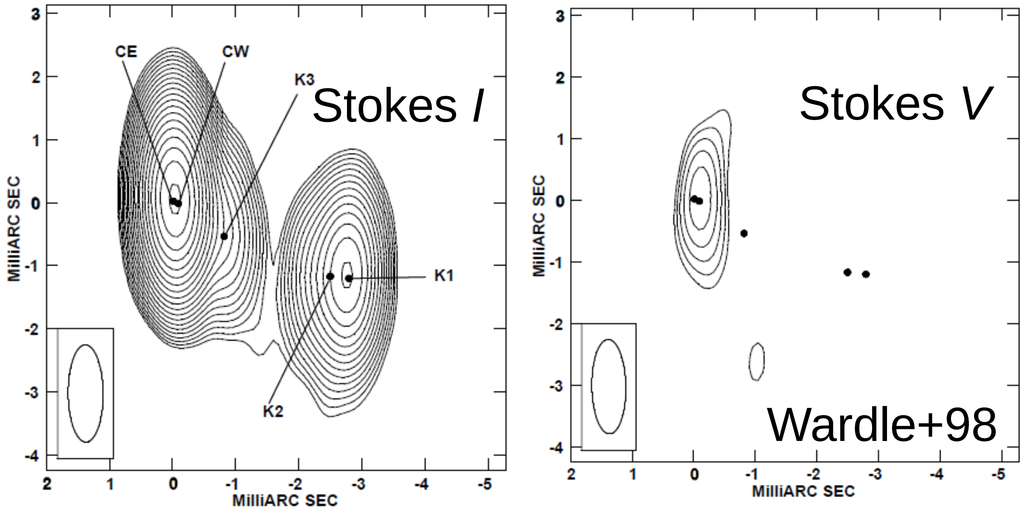
3C 279: an archetypal blazar

- Rapid (optical) polarization variability (e.g., Abdo+10)
  - EVPA swings over days, often coincident with fast gamma-ray flares
  - Polarization variability often deterministic (e.g., not random-walk events; Kiehlmann+16)

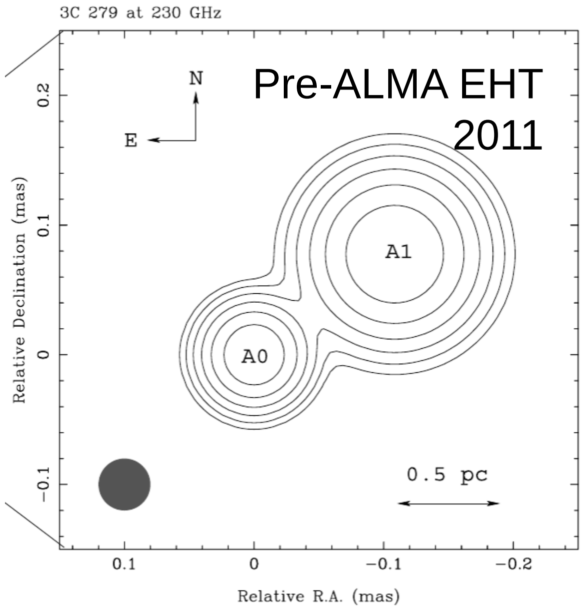
- High VLBI linear & circular polarization detections
  - Constrains jet plasma composition; significant amount of e^+e^- pair (e.g., Wardle+99; Homan+09)

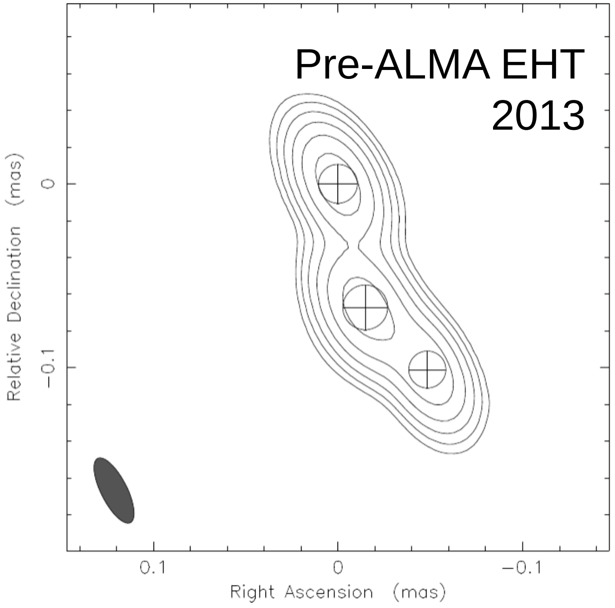
Optical polarization

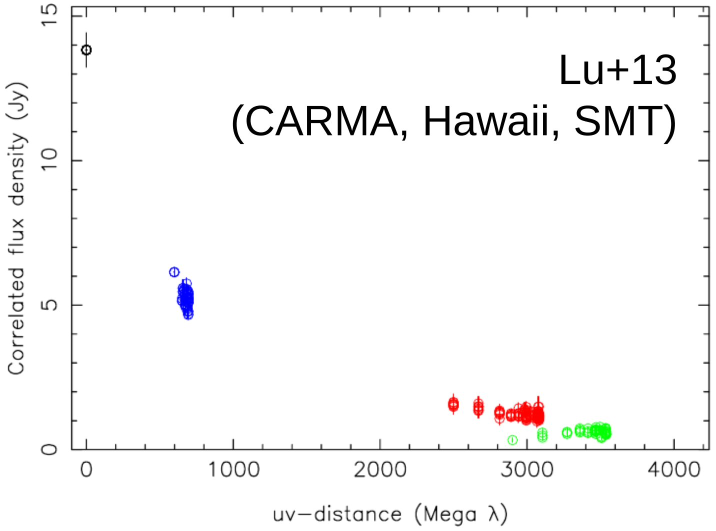


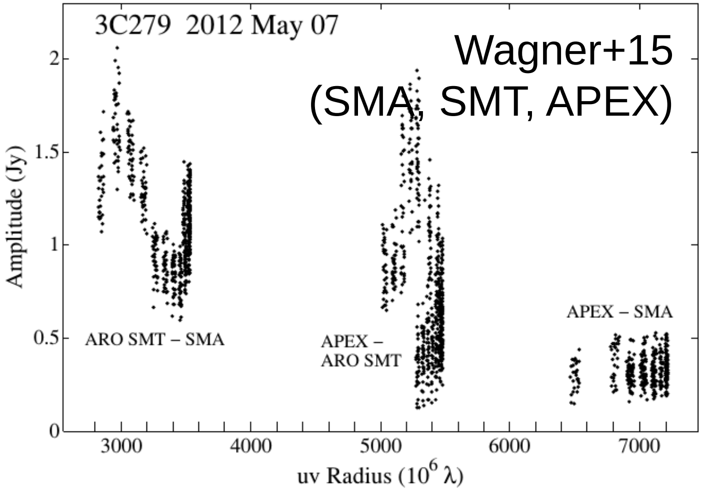


Past 1mm VLBI observations of 3C279









- Presence of **ultracompact jet features** repeatedly found: pilot 1mm VLBI obs. (up to 7Glambda; Lu+13; Wagner+15)

- **Detailed structure** of those compact features however remained **elusive** (only crude model-fitting)

- ***Imaging*** the ultracompact structure is **crucial**

Observations
& key findings

Event Horizon Telescope imaging of the archetypal blazar 3C 279 at an extreme 20 microarcsecond resolution

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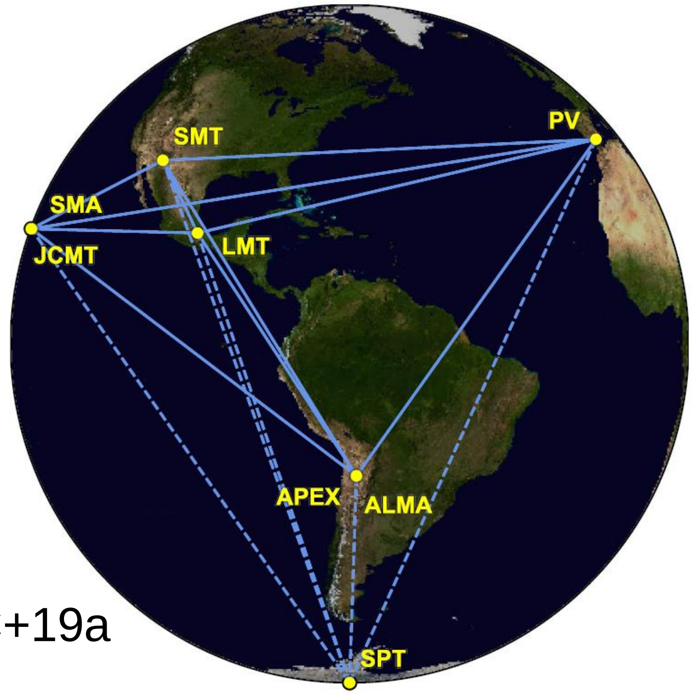
(Affiliations can be found after the references)

Submitted: January 13, 2020

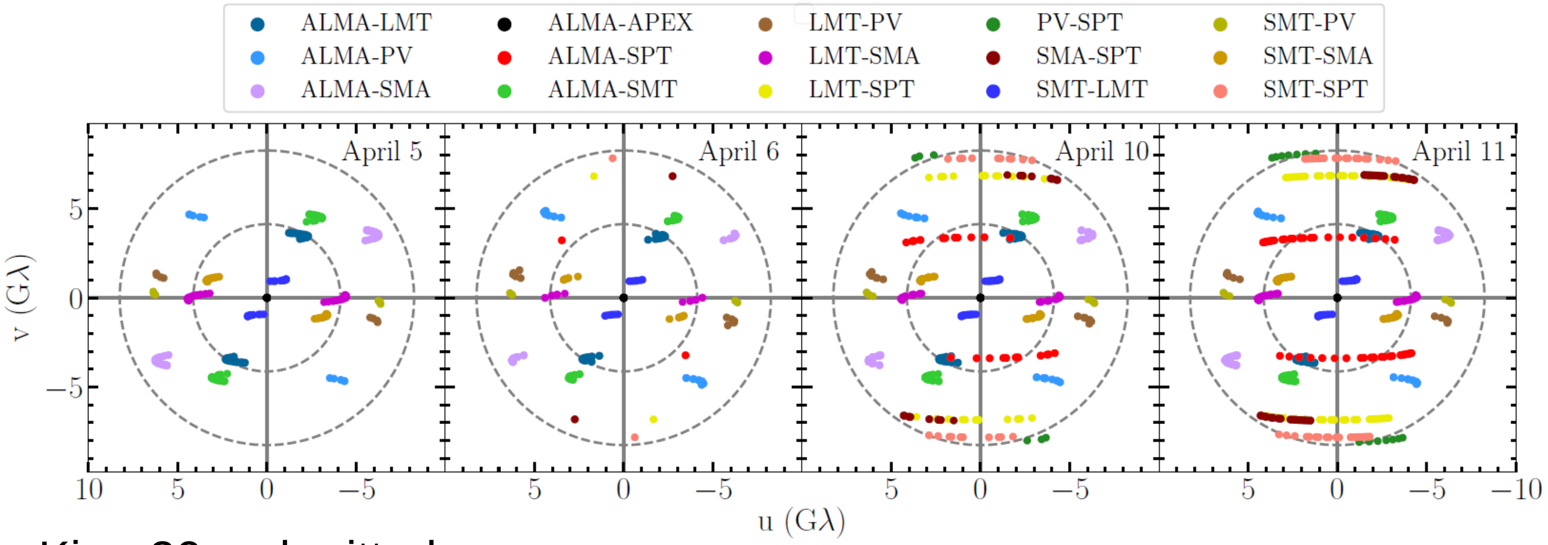
Kim et al. 2020, submitted

EHT 2017 observations of 3C 279



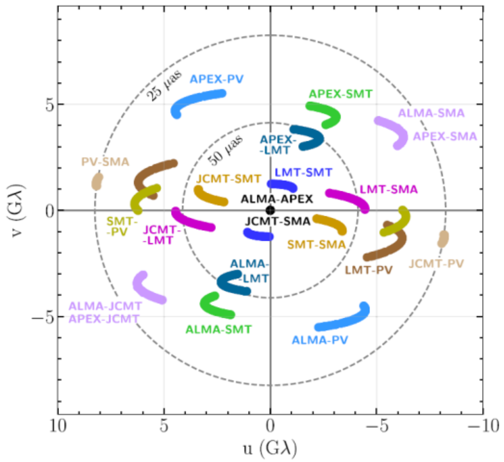
EHTC+19a

- Full-track observations over four nights in 2017 Apr (as main target and calibrator)
- SPT provides maximum N-S baselines: ~8.9 Glambda
- Also accompanying MWL VLBI observations by GMVA 86 GHz, VLBA 43/15 GHz
- Other dense MWL observations at all wavelengths (radio – TeV)

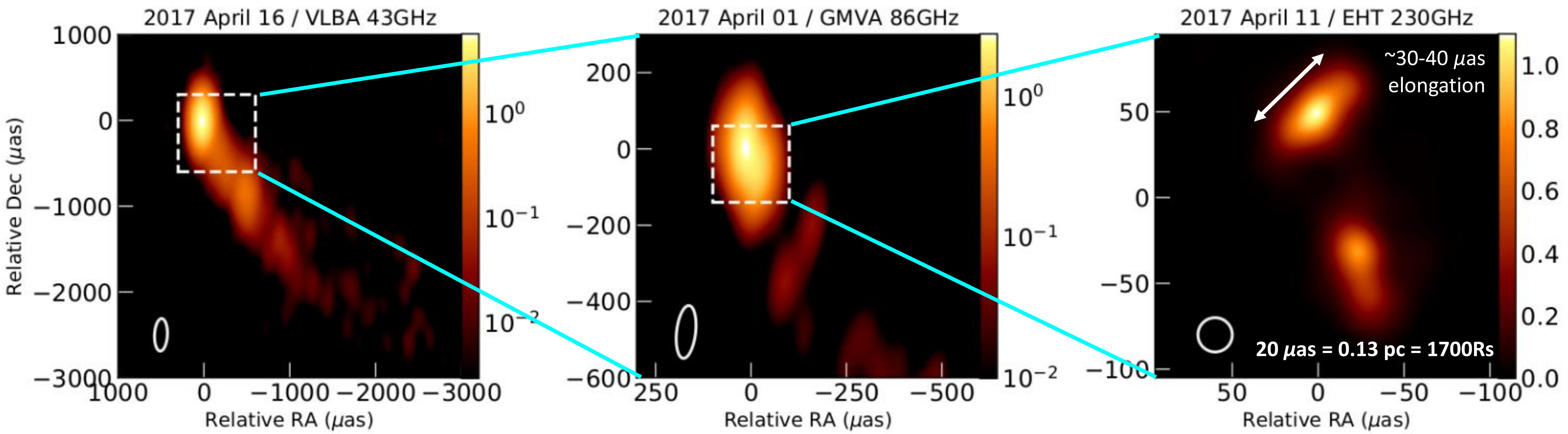


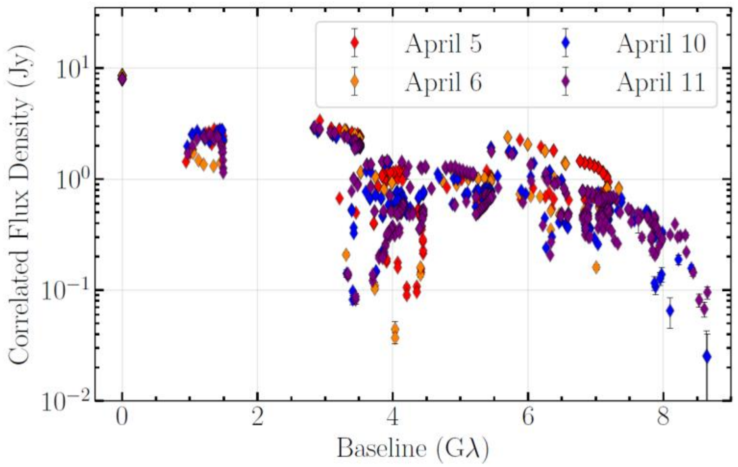
Kim+20, submitted

Comparison: M87 uv-coverage



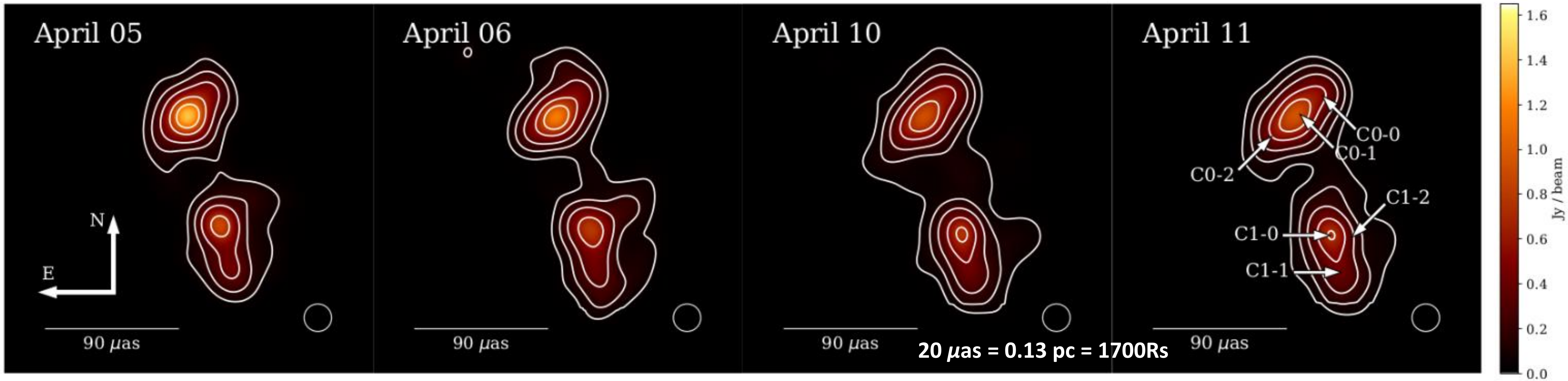
Zooming into the core of 3C279





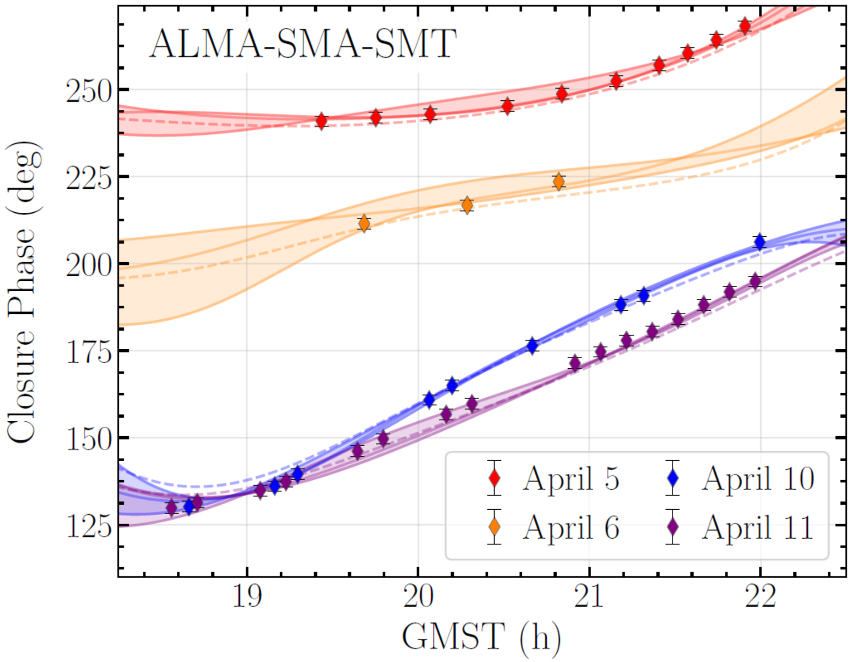
- First image of 3C279 at 20 μas resolution (see also EHTC+19c,d)
- Robust fringe detections up to 8.9 Glambda in all days, mild variability seen in the amplitudes
- The 1mm core structure elongated perpendicular to outer jet – not visible in the low-frequency images

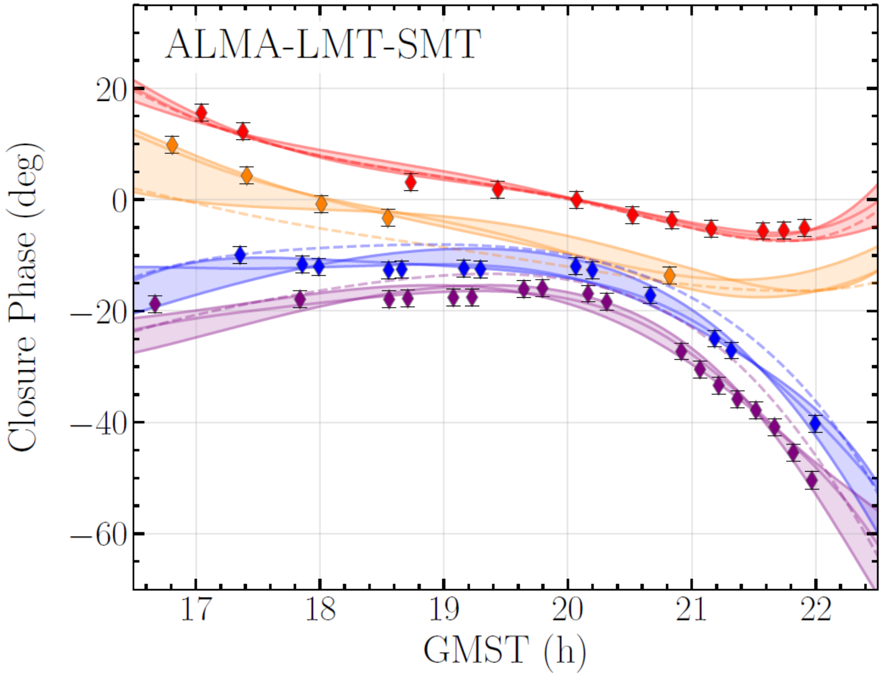
Zooming into the core of 3C279



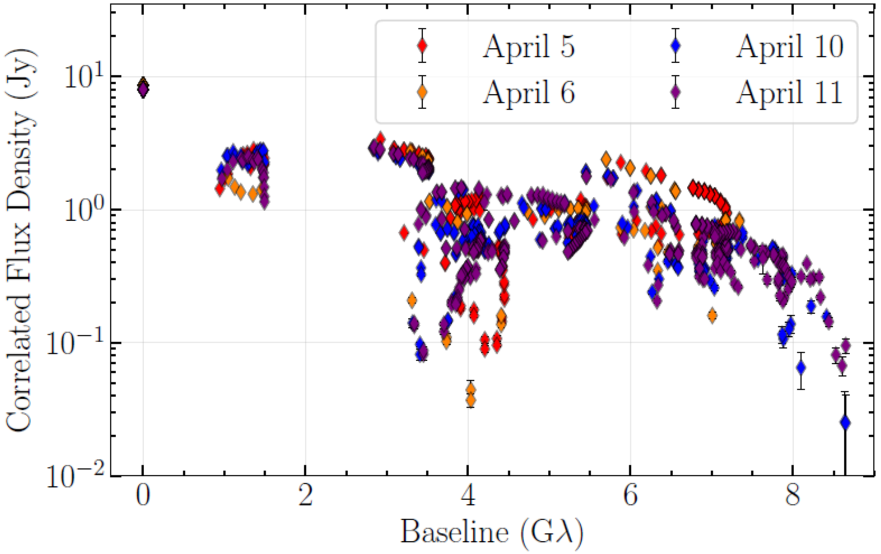
- Four days average images over three imaging pipelines (4x3; SMILI, ehtim, Difmap)
- The perpendicular core structure persistent over four days
- Significant flux variability in the core, and small changes in other details

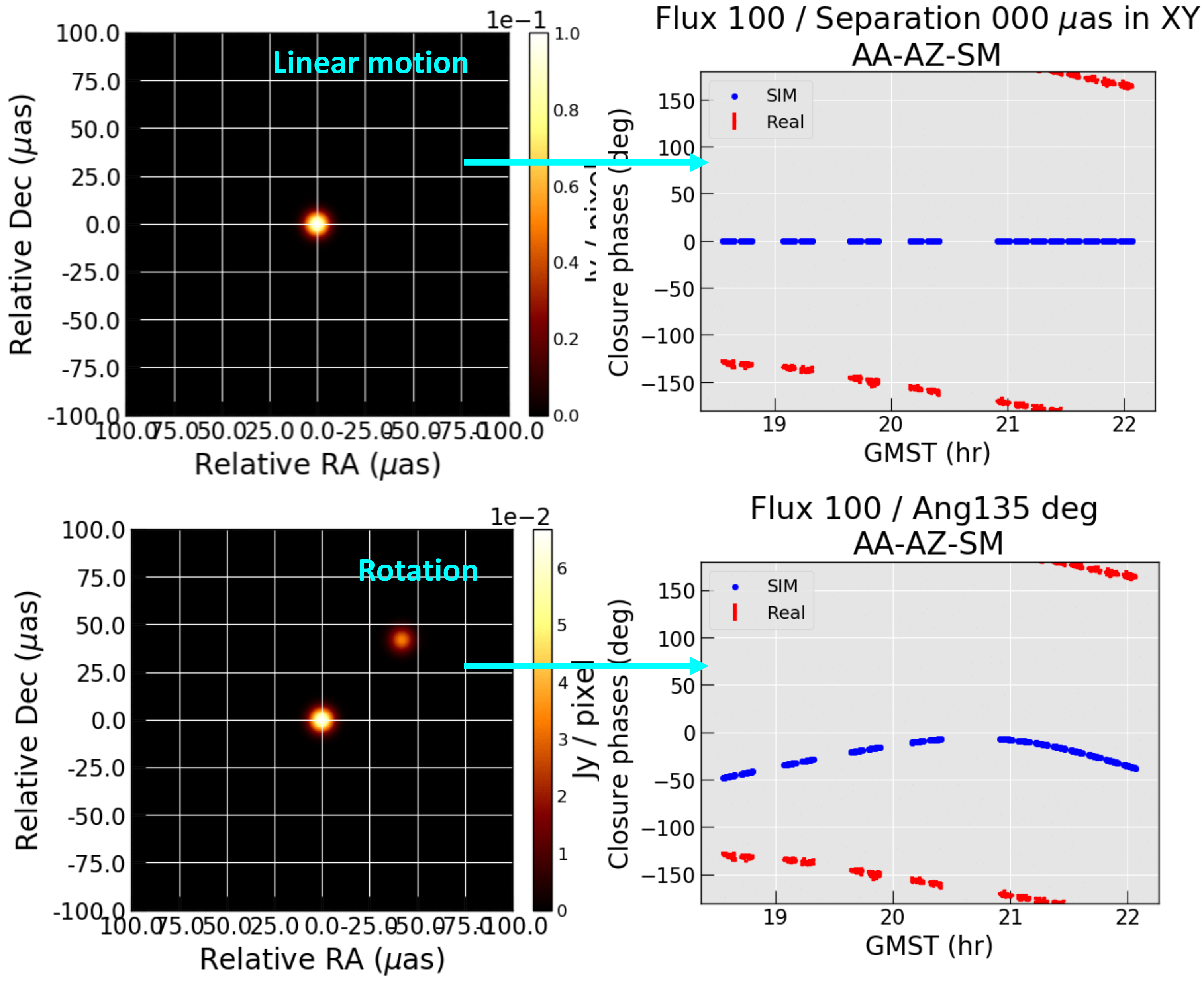
Substantial time variability!





- **CP clearly varies over days**; indicating structure change on inter/intra-day timescales
- More pronounced in bigger triangles; variability mainly comes from small scales
- Amplitudes don't change much
- **What is actually varying in images?**

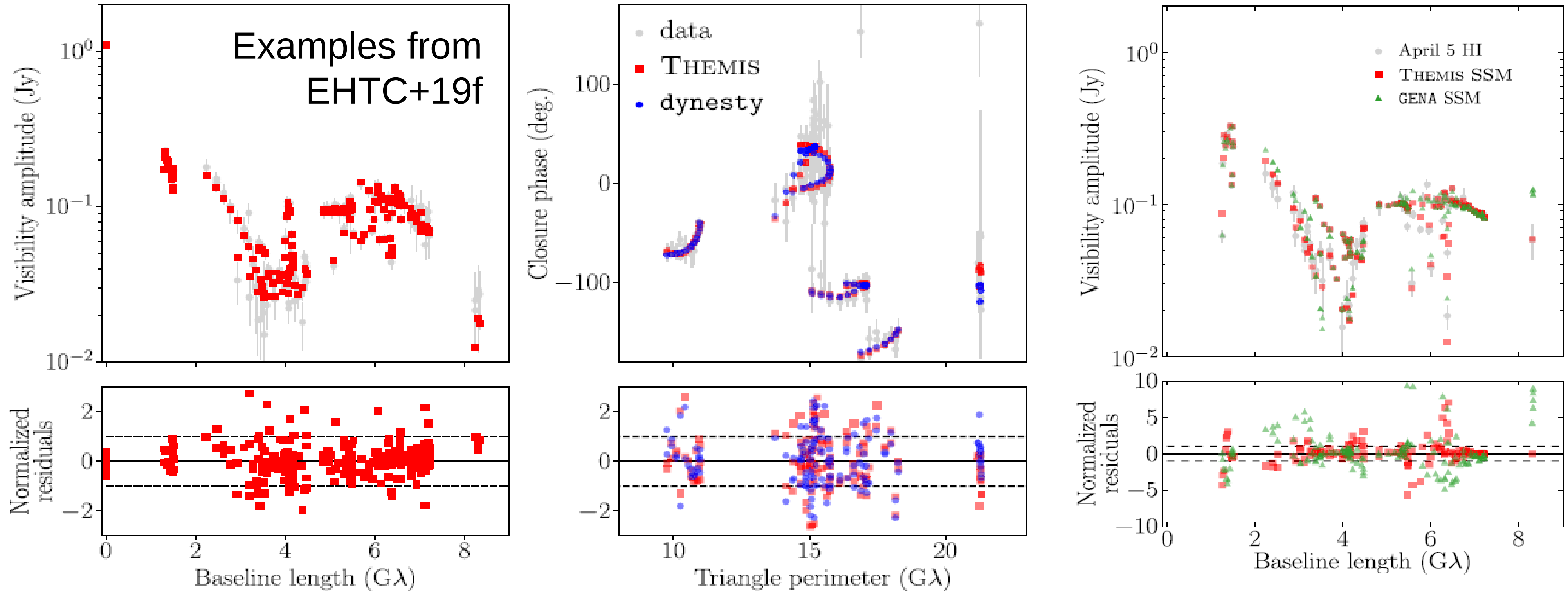




Can closure phases vary just by ~1 μas shift?

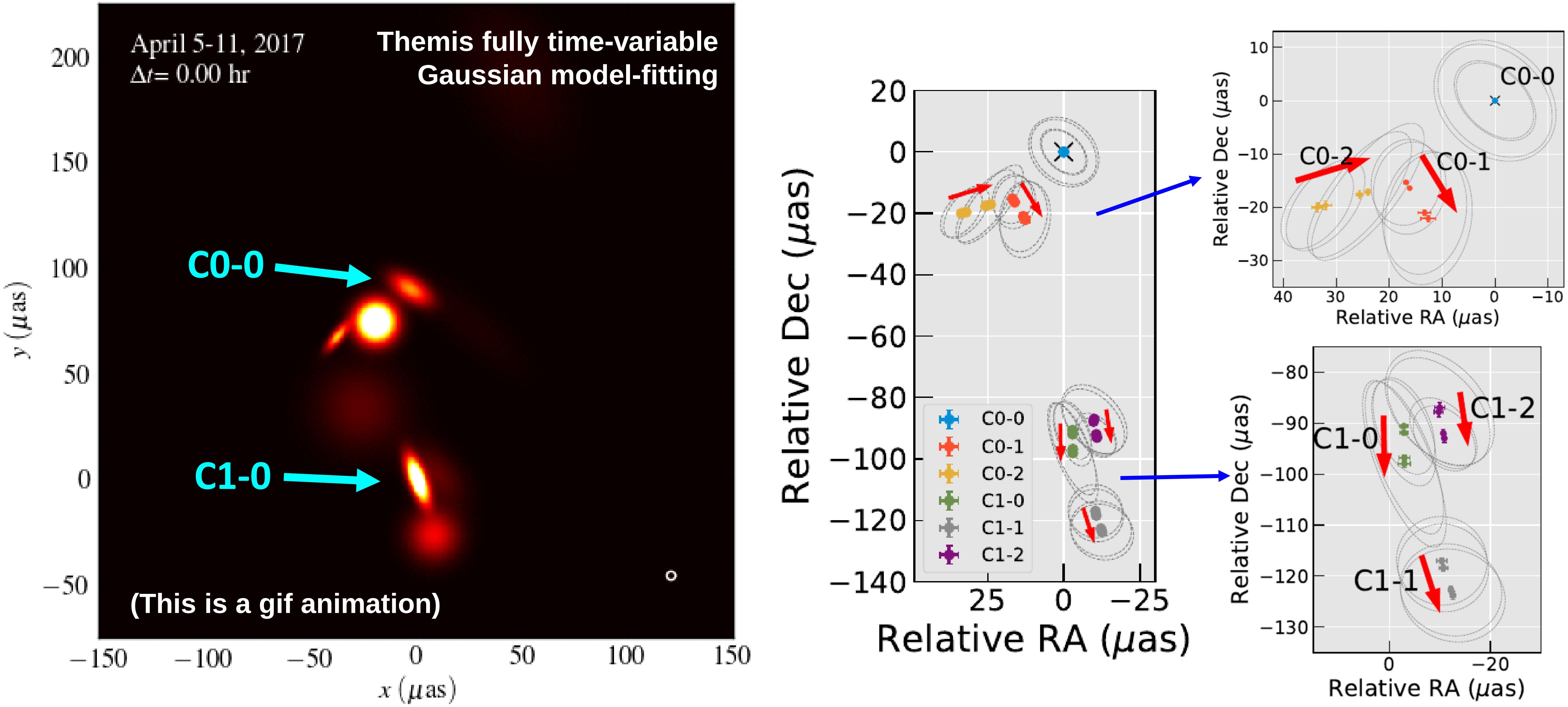
- **Yes, they can**
- Also by flux changes, but somewhat weaker effects
- High enough SNR make the data sensitive
- Challenges to traditional VLBI data analysis

EHT-specific model-fitting analysis tools

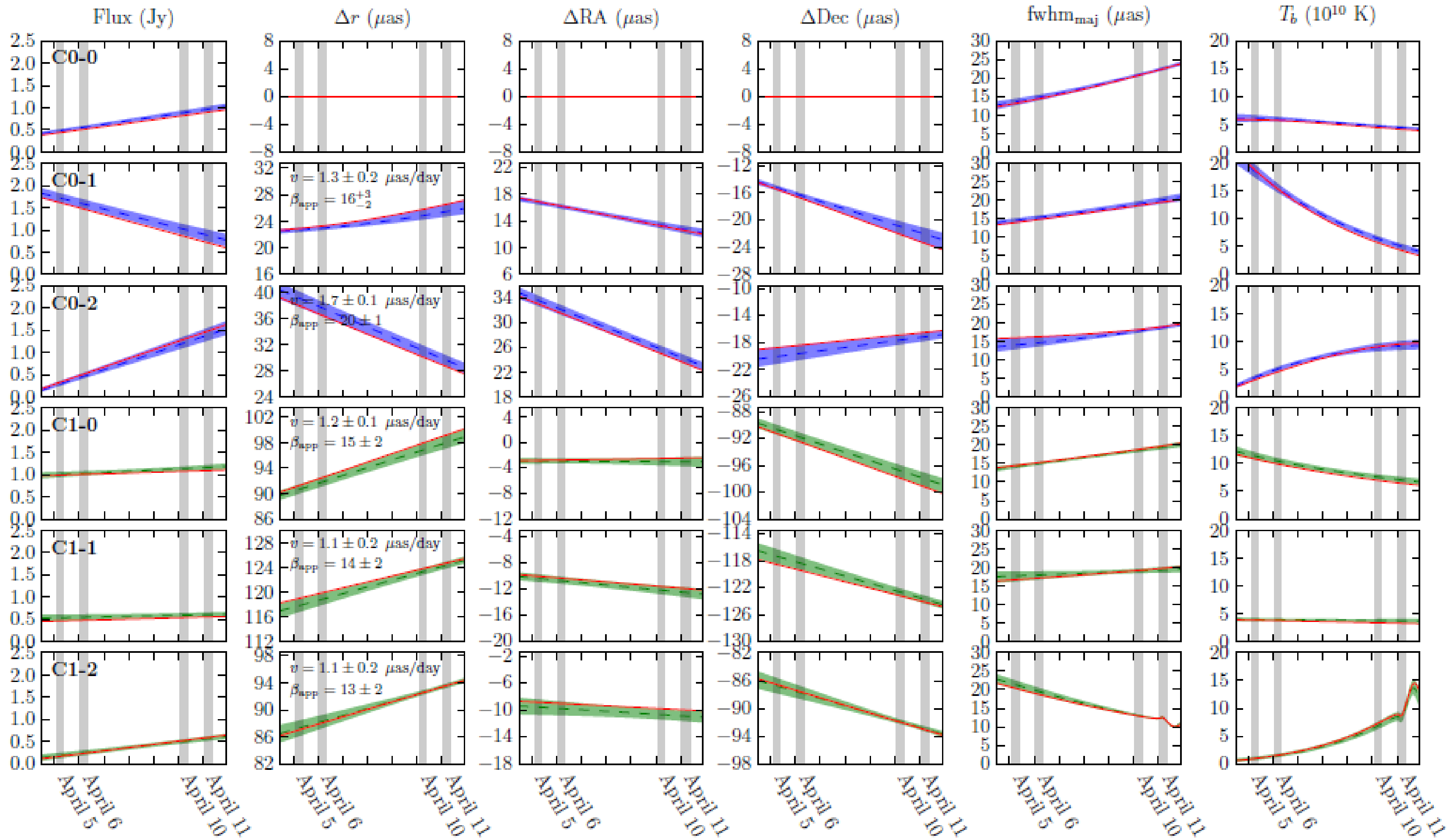


- Various MCMC and relevant packages available: **Themis** (Broderick+20), Dynesty (Pesce+), GENA (Fromm+19)
- Fitting to various EHT measurements possible (closures, baseline visibilities etc)
- **“Dynamic” modeling analysis also possible (in progress)**

3C279 jet kinematics on daily & μas scales

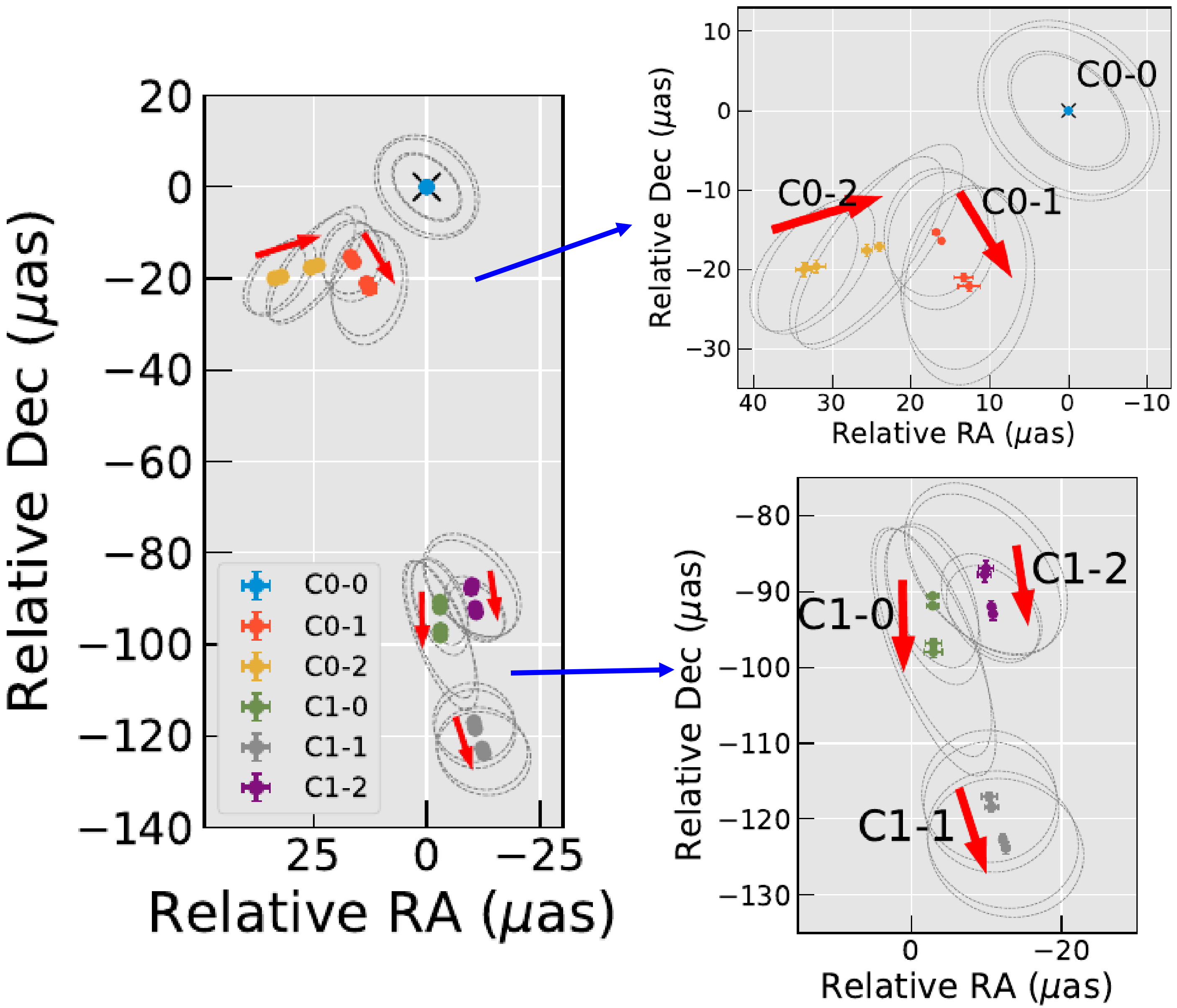


Full posterior distributions from Themis time-variable model-fitting



Fully dynamical model-fitting -- fluxes, positions, sizes, and their time derivatives

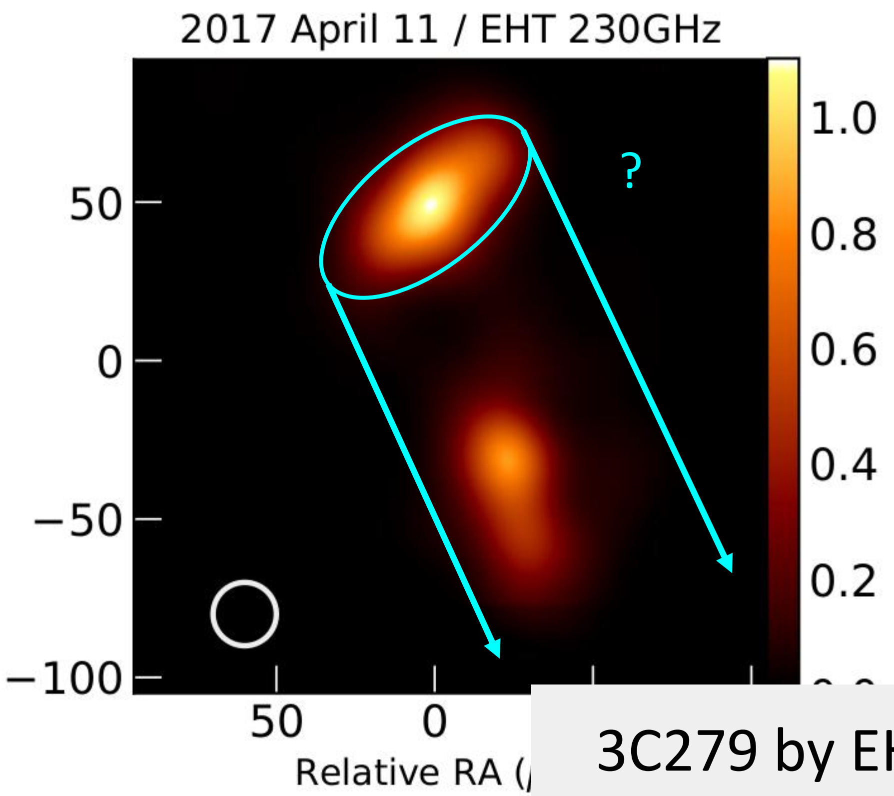
μas scale jet kinematics in detail



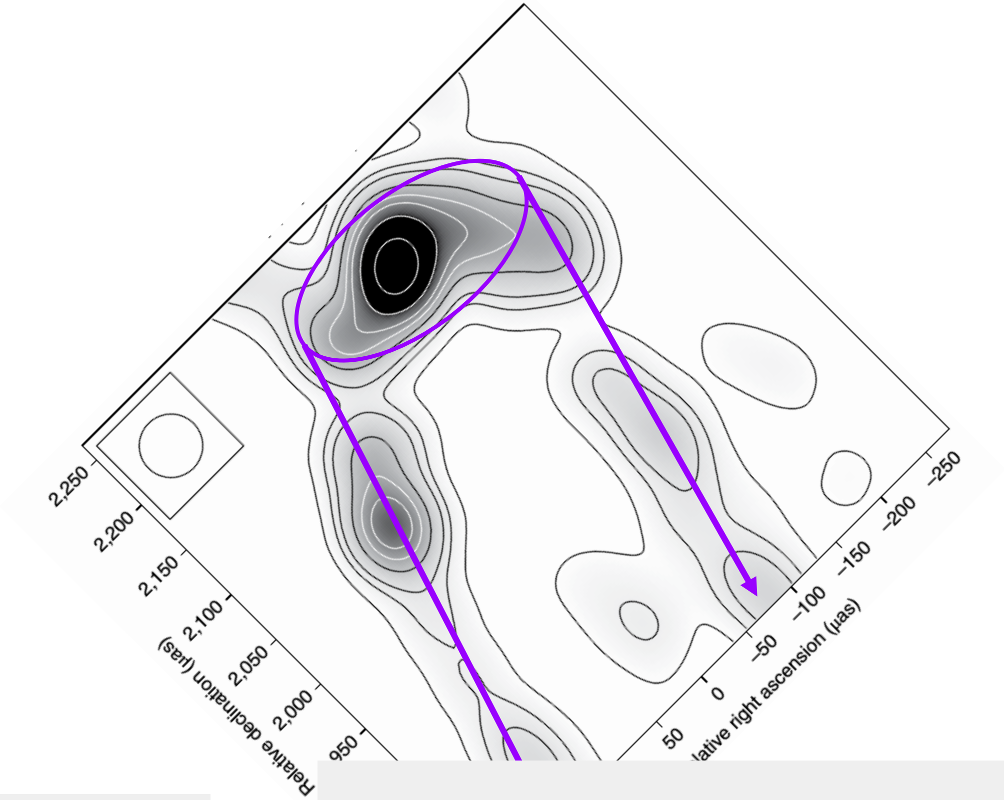
- Extremely high S/N → ~1-2 μas level of positional uncertainty (classically, positional accuracy ~ Beam/SNR).
- C1 components move southward, only when C0-0 is used as reference.
- All components move by ~1-2 μas/day (~10-20c) w.r.t. C0-0.
- App. speeds comparable to VLBA 15/43 GHz monitoring results on mas (pc) scales (e.g., Jorstad+17).
- C0-1 and C0-2 clearly show non-radial motions w.r.t. C0-0.

Discussions

Origin of the peculiar subnuclear structure



3C279 by EHT 230 GHz

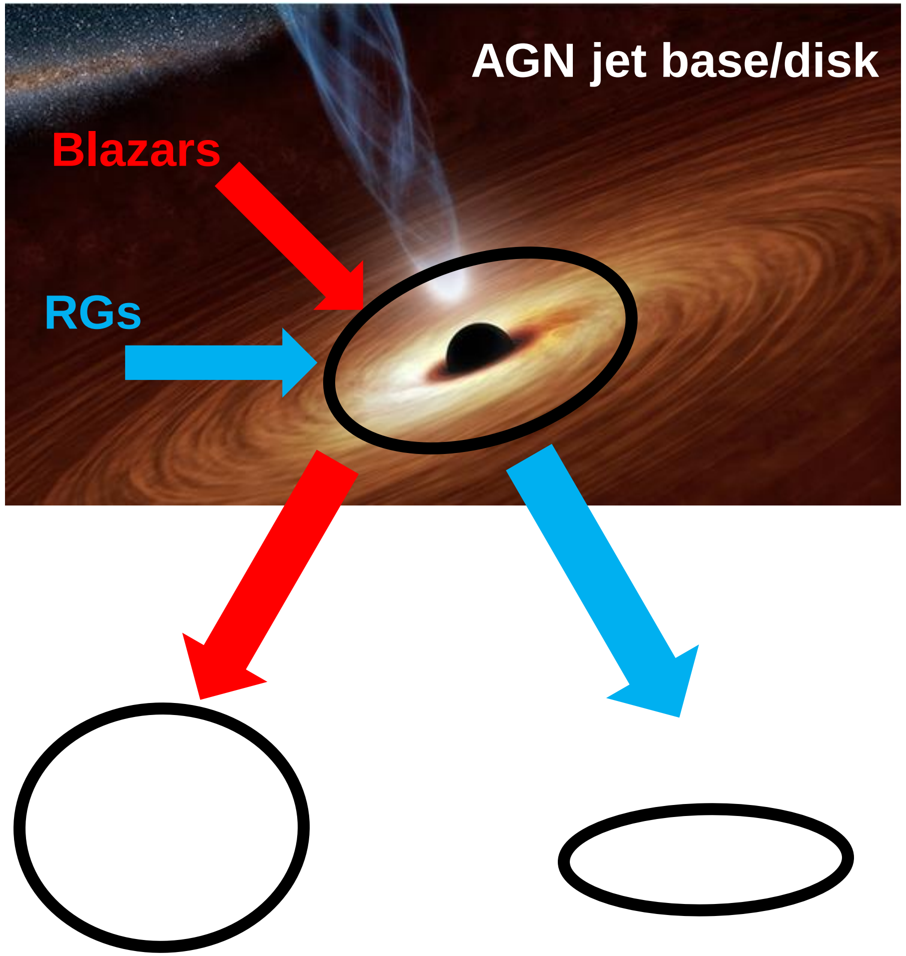


3C 84, RadioAstron 22 GHz

(Giovannini+18)

Broad jet base, perhaps associated with the accretion disk and/or edge-brightened jet, similar to 3C 84 (see Giovannini+18 for more discussions)?

Broad jet base/accretion disk?



Nearly **face-on view** of circular accretion disk (or jet base)

edge-on view
(thus more elliptical)

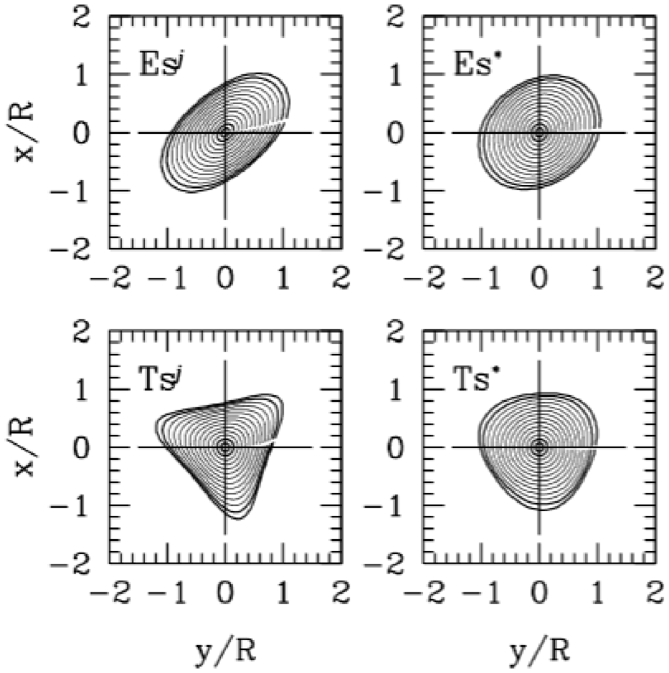
- Viewing angles differ by large amounts: Radio galaxies (e.g., M87, 3C84, … : ~> 20 deg) vs. Blazars (e.g., 3C279: ~< 2 deg)

- Accretion disk (or base of a circular jet) would rather appear circular than narrow elliptical for small viewing angle

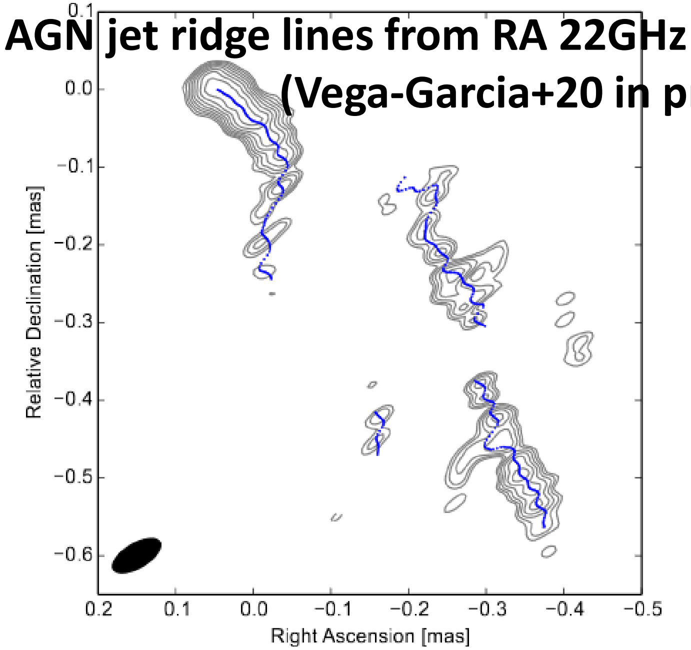
Other explanations?

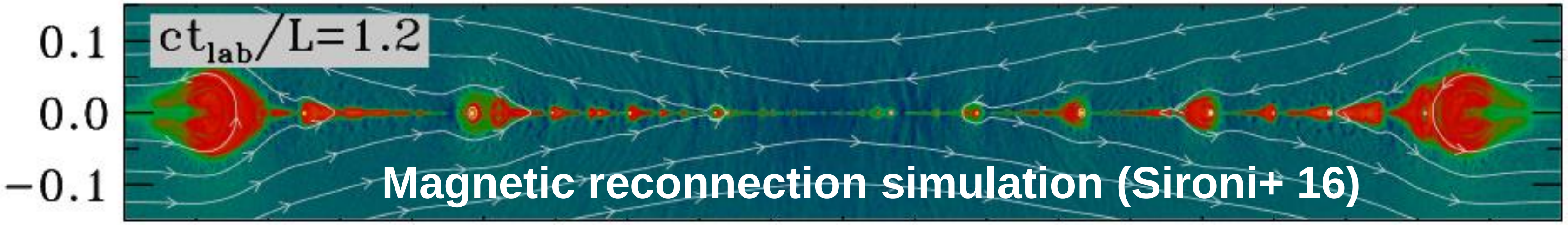
- Many! for example…
- Oblique shocks
- Illuminating patterns (plasma instabilities) on the jet surface
- Large scale magnetic reconnection (a long, linear string of “plasmoids”)

Jet cross-sections (Hardee 2000)



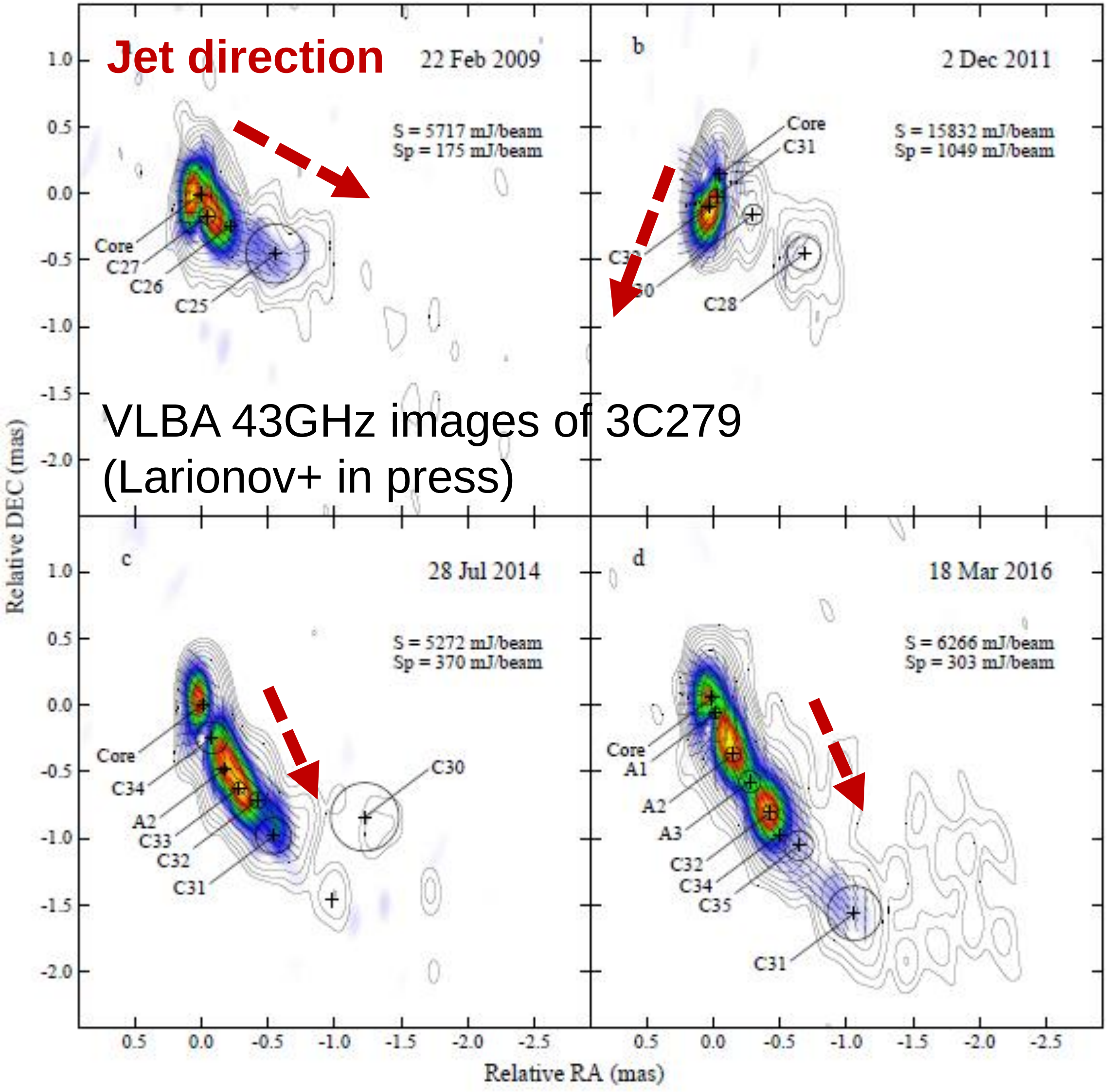
AGN jet ridge lines from RA 22GHz obs. (Vega-Garcia+20 in press)





Magnetic reconnection simulation (Sironi+ 16)

Spatially bent jet in 3C279



VLBA 43GHz images of 3C279
(Larionov+ in press)

- A number of evidence suggesting presence of curvature in the 3C279 jet (e.g., Homan+03, Jorstad+04, Abdo+10, Aleksic+14, Homan+15, …)
- May explain the complex geometry & kinematics without introducing unnecessary complexity

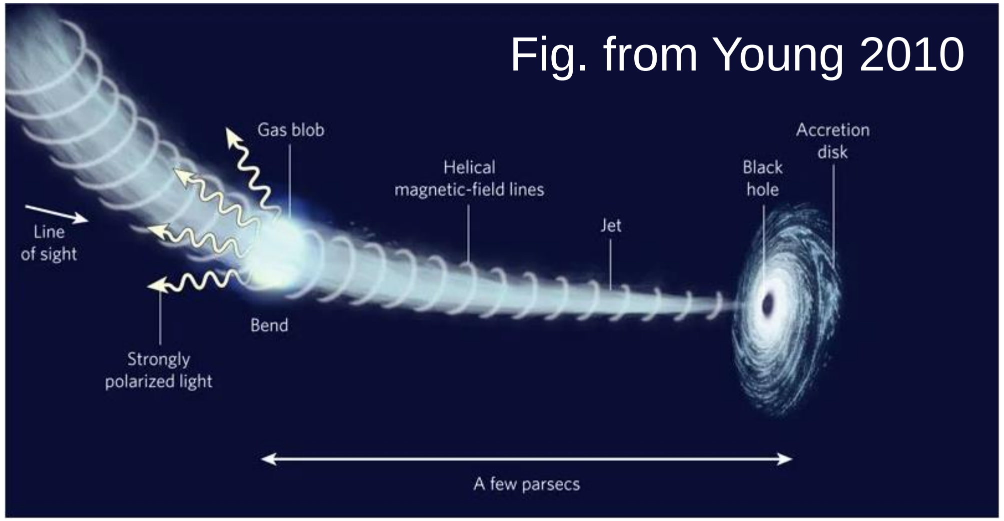
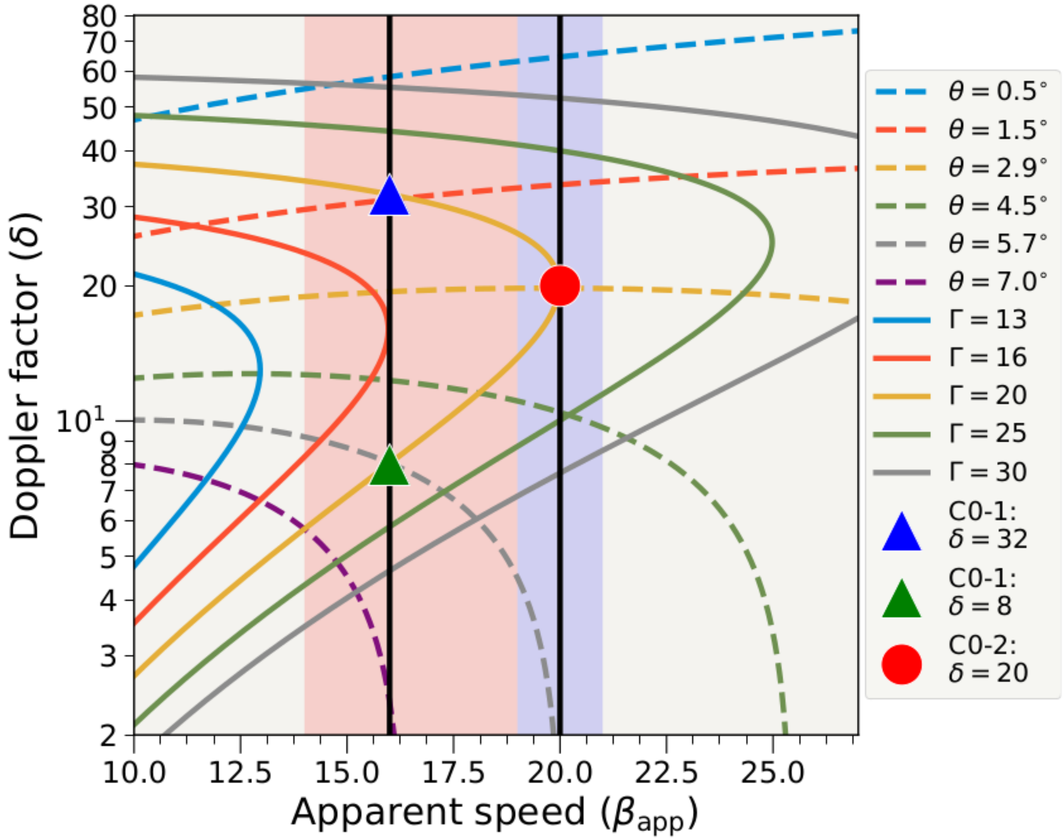
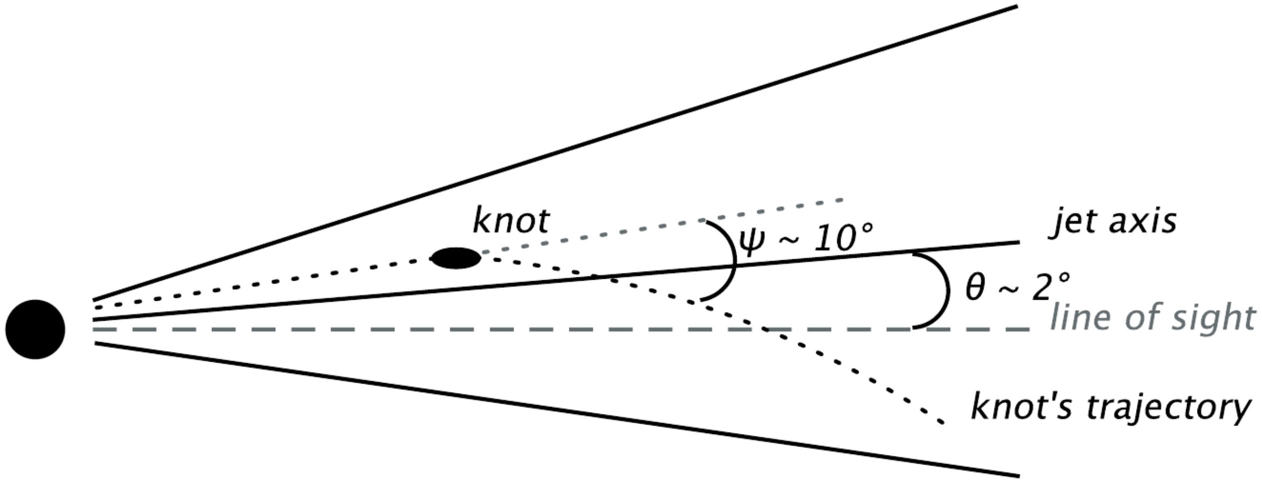


Fig. from Young 2010

Testing a bent jet model for the “core”



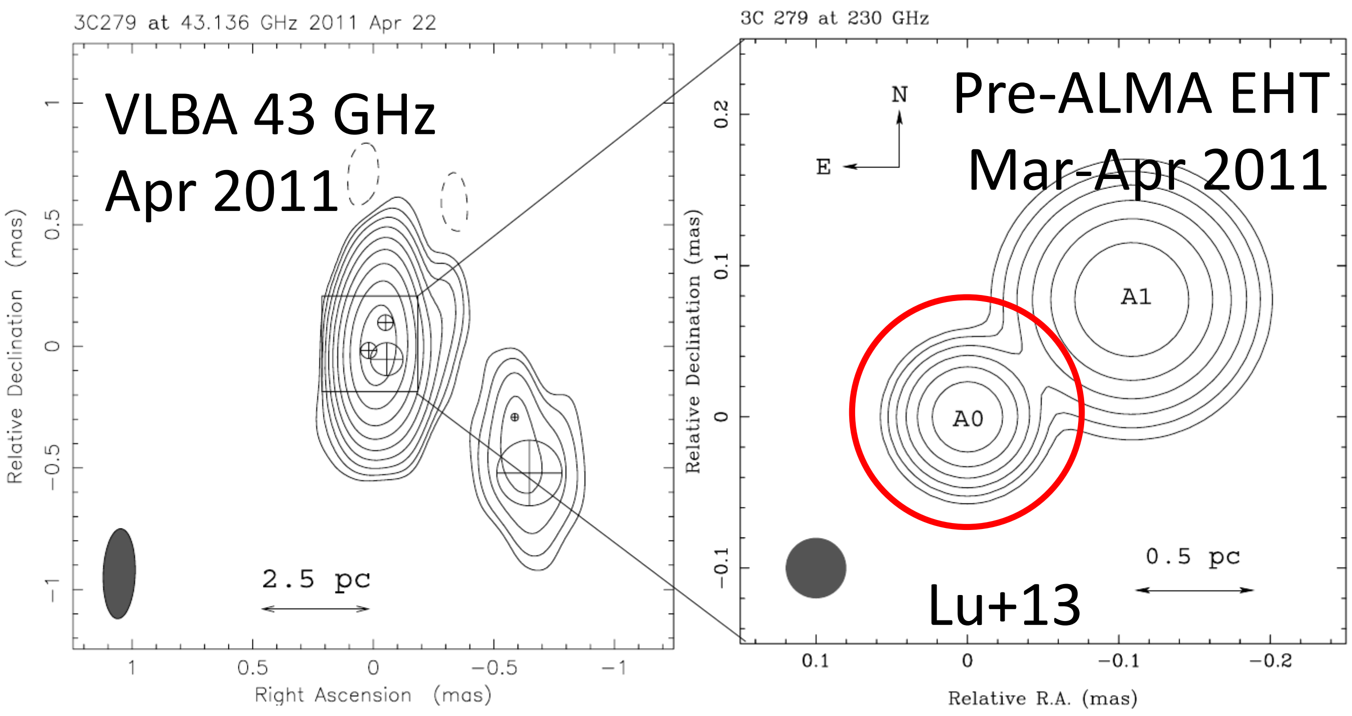
Assuming constant Gamma=20 for C0-1 and C0-2 (theta ~3 and 1.5 deg).

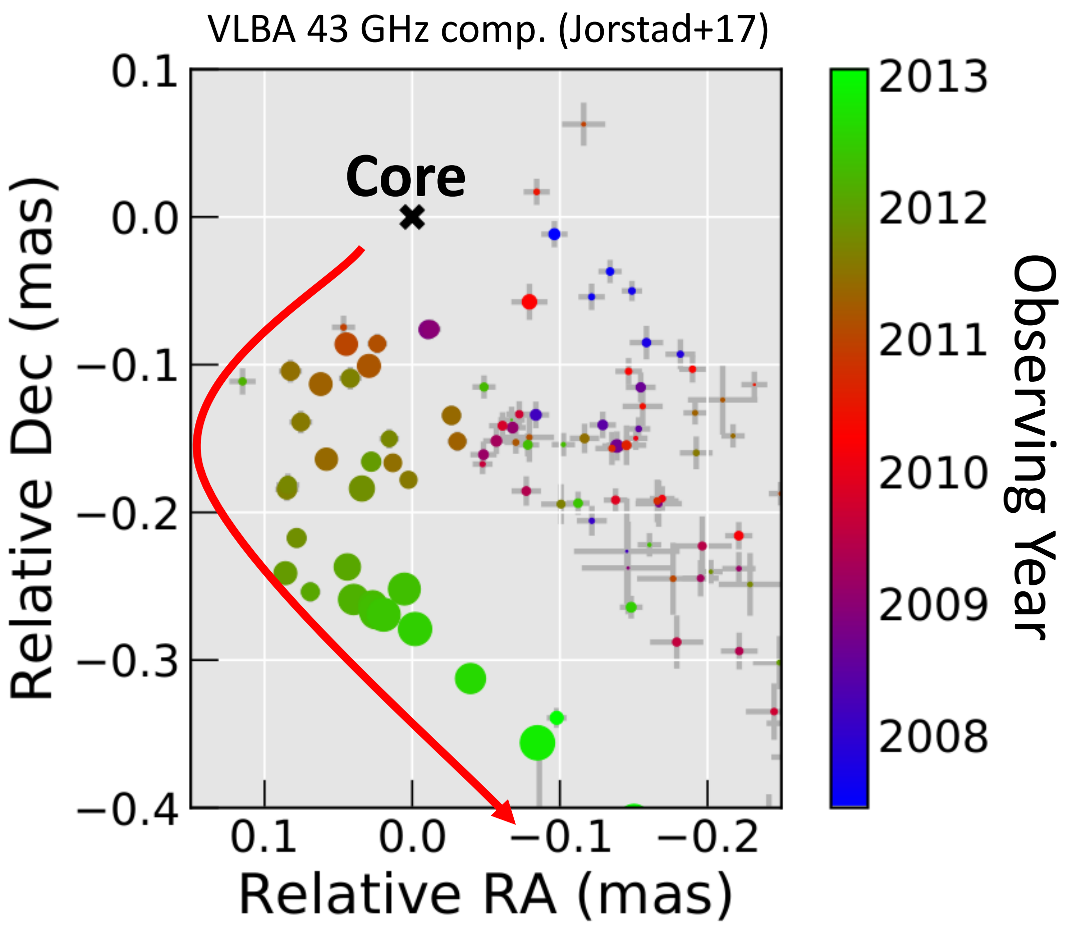


Sketch of bending jet model (from Aleksic+14)

- Many suitable families of parameters to fit the apparent speed using **a constant Lorentz factor but varying viewing angles along the jet (**by a few degrees.).
- 90 deg apparent P.A. change would require ~90*sin(1-2 deg) ~ 1.5-3.0 deg jet viewing angle change; internally consistent values.

Comparison with pre-ALMA EHT obs. of 3C 279





- In Apr 2011, similar innermost jet feature orientation was found by pre-ALMA EHT, during very high radio flux state.
- Later 2011, VLBA 43 GHz saw bright jet component in similar direction, later aligned to larger-scale jet.
- 2017 EHT observations may be similar.

NB: data point size ~ comp. flux.

What causes jet bending/rotation?

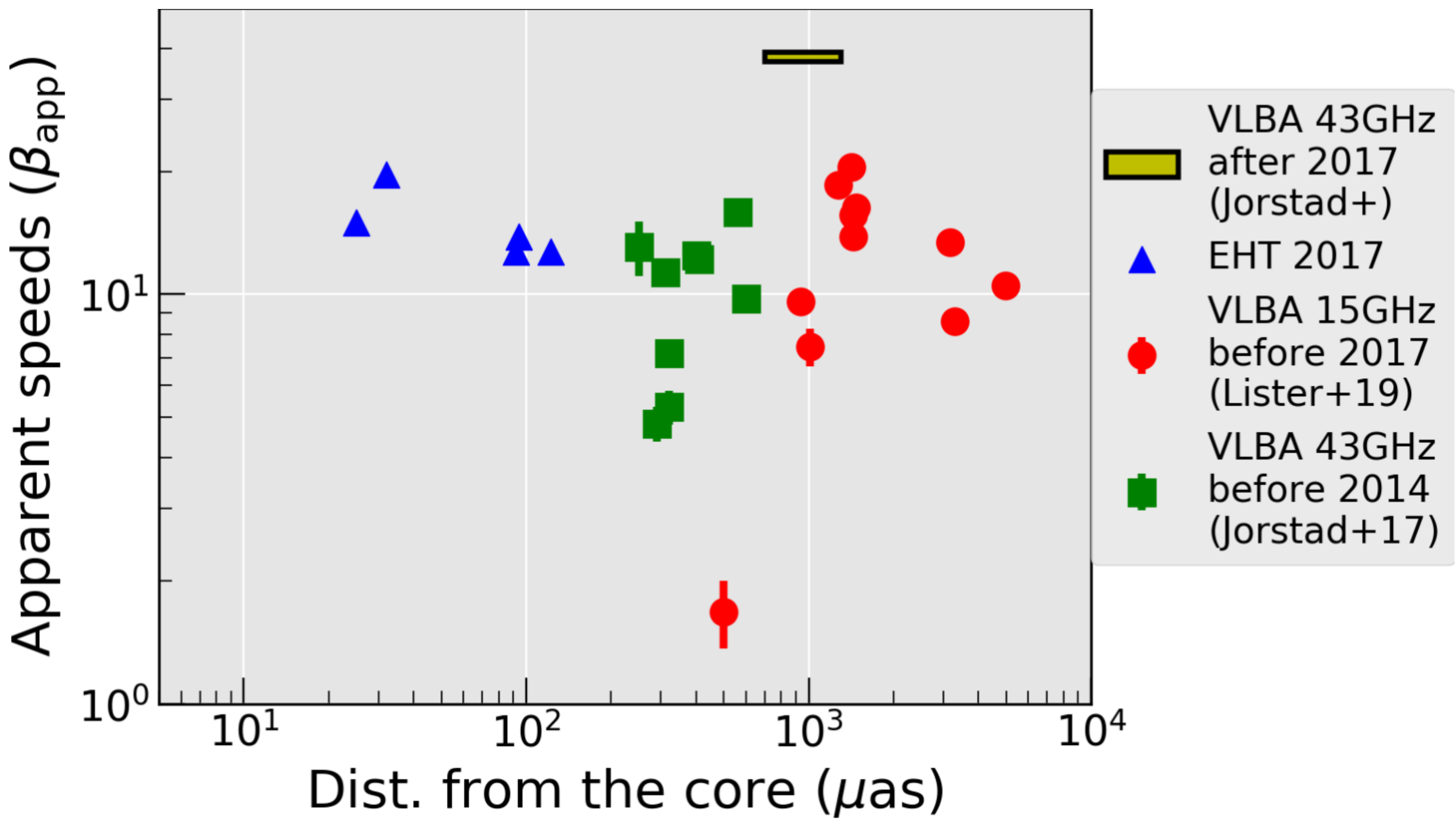
- **Binary SMBHs and/or BH+disk precession** (Abraham & Carrara 98; Qian+ 19; *P*~22 yrs for 3C 279) → EHT jet structure similarity between 2011 and 2017 would constrain period ~< 6 yrs, ruling out this scenario

- **Jet being collimated by interaction with ISM** (e.g., Homan+15) → misaligned AGN jet components tend to align with pre-established direction

- **Excitation of emission going along helical magnetic field in the jet** → Inner jet dynamics (e.g., Mertens+16) & polarization (Asada+02; Marscher+08; Hovatta+12; Kiehlmann+16)

- Understanding which one of these works better would require additional constraints (outlook)

How does the EHT 3C279 jet connect to the downstream?



- EHT jet speeds (~10-20c) are comparable to historical mas-scale speed measurements (before 2017)
- Constrains jet acceleration zone to be potentially < 3000Rs projected (~< 8x10^4 Rs deprojected)
- However in 2017 the 3C279 jet was exceptionally fast at ~>0.5 mas; ~37c speed (Larionov+20 in press)

Brightness temperature in the nuclear region

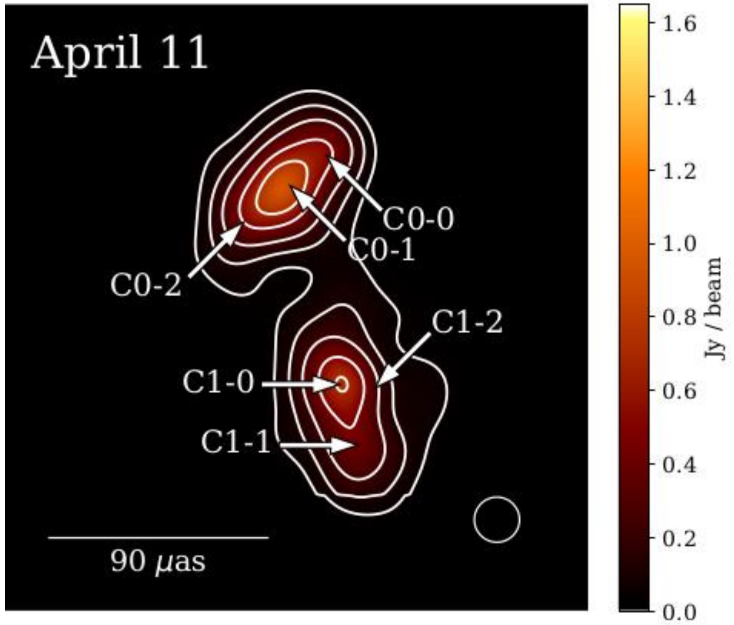


Table 2. Summary of geometric and dynamical properties of the jet components discussed in §4.2.1 and §4.2.2.

ID	β_{app} (c)	θ (°)	Γ	δ
Curved jet case[a]				
C0-1	16^{+3}_{-2}	≤ 1.5	≥ 20	≥ 32
C0-2	20 ± 1	≤ 2.9	≥ 20	≥ 20
C1-0/1/2	$(13 - 15) \pm 2$	$\geq 6 - 8$	≥ 20	$\leq 5 - 7$
Straight jet case[b]				
C1-0/1/2	$(13 - 15) \pm 2$	2	16 – 17	24 – 25

- Observed Tb ~ 10^(10-11) K → Intrinsic T'b ~< 10^(9-10) K considering Doppler factors of at least ~10-20
- Tb ~> 10^12 K and T'b ~ 10^11 K at lower frequencies (Kovalev+05; Jorstad+17)
- EHT values far below Compton limit (~5x10^11 K) and the equipartition value (~5x10^10 K)

Interpretations of the low T’b

- Much depends on the core opacity at 230 GHz
- Optically thick (turnover ~ 1mm)
  - may represent some upstream emission of the jet. Signature of under-accelerated (thus slow) jet underlying the 1mm core.
  - Also T’b ~10^(9-10)K << T’b,eq ~ 5x10^10 K: more magnetic energy dominated flow (cf. kinetic power dominated)
- On the other hand, Tb may simply decrease with freq. if 3C279 becomes optically thin @ 1mm
- EHT spectral index measurement between 230 and 345 GHz would be helpful (also EHT polarimetry).

Conclusions

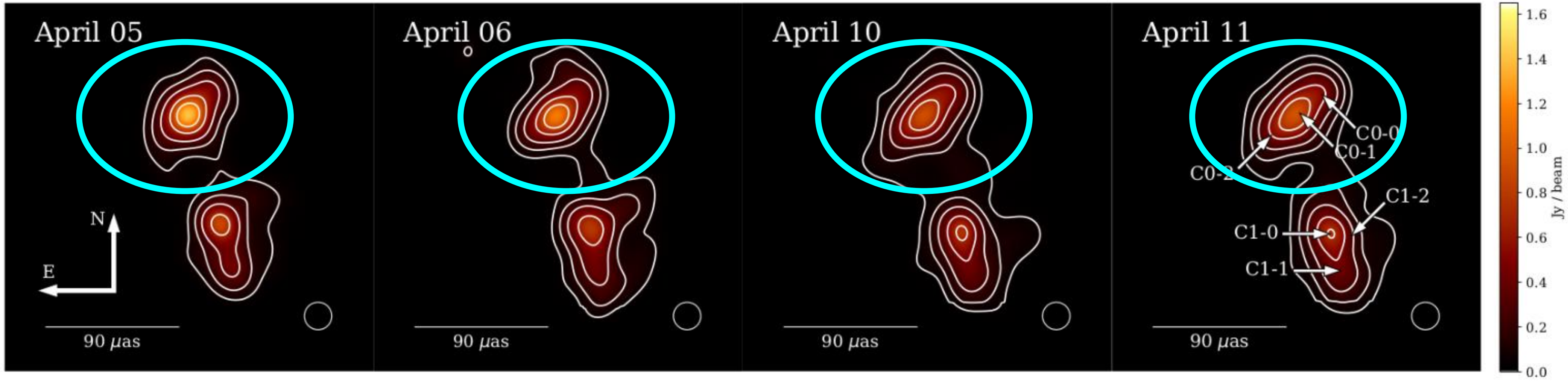
- EHT imaging analysis of the 3C 279 jet at 230 GHz
  - Peculiar “perpendicular” nuclear structure
    - Several physical interpretations
  - Rapid day-to-day closure phase variations; ~1-2 uas/day motions
    - Also complex kinematics; spatially bent jet provides good explanations
  - Unexpectedly low intrinsic brightness temperature (~< 10^10 K)
    - May be a signature of very low jet opacity at 230 GHz
- Still some details quite remain elusive
  - **How to improve / what to do more?**

Outlook

EHT and MWL connections

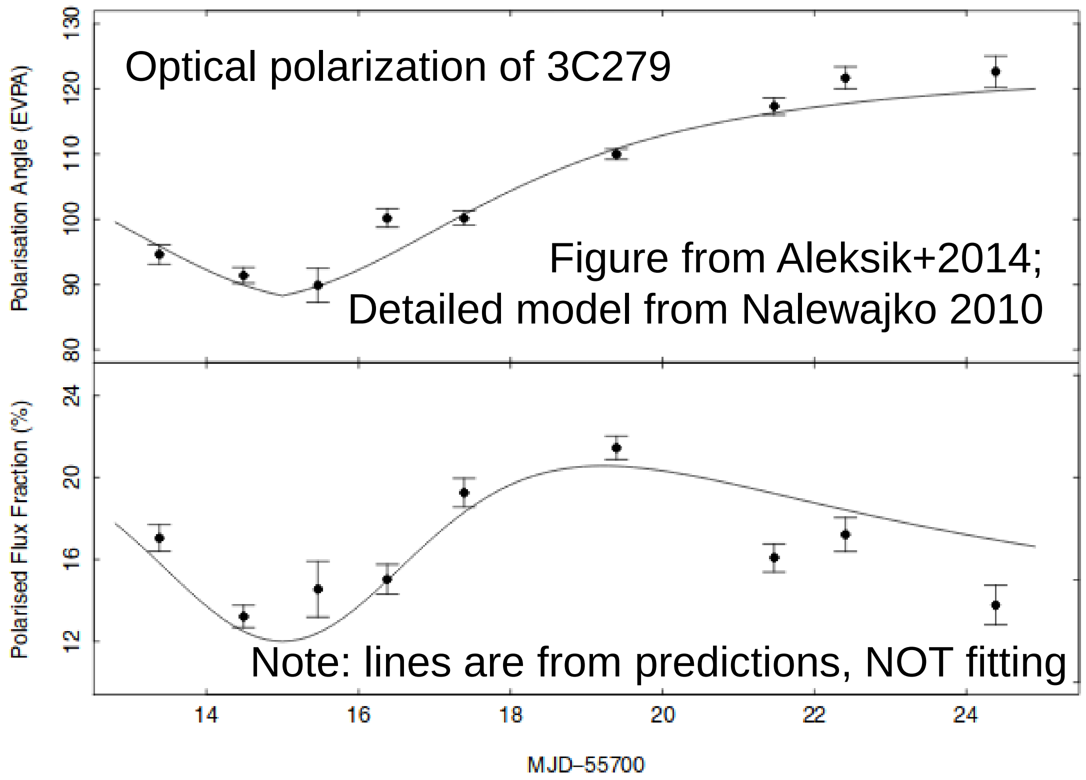
Plot removed

- Significant radio flux variability within the EHT subnuclear structure within ~1 week; factors ~2 or more changes
- Also rapid gamma-ray variability; details under analysis



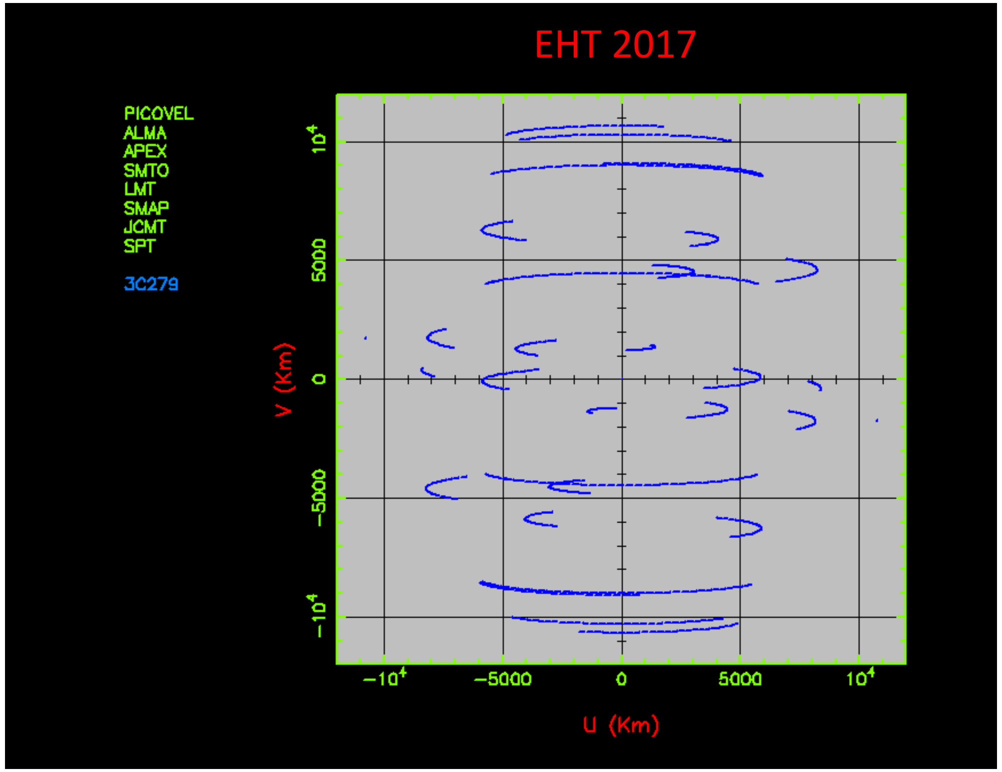
Constraining the curved jet structure

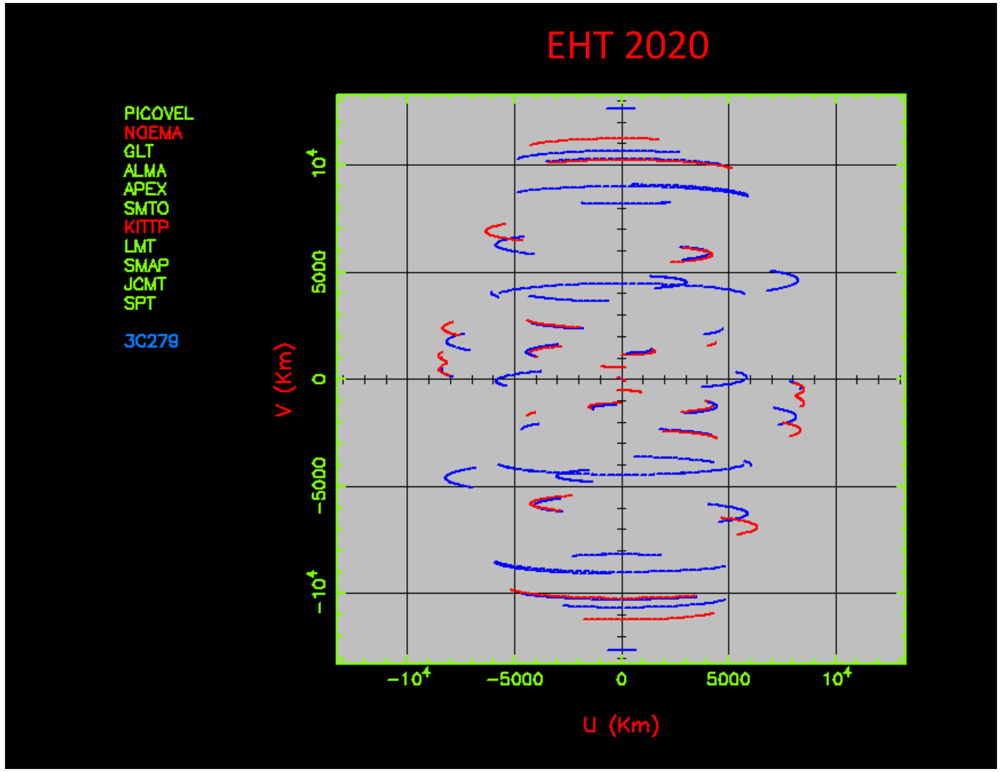
- Rapid linear polarization variability (both *mL* and EVPA)
- Indicates small variable size and ordered evolution of structure (associated with motions?)
- Can independently reconstruct the curved jet parameters



Plot removed

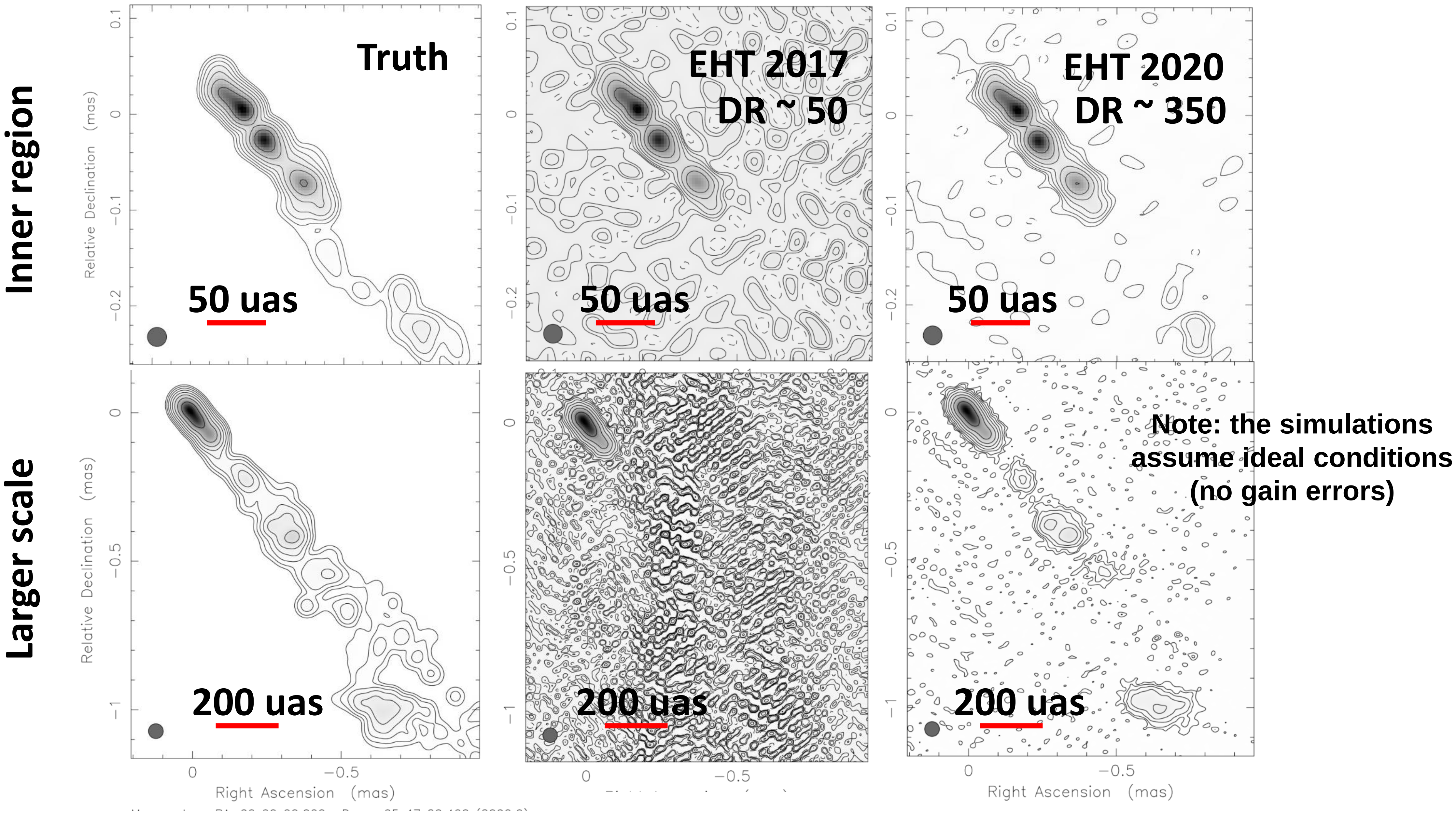
Comparison uv-coverages 2017 - 2020 *(for 3C279)*





8 stations

11 stations
(+GLT+KP+NOEMA)


Inner region
Larger scale
Truth
EHT 2017
DR ~ 50
EHT 2020
DR ~ 350
50 uas
50 uas
50 uas
200 uas
200 uas
200 uas
Note: the simulations
assume ideal conditions
(no gain errors)
Relative Declination (mas)
Relative Declination (mas)
Right Ascension (mas)
Right Ascension (mas)
0.1
0
−0.1
−0.2
0
−0.5
−1
0
−0.5

Final outlook – hope to have soon

- Science side:
  - MWL / polarization
  - More sources (many already observed in 2017; all under analysis)

- Instrument side:
  - Expanding EHT in 2020
  - e-KVN and EAVN-high 230 GHz
  - Will provide a lot of insights about future EHT time-variable studies

- **People, more people!**