Understanding AGN Accretion and Ejection with SKA

Chapter in **Advancing Astrophysics with the SKA – II**

The SKA-VLBI perspective on Radio-Quiet AGN

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The Main Players: Physics & Feedback

The activity of an Active Galactic Nucleus is governed by the complex interplay of several components:

- **Accretion Disk**
- **Hot Corona**
- **Wind -** uncollimated outflows
- **Jet -** collimated relativistic ejections

→ all Radio emitters!

The "Radio-Quiet" AGN population

90% of Population

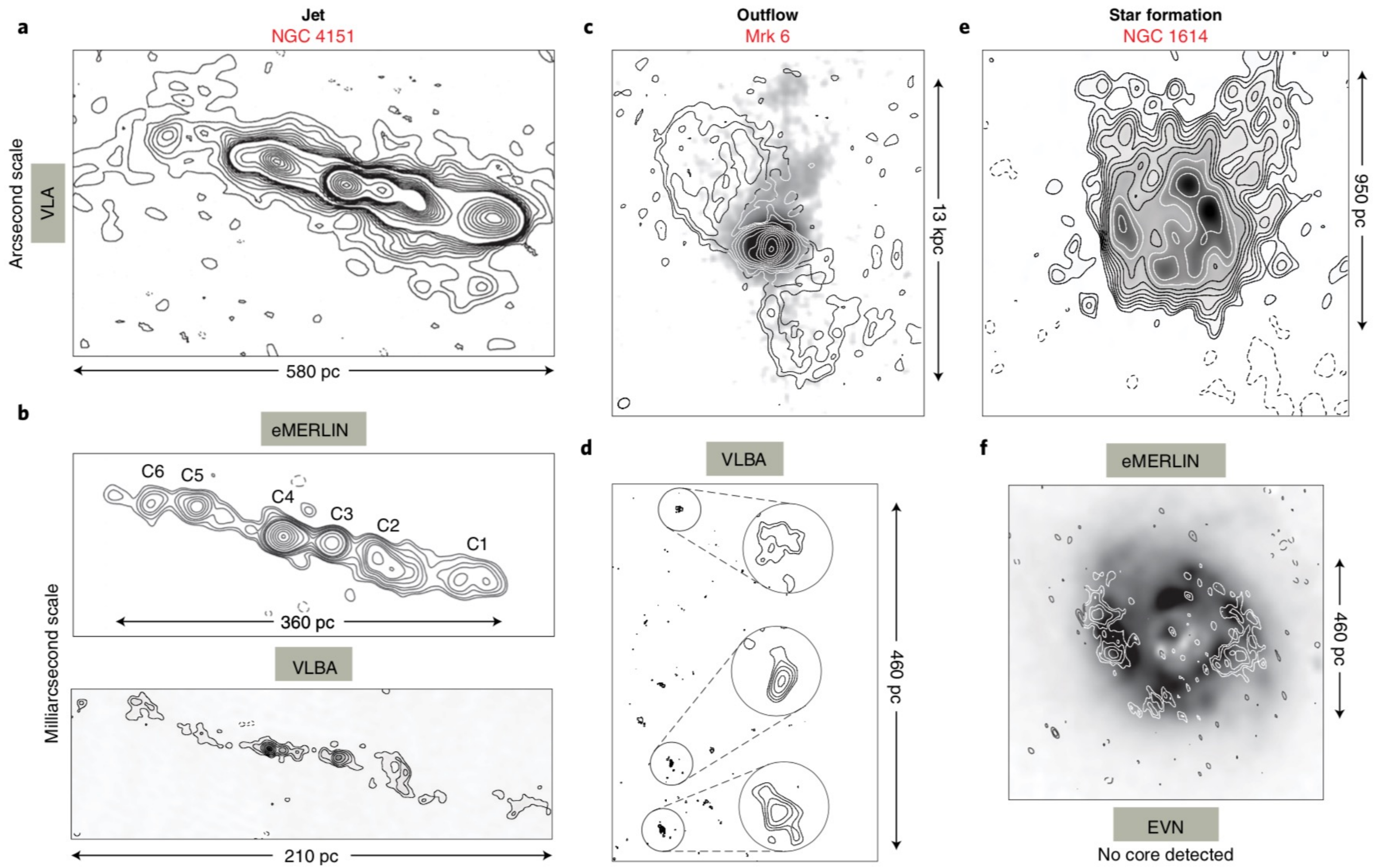
Radio-Quiet (RQ) AGN are not "silent". They represent the vast majority of the AGN population and dominate the faint radio sky.

Ubiquitous Detection

Contrary to the name, they show high detection rates at all frequencies, scales, redshifts, and Eddington ratios.

X. Yang+20; Jarvis+21; Alhosani+22; Chen+22; L. Yang+22; Järvelä+22; Song+22; Onic+22; Kawamuro+22

The "Radio-Quiet" AGN population



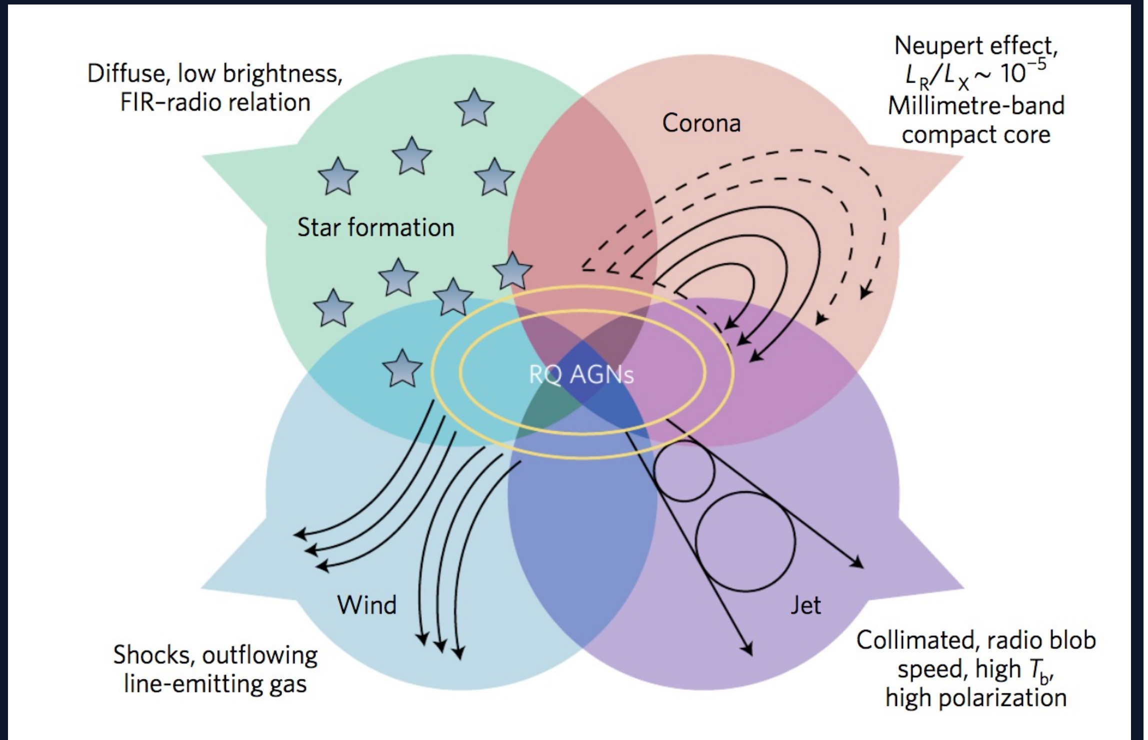
Faint radio sources (~mJy to tens of mJy)

Emission confined to sub kpc scales

The dominant SKA population

What Powers the Radio Emission?

- **Low-Power Jets:** Scaled-down, sub-relativistic, or "frustrated" jets confined to sub-kpc scales.
- **Winds & Shocks:** Outflows shocking the host galaxy gas (diffuse, steep spectrum).
- **Disk Corona:** Magnetic activity (Neupert effect, $L_R/L_X \sim 10^{-5}$).
- **Star Formation:** Host galaxy processes following the FIR-radio correlation.



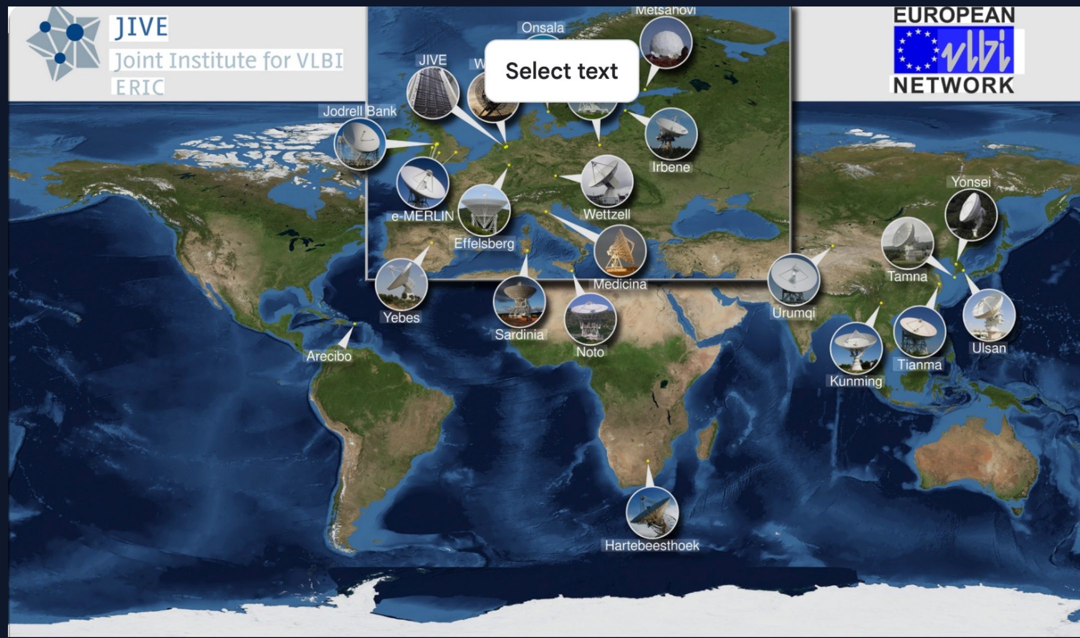
Panessa, Baldi, Laor, Padovani, Behar & McHardy 2019, Nature Astronomy Review

Giroletti & Panessa 2009, Bontempi et al. 2012, Panessa & Giroletti 2013, Baldi et al. 2018, Chiaraluce et al. 2019, Panessa et al. 2019, Chiaraluce et al. 2020, Panessa et al. 2022

Current VLBI Capabilities

High Resolution, Limited Sensitivity

- Current VLBI (EVN, VLBA) can resolve parsec-scale structures, effectively filtering out star formation.
- However, sensitivity limits mean we only detect the **brightest** cores, creating a biased view of the population.



The SKA-VLBI Revolution

Unprecedented Sensitivity

Reaching µJy levels allows for a complete census of the RQ population, not just the "tip of the iceberg."

Sub-milliarcsecond Resolution

Isolating the nucleus from the host galaxy with extreme precision (< 0.1 pc scales).

The SKA-VLBI Revolution

Table 1: SKAO VLBI Diagnostics for Radio-Quiet AGN Emission Mechanisms

Mechanism	Primary Physical Origin	Characteristic Observational Signatures (Pre-SKAO)	Key SKAO-VLBI Requirements & Estimates
Jets/Jet base	Scaled-down, mildly relativistic, collimated outflow from the accretion disk base.	**Morphology**: Compact core, unresolved, or core-jet structure (< 1 pc). **Spectrum**: Core: Flat or inverted ($\alpha \gtrsim -0.5$), SSA emission. Jet: optically thin steep spectrum. **Kinematics**: Proper motion detected	**Resolution**: $\lesssim 1$ mas imaging. **Sensitivity**: $\sim$ μJy (AA4) to detect faint cores. **Diagnostic**: Measure knot motions, map polarization structure
Corona	Non-thermal/thermal processes (magnetic reconnection) in the hot, compact accretion disk corona.	**Morphology**: Ultra-compact (< 0.1 pc), unresolved core. **Spectrum**: Flat/inverted ($L_R/L_X \sim 10^{-5}$). **Kinematics**: Expected rapid, non-steady flaring/variability.	**Resolution**: Required $\lesssim 1$ mas resolution to isolate the compact source. **Sensitivity**: High cadence monitoring; μJy detection for variability. **Diagnostic**: Simultaneous X-ray/radio monitoring to test the Neupert effect.
Winds	Synchrotron emission from shocks generated as an uncollimated AGN outflow interacts with the ISM.	**Morphology**: Diffuse, irregular structures, extending ~ 100 pc. **Spectrum**: Steep ($\alpha \approx -0.7$), optically thin. **Kinematics**: Slow bulk speeds.	**Resolution**: High mas-resolution needed to resolve the outflow base from the jet region. Sensitivity : ~ 2 μJy beam^{-1} (SKA-Low) for faint relic/shocked plasma. **Diagnostic**: Polarization mapping (Faraday RM).
Star Formation	Diffuse synchrotron emission from supernova remnants and thermal free-free from HII regions.	**Morphology**: Diffuse, host-like (kpc scales). **Spectrum**: Steep ($\alpha \approx -0.7$), matching the FIR-radio correlation. **Kinematics**: Non-variable; highly depolarized.	**Resolution**: $\lesssim 1$ mas resolution is necessary to resolve out the extended background. **Sensitivity**: $\sim$ μJy sensitivity ensures the faint nuclear component is cleanly isolated. **Diagnostic**: Spectral index mapping and spatial correlation with FIR tracers.

Jet and Wind Coexistence

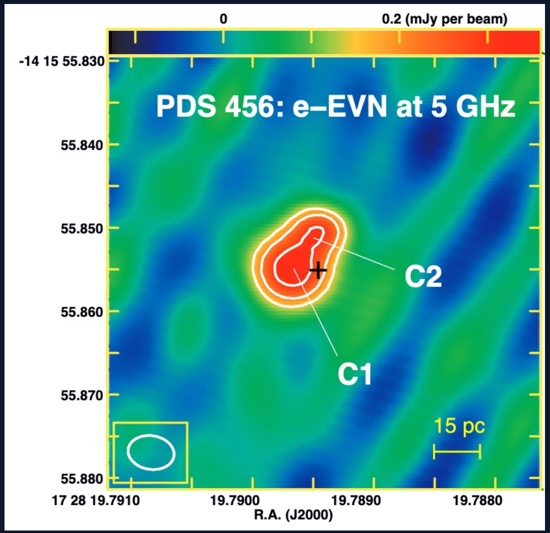
- Growing evidence of coexistence of a radio jet with ionised and molecular gas outflows
- Ultra-fast outflows in 27% of 26 Radio-Loud AGN sample (Tombesi et al. 2014)

Morganti+2015; Cresci+2015; Giroletti+2017; Jarvis+19, 21; Venturi+2021, Girdhar+22; Cresci+2023, Fanelli et al. in prep, Amenta et al. In prep.

Jet and Wind Coexistence

Observations reveal both a relativistic radio jet and a powerful, ultra-fast X-ray wind in the same object

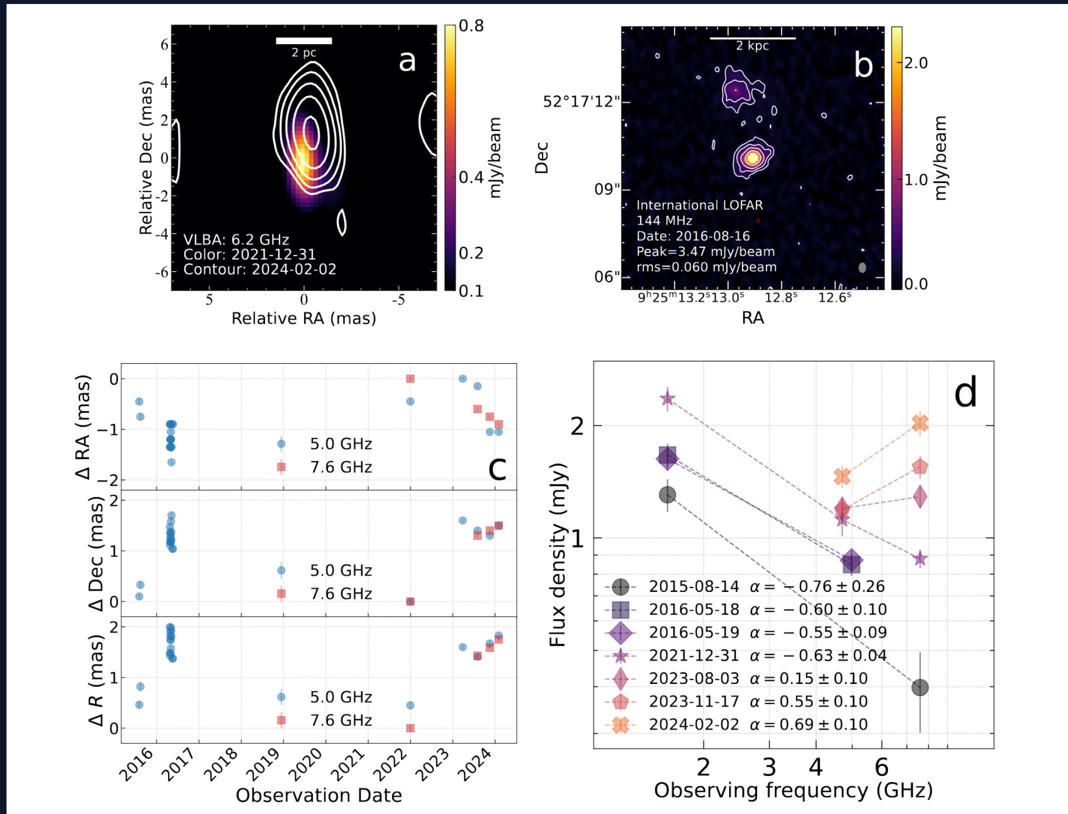
This implies a complex magnetic geometry where collimated jets and wide-angle winds are launched simultaneously from the accretion flow



Yang+19

SKA VLBI → Different angular resolution, sensitivity, range of frequency

Jet ejection in a RADIO QUIET AGN: Mrk 110



dramatic spectral evolution from steep to inverted

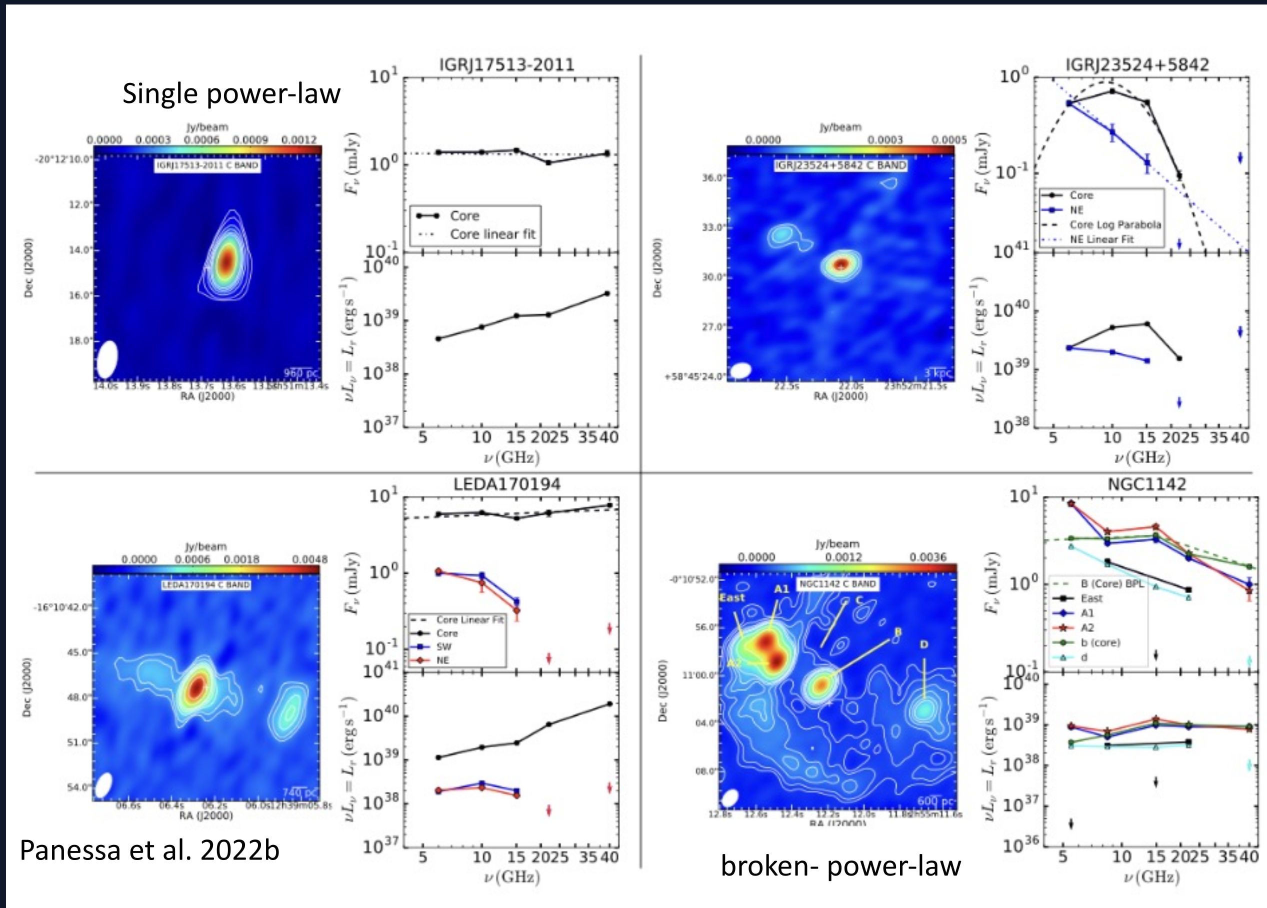
→ emergence of a new self-absorbed dominating high frequency emission

Wang+24

SKA VLBI → Spectral coverage & high angular resolution

Spectral slope to disentangle physical mechanisms

Panessa et al. 2022a



Convex

SKA VLBI → Large range of frequency

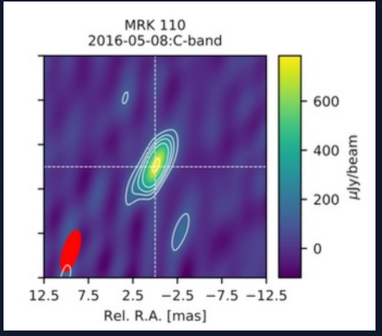
Time Domain: Mrk 110 Case Study

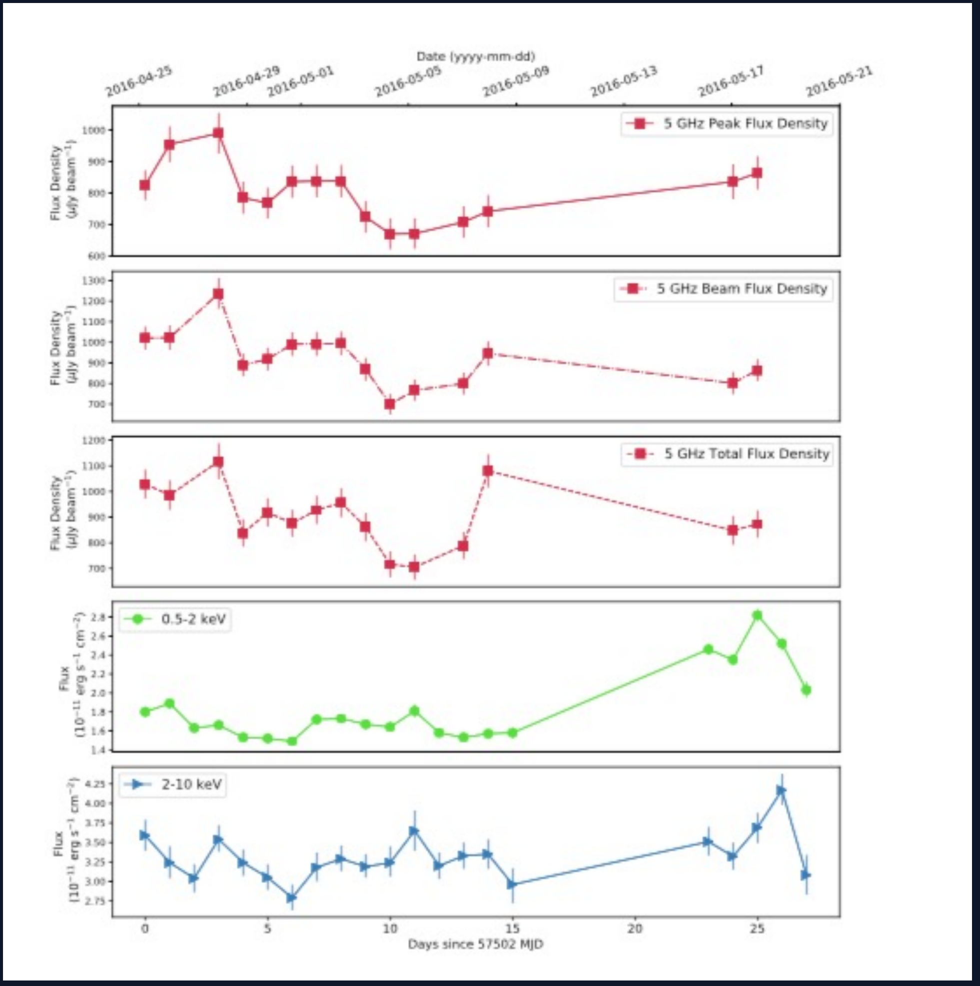
Panessa et al. 2022b

Daily Variability

VLBI monitoring of Mrk 110 reveals significant flux density changes on **daily timescales**.

- Implies an extremely compact emitting region (< 1 light day).
- Size constraint: < 180 Schwarzschild radii (R_s).
- Supports the **Coronal** origin or a very compact jet base.

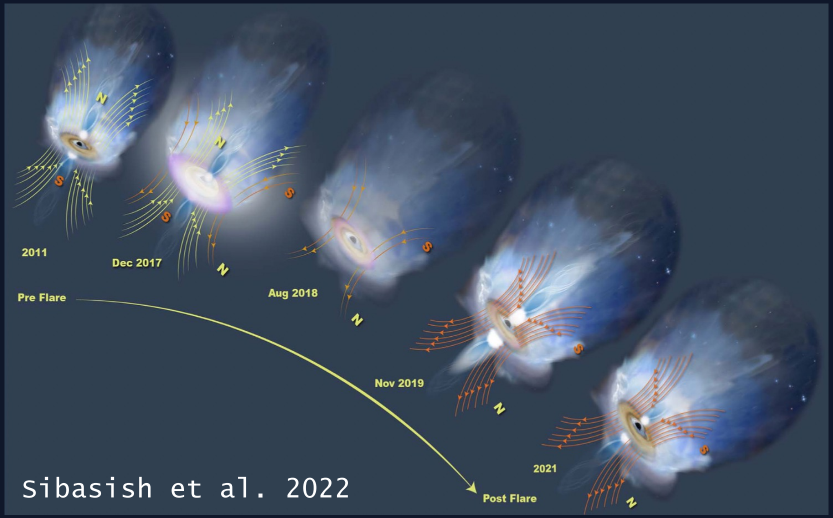




Time Domain with SKA

The Dynamic Sky

We are discovering "Changing-Look" AGN and TDE-like events where the accretion state changes dramatically on human timescales.



Polarization: The Telltale Sign

Ordered Polarization

Indicates a structured magnetic field, favoring a **Jet** origin.

Low/Zero Polarization

Indicates isotropic emission or tangles fields, favoring a **Corona** or thermal origin.

The Early Universe (High-z)

Cosmic Noon (z ~ 2-3)

RQ AGN dominate the population. Understanding their feedback is crucial for galaxy evolution models.

The Challenge

At high redshift, star formation is intense. SKA-VLBI's high brightness temperature sensitivity is the ONLY way to disentangle AGN activity.

Conclusions

- **Dominant Population:** Radio-Quiet AGN are the "sleeping giants" of the radio sky (90% of population).
- **SKA-VLBI is Critical:** It provides the resolution to isolate the core and the sensitivity to detect it.
- **Time Domain & Polarization:** rapid variability connects radio emission to the inner corona & ordered magnetic fields to identify jets
- **Complex Physics:** We are moving from simple classifications to complex models of coexisting jets, winds, and coronae.