Jet morphology and polarization: the role of ultra-high resolution radio surveys

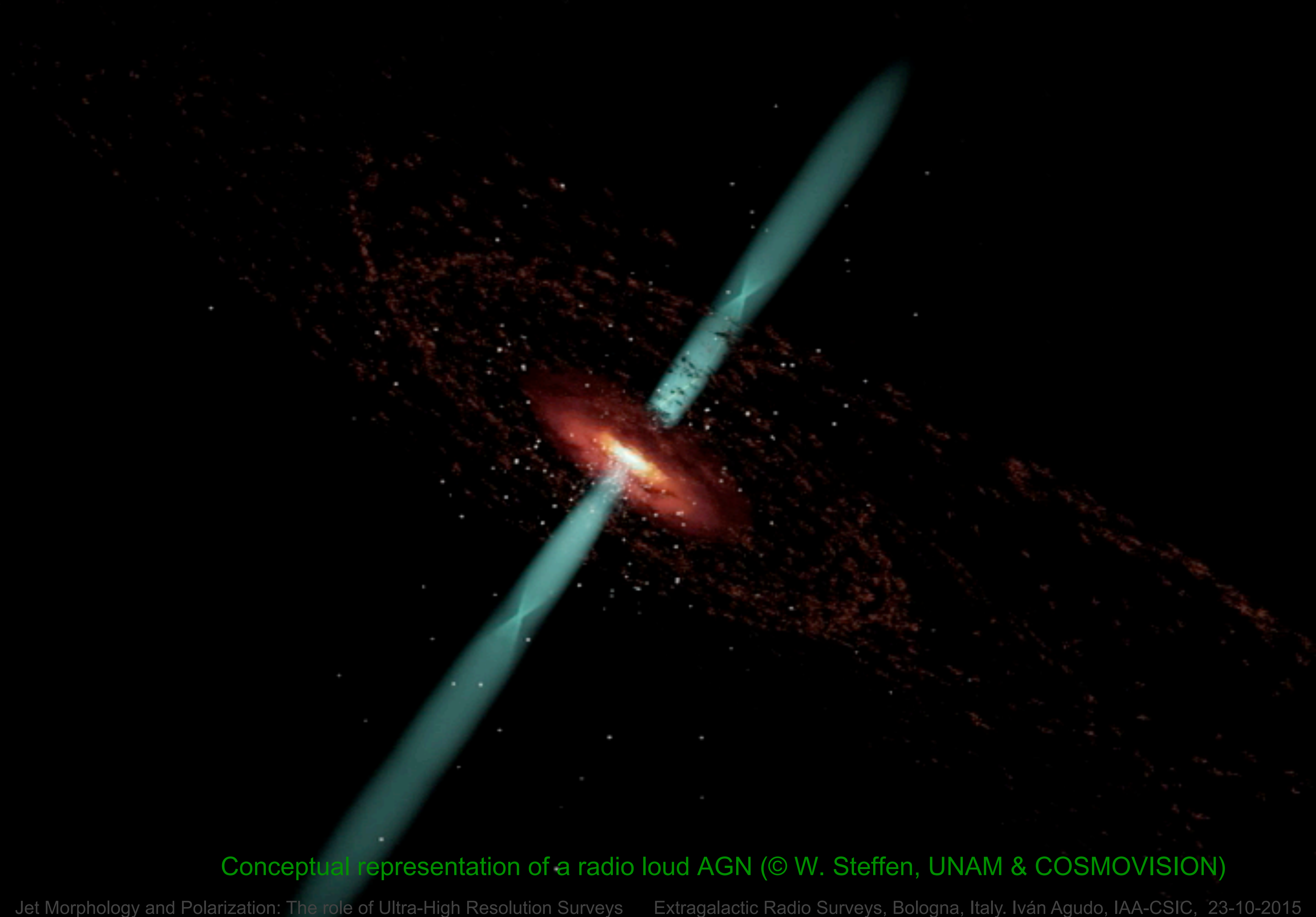
Iván Agudo

Instituto de Astrofísica de Andalucía-CSIC,
Granada (Spain)

I·A·A

CSIC
Consejo Superior de Investigaciones Científicas

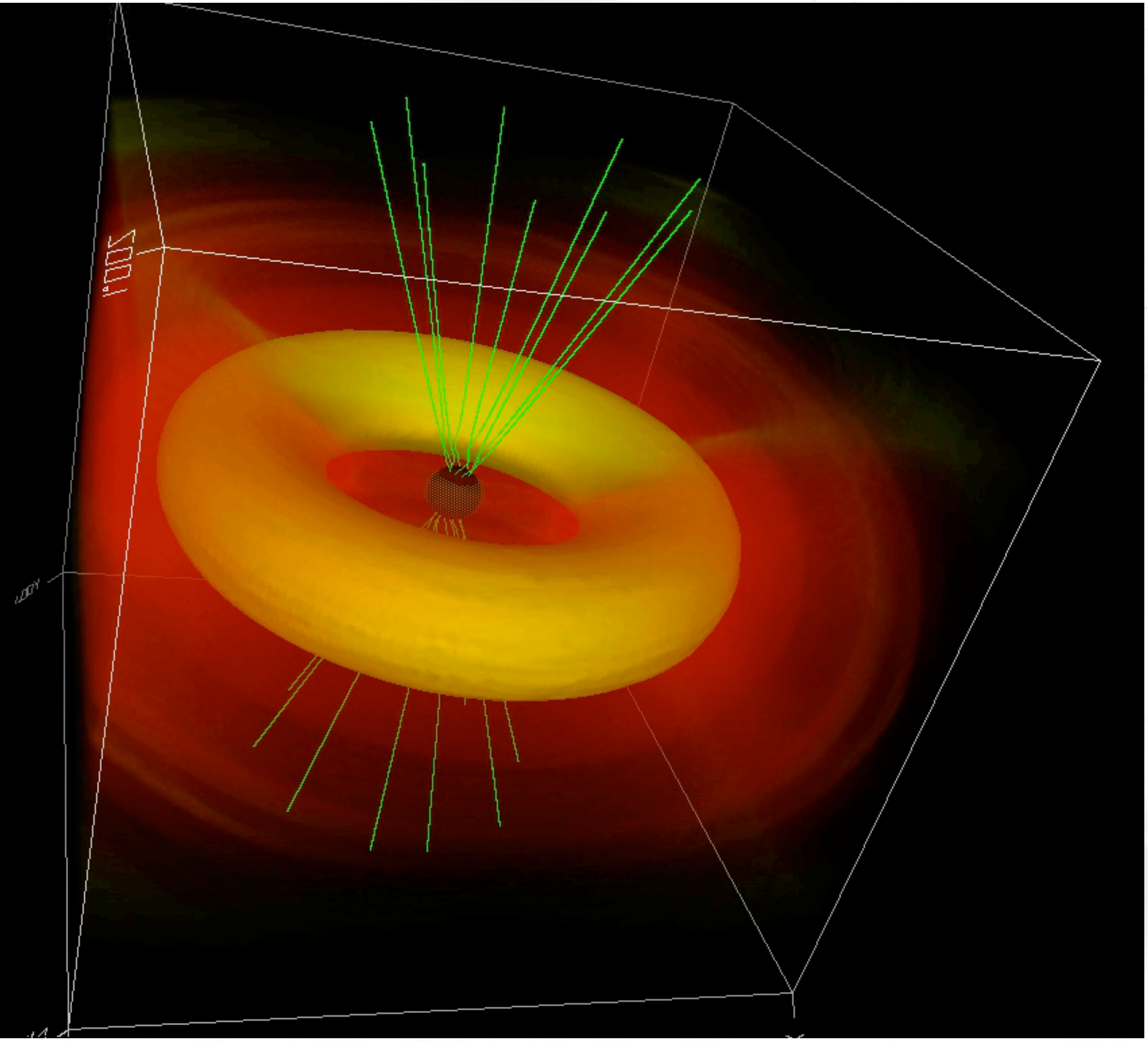
Introduction



Conceptual representation of a radio loud AGN (© W. Steffen, UNAM & COSMOVISION)

Relativistic Jet Formation, Collimation and Acceleration

3D RMHD simulations of relativistic jet formation



McKinney & Blandford (2009)

Essential ingredients:

- The gravitational potential of the rotating BH
- Material from the rotating accretion disk
- Co-rotating magnetic fields

Jet formation studies as a tool for SMBH and plasma physics

Studying magnetic fields is crucial to understand the jet phenomenon

Relativistic Jet Collimation

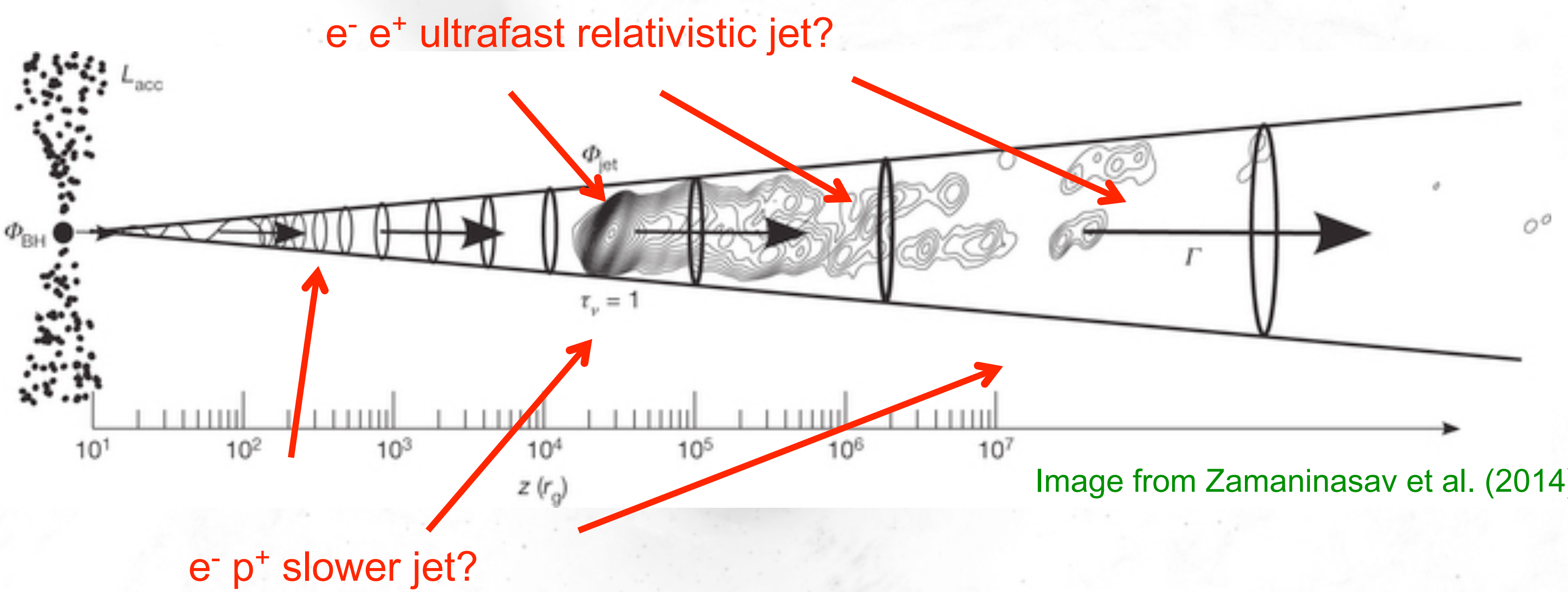
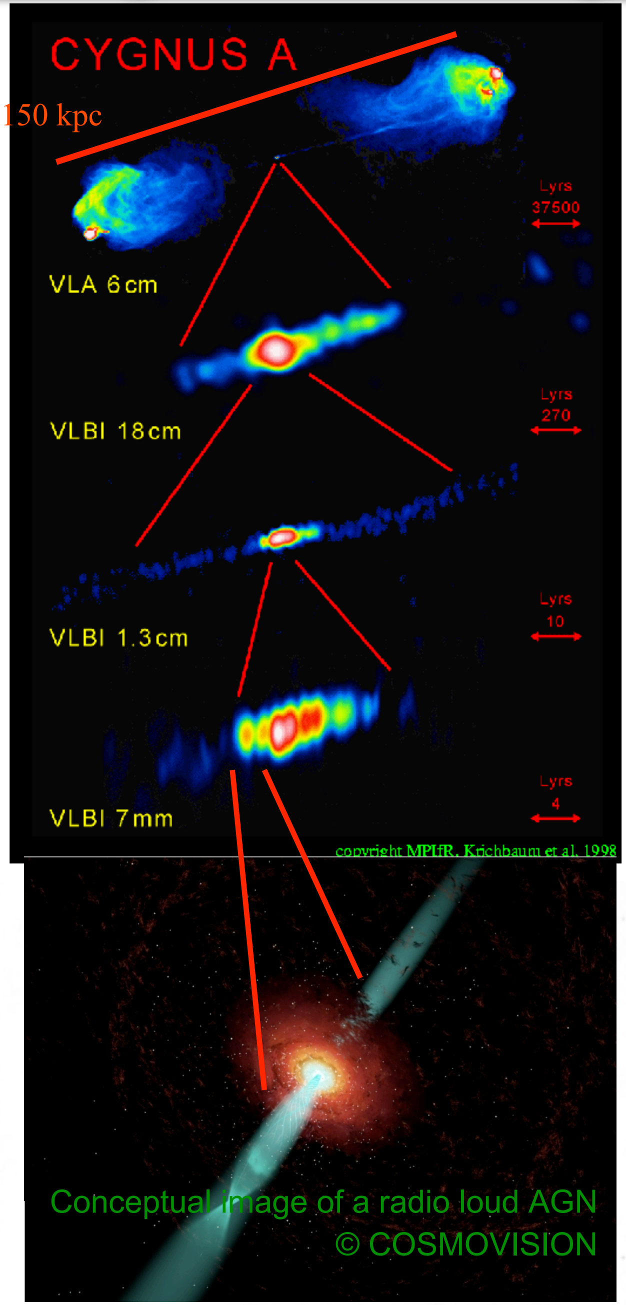


Image from Zamaninasav et al. (2014)

Full polarization involving high precision circular polarization observations along the radio spectrum may provide definite answers! (also provide B, e^- distrib)

From ~5 to ~20 GHz observations (including circular polarization with precisions better than 0.1% [typical CP≤0.1-0.5%]), Homan et al. (2009)

Particle Acceleration in AGN Relativistic Jets



Further current challenges:

- How and where jets convert from Poynting-flux dominated into particle(/kinetic energy) dominated?

- How are AGN jets able to radiate such enormous amounts of power (up to ~10^{48} erg/s) from sub-pc scales, up to 100s of kpc?

Need understanding of the particle acceleration processes!

In particular, on innermost jets at the pc and sub-pc scales, where the jet formation, and most of its acceleration takes place

Region only visible through VLBI observations in general

Current VLBI Facilities (Non-Complete)

EVN

Image credit: EVN

VSOP

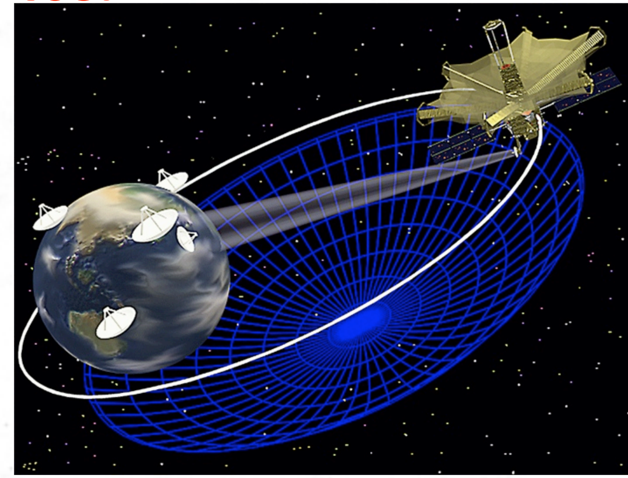


Image credit: JPL

VLBA

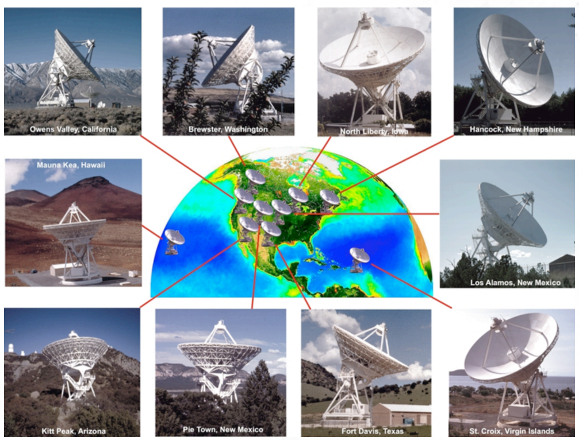


Image credit: NRAO

LBA

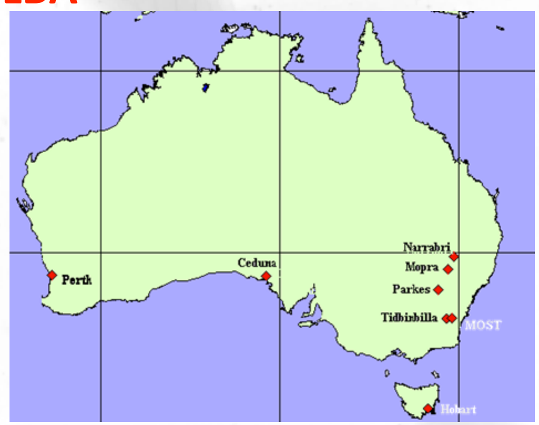


Image credit: LBA

Radio Astron

Image credit: Radio Astron

- With the EVN+ and HSA (VLBA+Arecibo+VLA+GBT+Effelsberg), one can reach image thermal noise of ~3 μJy/beam in 30 min. int. time (L-band 2Gbps) at a few milli-arcesecond resolutions.
- At shorter λλ (1-2 cm), sub-milliarcsecond angular resolutions are routinely achieved, even ~7 μarcsecond resolutions can be achieved with Radio Astron @1cm (Yuri´s talk)

Previous VLBI Surveys: A Few Examples (Total Flux Only)

- **Caltech-Jodrell Bank Survey** (Taylor+ 1995; Polatidis+ 1995; and refs. therein)
  - VLBA total flux images at both 5 and1.7GHz for a complete flux density limited sample of ~300 bright , flat spectrum AGN (>350 mJy ~5GHz).
  - First milli-arcsecond scale morphological classification of a very large sample of radio loud AGN sources.

- **VLBA Pre-Launch VSOP Survey** (Fomalont+ 2000)
  - Observations of 374 strong flat-spectrum radio sources north of declination -44° using the VLBA at 5GHz in June 1996
  - Preparation for big AGN jet survey with VSOP (250 sources selected for VSOP)

- **VSOP Survey** (Hirabayashi+ 2000; Lovell+ 2004; Scott+ 2004; Horiuchi+ 2004)
  - 294 flat-spectrum AGN stronger than 1 Jy at 5 GHz
  - Significant fraction 54% have core Tb>10^{12} K (max. observed 1.2 × 10^{13} K), therefore requiring a large amount of relativistic Doppler beaming.

- **Radioastron AGN survey** (see Yuri Kovalev's talk, next)

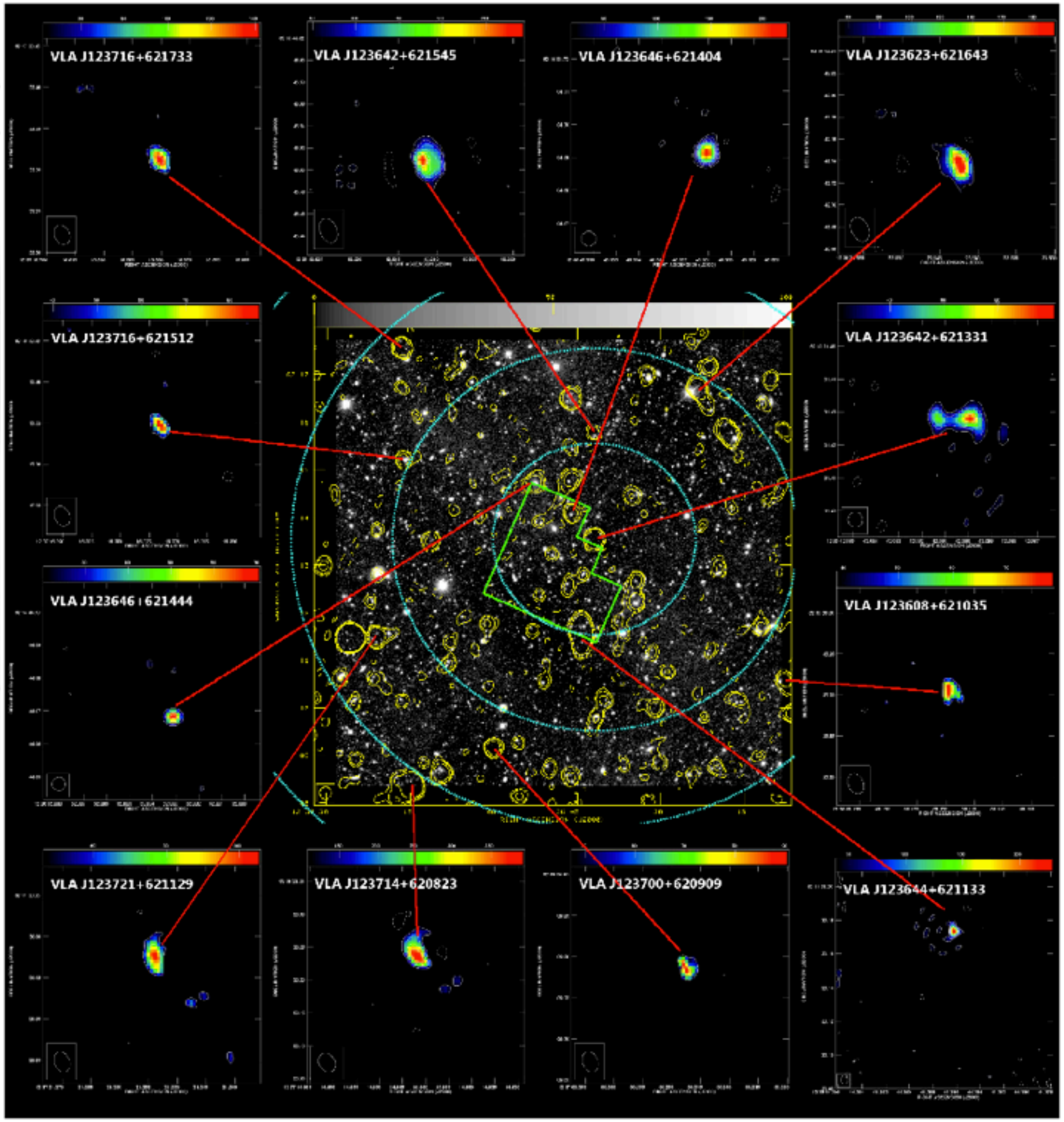
Previous VLBI Surveys: A Few Examples (Total Flux Only)

- **VLBI deep field & wide area of the HDF-N** (Chi, Barthel & Garrett 2013, also J. Radcliffe's talk this meeting)

  - Weak AGN with Global 1.4 GHz VLBI observations. (~201 arcmin^2). Deeper and wider than previous VLBI obs. of the field (rms=7.3 μJy/beam @ 4 mas resolution)

  - Found 25% of SFG contain faint AGN

  - Shows potential of deep-WF VLBI observations for AGN-SFG connection studies.



Chi, Barthel & Garrett (2013)

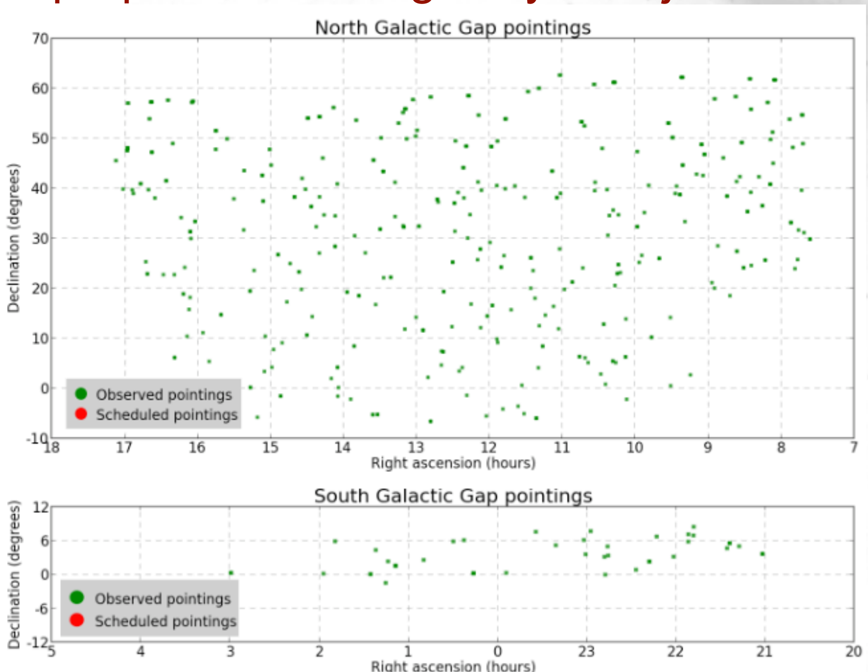
Previous VLBI Surveys: A Few Examples (Total Flux Only)

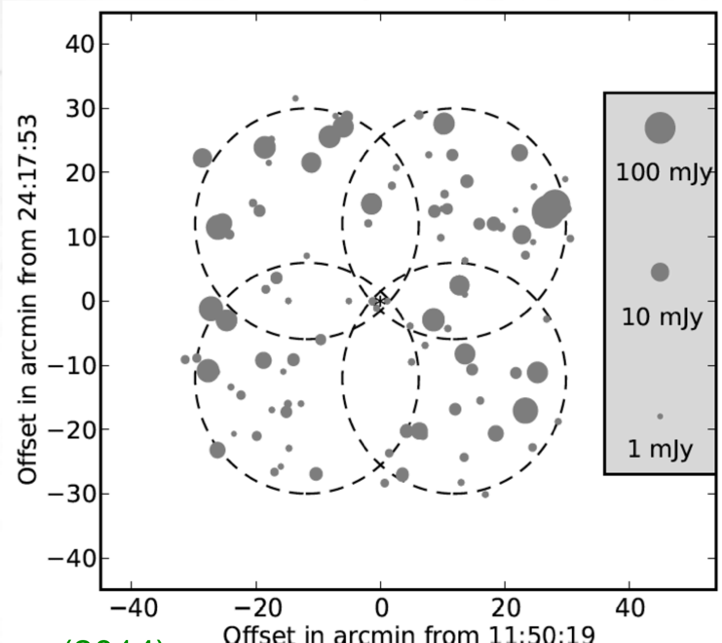
• **mJIVE-20 Survey** (Deller & Middelberg 2014)

- Largest 20 cm VLBI imaging survey so far. Imaged hundreds of wide fields through multi-phase center correlation at the VLBA. 25973 radio sources cauched and detected thousands of new VLBI sources down to ~1mJy.

- A large scale extension of previous program. Investigates the compact fraction of radio sources as a function of flux density from microJy to Jy levels.

- Merging is an important trigger for radio AGN. In galaxies with pc-scale jets, jets are perpendicular to galaxy's major axis ==> strong galaxy-accr. disk alignment





Deller & Middelberg (2014)

Previous VLBI Surveys: A Few Examples (Polarimetry)

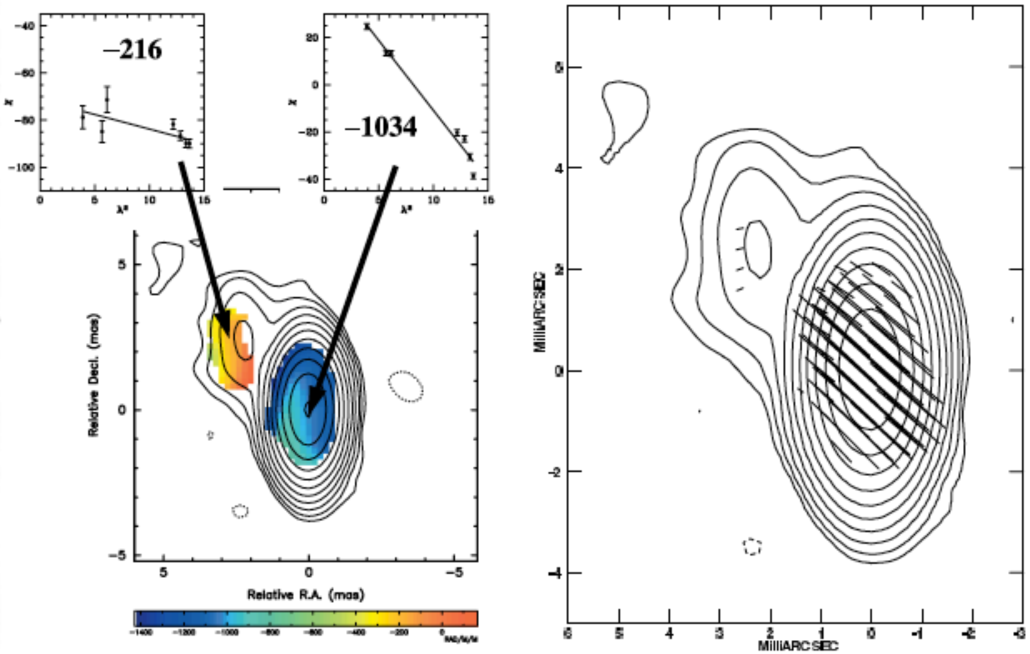
- **Survey of pc-scale RM in 40 AGN** (Zavala & Taylor 2004, and references therein)

  - 40 quasars, radio galaxies, and BL Lacs, single epoch VLBA, seven frequencies between 8.1 and 15.2 GHz.

  - Core RMs for quasars & BL Lacs from ~500 to few x 1000's rad/m^2.

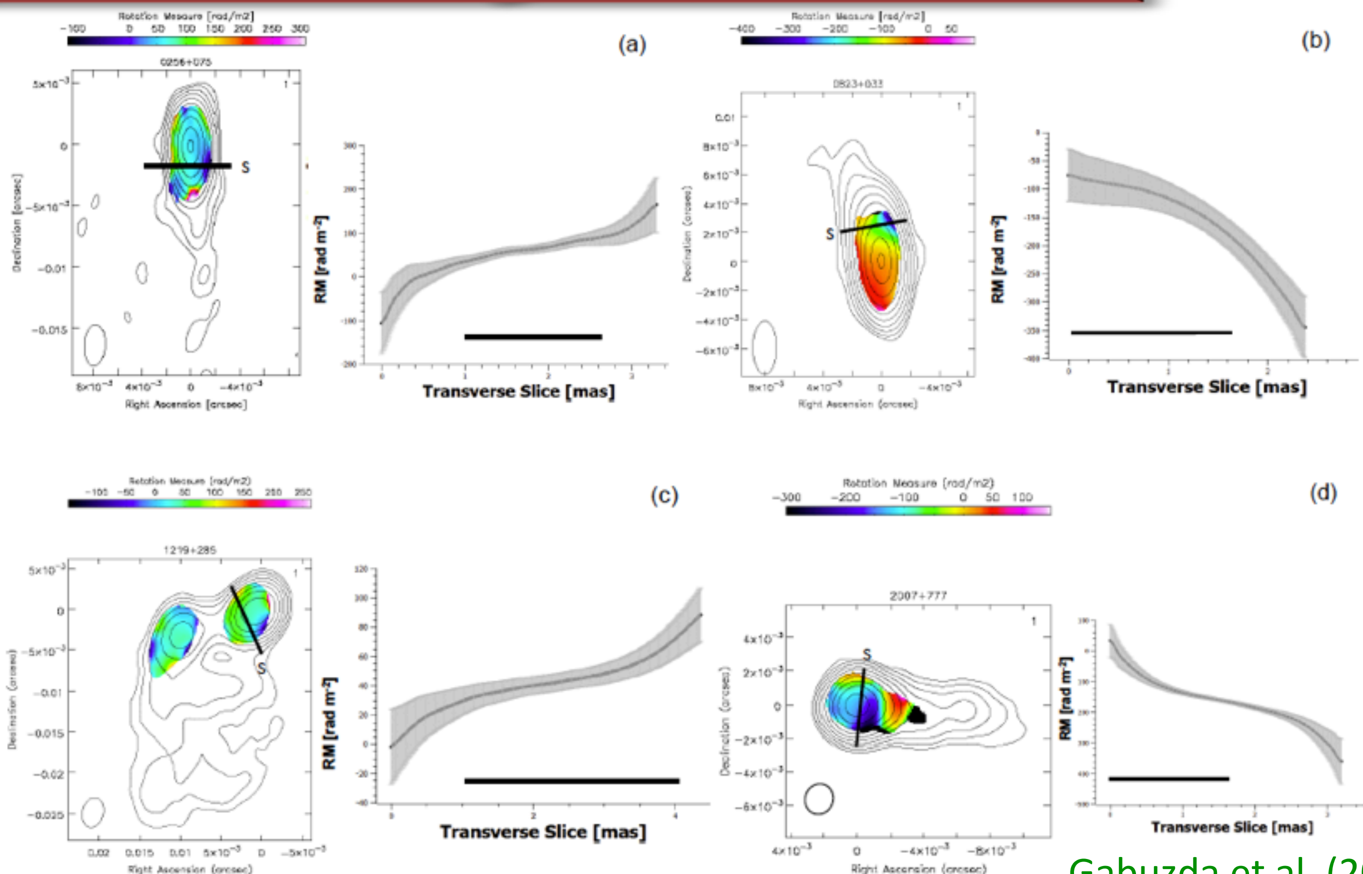
  - Quasar & BL Lac jets show <500 rad/m^2.

  - The jets of RG show RMs from a few x 100's ~10000 rad/m^2. Radio galaxy cores are generally depolarized. Properties of the Faraday screen still under debate



Zavala & Taylor (2004)

Previous VLBI Surveys: A Few Examples (Polarimetry)

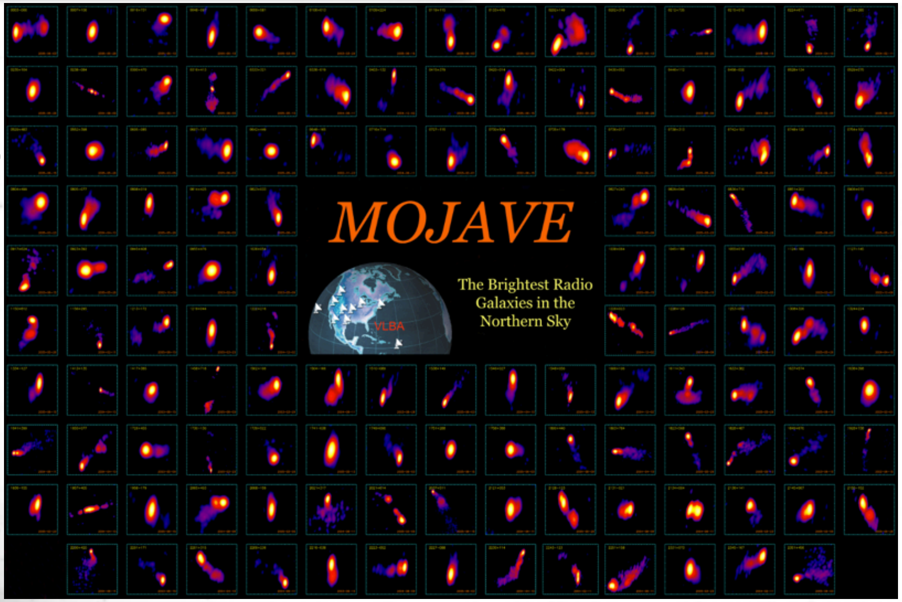


Gabuzda et al. (2015)

- **Transverse Rotation Measure Survey** (Gabuzda+ 2015, see also Hovatta+ 2012)
  - Set of 15 transversely resolved jets observed simultaneously at ~7 observing frequencies from ~ 5 to ~ 15 GHz with the VLBA
  - Systematic transverse monotonic rotation measure gradients accross these jets, consistent with the presence of helical magnetic fields threading the jets (relevant for jet formation theories, but still to be confirmed obsevationaly)

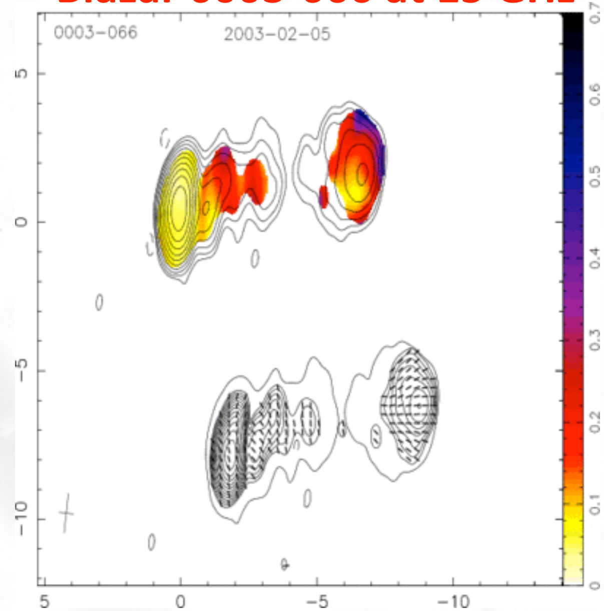
Previous VLBI Surveys: A Few Examples (Polarimetry)

- **MOJAVE Survey** (Lister et al. 2009)
  - Time monitoring of a big (>200 sources) sample of radio-bright AGN every month. mas resolution VLBA monitoring at 15 GHz from 1994 (full polarization since 2002)



- Jet parameter definitions for 100´s of jets
- **Lorentz factors from ~a few** (typical AGN) **up to ~50** (most powerful blazars)
- **Jets speed up and collimate up to ~50 pc**, and decelerate further out (relevant for formation models)
- **Cores** weakly polarized **<5%**, but **larger pol deg for regions downstream** (depol. on upstream jet regions).
- **Cores and jets of RG weaker or not linearly polarized** compared to QSOs and BL Lacs.
- **"Strong" circular polarization (up to ~0.3%)**, usually in the cores of the sources, within ~ 15% of the sample

Blazar 0003-066 at 15 GHz

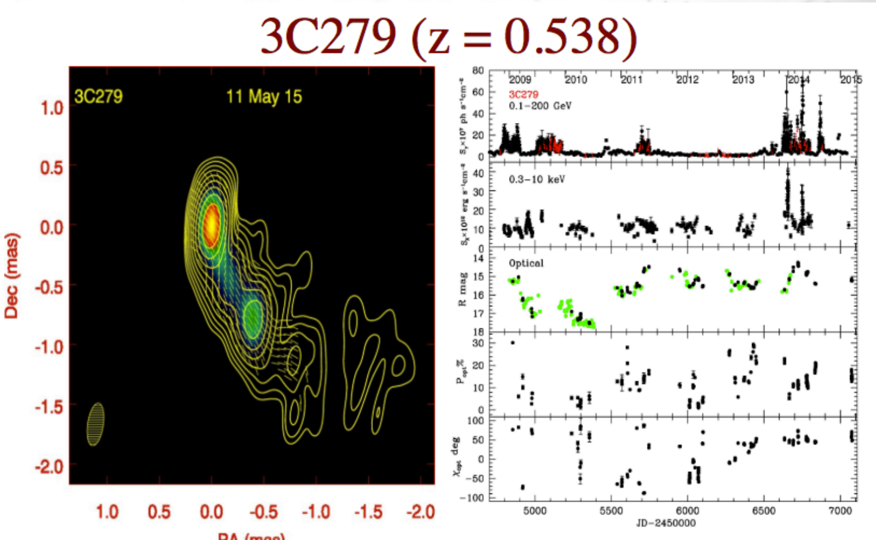


Colors: fractional linear polarization

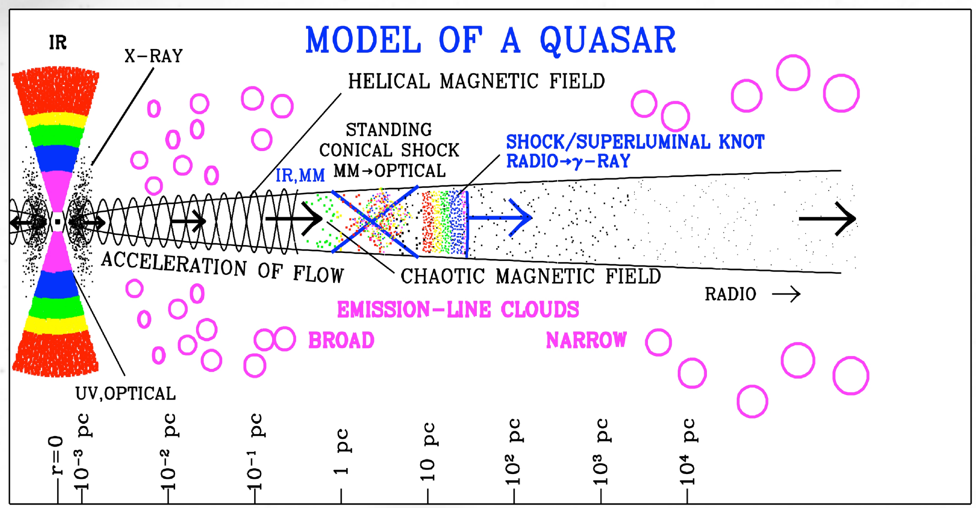
Full publication list at: www.astro.purdue.edu/MOJAVE

Previous VLBI Surveys: A Few Examples (Polarimetry)

- **BU Blazar Monitoring Program** (Marscher+ 2008,2010; Jorstad+ 2010,2013; IA+ 2011a,b)
  - VLBA 43 GHz, total flux and polarization imaging of a sample of ~40 of the brightest gamma ray blazars on the northern sky. Time monitoring every month
  - Excelent program for **kinematics** of the innermost (**sub-pc scale**) jet.
  - Combined with multi-spectral-range data, allows to constrain the **location of the emission along the spectrum**
  - And therefore the emission mechanism, **even at gamma-ray energies**!



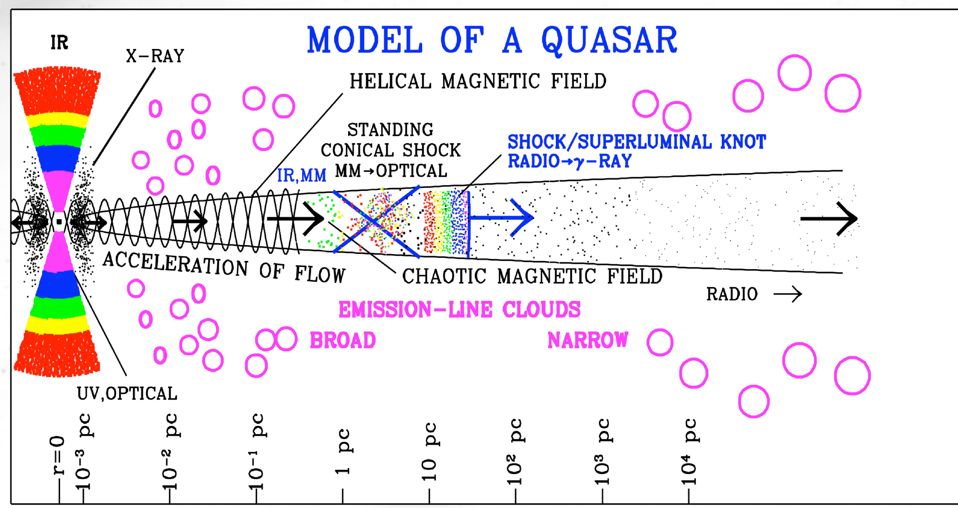
https://www.bu.edu/blazars/VLBAproject.html



Conceptual image of a quasar emission and structure
© A. Marscher

Previous VLBI Surveys: A Few Examples (Polarimetry)

- **BU Blazar Monitoring Program** (Marscher+ 2008,2010; Jorstad+ 2010,2013; IA+ 2011a,b)
  - VLBA 43 GHz, total flux and polarization imaging of a sample of ~40 of the brightest gamma ray blazars on the northern sky. Time monitoring every month
  - Excelent program for **kinematics** of the innermost (**sub-pc scale**) jet.
  - Combined with multi-spectral-range data, allows to constrain the **location of the emission along the spectrum**
  - And therefore the emission mechanism, **even at gamma-ray energies**!



RA (mas)

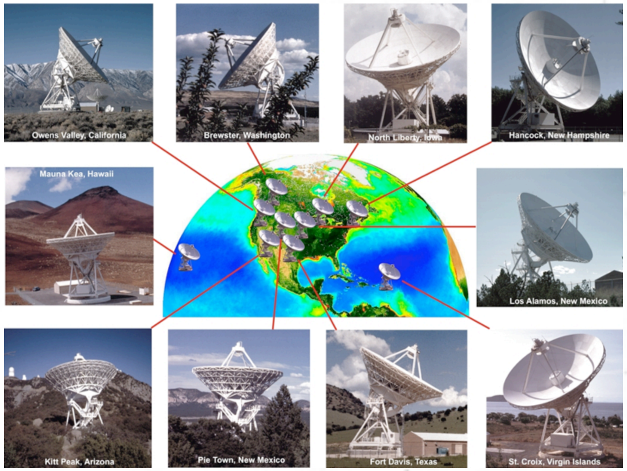
https://www.bu.edu/blazars/VLBAproject.html

Conceptual image of a quasar emission and structure
© A. Marscher

VLBI: The Near Future

EVN

VLBA



AVN Concept

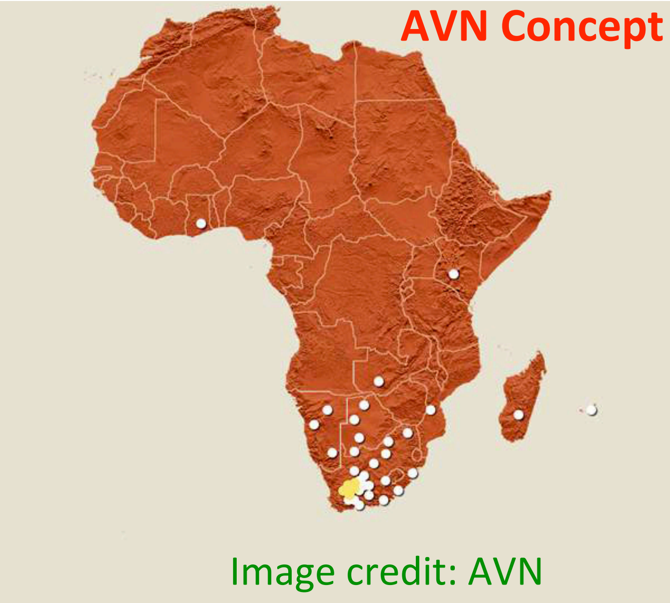
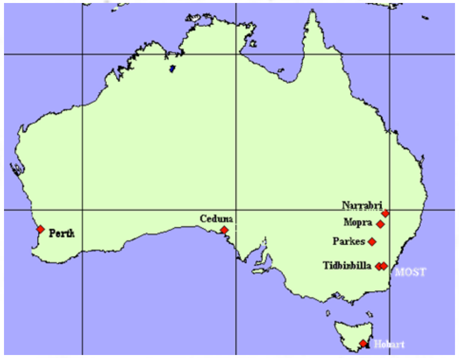


Image credit: AVN

LBA



- Very Long Baseline Interferometry at the SKA-1 times:
  - SKA1-MID (phased array) + AVN + EVN
  - High angular resolution up to ~0.5 milli-arcseconds at μ-Jy levels (thermal noise)
  - Astrometric precisions of ~few μ-arcseconds

Paragi et al. (AASKA14.143)

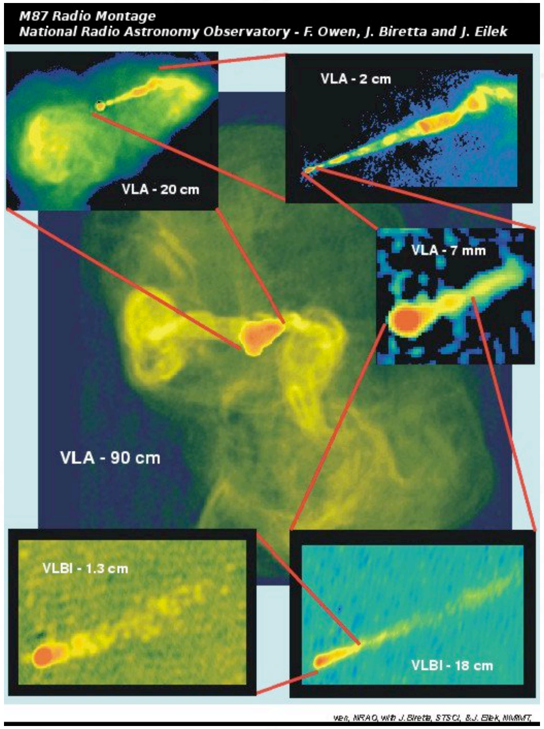
Distinguishing from AGN Jet and SFG Emission

Agudo et al. (AASKA14.093)

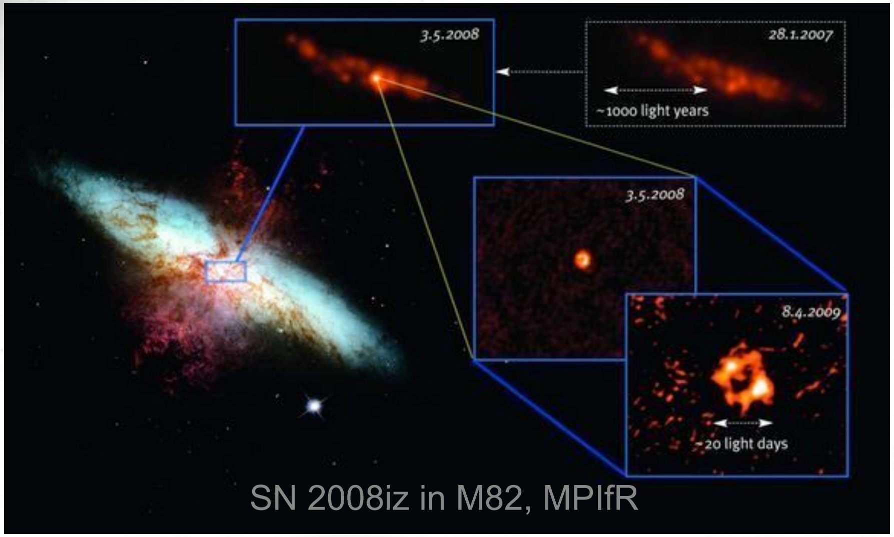
- Clearly, linear polarization and spectral index information from SKA1 will be a useful tool for that, as well as, optical data and photometric redshifts from LSST

- VLBI will be THE TOOL for confirmation of radio AGN nature of those sources with high Tb (perhaps at L-band to optimize UV coverage and sensitivity)

- Polarimetric measurements will also be very useful in VLBI mode (for free)



vs.



Cosmological studies of radio loud AGN.

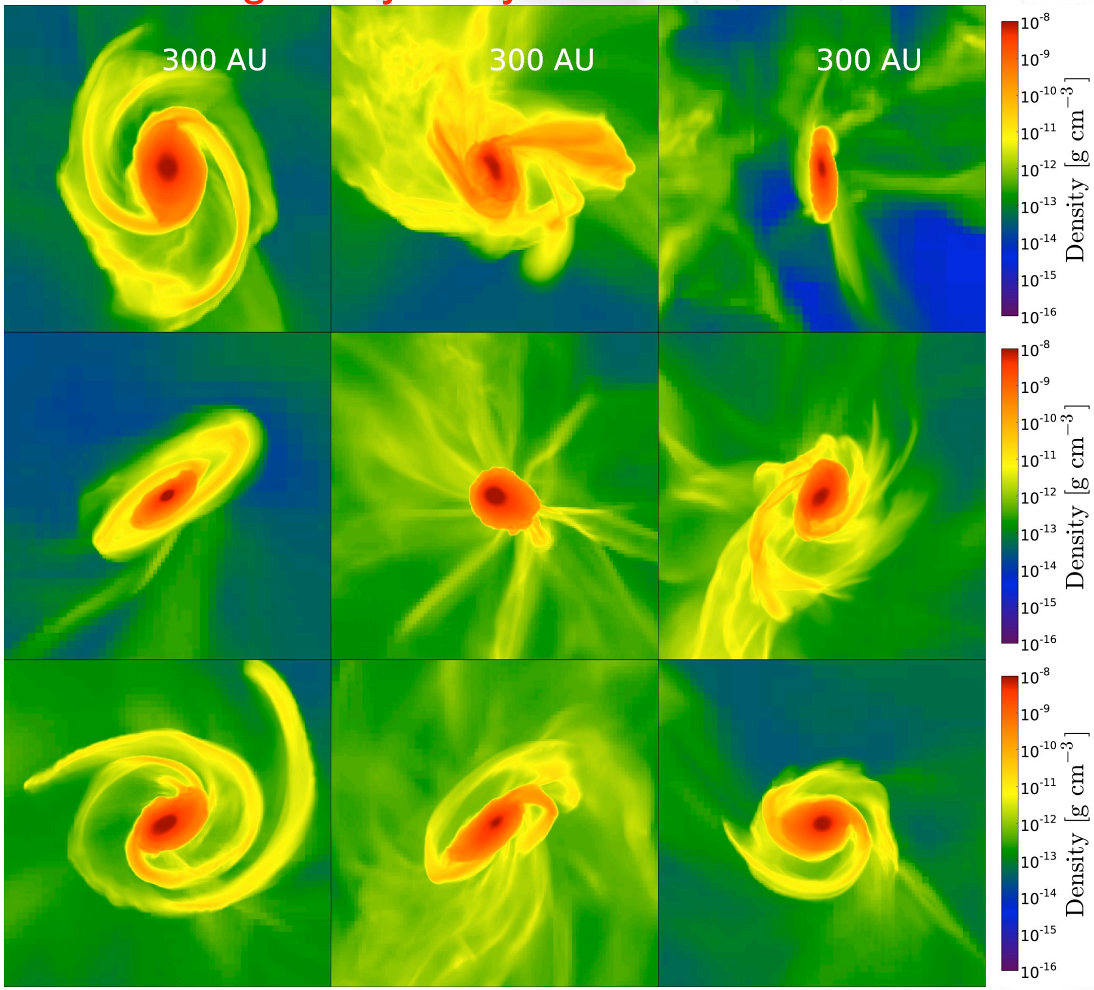
Needs to answer questions as,

- When the first AGN were formed?
- How where they formed (properties of environments, SMBH and accretion systems)?
- How they evolved with time up to z~0.
- **VLBI will be instrumental both on the identification and characterization** of the properties of AGN through cosmic time

AGN Jets Along the Cosmic Time

Detection and characterization of the first AGN/black holes.

Cosmological hydrodynamic simulations.



Latif et al. (2014)

Their appearance is highly speculative, but

Simulations predict that dense clouds are able to form massive compact objects containing accretion disks.

Then there is the possibility of the formation of small scale jets (GPS)

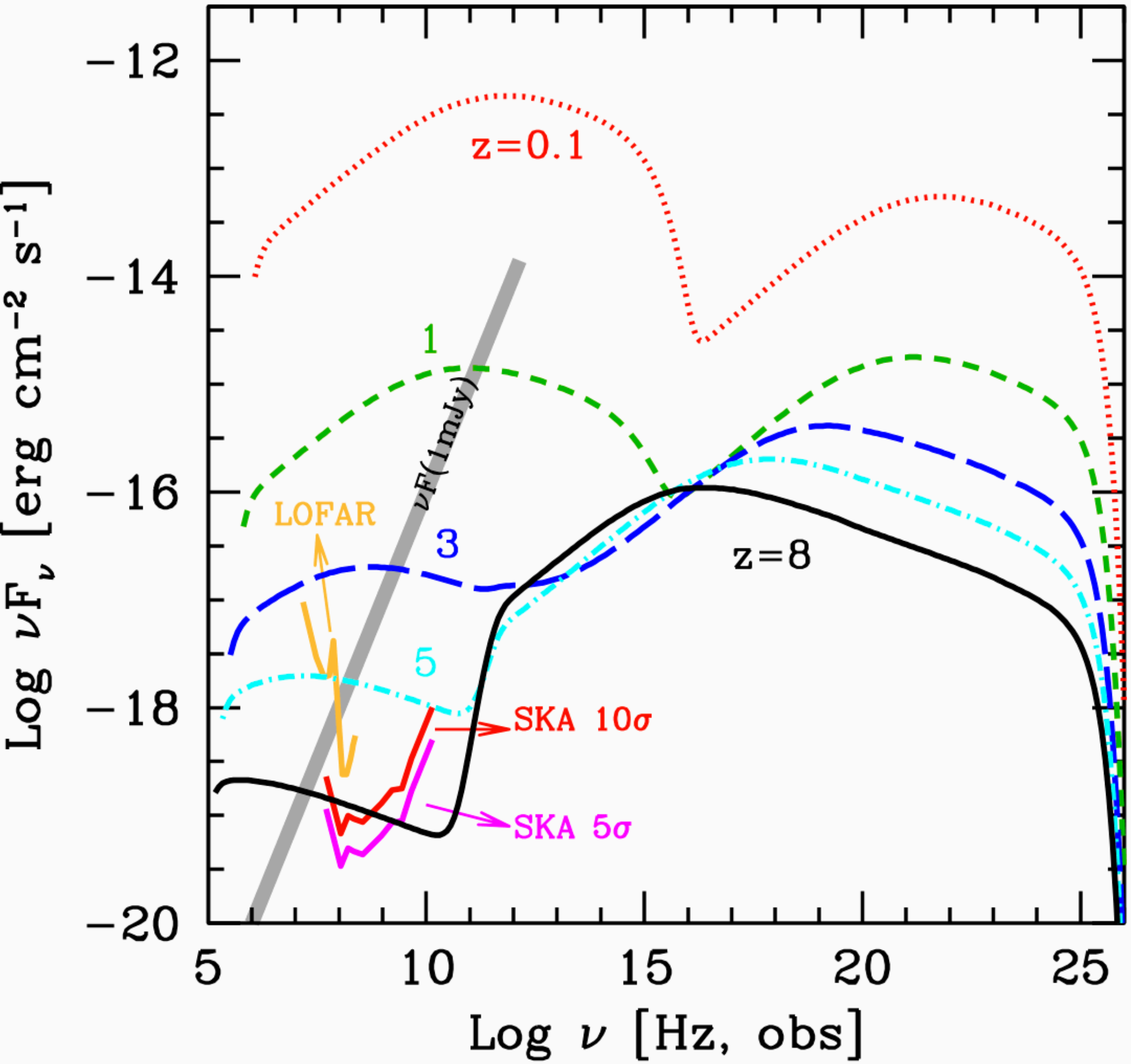
Radio emission of GPS/CSS is not so much affected by IC looses by the dense CMB

Possibility to detect at low freqs.; high sensitivities; arcsec resolution; +VLBI Falcke et al. (2004)

AGN Jets Along the Cosmic Time

Detection and characterization of the first powerful radio jets

Importance of the CMB at high redshifts



Ghisellini+ 2014, MNRAS, 438, 2694

Relevant problem: Detection of radio loud AGN at high z (≥8)

Same source, located at different z: the larger the redshift, the larger the IC cooling, the fainter at radio

Discovery space for SKA, pehaps by finding many more jetted sources than predicted on the basis of current surveys.

Need to use data from wide and deep surveys at the widest possible frequency range to characterize SED

VLBI key for source characterizat.

Tidal Disruption Events (TDEs)

- SKA will allow studying jet formation processes in dormant AGN in "real time" for 100's or 1000's of TDEs

Donnarumma et al. (AASKA14.054)

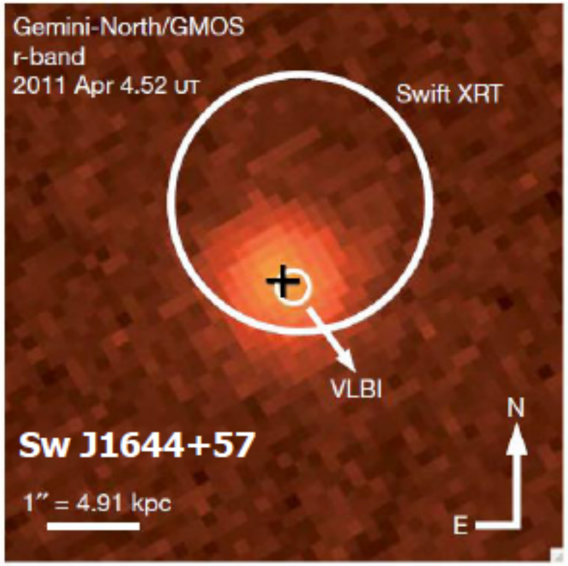
- SKA-VLBI will provide superior localization of events

- Sub-milliarcsecond resolution needed to measure source expansion/deceleration (will give clues on environment where the new jet is expanding)

- SKA-VLBI, -at ~5-20 GHz - will measure accurate sub-mas source sizes down to ~0.1 mJy level (which is not possible today)

- SKA-VLBI will routinely provide astrometry accurate at the ≤10 μas level to measure jet ejecta proper motions

Image credit: M. A. Garlick, UW



Zauderer et al. (2011)

Ideas About Possible VLBI Surveys/Programs for SKA (and Precursors)

- **SKA-VLBI survey-monitoring of ~300 southern sources in full-polarization** (also high precission **CP** imaging), at **4 frequencies from 5 GHz to 24 GHz** (if SKA-MID Band 5+ feasible) with a cadency of **1-2 months**. This kind of survey would be instrumental to solve most of the current open questions on jet formation-collimation and acceleration of jets, **CP and RM imaging is critical**.

- Source/field **targetted deep & wide-field SKA-VLBI survey** based on previous SKA surveys to **discriminate and identify source classes (radio AGN vs. SFG,** also useful for cases of source confusion), better **at L-band.**

- **Ultra-deep VLBI-SKA targetted follow ups of high z sources** (best made at the lowest available frequencies for VLBI, [**L or P band**]) to study the first radio AGN and super-massive black-hole environments.

- **VLBI-SKA follow up monitoring programs of transient** phenomena (TDE & extraordinary blazar flares). Ideally multi-frequency (**minimum 3 bands [better 4 or 5] for RM studies in SKA Band 5+**), with adequate time cadence for every kind of event.

Concluding Remarks

• At the times of SKA1, a sensitive VLBI facility with good polarimetric capabiities in the southern hemisphere will be an essential tool for the most relevant studies of radio loud AGN along time (both on short time scales [months to days] and on cosmological time scales).

• As a starting point, both for MeerKAT and ASKAP, any addition in terms of VLBI capabilities would perhaps be a good idea.

• For MeerKAT, there may be more uncertainties about the availability of the AVN.

• In the mean time, MeerKAT can use any existing African VLBI station and the EVN for fields at relatively high declinations.