New Insights on AGN Radio Cores from Ground and Space Observations

J. Anton Zensus

Max-Planck-Institut für Radioastronomie

Oct 15th, 2015

Max-Planck-Institut
für Radioastronomie

MAX-PLANCK-GESELLSCHAFT

Note to the speaker

- Notice that earlier speakers will be:
  - Mangalam on SMBH & Jet Formation
  - Gabuzda on Blazar VLBI
  - Rani on high-E emission from Blazars
  - Laing on Jets
  - Gabuzda on B in jets
  - Hovatta on SPIX in MOJAVE
  - Orienti on Seyferts with VLBI
  - Falcke on Sgr A*
- Later talks:
  - Pearson on blazar jets and gamma
  - Rani on 0716+714
  - Tchekhovskoy on MAD
  - Perucho on jet deceleration

On FR-I and FR-II

Mon. Not. R. astr. Soc. (1974) **167,** *Short Communication,* 31P–35P.

THE MORPHOLOGY OF EXTRAGALACTIC RADIO SOURCES OF HIGH AND LOW LUMINOSITY

B. L. Fanaroff and J. M. Riley

(Received 1974 March 6)

SUMMARY

The relative positions of the high and low brightness regions in the extragalactic sources in the 3CR complete sample are found to be correlated with the luminosity of these sources.

On the same issue of MNRAS:
1st paper by R.W. Porcas (UMan) and poineering paper by Fanaroff & Riley

Mon. Not. R. astr. Soc. (1974) **167,** *Short Communication,* 41P–42P.

HIGH RADIO POLARIZATION OF 4C 47.08

R. W. Porcas, A. M. Treverton and A. Wilkinson

(Received 1974 February 22)

SUMMARY

Measurements are presented of the radio position and linear polarization of the unusual radio source 4C 47.08. A neutral stellar object identified with the source has been shown to have a featureless optical spectrum.

On FRI and FRII galaxies

- FR I
  - Two-sided
  - Distorted (plume-like) radio structure
  - Radio weaker

- FR II
  - Smooth
  - One-sided, collimated
  - End in hot spots at kpc-scales
  - Radio louder

Sensitivity enhancement: VLBI studies ← Traditionally VLBI targets

Acknowledging material provided by

A.K. Baczko / B. Boccardi / G. Bruni / J. Hodgson / M. Kadler / V. Karamanavis / T.P. Krichbaum / Y.Y. Kovalev / S. Koyama / A.P. Lobanov / B. Rani / E. Ros / T.K. Savolainen / R. Schulz / L. Vega García / J. Wagner

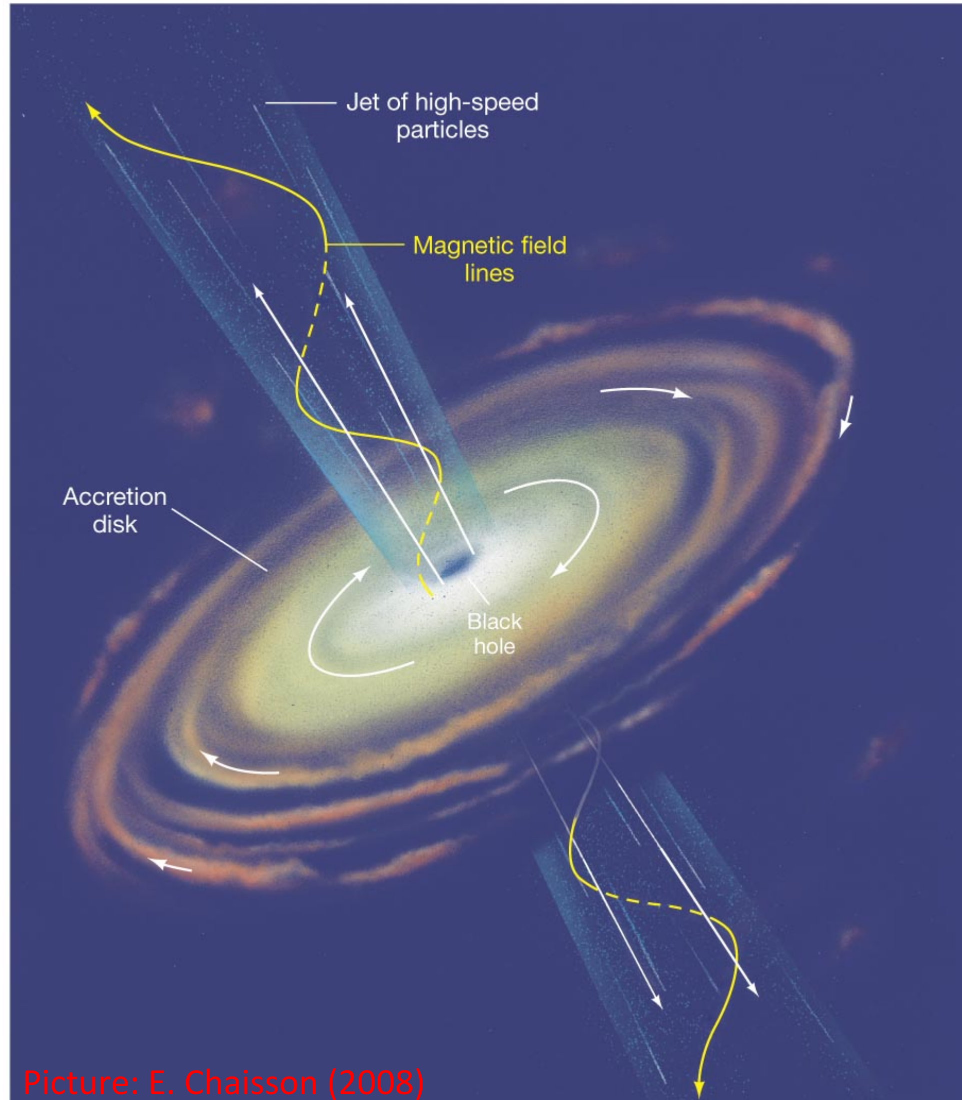
Outline

- Scientific Motivation for high resolution interferometry
- Towards high resolution
  - RadioAstron
  - Millimetre VLBI, new era with ALMA
- Outlook

Central Engine of an Active Galaxy

- Black hole, surrounded by an accretion disk. The strong magnetic field lines around the black hole channel particles into jets perpendicular to the magnetic axis.

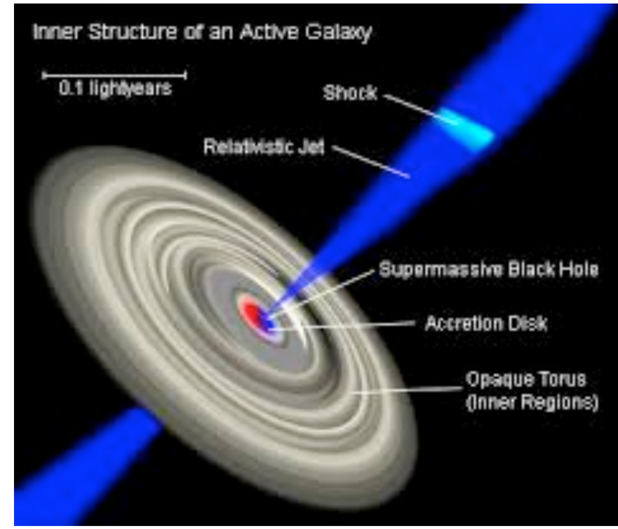
- Central BH mass of $\approx 10^9\,M_\odot$
- The accretion disk may radiate away as much as 10–20% of its mass before disappearing



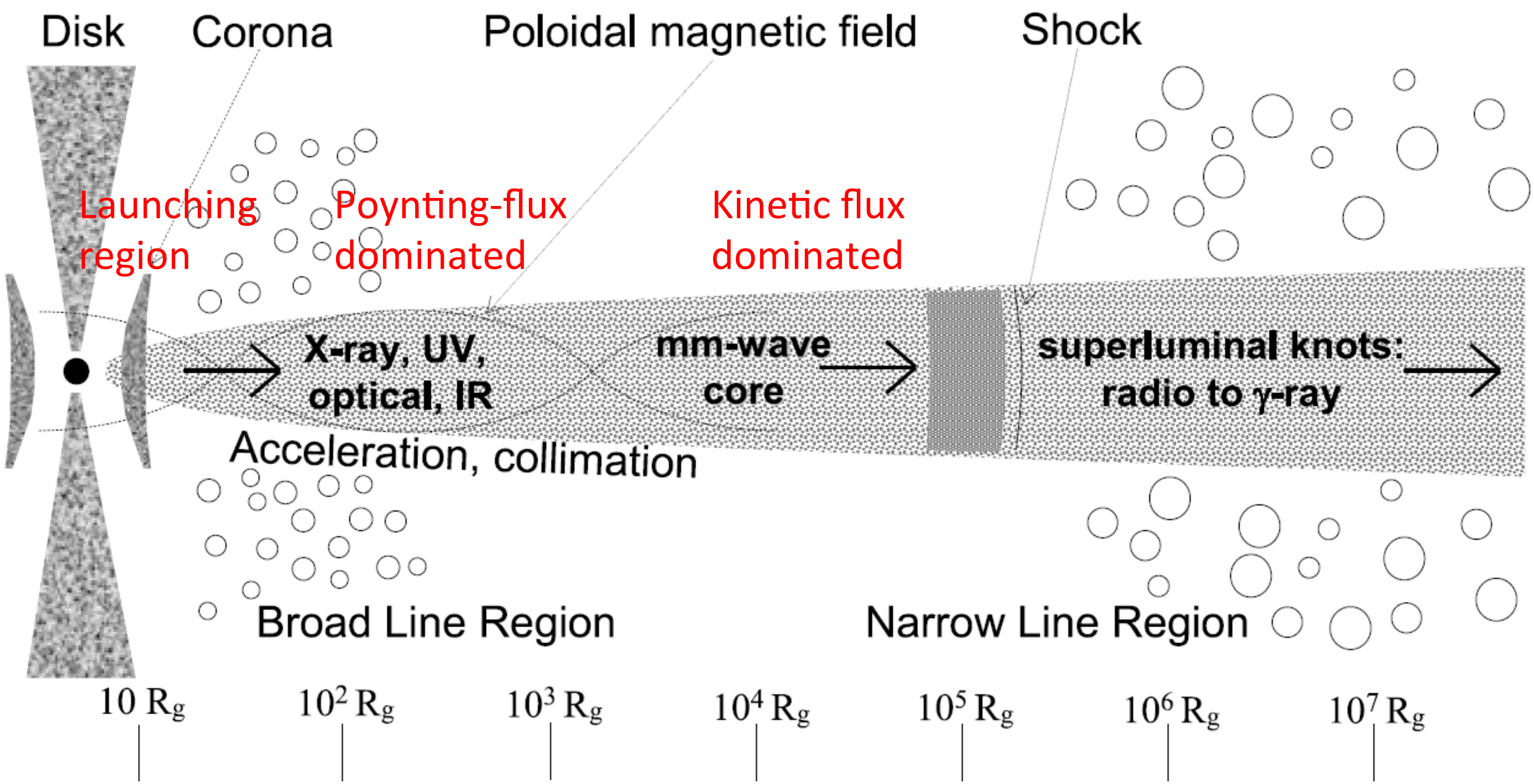
Picture: E. Chaisson (2008)

Key science

- Investigations of Active Galactic Nuclei (AGN), its non-thermal continuum emission and rapid variability:
  - Jet launching (acceleration and collimation)
  - Effects of opacity in the “core” near the jet base
  - Propagation of shocks in the jet and energy dissipation
- Use of Very-Long-Baseline Interferometry at cm and mm-wavelenghts



Collimated outflows interacting with all AGN constituents (jets)



A. Lobanov, COSPAR 2010

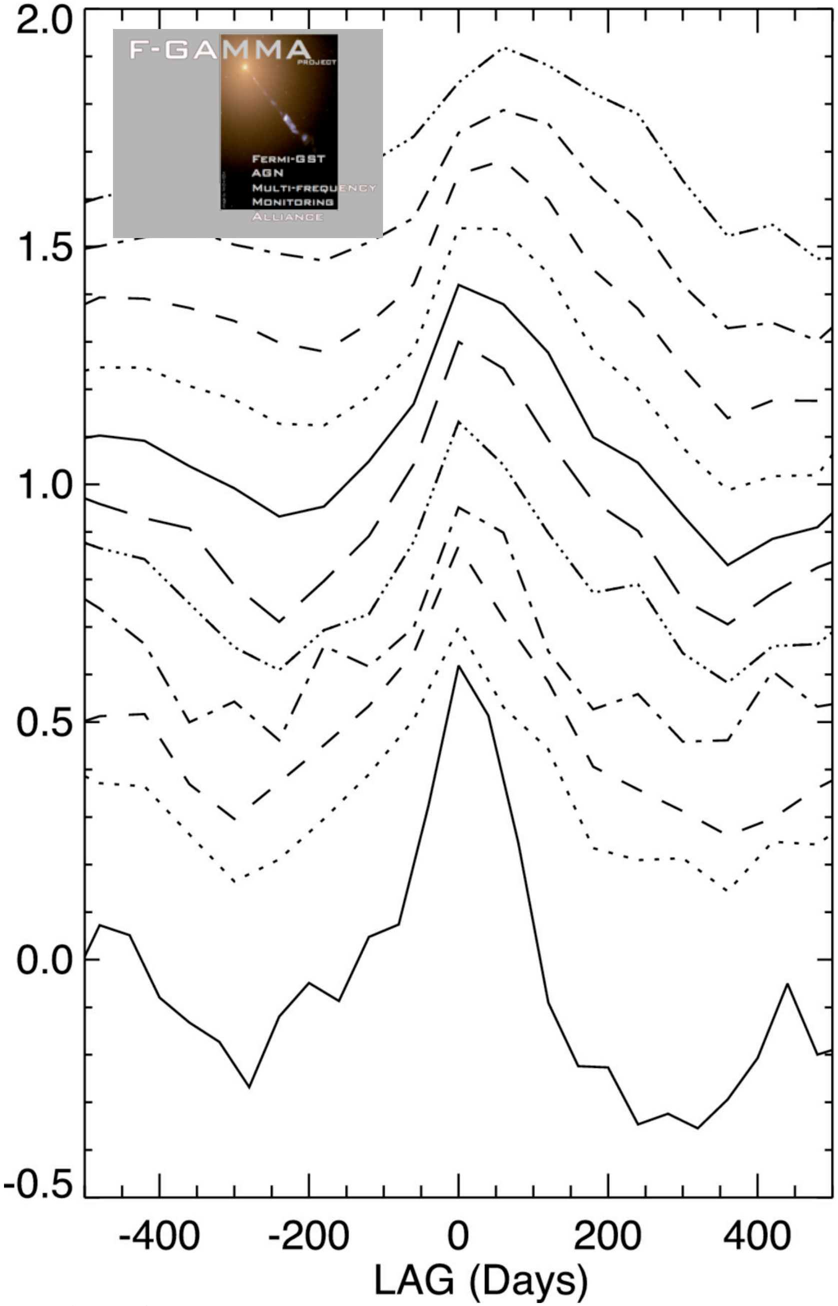
Radio Monitoring

F-GAMMA program

L. Fuhrmann, E. Angelakis, J. A. Zensus, I. Nestoras, V. Karamanavis, I. Myserlis,
T. P. Krichbaum, C. Fromm, B. Rani, A. Weiss | MPIfR
H. Ungerechts, A. Sievers | IRAM
S. Larsson | Uni. Stockholm,
N. Marchili | Uni. Padova,
V. Pavlidou | Uni. of Crete
& the *Fermi*/LAT collaboration

cm to sub-mm monitoring of *Fermi* bright blazars

start: 2007 – 61 blazars – Facilities: Effelsberg 100-m, IRAM 30-m & APEX 12-m telescopes



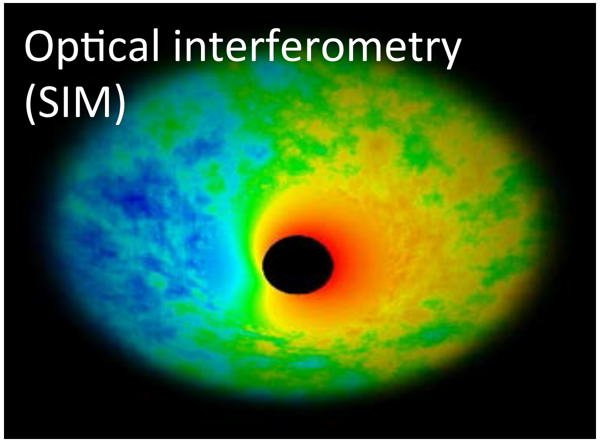
F-GAMMA monitoring: γ-radio correlation

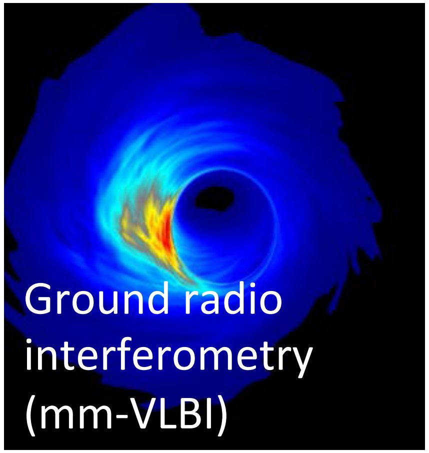
- Significant correlation: stacked radio/γ-ray DCCFs across all radio bands from the F-GAMMA program
- Average time delays from 76±23 d to 7±9d decreasing to mm (10±3 pc to 0.9±1.1 pc location)
- Γ-ray production located upstream of the 3mm core region

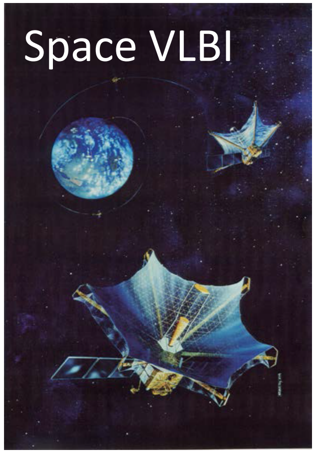
Fuhrmann et al. MNRAS 441, 1899 (2014)

Observing the BH vicinity

- X-ray: spectroscopy (1D, model dependent); interferometry (not available)
- Optical, IR: interferometry (good uv-coverage, phase closures)
- Grav. waves: interferometry
- Radio: pulsar timing (GR extended test, needs PSR-BH system)
- Radio: interferometry, ground (2D, calibration), space (2D, orbit determination)







Enhancing VLBI

- Sensitivity (area of antennas)

$$\sigma \propto \Sigma D_i^2$$

Square Kilometre Aray

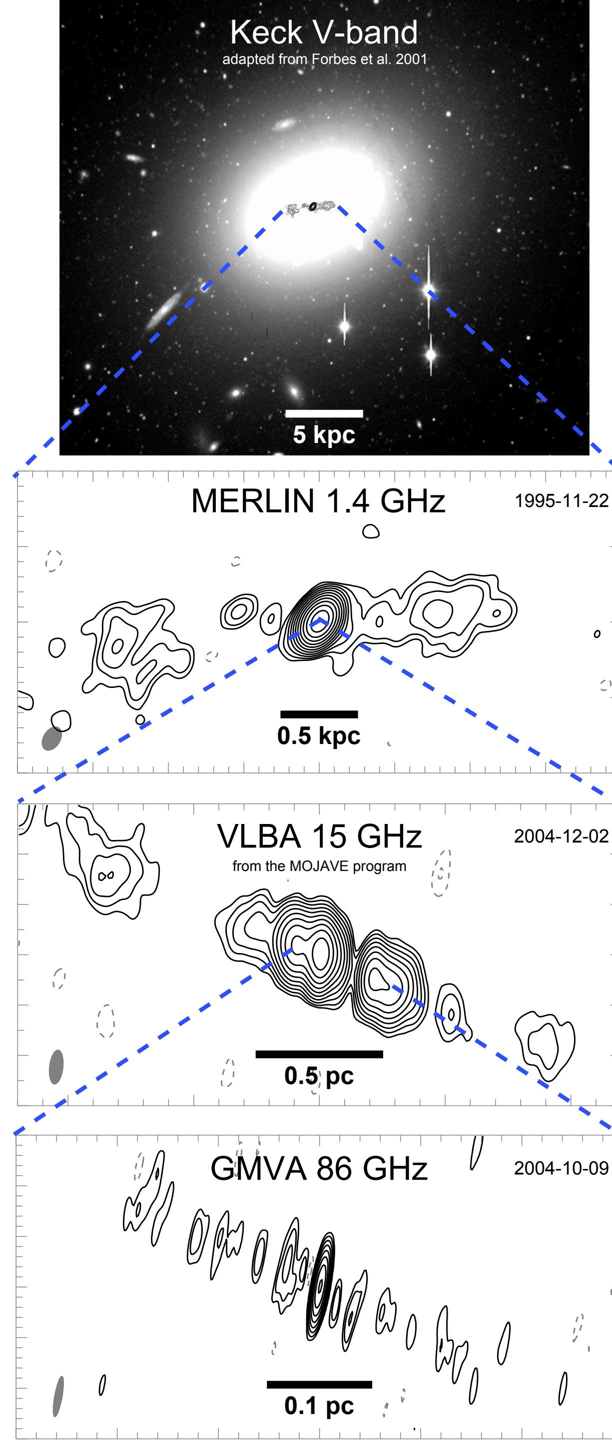
- Resolution (wavelength and baseline length)

Millimetre VLBI

$$\theta \propto \lambda_{\mathrm{obs}} / B_{\mathrm{max}}$$

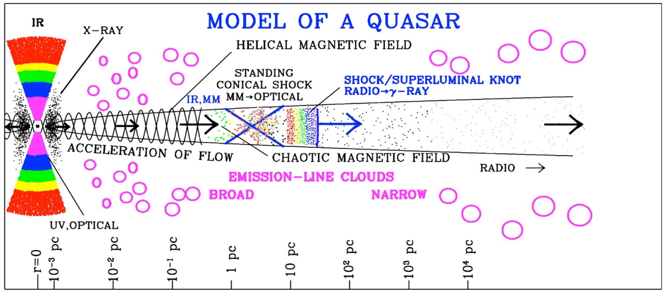
Space VLBI

Tune λ or D: towards the base of the jet: mm-VLBI



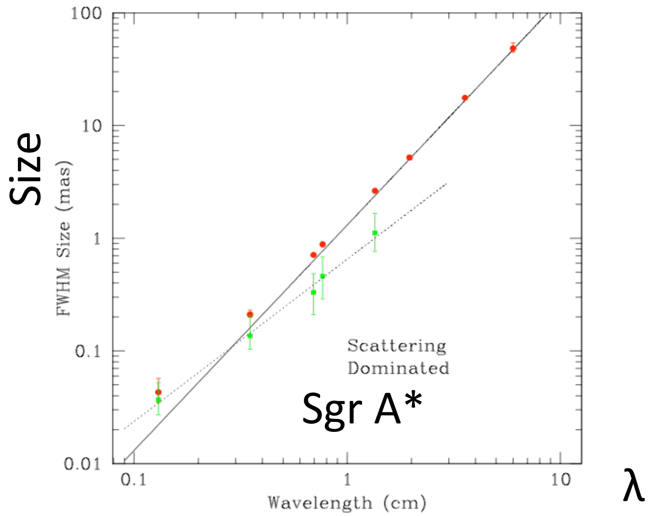
NGC 1052 at all scales

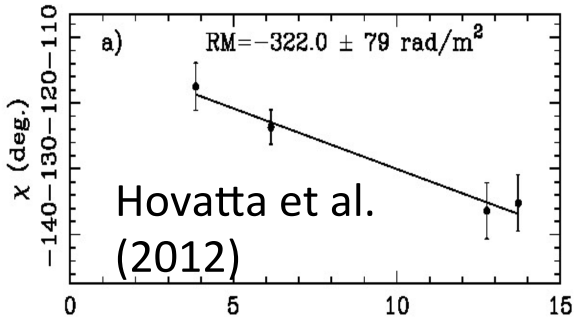
Marscher et al.



Why mm-wavelengths?

- Synchrotron-emitting outflows (jets)
  - Looking deeper
- Scattering (size ∝ λ^2)
  - Intrinsic sources structure
- Faraday rotation ($\chi \propto \lambda^2$)
  - Intrinsic polarisation angle





The Global mm-VLBI Array (GMVA)

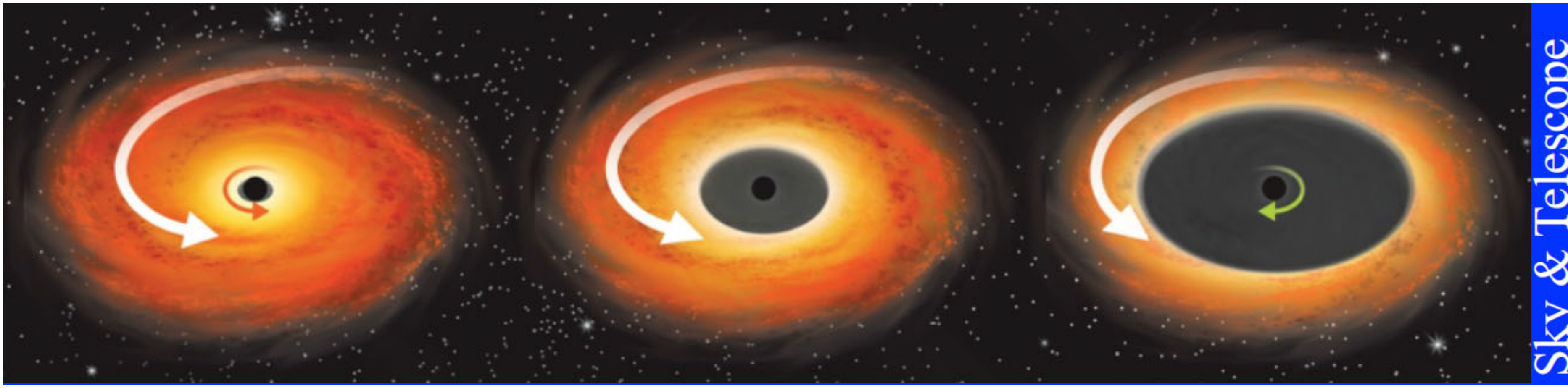
The science of mm-VLBI

- Achieve highest resolution
- Trace AGN jets down to origin
- Understand jet formation & collimation in the inner 1000 grav. radii
- Spectral decomposition, brightness temperature and polarisation to determine physical properties
- Kinematics in the shocked region (curvature, accelerations)
- Outburst-ejection relations, comparison with broadband measurements

mm-VLBI limitations

- Few experiments per year (logistical limitations)
- Variable weather & phase coherence
- Limitation in some telescopes: gain, receiver, bandwidth
- Ongoing upgrades of recording equipment
- Complex correlation and post-processing (averaging, fringe-search, calibration)

Innermost Stable Circular Orbit (ISCO)

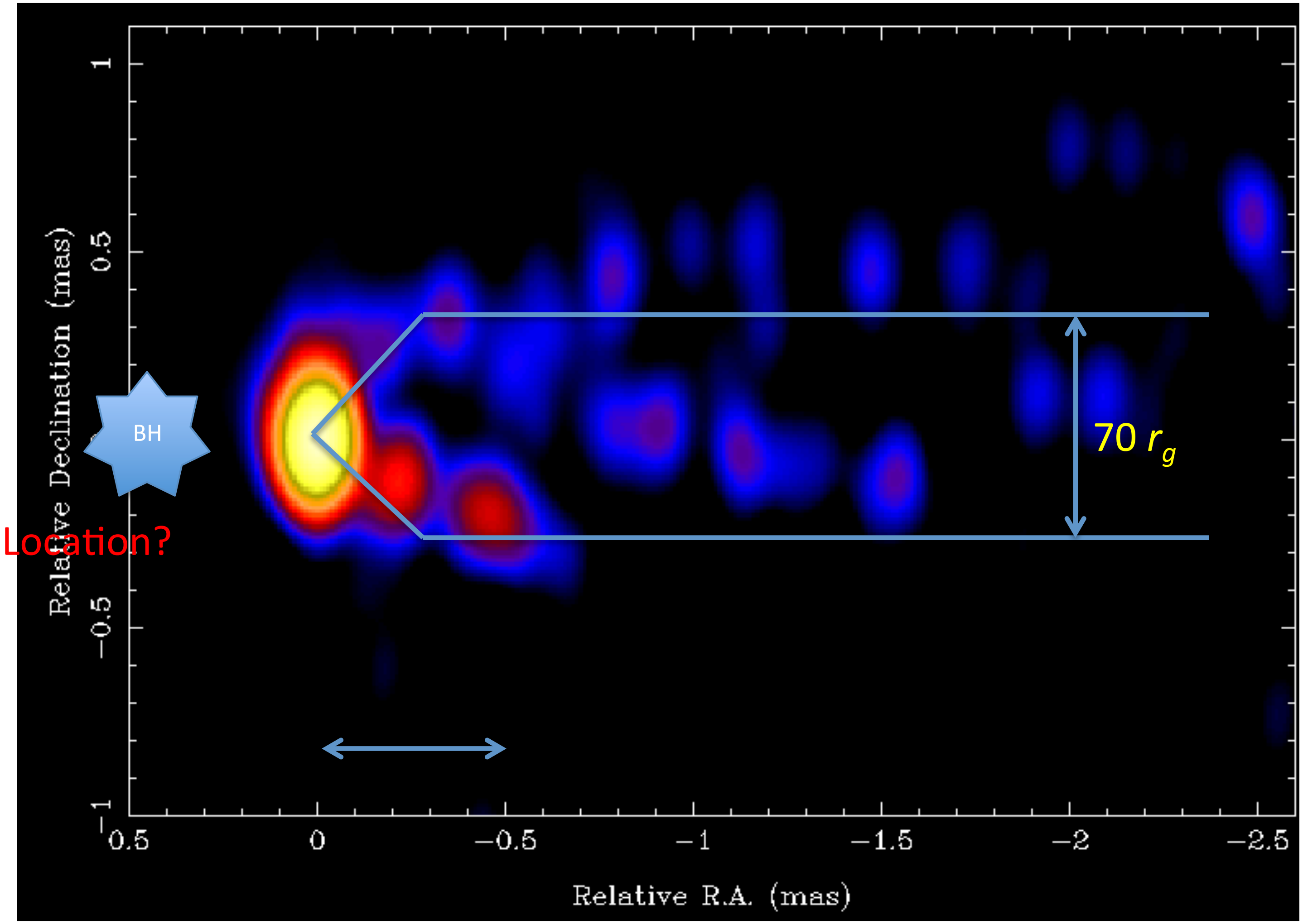


Prograde BH
ISCO at R=1 GM/c^2
Frame-dragging rotationally supports orbits close to BH

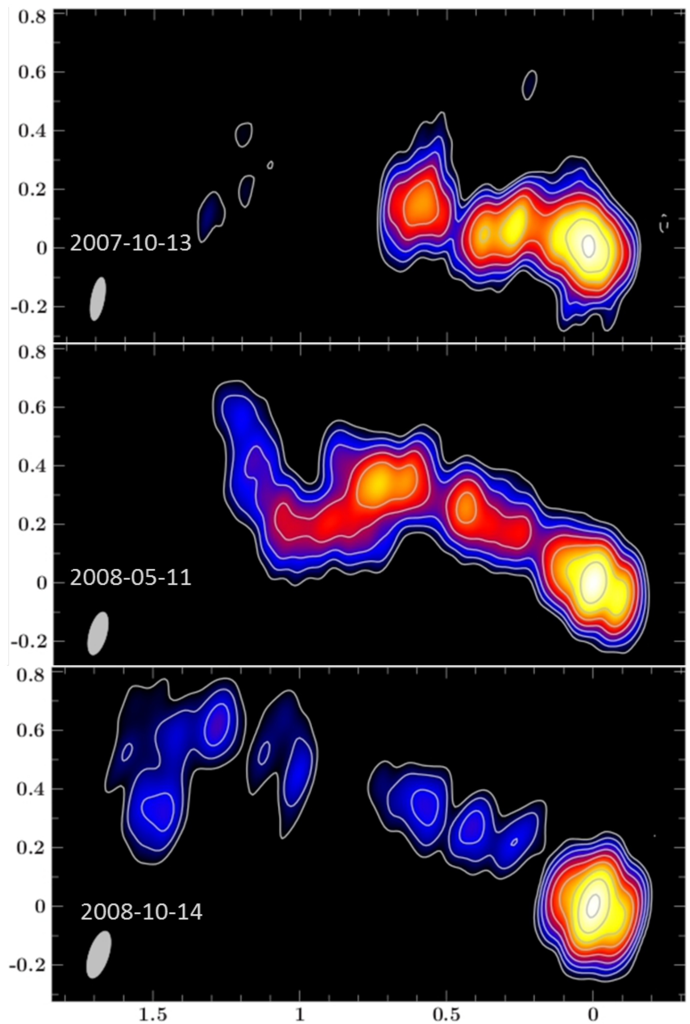
Non-spinning BH
Accretion disk rotates
ISCO at R = 6 GM/c^2
No frame-dragging

Retrograde BH
ISCO at R = 9 GM/c^2
Frame-dragging opposes to disk

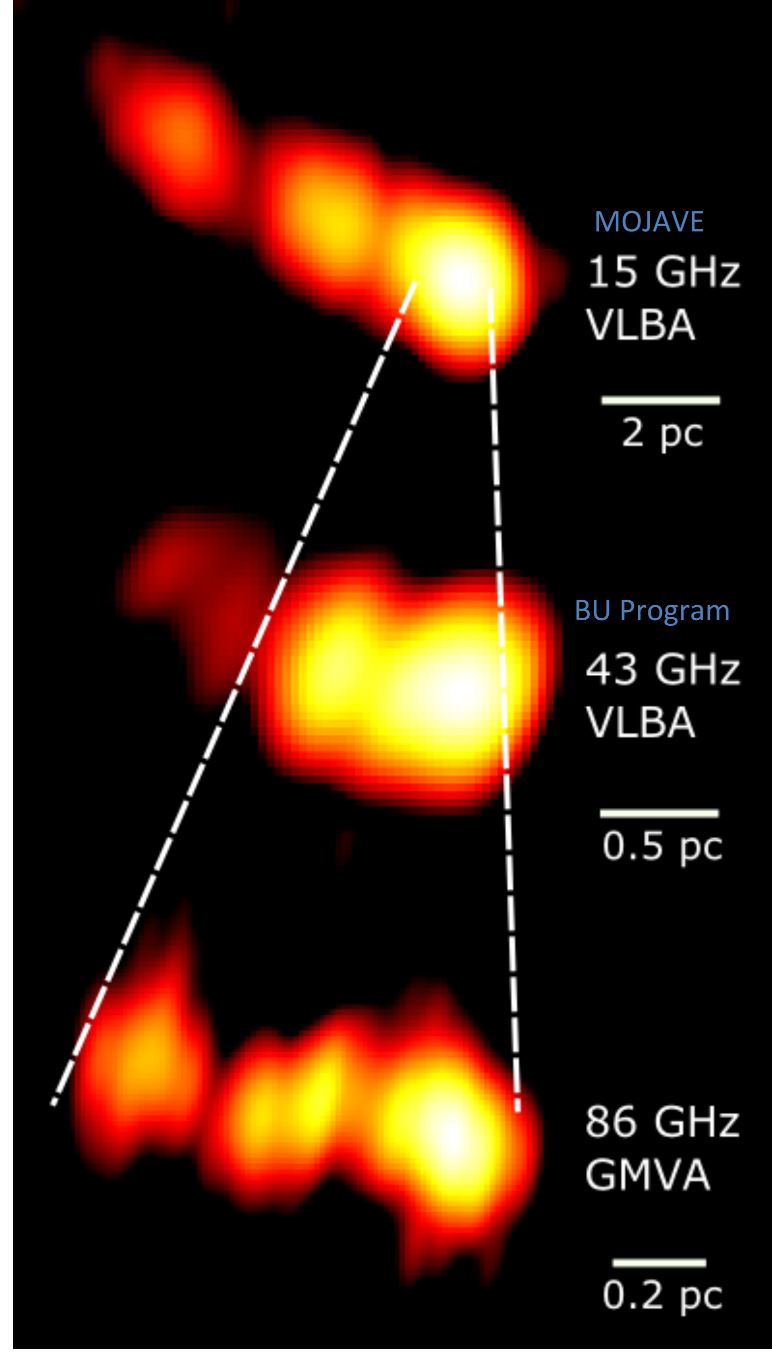
Size of jet base in M87: 27×8 r_g



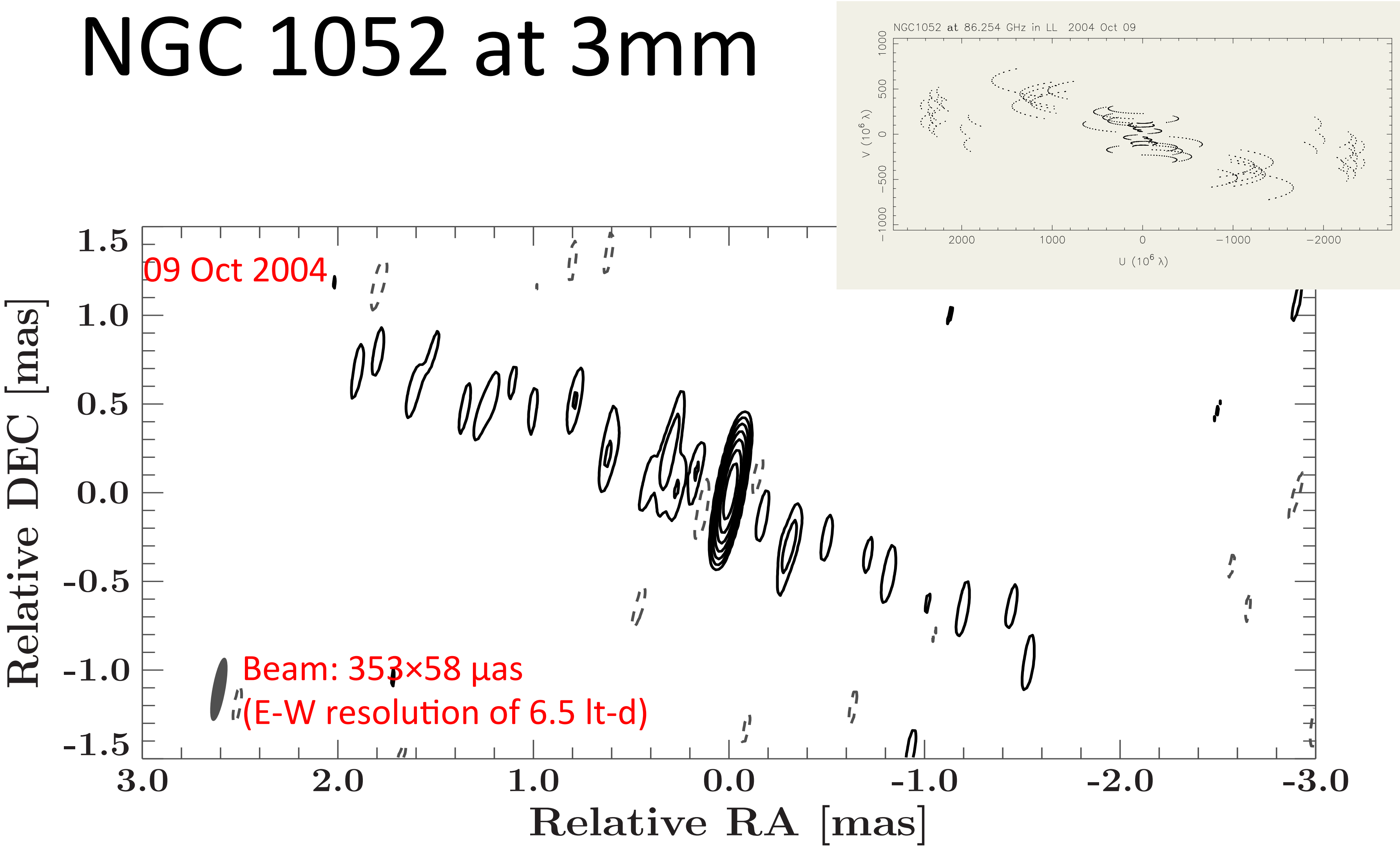
GMVA: 3C 111



R. Schulz et al. (MSc 2012, & in prep.)

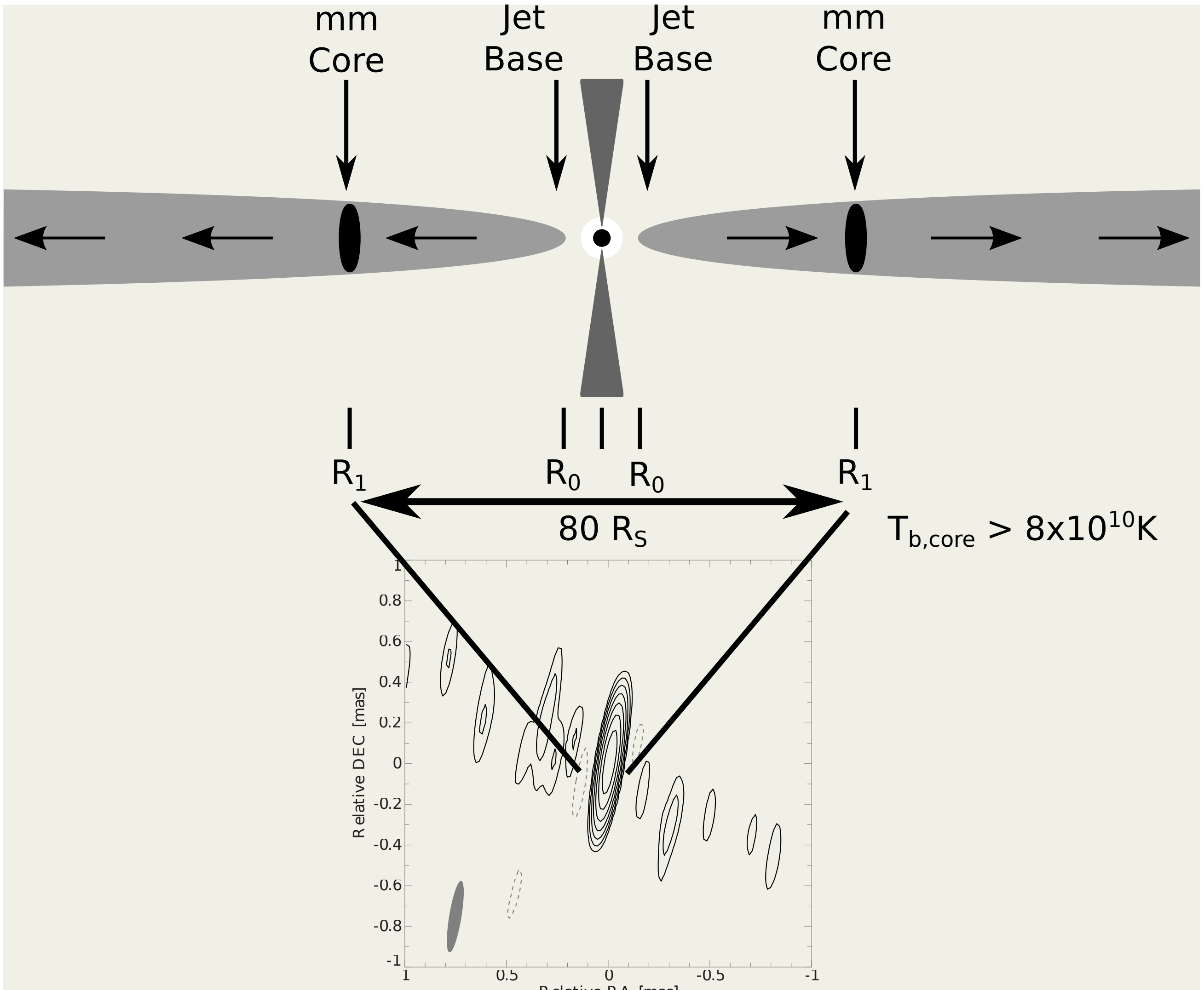


NGC 1052 at 3mm



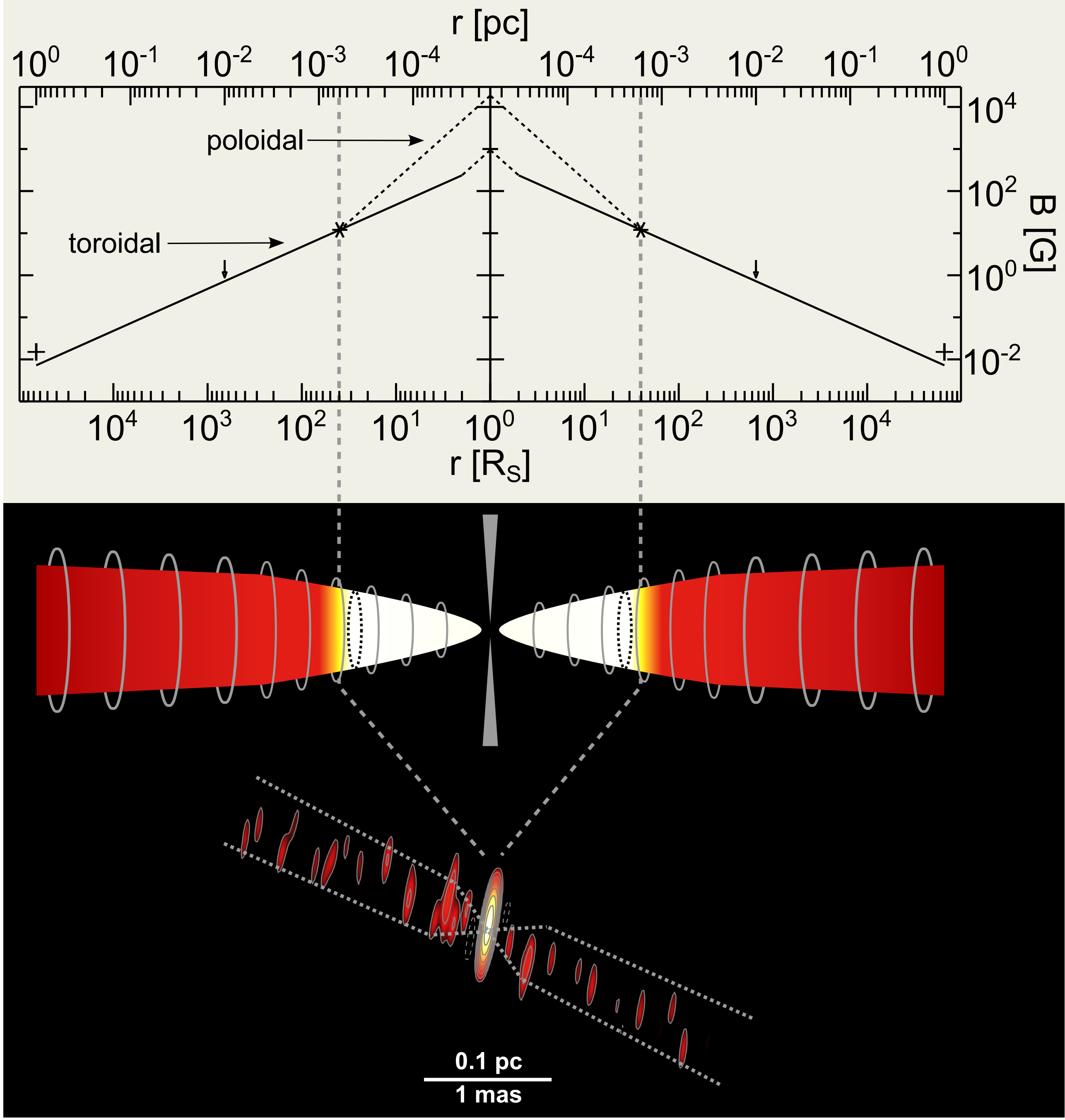
Baczko et al. (in prep.)

NGC1052 at 3mm



Baczko et al. (in prep.)

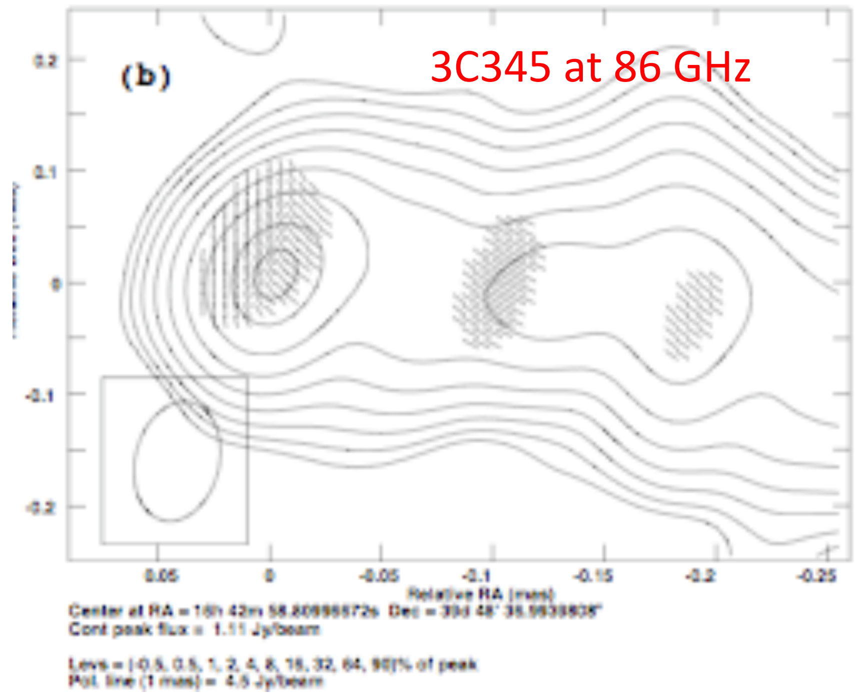
NGC1052 at 3mm: High magnetic fields



Baczko et al. (in prep.)

Polarization with mm-VLBI

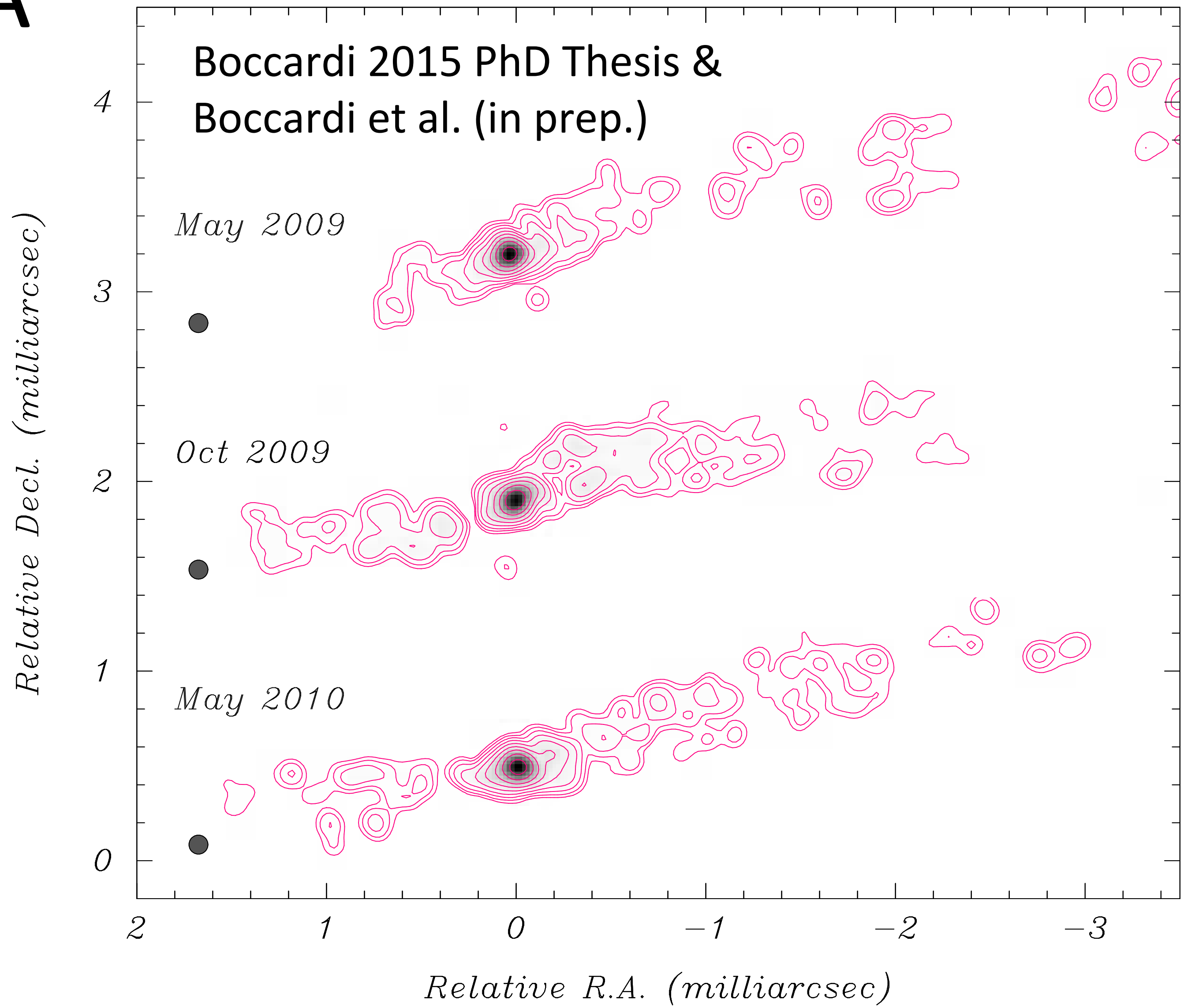
- Improvements in sensitivity by bandwidth and performance enhancements
- Improvements in resolution:
  - 86 GHz new calibration methods (see Martí-Vidal et al. 2012)
  - RadioAstron observations



Martí-Vidal et al. (2012)

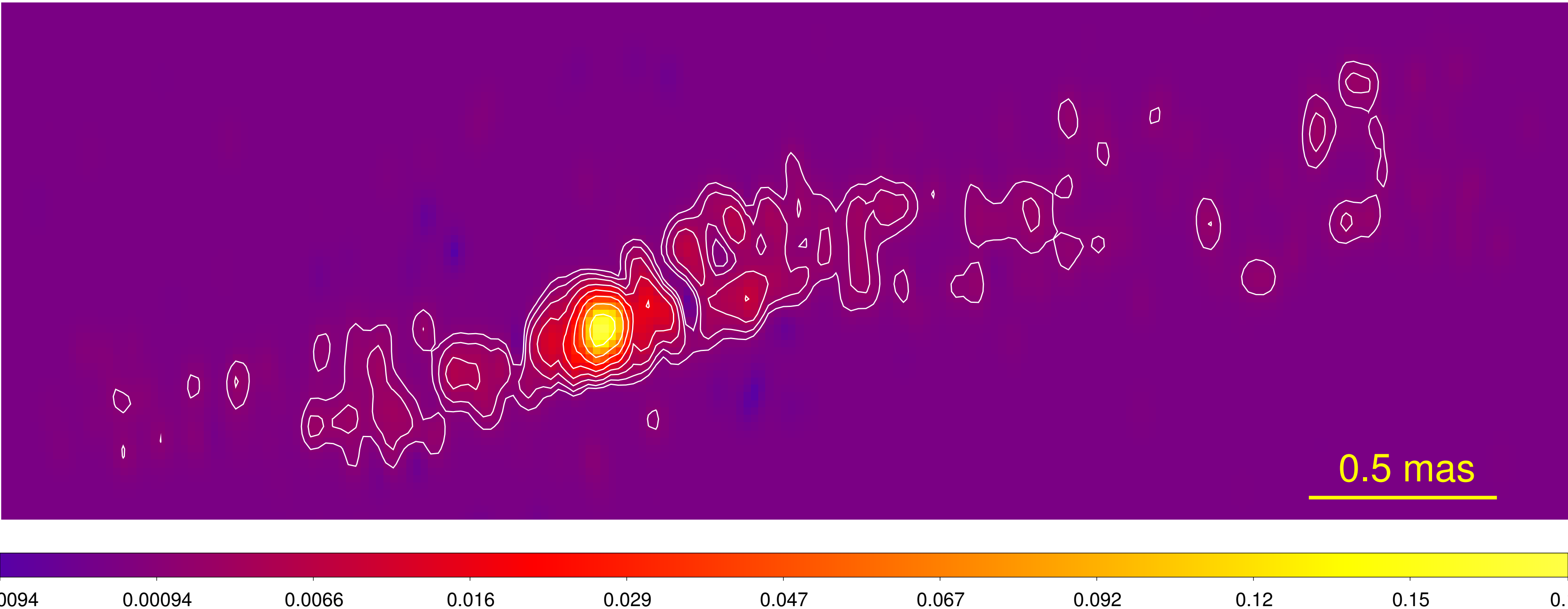
Cygnus A

GMVA imaging



Cygnus A

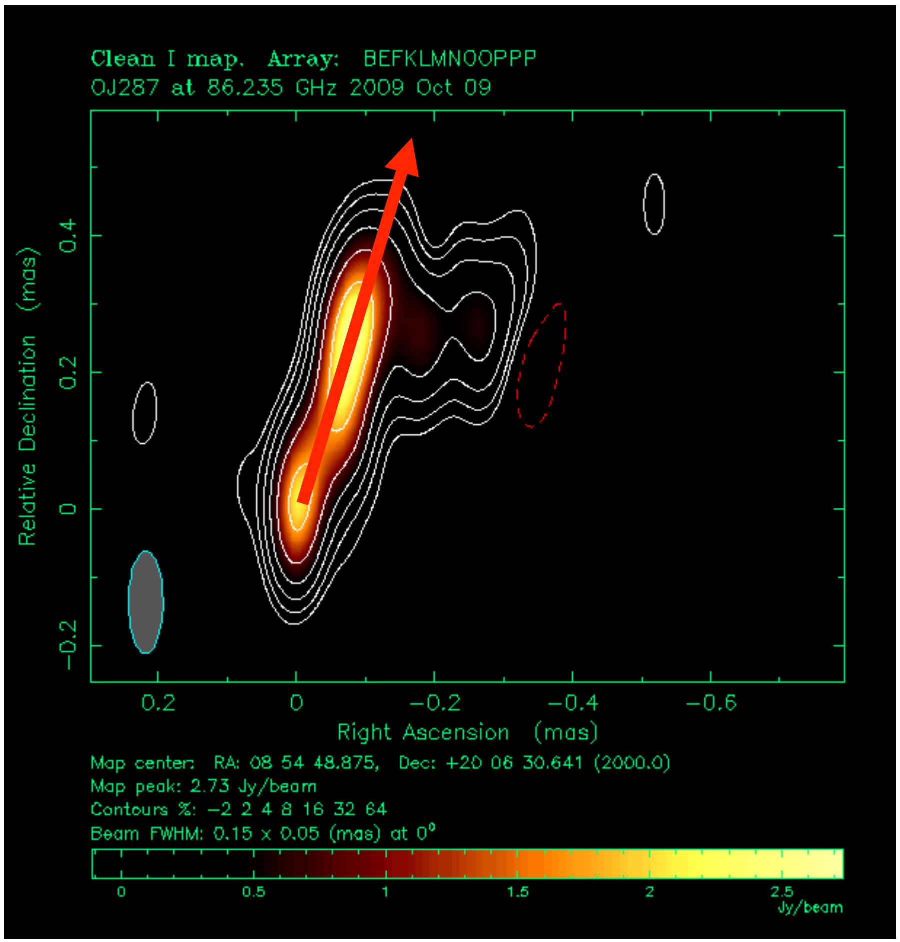
Boccardi et al. (in press)



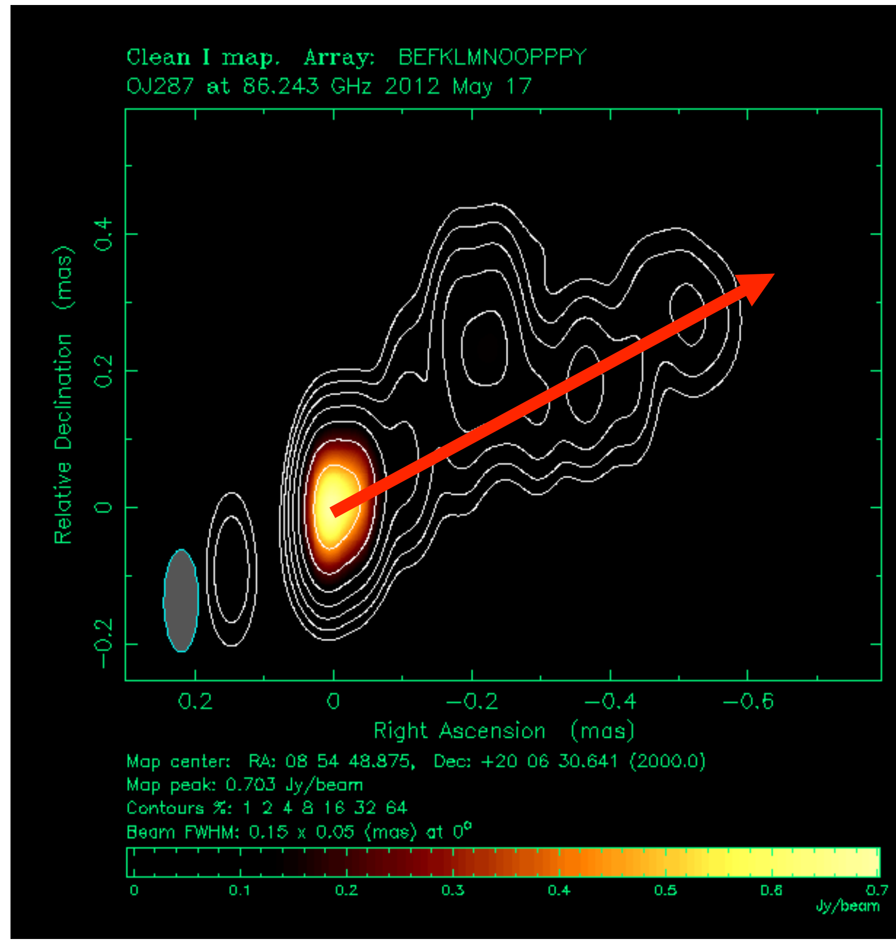
Stacked 3-mm images

OJ 287: Jet position angle swings

Oct. 2009

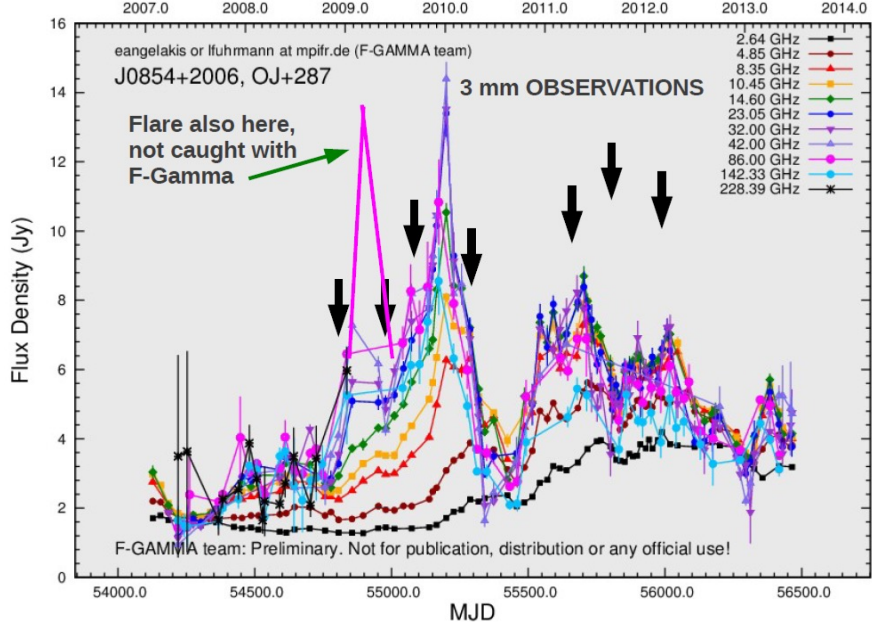


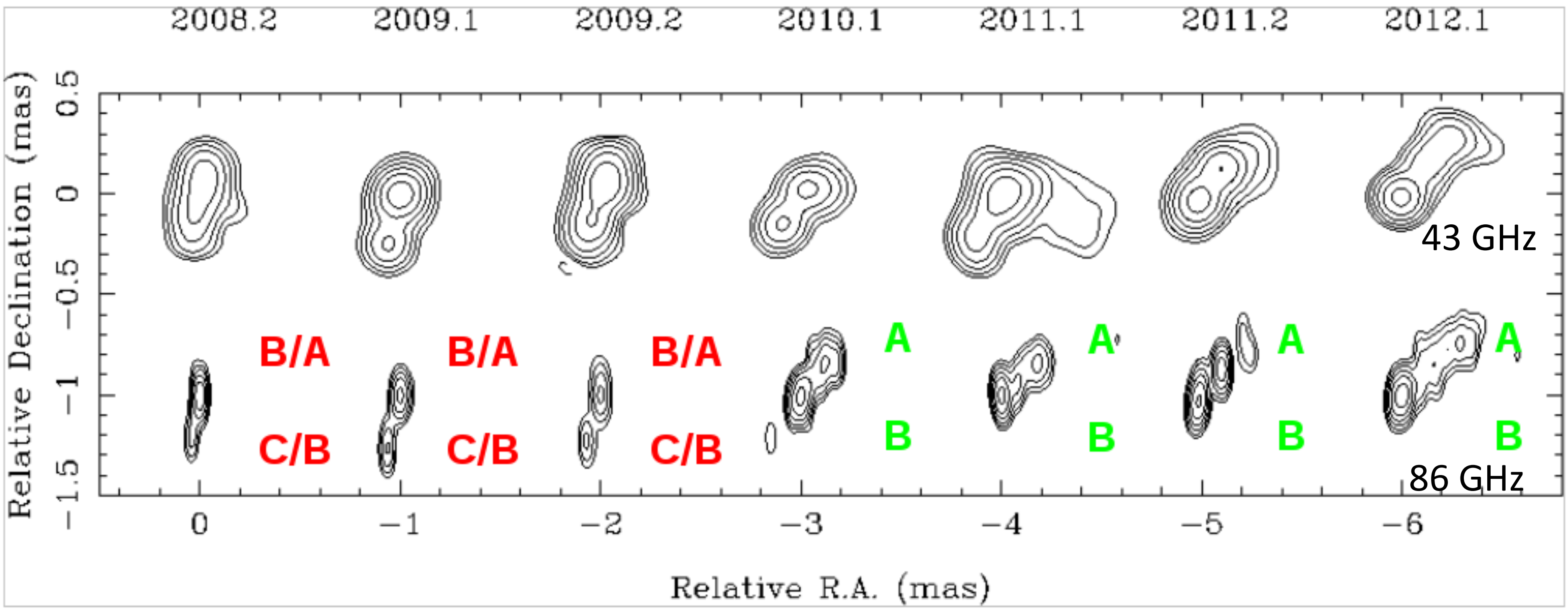
May 2012



Jeff Hodgson et al.

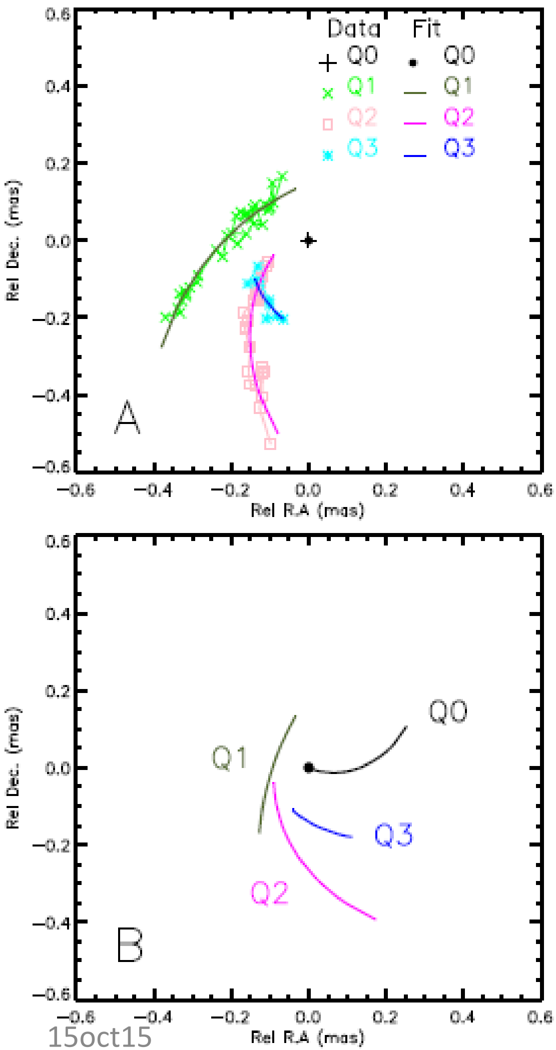
Jet position angle swing and broadband flares in OJ 287

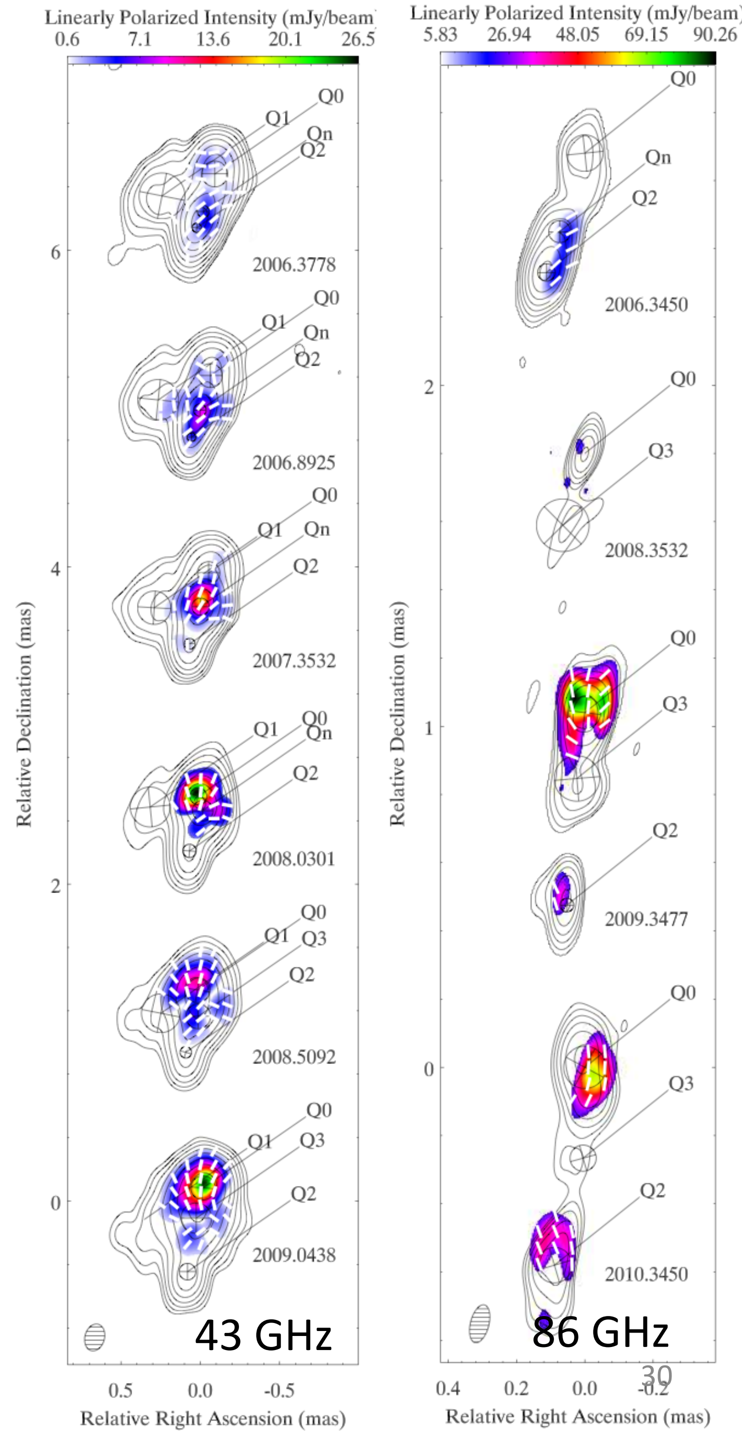




Jeff Hodgson, PhD Thesis, 2015

Swing in the rotating jet of NRAO 150



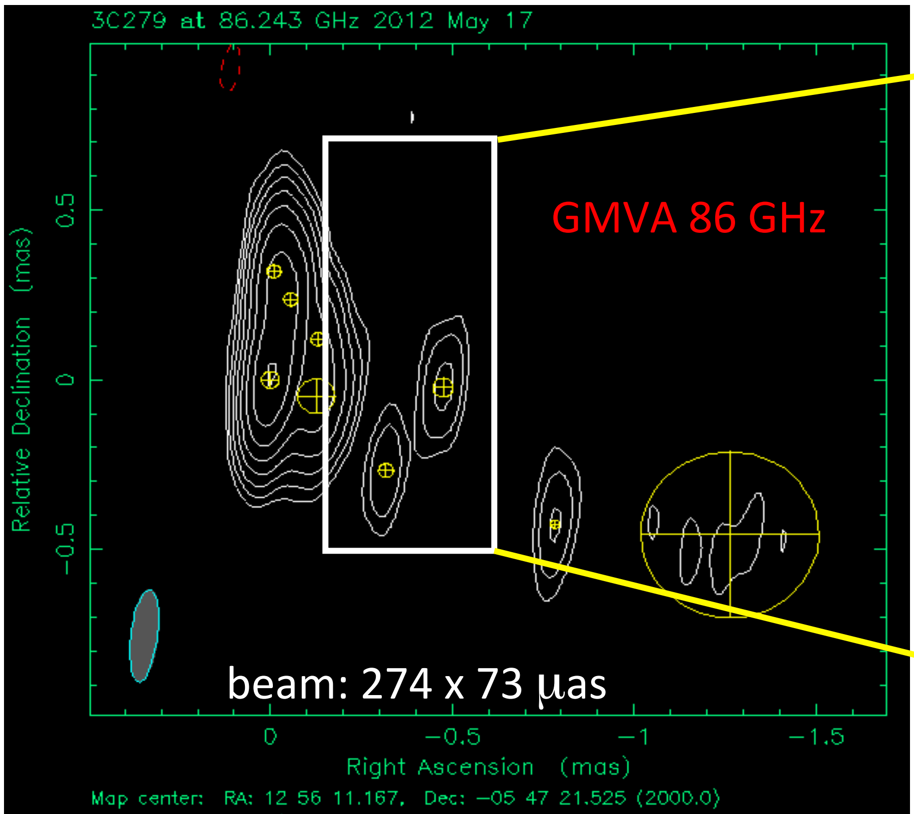


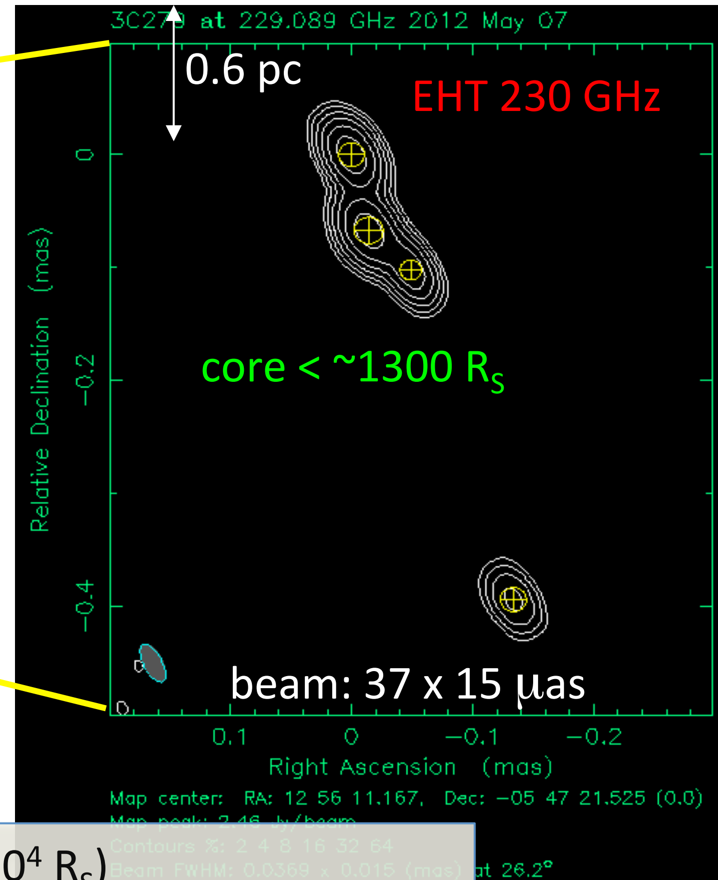
http://dx.doi.org/10.1051/0004-6361/201423479

Molina et al. A&A 566 A26 (2014)

λ1.3mm detection of 3C 279
APEX-SMA-SMT

Wagner et al. (2015)

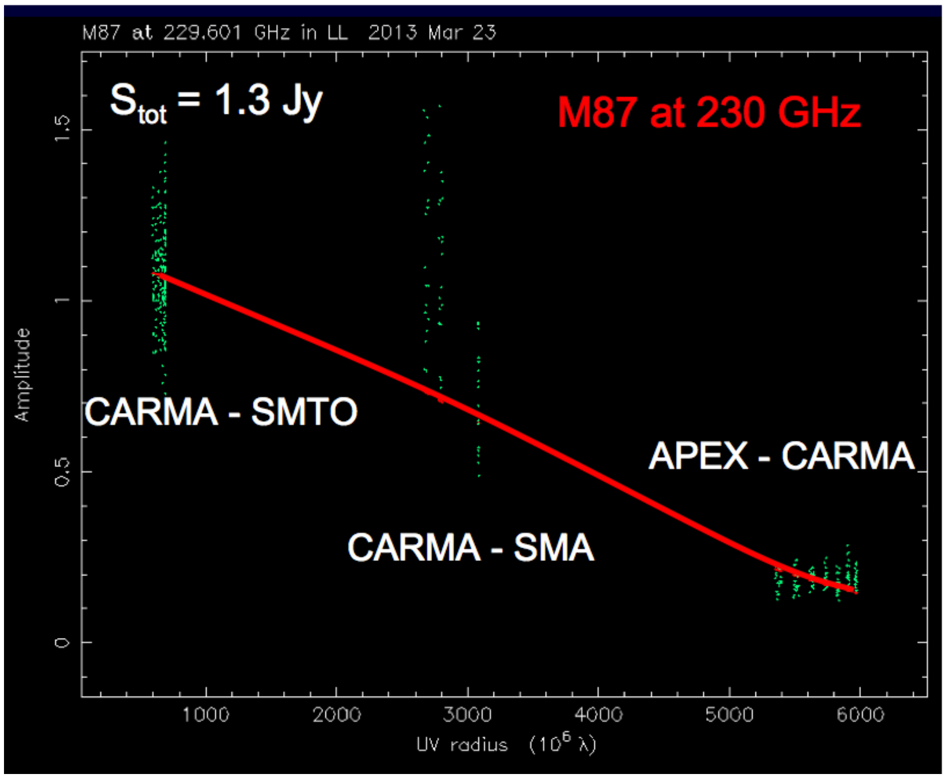




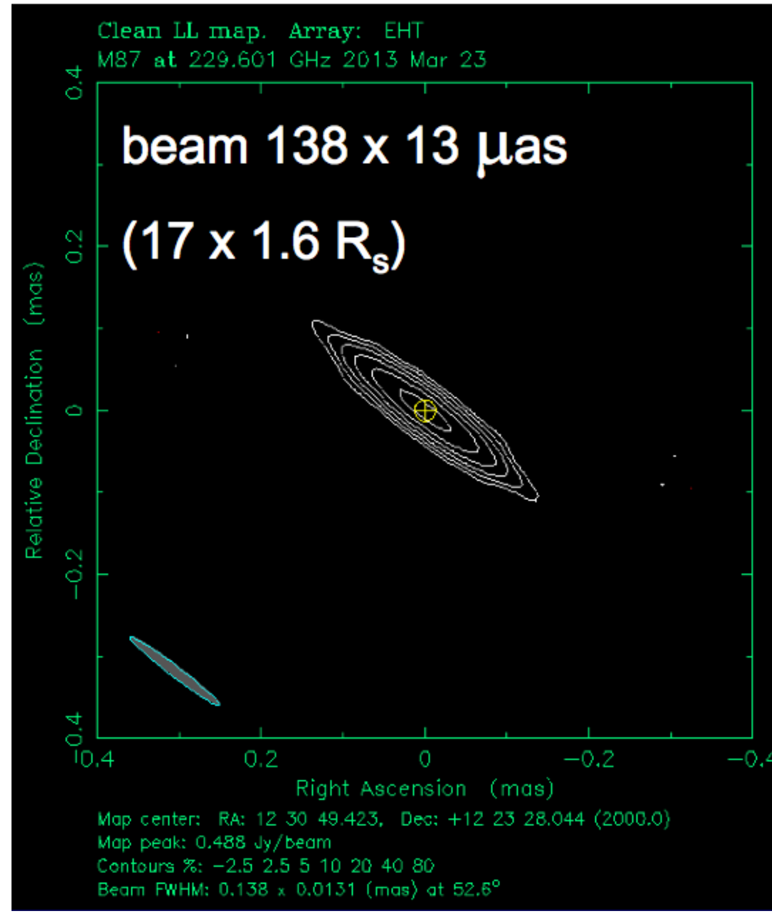
base of jet transversely resolved, width of ~1 pc (~10^4 R_S)

size of individual components (emission regions) < 0.1 pc (1000 R_S)

M87: New size estimate at λ1mm with APEX



Krichbaum et al. (in prep.)



Circular Gaussian: S=1.1 Jy, ϑ=26 μas, R=3.3 R_s

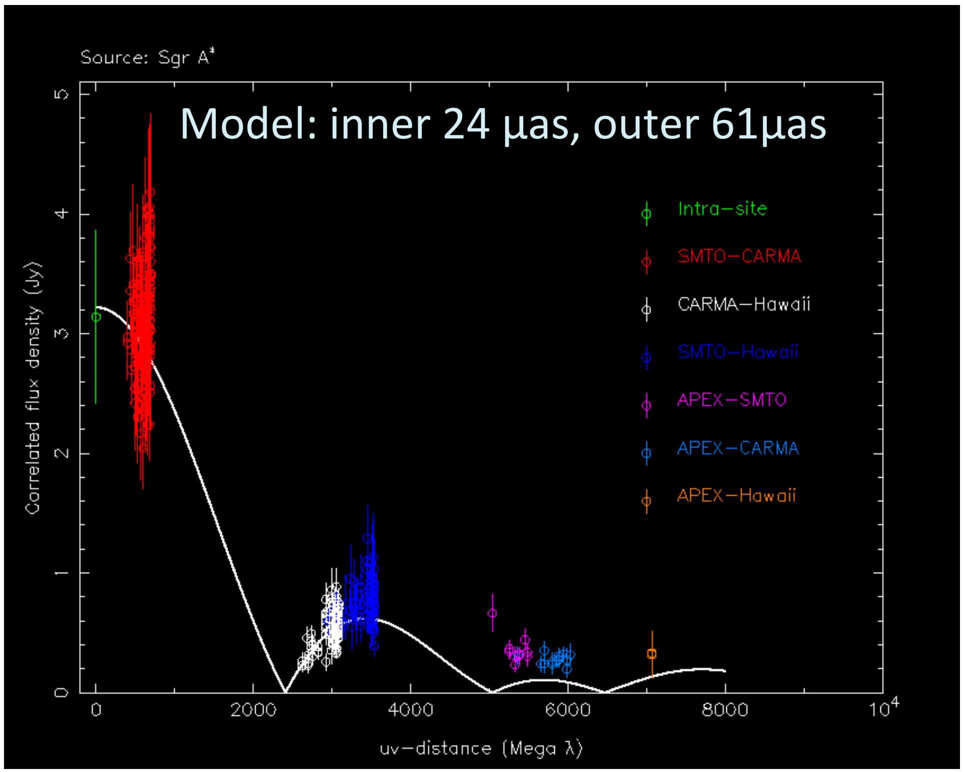
S=0.2 Jy at 6 Gλ, ϑ=34 μas; jet nozzle R=4.3 R_s, $T_b \geq 4\times10^9$ K

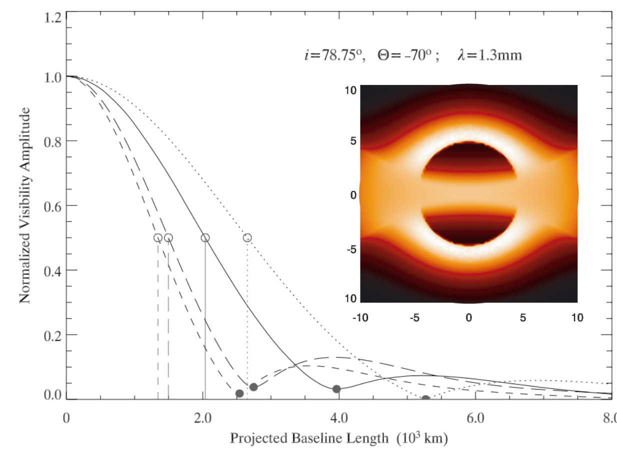
1.3mm-VLBI observations of Sgr A* in 2013

with APEX detections

signature of the shadow?

(deblurred) amplitude

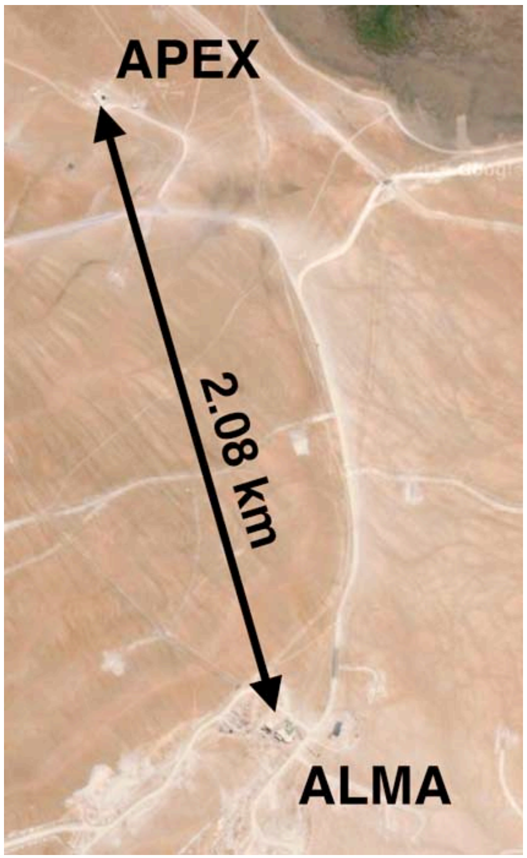




Huang et al. 2007

Lu et al., in prep.

Test observations on 13jan2015

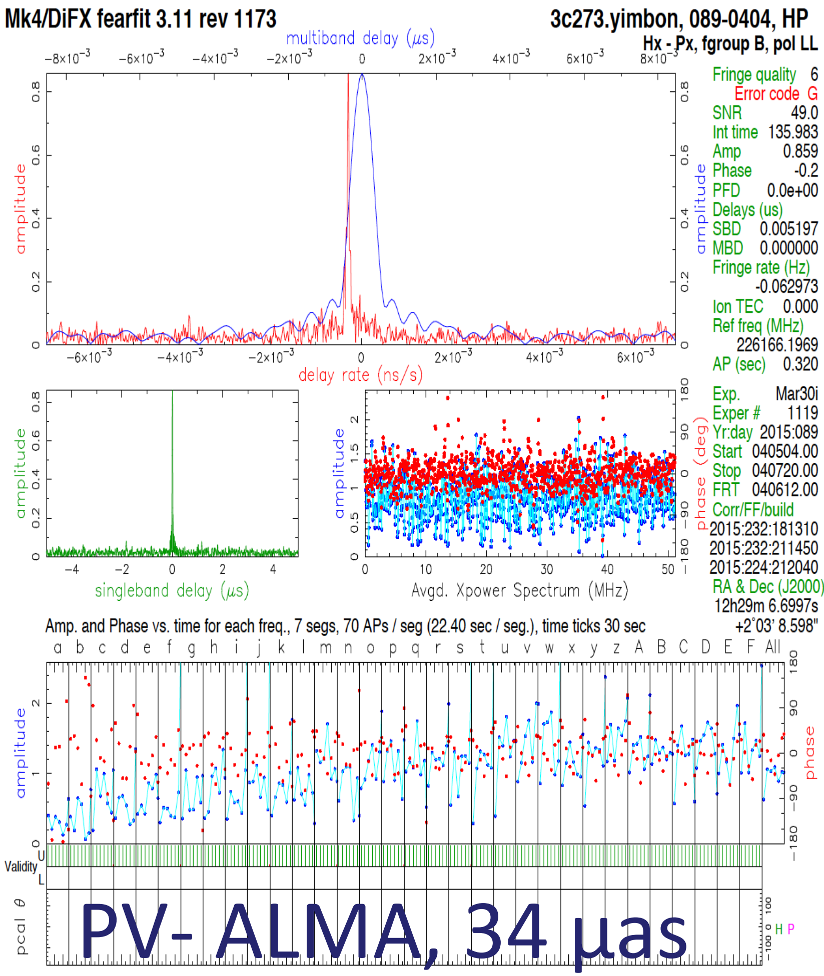


Fringes on B0522−364 at APEX-ALMA baseline

7000 km !

Fringes on Centaurus A at APEX-SPT baseline

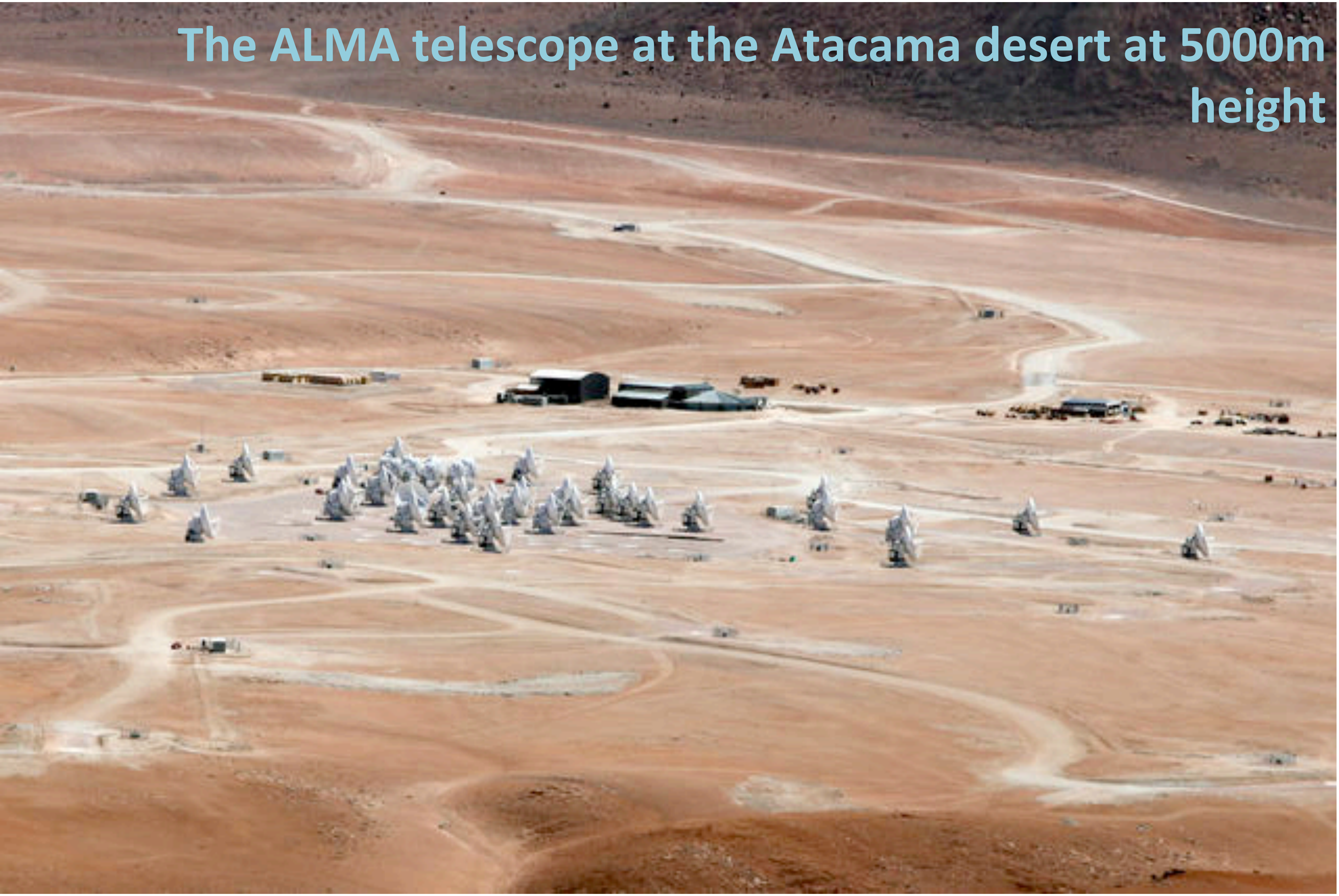
Current developments at λ1.3mm



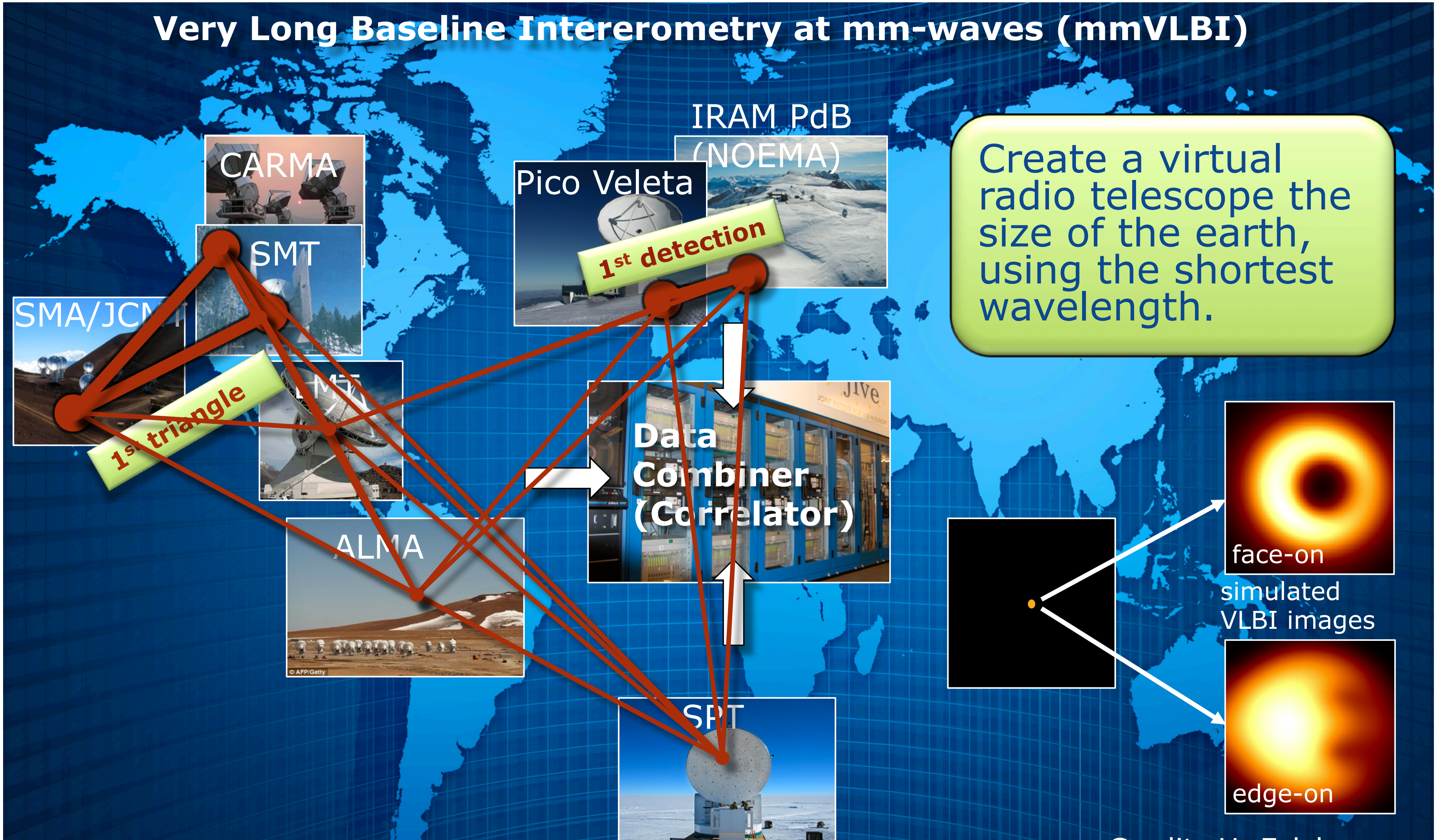
- Mauna Kea, Hawaii:
  - SMA, JCMT (D_eff: 23m)
- Mount Graham, Arizona:
  - SMT (10-m)
- Inyo Mountains, California:
  - CARMA (D_eff: 27m)
- Sierra Negra, Mexico:
  - LMT (50-m)
- Atacama desert
  - ALMA, (D_eff: 85-m)
  - APEX, (12-m)
- Pico Veleta (Sierra Nevada, Spain, 30-m)
- Plateau de Bure (France, D_eff: 37-m)
- South Pole Telescope (10-m)
- Greenland Telescope (12-m)

New 1.3mm VLBI fringes for SPT, LMT, phased ALMA in 31jul2015!

The ALMA telescope at the Atacama desert at 5000m height



The Event Horizon Telescope

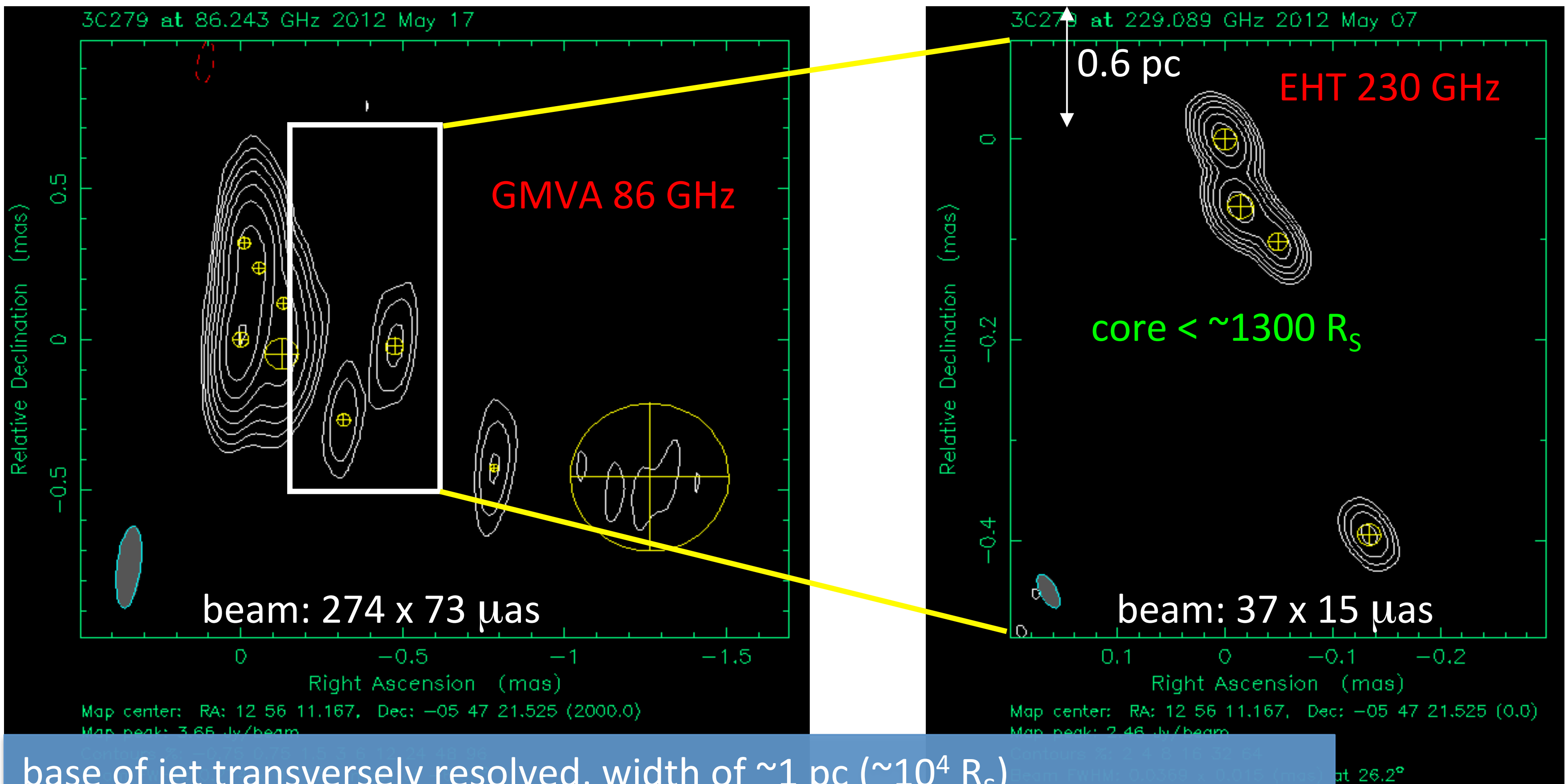


The path towards N-S λ1mm baselines: APEX

07may2012: 1st fringes
e.g., APEX-SMA, 9447 km, 28.4 μas

λ1mm detection of 3C 279
APEX-SMA-SMT

Wagner et al. (2015)

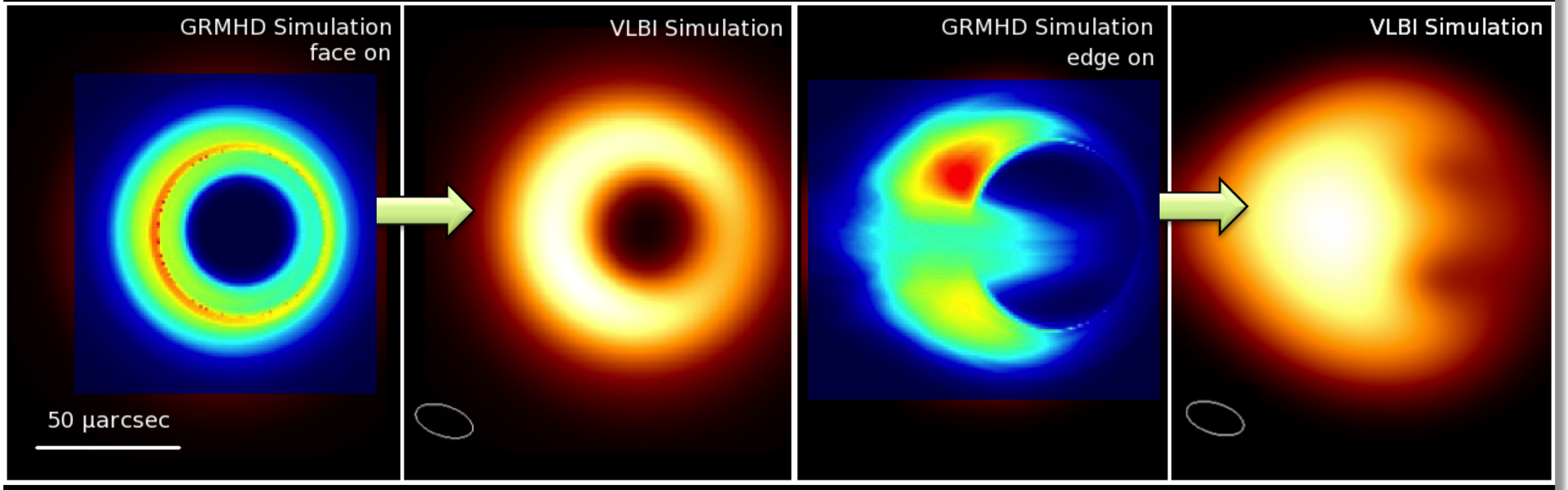


base of jet transversely resolved, width of ~1 pc (~10^4 R_S)

size of individual components (emission regions) < 0.1 pc (1000 R_S)

What can we expect to see?

The event horizon shadow is 50μas in diameter –
global mm-wave VLBI has the resolution (12-20μas) to see it.



Simulated black hole & accretion disk
Left: face-on
Right: edge-on

Next steps

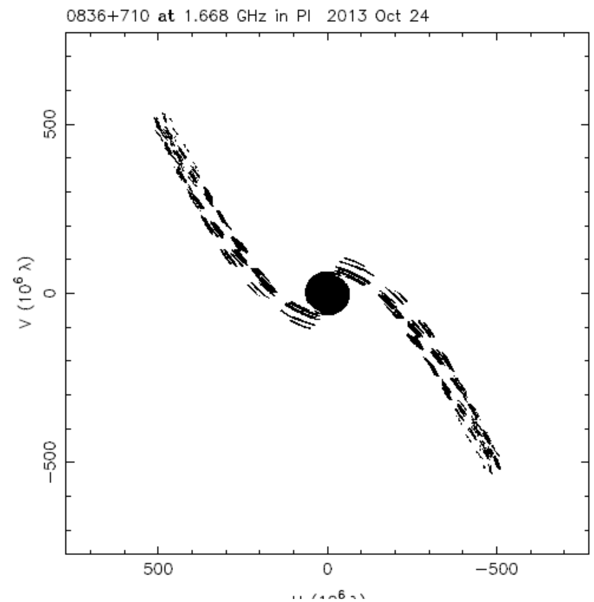
- Build and support a European mm-VLBI community, expanding the GMVA with ALMA (ESO upgrade proposal)
- Building a global sub-mm VLBI array: the Event Horizon Telescope
  - 10-25 μas resolution
- A phased ALMA will provide mJy sensitivities at mm-λ
- Imaging nearby radio galaxies at few r_g resolution
- SMBHs at high redshifts, AGN studies in survey mode

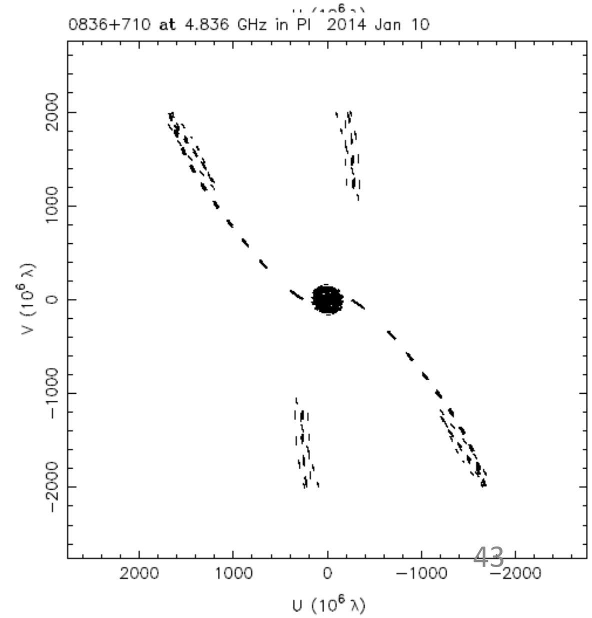
RadioAstron

- 10-m dish
- 0.3/1.6/5/18-25 GHz
- Orbit 10000 to 3000 km (9-days period)
- Software correlators: ASC, DiFX-Bonn, JIVE SFXC

Imaging

- **Imaging with RA is not easy**, both methodologically and logistically.
- **Methodology:** orbital plane or perigee imaging. Both imply specific (and restrictive) time constraints.
- **Logistics:** must split the observing time into
  - Perigee imaging: 1-10 $D_{\oplus}$, full-track observations with large ground arrays)
  - Visibility tracking: 10-20 $D_{\oplus}$, several ~1-hour segments spread over 3-4 days, with one large and ~3 small antennas on the ground.
- **Targets:** so far, about 30 imaging observations of about 20 targets; mostly in the framework of three Key Science Programmes for AGN imaging.





Key Space Programs on AGN imaging

- Structure of compact jets in strong AGN (*AGN-S*)

  M. Perucho, A.P. Lobanov, T. Savolainen, T.B. Muxlow, I. Agudo, J.M. Anderson, U. Bach, R. Beswick, R. Davis, P. Edwards, J.A. Eilek, C.M. Fromm, S.T. Garrington, J.L. Gómez, P.E. Hardee, Y.Y. Kovalev, T.P. Krichbaum, S.-S. Lee, J.M.Martí, D.L.Meier, P. Mimica, E. Ros, F. Schinzel, K. Sokolovsky, L. Vega, P. Wilkinson, J.A. Zensus

– internal structure and spectral evolution of jets on sub-pc to pc scales

- Nearby AGN at scales of 5—500 gravitational radii (*AGN-N*)

  T. Savolainen, G. Giovannini, K. Hada, S. Tingay, T.P. Krichbaum, A. Lobanov, M. Orienti, J.M. Anderson, U. Bach, B. Boccardi, C. Casadio P. Edwards, J. Eilek, C.M. Fromm, M. Giroletti, P. Hardee, Y. Hagiwara, M. Honma, M. Kino, Y.Y. Kovalev, S.-S. Lee, D.L. Meier, H. Nagai, S.P. O'Sullivan, C. Reynolds, F. Schinzel, B.W. Sohn, K.V. Sokolovsky, J.A. Zensus

– physics of jets at smallest linear scales

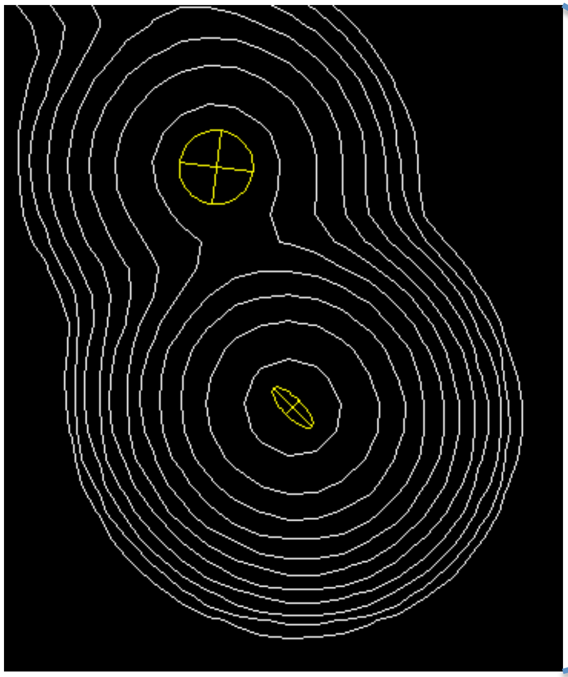
- Polarization and magnetic fields in compact jets (*AGN-P*)

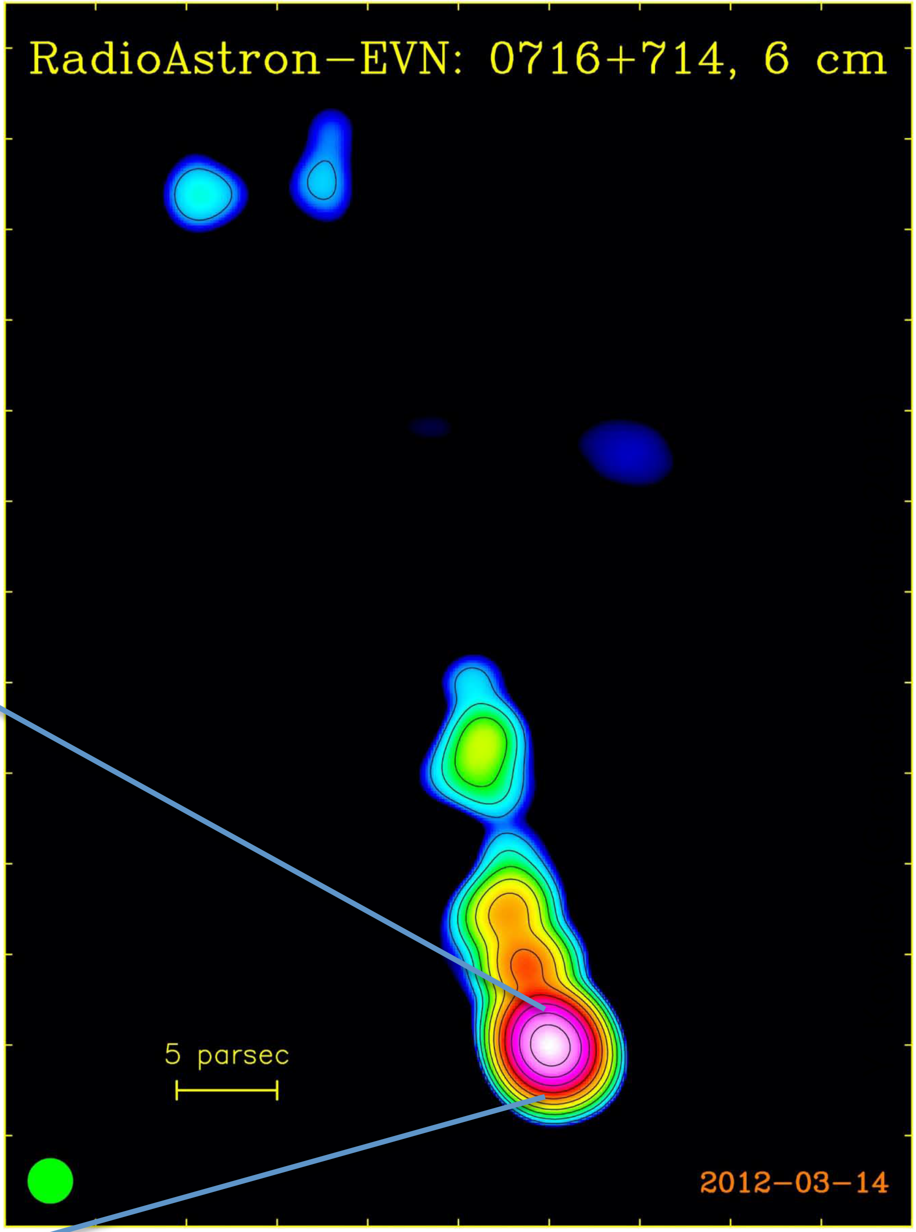
  J. L. Gómez, A. P. Lobanov, I. Agudo, A. Alberdi, J. M. Anderson, U. Bach, M. Bell, S. Bernhart, C. Casadio, T. V. Cawthorne, E. Clausen-Brown, J. Eilek, C. Fromm, D. Homan, S. G. Jorstad, M. Keck, Y. Y. Kovalev, T. P. Krichbaum, S. S. Lee, A. P. Marscher, J. M. Mart, S. Molina, K.-I. Nishikawa, M. A. Perez Torres, M. Perucho, E. Ros, T. Savolainen, B. W. Sohn, K. V. Sokolovsky, G. B. Taylor, J. A. Zensus

– magnetic fields in jets and in extreme vicinity of SMBH

RadioAstron first science

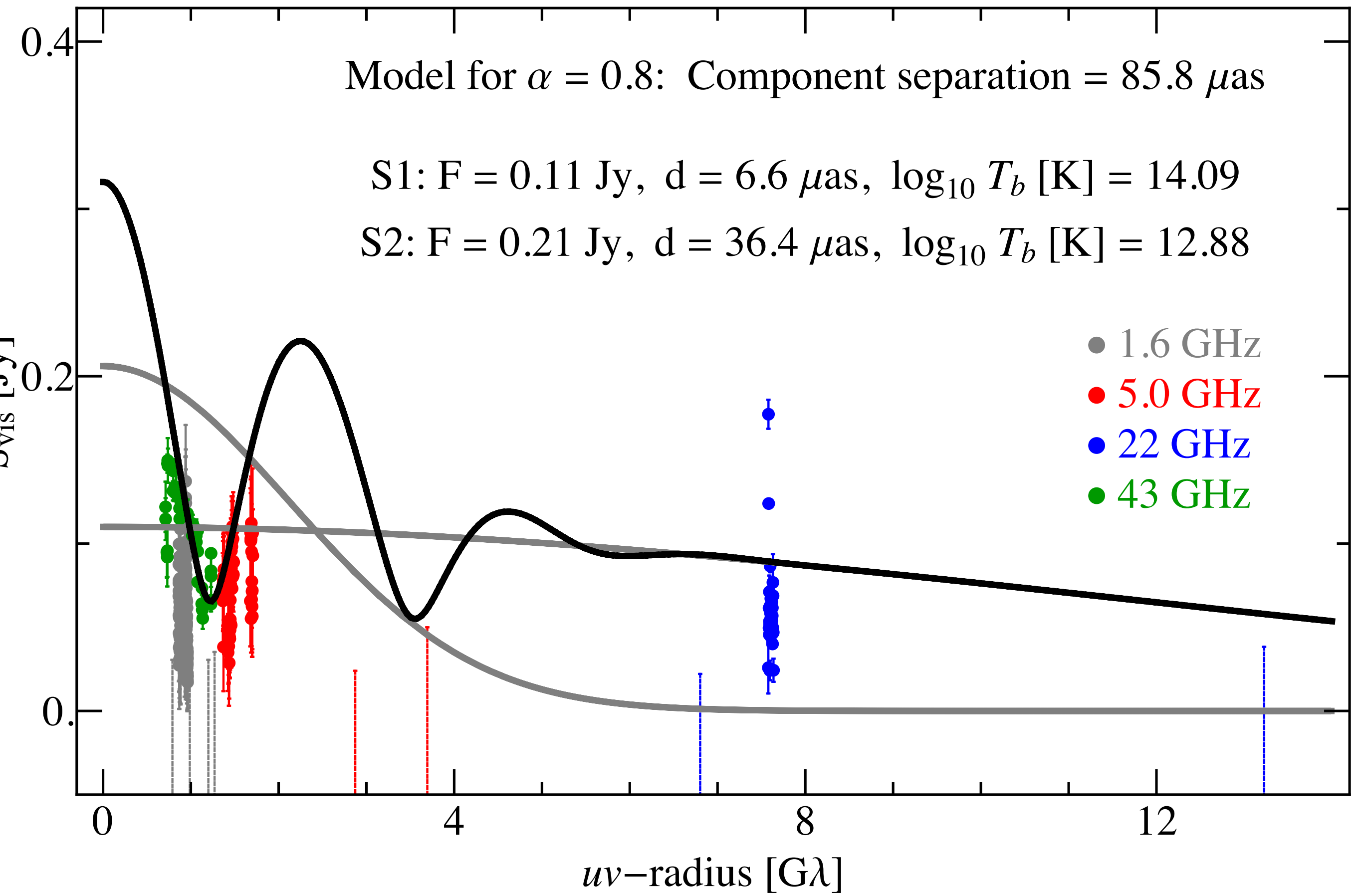
- Jet base of 0.3 pc (70μas at z=0.3)
- T_b~3×10^{12} K





3C 273 with RadioAstron: extreme brightness temperature

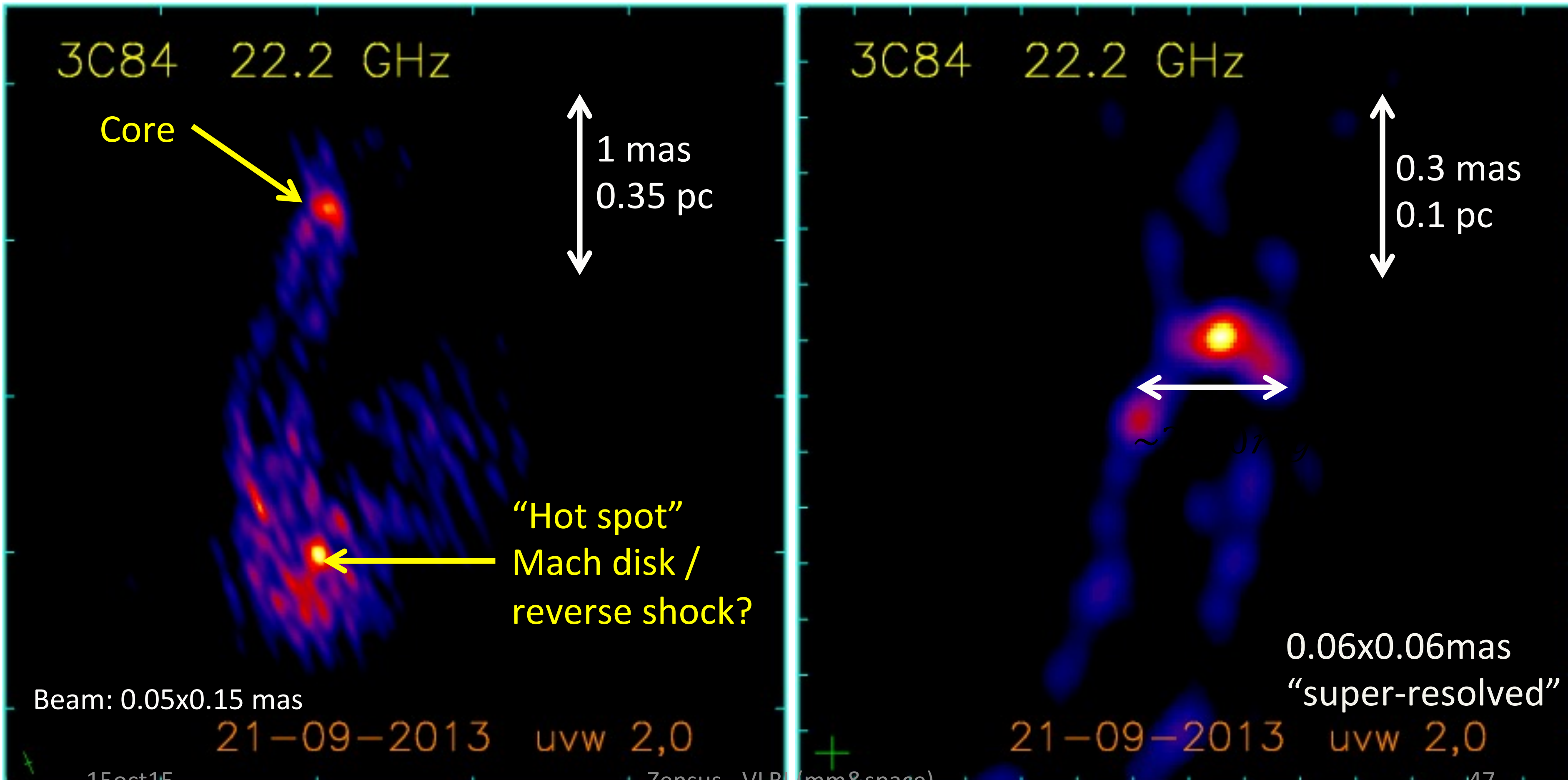
Kovalev et al., in preparation



Two-component Gaussian model fit for the 3C 273 visibility
Best fit for a spectral index of 0.8

Approaching the event horizon

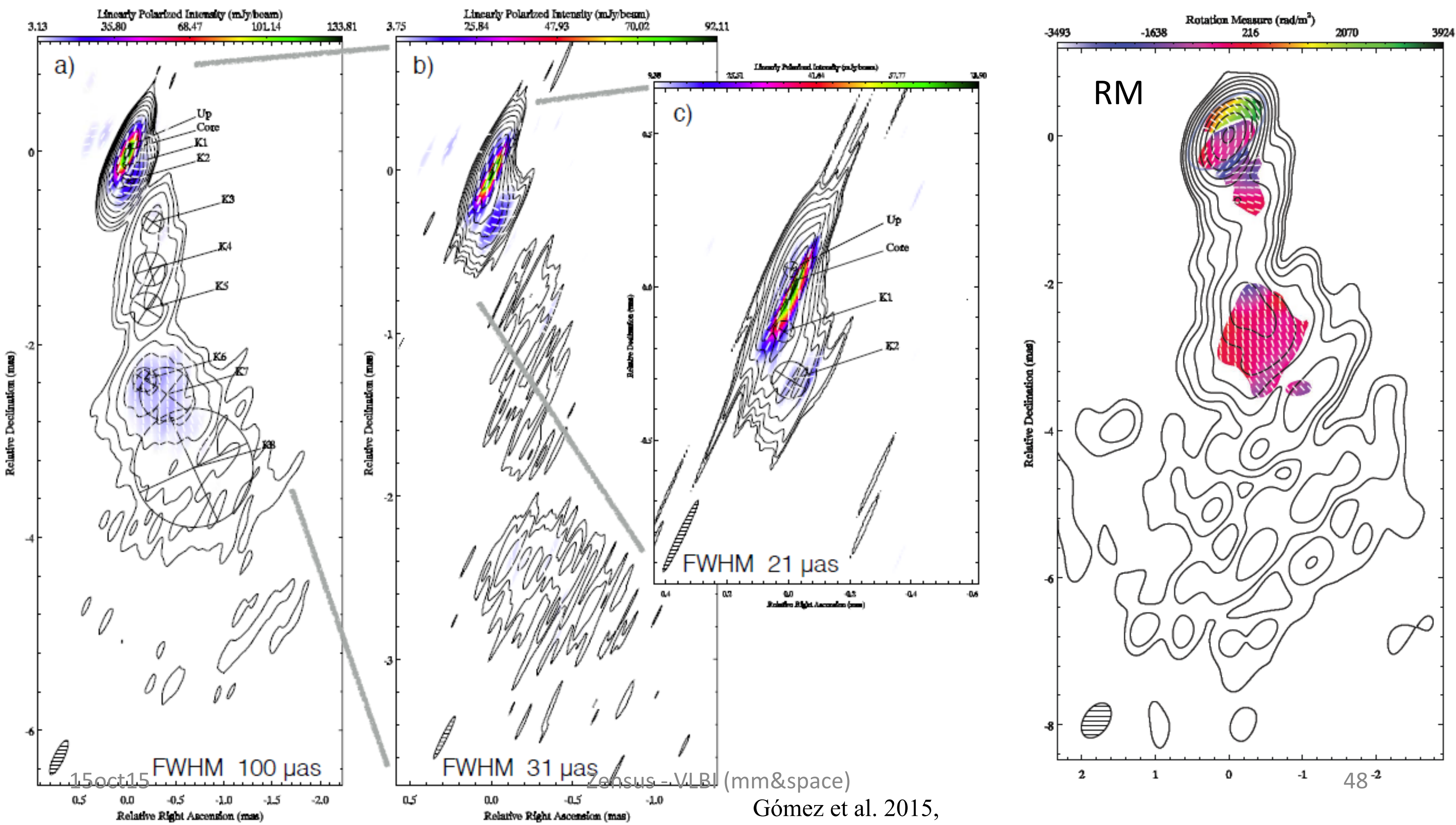
- RA imaging of 3C84 at a ~100 R_g resolution. The most detailed image of a jet base



Giovannini et al. 2015, Savolainen et al. 2015

AGN Polarisation

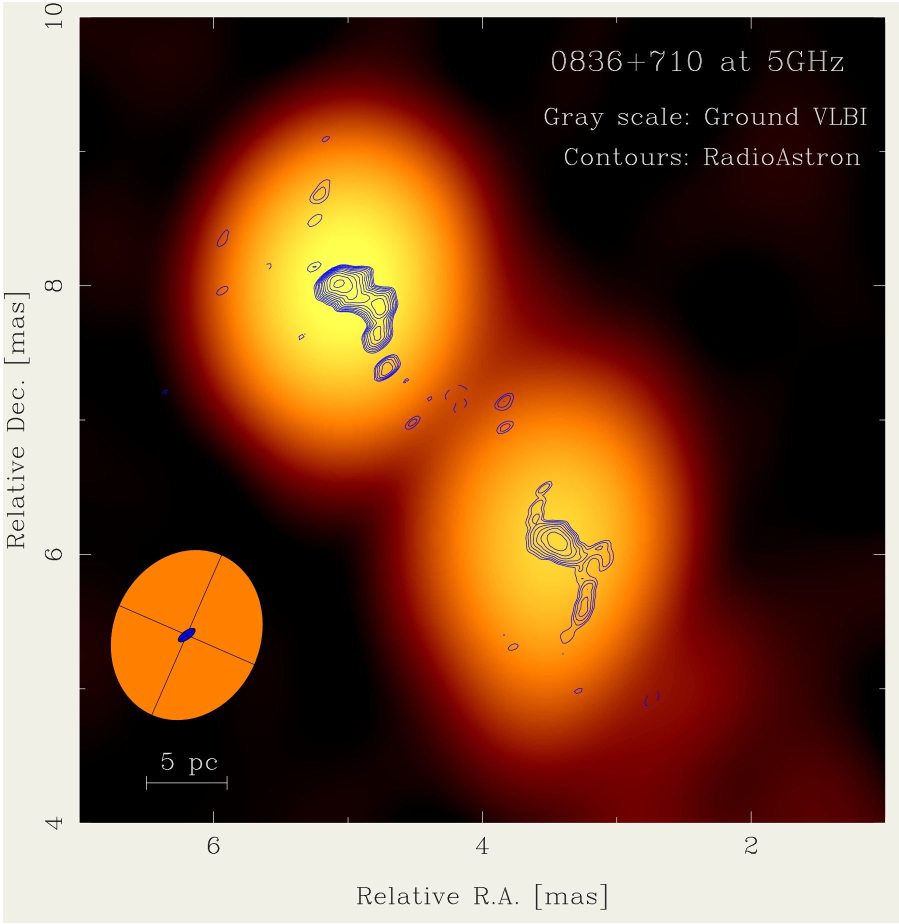
- Polarization images of BL Lac at 22 GHz: a detailed view of magnetic field in the inner jet. Can be explained with the turbulent cell model.

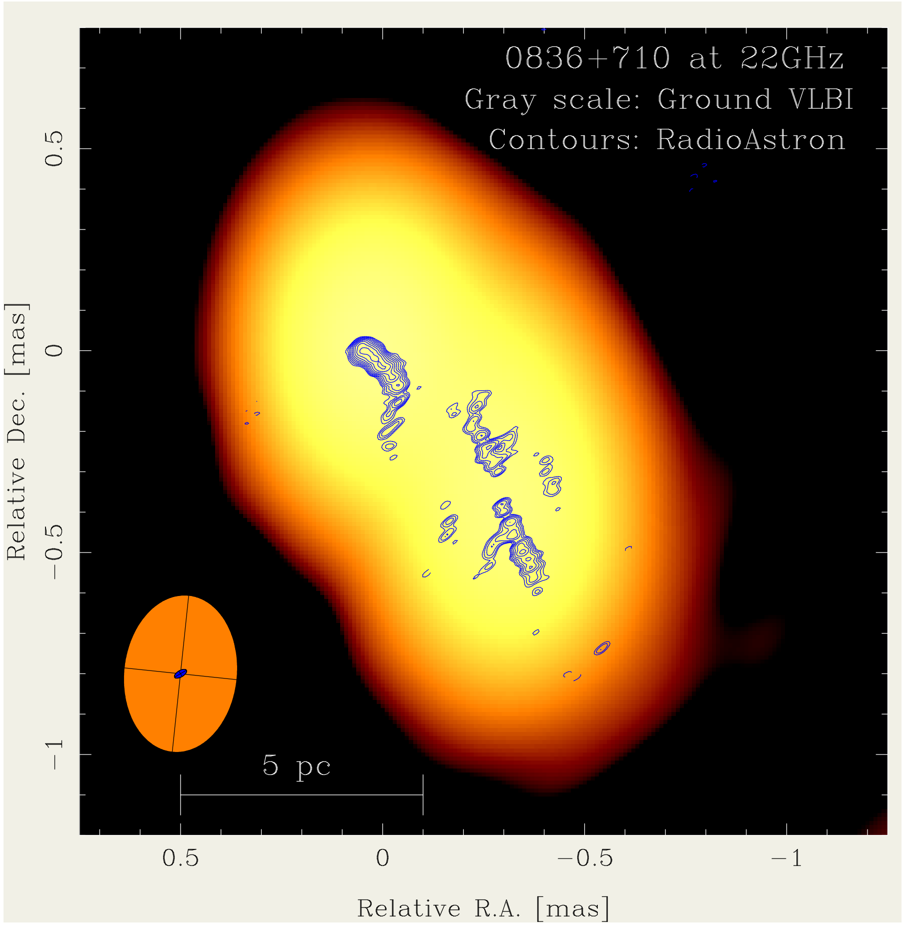


Gómez et al. 2015,

B0836+710

Vega-García et al. (in prep.)





Resolution improvements by factors 7 to 10.

Wealth of structural information.

BL Lac Polarisation

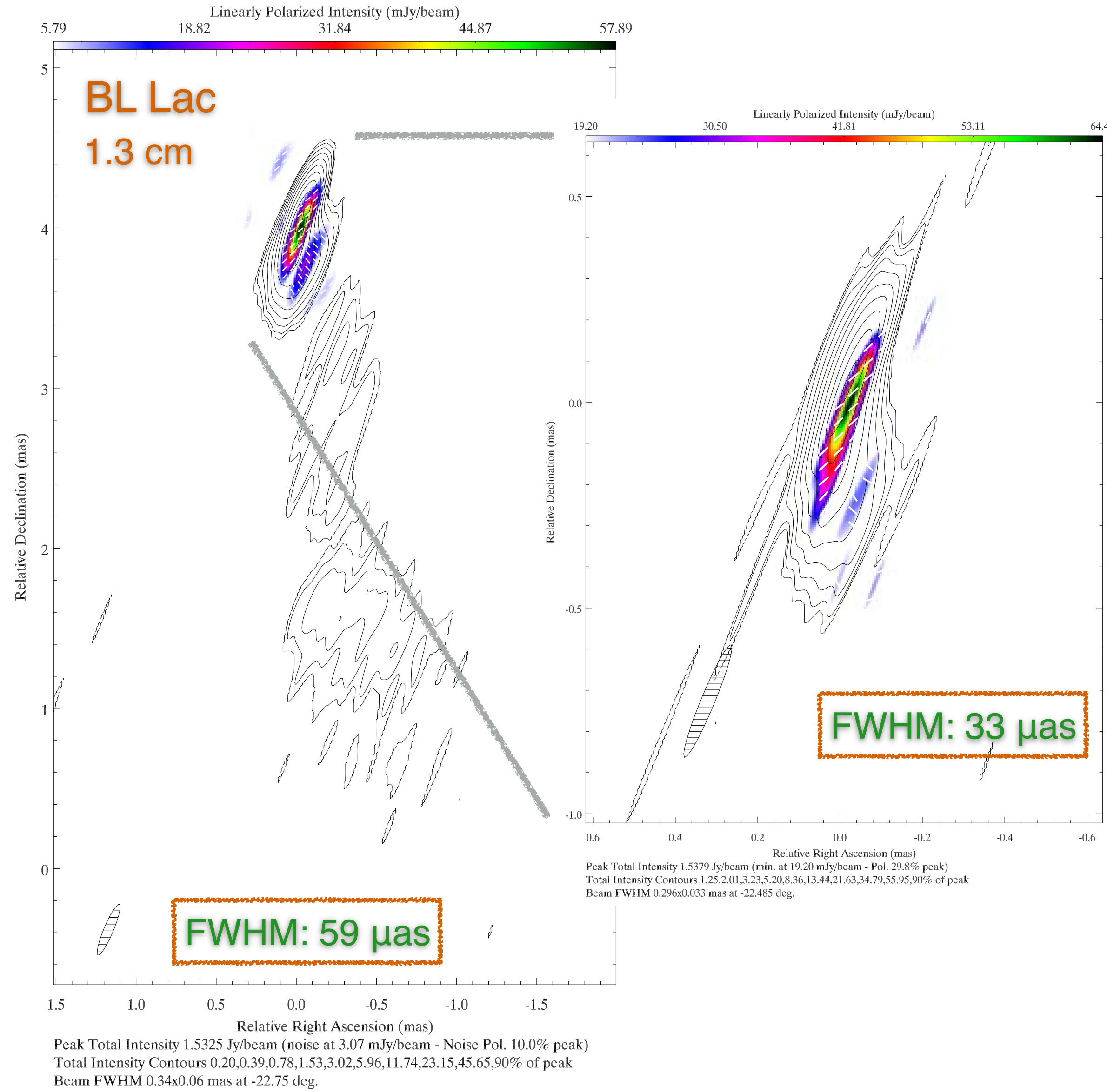
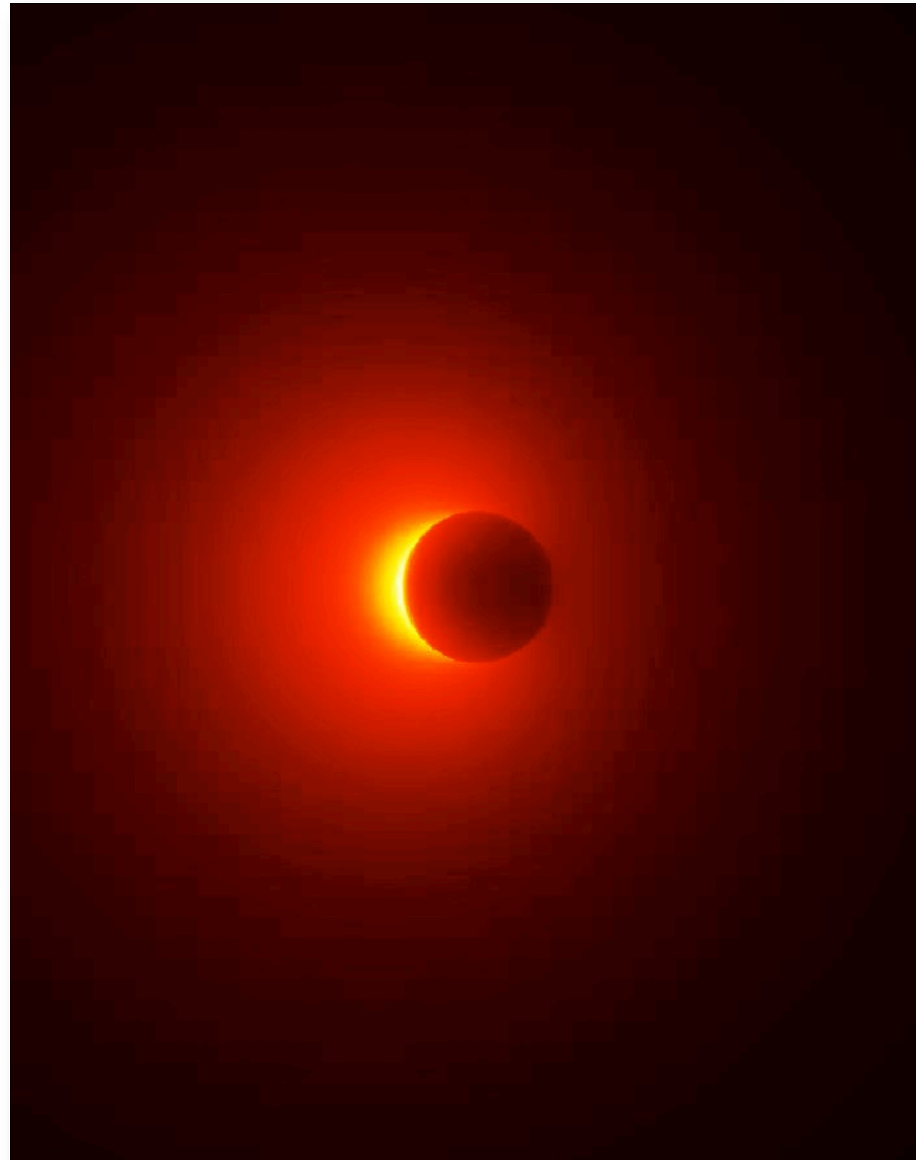


Figure 2: RadioAstron images of BL Lac at 1.3 cm obtained in November 11, 2013. Total intensity is shown in contours, linearly polarized intensity in color scale, and white bars indicate the electric vector position angle. Inset panel shows the highest angular resolution image, with FWHM of 33 μas, obtained using a "super" uniform weighting for the correlated visibilities.

Summary

- Neighbourhood of Black Holes can only be probed by radio interferometry (VLBI)
- RadioAstron: Space VLBI beating all resolution records
- mm-VLBI: Possibility of imaging the shadow of the black hole in the Galactic Centre very soon!



- www3.mpifr-bonn.mpg.de/div/vlbi/globalmm/ google: “gmva vlbi”

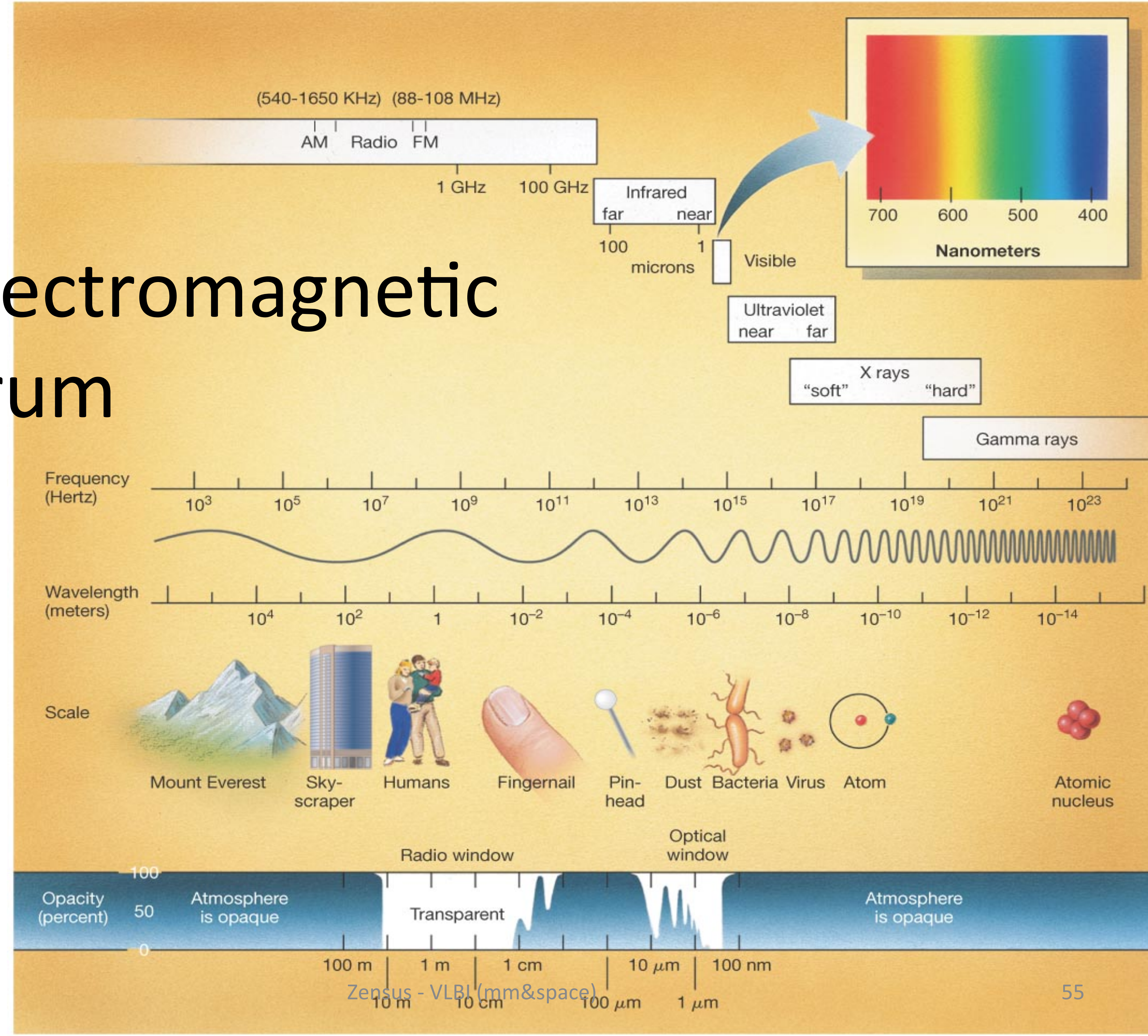
- evlbi.org

- imprs.mpifr.de

DHAN’YAVĀDA !
THANKS !

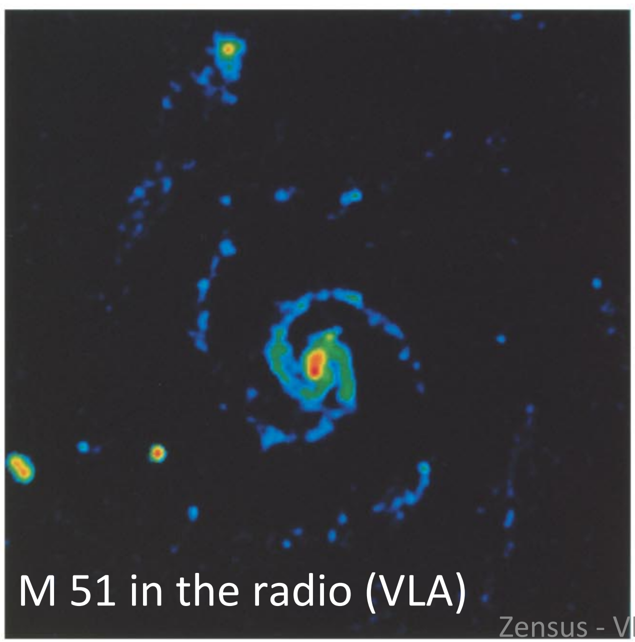
ADDITIONAL MATERIAL

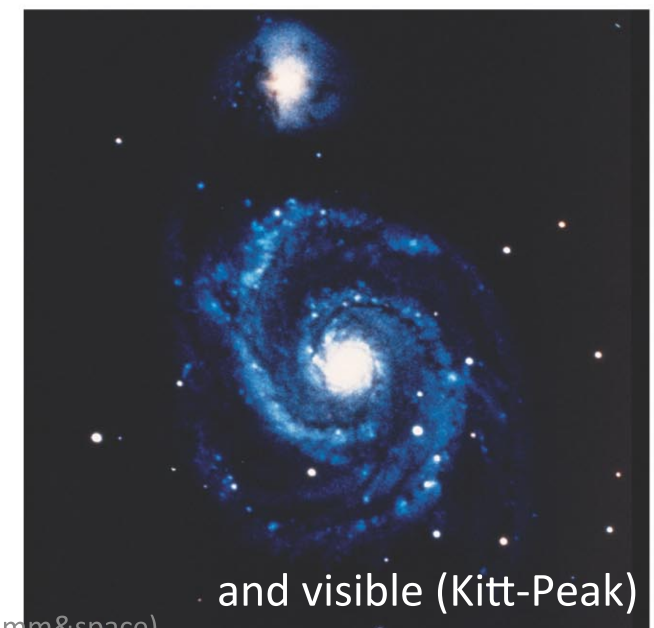
The electromagnetic spectrum



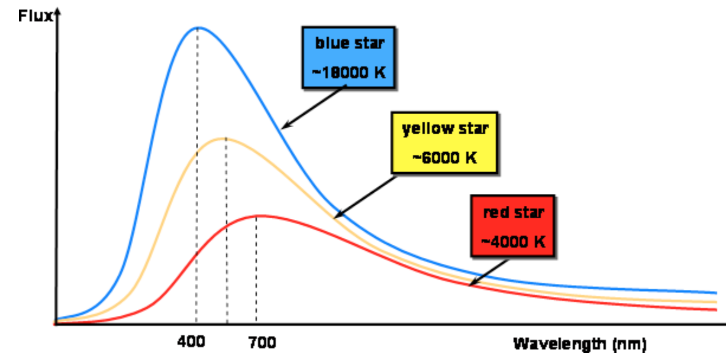
Radio astronomy: observing a ‘parallel universe’

- Longer wavelengths (low resolution)
- 24 hr a day
- Clouds, rain or snow do not interfere
- Sky has “another colour”


M 51 in the radio (VLA)


and visible (Kitt-Peak)

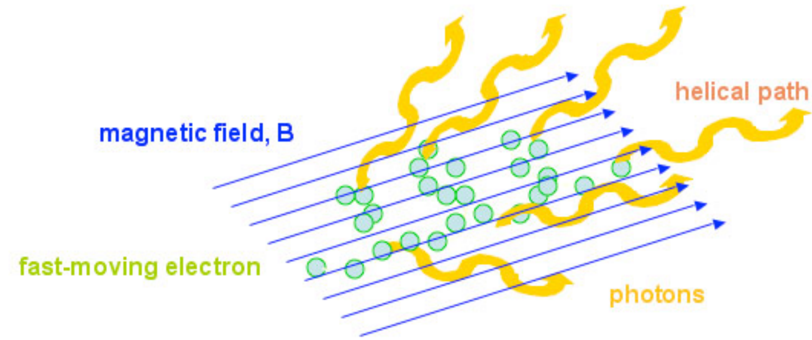
Radio emission



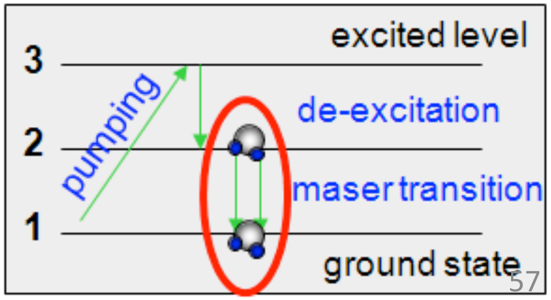
- Thermal radiation (blackbody)

$$E_\lambda = \frac{8\pi hc}{\lambda^5 (e^{(hc/\lambda kT)} - 1)}; P = A\sigma T^4$$

- Synchrotron radiation



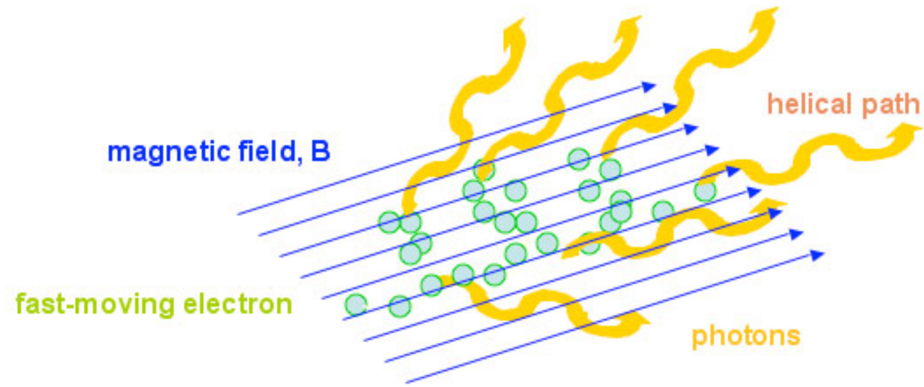
- Bremsstrahlung (aka free-free) emission
  – Radiation given away by a charged particle due to its acceleration caused by another charged particle
- Maser emission
  – Spectral-line emission

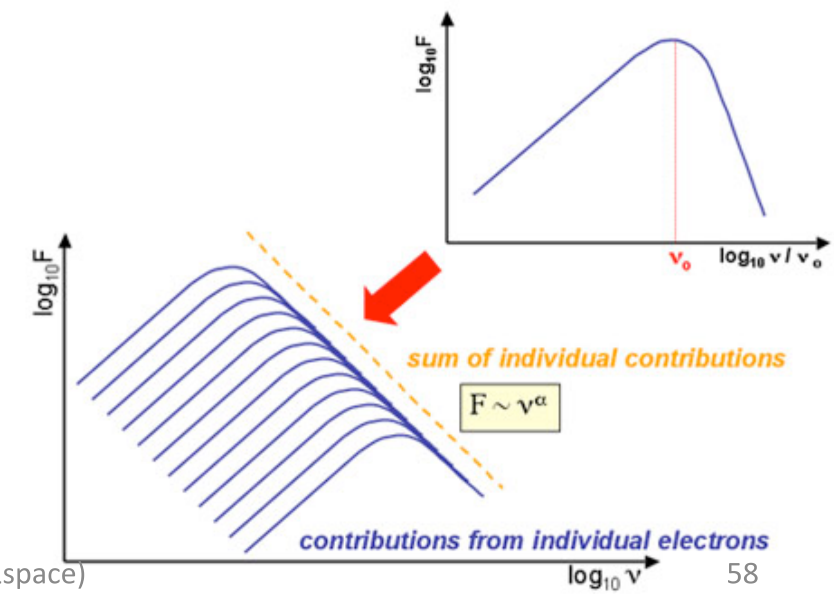


Source: http://astronomy.swinburne.edu.au

Synchrotron radiation

- Non-thermal emission generated by charged particles spiralling around magnetic field lines at close to the speed of light
- Radiation peaks at a critical frequency ν_0, different contributions add to a spectrum with spectral index α

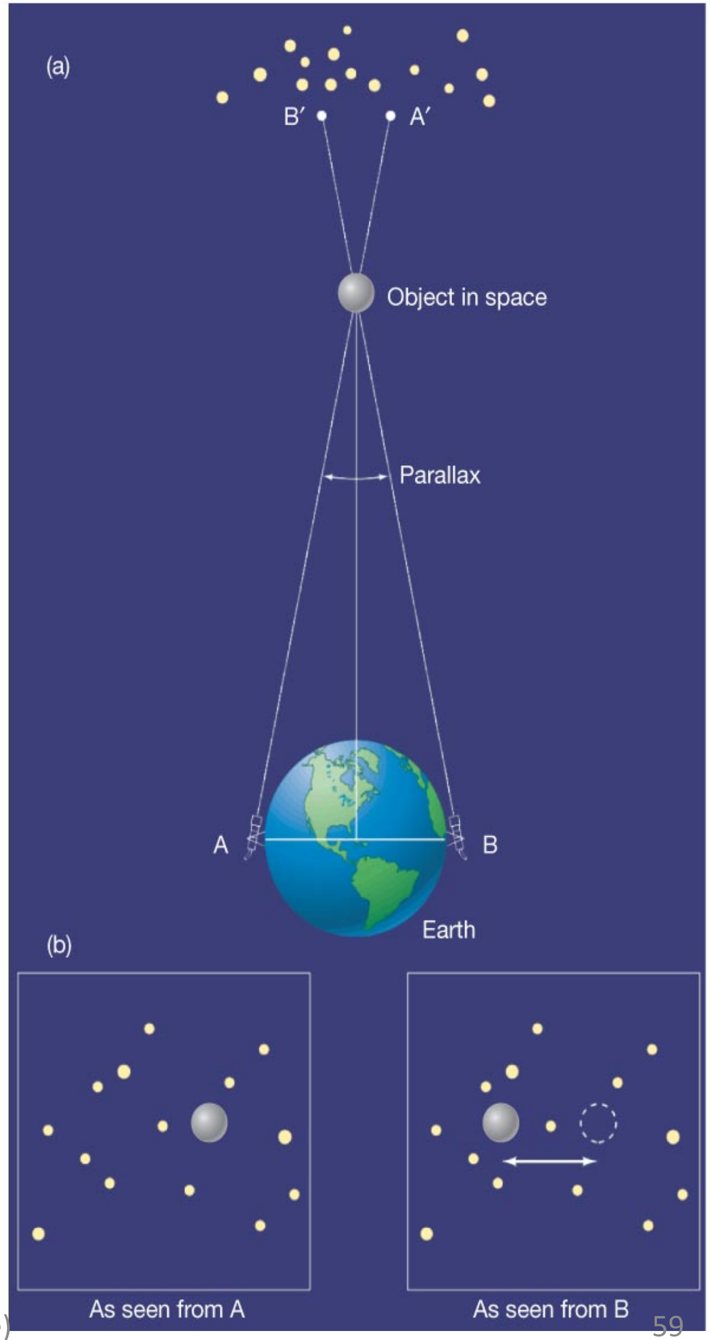




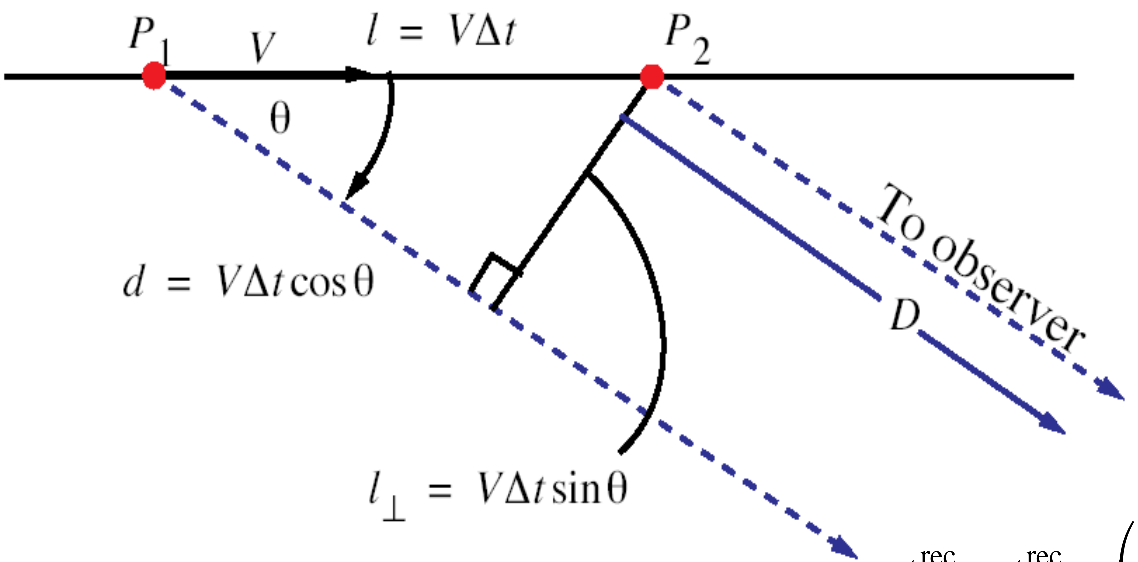
Source: http://astronomy.swin.edu.au/cosmos/S/Synchrotron+Emission

Parallax

Parallax is a way of "triangulation", using the earth size or even better, its motion around the Sun



Superluminal motions (i)



$$t_2^{\mathrm{rec}} - t_1^{\mathrm{rec}} = \left(t_2 + \frac{D}{c}\right) - \left(t_1 + \frac{D + V\Delta t\cos\theta}{c}\right)$$

$$= (t_2 - t_1) - \frac{V}{c}\cos\theta$$

$$= \Delta t\left(1 - \frac{V}{c}\cos\theta\right)$$

- Time elapsed since photon arrival
- Apparent distance traveled by the object, VΔt sinθ

Superluminal motions (ii)

- Distance traveled by an object:

$$l_{\perp} = V\Delta t \sin\theta$$

- Apparent speed:

$$V_{\text{app}} = \frac{V\Delta t \sin\theta}{\Delta t\left(1 - \frac{V}{c}\cos\theta\right)} = \frac{V\sin\theta}{\left(1 - \frac{V}{c}\cos\theta\right)}$$

$$\beta_{\text{app}} = \frac{V_{\text{app}}}{c} = \frac{\frac{V}{c}\sin\theta}{\left(1 - \frac{V}{c}\cos\theta\right)} = \frac{\beta\sin\theta}{1 - \beta\cos\theta}$$

Superluminal motions (iii)

- Speed is maximised for the angle

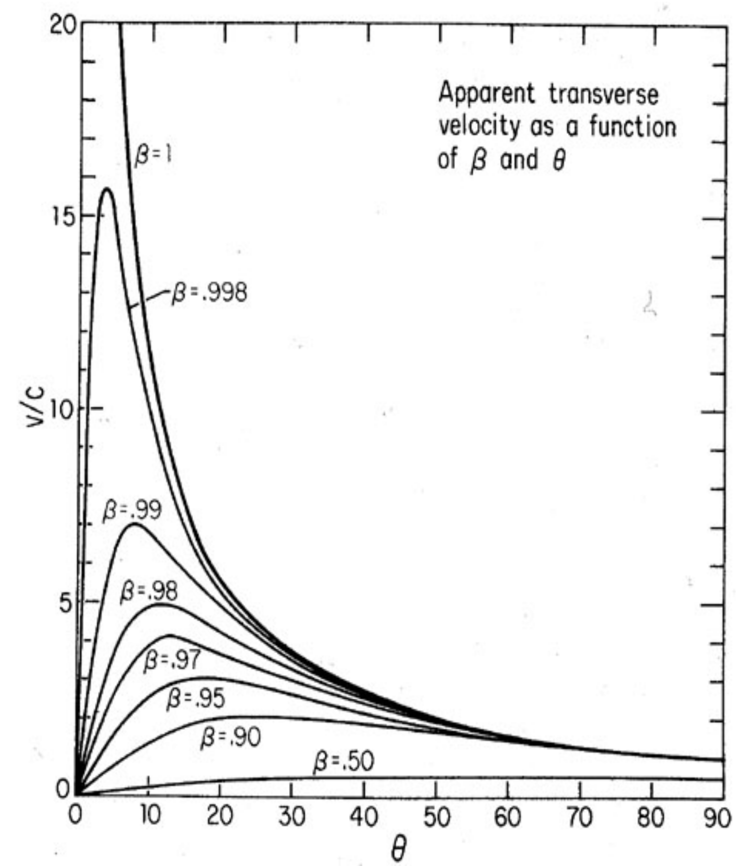
$$\frac{d\beta_{\rm app}}{d\theta} = \frac{(1-\beta\cos\theta)\beta\cos\theta - \beta\sin\theta\beta\sin\theta}{\left(1-\beta\cos\theta\right)^2} = \frac{\beta\cos\theta - \beta^2}{\left(1-\beta\cos\theta\right)^2}$$

- Derivative is zero for $\cos\theta = \beta$
- At the maximum,

$$\beta_{\rm app} = \frac{\beta\sin\theta}{1-\beta\cos\theta} = \frac{\beta\sqrt{1-\beta^2}}{1-\beta^2} = \frac{\beta}{\sqrt{1-\beta^2}} = \gamma\beta$$

Apparent superluminal motion

- β_{app}=f(β,θ), especially for β~1
- V_{app}>c if γ>3 !!
- Maximum:
  - – $\cos\theta_{max}=\beta$
  - – $\beta_{app,max}=\beta\gamma$



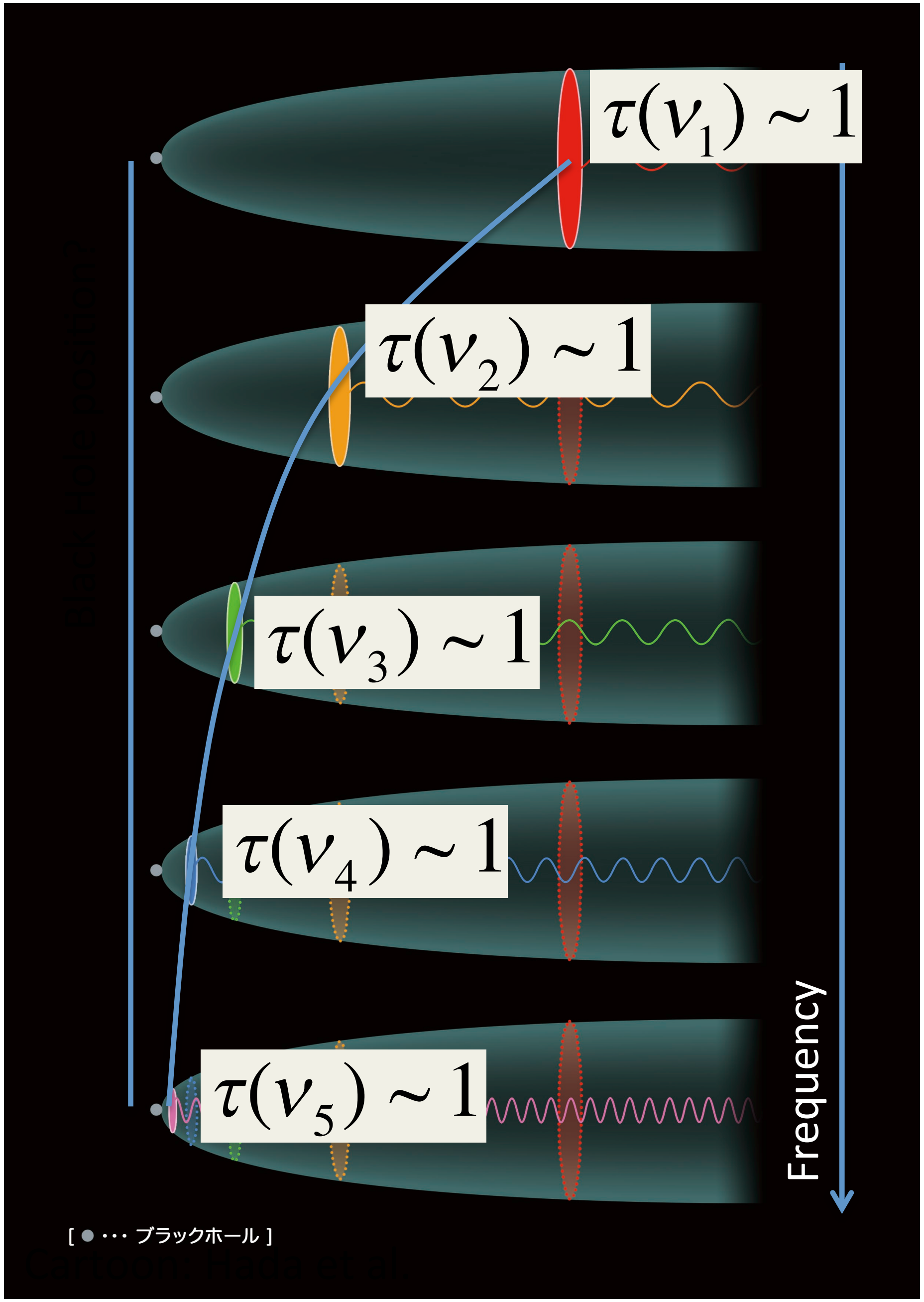
Core-shift

- Location as function of frequency

$$r_{\mathrm{core}}(\tau_{\nu,\mathrm{SSA}}) \propto \nu^{-1/k_r}$$

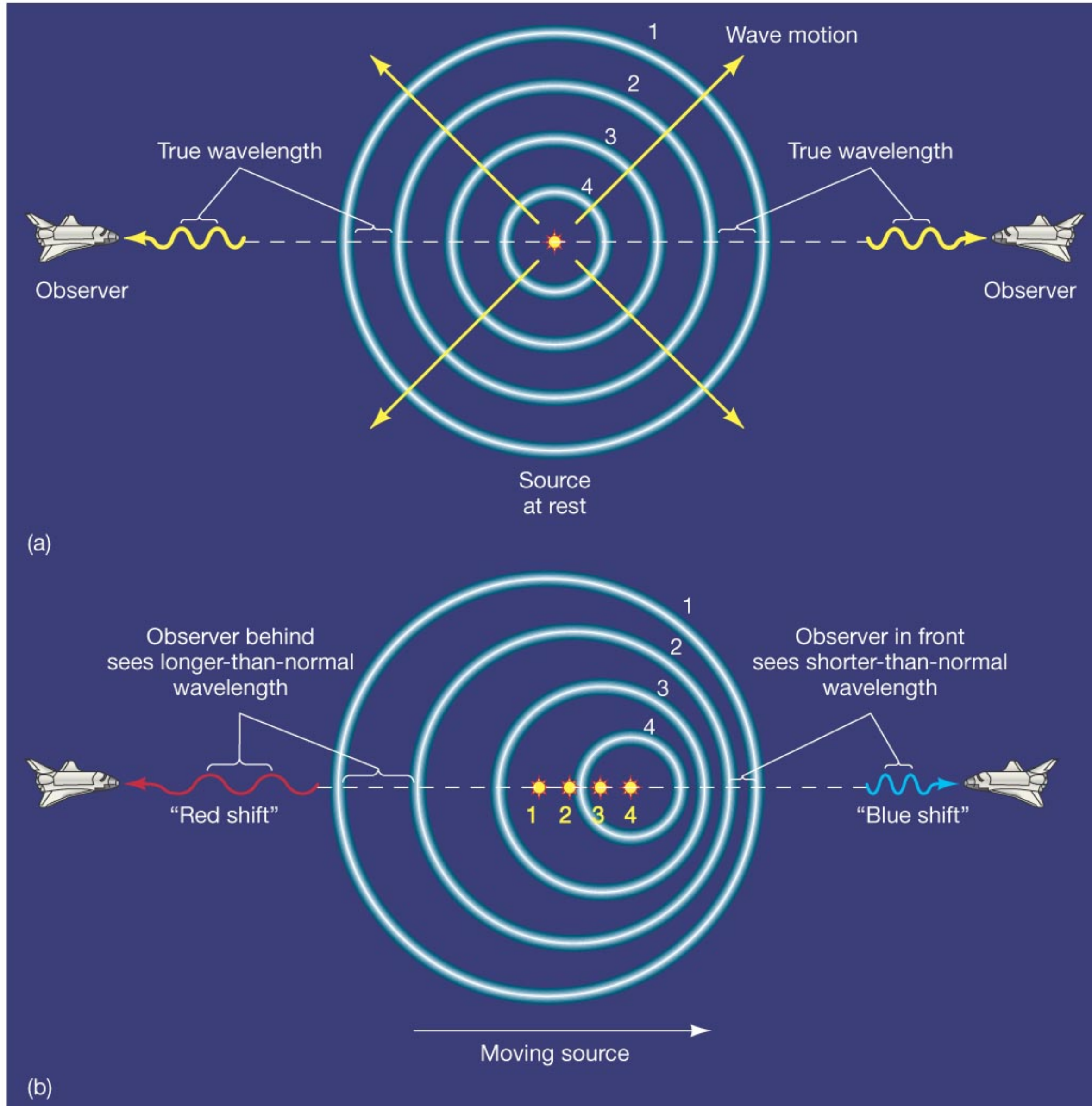
  – k_r~1 (Lobanov 1998)

- Determination of physical properties in jet and environment



Doppler factor & redshift

- Observed avelength depends from relative motion to the viewer



Ingredients of the radio sky

- Galactic continuum radiation
  - Magnetic field and cosmic rays: synchrotron ($\alpha = -0.55$)
- Interstellar medium
  - Spectral lines: Neutral H (HI) at λ21 cm, ionized H (HII), rotational and vibrational lines for another molecules (O_2, N_2, CH_4, CO_2, etc.)
  - Supernova remnants: synchrotron
- Stars
  - Circumstellar masers (SiO, H_2O, OH)
  - Novae
  - Binaries and flare stars (recurrent novae, X-ray binaries): non-thermal
- Pulsars
  - Neutron stars emitting coherent radiation with $\alpha = -2 \pm 1$
- Radio galaxies and quasars
  - Radio galaxy lobes: synchrotron
  - AGN cores: synchrotron, flat spectrum (parts self-absorbed)
- Cosmic microwave background
  - Thermal radiation from the Big Bang

Eddington Luminosity

- To be stable under radiation pressure, any object with mass *M* cannot have a luminosity larger than

$$L_{\rm Edd} \equiv \frac{4\pi GMc}{\kappa_{\rm es}} = 1.25 \times 10^{38} {\rm erg\ s^{-1}} \left(\frac{M}{M_{\rm Sun}} \right)$$

  - Where κ_{es} is the opacity of ionized matter to electron scattering
- Any object with a luminosity *L* and BH mass of $M_\bullet$ has a minimum mass of:

$$M_{\rm min} = (L / L_{\rm Edd}) M_\bullet$$

Accretion onto SMBH

- For very massive objects we can write:

$$\dot{M}_{\mathrm{Edd}} = 22.0 M_{\mathrm{Sun}} \mathrm{yr}^{-1} \left(\frac{\varepsilon_{\mathrm{acc}}}{0.1} \right)^{-1} \left(\frac{M}{10^9 M_{\mathrm{Sun}}} \right)$$

- For $\dot{M} \leq \dot{M}_{\mathrm{Edd}}$ the accretion luminosity is smaller than the Eddington one
- For $\dot{M} > \dot{M}_{\mathrm{Edd}}$ not all matter accreting toward the BH will arrive there, due to radiation pressure, and may be blown out as wind or outflow

The Blandford-Znajek mechanism

- Extraction of energy from a rotating BH with a large accretion disk and strong magnetic fields
- May explain how to power QSOs
- Power is estimated as the energy density at the speed of light cylinder times the area (*B* magnetic field, r_c speed of light radius, ω angular speed)

$$P = B^2 \left(\frac{r}{r_c} \right)^4 r_c c = \frac{B^2 r^4 \omega^2}{c}$$

Blandford & Znajek, MNRAS 179, 433 (1977)

What is the innermost jet?

- The core is not the ‘base’ of the jet
  - The spectral turnover ν_m would be at IR or optical
- Region of the jet where τ~1 (Blandford & Königl 1979; Königl 1981) ?
  - The observed core position shifts towards the central engine at high frequencies (Lobanov 1998)
- ⦿ A recollimation shock (Daly & Marscher 1998; Gómez et al. 1995; Perucho 2009) with particle acceleration and field compression
  - A conical jet can have a series of recollimation shocks where the first one at $\nu=\nu_m$ is the ‘core’
- Alternatively: first beamed feature of a curved stream

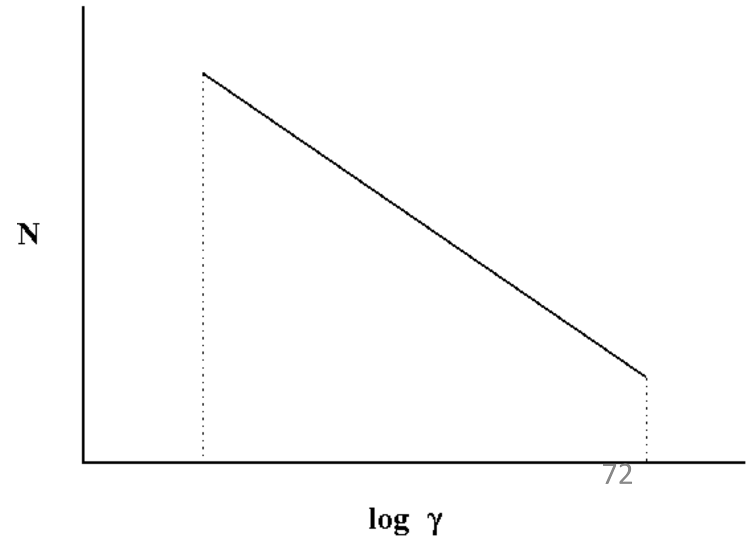
Further down the jet: re-collimation shocks

- The jet interacts with the environment
  - Cocoon & cavity formation (Scheuer 1974)
  - Self-collimation by cocoon pressure (Falle 1998, Komissarov & Falle 1998)
- In a jet, when the sideways pressure equals the ambient pressure, recollimation happens
  - Daly & Marscher (1988), Gómez et al. (1995), Scheck et al. (2002), Perucho & Martí (2007) study these effects

Polarisation as a Probe of Jet Physics

- Jet Structure and Composition
  - 3-D Magnetic Field Structure of Jets
    - Connection with SMBH/Accretion Disk System
  - Low energy end of particle spectrum
    - Dominates Kinetic Luminosity of Jets:
    - Important for constraining particle accel. mechanisms
  - Particle Composition of Jets
    - Electron-Proton? Electron-Positron?

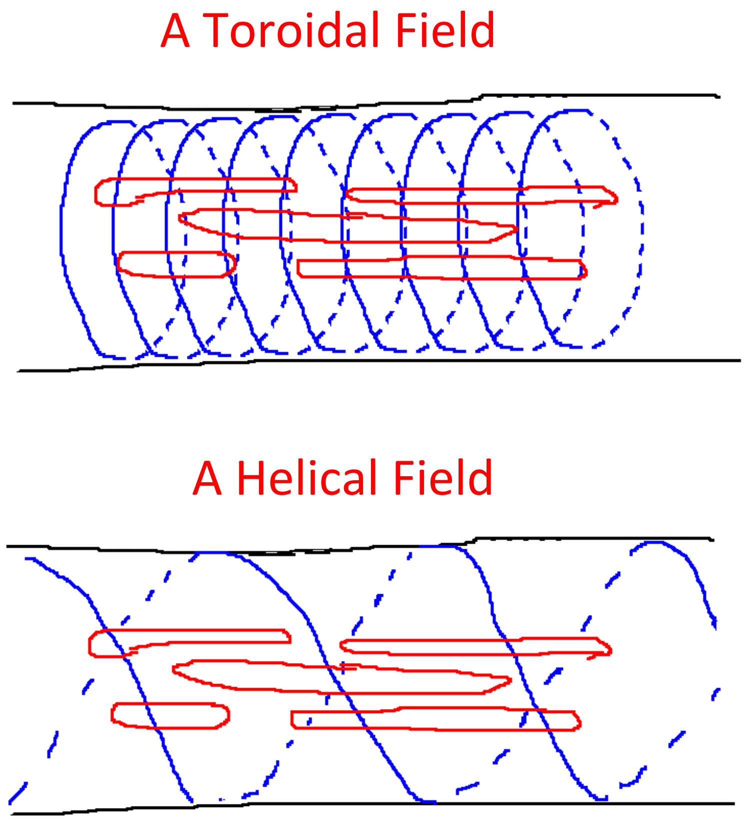
$$N_{total} \propto 1/\gamma_{\min}^{2\alpha}$$



Polarisation as a Probe of Jet Physics

- Magneto-Hydrodynamics of Jets
  - Field signatures of Oblique Shocks
  - Time evolution of Field Structures
    - Compared to simulations
  - Dependence on Optical Class
- Jet Environment
  - Jet Polarization as "Backlighting"
  - Nature of Faraday Screen on Parsec Scales
    - Scale Height
    - Relation to Jet Magnetic Field
    - Are we seeing Narrow Line Clouds?

Possible Field Order in Jets



Picture: D. Homan (2003)