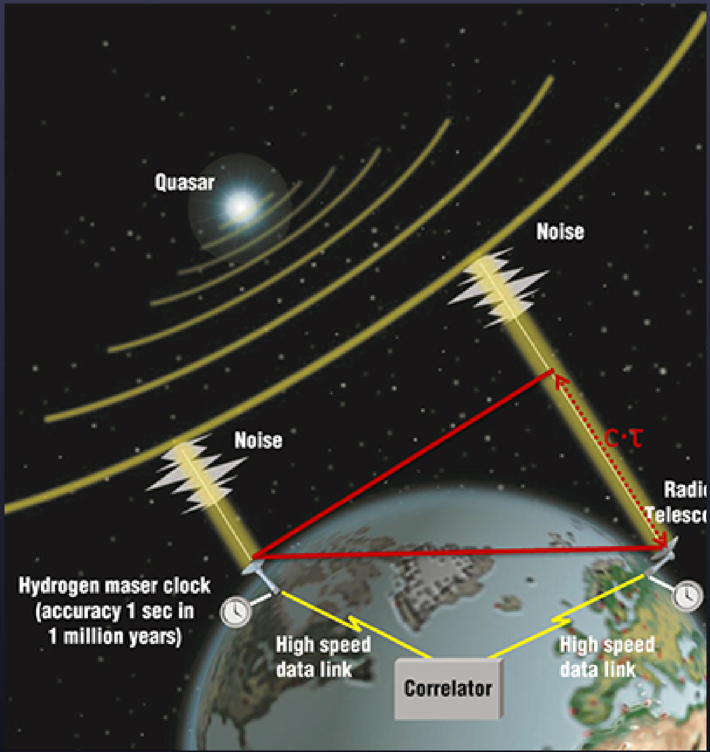
VLBI Fundamentals

Michael Bietenholz

With slides from George Moellenbroek and Craig Walker NRAO

What is VLBI?



Original image: NASA

- An interferometer made using radio telescopes that are not physically connected
- Gets you very high angular **resolution**: typical wavelength 3 cm, typical baseline 3000 km → resolution ~0.03 m/ 3×10^{6} m = 1×10^{-8} radians = 2 milli-arcseconds
- Many astronomical objects subtend small angles: e.g. our sun at 10 pc: $(7\times10^{10}$ cm$)/(10 \times 3.086 \times10^{18}$ cm$) = 2.3 \times10^{-9}$ radians = 0.47 milli-arcseconds
- VLBI comes with its own set of challenges: accurate timekeeping (to fractions of a period or typically 10s of picoseconds) is required. Accurate determination of the positions of the telescopes, to fractions of a wavelength, typically a few mm is also required.
- Data transport of large amounts of data

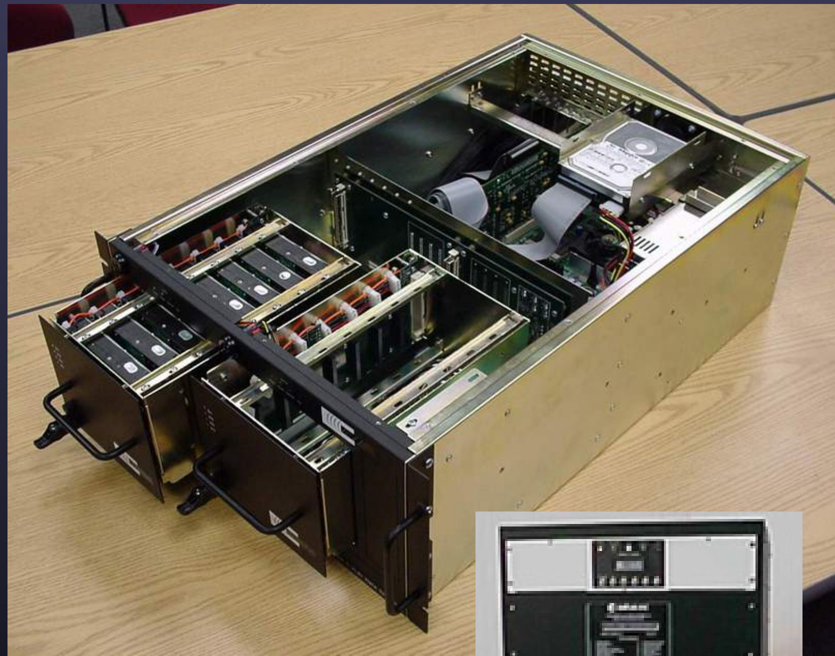
VLBI Equipment

(Dr. Colomer's will discuss VLBI networks)

VLBI antennas are not fundamentally different from other radio astronomy antennas, and indeed VLBI is not fundamentally different from other interferometers)

The differences are: at VLBI stations the data is recorded before being sent to the correlator (or possibly transferred over the internet)

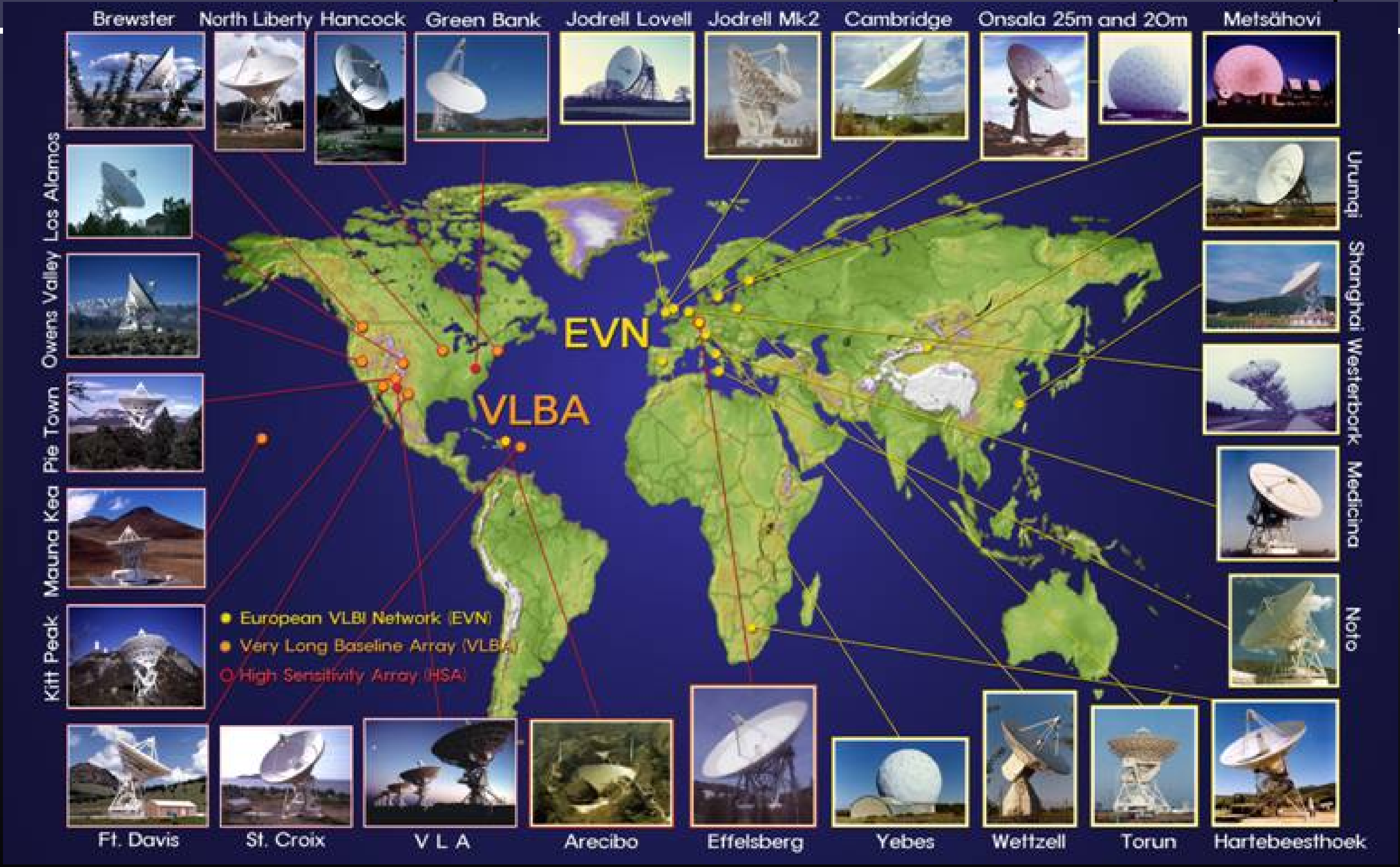
Most VLBI antennas are mostly independent instruments, often not built for the purpose of doing VLBI that spend part of their time doing VLBI
(the European VLBI Network, the Australian Long Baseline Array, the Korean VLBI Network...)



Mark V recorder and disk packs

Hydrogen Maser

The Global VLBI Array (Astronomy)



Note: outdated figure, some newer stations missing

Figure: Krichbaum, MPIfR

The Quest for Resolution

Resolution = Observing wavelength / Telescope diameter

Angular	**Optical (5000A)**		**Radio (4cm)**	
Resolution	**Diameter**	**Instrument**	**Diameter**	**Instrument**
1′	**2mm**	**Eye**	**140m**	**GBT+**
1″	**10cm**	**Amateur Telescope**	**8km**	**VLA-B**
0.″05	**2m**	**HST**	**160km**	**MERLIN**
0.″001	**100m**	**Interferometer**	**8200km**	**VLBI**

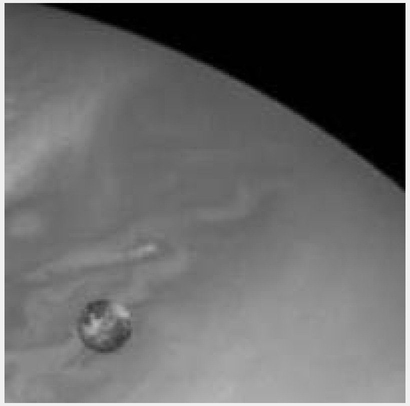
Atmosphere gives 1" limit without corrections which are easiest in radio

Jupiter and Io as seen from Earth with different resolutions

1 arcmin

1 arcsec

0.05 arcsec



0.001 arcsec

Simulated with Galileo photo

What Sources can be observed with VLBI?

Any sufficiently compact radio source can be studied with VLBI

Active Galactic Nuclei (AGN)

Masers

Supernova and (distant) supernova remnants

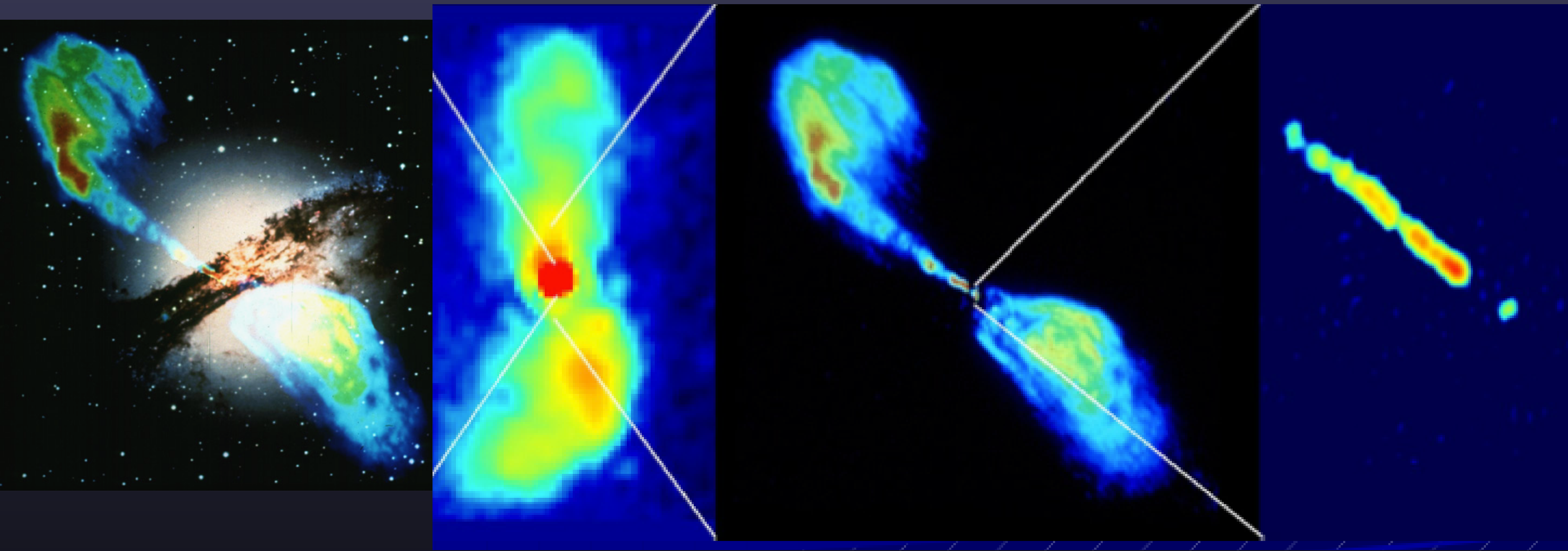
Stars (some)

Pulsars

......

Almost always non-thermal emission – VLBI only sensitive to high brightness temperatures.

Resolution: Centaurus A



Galaxy in the optical with radio (VLA overlay)

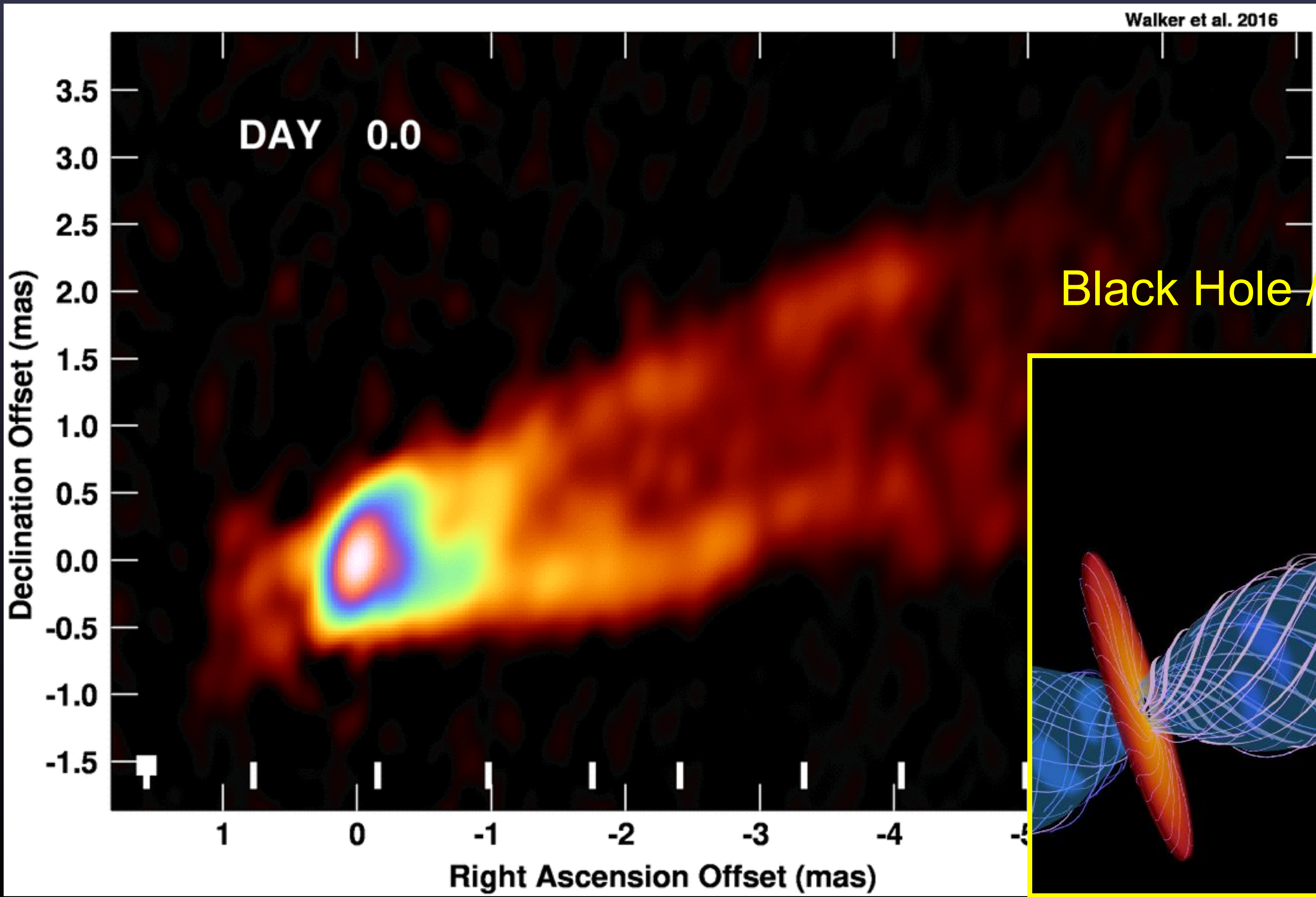
The full radio emission covers nearly 10 degrees on the sky. HartRAO 26m at 13cm, resolution of 20 arcmin

VLA radio continuum observations of the inner lobes a field of view 11 arcmin, resolution ~20 arcsec

VLBI (LBA + HartRAO) image show fine details of jet near the black hole (centre). Field of view is jet ~0.08 arcsec, resolution is ~0.003 arcsec (milliarcsec)

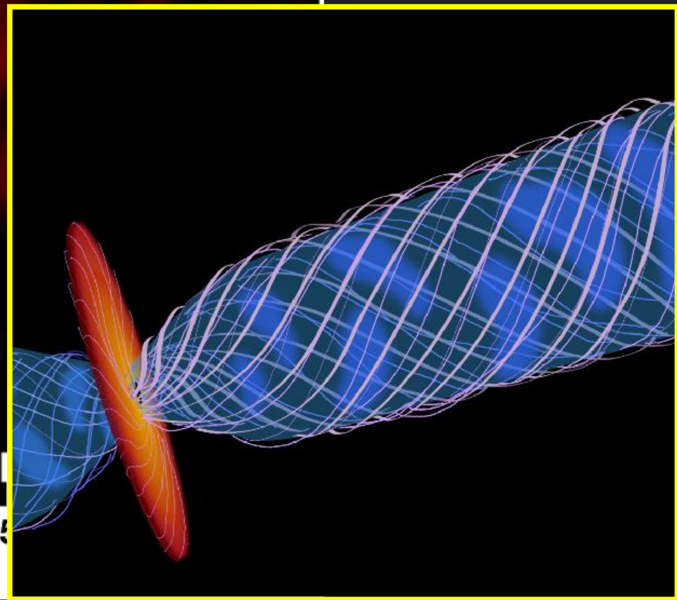
Core of Active Galactic Nucleus in M87

The inner 2 pc of M87 AGN jet (C. Walker et al.) M87 is the dominant galaxy in the Virgo cluster, at ~17 Mpc, and contains a very massive black hole



43 GHz = 7 mm

Black Hole / Jet Model



Event Horizon Telescope

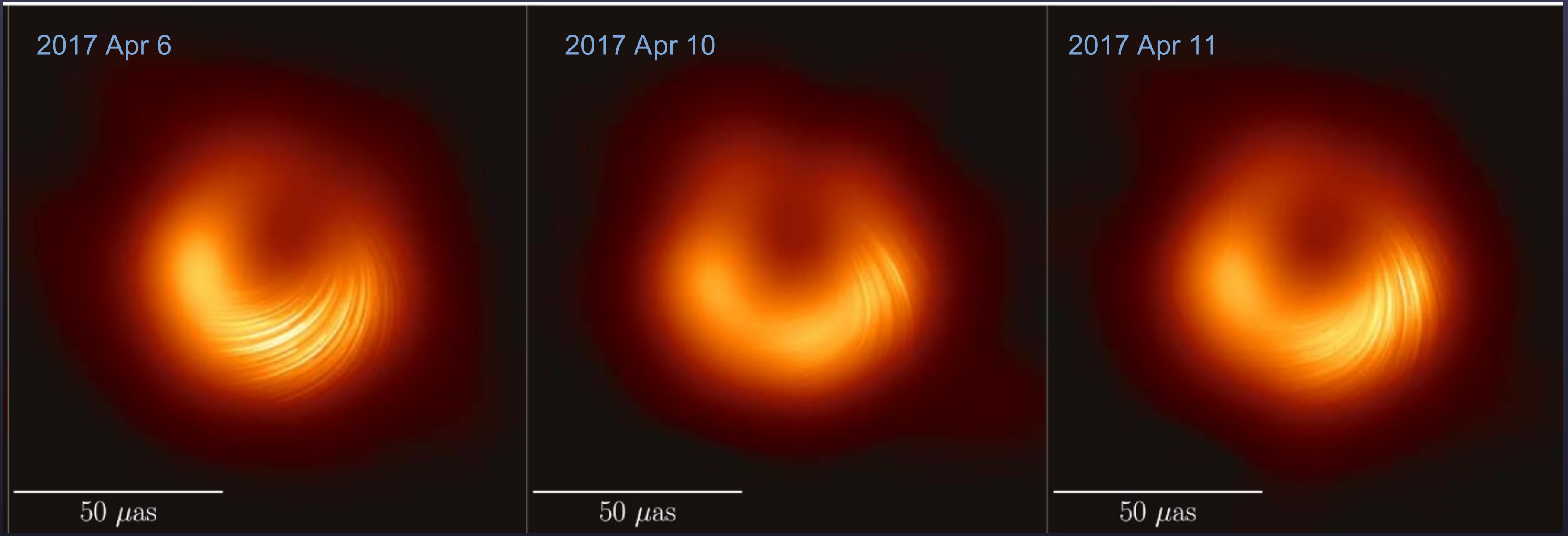
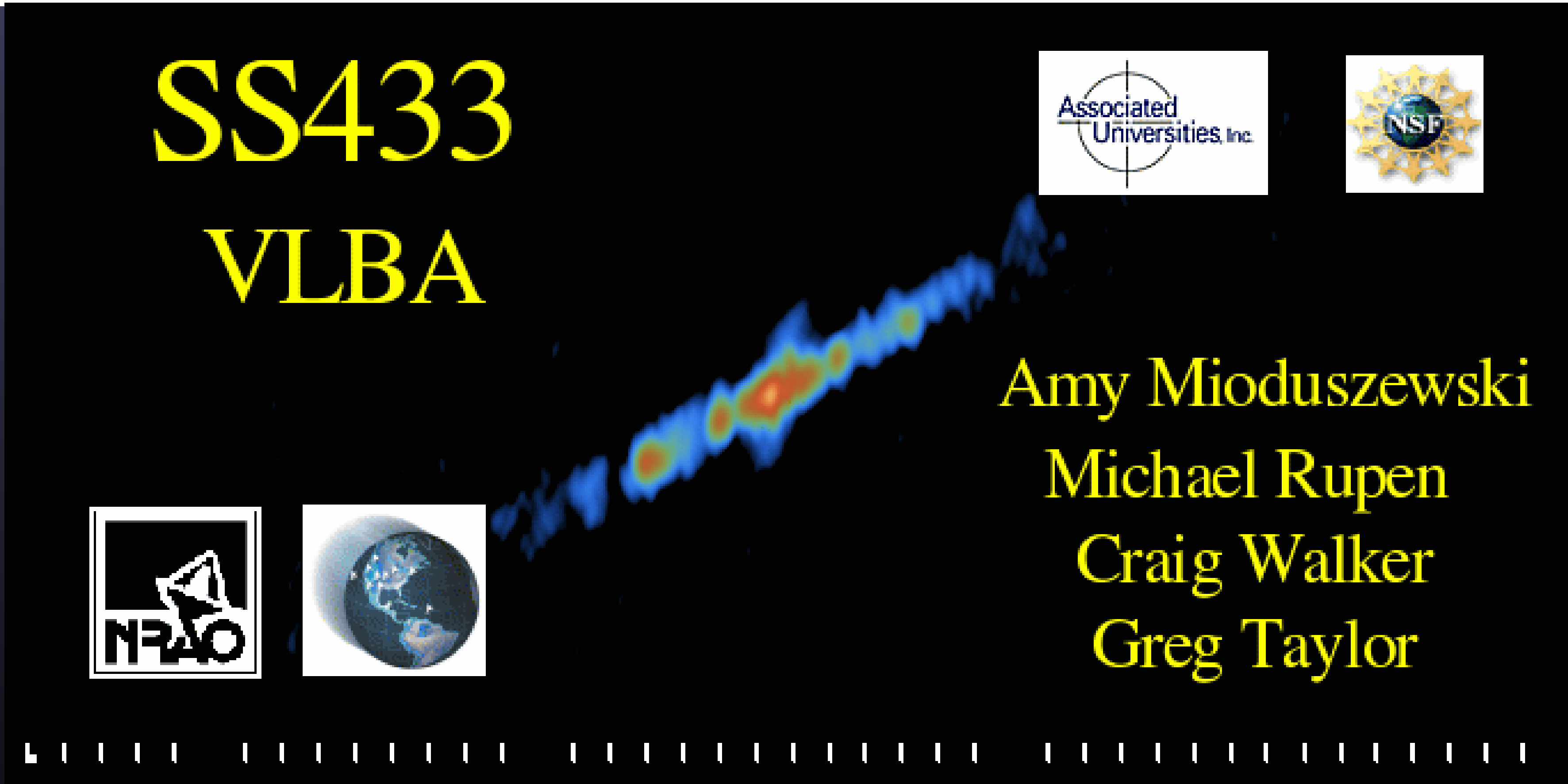


Image of the “shadow of a black hole” in M87 produced by the Event Horizon Telescope. The colorscale shows the intensity at 230 GHz (1.3 mm wavelength), and the striations indicate the direction and degree of polarization. Mass of black hole = 6.5 x 10^9 $M_\odot$ Figure Akiyama et al 2021.

This is our most detailed view of any black hole, with a resolution only a few times larger than the event horizon

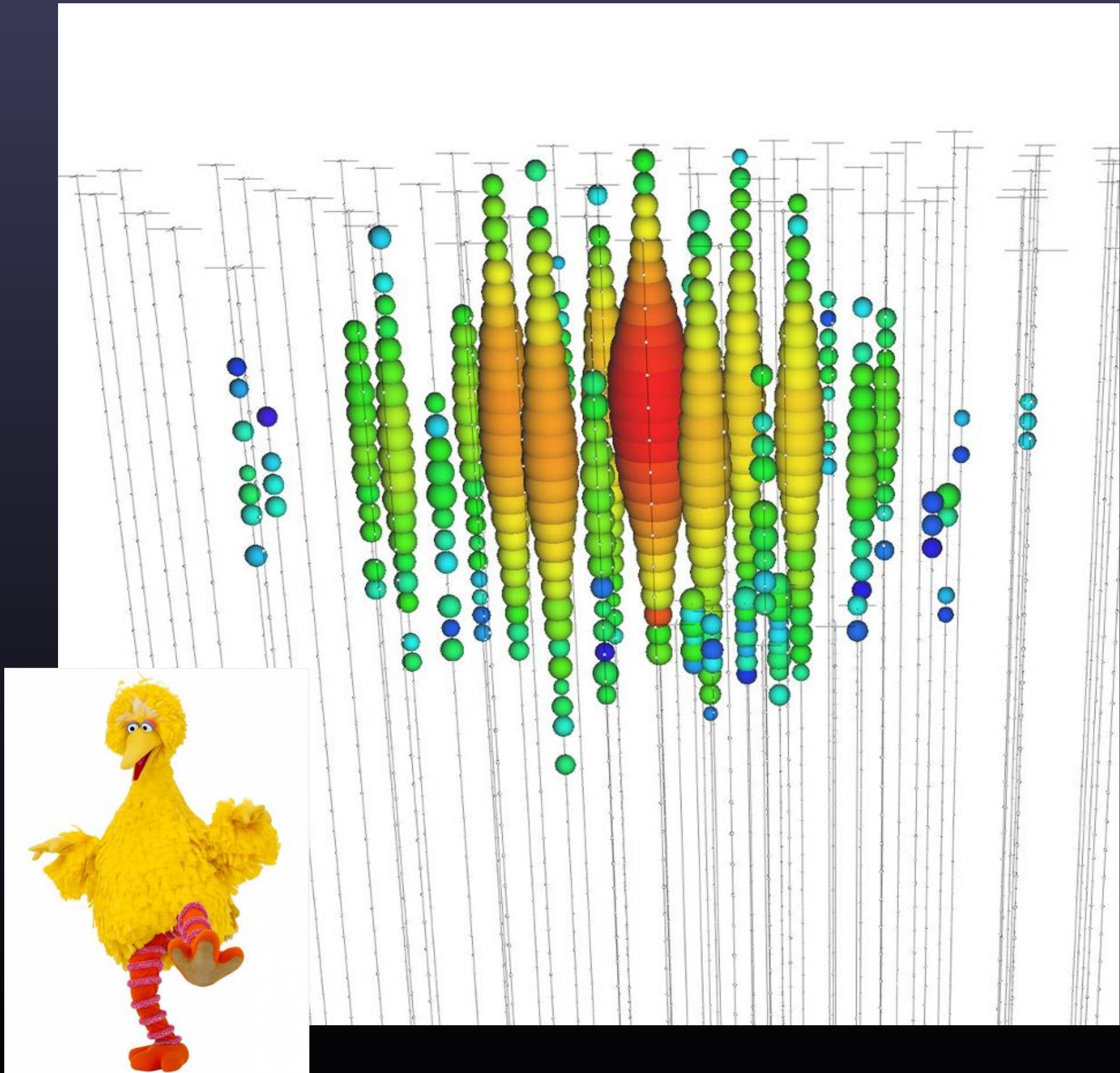
What kinds of science use VLBI?



A. Mioduszewksi et al.

Micro-quasar: Galactic object, black-hole mass of a few solar masses, behaves similarly to AGN, but much shorter timescales. SS433 is the first one discovered

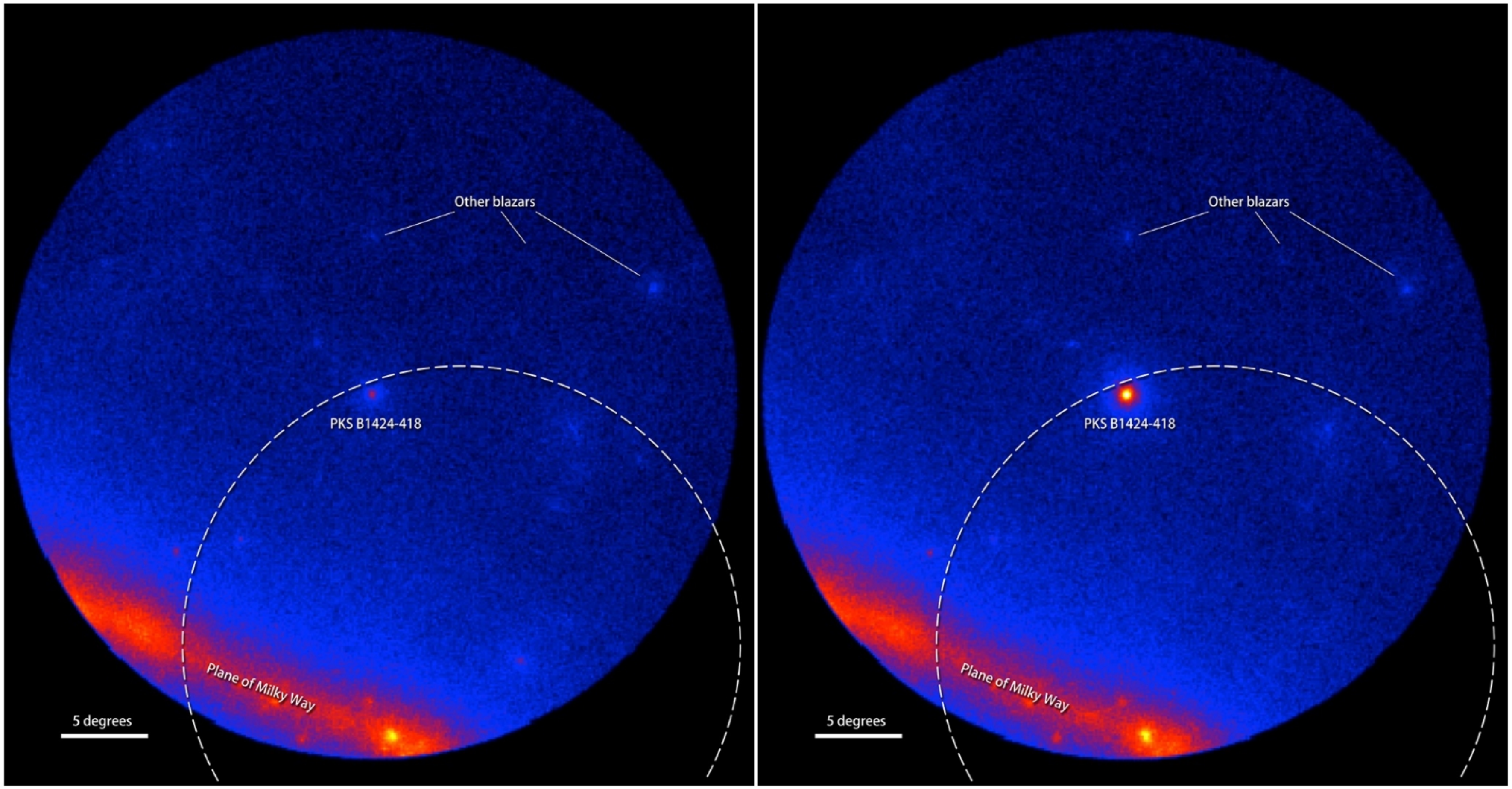
The Big Bird Neutrino



- A neutrino with energy of 2 peta-electron Volts detected by the Ice Cube Neutrino observatory in 2014. The neutrino was called “Big Bird”
- =3200 erg (1 gm at 80 cm s^{-1} !!)
- where is it from??

Image: Jakob van Santen/IceCube

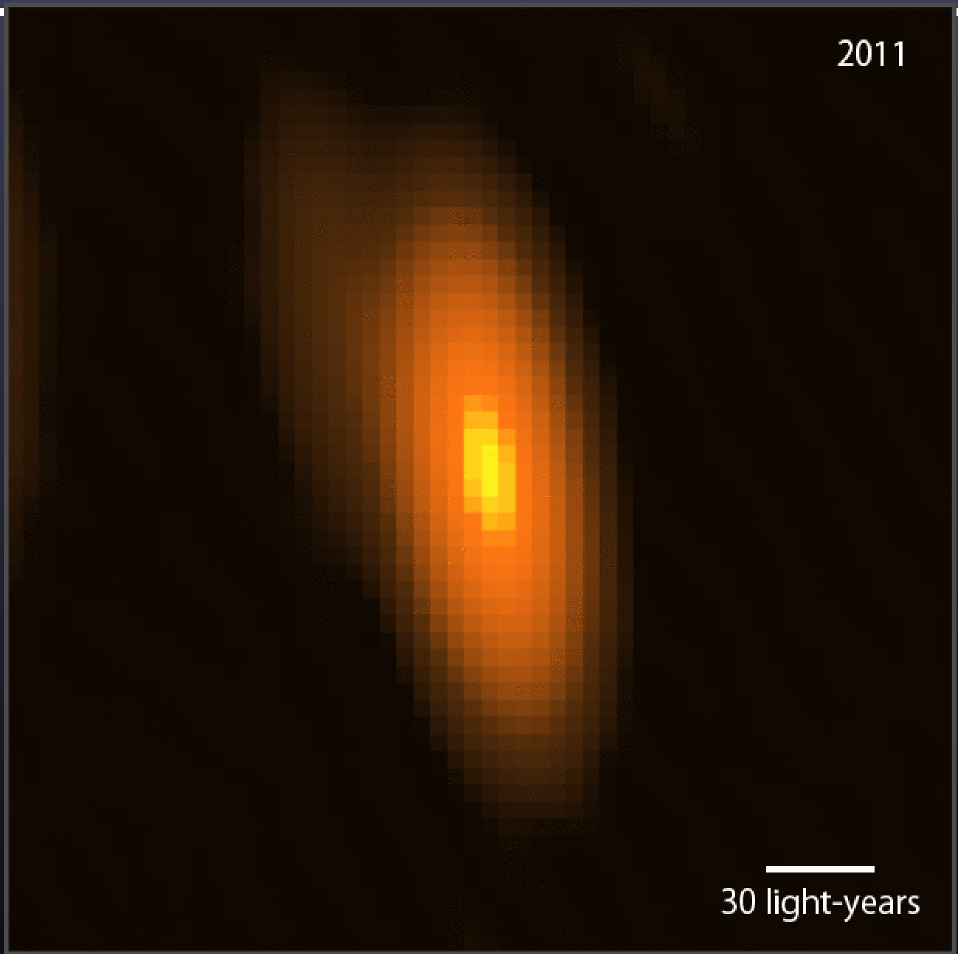
The Source of High-Energy Neutrinos?



Fermi LAT images showing the gamma-ray sky
around the blazar PKS B1424-418. B

NASA/DOE/LAT-collaboration

VLBI Images of the Blazar PKS B1424-418



- VLBI radio images from the TANAMI project reveal the 2012-2013 eruption of PKS B1424-418 at 8.4 GHz. The core of the blazar's jet brightened by four times, producing the most dramatic blazar outburst
- PKS B1424-418 seems a likely source for Big Bird (although there is a 5% chance its a coincidence)

Image & Caption Credit: TANAMI

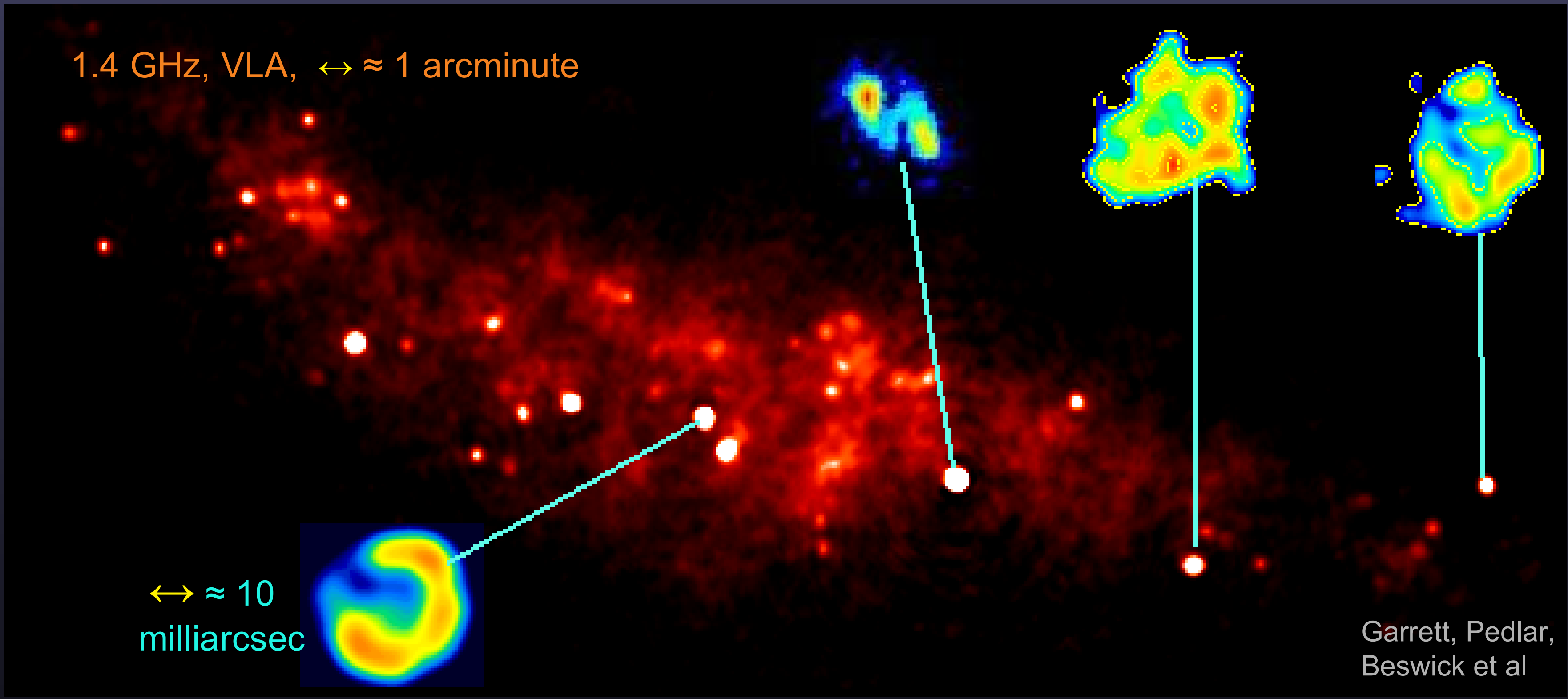
Maser Emission from TX Cam

TX Cam (pulsating star) SiO maser ring showing outflow from star's surface.

The first-ever time-lapse "movie" showing details of gas motions around a star other than our Sun. The study was one of the largest observational projects yet undertaken using Very Long Baseline Interferometry,

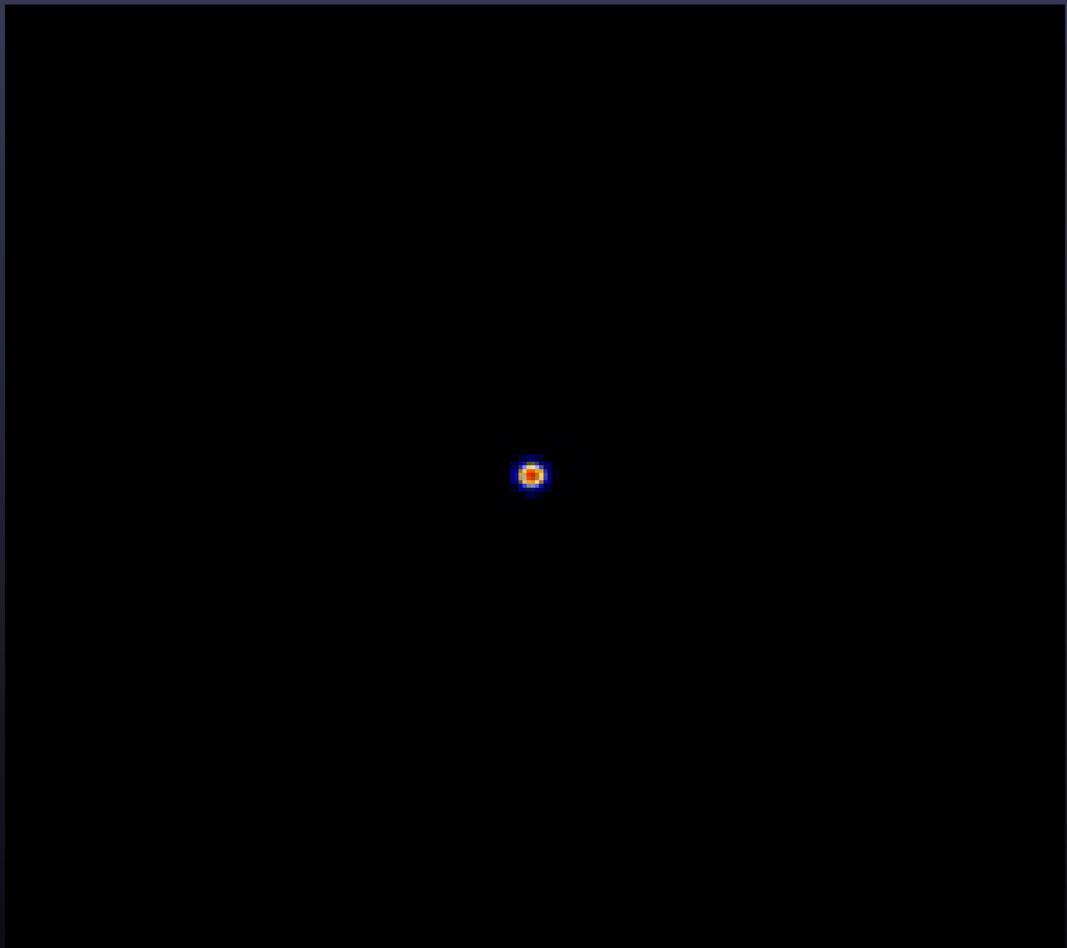
P. Diamond et al.

Radio Supernovae in M82



- Over 50 compact sources discovered in M82, most are supernovae/supernova remnants
- M82 is a nearby (~3.6 mega-parsec) “starburst” galaxy, with a high rate of star-formation, and thus a high rate of supernovae

VLBI Movie of Supernova 1993J



1 milli-arcsecond

Bietenholz, Bartel et al, 2001 to 2007

- Nearby supernova (3.6 Mpc)
- Very radio bright (~100 mJy peak)
- Expanding at ~20,000 km s^{-1}
- VLBI Images: 1987 to 2014 (and continuing…)
- ~30 global-array VLBI images at 8.4, 5 and 1.7 GHz

VLBI Measurements of Supernova 1993J

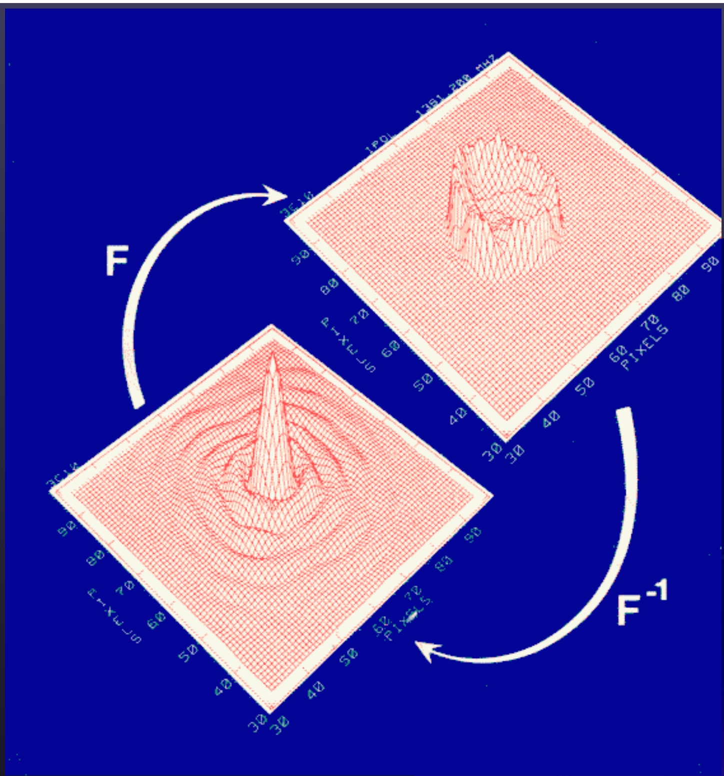
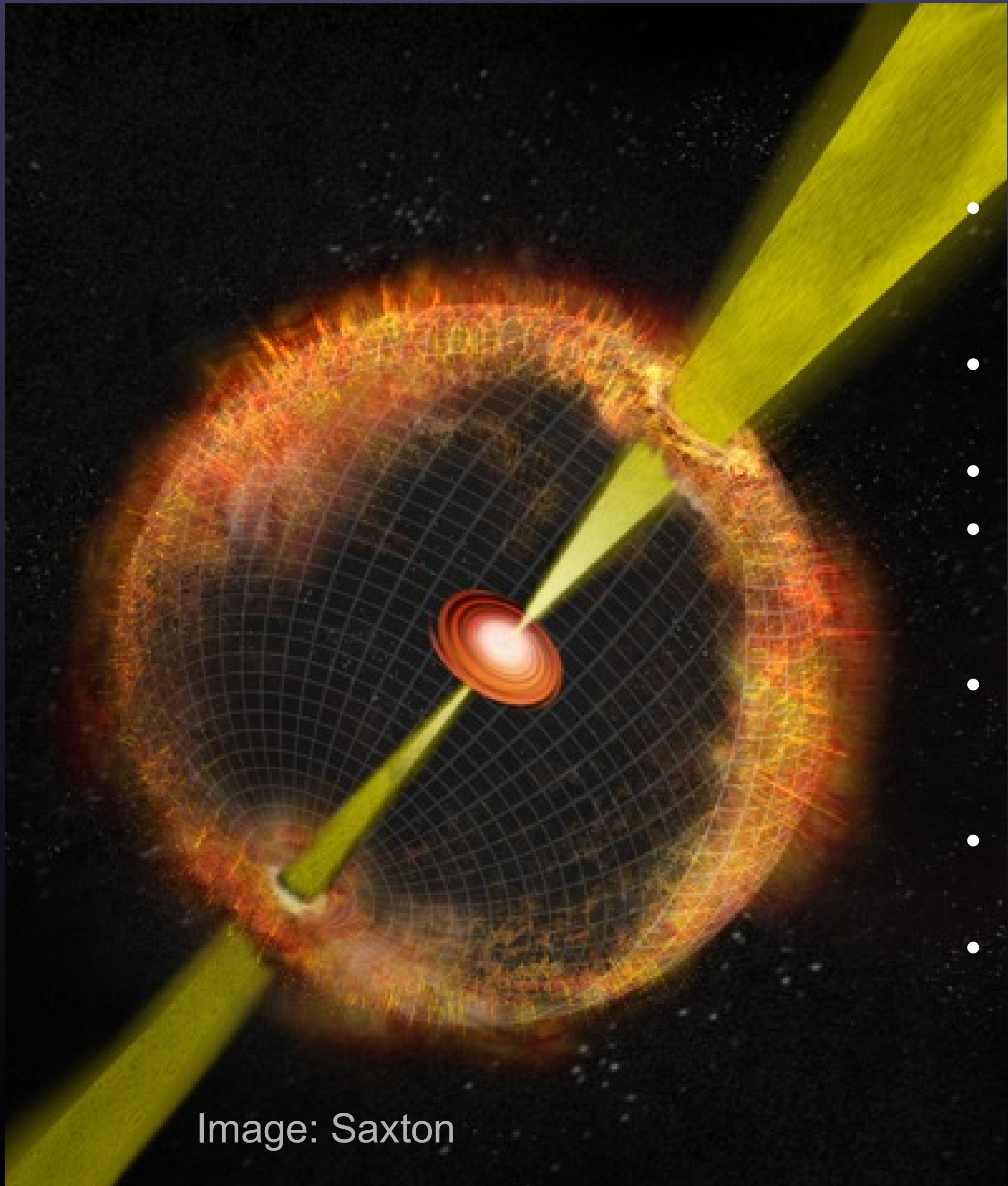


Image: NRAO

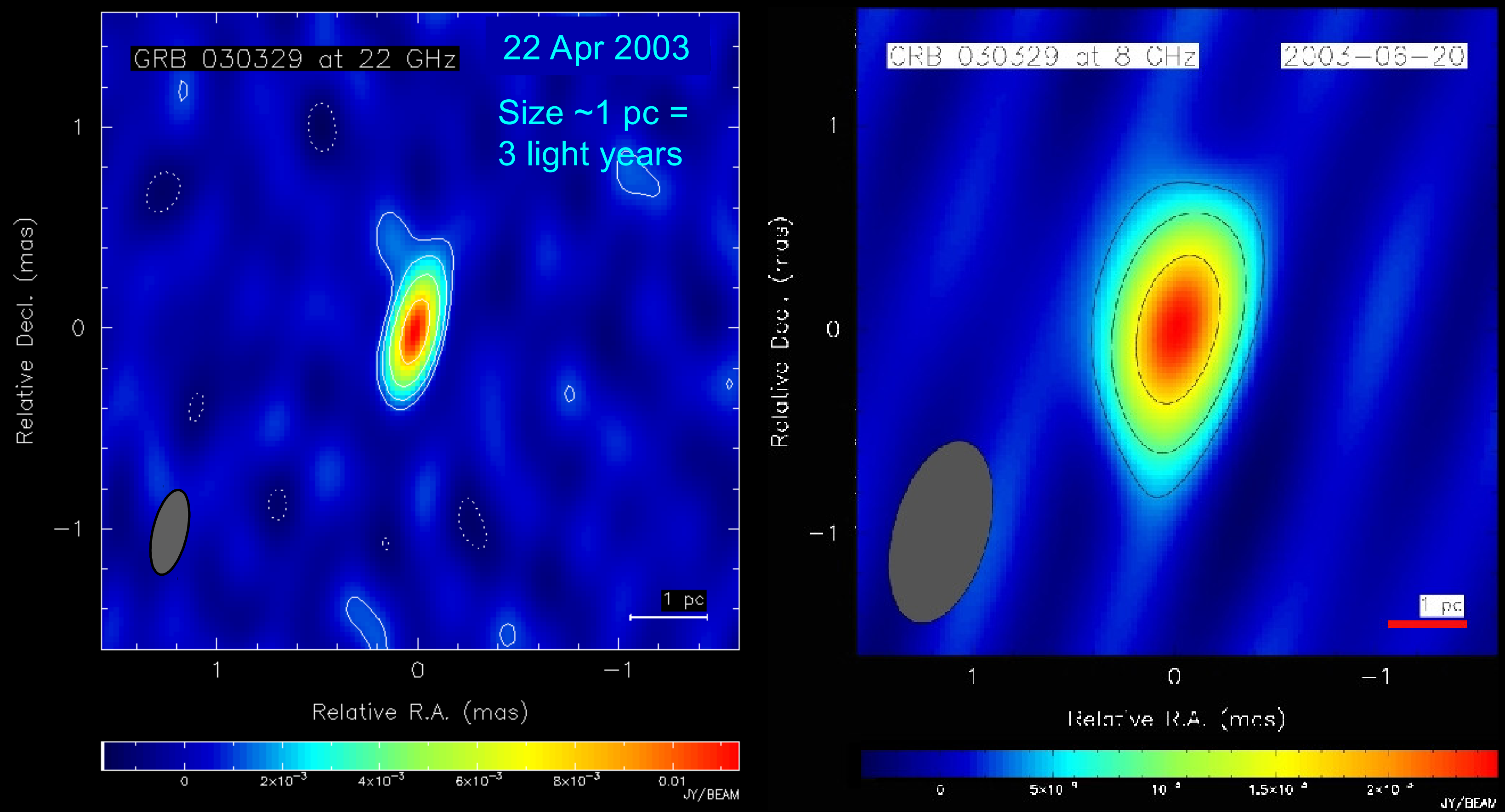
Image: Bietenholz

Gamma-Ray Bursts



- Bursts of Gamma-rays, ~1 per day – duration <1 seconds to hours!
- Cosmological distances → very high luminosity
- Afterglows discovered
- Long Duration GRB's are associated with Type Ibc supernovae
- Collapse of massive star into a black hole powers highly relativistic jet
- GRB's are jets oriented near the line of sight
- The jets *not* near the line of sight may be visible in radio

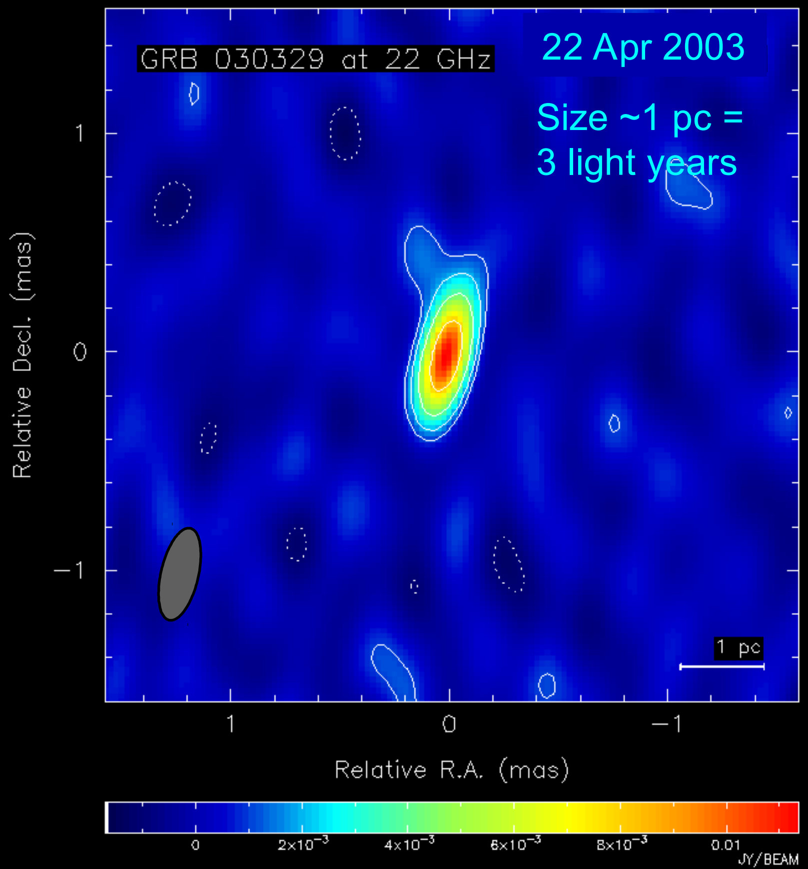
Relativistic Expansion: GRB 030329 (SN 2003dh)

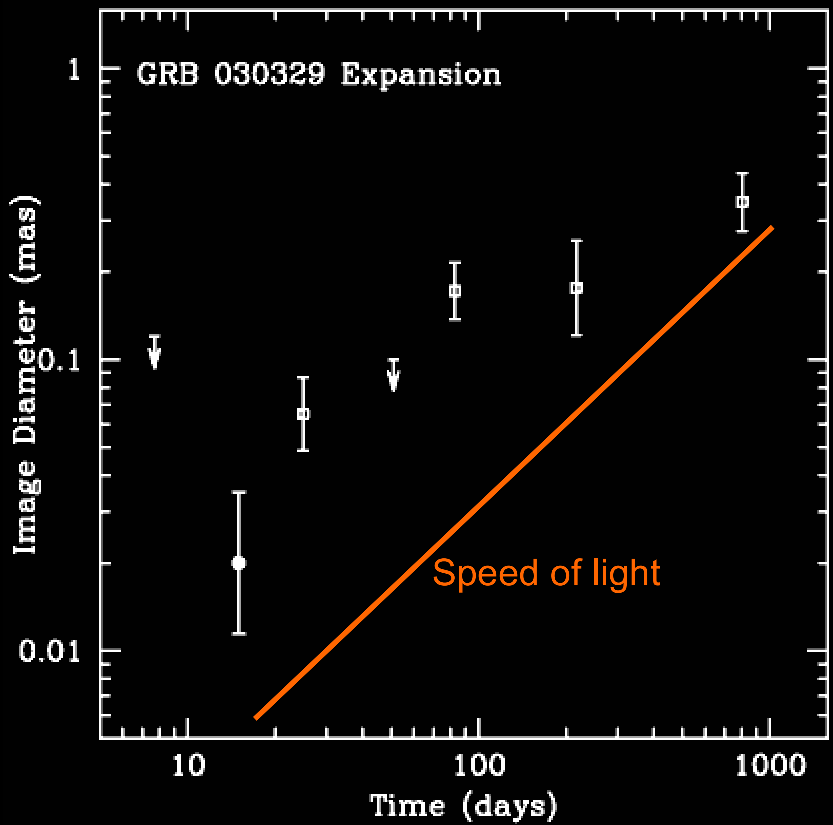


VLBI expansion measurements: by Taylor et al. & Pihlstrom et al. show clear deceleration, with transition to non-relativistic regime at t ~ 1 yr

Taylor et al, 2004, 2005; Pihlstrom et al. 2007

Relativistic Expansion: GRB 030329 (SN 2003dh)





VLBI Expansion Measurements: by Taylor et al. & Pihlstrom et al. show clear deceleration, with transition to non-relativistic regime at $t \sim 1$ yr

Taylor et al, 2004, 2005; Pihlstrom et al. 2007

Astrometry: Measuring Positions on the Sky

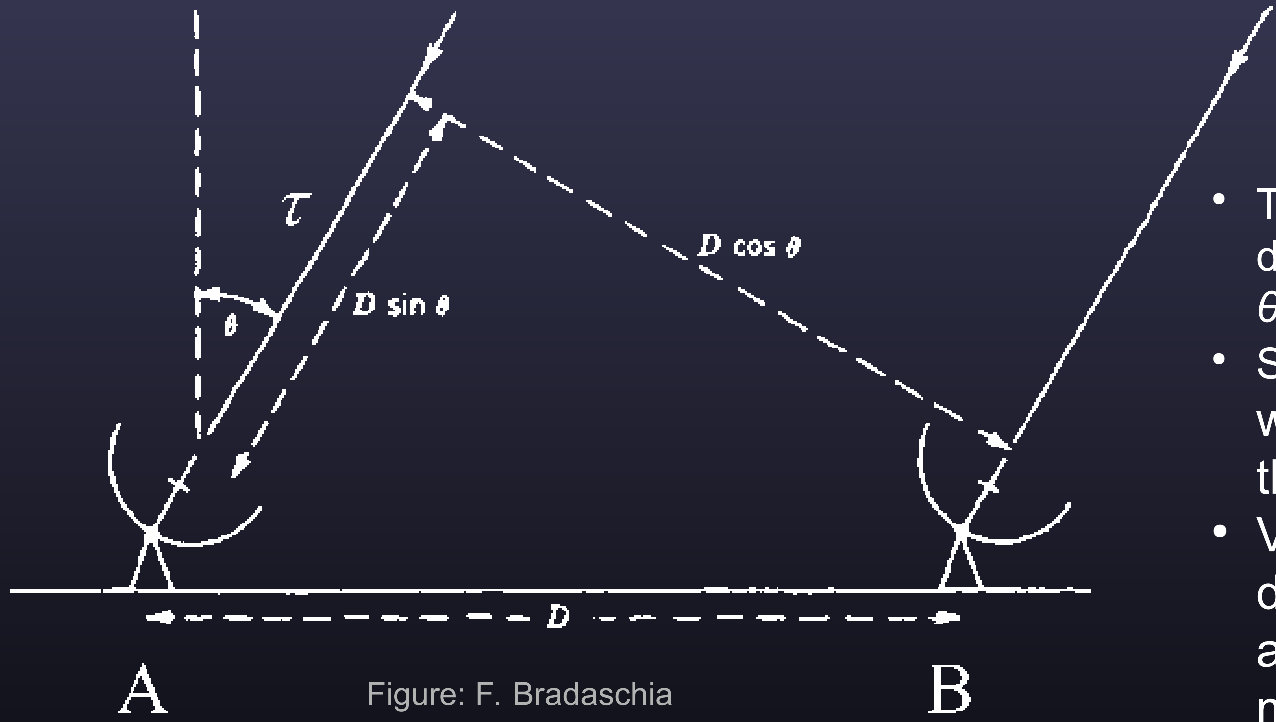
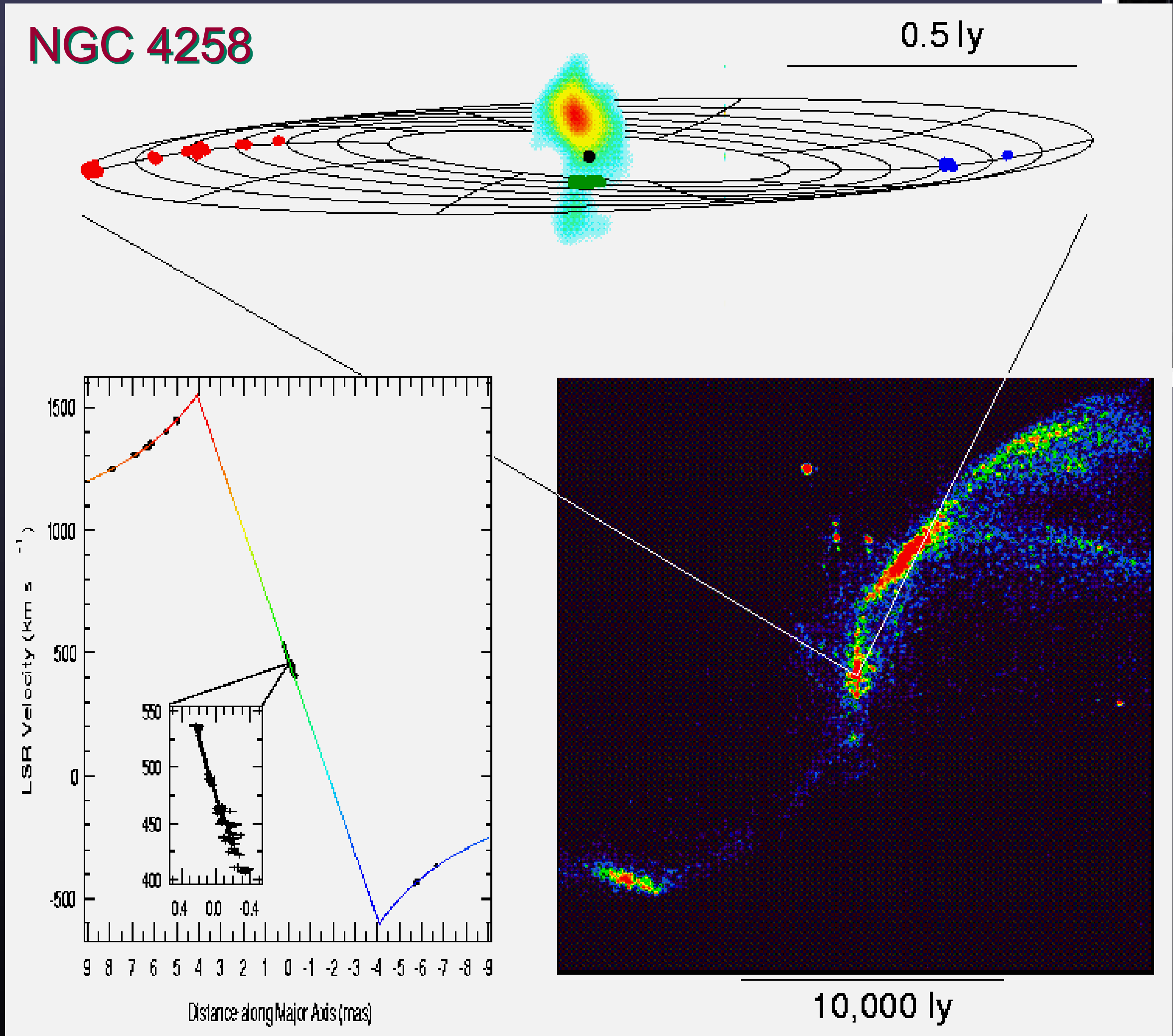


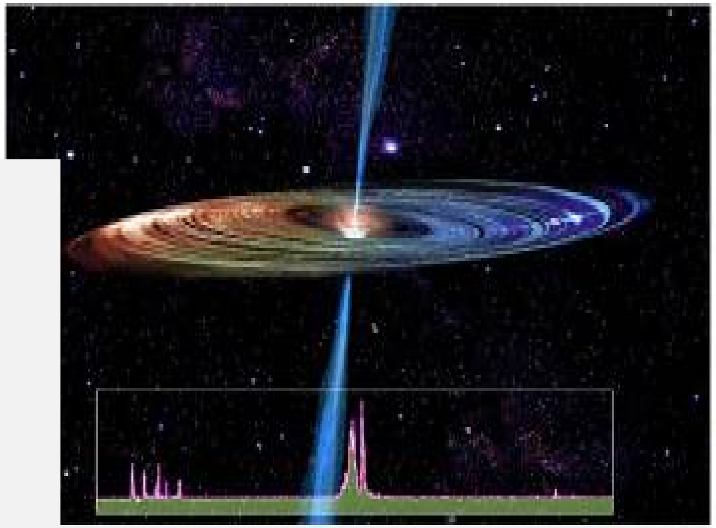
Figure: F. Bradaschia

- The delay, τ, depends on the angle θ
- So by measuring τ we can determine the angle θ
- VLBI allows us do determine θ very accurately and thus measure positions on the sky very accurately

Maser Disc NGC 4258



Herrnstein, Greenhill et al

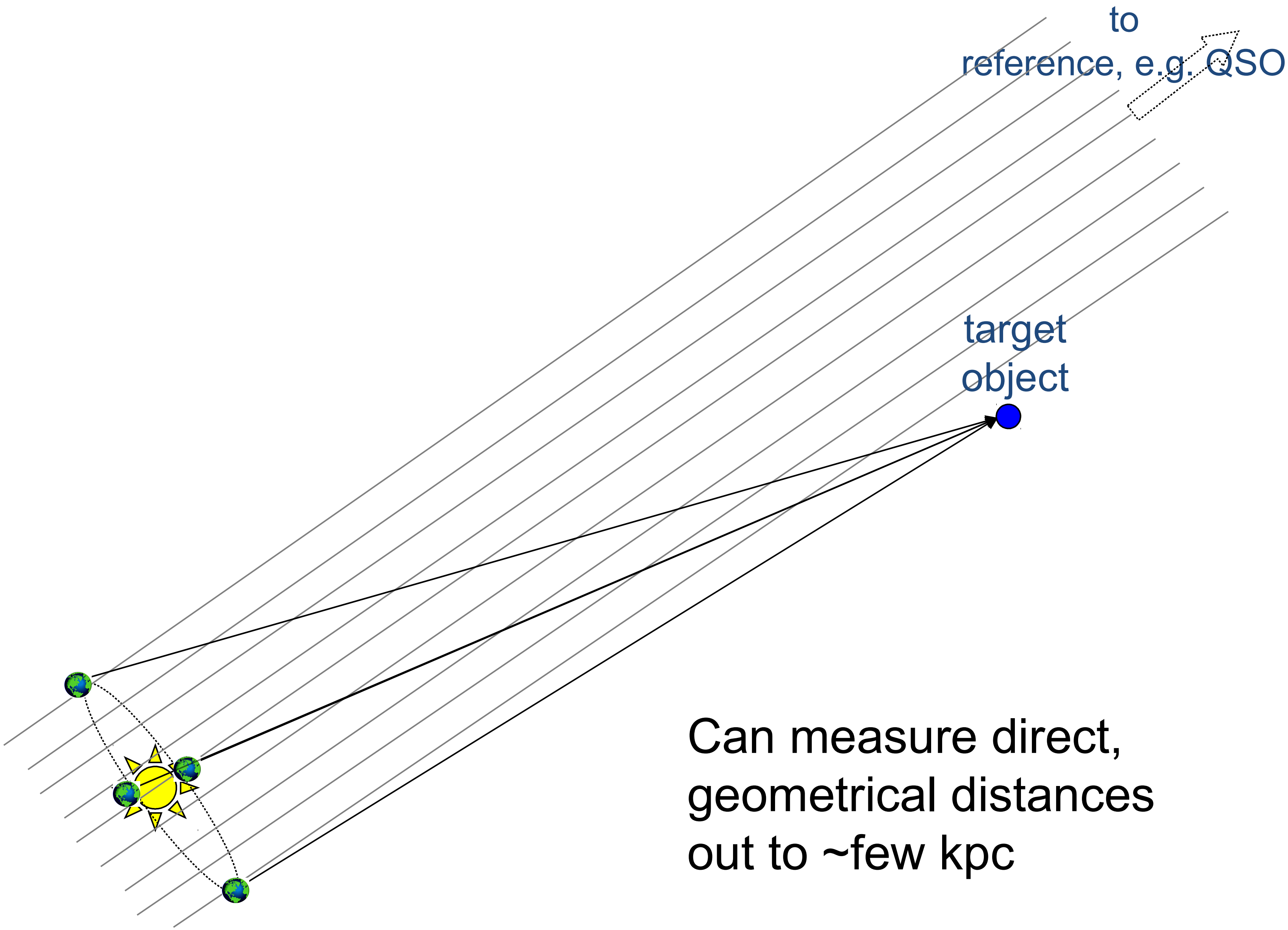


VLBI to measure both proper motions (in the plane of the sky) and radial motion of narrow-line maser spots

Direct distance: 7.5±0.3 Mpc and

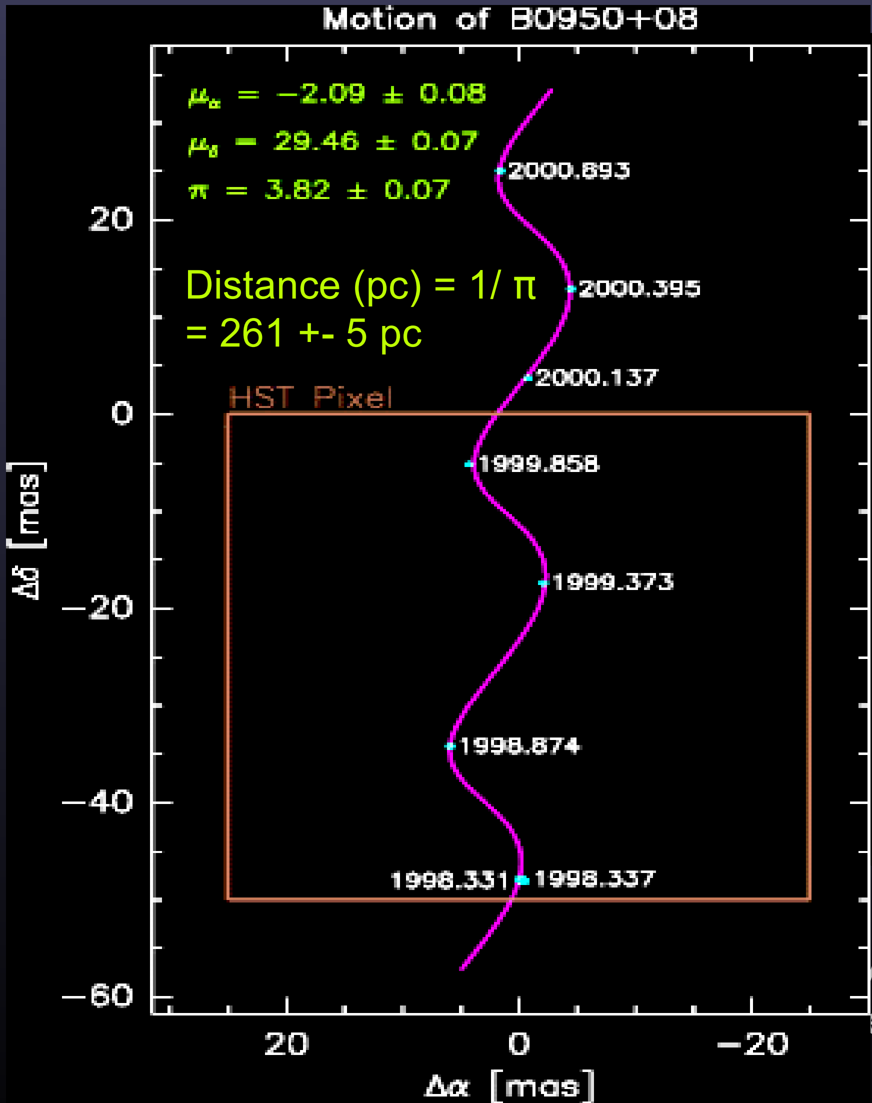
Mass of black hole: 3.9 x 10^7 $M_\odot$

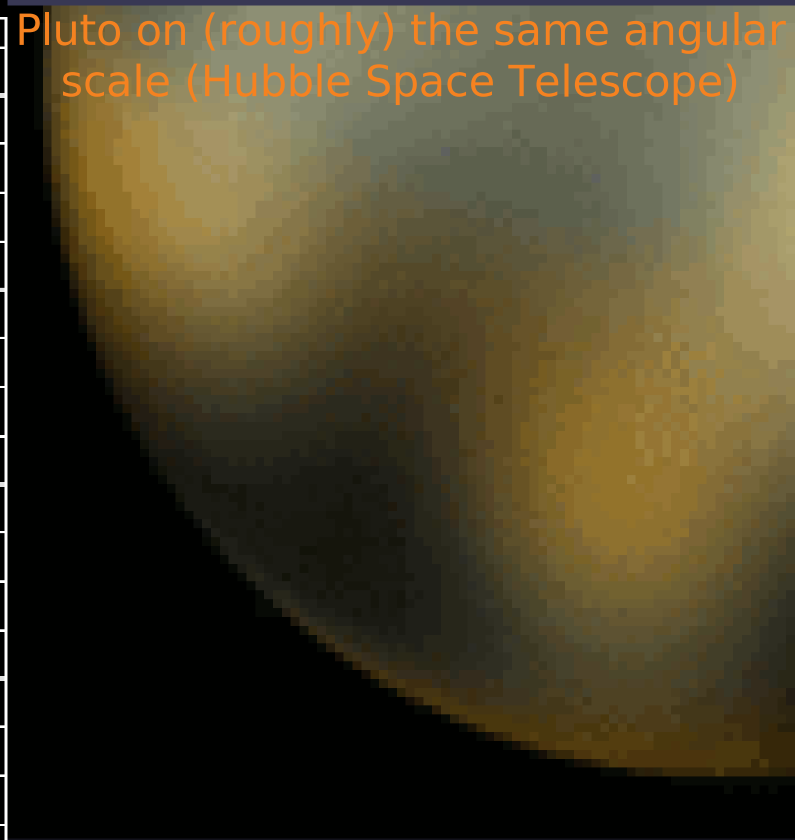
Astrometry: Parallax



Can measure direct, geometrical distances out to ~few kpc

Proper Motion of Pulsar B0950+08

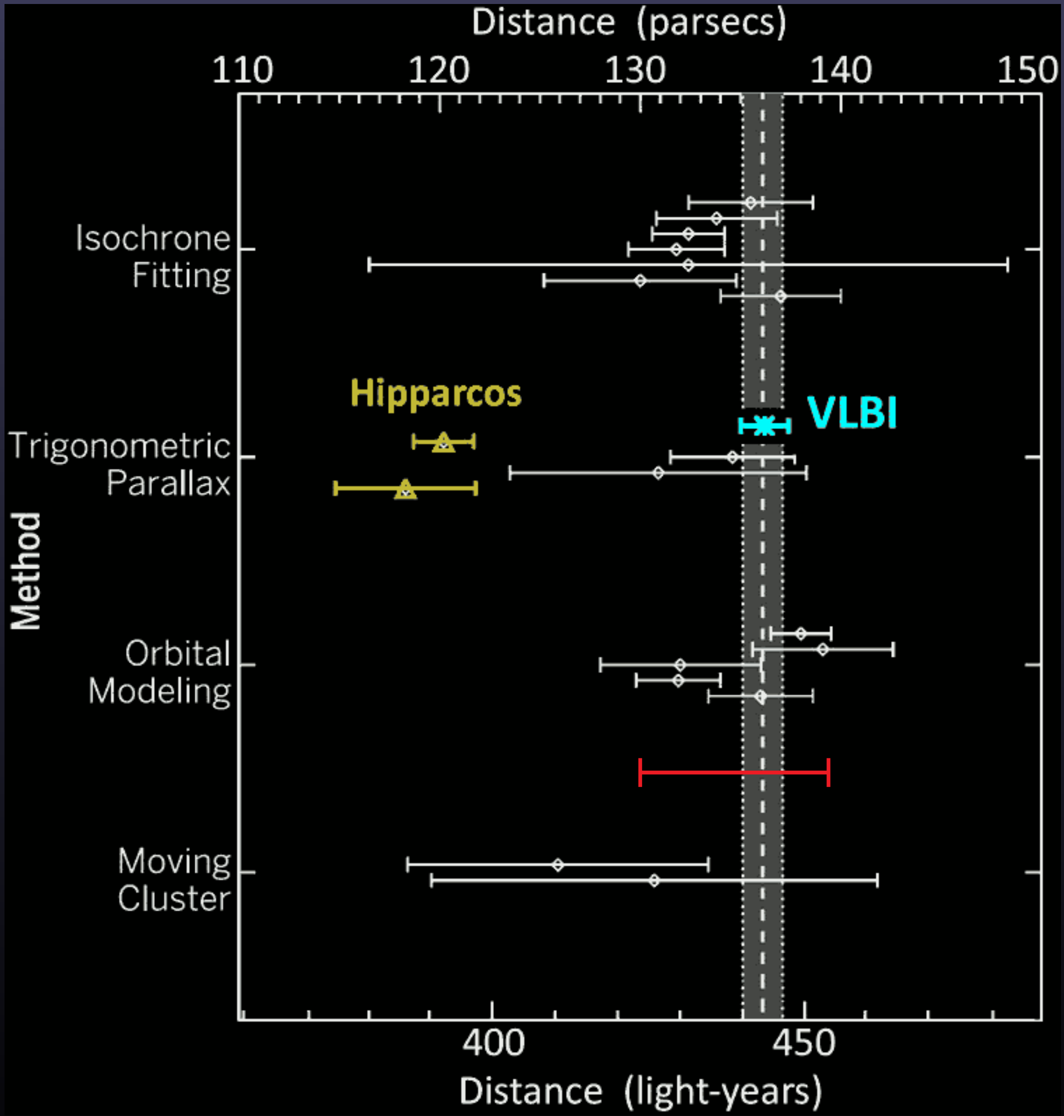




ASA, ESA, and M. Buie (Southwest
esearch Institute)

milli-arcsec level pulsar parallax measurement (W. Brisken et al., 2005)

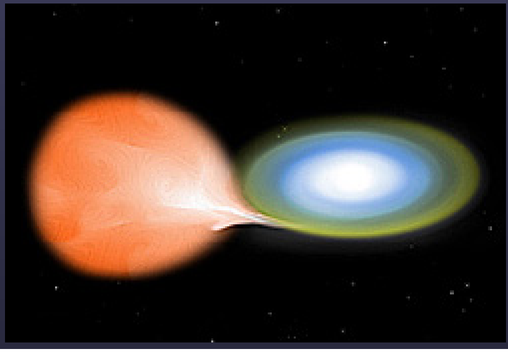
Distance Measurements to Pleiades

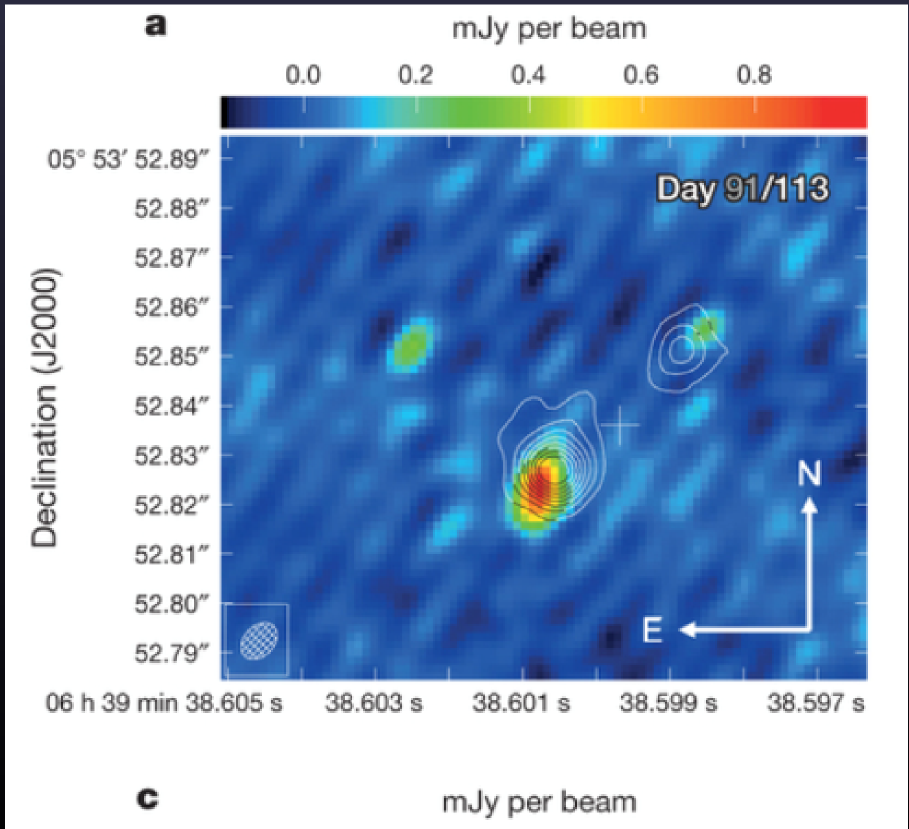


- Hipparcos – satellite to measure parallaxes got a somewhat discrepant distance to Pleiades.
- VLBI measurements determined parallax with respect to a background quasar over 18 months: 136.2 +- 1.2 pc
- Stars are weak radio sources so a sensitive network was needed, wich included the VLBA, GBT, Arecibo and Effelsberg.
- Settled distance controversy
- GAIA satellite: new measurement of optical parallax 134 ± 6 pc

Melis et al 2014

VLBI observations of a Nova in Outburst

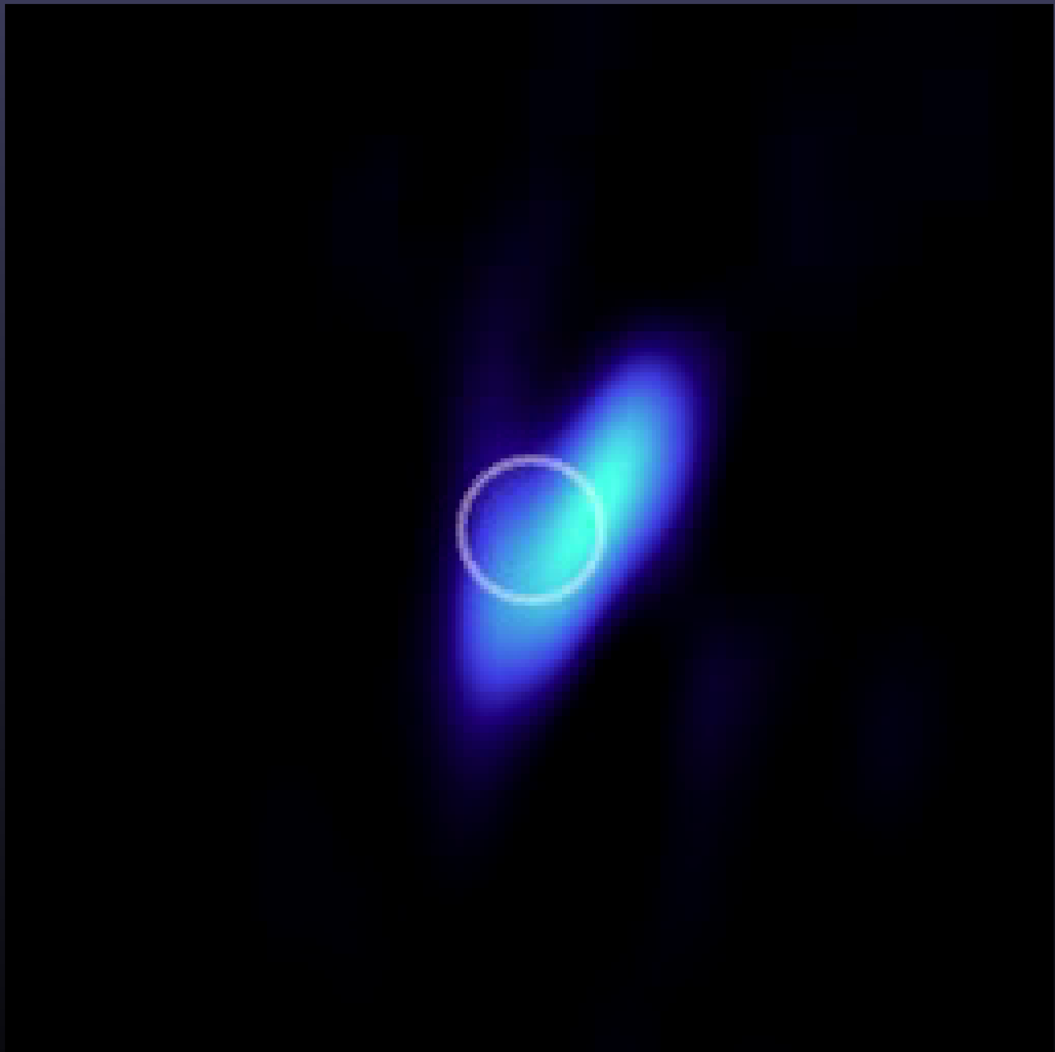




- VLBI image of Nova V959 Mon.
- Nova is a binary system, where a companion star dumps matter onto the surface of a white dwarf untill a runaway thermonuclear reaction happens
- VLBI images made with European VLBI Network (EVN)
- images at age 91 days (contour lines) and 113 days (in colour) after the γ-ray which signaled the nova explosion.
- These images show the compact radio knots expanding diagonally.

Chomiuk et al, 2014

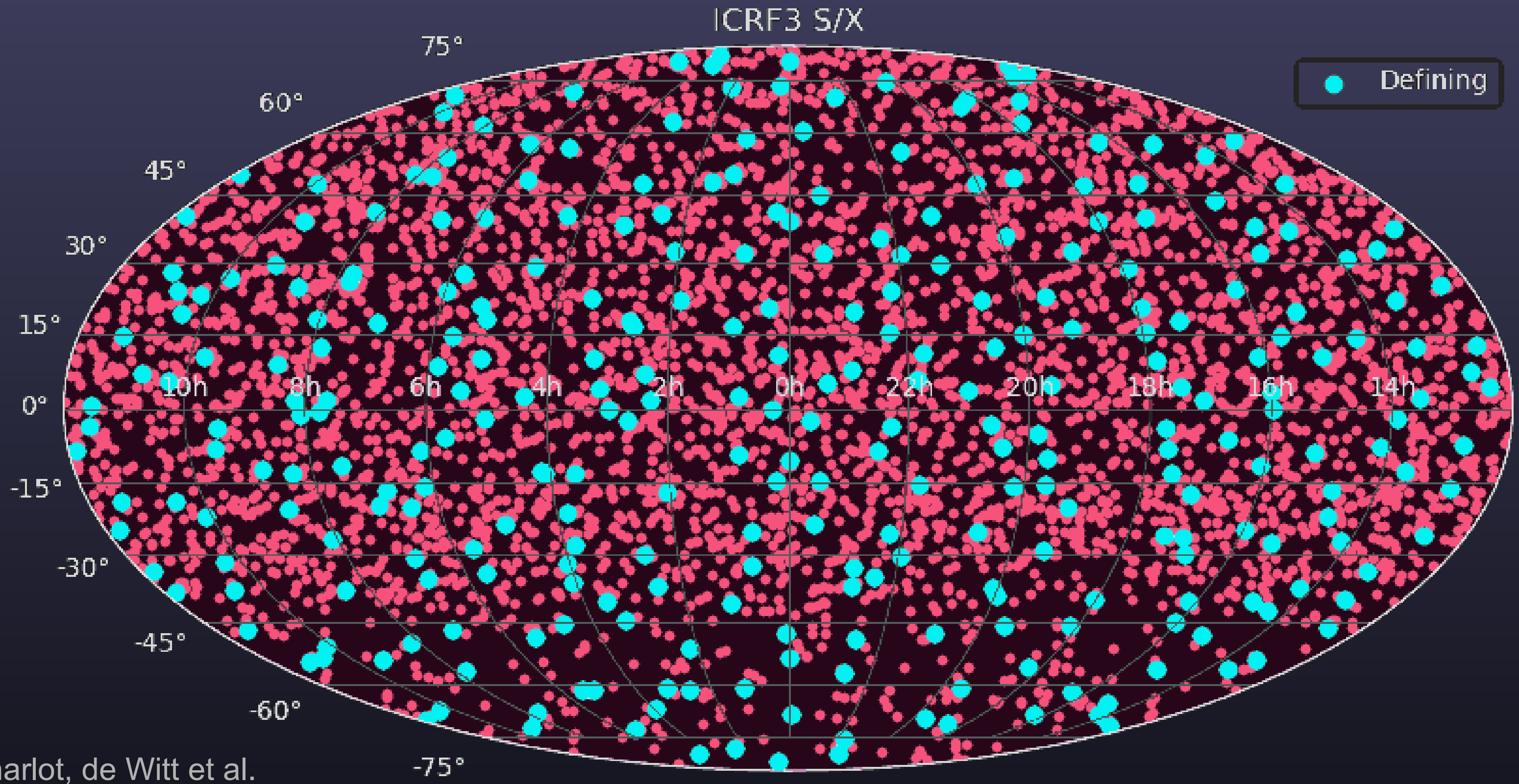
A Movie Star Star Movie



- 35 sessions 8.4 GHz VLBI observations of the radio-emitting star IM Pegasi over 8 years
- (made in support of Gravity-Probe B)
- circle indicates the position of the disk of the star (radius ~13 R_{sun} = 0.64 milliarcsec)
- color indicates brightness: blue is low and red is high

Bietenholz et al, 2012

VLBI Astrometry



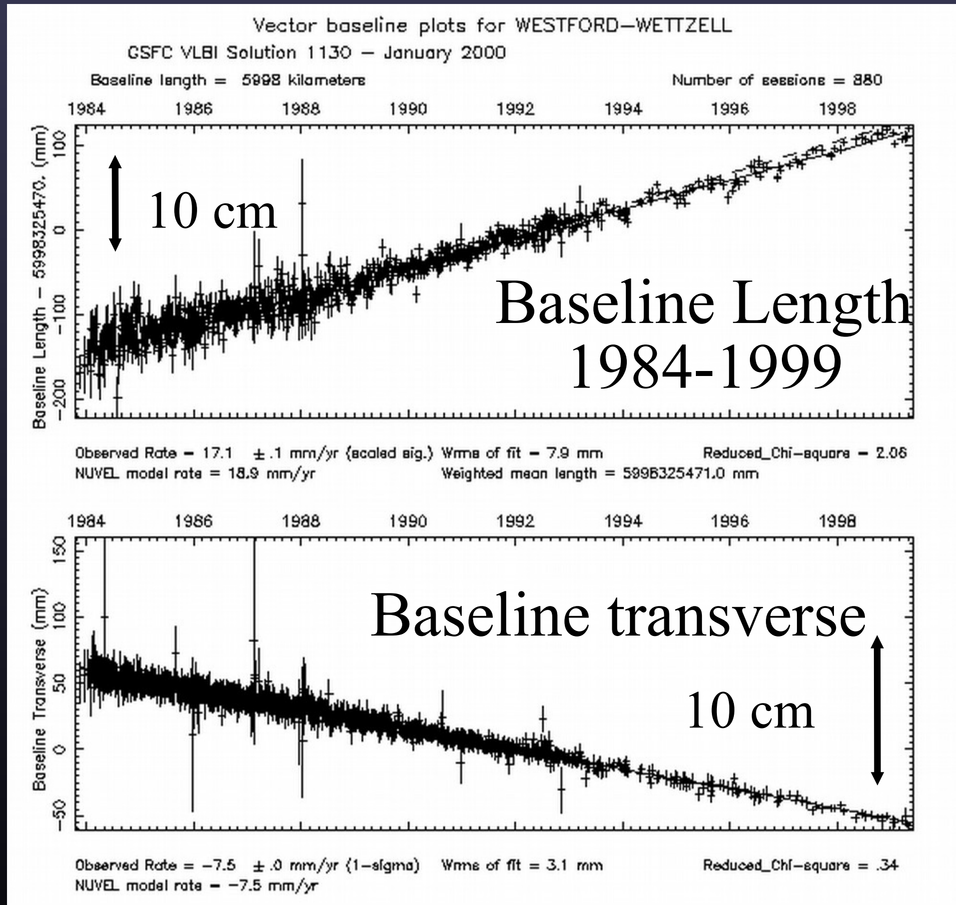
Charlot, de Witt et al. 2020

- The **International Celestial Reference Frame** (ICRF)
- Current: ICRF-3, adopted in 2019, based on coordinates of 4536 extragalactic sources (AGN's), including 303 defining sources
- Our most accurate reference frame for positions on the sky
- Related to the International Terrestrial Reference Frame (ITRF) which gives position on the earth

Geodesy and Astrometry

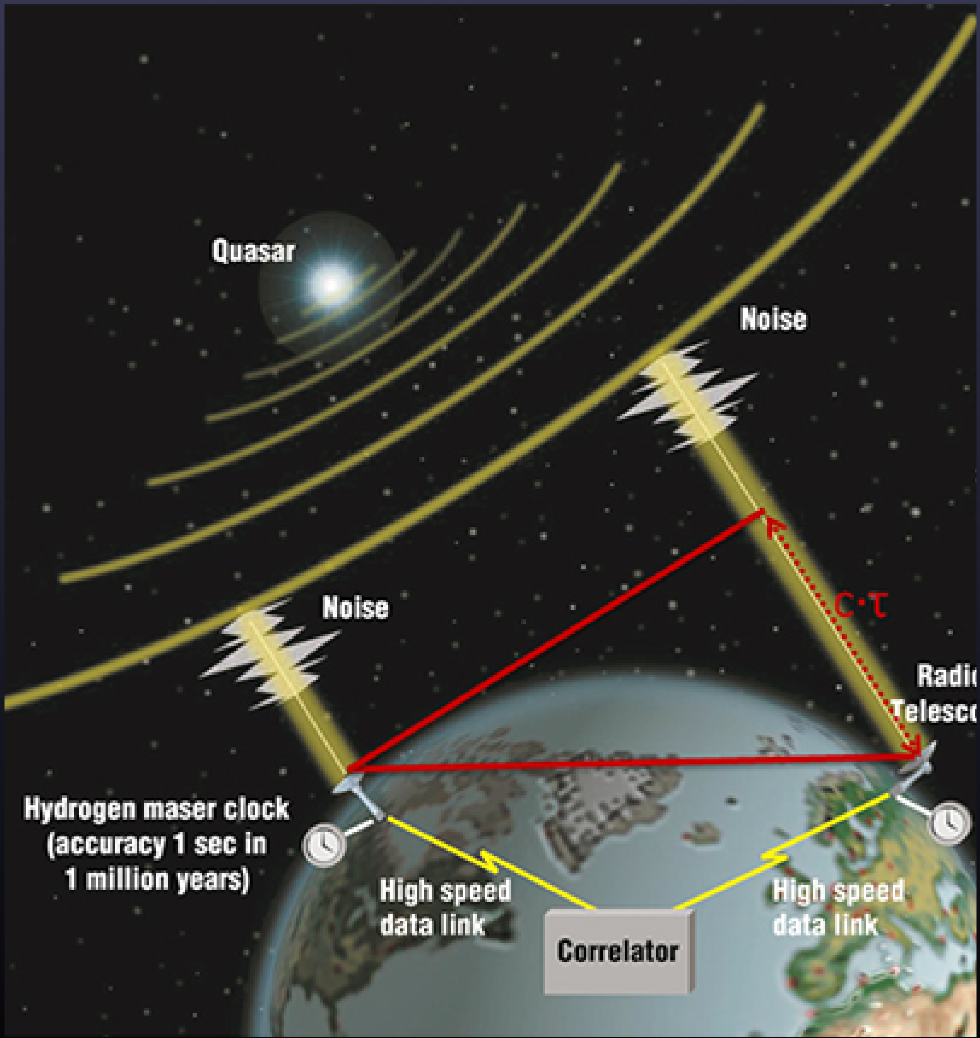
- Fundamental reference frames
  - International Celestial Reference Frame (ICRF)
  - International Terrestrial Reference Frame (ITRF)
  - Earth rotation and orientation relative to inertial reference frame of distant quasars
- Tectonic plate motions measured directly
- Earth orientation data used in studies of Earth's core and Earth/atmosphere interaction

Wetzel, Germany to Westford MA, USA



GSFC Jan 2000

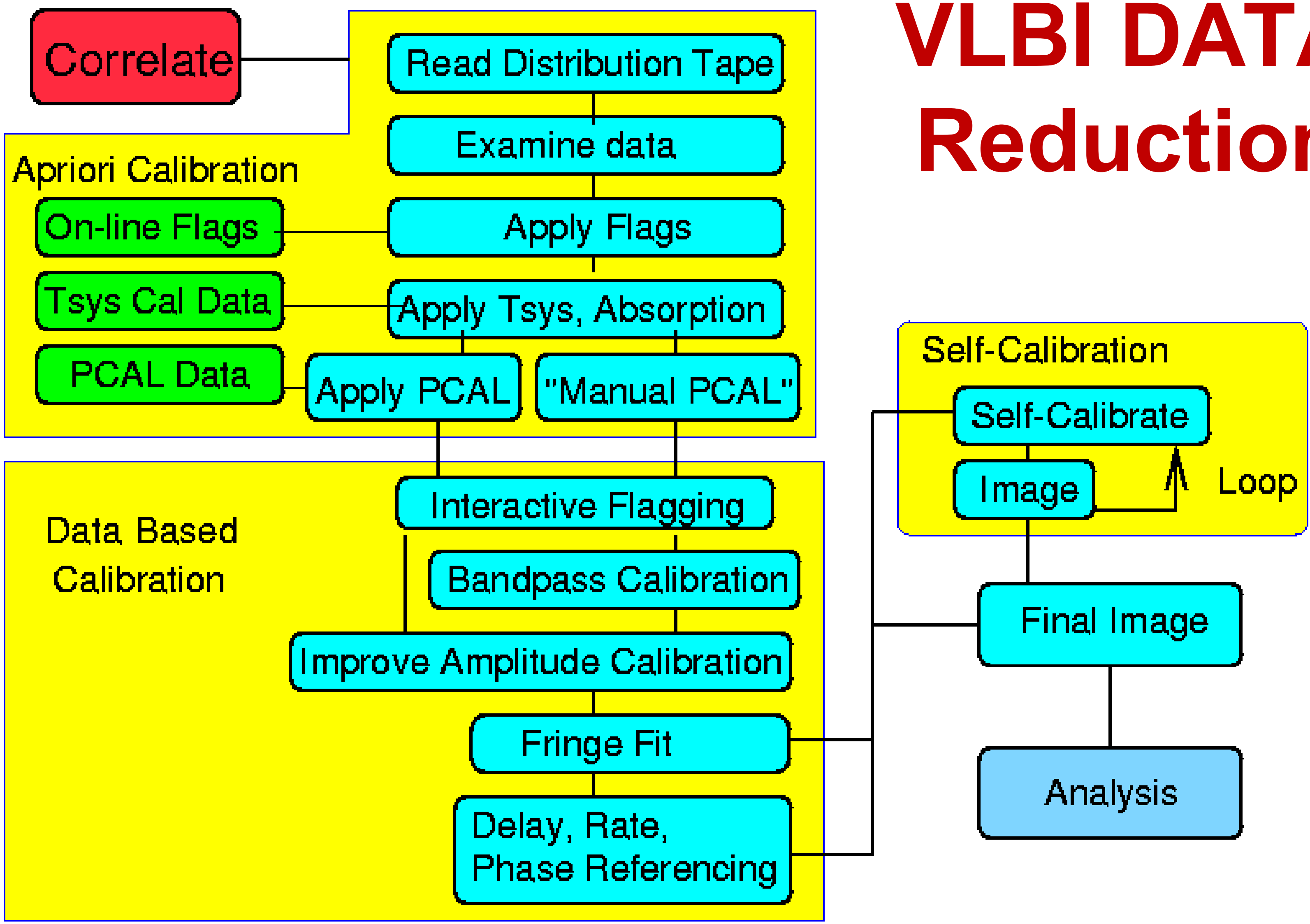
How Do We Do VLBI?



Original image: NASA

- Telescopes that are not physically connected
- Challenges: accurate timekeeping (to fractions of a period or typically a 10s of picoseconds) is required
- Accurate determination of the positions of the telescopes, to fractions of a wavelength, typically a few mm is also required
- Different paths through the atmosphere – different delays, which vary with time as the earth rotates
- Data must be transported to the correlator, either by shipping disks or by high-bandwidth internet connections (each station produces > 1 Gigabit/second)

VLBI DATA Reduction



What Is Delivered by a Synthesis Array?

An enormous list of complex numbers!

E.g., the Very Long Baseline Array – 10 antennas:

- At each timestamp: 45 [N*(N-1)/2] baselines (+ 10 auto-correlations)
- For each baseline: 8 Spectral Windows (“IFs”)
- For each spectral window: tens – 100's of channels
- For each channel: 1, 2, or 4 complex correlations
  - RR or LL or (RR,LL), or (RR,RL,LR,LL)
- With each correlation, a weight value
- Meta-info: Coordinates, field, and frequency info

$N = N_t \times N_{bl} \times N_{spw} \times N_{chan} \times N_{corr}$ visibilities

- a few x 10^8 vis/hour – 10 to 100s of GB per observation

Connected-element interferometers mostly worse:

VLA: 27 antennas → 351 baselines

MeerKAT: 64 antennas → 2016 baselines)

Visibility Measurement in Theory

- Formally, we wish to use our interferometer to obtain the visibility function:

$$V(u,v) = \int_{sky} I(l,m) e^{-i2\pi(ul+vm)} dl dm$$

- ….a Fourier transform which we intend to invert to obtain an image of the sky:

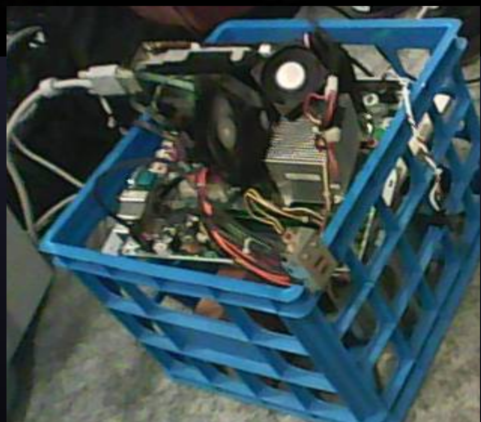
$$I(l,m) = \int_{uv} V(u,v) e^{i2\pi(ul+vm)} du dv$$

  – *V(u,v)* describes the amplitude and phase of 2D sinusoids that add up to an image of the sky
    - Amplitude: "~how concentrated?"
    - Phase: "~where?"

But in Reality....

Weather

Real Clocks



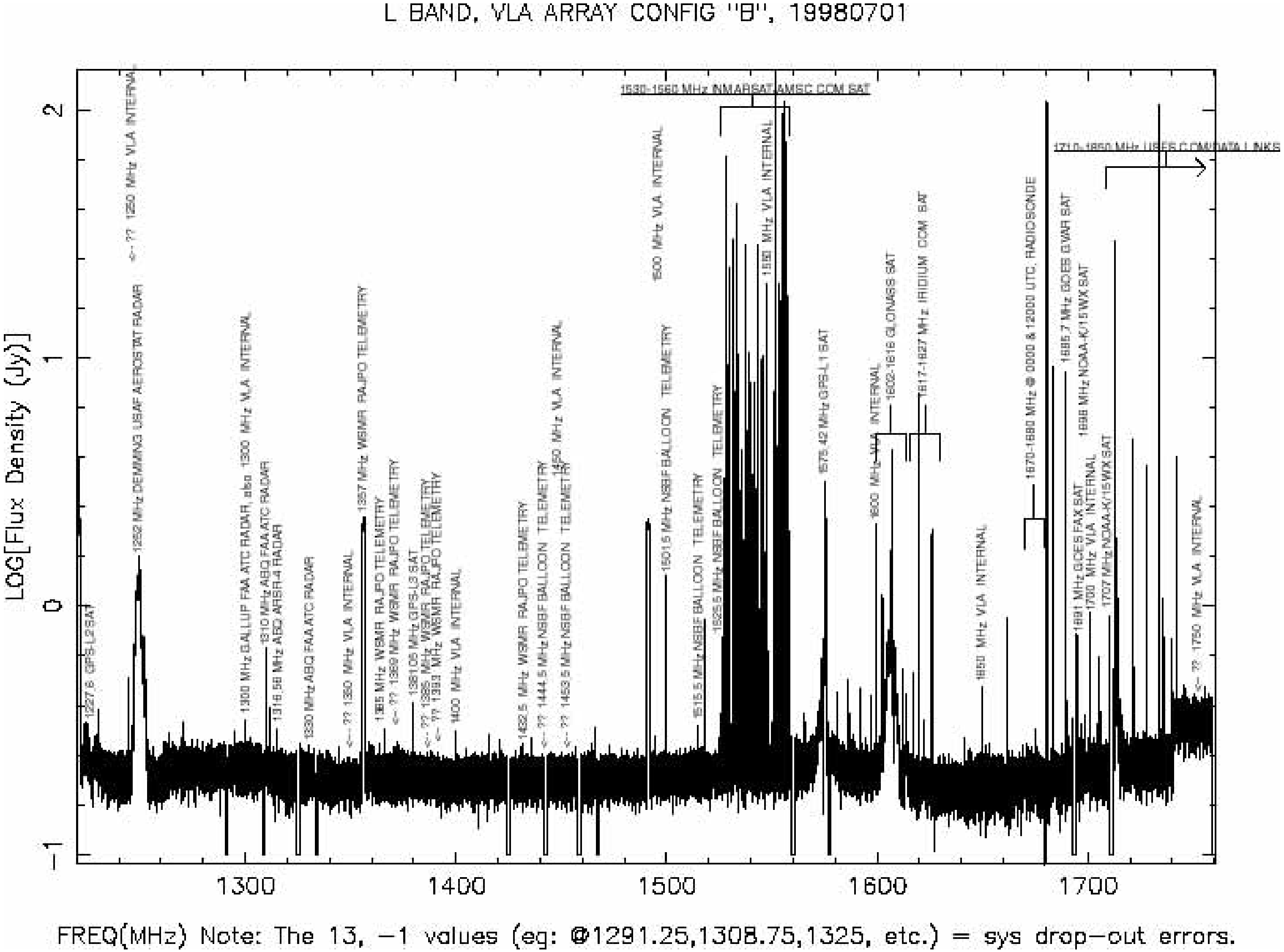
Real electronics

Real antennas

Interference (RFI)

Radio Frequency Interference

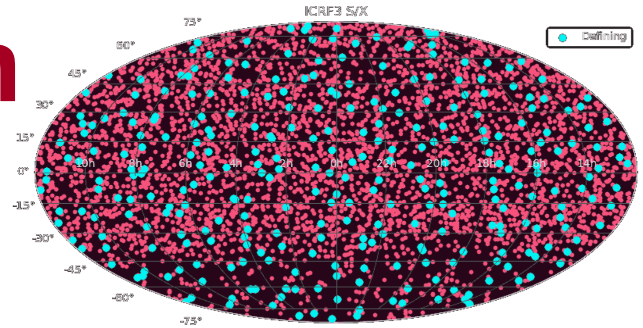
Growth of telecom industry threatening radio astronomy!



Why Calibration and Editing?

- Synthesis radio telescopes, though well-designed, are not perfect (e.g., surface accuracy, receiver noise, polarization purity, stability, etc.)
- Correlator model is good, but not perfect
- Typically, antenna models and locations are now very good, but...
- Source positions are imperfect, and can vary with time, and peak brightness points may vary with frequency
- Atmosphere and ionosphere are time-variable and unpredictable
- Radio Frequency interference – terrestrial radio signals
- clock information has significant errors at the VLBI level of accuracy
- Determining *instrumental properties* (calibration) is a prerequisite to determining *radio source properties*
- But: absolute calibration is very hard

Practical Calibration: Cross Calibration



- ***Cross-calibration*** a better choice
  - Observe strong sources – calibrator sources or just calibrators - near the science target whose characteristics, position, flux density, are known!
  - solve for calibration against calibrators and transfer solutions to target observations
  - Choose appropriate calibrators; usually strong point sources because we can easily predict their visibilities: amplitude = constant, phase = 0
    - VLBI: not so easy! most sources somewhat resolved
  - Choose appropriate timescales for calibration (typically minutes; usually longer at low frequencies, shorter at high frequencies)

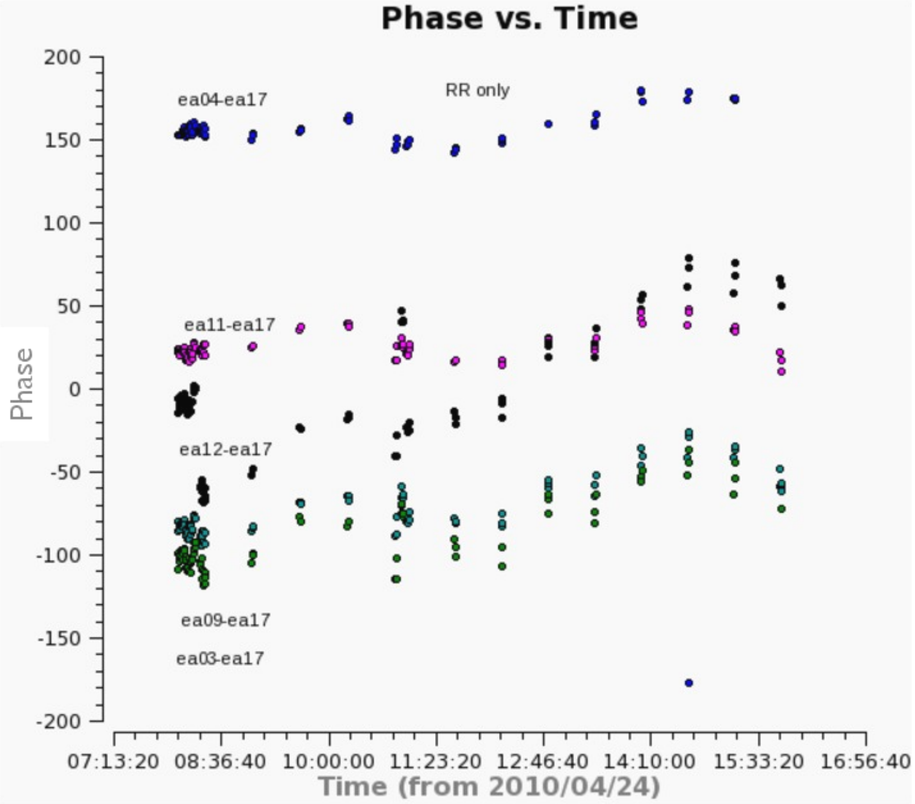
Practical Calibration Considerations

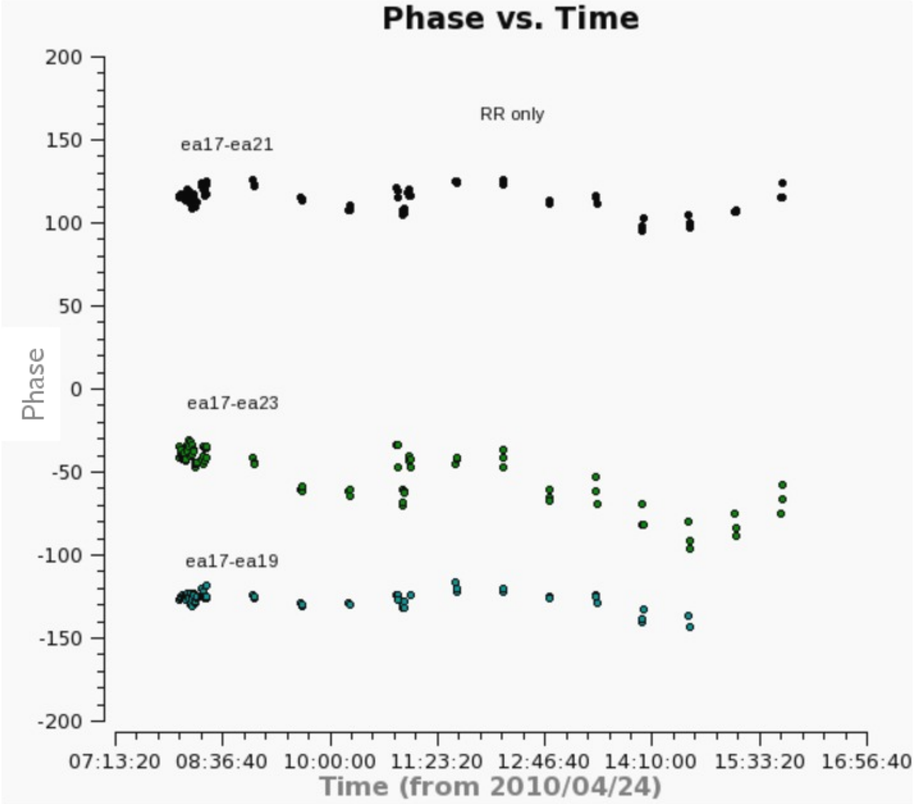
- A priori "calibrations" (provided by the observatory)
  - Antenna positions, earth orientation and rate
  - Clocks, frequency reference
  - Antenna pointing/focus, voltage pattern, gain curve
  - Calibrator coordinates, flux densities, polarization properties
  - T_{sys}, nominal sensitivity
- Absolute *engineering* calibration (dBm, K, Volts)?
  - Very difficult, requires heroic efforts by observatory scientific and engineering staff
  - **Amplitude:** T_{sys}, or switched-power monitoring to enable calibration to nominal K, or Jy with antenna efficiency information
  - Phase: inject phase-cal, water vapor radiometer (ALMA)
  - Traditionally we concentrate instead on ensuring instrumental *stability* on adequate timescales

Antenna-based Cross Calibration

- Measured visibilities are formed from a product of *antenna-based* signals – we can take advantage of this:
- N antennas, there are $N_{baseline} = N*(N-1)/2 \sim N^2/2$ baselines.
- Take calibration factor for baseline *i,j* to be G_{ij}, so you need to determine $N_{baseline}$ factors G_{ij},
- If calibration factors into antenna-based factors. so calibration for baseline *i,j* then $G_{ij} = G_i \times G_j$, and you need only N factors G_i - much easier if N is large
- Luckily many effects *are* antenna dependent – that is they effect all baselines to any antenna (at some given time) the same way.

Rationale for Antenna-Based Solution





Antenna-based Calibration and Closure

- Success of synthesis telescopes relies on antenna-based calibration
  - Fundamentally, any information that can be factored into antenna-based terms, could *be* antenna-based effects, and not source visibility
  - For N_{ant} > 3, source visibility information cannot be *entirely* obliterated by any antenna-based calibration
- Observables independent of antenna-based calibration:
  - Closure phase (3 baselines):

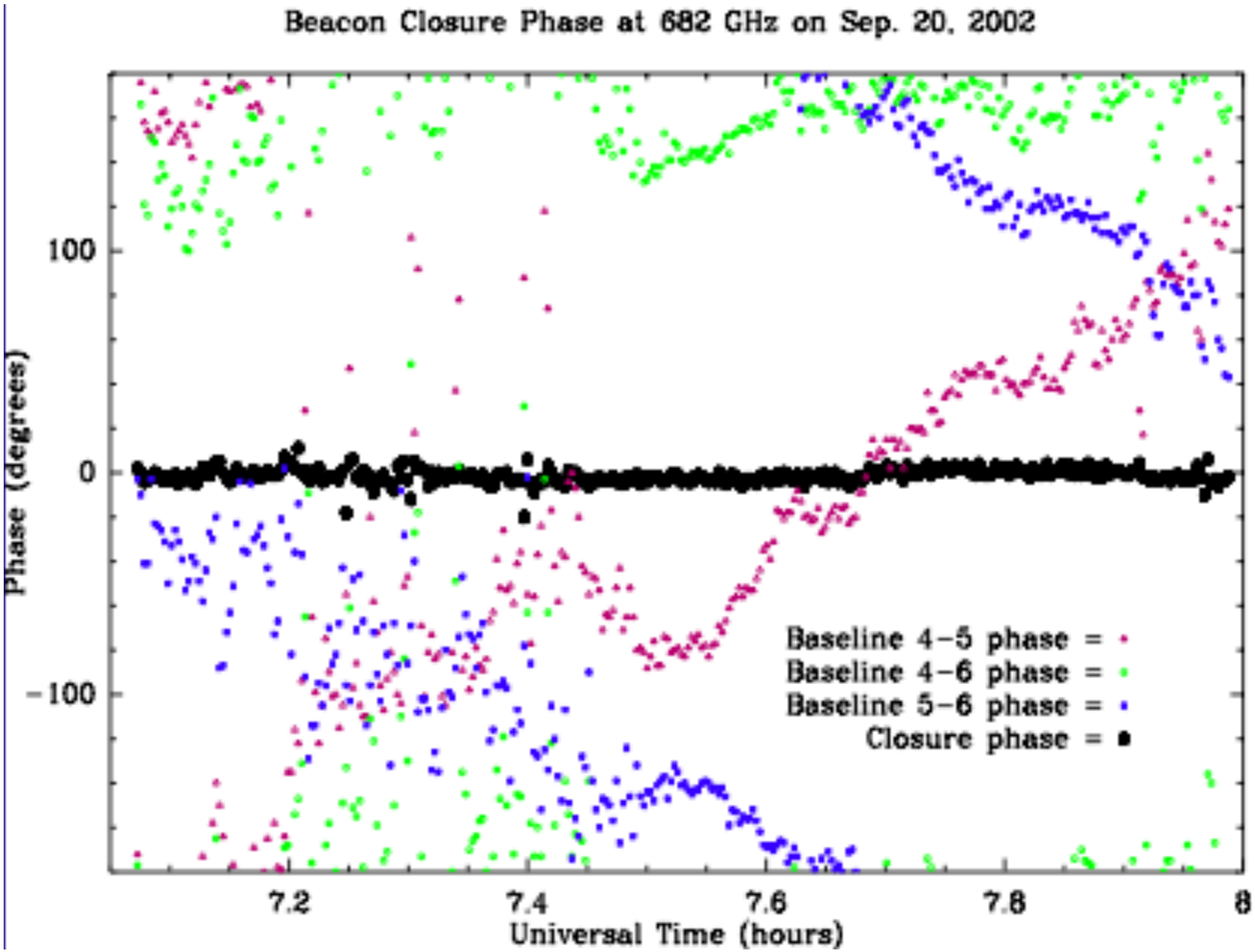
$$\phi_{ij}^{obs} + \phi_{jk}^{obs} + \phi_{ki}^{obs} = \left(\phi_{ij}^{true} + \theta_i - \theta_j\right) + \left(\phi_{jk}^{true} + \theta_j - \theta_k\right) + \left(\phi_{ki}^{true} + \theta_k - \theta_i\right)$$

$$= \phi_{ij}^{true} + \phi_{jk}^{true} + \phi_{ki}^{true}$$

  - Closure amplitude (4 baselines):

$$\left|\frac{V_{ij}^{obs} V_{kl}^{obs}}{V_{ik}^{obs} V_{jl}^{obs}}\right| = \left|\frac{J_i J_j V_{ij}^{true} J_k J_l V_{kl}^{true}}{J_i J_k V_{ik}^{true} J_j J_l V_{jl}^{true}}\right| = \left|\frac{V_{ij}^{true} V_{kl}^{true}}{V_{ik}^{true} V_{jl}^{true}}\right|$$

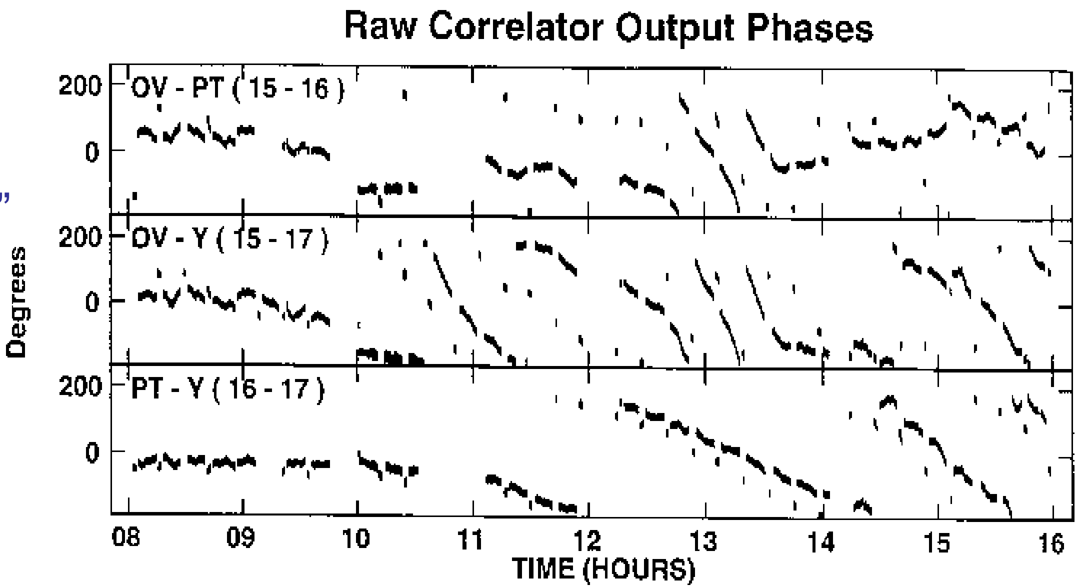
Closure Phase



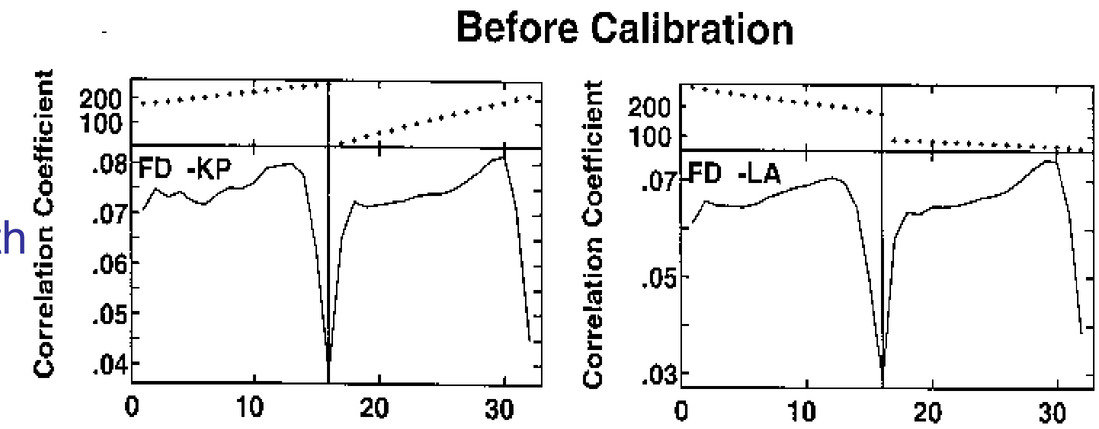
Sub-millimetere Array 682 GHz

Fringe Fitting

- Raw correlator output has phase slopes in time and frequency
  - Slope in time is “fringe rate”
    - Usually from imperfect troposphere or ionosphere model
  - Slope of visibility phase in frequency is “delay”
    - A phase slope because $\phi = \upsilon \tau$
    - Fluctuations worse at low frequency because of ionosphere
    - Troposphere affects all frequencies equally ("nondispersive")
- Fringe fit is self-calibration with first derivatives in time and frequency



S. Doeleman



Channel (corresponds to frequency)

Why do we need to Fringe Fit?

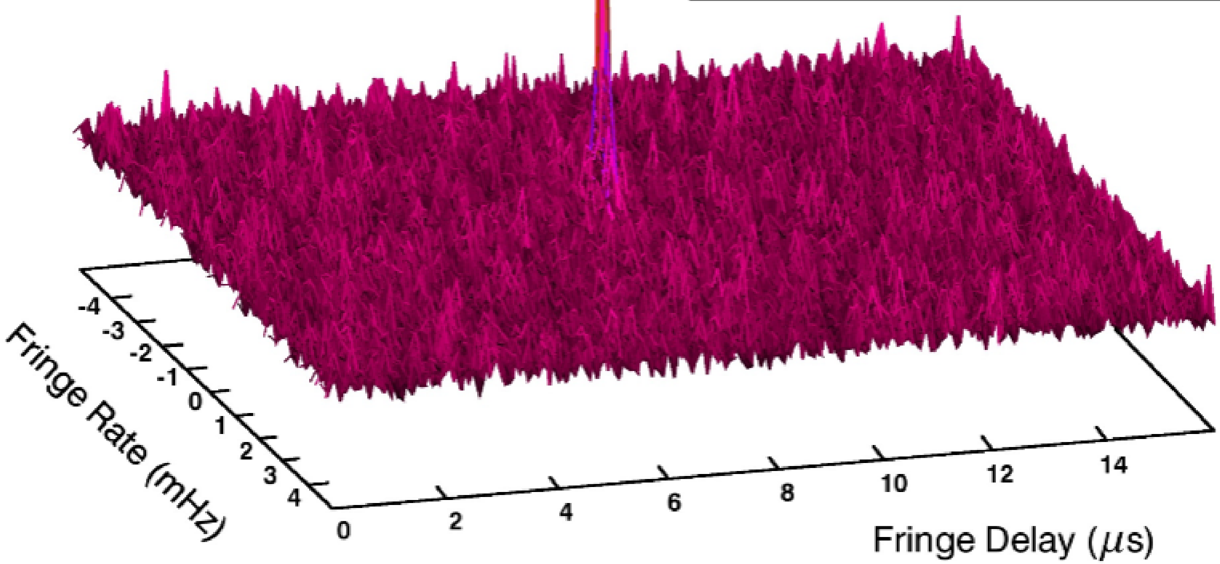
- Correlator model is good, but not perfect
  - Typically, antenna models and locations are now very good, but...
  - Source positions are often not known at the milliarcsecond level. Sometimes sources move
- Atmosphere and ionosphere are time-variable and unpredictable
- Clock information has significant errors at the VLBI level of accuracy

Fringes: Example

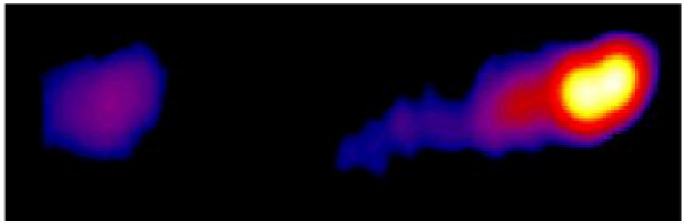
November 15, 2011
Wavelength 18 cm

Baseline projection: 50 Mλ

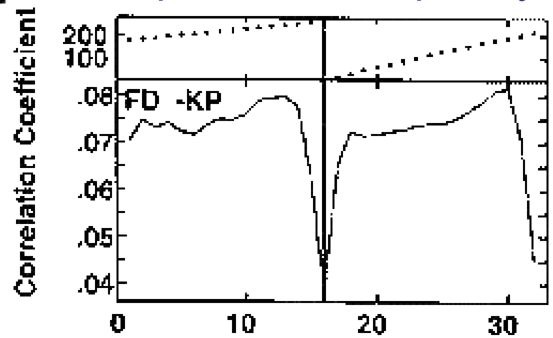
SRT-Effelsberg



Interferometric signal
from quasar 0212+735



Raw phase vs. frequency



The Delay Model

For an 8000 km baseline,
1 milliarcsec
= 3.9 cm
= 130 picosec

Adapted from Sovers et al., 1998
Reviews of Modern Physics

Item	Approx Max.	Time scale
Zero order geometry.	6000 km	1 day
Nutation	~ 20”	< 18.6 yr
Precession	~ 0.5 arcmin/yr	years
Annual aberration.	20"	1 year
Retarded baseline.	20 m	1 day
Gravitational delay.	4 mas @ 90° from sun	1 year
Tectonic motion.	10 cm/yr	years
Solid Earth Tide	50 cm	12 hr
Pole Tide	2 cm	~1 yr
Ocean Loading	2 cm	12 hr
Atmospheric Loading	2 cm	weeks
Post-glacial Rebound	several mm/yr	years
Polar motion	0.5 arcsec	~ 1.2 years
UT1 (Earth rotation)	Several mas	Various
Ionosphere	~ 2 m at 2 GHz	All
Dry Troposphere	2.3 m at zenith	hours to days
Wet Troposphere	0 – 30 cm at zenith	All
Antenna structure	<10 m. 1cm thermal	—
Parallactic angle	0.5 turn	hours
Station clocks	few microsec	hours
Source structure	5 cm	years

VLBI Amplitude Calibration

$$S_{cij} = \rho \frac{A}{\eta_s} \sqrt{\frac{T_{si} T_{sj}}{K_i K_j e^{-\tau_i} e^{-\tau_j}}}$$

S_{cij} = Correlated flux density on baseline *i - j*

ρ = Measured (normalized) correlation coefficient (amplitude 0 to 1)

A = Correlator specific scaling factor

η_s = System efficiency including digitization losses

T_s = System temperature

Includes receiver, spillover, atmosphere, blockage

K = Gain in degrees K per Jansky

Includes dependence of antenna gain on elevation

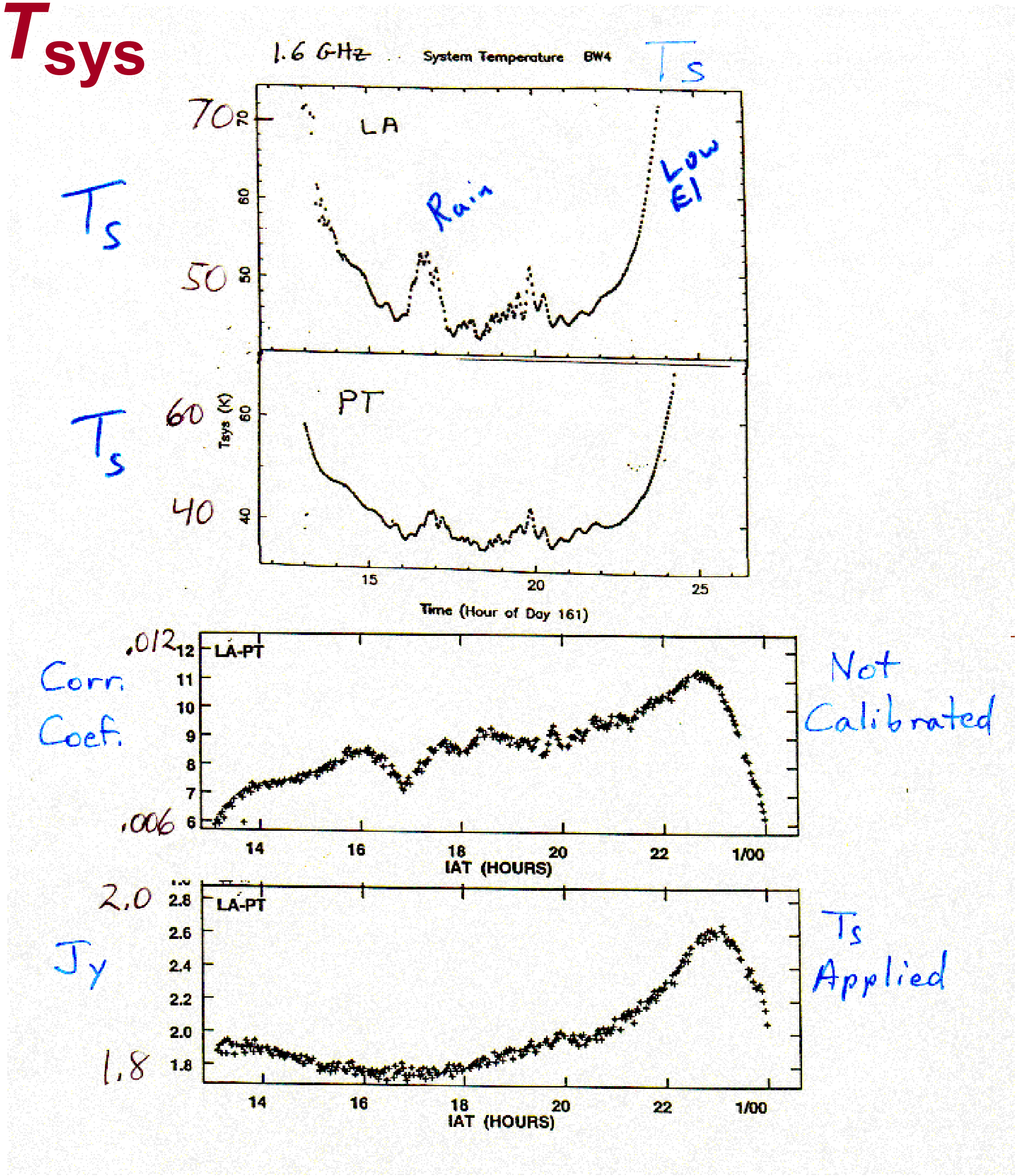
$e^{-\tau}$ = Absorption in atmosphere

Note T_s/K = *SEFD* (System Equivalent Flux Density)

Calibration with T_{sys}

Example shows removal of effect of increased T_{sys} due to rain and low elevation

The noise does not correlate, between two antennas, so adding more noise decreases any correlation and thus the signal we are interested in



Phase Referencing

- One kind of antenna-based cross- calibration
- Observe a calibrator source nearby your target
- Calibrator source needs to have accurately known position and ideally be point-like
- Derive calibration: complex gains (amplitude and phase), rates, delays from calibrator
- Transfer them to target

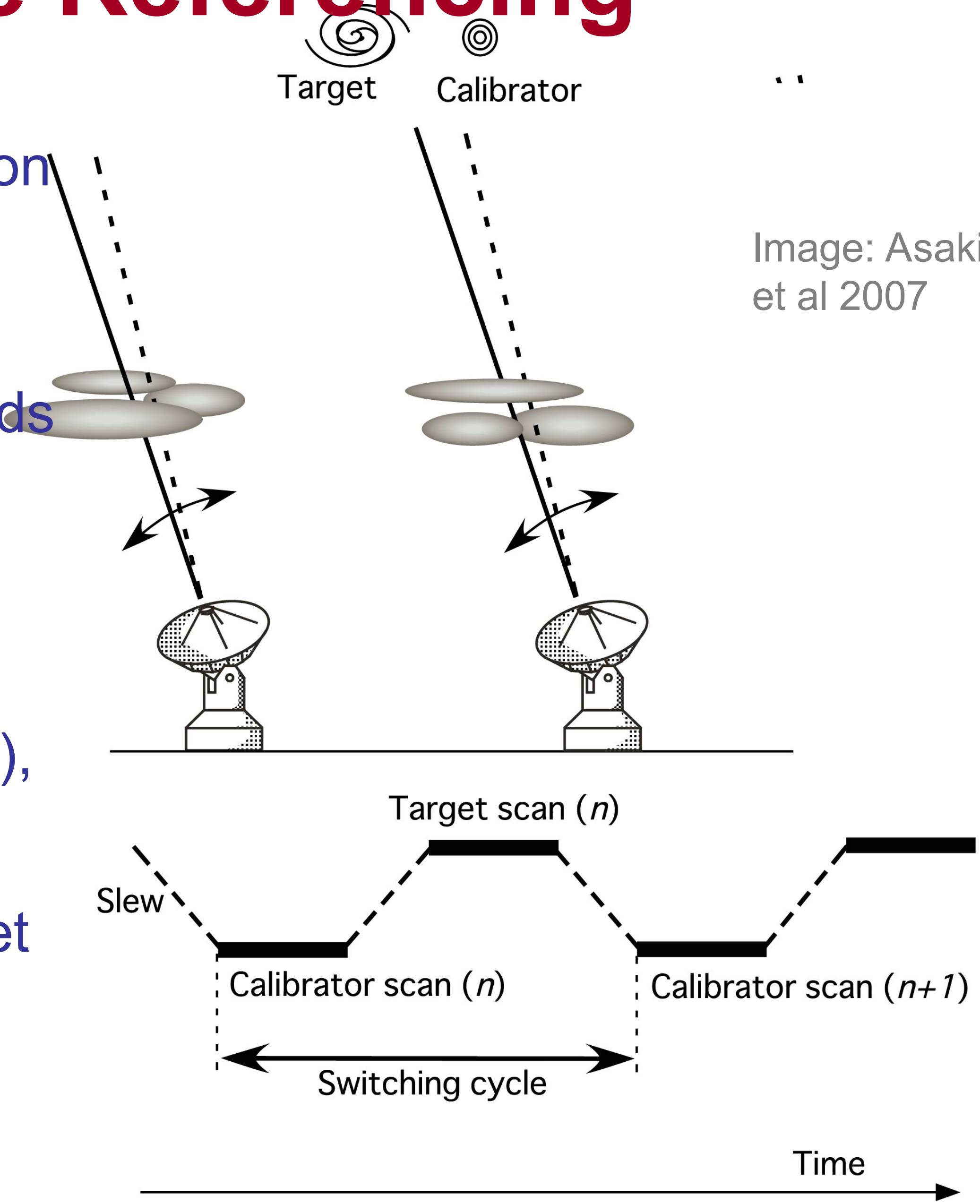
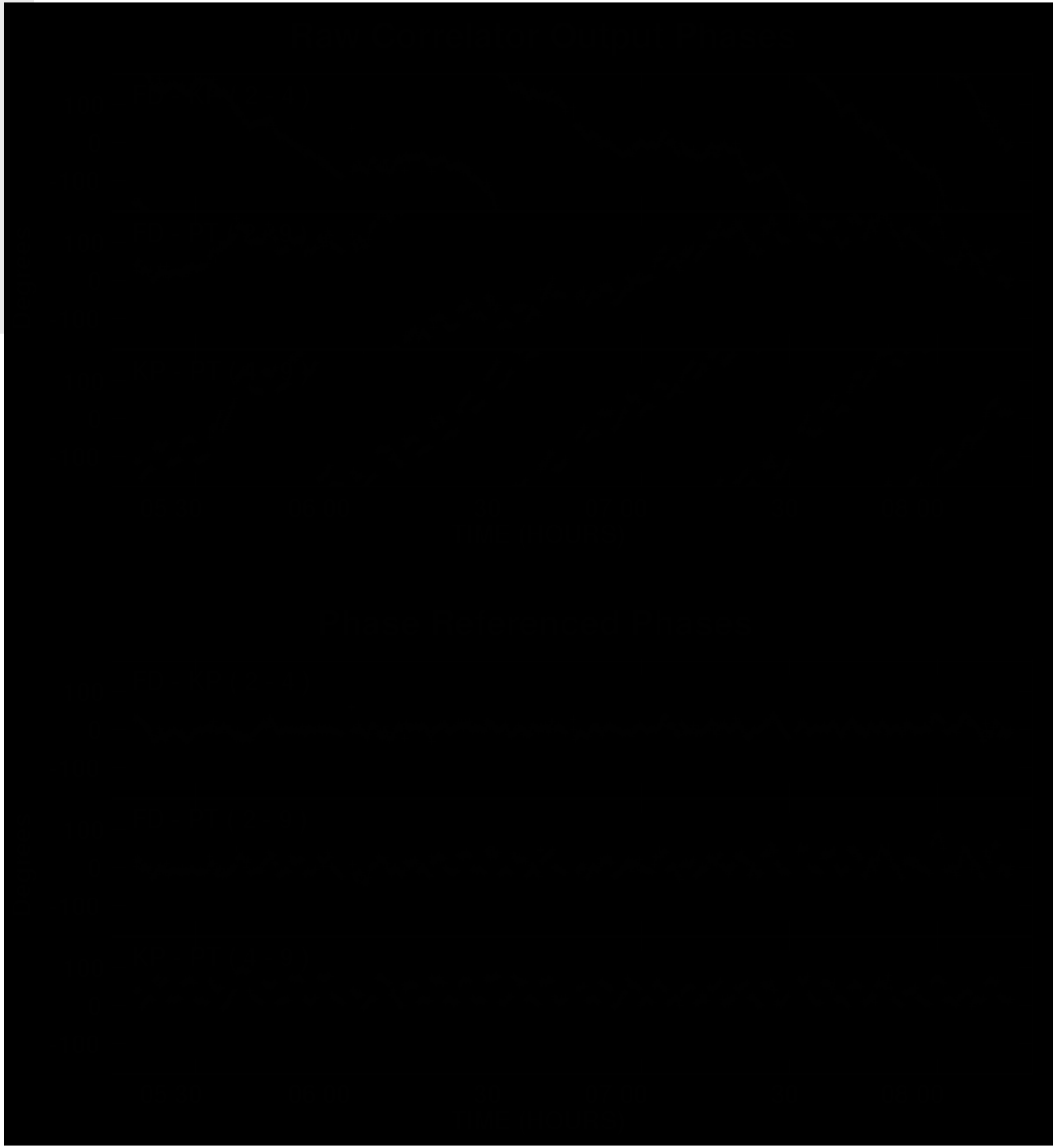


Image: Asaki et al 2007

Example of Referenced Phases

- 6 min cycle – 3 min on each source
- Visibility phases of one source were self-calibrated (so after calibration, phases are near zero)
- Phases of the visibilities of the other source phase-shifted by same amount

Slide: Lo & Cornwell



Stages of a VLBI project

1. Formulate observational science question(s) you wish to investigate.
2. Consider practical observational details:

   -- desired angular resolution, field of view, image sensitivity, observing frequencies, spectral resolution, polarization, temporal coverage

   -- select an appropriate telescope/array
3. Submit an observing proposal
4. Construct an observing schedule file
5. Download, reduce, and analyze the data
6. Publish your results
7. Book your ticket to the Nobel ceremoniy in Stockholm

Slide from Matt Lister,
Purdue U., USA

Summary

- Very Long Baseline Interferometry, VLBI, is the process of using unconnected telescopes, typically 1000’s of km apart, to form an interferometer
- Signals from each telescope must be brought to a *correlator,* which cross correlates the signals from pairs of antennas
- VLBI allows high angular resolution, milliarcseconds or less (depending on frequency). Such high resolution is only possible with VLBI
- Many astronomical sources have structure on such small angular scales, which can therefore only be resolved with VLBI
- VLBI can also provide very accurate measurements of position on the sky
- There are significant challenges in doing VLBI: the signals have to be aligned in time very accurately, and the relative positions of the telescopes have to be known very accurately
- Delay as signals propagate through the atmosphere is not well known and time-variable. Mostly calibration is done in a relative manner, by using reference sources with well known positions and structures.