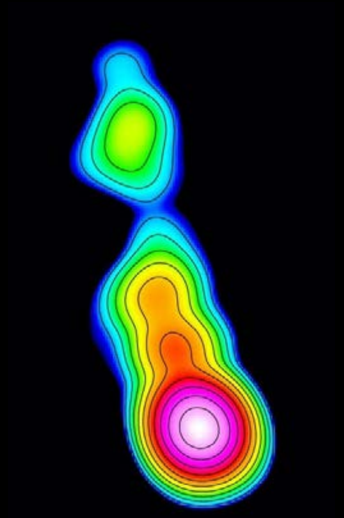
Space VLBI
---- RadioAstron



Rui Huang

Instructed by Prof. Xu Dandan and Prof. Zhou Jianfeng

Outline

- Introduction
- VLBI technology
- RadioAstron
- Science contribution

Radio Telescopes: Resolution

- Resolving power (how small of a thing you can "see") depends on the size of the telescope and the wavelength of the light

$$\frac{\lambda}{\text{size}}$$

λ ← For radio waves, this is large…

size ← So this must also be large

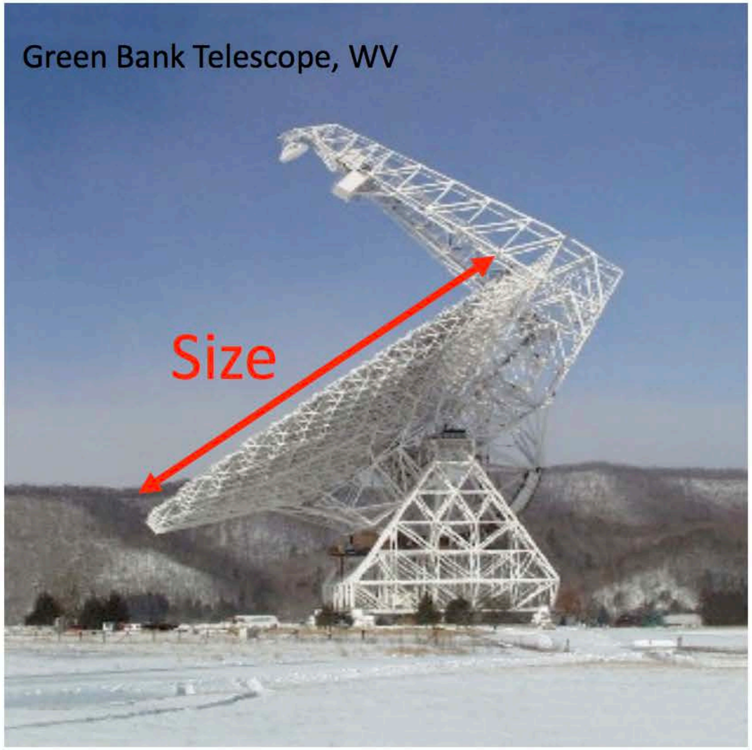
- "Size" = diameter of telescope for single dish; maximum distance between telescopes for arrays

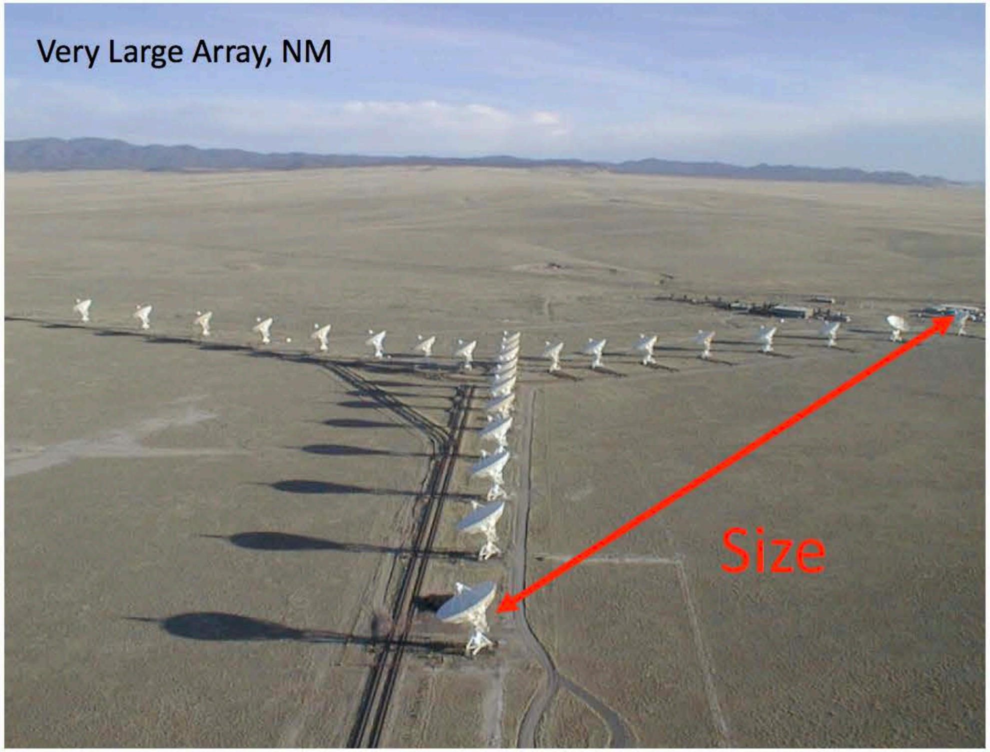
10^{-6}m 10^{-1}m

HST: 0.05'' @2.4m FAST: 3'@500m

Radio Telescopes: Resolution

VLBI: Very Long Baseline Interferometry



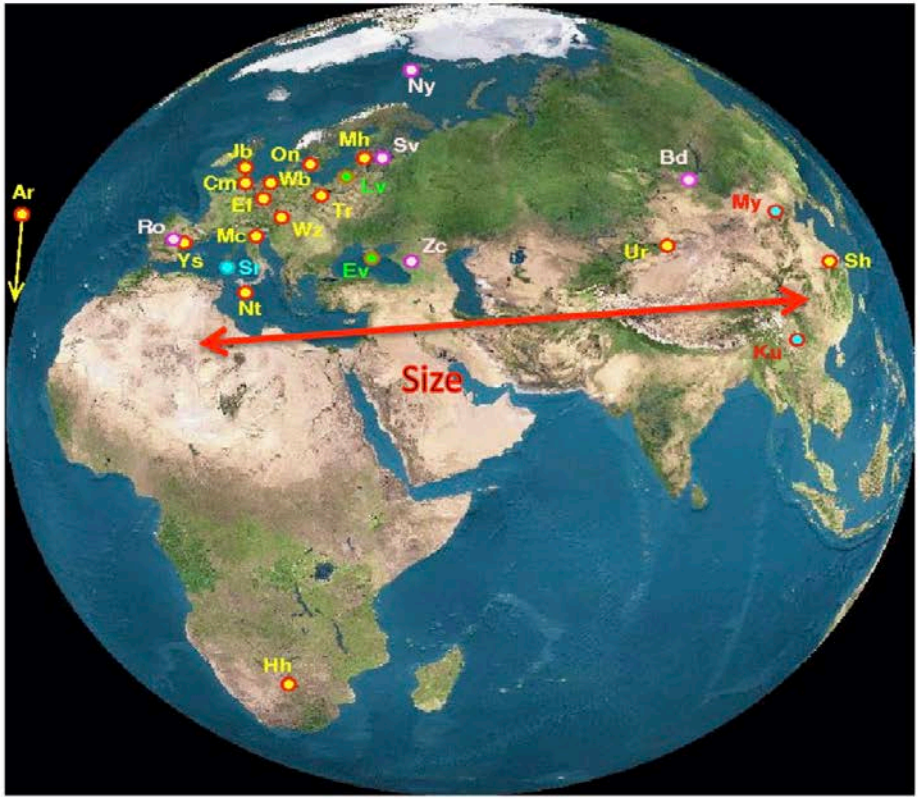


Single Dish

Connected Arrays

European VLBI Network

Very Long Baseline Interferometry



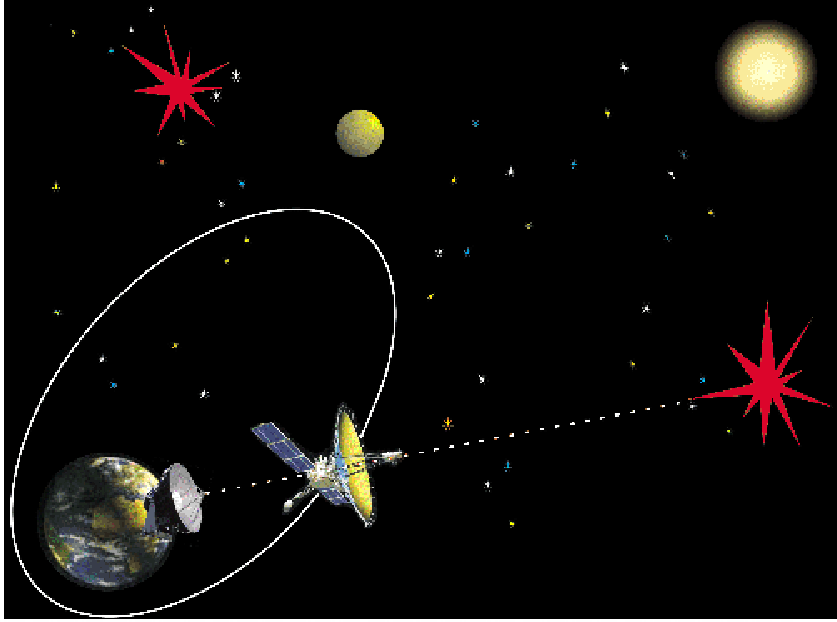
VLBI array

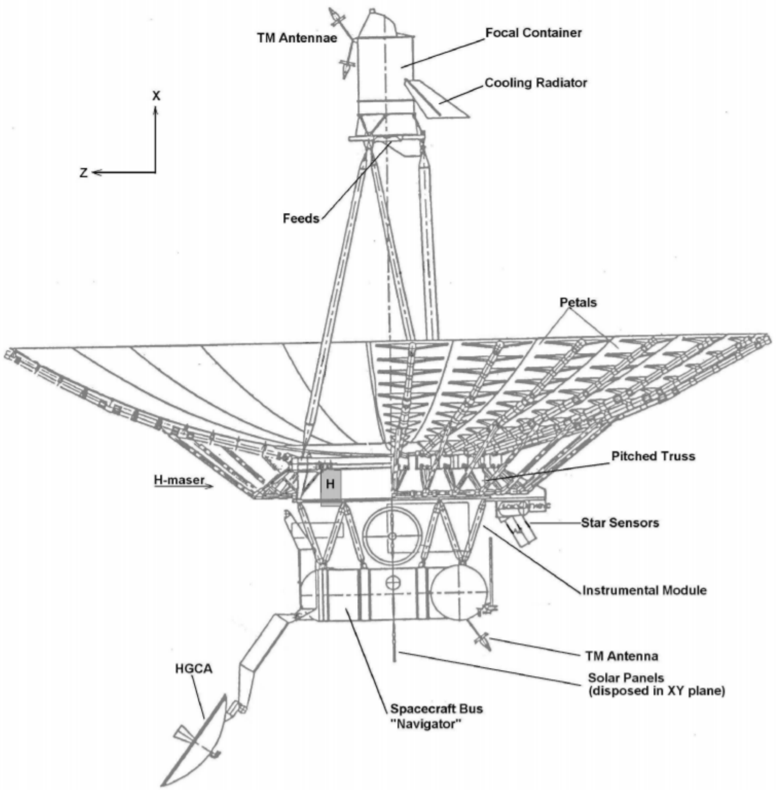
HST: 0.05'' @2.4m FAST: 3'@500m,1GHz

VLBI: 0.01'' @6000km,1GHz

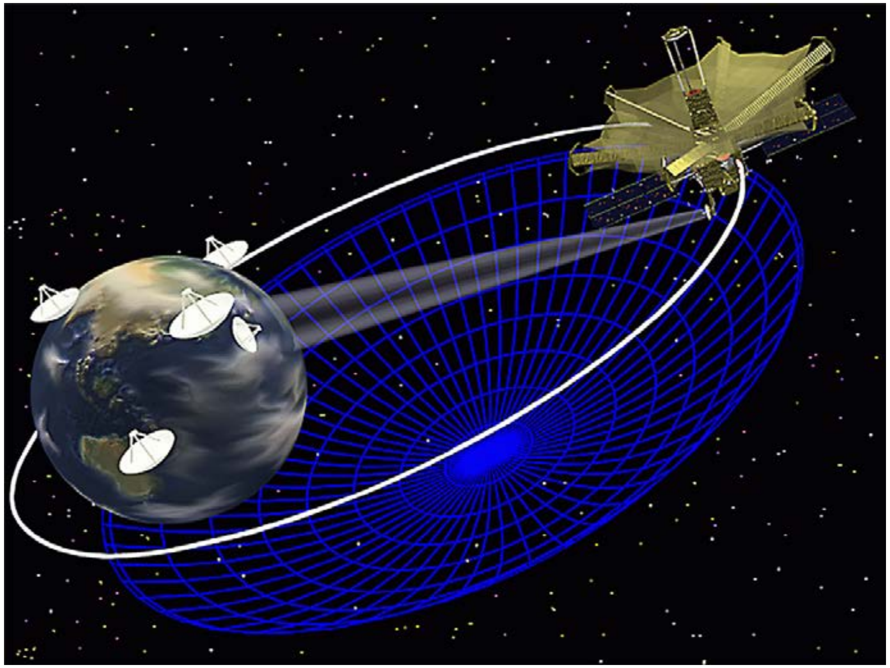
RadioAstron

- Russian
- Launched in 2011
- 10m
- Very elliptical orbit
  - Perigee 7,000 ~ 80,000 km
  - Apogee: 270,000 ~ 370,000 km,
  - Period of 8 to 9 days
- fringe size of 7 μas at the highest frequency and the longest baselines





VSOP(VLBI Space Observatory Programme)



- Japan
- 1997 → 2003
- 8m
- Baseline of twice the diameter of Earth

How VLBI works?

- **Two** element **quasi-monochromatic** interferometer
- Receive signals V_1 and V_2 caused by geometry delay

$$V_1 = V cos[\omega(t - \tau_g)]$$
$$V_2 = V cos(\omega t)$$

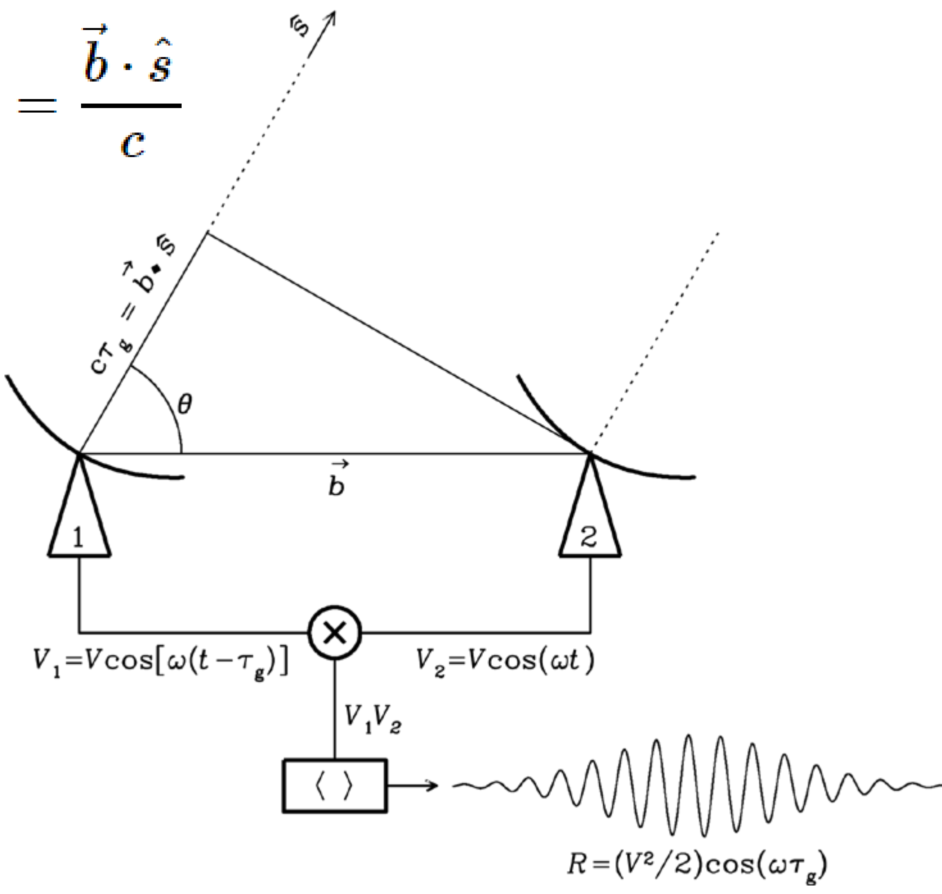
$$\tau_g = \frac{\vec{b} \cdot \hat{s}}{c}$$

- Cross Correlator

$$V_1 V_2 = V_2 \cos[\omega(t - \tau_g)] \cos(\omega t)$$
$$= \frac{V^2}{2} [\cos(2\omega t - \omega\tau_g) + \cos(\omega\tau_g)]$$

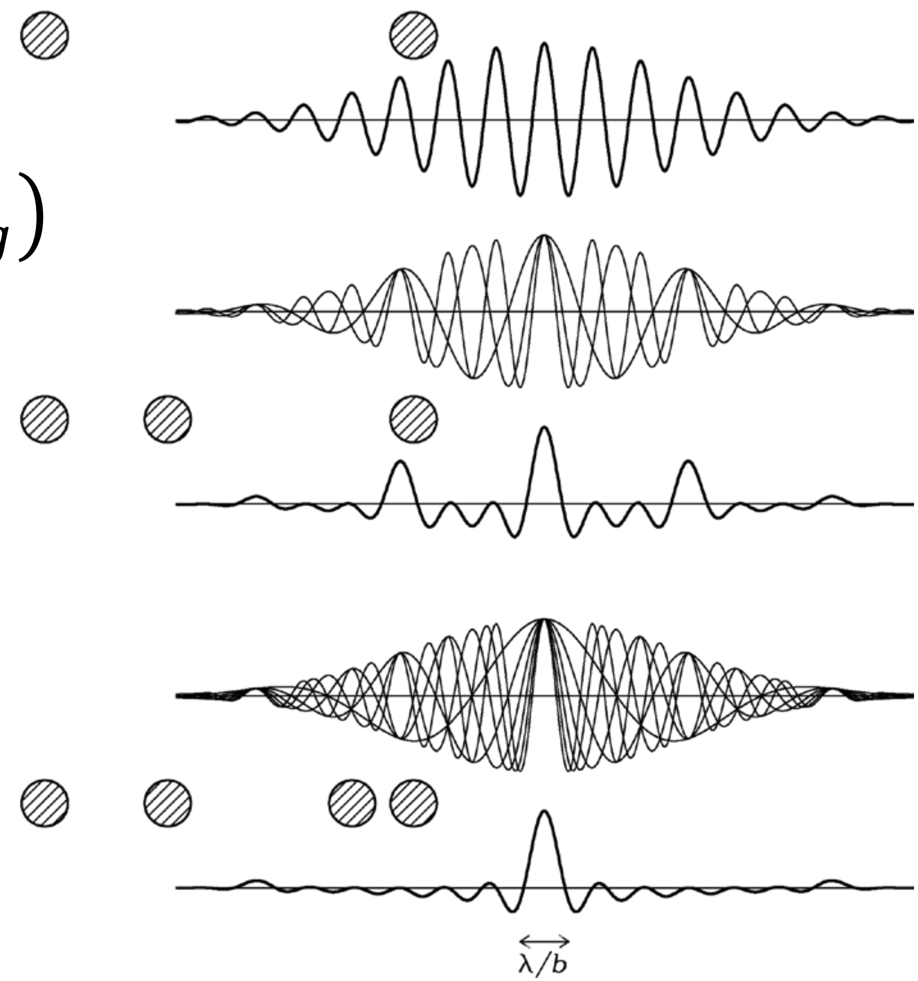
- Take time average long enough

$$R = \langle V_1 V_2 \rangle = (\frac{V^2}{2}) \cos(\omega\tau_g)$$



More element?

$$R = \langle V_1 V_2 \rangle = \left(\frac{V^2}{2}\right)\cos(\omega\tau_g)$$
$$= \left(\frac{V^2}{2}\right)\cos\left(\omega\hat{b}\cdot\frac{\hat{s}}{c}\right)$$
$$= \left(\frac{V^2}{2}\right)\cos(2\pi\frac{\hat{b}}{\lambda}\cdot\hat{s})$$



synthesized beam

Slightly Extended Sources?

$$R = \langle V_1 V_2 \rangle = (\frac{V^2}{2})\cos(\omega\tau_g) = (\frac{V^2}{2})\cos(\omega\hat{b}\cdot\hat{s}/c)$$

$$R_c = \int I_\nu(\hat{s})\cos\left(2\pi\nu\hat{b}\cdot\hat{s}/c\right) d\Omega$$

$$R_s = \int I_\nu(\hat{s})\sin\left(2\pi\nu\hat{b}\cdot\hat{s}/c\right) d\Omega$$

$$\mathcal{V} = \int I_\nu(\hat{s})\exp\left(2\pi\hat{b}\cdot\hat{s}/\lambda\right) d\Omega$$

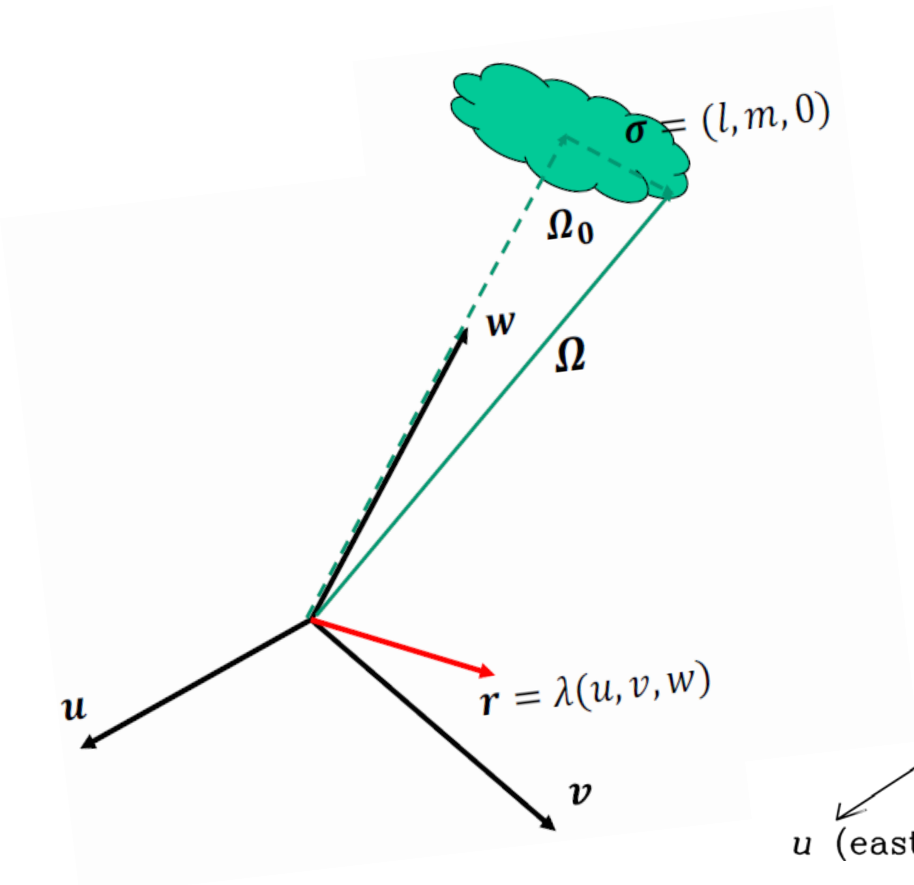
$$\mathcal{V} = Ae^{-i\phi},$$

$$A = (R_c^2 + R_s^2)^{1/2}$$

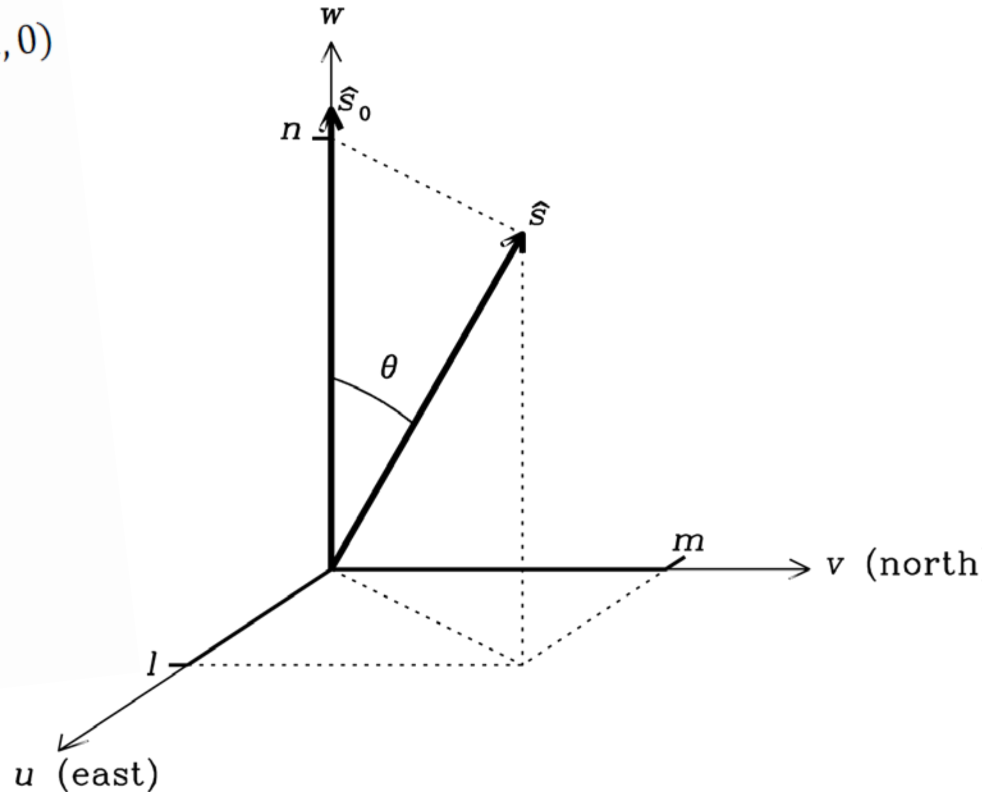
$$e^{i\phi} = \cos\phi + i\sin\phi.$$

Visibility:

$$\mathcal{V} = \int I(\hat{s})\exp\left(-i2\pi\vec{b}\cdot\hat{s}/\lambda\right)\ d\Omega.$$



σ = (l, m, 0)
Ω0
w
Ω
u
r = λ(u, v, w)
v



w
ŝ0
n
ŝ
θ
m
v (north)
l
u (east)

UV plane

$\hat{s} = (l, m, n); \hat{b} = (u, v, \omega)$

$$\mathcal{V} = \int I(\hat{s}) \exp\left(-i2\pi\vec{b}\cdot\hat{s}/\lambda\right) \; d\Omega.$$

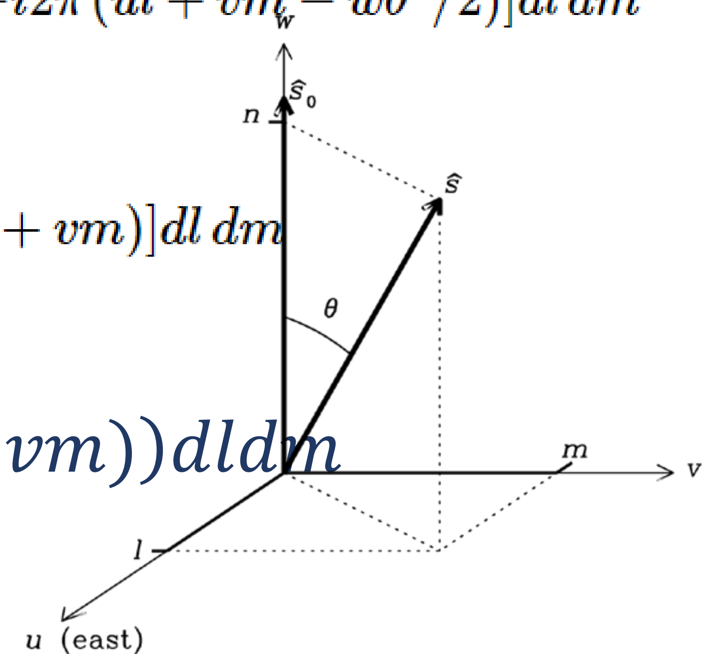
$$d\Omega = \frac{dl\,dm}{\left(1 - l^2 - m^2\right)^{1/2}},$$

$$\mathcal{V}(u,v,w) = \int\int \frac{I_\nu(l,m)}{\left(1 - l^2 - m^2\right)^{1/2}} \exp\left[-i2\pi\left(ul + vm + wn\right)\right] dl\,dm.$$

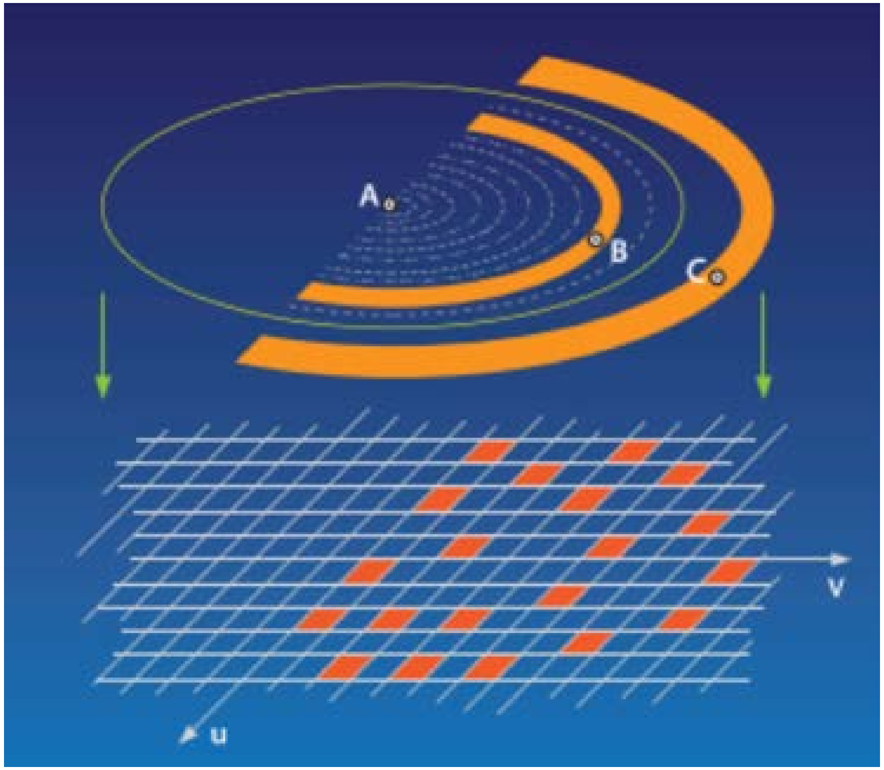
$$\mathcal{V}(u,v,w) \approx \exp(-i2\pi w) \int\int \frac{I_\nu(l,m)}{\left(1 - l^2 - m^2\right)^{1/2}} \exp[-i2\pi\left(ul + vm - w\theta^2/2\right)] dl\,dm$$

$$\mathcal{V}\exp(i2\pi w) = \int\int \frac{I_\nu(l,m)}{\left(1 - l^2 - m^2\right)^{1/2}} \exp[-i2\pi\left(ul + vm\right)] dl\,dm$$

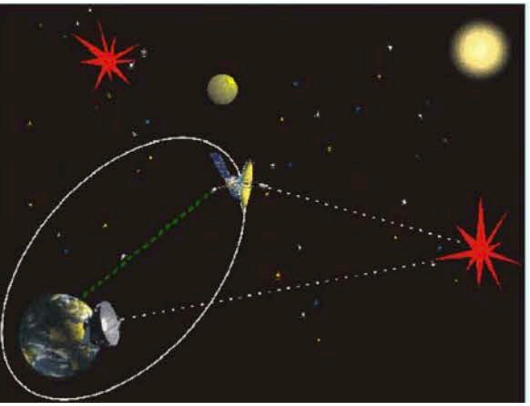
- $I(l,m) = \iint V'(u,v) \exp(i2\,\pi(ul + vm))dldm$

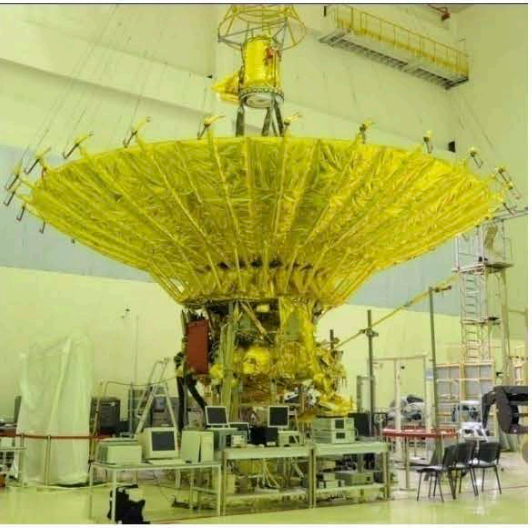


- If all of the (u,v) plane can be filled with data, we can obtain almost the same detail as that measured with a filled aperture of the same size.



RadioAstron: general information





- ✓ Space radio telescope: 10 meters diameter
- ✓ Launch in 2011, significantly delayed from original schedule
- ✓ Frequency bands: 0.3, 1.6, 5, 22 (18-25) GHz (H, L, C, K)
- ✓ Highest resolution (at 1.3 cm): ~7 μas.
- ✓ Orbit: gravitationally perturbed by Moon, perigee ≥ 10,000 km, apogee ~300,000 km, ~9 days period
- ✓ Five methods of orbit measurements including Doppler measurements, laser ranging, VLBI.
- ✓ Required accuracy of the orbit reconstructon: distance 500 m, velocity 2 cm/s.
- ✓ Expected lifetime: 5 years (general estimate)
- ✓ Control stations: Ussurijsk, Bear Lakes.
- ✓ Tracking station: Pushchino, Russia; Green Bank, USA; South Africa – expected.
- ✓ Bitrate: 128 Mbps coming from space.
- ✓ Two methods of time synchronization: on-board (open loop at 8 and 15 GHz) and ground (closed loop at 7, 8, and15 GHz) hydrogen maser.
- ✓ Software correlators: ASC, DiFX-Bonn, JIVE SFXC.

All GRTs involves in interferometry: about 30

- Kvazar network: Sv,Bd,Zc(Russia);
- Kalyazin (Russia);
- Evpatoriya (Ukraine);
- Effelsberg (Germany)
- WSRT (the Netherlands);
- Torun (Poland);
- Medicina, Noto, Sardinia (Italy);
- Yebes (Spain);
- Jodrell Bank 1 & 2 (UK);
- Robledo (Spain);
- Usuda (Japan);
- Shanghai 25 & 64, Urumqi (China);
- VLA,GBT,Arecibo (USA);
- HartRAO (South Africa);
- Networks: EVN,LBA:KVN,VLBA,global.

“officially amazing”


GUINNESS WORLD RECORDS

CERTIFICATE

The largest radio space telescope
is the Spektr-R,
which is 10 metres across,
and was launched from the
Baikonur Cosmodrome
in Kazakhstan,
on 18 July 2011

OFFICIALLY AMAZING

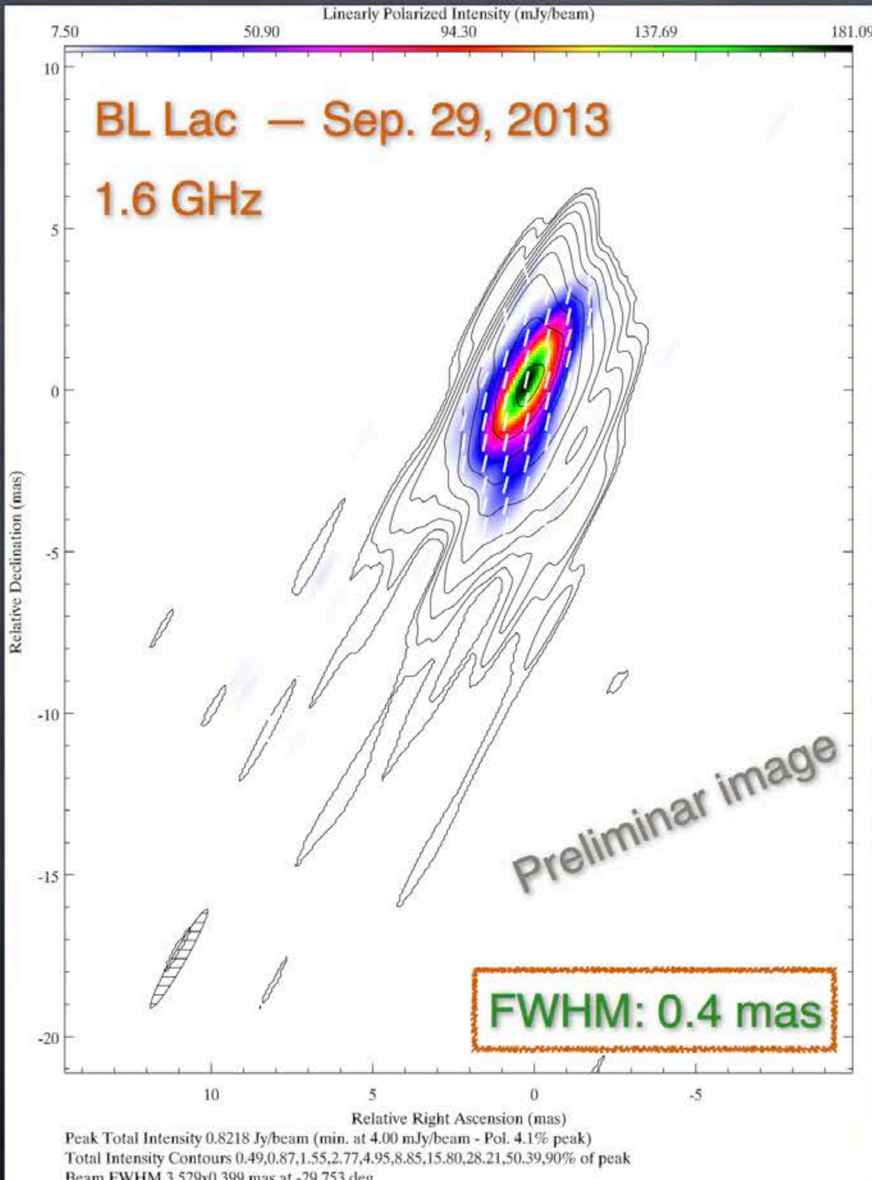
Science contribution

Bright Radio compact source

- Imaging program
  - Center supermasive blackhole
  - AGN
  - Jet
- Interstellar Medium
- Maser
- ……

A KSP for polarimetric Space-VLBI with RadioAstron

First Science Observations



Achieved angular resolution:
FWHM: 3.53x0.40 mas

5σ sensitivity:
4 mJy/beam in Total
7.5 mJy/beam in Polarization

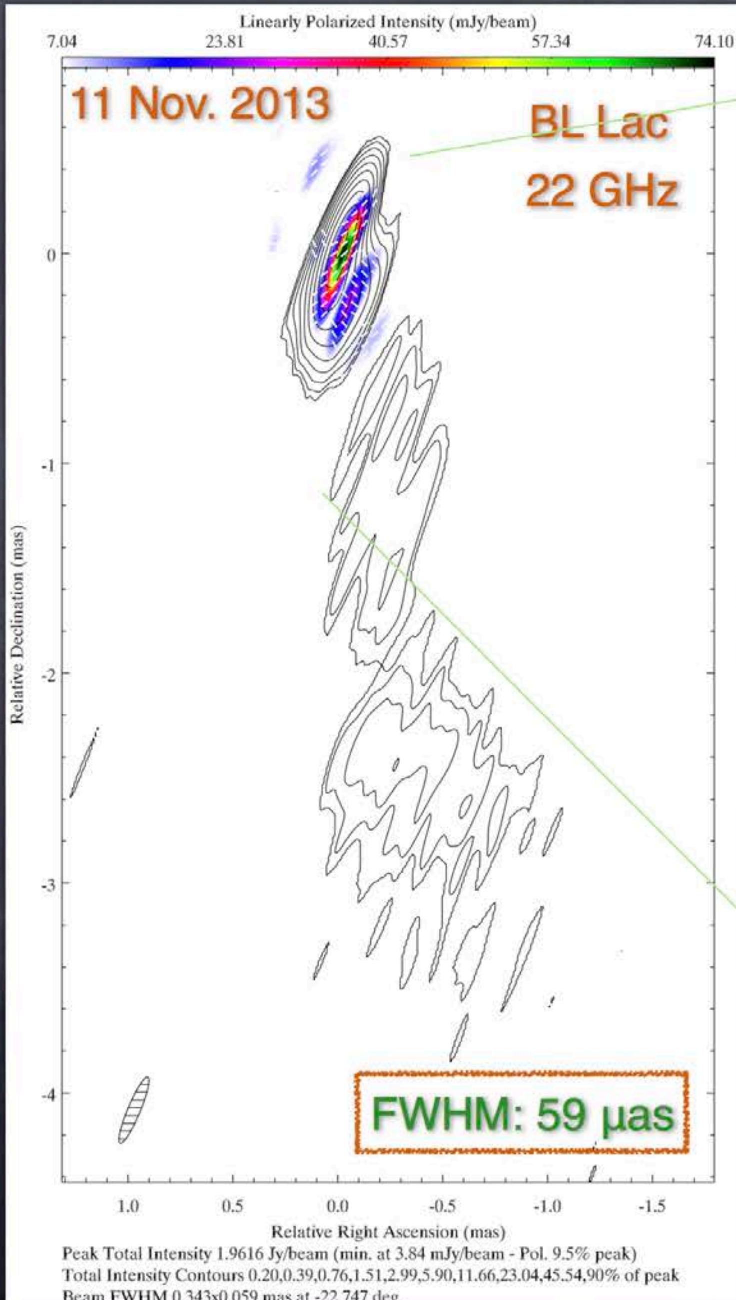
Recovered 4.84 Jy of 5.2 Jy (Effelsberg)

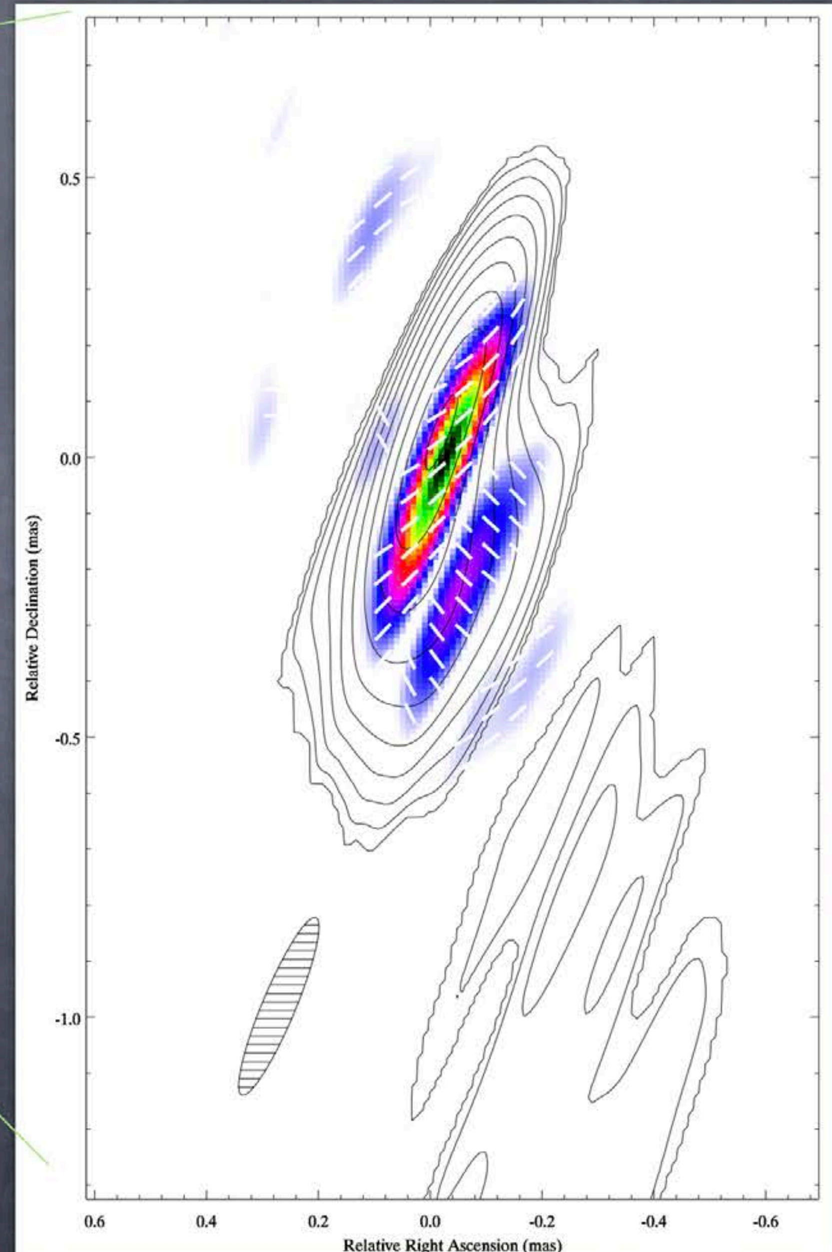
Total intensity image shows three different components, while polarization shows a single component with EVPAs in the direction of the jet.

Calibration of the EVPAs through comparison with Effelsberg.

Stole from J. L. Gómez's slide for COSPAR2014

A KSP for polarimetric Space-VLBI with RadioAstron

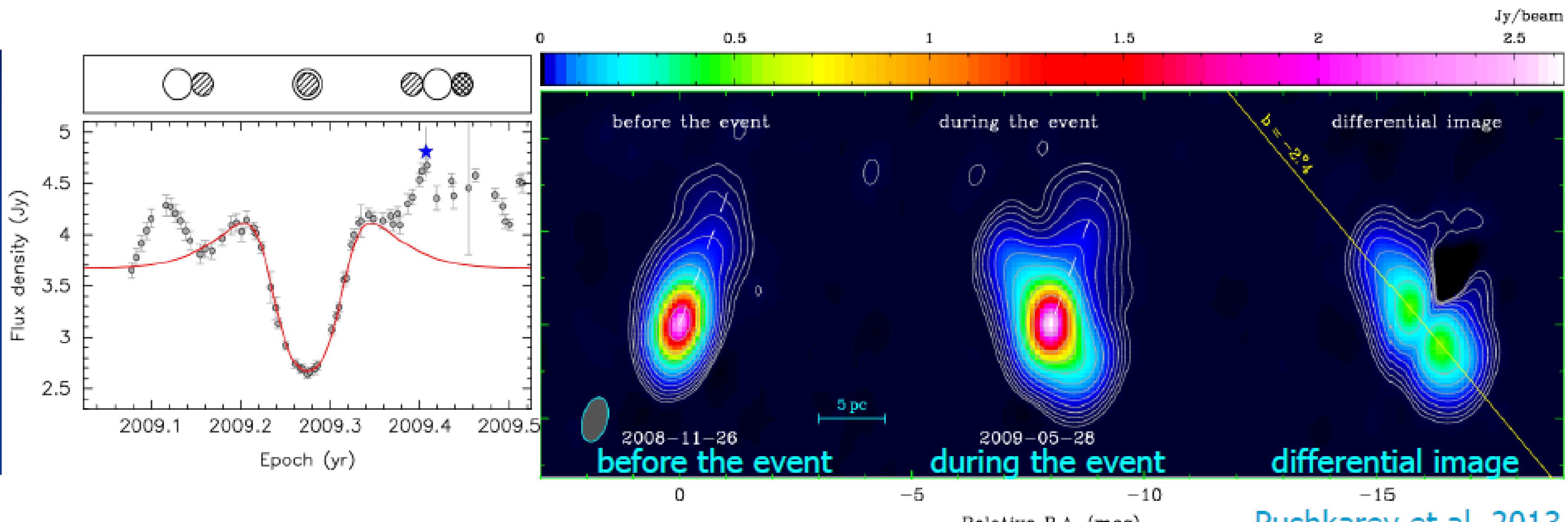




Interstellar Medium

- Radio emission from AGN as compact and strong radio sources is influenced by propagation effects

- First detection of multiple quasar imaging induced by anisotropic refraction in localized AU-sized plasma lenses in the interstellar medium.

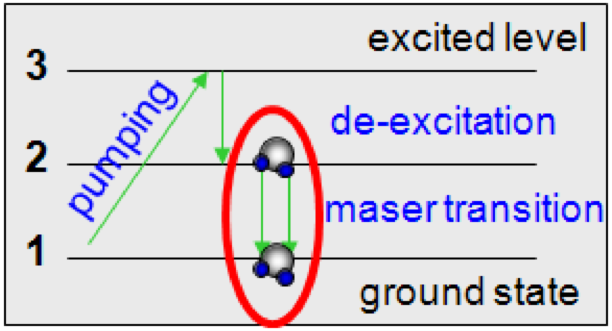


Pushkarev et al. 2013

RadioAstron study of galactic and extragalactic water masers

MASER Microwave Amplification by Stimulated Emission of Radiation

- RadioAstron has detected water maser emission from the circumnuclear disk of NGC 4258 galaxy
- Successful detection of interferometric fringes from very compact water maser feature associated with the nearest and well studied high-mass star-forming region Orion KL



Schematic of the stimulated emission process in a maser. The molecule is pumped to an excited state and decays non-radiatively to a metastable state where a population inversion is created. An incident photon of the correct frequency stimulates the emission of another photon of the same frequency, phase and direction and both are emitted simultaneously, thus amplifying the incident radiation field.

Summary

- VLBI
  - Baseline
  - Resolution
  - Depend on Time delay
  - Cross correlation
- Space VLBI   --great future
  - RadioAstro
    - 10 m
    - ~ 25 diameter
    - 10^{-5} arcsec
- Science contribution
  - High resolution substructure
  - Maser
  - ……

reference

- https://en.wikipedia.org/wiki/Very-long-baseline_interferometry
- https://science.nrao.edu/opportunities/courses/era/
- https://www.cv.nrao.edu/~sransom/web/Ch3.html
- http://www.asc.rssi.ru/radioastron/index.html
- COSPAR 2014 Report: ftp://www.asc.rssi.ru/COSPAR_2014