



International  
Centre for  
Radio  
Astronomy  
Research

# Very Long Baseline Interferometry (VLBI)

## *Potential, Challenges and Astrophysical Applications.*

Maria J. Rioja  
ICRAR-UWA & CSIRO

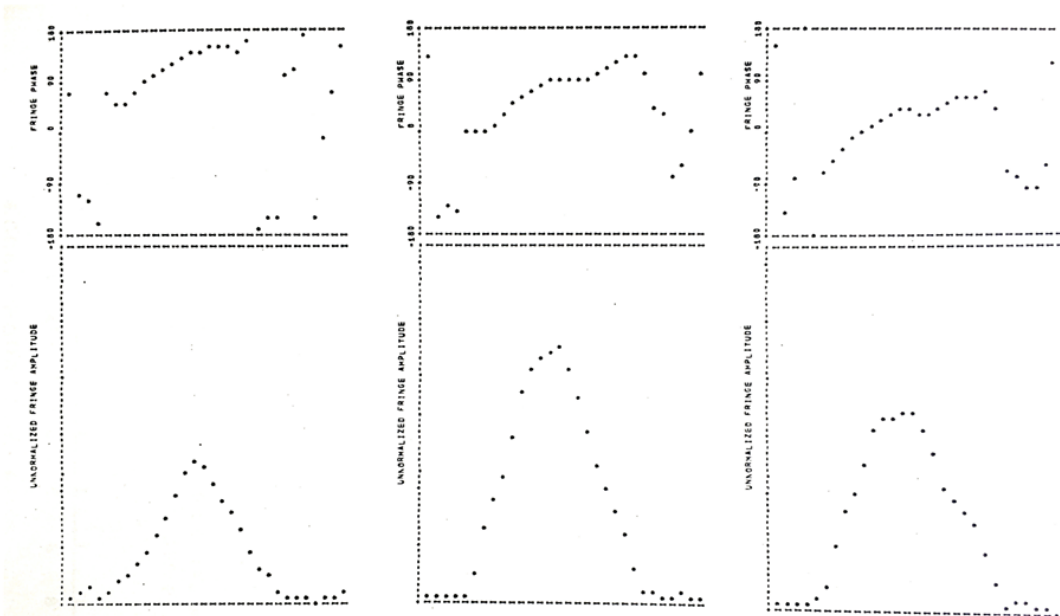


THE UNIVERSITY OF  
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# 50 Years of Very Long Baseline Interferometry (VLBI)

First VLBI measurement OH emission (J.Moran)



*Challenges and  
cal Applications.*

ia J. Rioja  
AR-UWA & CSIRO

The first VLBI measurements between Haystack and NRAO from data recorded June 8, 1967. (Image credit: Moran, J.M., 1968, "Interferometric Observations of Galactic OH Emission," PhD thesis, MIT, p. 160.)



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# Outline

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- VLBI holds the **POTENTIAL** for highest resolution and highest precision astrometry.
- **CHALLENGES** to overcome.
- A flavor of **WHAT ONE CAN DO** with high resolution and high precision astrometry.

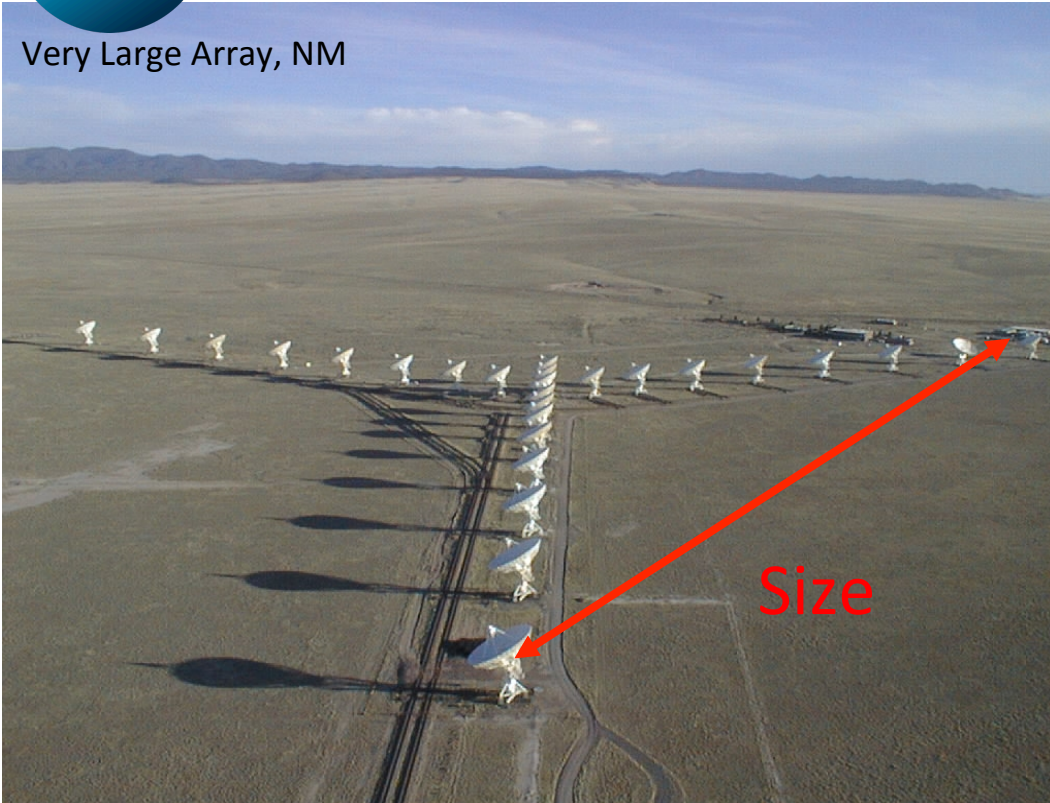




# Radio Telescopes: Resolution



Very Large Array, NM



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

Arrays

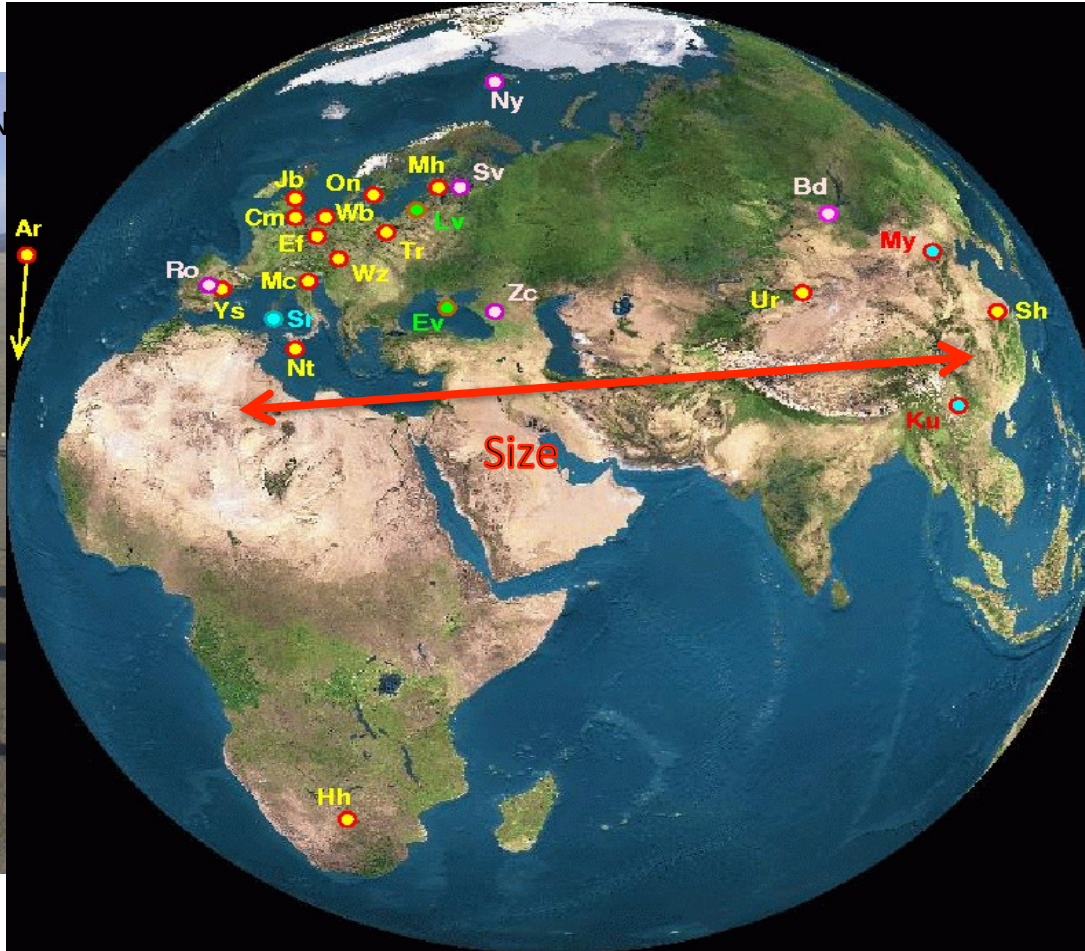
10 km



# Radio Telescopes: Resolution



Very Large Array, N



Arrays  
10 km

6000km



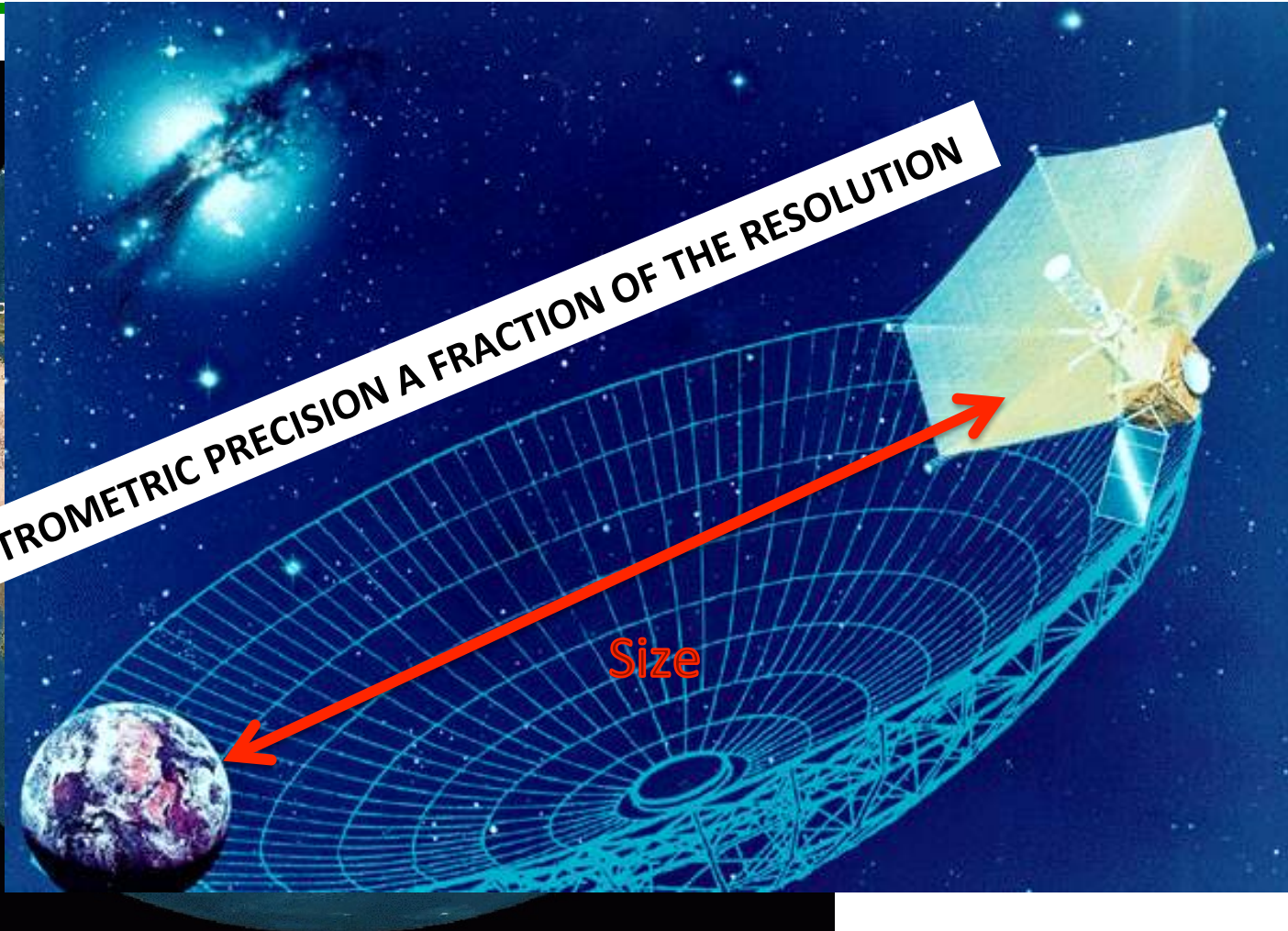
# Radio Telescopes: Resolution



Very Large Array, N



POTENTIAL: ASTROMETRIC PRECISION A FRACTION OF THE RESOLUTION



Arrays

10 km

250 mas

6000km

0.4 mas

20.000km; 350.000km

100  $\mu$ as ; 10  $\mu$ as

# VLBI provides.....

**HIGHER SPATIAL RESOLUTION** (*small  $\Theta_{\text{synt}}$* ):

**High resolution imaging and high precision astrometry**

**What they look like and where they are**

**TRADE-OFF WITH SENSITIVITY** (*collecting area and coh time*):

Targets: Very bright, compact ( $\rightarrow$  High  $T_B$  emission)

e.g.: Active Galactic Nuclei (AGNs), pulsars, supernova,  
astrophysical masers: SFR, AGB; grav. lenses...

**Calibration plays a significant role**

# Extreme interferometry: Very Long Baseline Interferometry (VLBI)

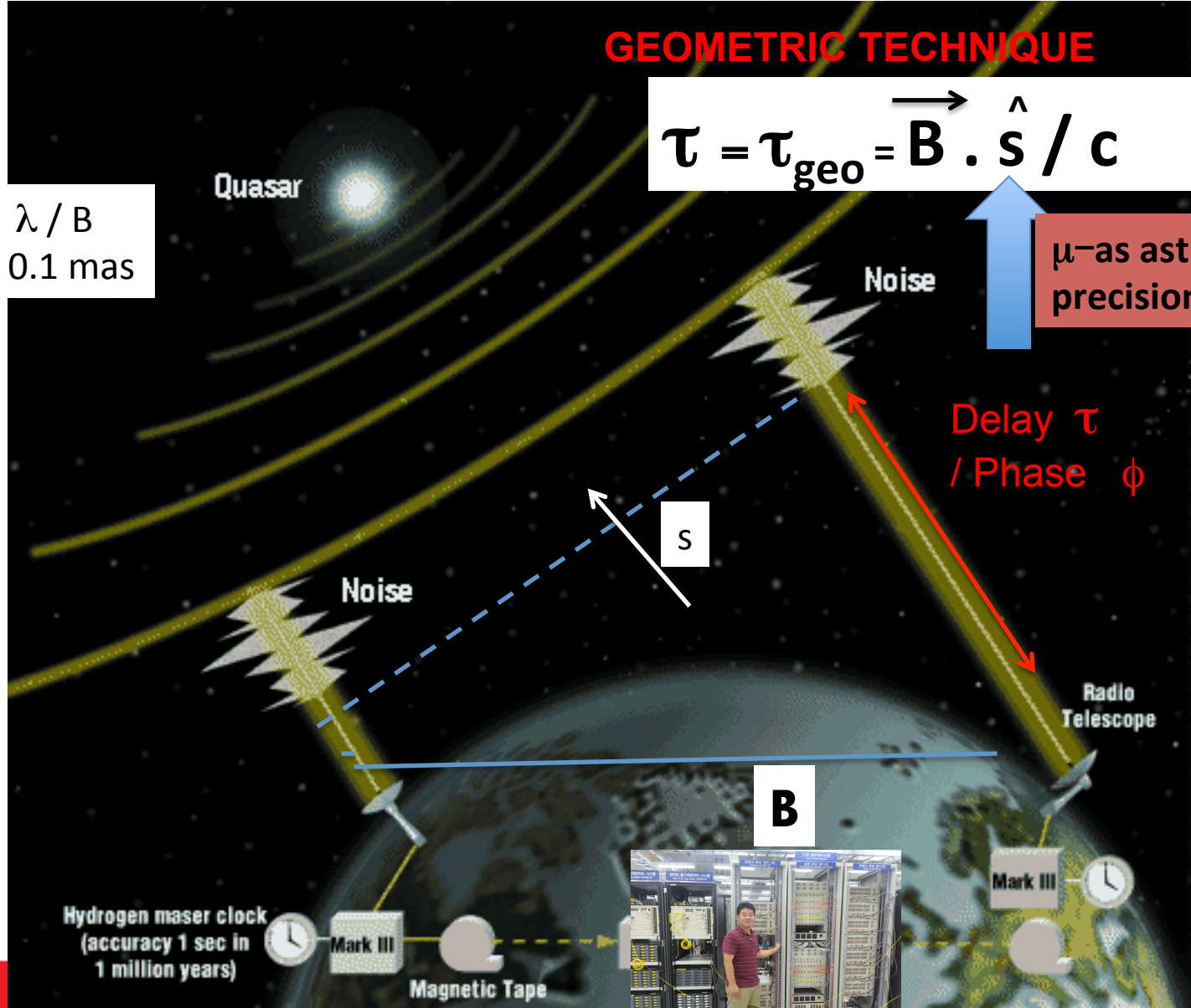
Resolution  $\sim \lambda / B$   
 $\sim$  few mas – 0.1 mas

## GEOMETRIC TECHNIQUE

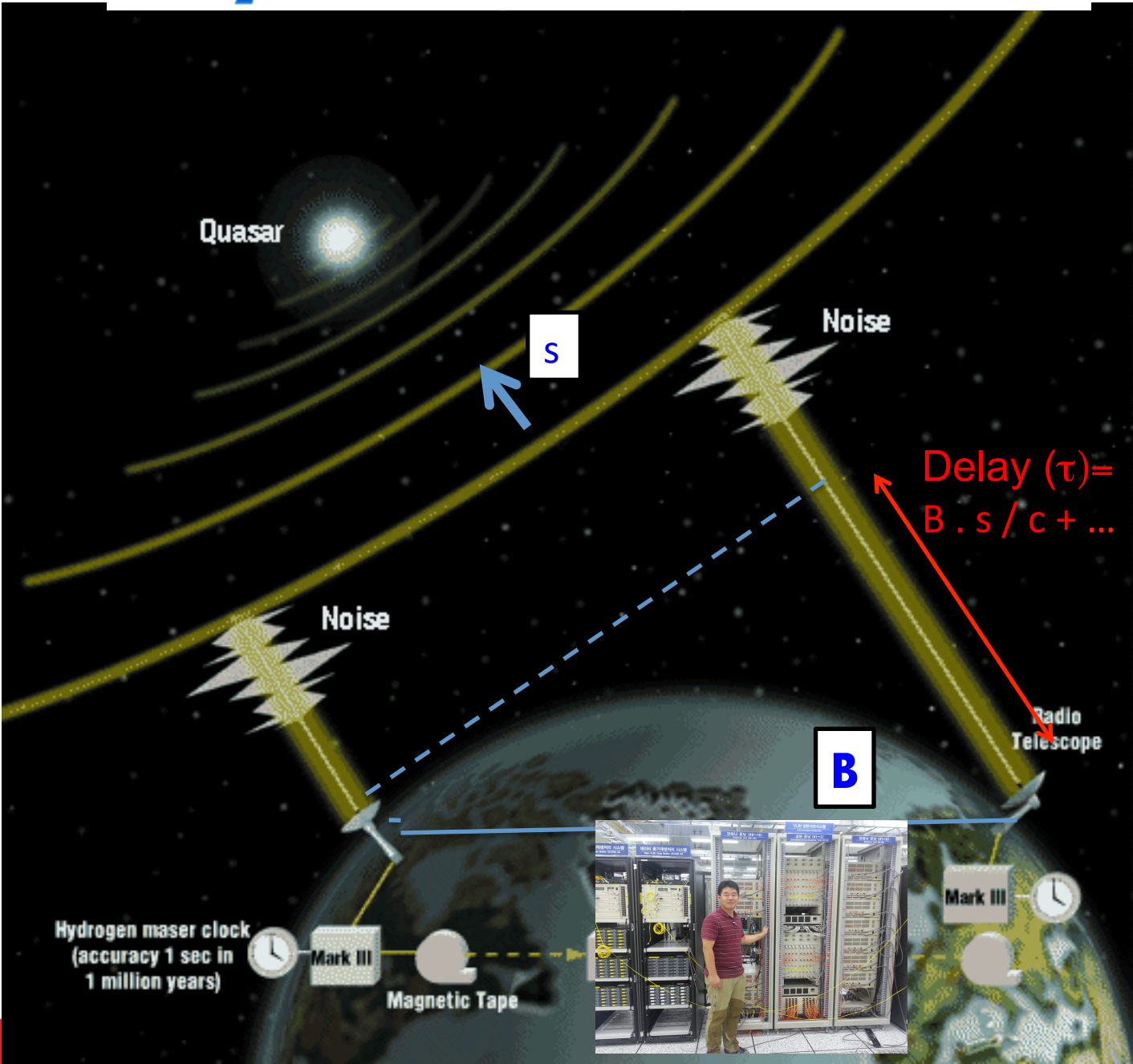
$$\tau = \tau_{\text{geo}} = \vec{B} \cdot \hat{s} / c$$

$\mu$ -as astrometric precision

Delay  $\tau$   
/ Phase  $\phi$



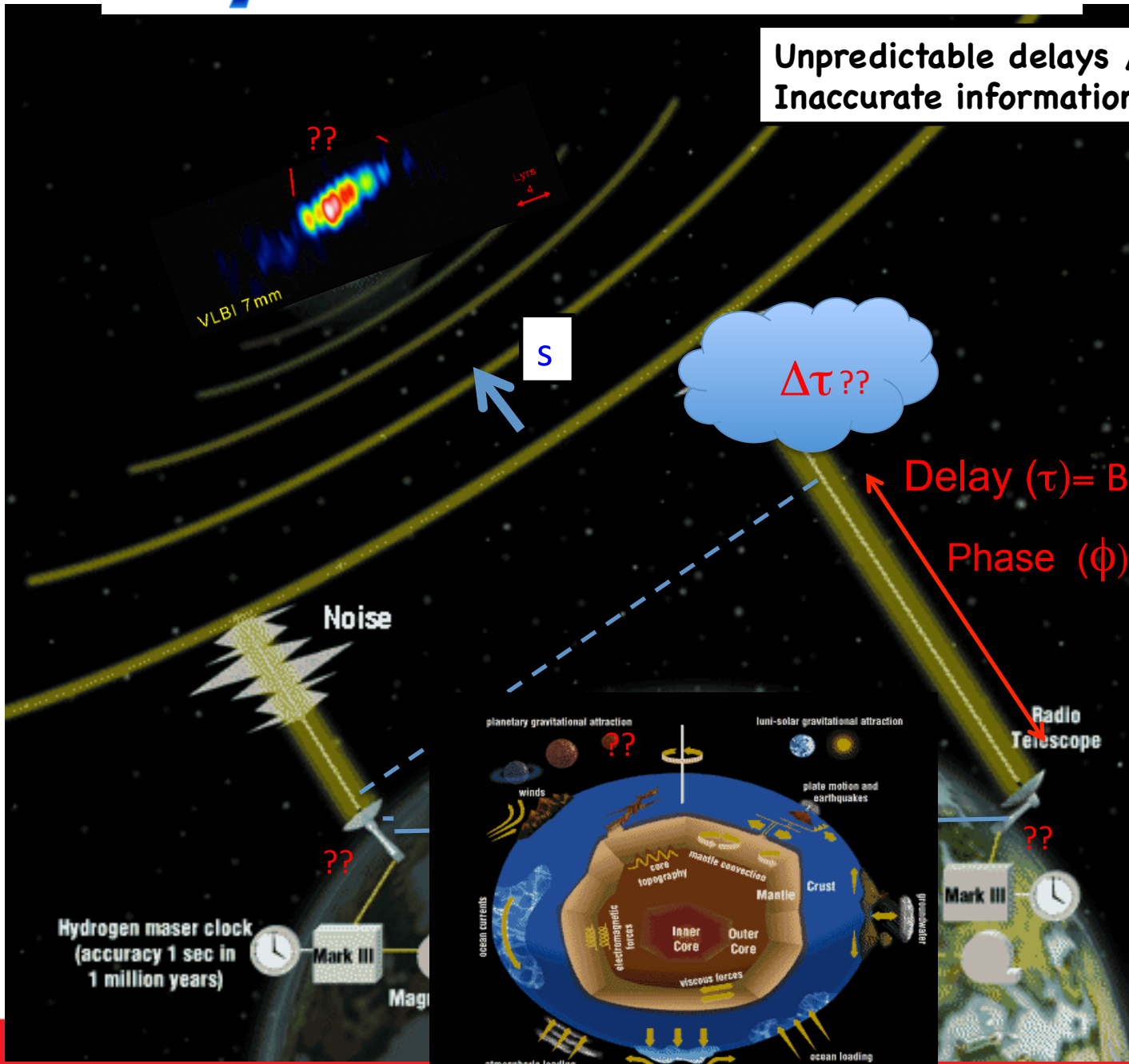
# Why need VLBI calibration?



# Why need VLBI calibration?



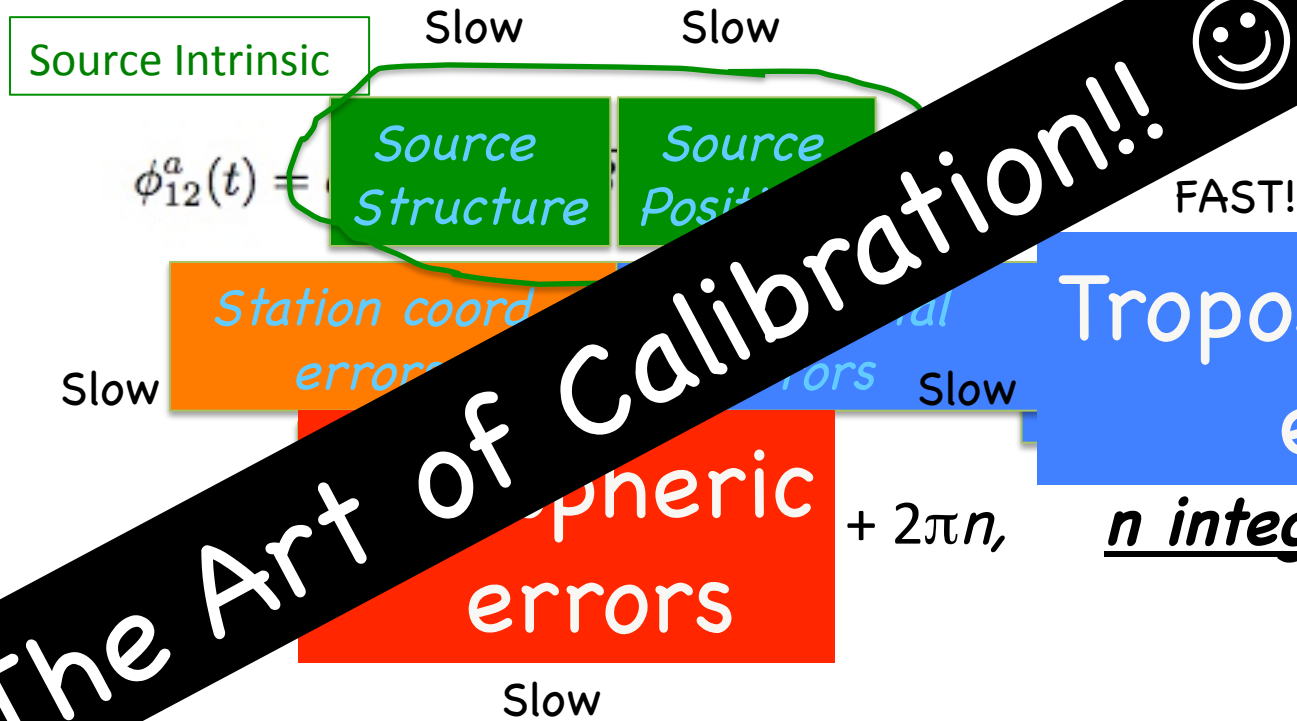
Unpredictable delays / Inaccurate information





# VLBI Observables: The interferometric Phase, $\phi_{12}^a$

(or errors in the "a priori" delay models)



**The Art of Calibration!!** 😊

Earth's atmosphere is the largest source of error in typical VLBI observations.

# Calibration Technique (1): Self-Calibration

(or errors in the "a priori" delay

Closure Phases:

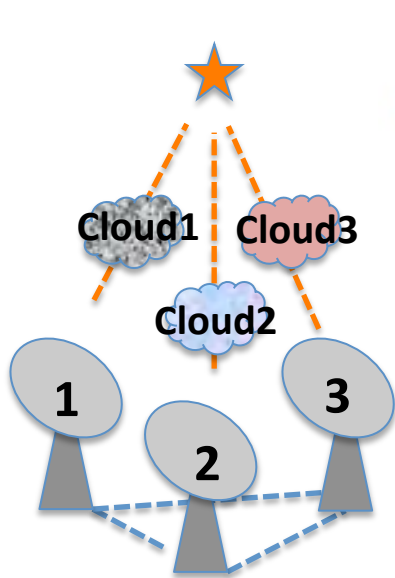
$$\Phi_{12} + \Phi_{23} + \Phi_{31} =$$

$$\text{Cloud}_2 - \text{Cloud}_1 +$$

$$\text{Cloud}_3 - \text{Cloud}_2 +$$

$$\text{Cloud}_1 - \text{Cloud}_3 +$$

.....



$$\phi_{12}^a(t) = \begin{matrix} \text{Source} & \text{Structure} & \text{Phase} & \text{Errors} \\ \text{Station} & \text{Coord.} & \text{Instrumental} & \text{Errors} \\ \text{Ionosphere} & \text{Errors} & \text{Troposphere} & \text{Errors} \end{matrix} + 2\pi n, \quad n \text{ integer}$$

Goal: **IMAGING STRONG SOURCE**

(requires detection within coh time)

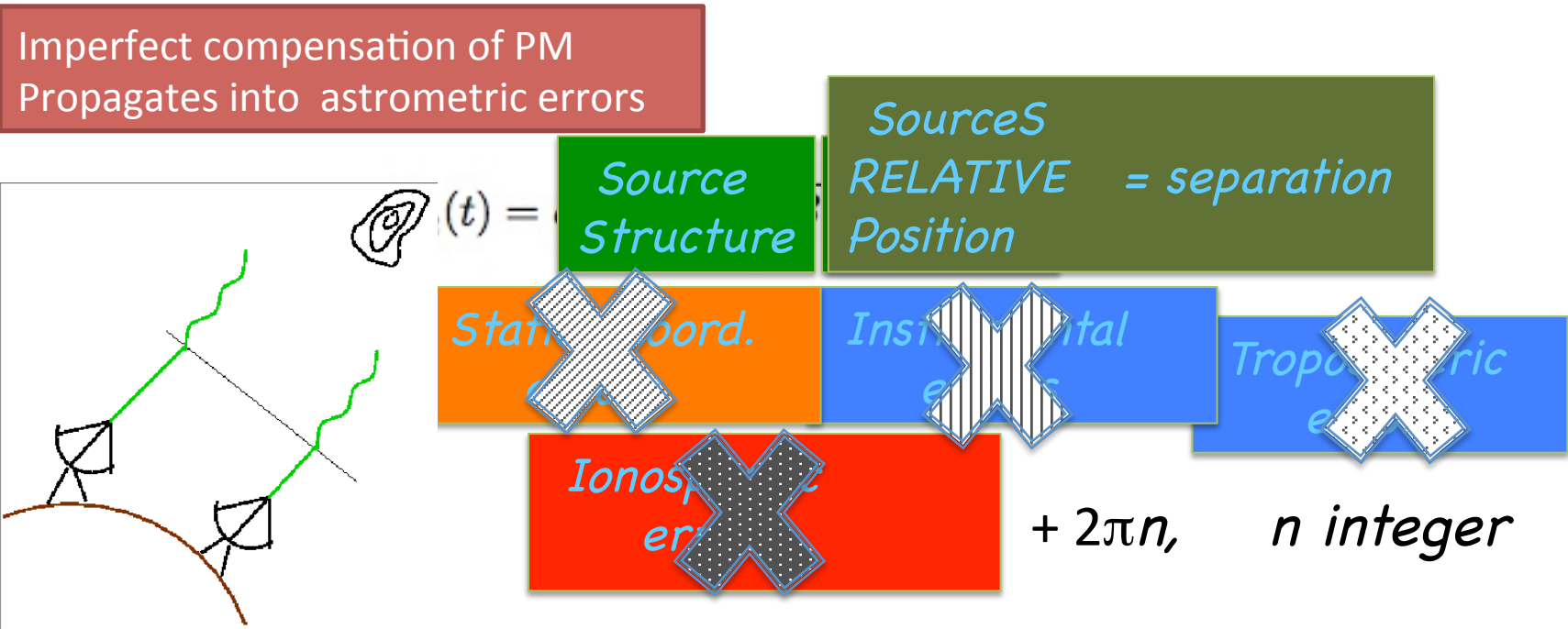
Obs. strategy: Tracking

Obs. Freq.: wide range

ONLY STRONG SOURCES  
&  
NO ASTROMETRY

# Calibration Technique (2): Phase Referencing

(or errors in the "a priori" delay models)



Goal: **IMAGING** weak (and strong)  
**precise ASTROMETRY**

Obs. strategy: Alternate fast btw 2 nearby sources

Obs. Freq.: 8-22(43) GHz (for precise astrometry)

Astrometric Precision:  $0.5\theta_B/\text{SNR}$  (10's micro-as) +

# The Many Faces of the Propagation Medium

$$\tau_{\text{ION}} \propto \lambda^2$$

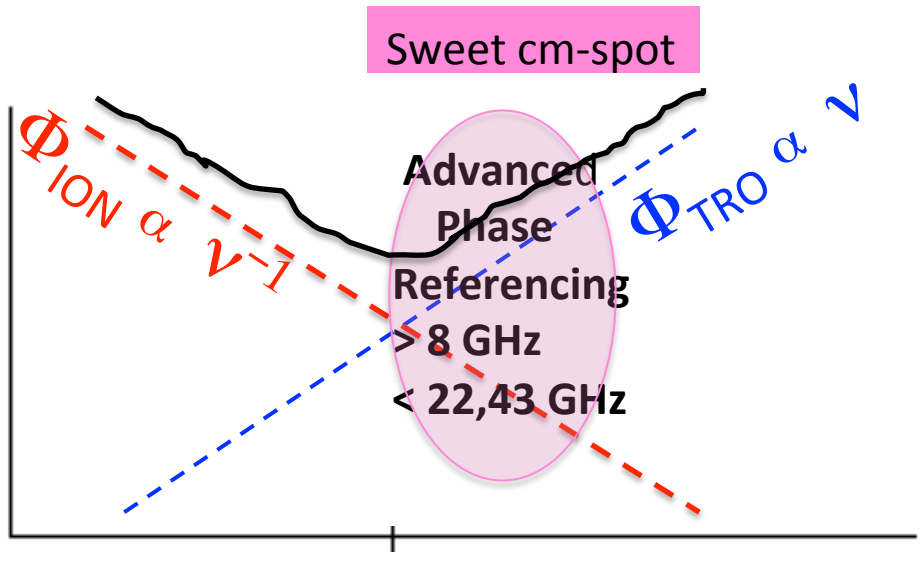
( $\lambda^2$  signature)

**IONOSPHERE**  
(dispersive)

**TROPOSPHERE**  
(non dispersive)

$$\tau_{\text{TRO}} = C$$

Log Phase<sub>ERROR</sub> ( $\Phi$ )



Typical errors:  
ZPD=3cm (trop)  
 $\Delta I=5$  TECU (ion)

Low Frequency

$\sim 8$  GHz

High Frequency



SKA-Low

SKA-Mid

SKA

Micro-Jy sensitivity  
Micro-as astrometry  
Wide applicability  
A history of success!

\* (a-b) mm-VLBI\*

ALMA



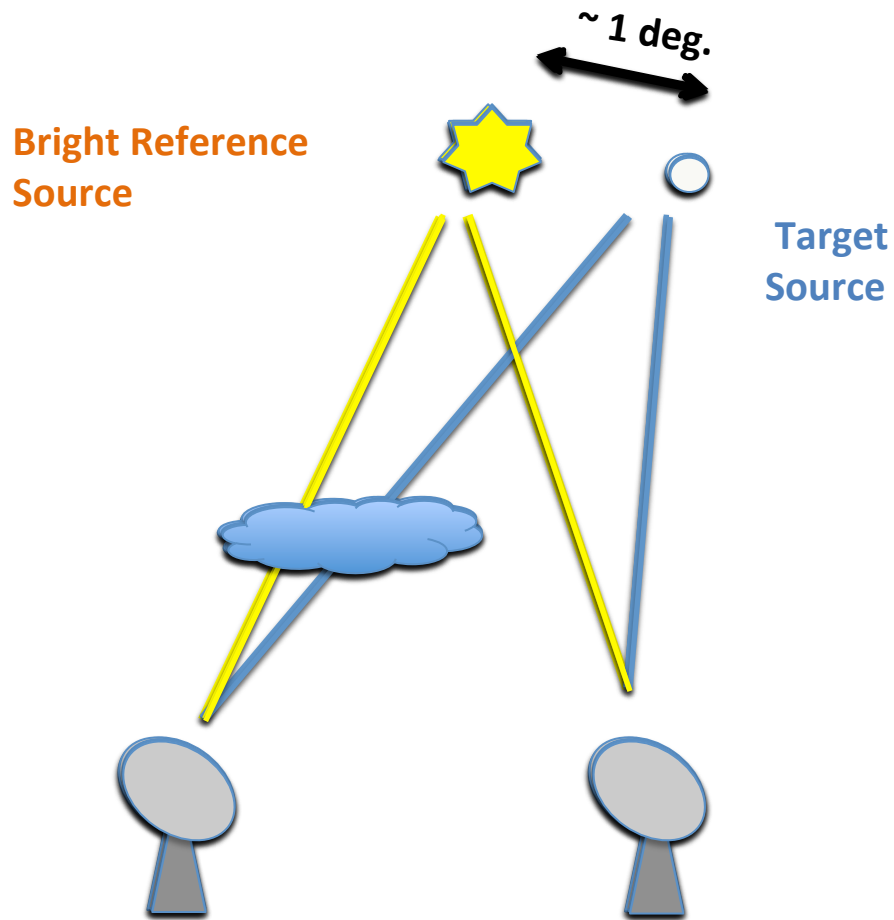
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# High Frequencies ( $> 22$ GHz) & Troposphere

GOAL: Precise Astrometry → wider applicability

# Phase Referencing “*trans-source*”

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# Phase Referencing “trans-source”

# Paradigm Shift: “trans-frequency” calibration

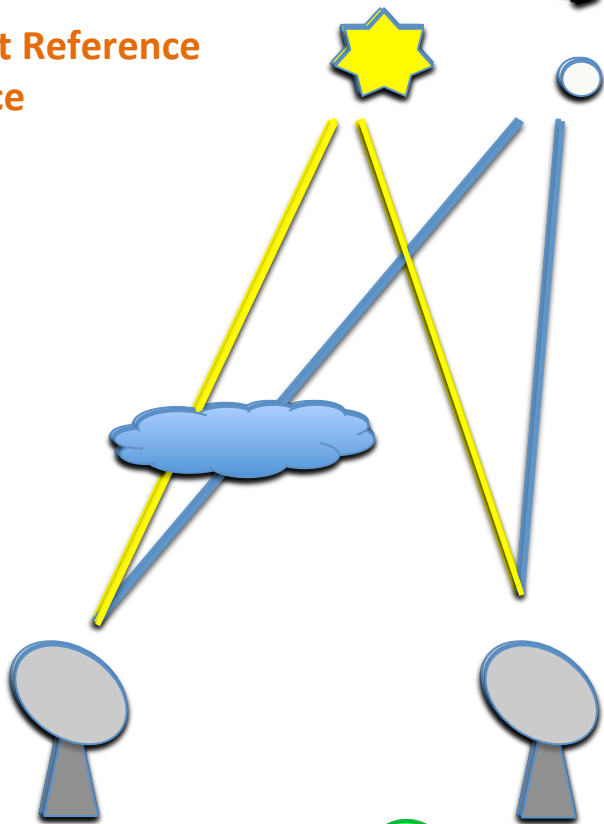
“fast-frequency switching”  
with VLBA

PR @ 43 GHz

Bright Reference  
Source

~ 1 deg.

Target  
Source



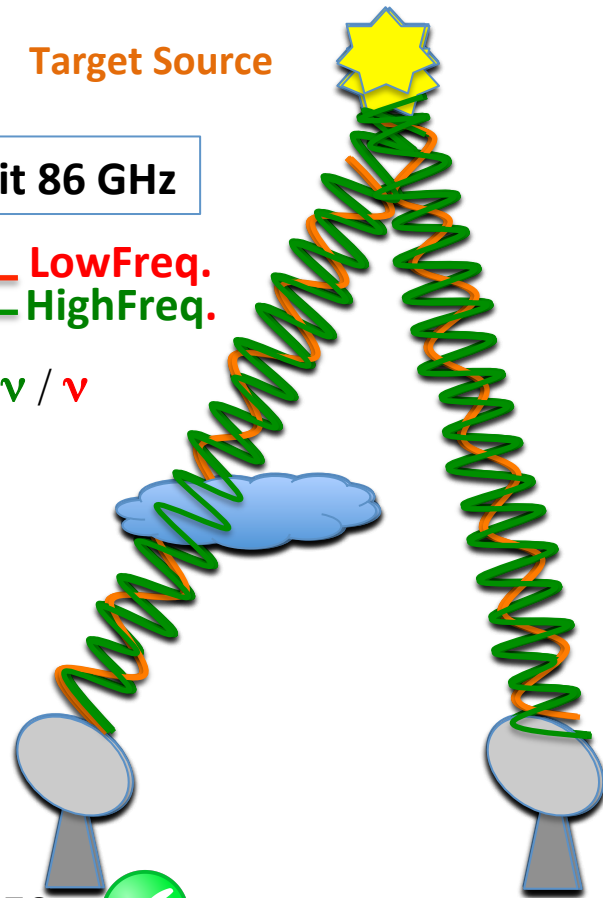
SFPR

Target Source

Upper Limit 86 GHz

— LowFreq.  
— HighFreq.

$$R = \nu / \nu$$



WEAK SOURCES  
ASTROMETRY



WEAK SOURCES  
ASTROMETRY



# Phase Referencing “trans-source”

# Paradigm Shift: “trans-frequency” calibration

“Simultaneous Multi-channel receivers”  
with KVN

PR @ 43 GHz

Bright Reference  
Source

~ 1 deg.

Target  
Source

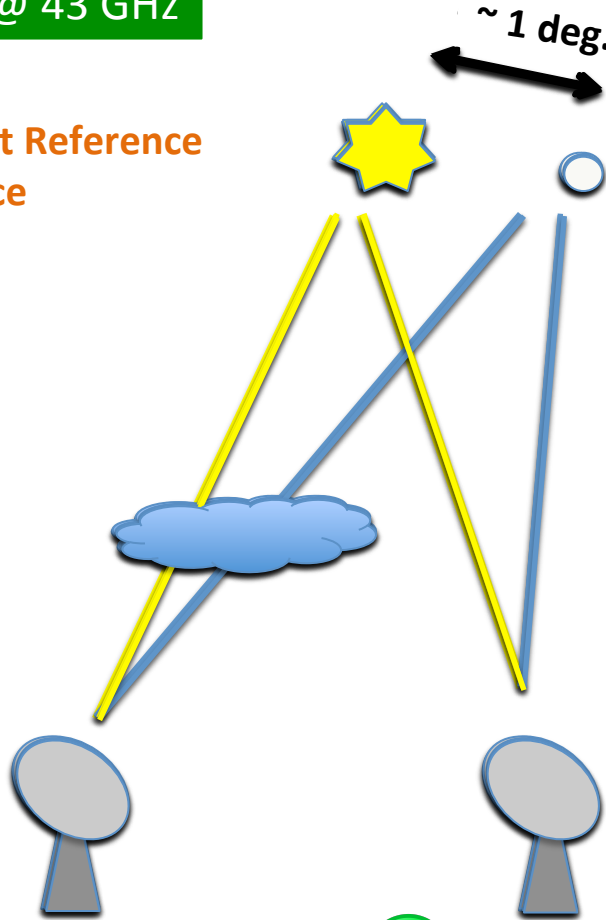
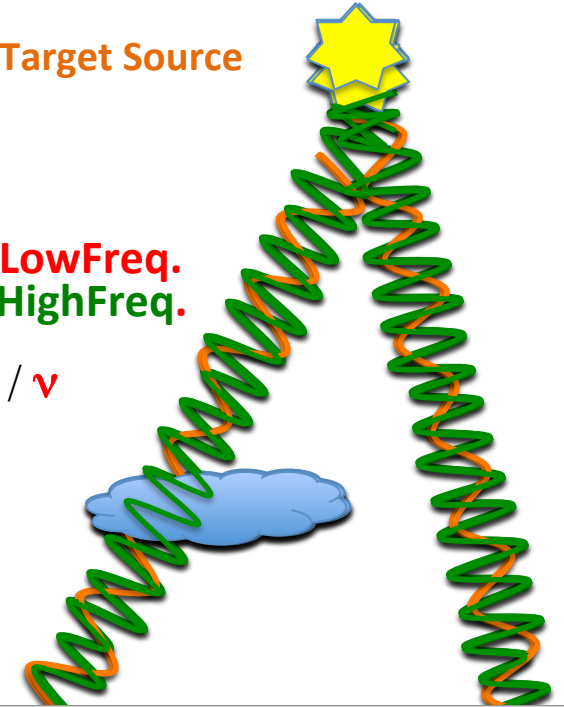
Target Source

SFPR

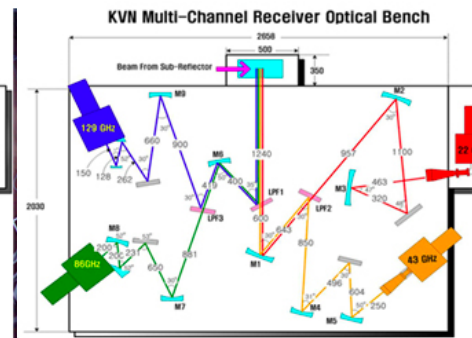
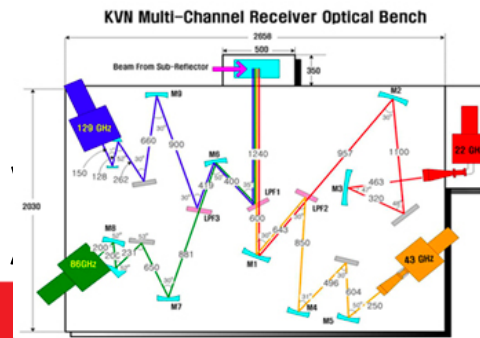
> 130 GHz

LowFreq.  
HighFreq.

$$R = \nu / \nu$$



WEAK SOURCES  
ASTROMETRY





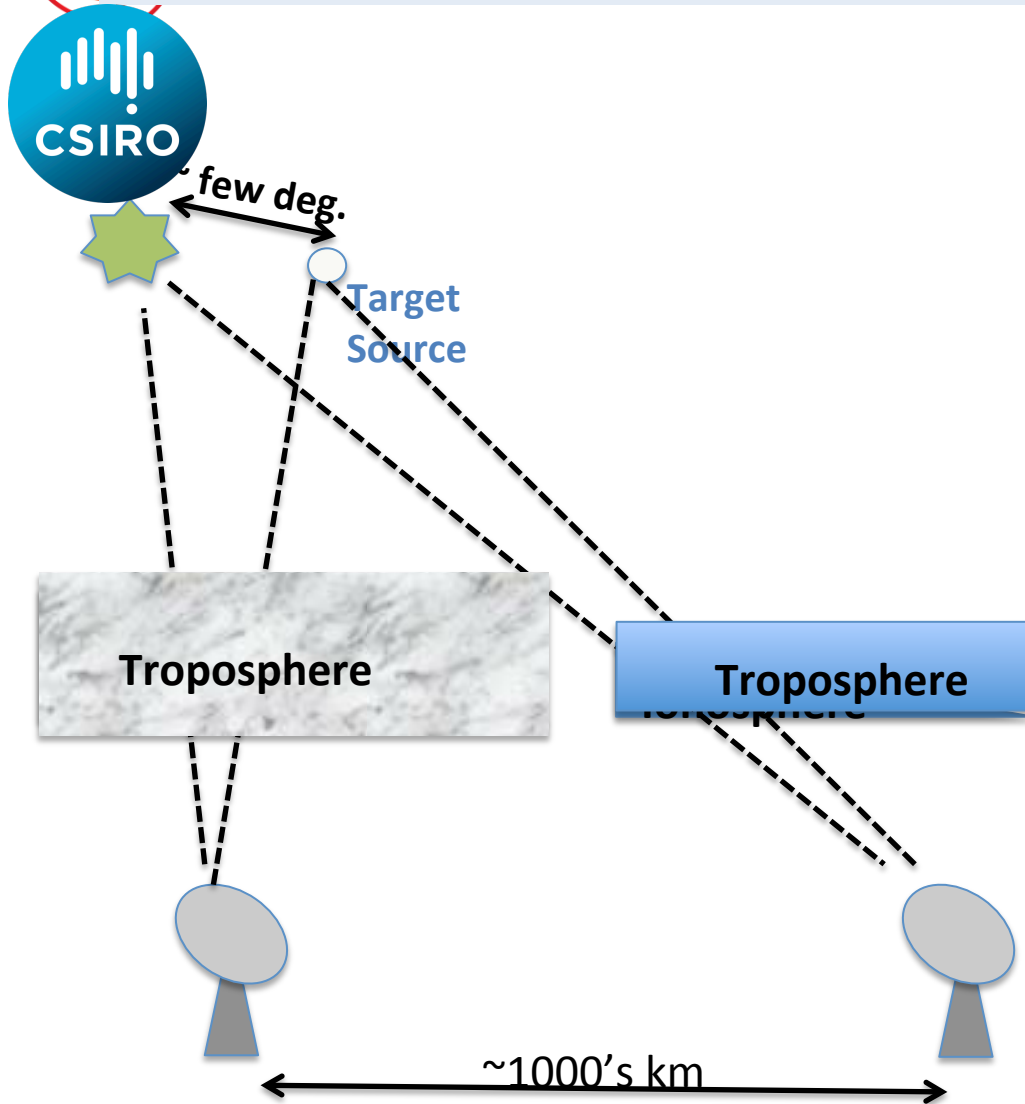
Low Freq VLBI also very interesting.  
\*\*Steep Spectrum sources (pulsars)  
\*\* SKA era

# Low Frequencies (< 8 GHz) & Ionosphere

GOAL: Precise Astrometry → wider applicability



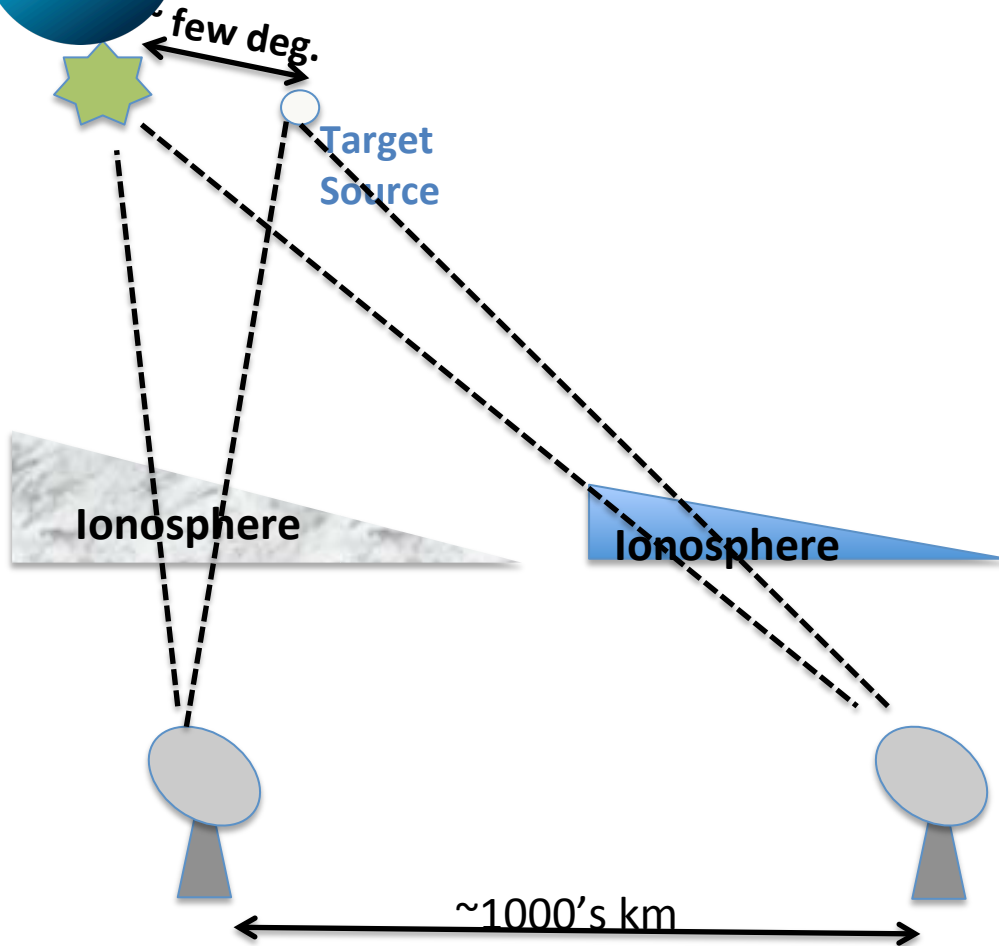
# Low Frequencies & Ionosphere



*Sketch representing ionospheric direction dependent effects*



# Low Frequencies & Ionosphere

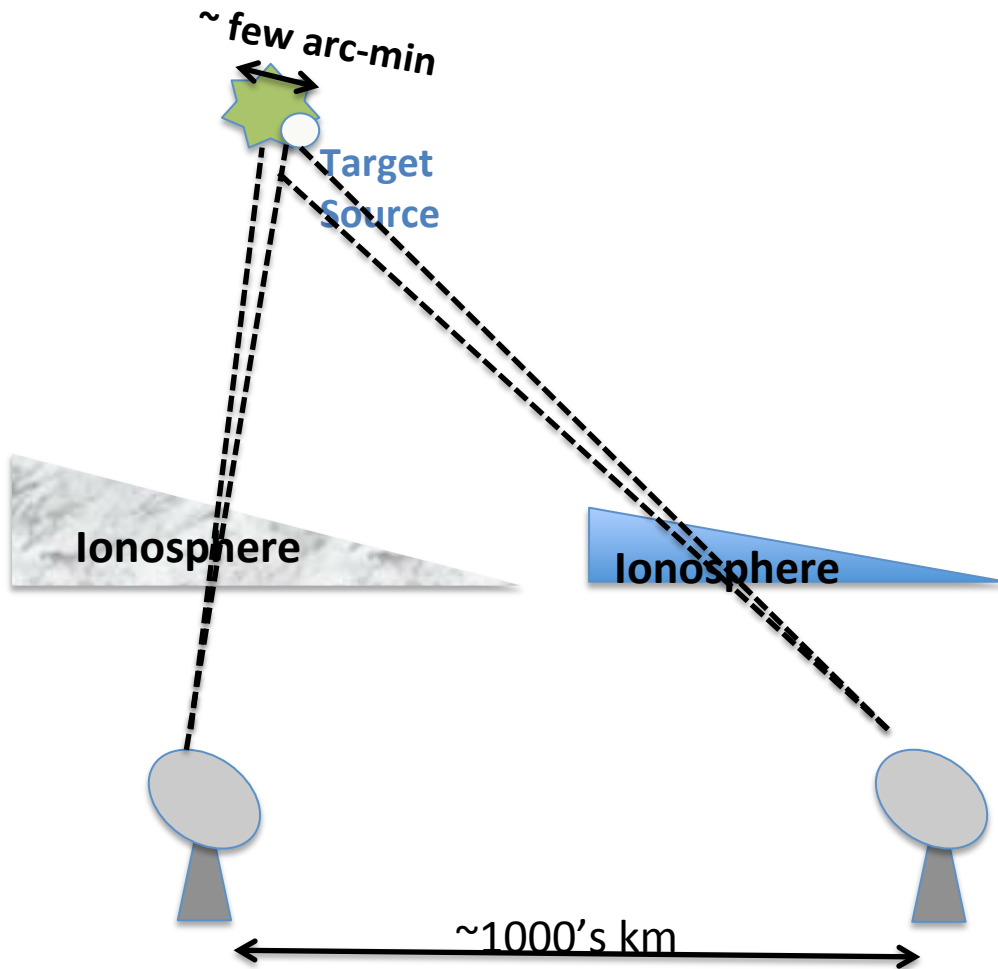


**THE PROBLEM:**  
"IONOSPHERIC WEDGE"  
Spatial structure  
Direction Dependent Effects

*Sketch representing ionospheric direction dependent effects*



# Low Frequencies & Ionosphere

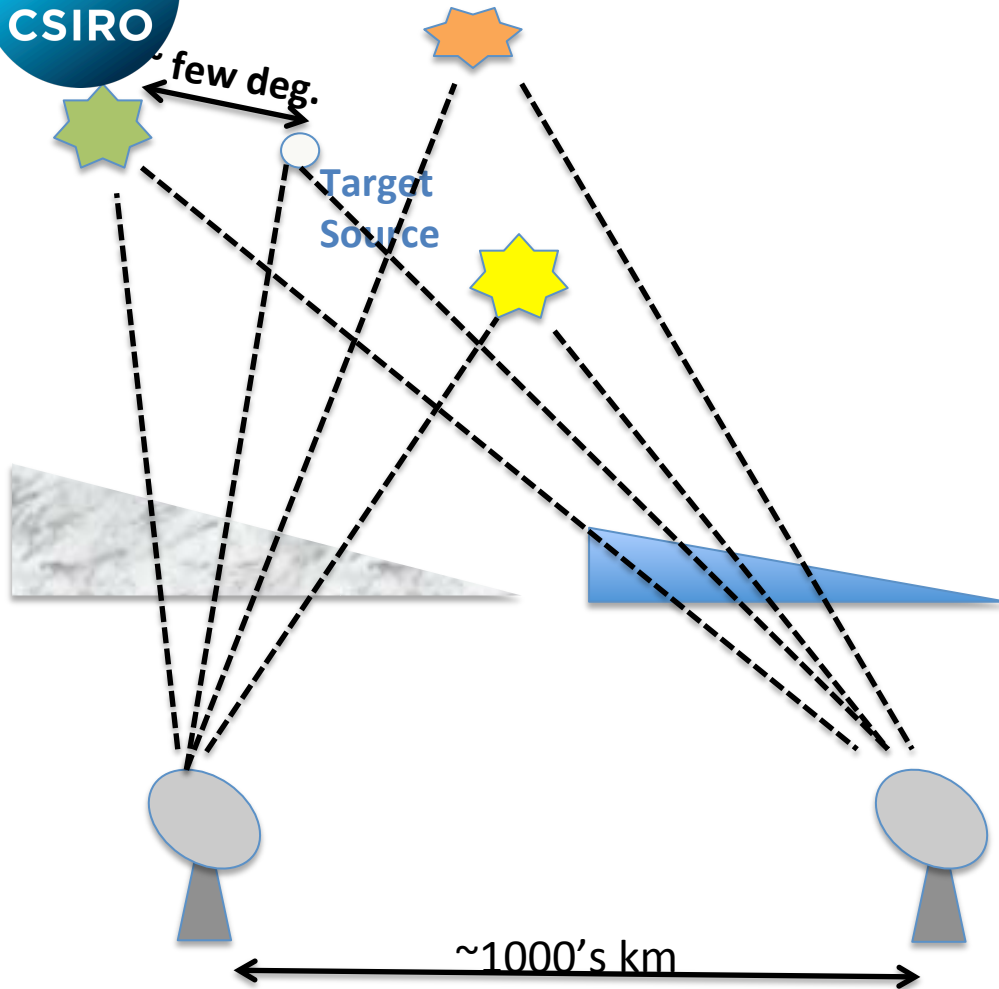


**THE PROBLEM:**  
"IONOSPHERIC WEDGE"  
Spatial structure  
Direction Dependent Effects

*Sketch representing ionospheric direction dependent effects*



# Low Frequencies & Ionosphere

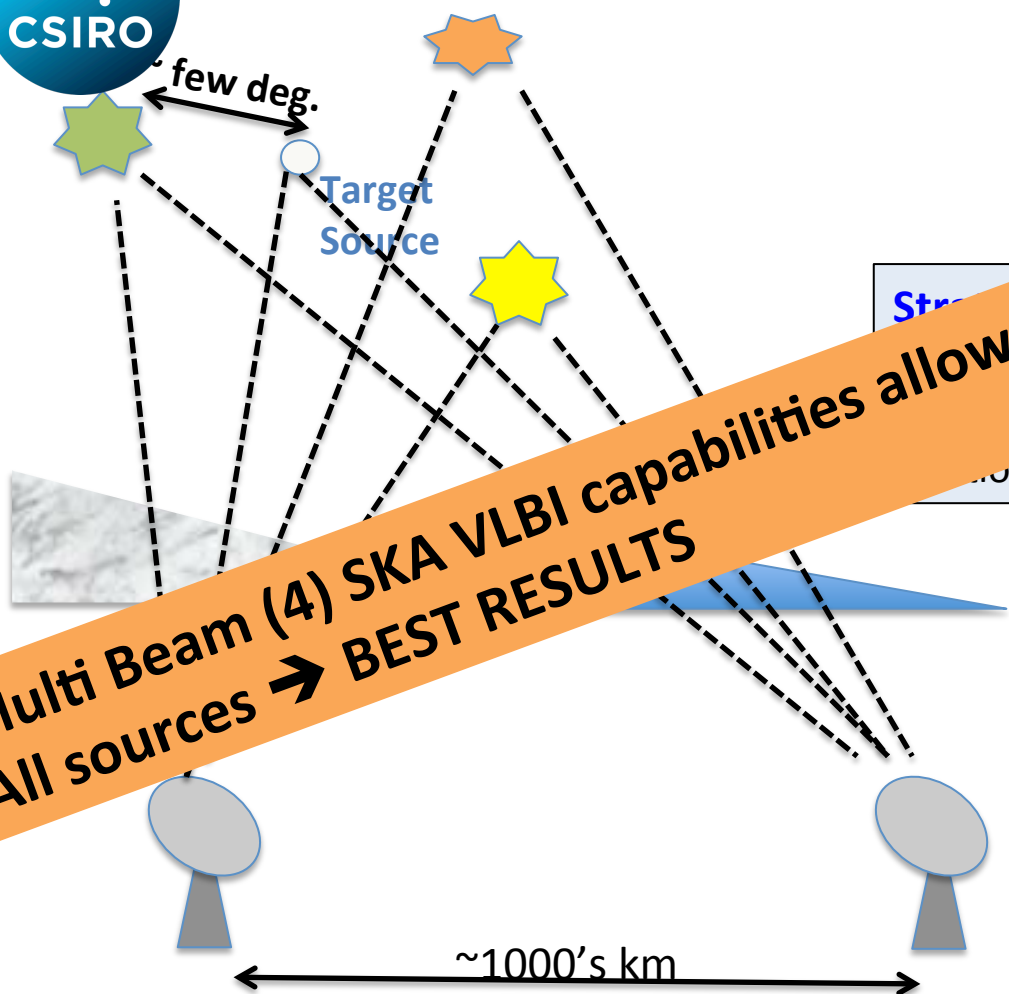


**THE PROBLEM:**  
"IONOSPHERIC WEDGE"  
Spatial structure  
Direction Dependent Effects

MultiView



# Low Frequencies & Ionosphere



**Multi Beam (4) SKA VLBI capabilities allow for simultaneous observations of All sources → BEST RESULTS**

**THE PROBLEM:**  
 "IONOSPHERIC WEDGE"  
 Spatial structure  
 Directional

Structure  
 Multiple calibrators  
 Interpolation of the calibrator  
 Corrections to the line of sight for the target.

**Outcome:**  
 Now the spatial structure is accounted for,  
 Resulting in high precision astrometry  
 achievable at low frequencies..

(Rioja et al. 2017)

Sketch representing ionospheric direction dependent effects

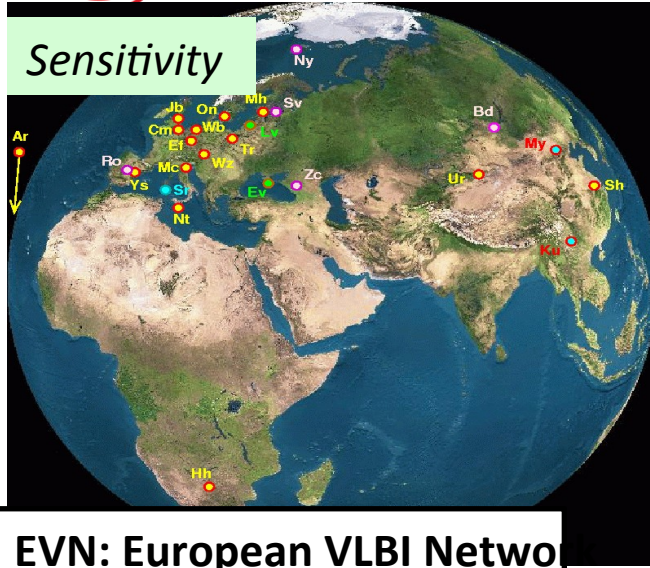


# VLBI NETWORKS

General Purpose



Sensitivity



EVN: European VLBI Network

<~ 22GHz

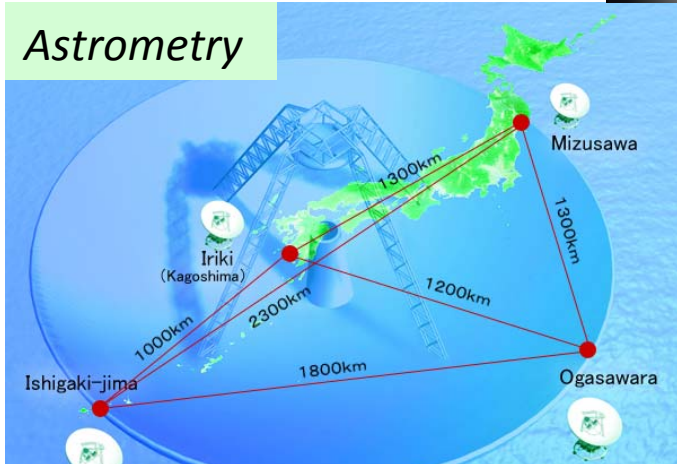
Highest Frequency Astrometry



VLBA Very Long Baseline Array

<~ 86GHz

Astrometry



KVN Korean VLBI Network

22/43/86/129 GHz

Southern Hemisphere



LBA Long Baseline Array

<~ 22GHz

VERA VLBI for Earth Rotation and Astrometry

22/43 GHz



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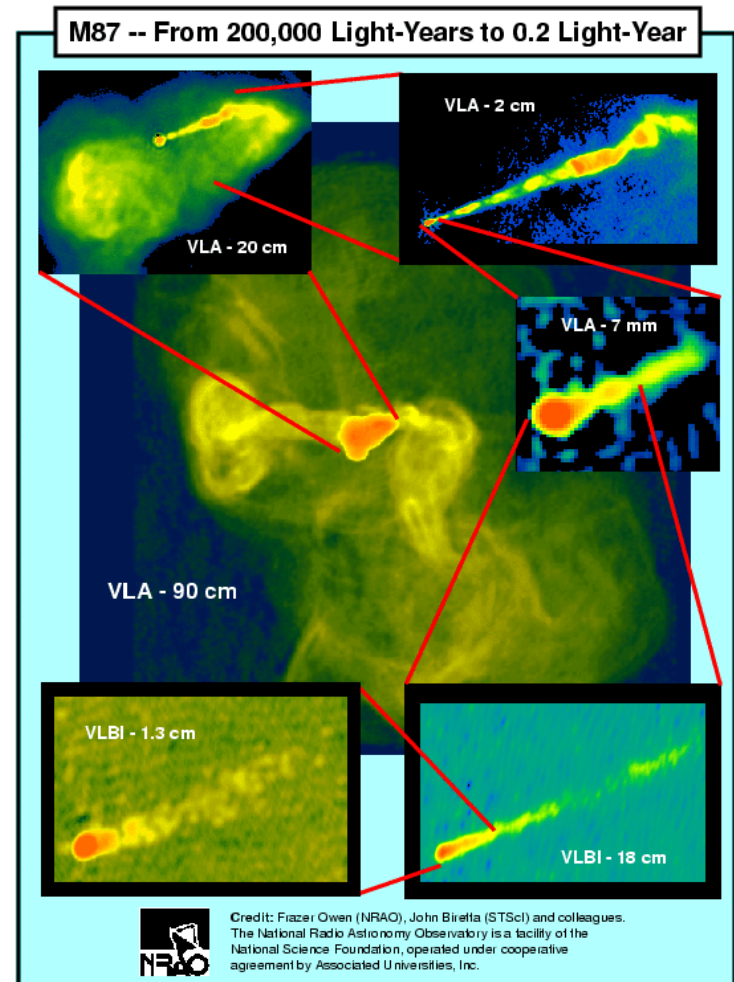
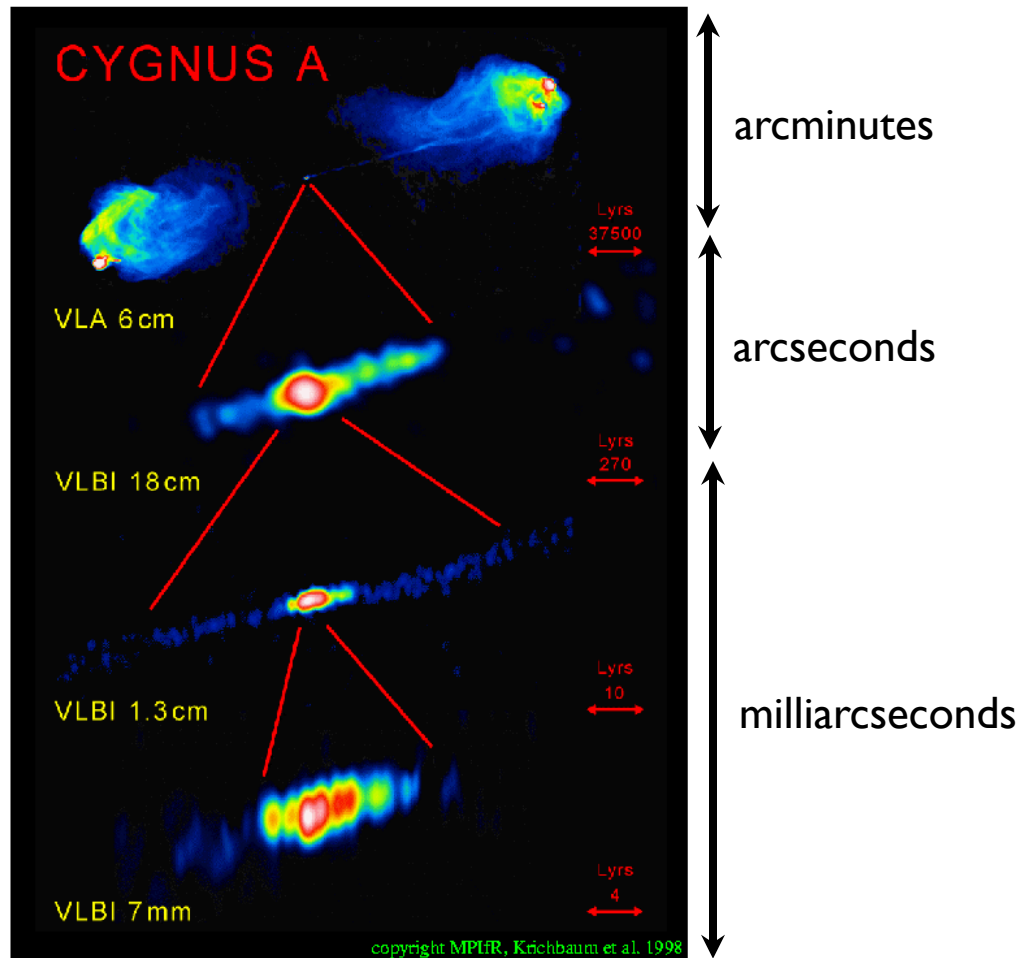
# Astrophysical Applications

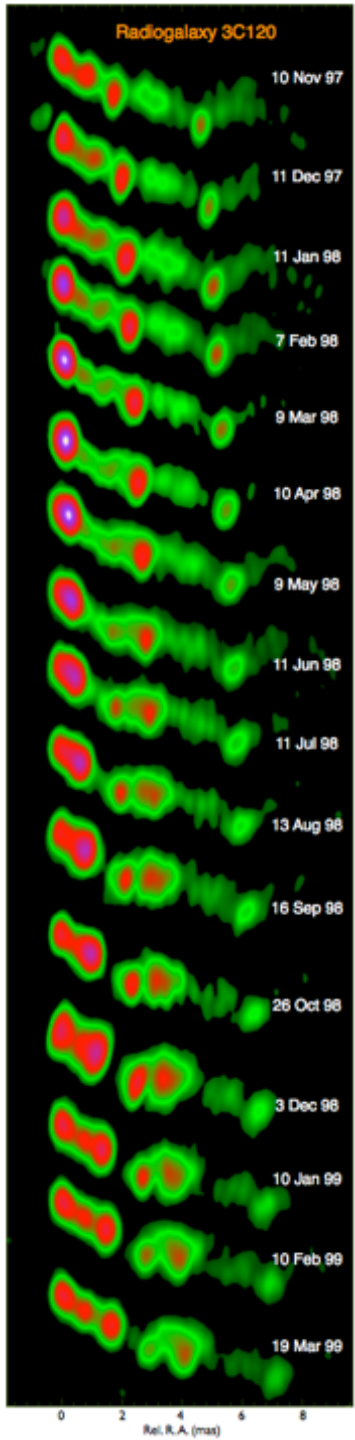


# Radio jets and BH physics

Arc-minute resolution is often not good enough to resolve the detailed structure of many astrophysical objects e.g. distant galaxies, quasars etc.

Radio sources can show emission on scales of arcminutes --> arcseconds --> milliarcseconds...

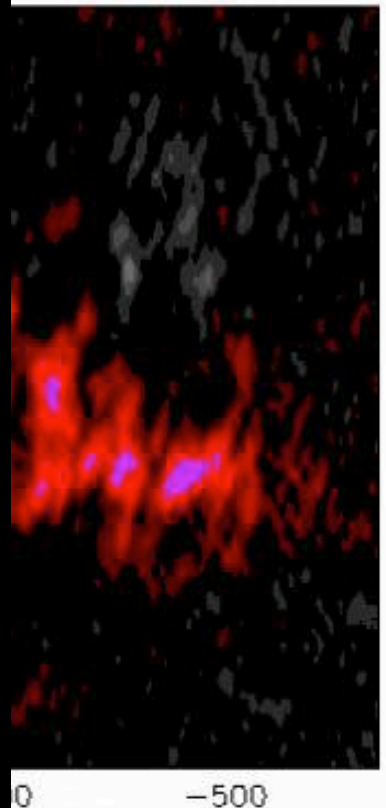
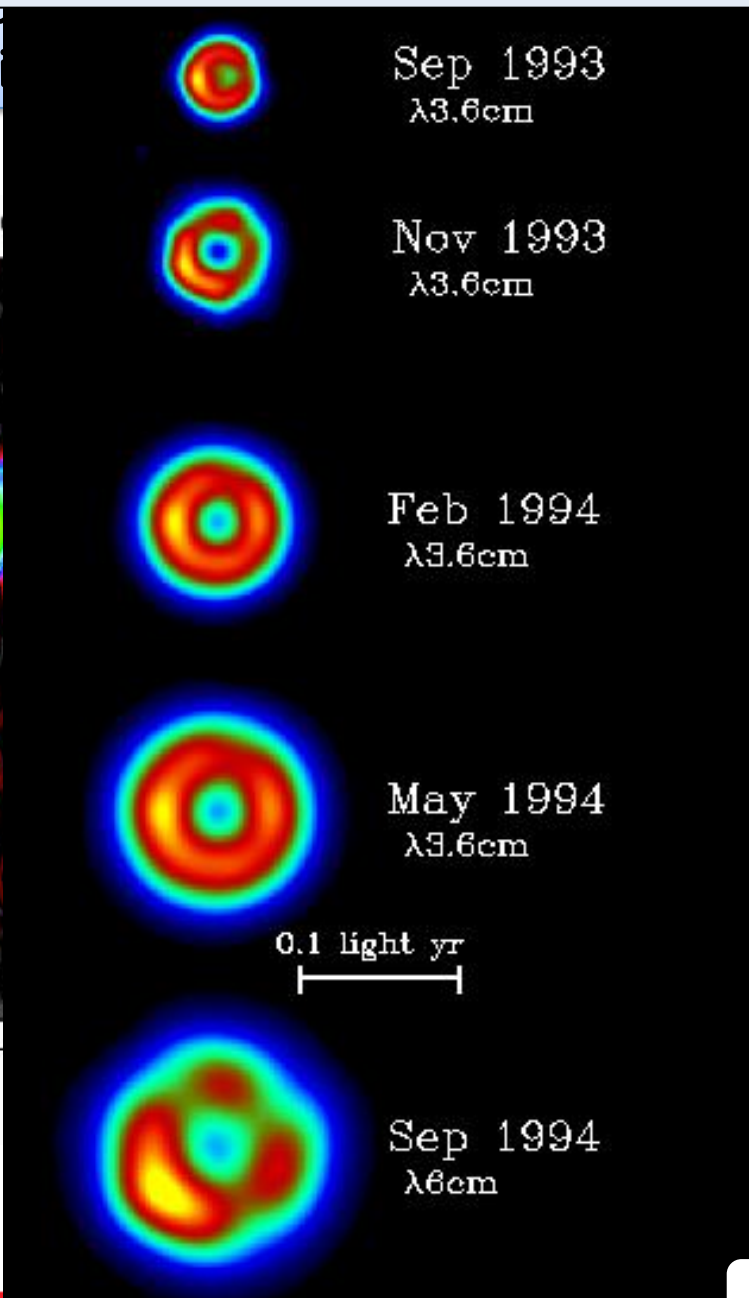
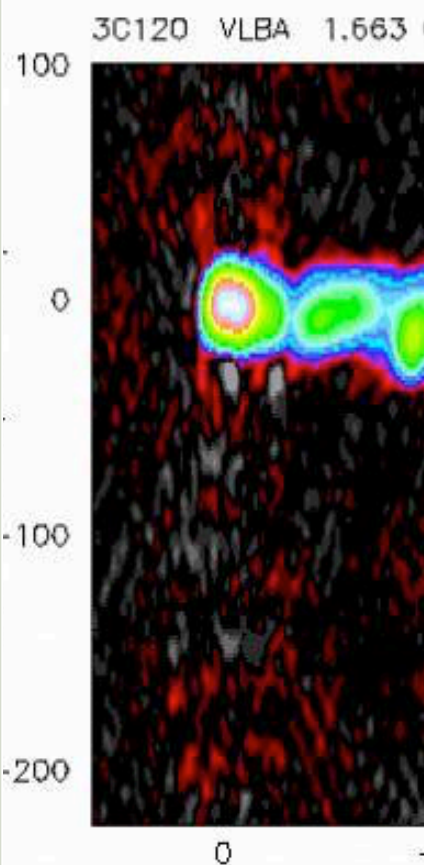




Radiogalaxy  
Motion

Movie of the Expansion of SN 1993J

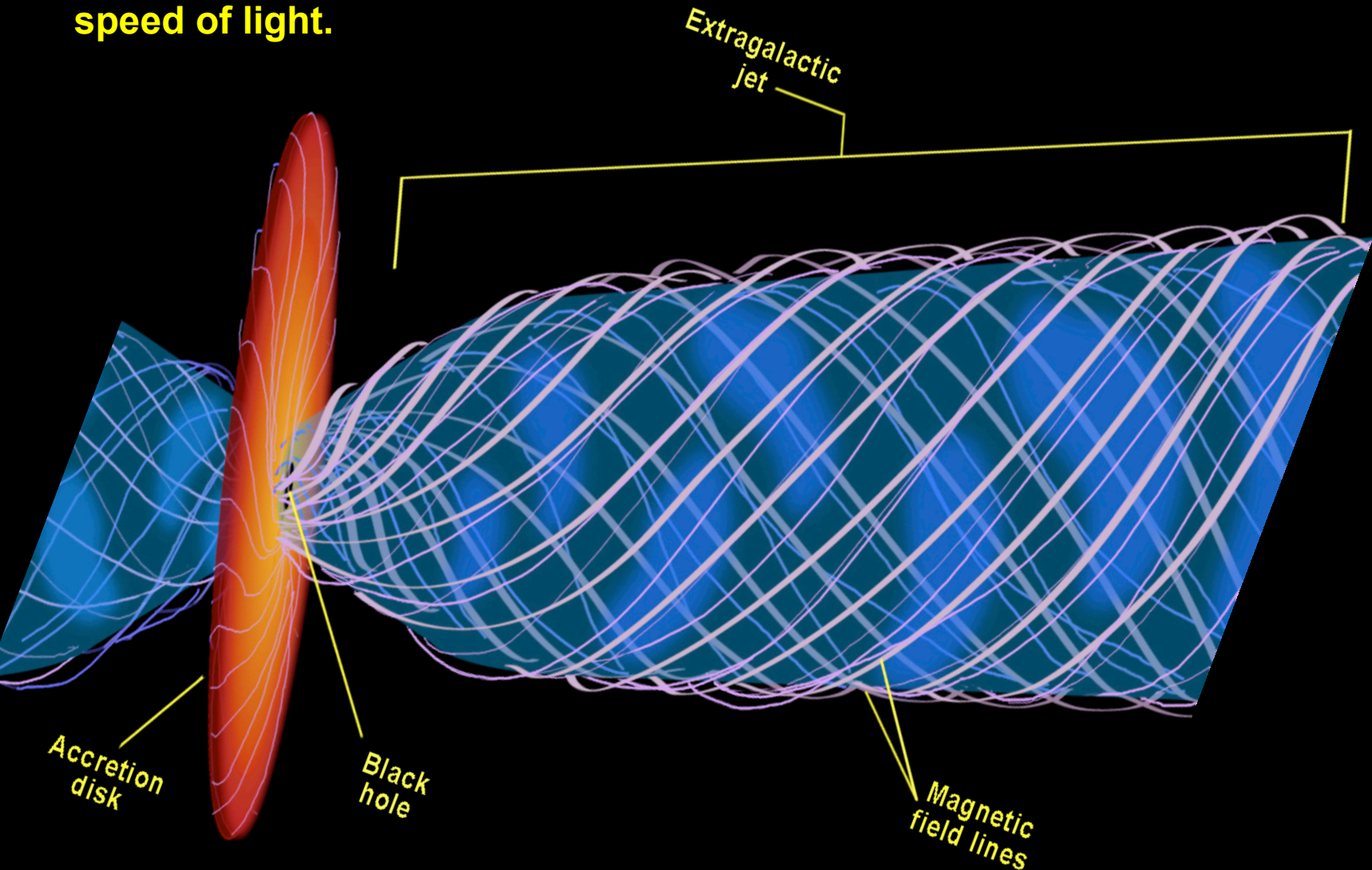
Expansion speeds



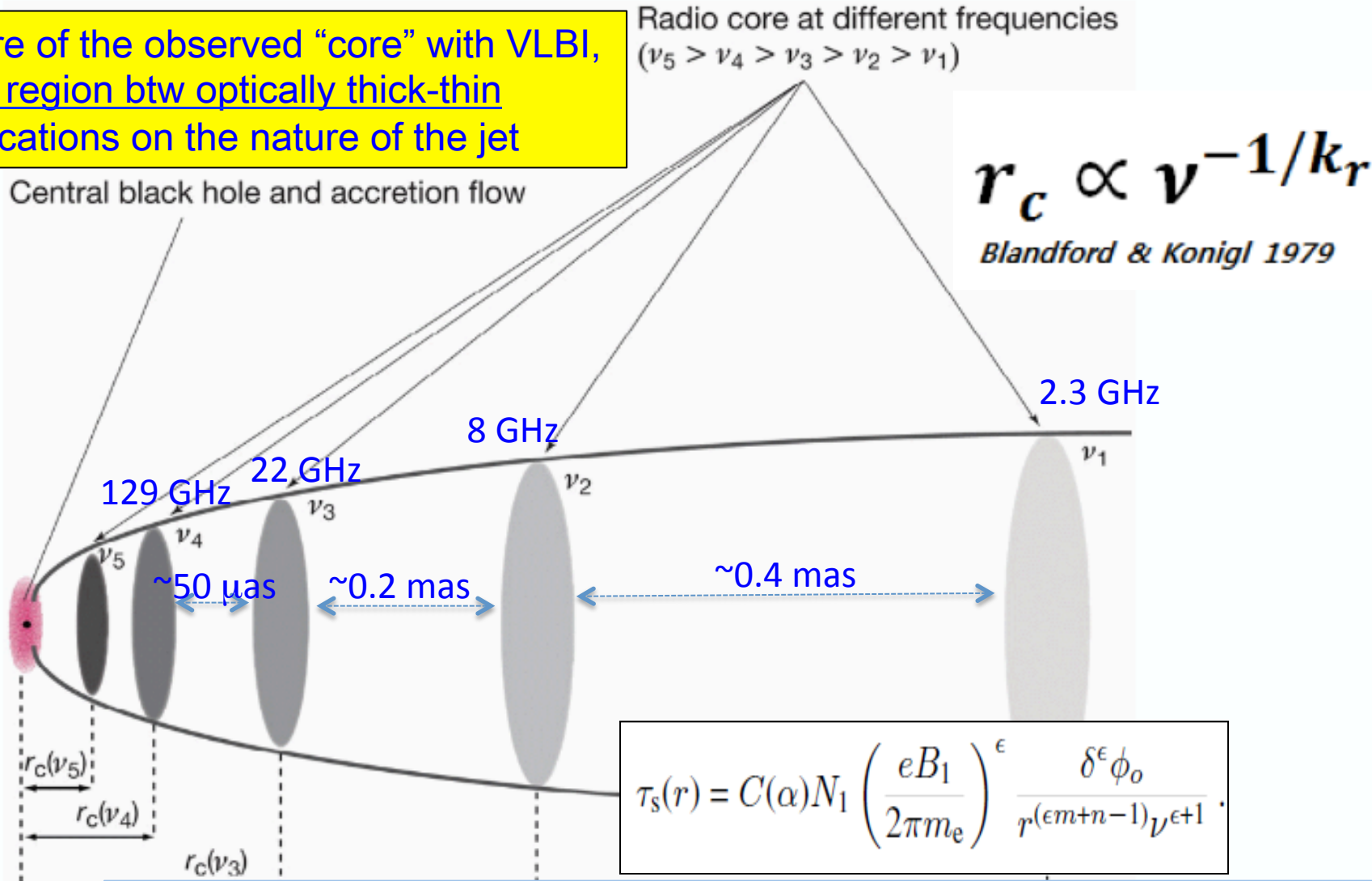
## AGN Jet Studies

Accretion of gas onto a massive central black hole releases tremendous amounts of energy.

Magnetic field collimates outflow and accelerates particles to close to the speed of light.

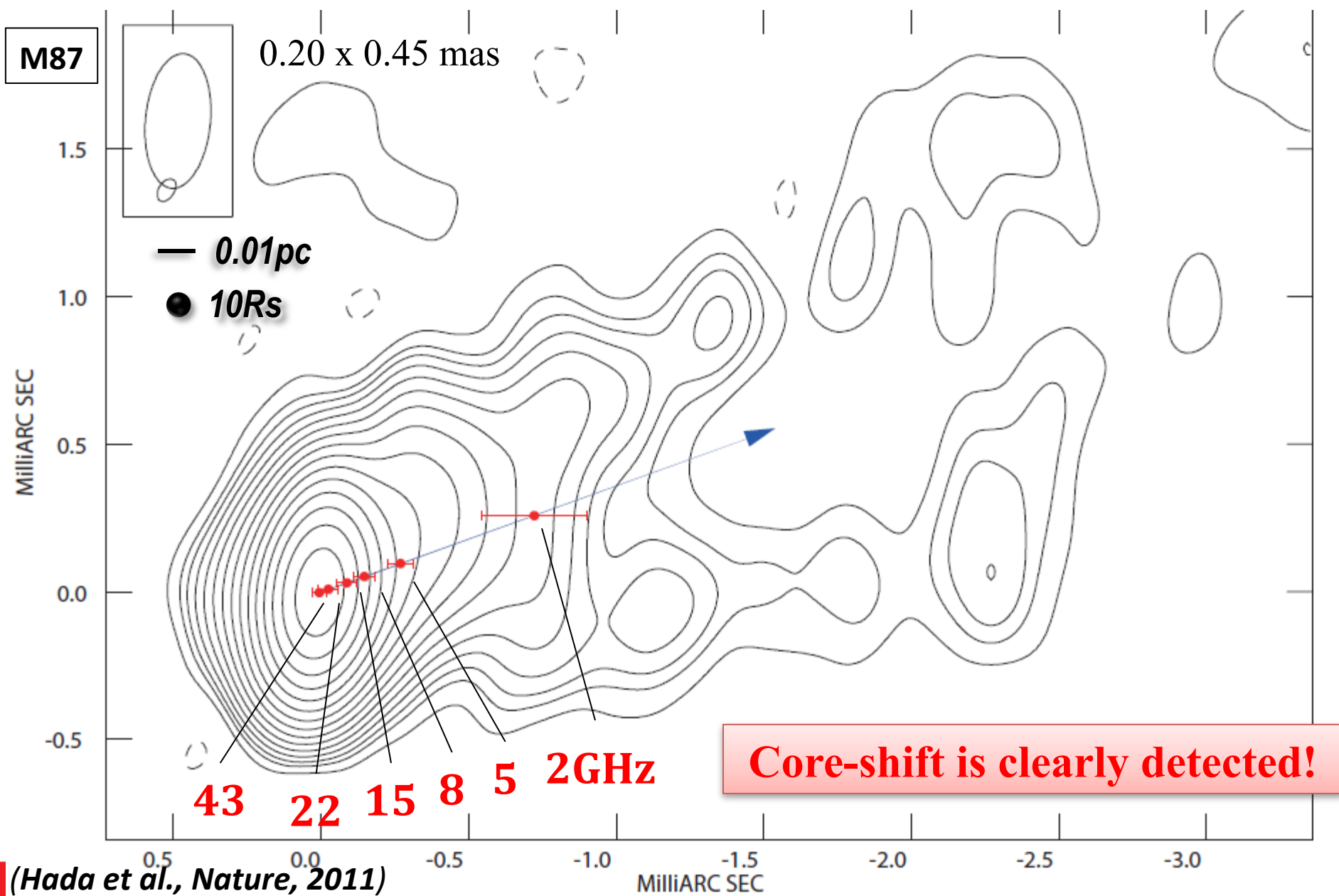


The nature of the observed “core” with VLBI,  
transition region btw optically thick-thin  
 And implications on the nature of the jet

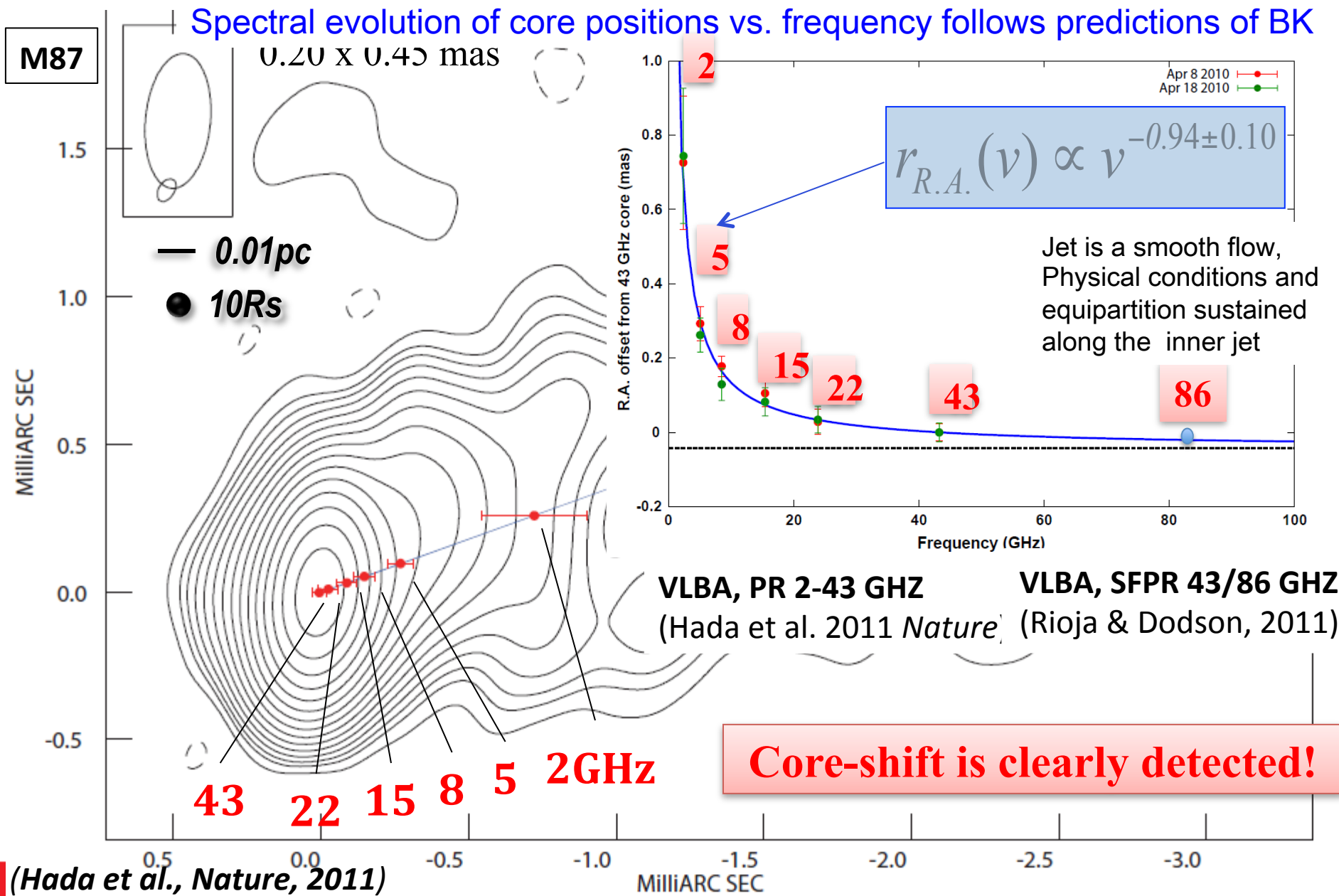


Core Shifts convey information on physical parameters in the jet region  
 Higher Frequencies probe the innermost regions of the jet  
 High precision astrometry required because core shifts smaller ( $\rightarrow$  SFPR)

# AGN Jets – Measured “Core shifts” in M87



# AGN Jets – Measured “Core shifts” in M87



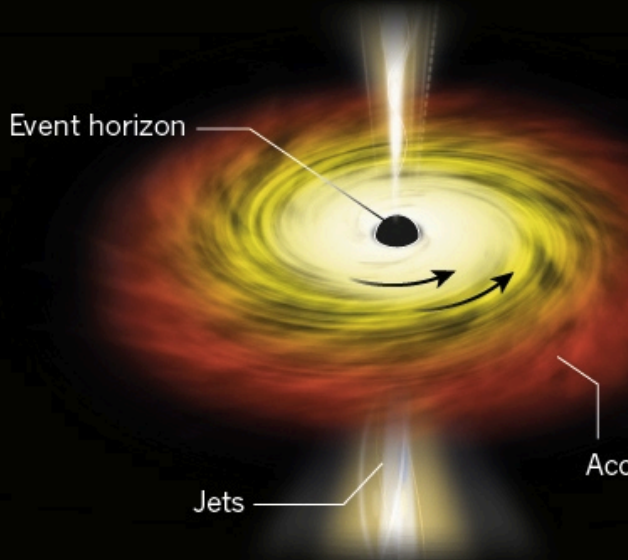
(Hada et al., Nature, 2011)



# Event Horizon Telescope

## POWER OF THE DARK

The Event Horizon Telescope aims to reveal the edge of a black hole. These objects are surrounded by accretion disks: swirling masses of matter that spiral inwards. Anything that falls past the event horizon disappears from view because light cannot escape from inside that boundary.



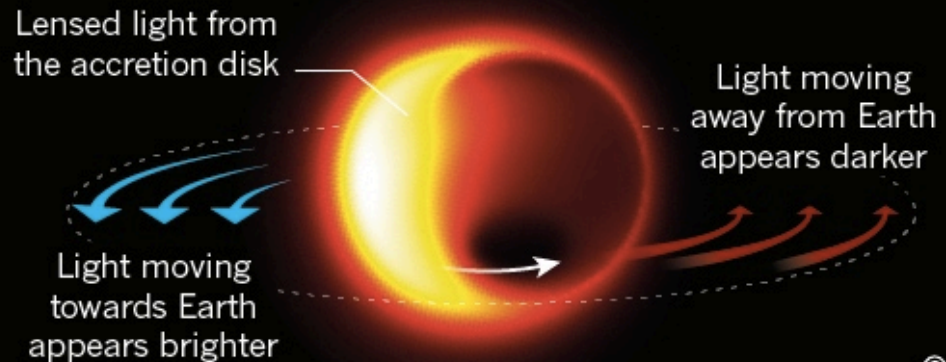
“How to hunt for a black hole with a telescope the size of the Earth... “

VLBI with ALMA

$\lambda \sim 1\text{mm}$ ; Resolution  $\sim 35 \mu\text{as}$

## UNEVEN HALO

Radiation collected by the Event Horizon Telescope could resemble this simulation of light bending around a black hole. One side appears brighter because more of the radiation is shifted towards the observing wavelengths.





# Astrophysical Applications

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Masers and VLBI:  
Extragalactic and Galactic

To measure geometric distances, BH masses, cosmology...

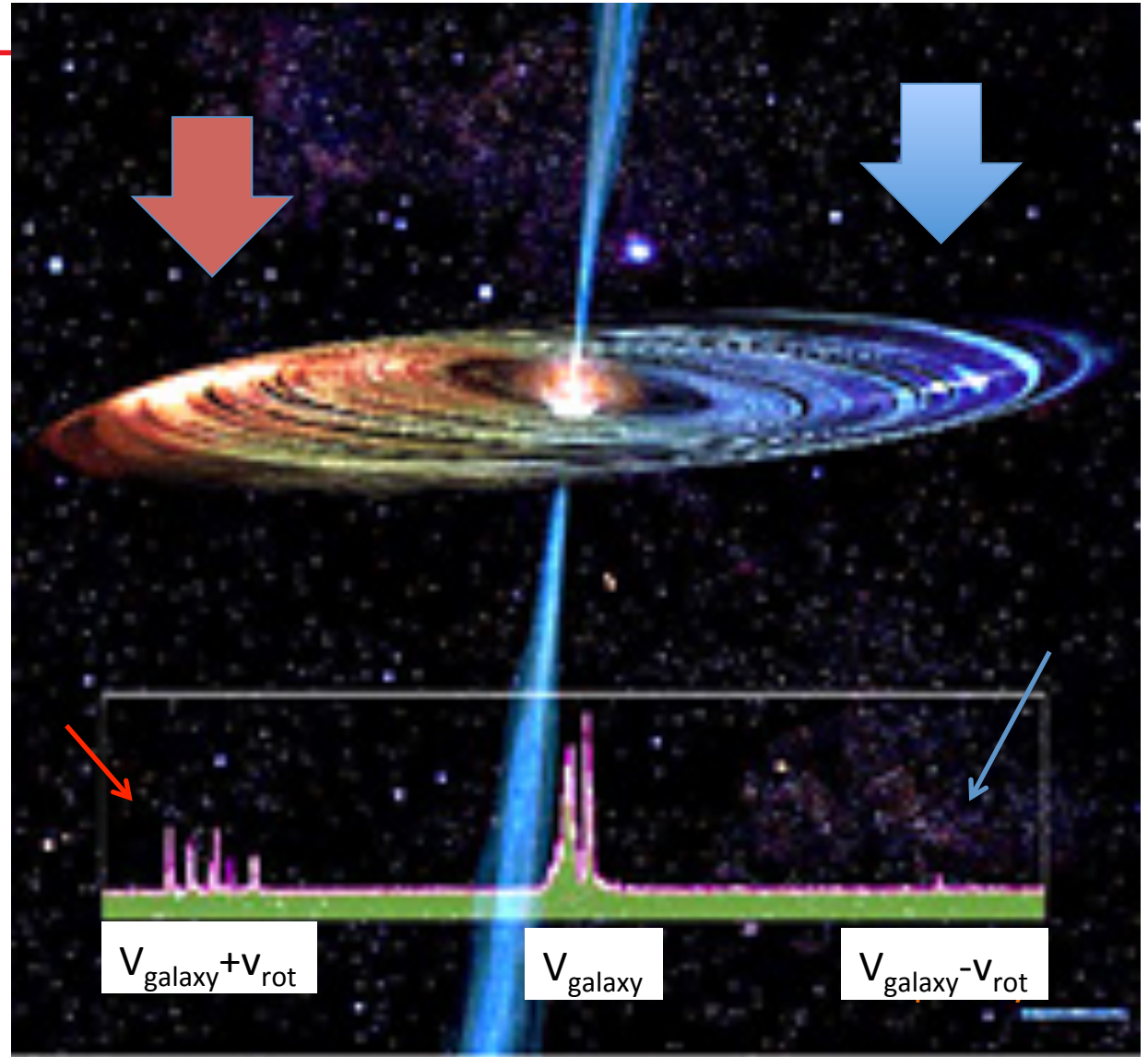


# NGC 4258: The Maser Disk Archetype

H<sub>2</sub>O masers in edge-on accretion disk

Orbit speed from Doppler shifts of masers, from single VLBI epoch

Transversal motion across the sky from multiple VLBI epochs of obs.

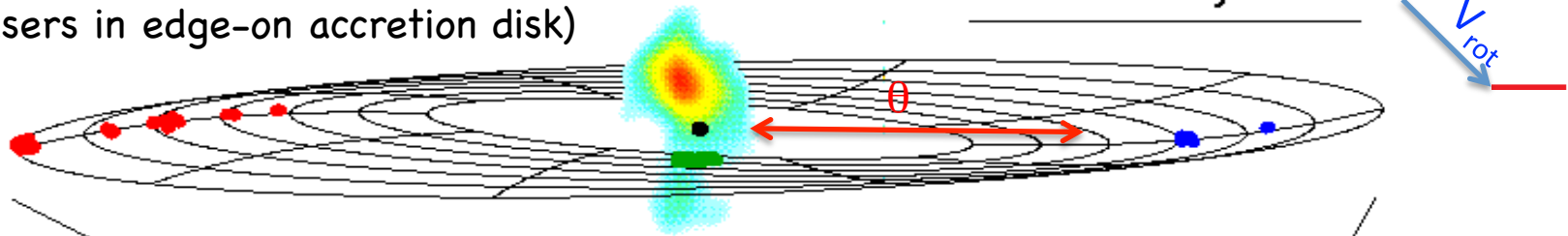


H<sub>2</sub>O Megamasers in Active Galactic Nuclei

NGC4258 – Best evidence of a BH (extragalactic masers in accretion disk )

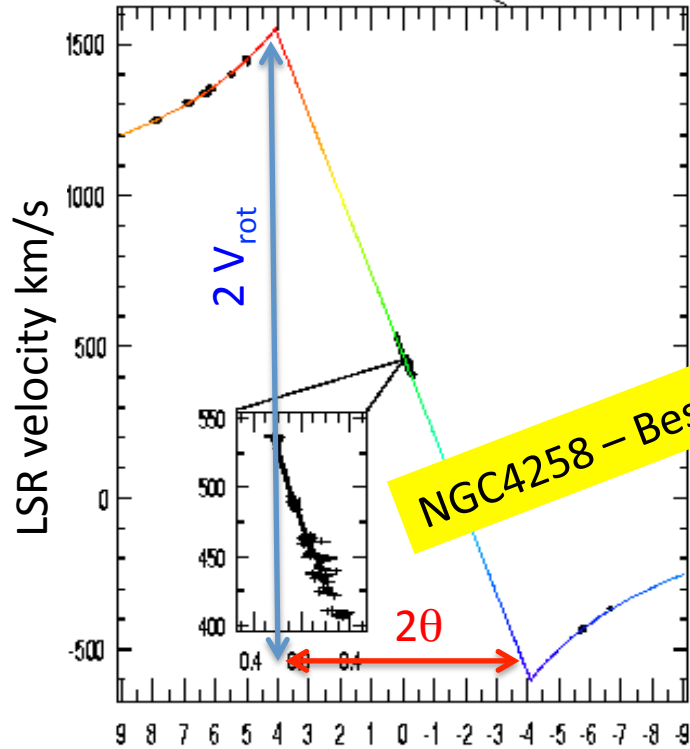
VLBI imaging determines positions of maser components

(water masers in edge-on accretion disk)

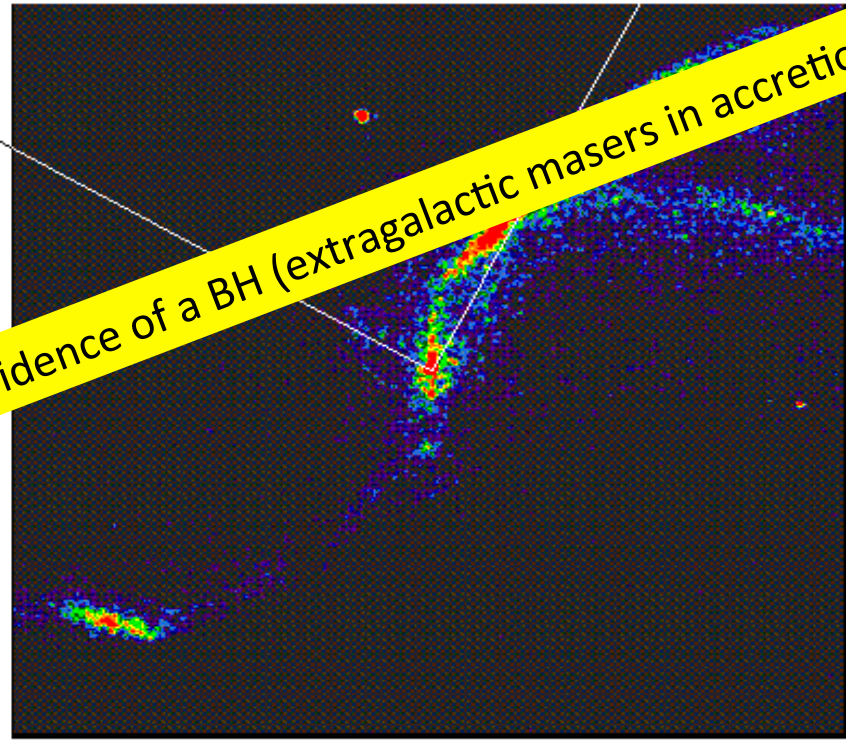


$$V_c = (G M / R)^{1/2}$$

DISTANCE = Orbital velocity / Transverse Angular velocity



NGC4258 – Best evidence of a BH (extragalactic masers in accretion disk)



Distance along major axis (mas)

10,000 ly

Central mass =  $3.6 \times 10^7$  solar mass (Miyoshi et al. Nature 373, 127) (size < 0.13pc radius)

Distance =  $7.2 \pm 0.3 \pm 0.5$  Mpc (Herrnstein et al. Nature 400, 539)

using the technique pioneered on the nearby galaxy NGC 4258...



## Extragalactic Maser Surveys: Megamaser Cosmology Project (MCP)

The MCP is a multi-year VLBA “Key Project”

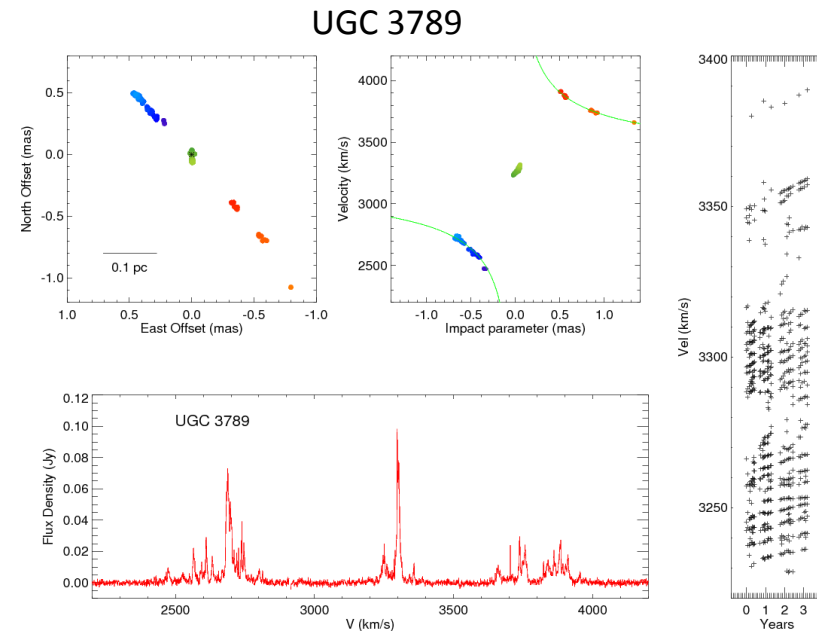
With the goal of determining  $H_0$  precisely (better than 3%) by measuring direct geometric distances to circumnuclear  $H_2O$  megamasers in galaxies well into the the Hubble flow (at distances 50--200Mpc).

$$V = H_0 D$$

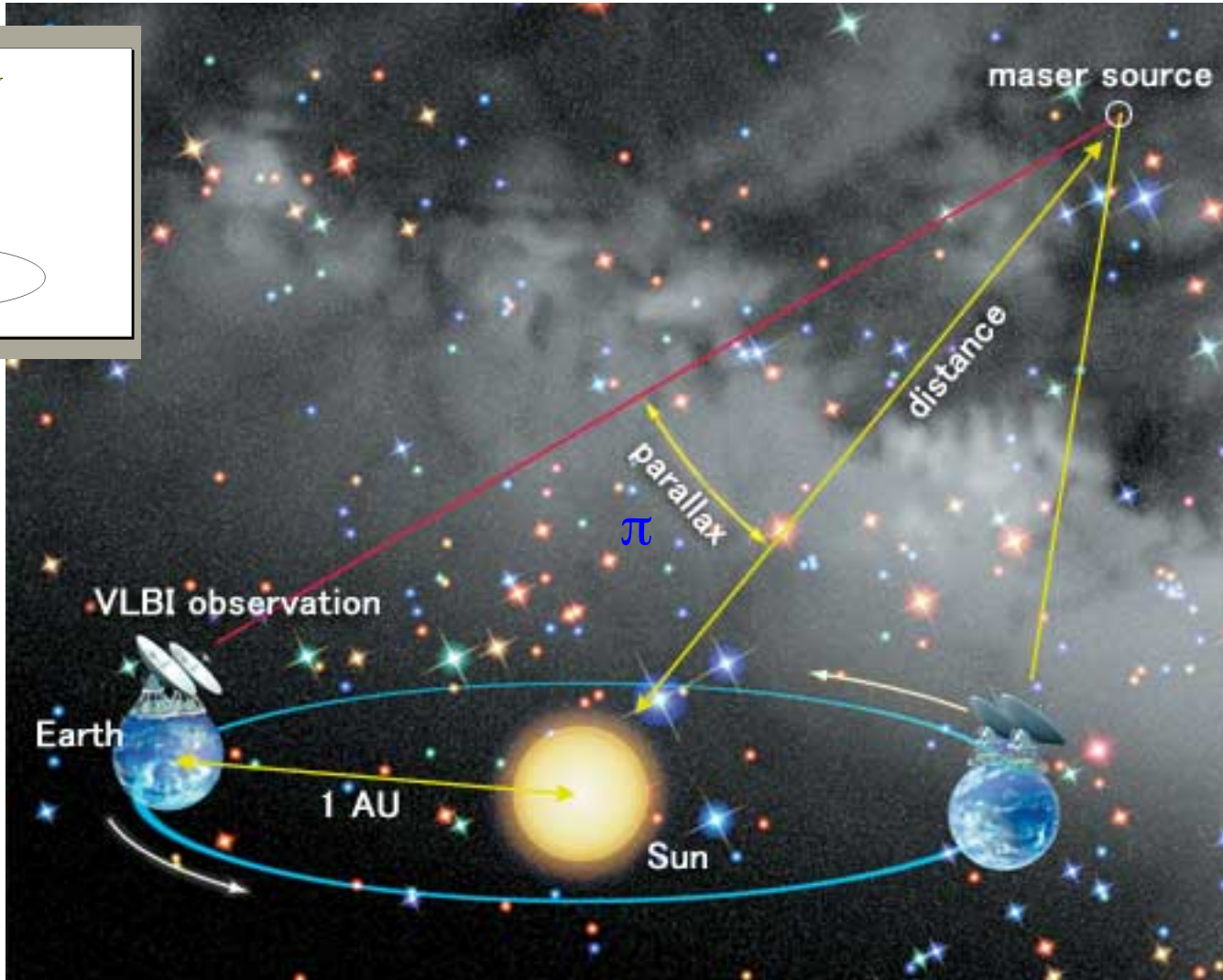
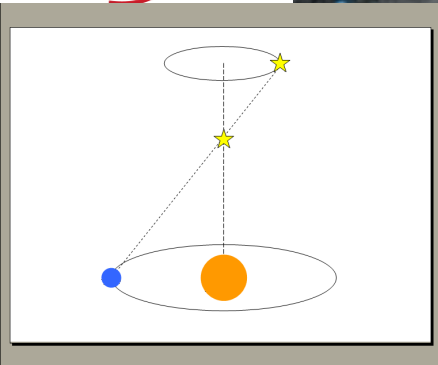
$H_0 = 69.3 \pm 4.2 \text{ km/s/Mpc}$

*Current estimate (from 4 sources).*

*Expect to achieve ~4% total uncertainty next year*



# Astrometry is the most precise way to Measure Distances

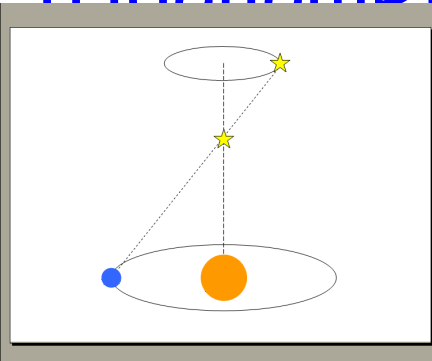


**TRIGONOMETRIC  
PARALLAX:**

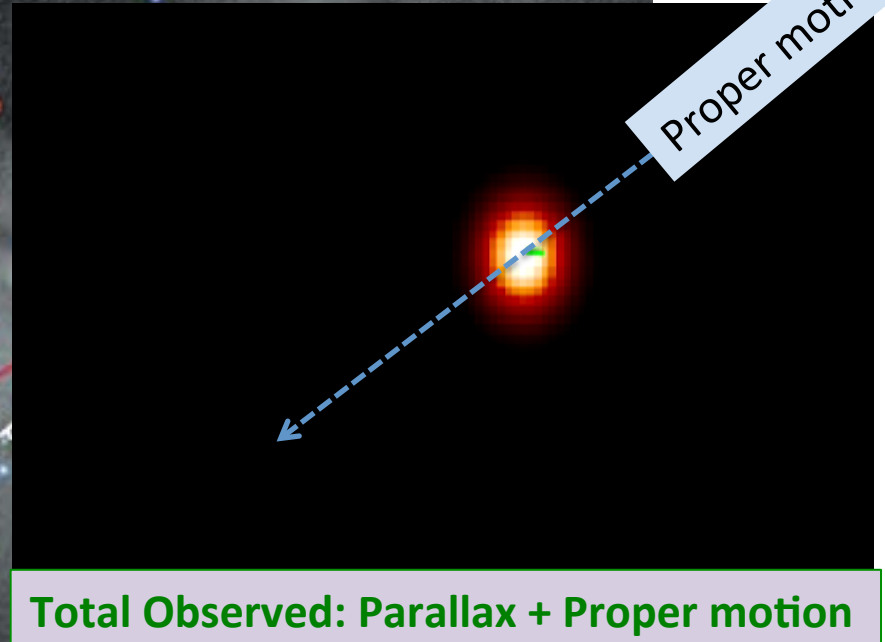
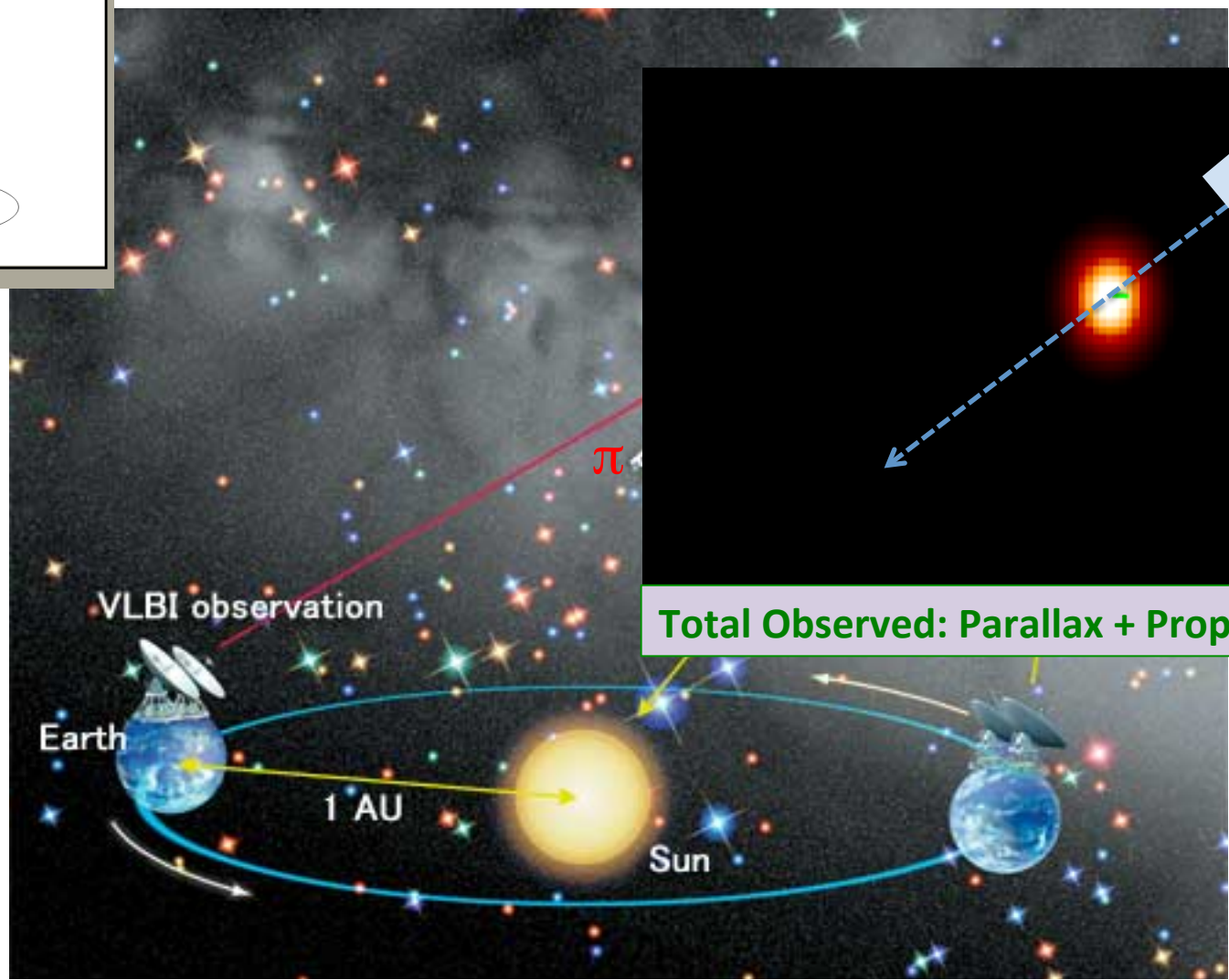
$$\pi \text{ (mas)} = 1 / D \text{ (Kpc)}; \quad 10 \text{ Kpc away, Parallax } 0.1\text{mas} = 100 \text{ micro-as}$$

# 3D Structure and Kinematics of the Milky Way

## Trigonometric Parallax – Measure Distances



Source parallax

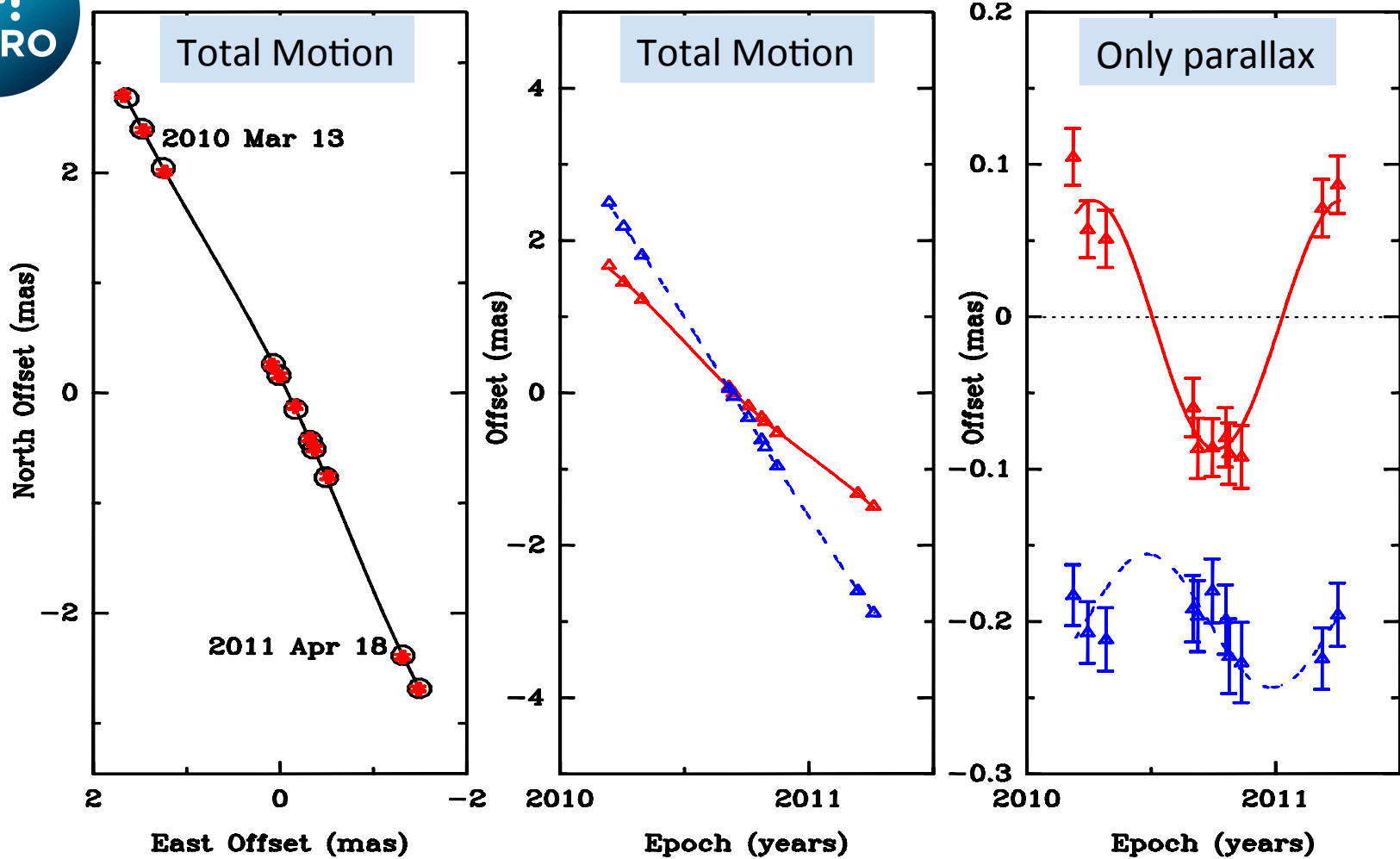


$\pi$  (mas) = 1 / D (Kpc); 10 Kpc away, Parallax 0.1mas = 100 micro-as



# Parallax for W 49N H<sub>2</sub>O masers

$$\pi = 90 \pm 7 \mu\text{as} \quad (D=11.1 \pm 0.9 \text{ kpc})$$



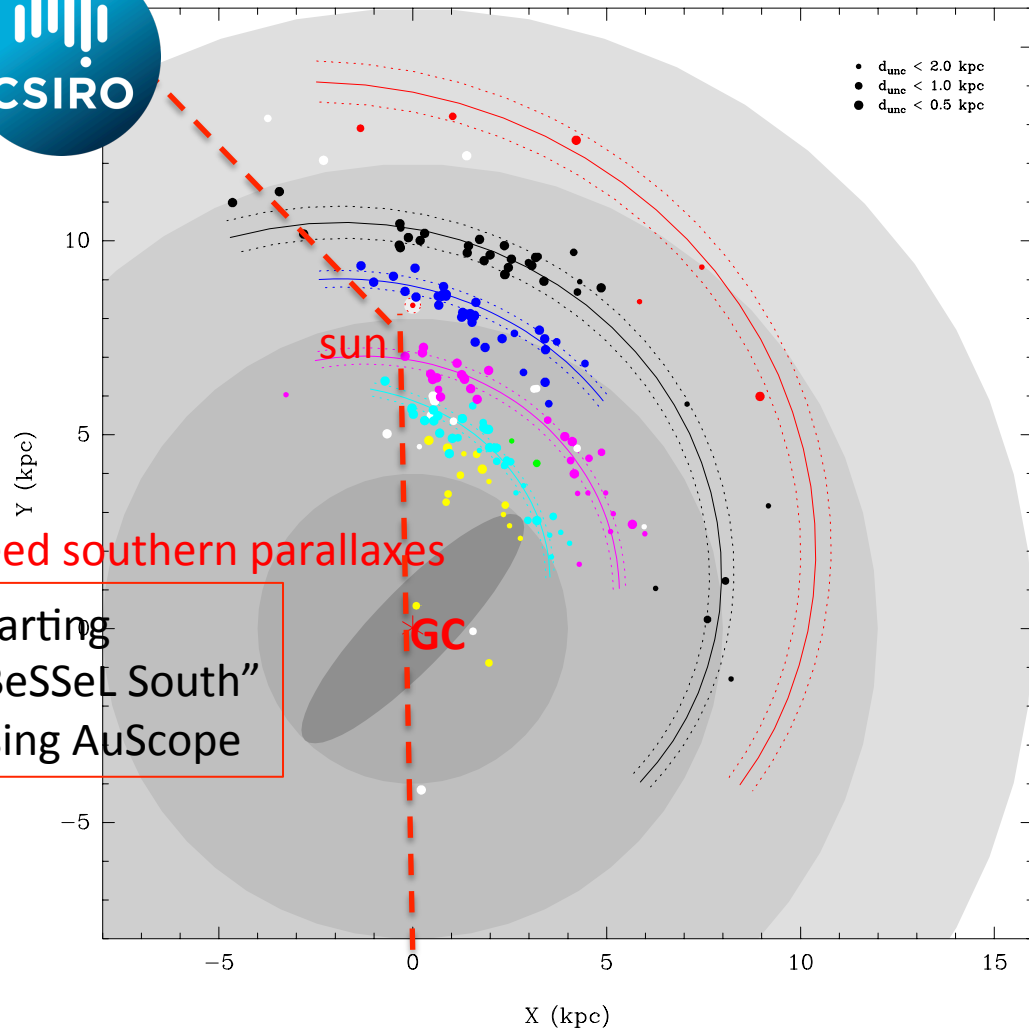
Red: East Offset  
Blue: North Offset

Zhang+ 2013



# Mapping Spiral Structure

Major “Key Science” Projects for VERA and VLBA (BeSSeL survey)



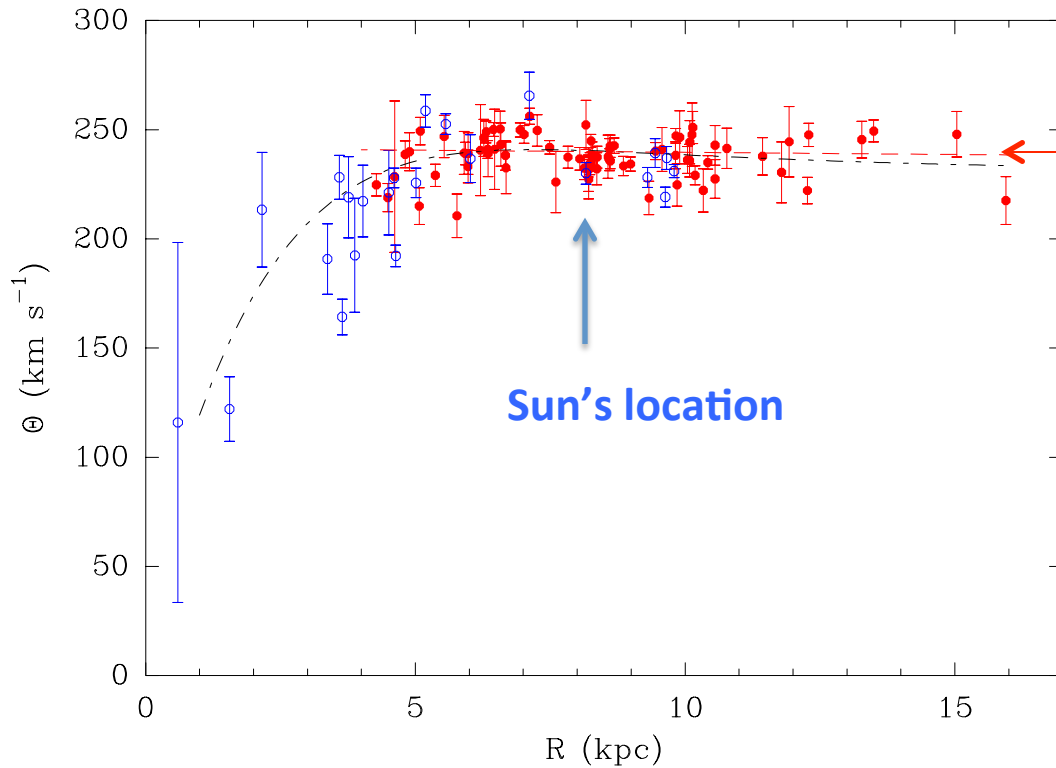
- Parallaxes: ~170 parallaxes for massive young stars
- Arms assigned by CO  $l-v$  plot
- Tracing most spiral arms, eg...
  - Outer arm traced
  - Perseus arm “gap”
  - Local arm significant
- Inner, bar-region is complicated

Reid et al. 2016  
 Honma et al. 2012

Plan view of the Milky Way with locations of HMSFR with trigonometric parallaxes.



# The Milky Way's Rotation Curve



Revised IAU recommendation:

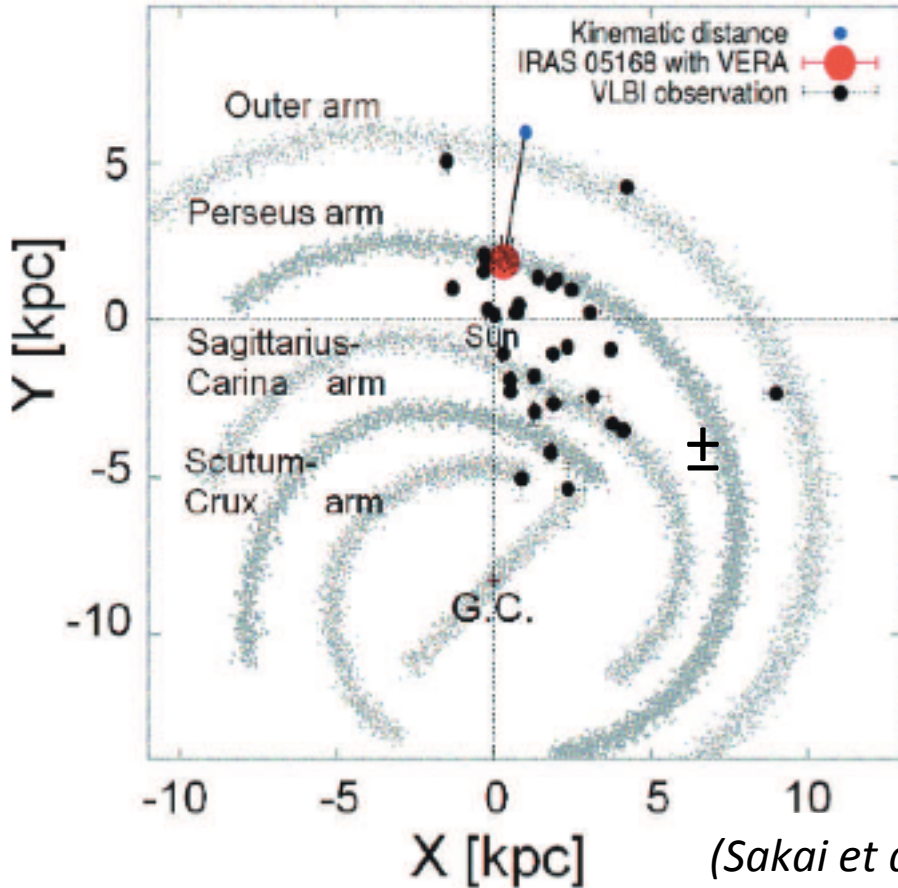
$\Theta_0 = \sim 240$  km/s and nearly flat based on 3-D motions and “gold standard” distances

Replacing

Gunn, Knapp & Tremaine (1979) for a flat rotation curve...  
slope =  $\Theta_0 = 220$  km/s

The increase in speed increases the Milky Way's mass by 50 percent, bringing it even with the Andromeda Galaxy

# REVISING DISTANCES



**Kinematic Distance 6.08 Kpc**

**VLBI Trigonometric Parallax  $1.88 \pm 0.2$  Kpc**

(Sakai et al, 2012, VERA H<sub>2</sub>O Masers, 22 GHz)

## Physical Parameter

Kinematic distance of 6.08 kpc (Molinari et al. 1996)

Our parallax measurement of 1.88 kpc

Virial mass ( $M_{\odot}$ )

$2.4 \times 10^3$

$7.4 \times 10^2$

LTE mass ( $M_{\odot}$ )

$>1.2 \times 10^4$

$>1.1 \times 10^3$

$\alpha = M_{\text{vir}} / M_{\text{LTE}}$

0.2

0.7

Bolometric luminosity ( $L_{\odot}$ )

17,130

1638

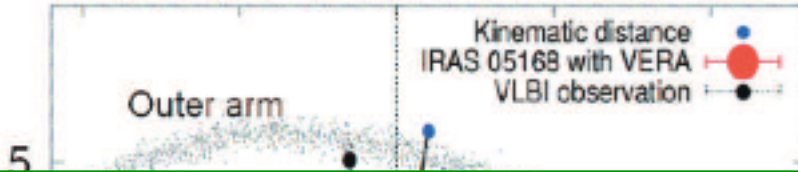
Spectral type

B0.5\*

B3\*

\*Panagia, 1973.

# REVISING DISTANCES



## Other cases:

- Star Clusters “Pleiades Distance Controversy”, 8.4 GHz  $\mu$ Jy sources, VLBA+GB+Arecibo+Eff  
Hipparcos parallax  $120.2 \pm 1.5$  pc vs. VLBI parallax  $133.5 \pm 1.2$  pc  
(Melis et al. 2014, Science)

## RELEVANCE:

- Model-independent distance  $\rightarrow$  massive revision of physical parameters
- Distance to prototypical cluster  $\rightarrow$  underpin stellar population studies.

### Physical Parameter

Kinematic distance of 6.08 kpc (Molinari et al. 1996)

Our parallax measurement of 1.88 kpc

Virial mass ( $M_{\odot}$ )	$2.4 \times 10^3$	$7.4 \times 10^2$
LTE mass ( $M_{\odot}$ )	$>1.2 \times 10^4$	$>1.1 \times 10^3$
$\alpha = M_{\text{vir}} / M_{\text{LTE}}$	0.2	0.7
Bolometric luminosity ( $L_{\odot}$ )	17,130	1638
Spectral type	B0.5*	B3*

\*Panagia, 1973.



# Summary

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VLBI: Presented the basics: connected array – taken further

Challenges:

- Everything needs correcting for – all the time
- Atmosphere, Etc
- Different regimes, different solutions

Methods with Wide applicability – at all frequencies

- High Angular resolution (mas) with Self Calibration
- precision astrometry ( $\mu\text{as}$ ) with Phase Referencing, SFPR, MV

Examples:

- Probe AGN radio jets, and movie of SN expansion
- Black Hole shadows
- Distance and mass of BH, dynamics of accretion disks
- Cosmological implications, determine  $H_0$
- Parallax distances, 3D structure of Milky Way