ICRAR

International Centre for Radio Astronomy Research

Very Long Baseline Interferometry (VLBI)

Potential, Challenges and Astrophysical Applications.

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THE GOVERNMENT OF WESTERN AUSTRALIA

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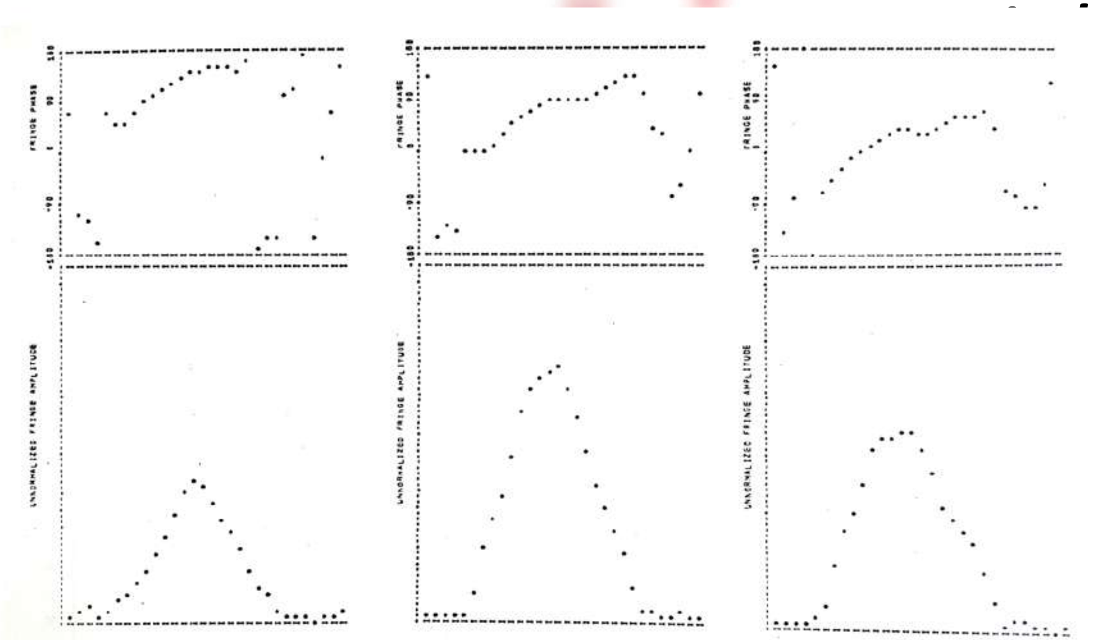
Long Baseline Interferometry (VLBI)

First VLBI measurement OH emission (J.Moran)



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.)

Challenges and
cal Applications.

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AR-UWA & CSIRO

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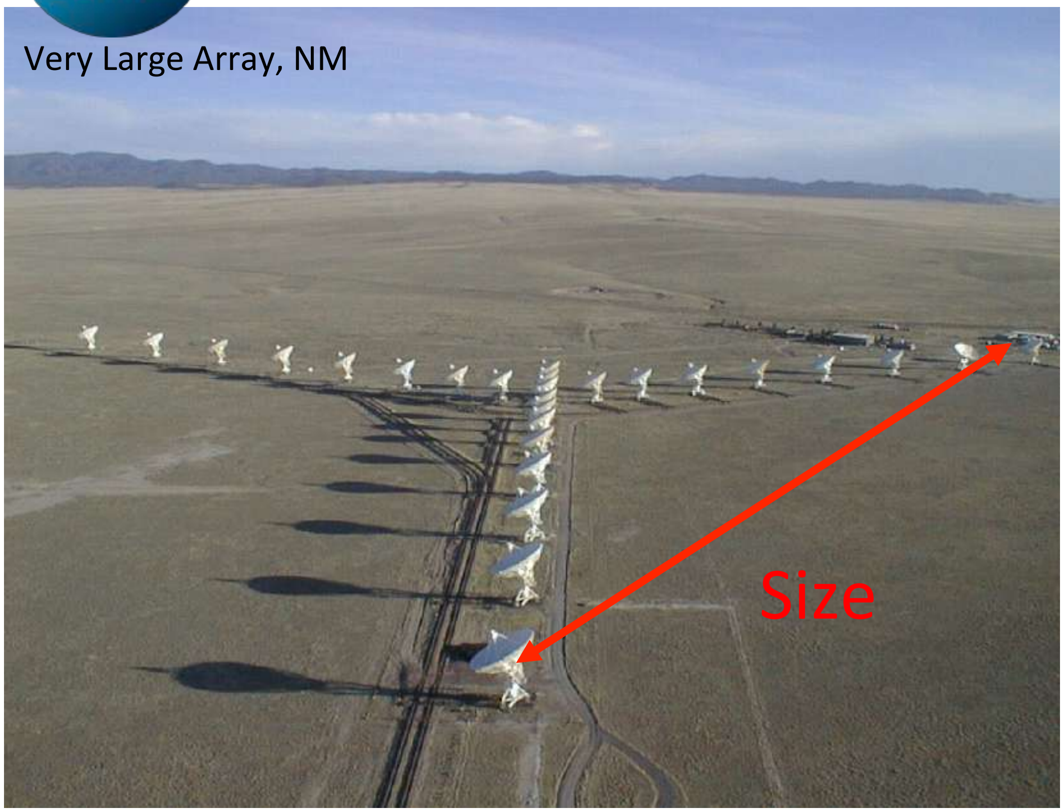
Outline

- 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



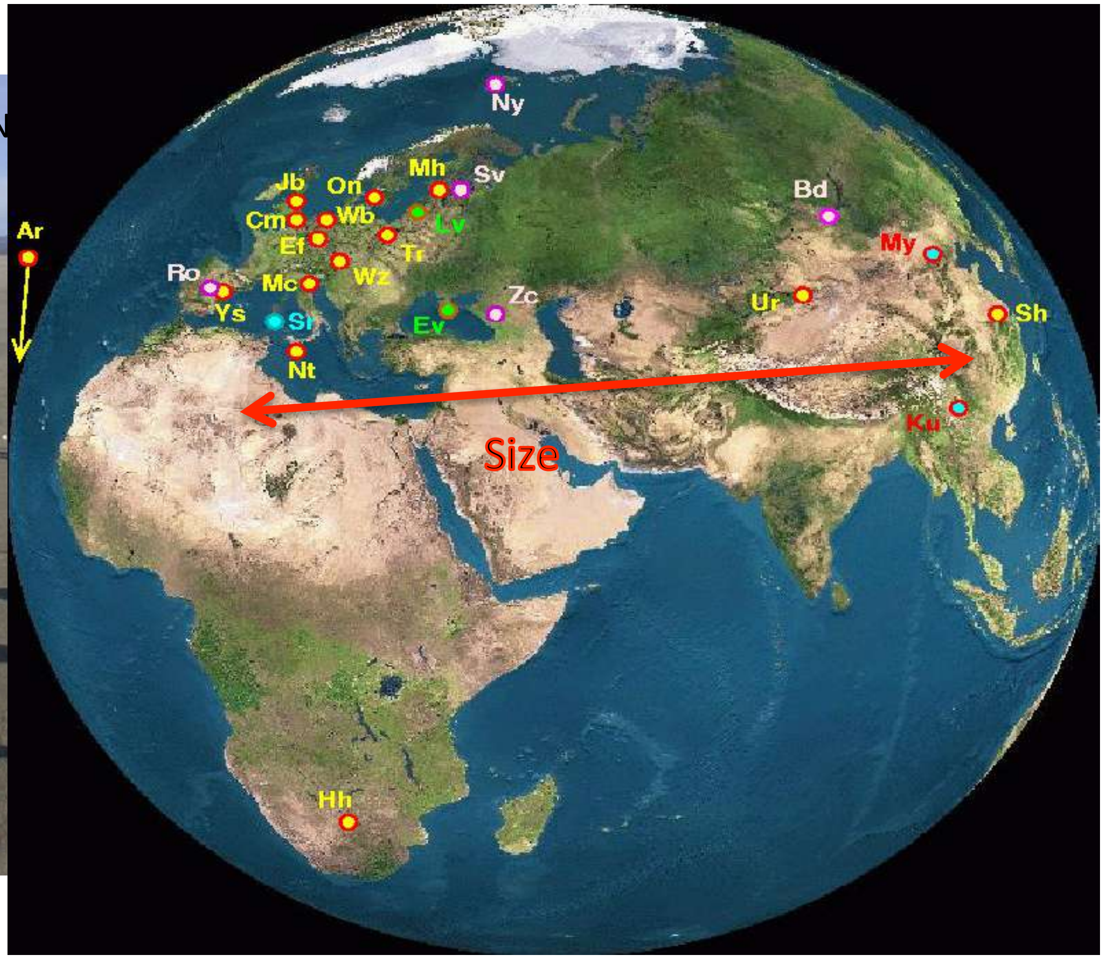
$$\frac{\lambda}{\text{size}}$$

Arrays

10 km

Radio Telescopes: Resolution

Very Large Array, N

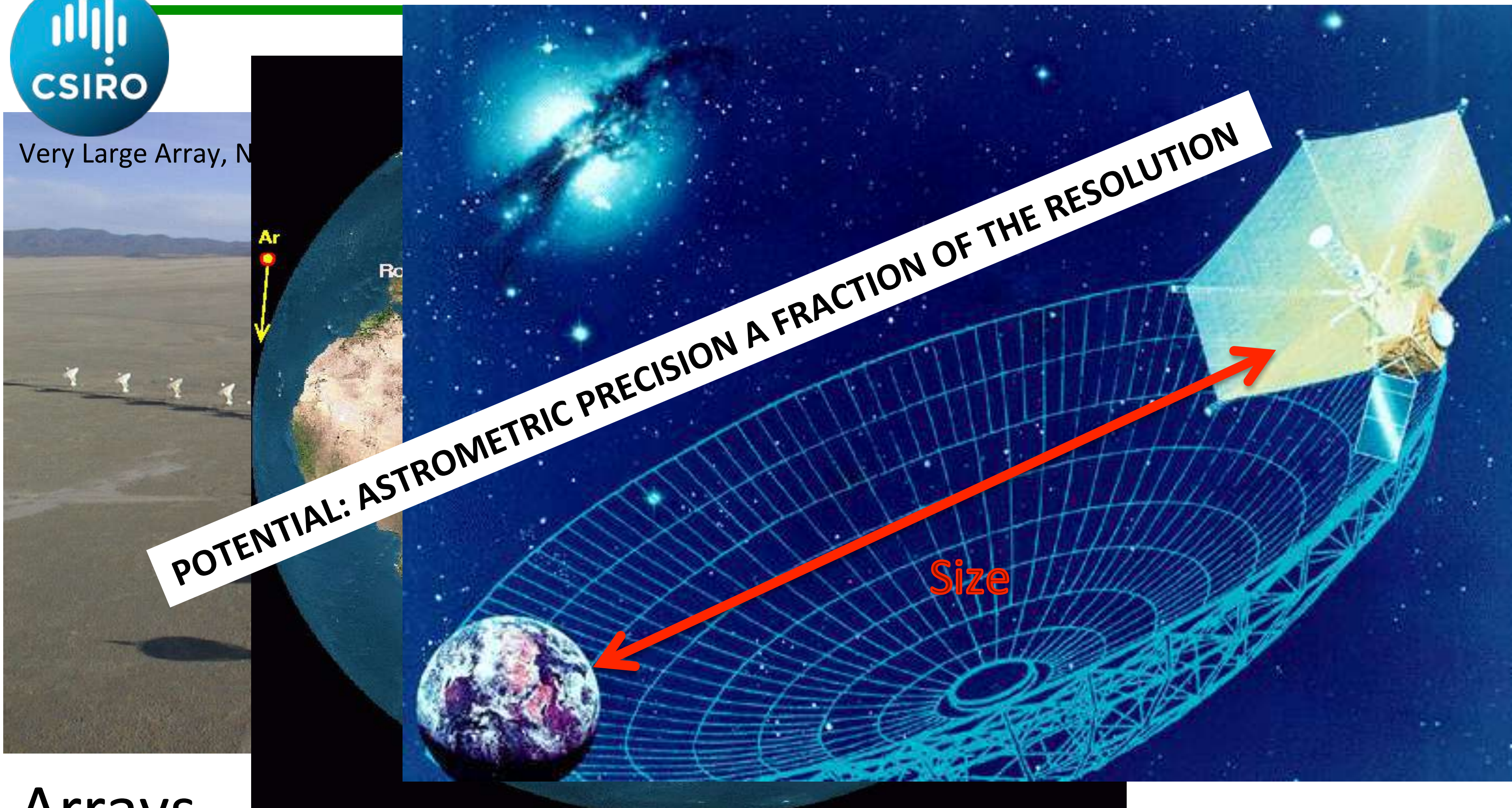


Arrays

10 km

6000km

Radio Telescopes: Resolution



Arrays

10 km	6000km	20.000km; 350.000km
250 mas	0.4 mas	100 μas ; 10 μas

VLBI provides.....

HIGHER SPATIAL RESOLUTION *(small Θ_{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)*:

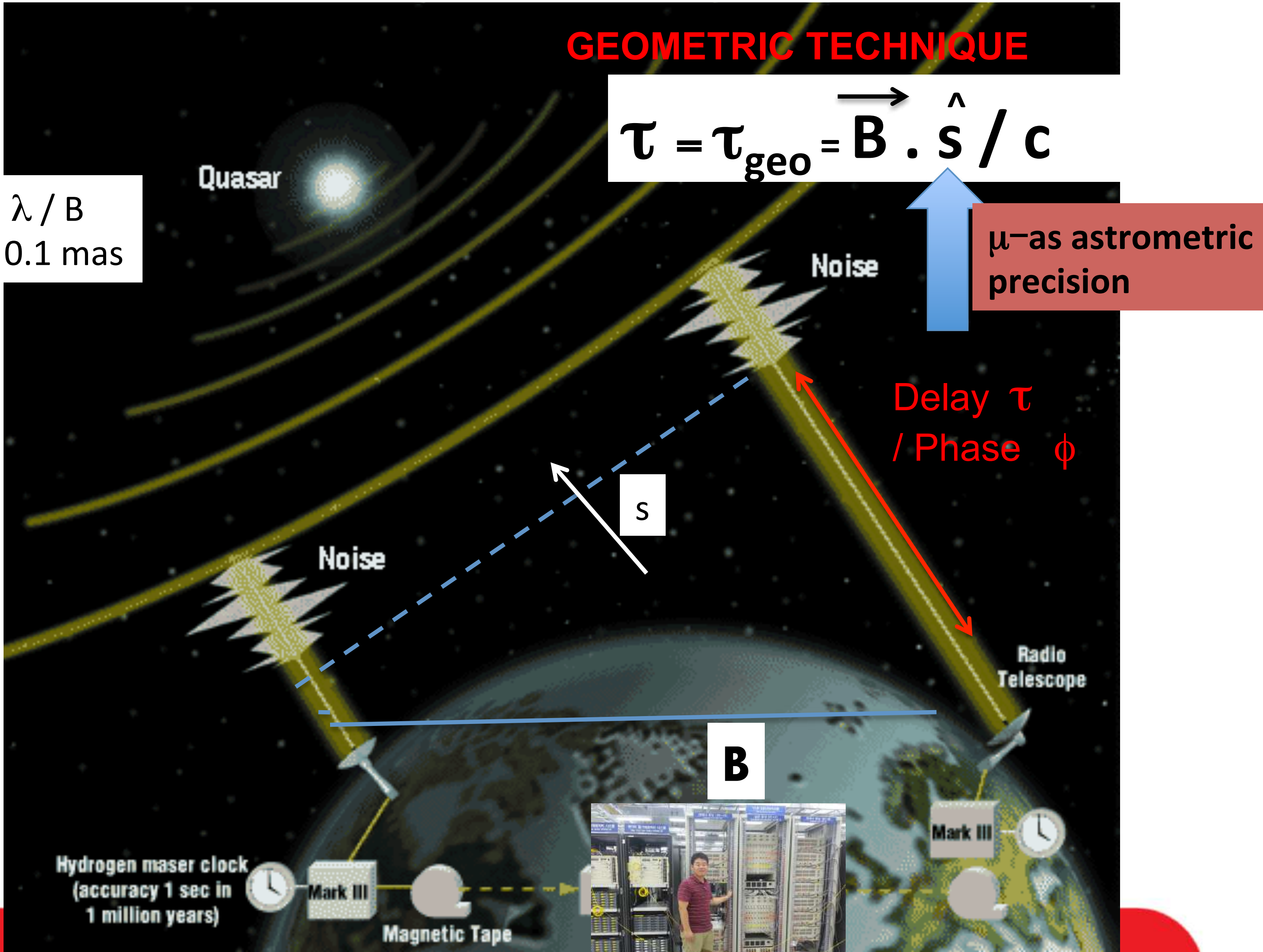
Targets: Very bright, compact (➔ High T_B emission)

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

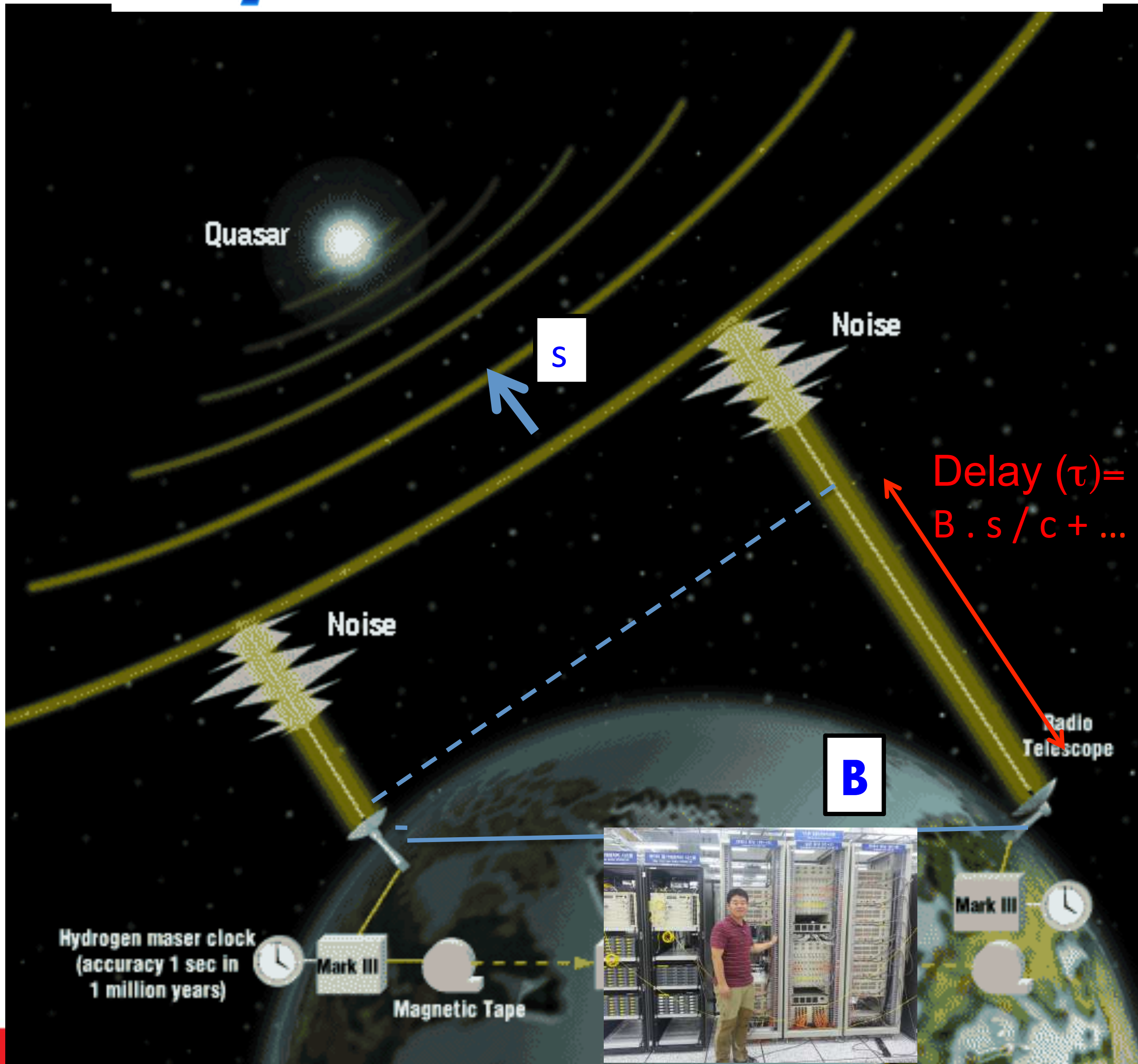
Calibration plays a significant role

Extreme interferometry:
Very Long Baseline Interferometry (VLBI)

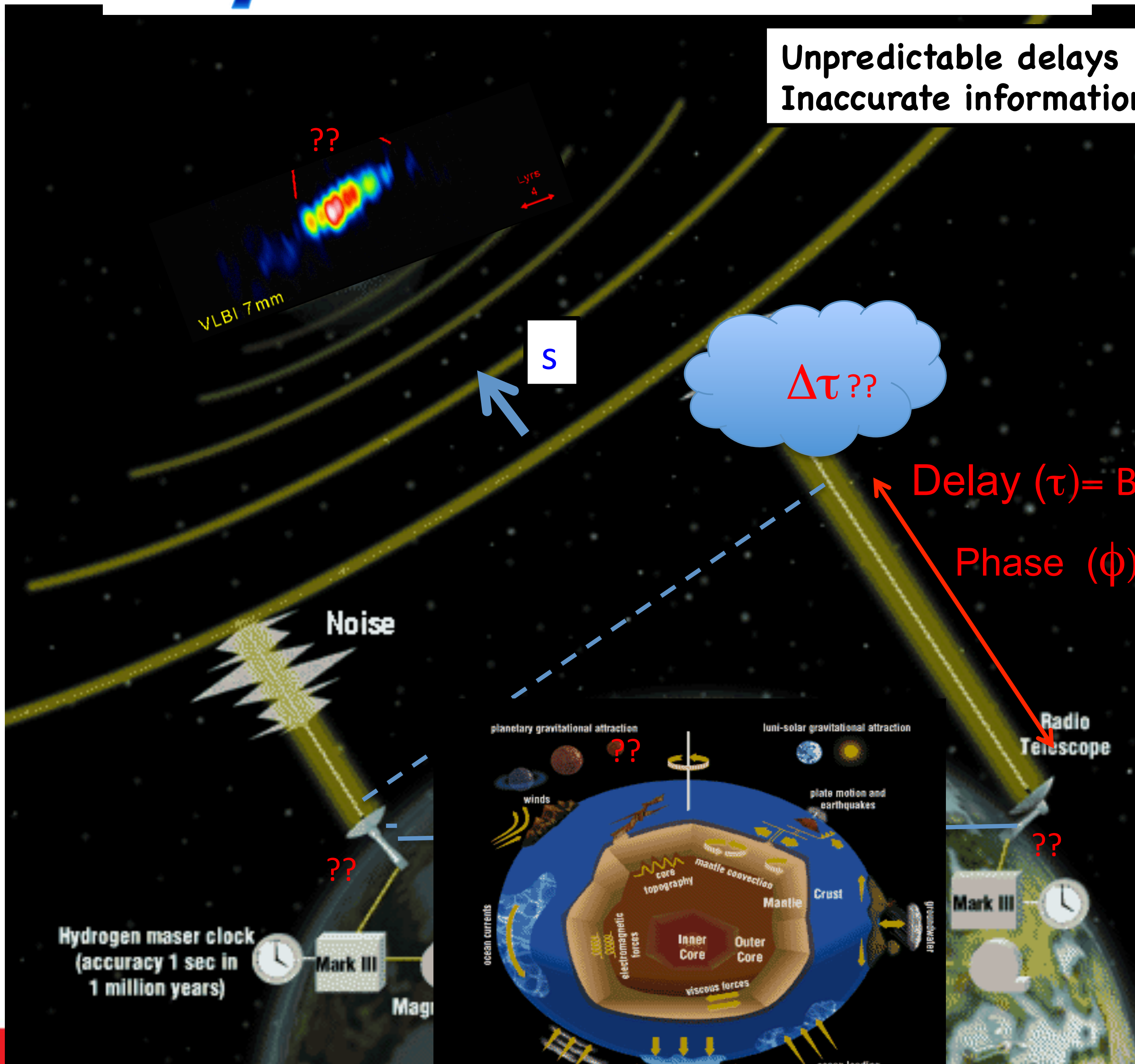
Resolution ~ λ / B
~ few mas – 0.1 mas



Why need VLBI calibration?



Why need VLBI calibration?



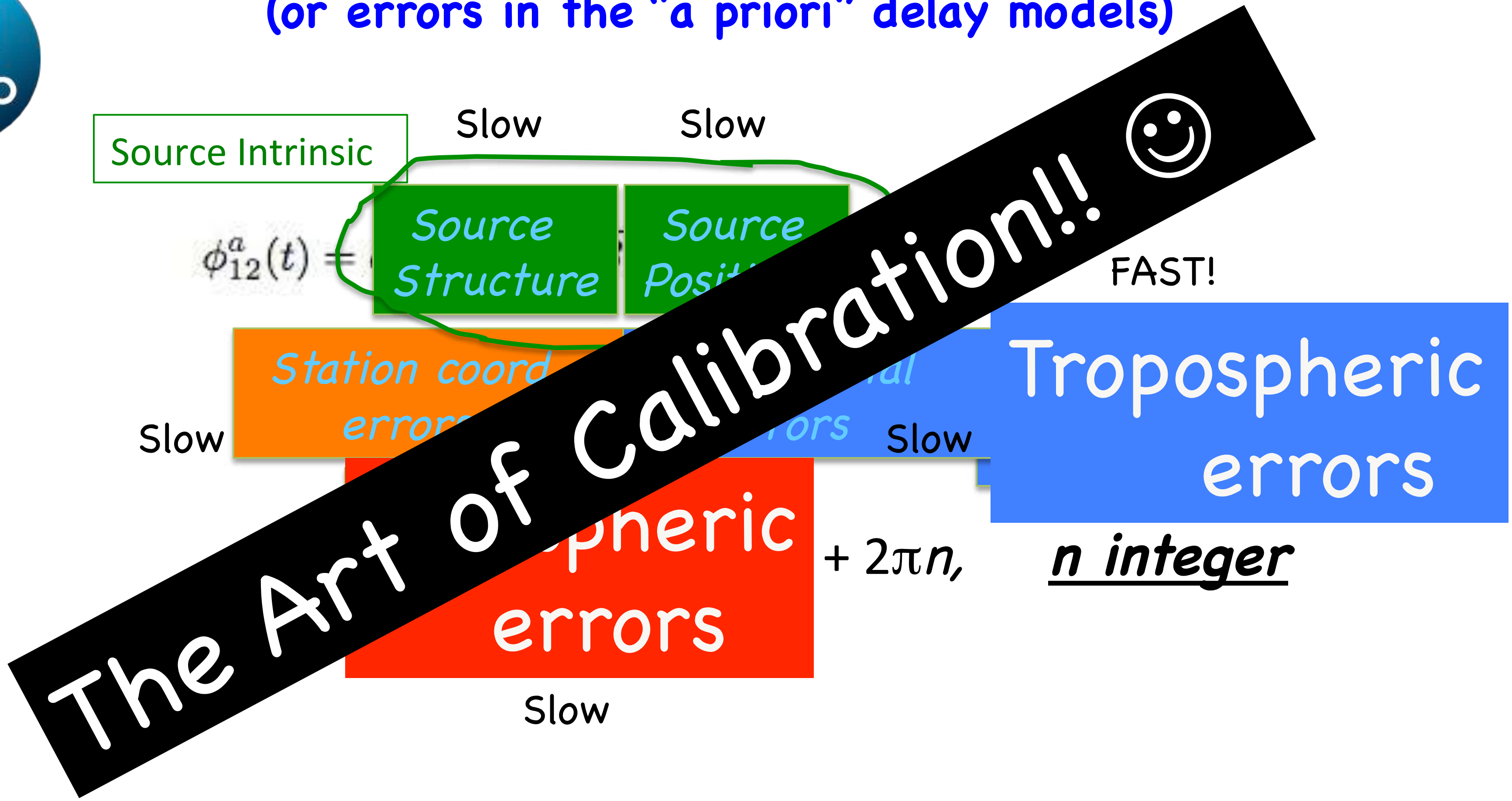
Unpredictable delays / Inaccurate information

Delay (τ)= B . s / c + ??

Phase $(\phi) = 2\,\pi\,\nu\,\tau$

VLBI Observables: The interferometric Phase, ϕ_{12}^{a}

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



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:

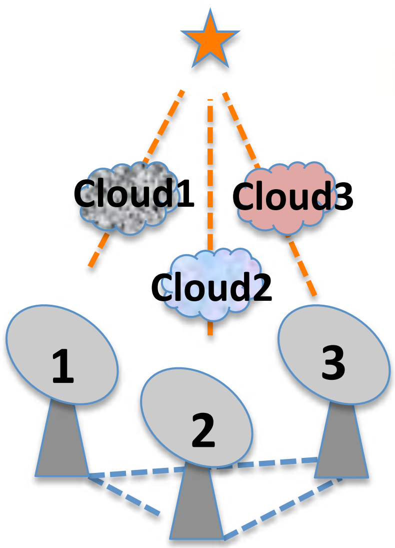
$\Phi_{12} + \Phi_{23} + \Phi_{31} =$

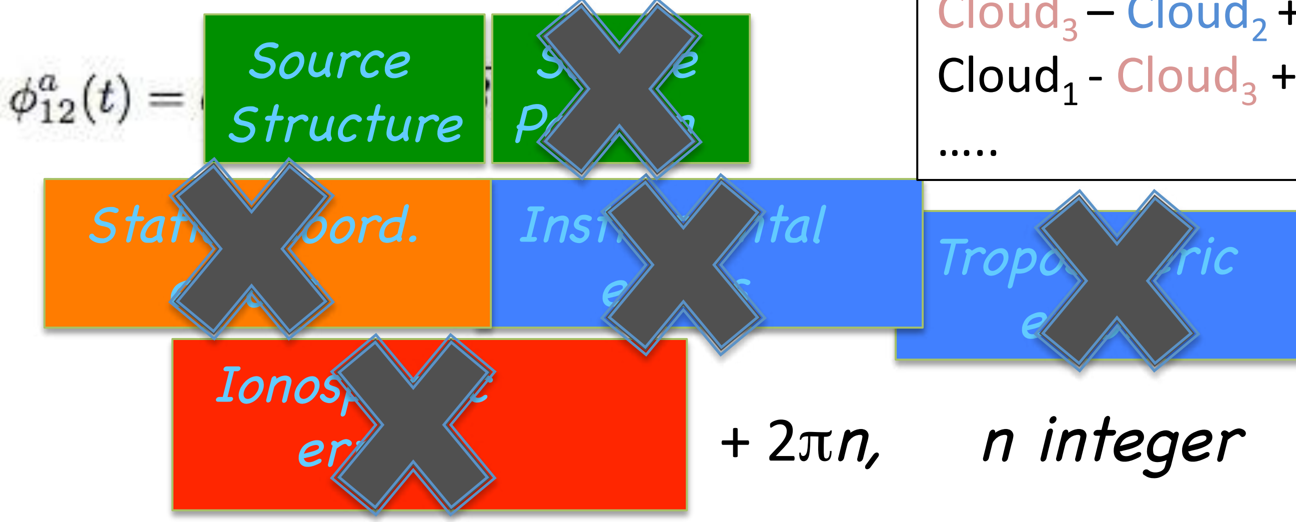
$\text{Cloud}_2 - \text{Cloud}_1 +$

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

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

.....





$+ 2\pi n,$ *n integer*

Goal: **IMAGING STRONG SOURCE**

(requires detection within coh time)

Obs. strategy: Tracking

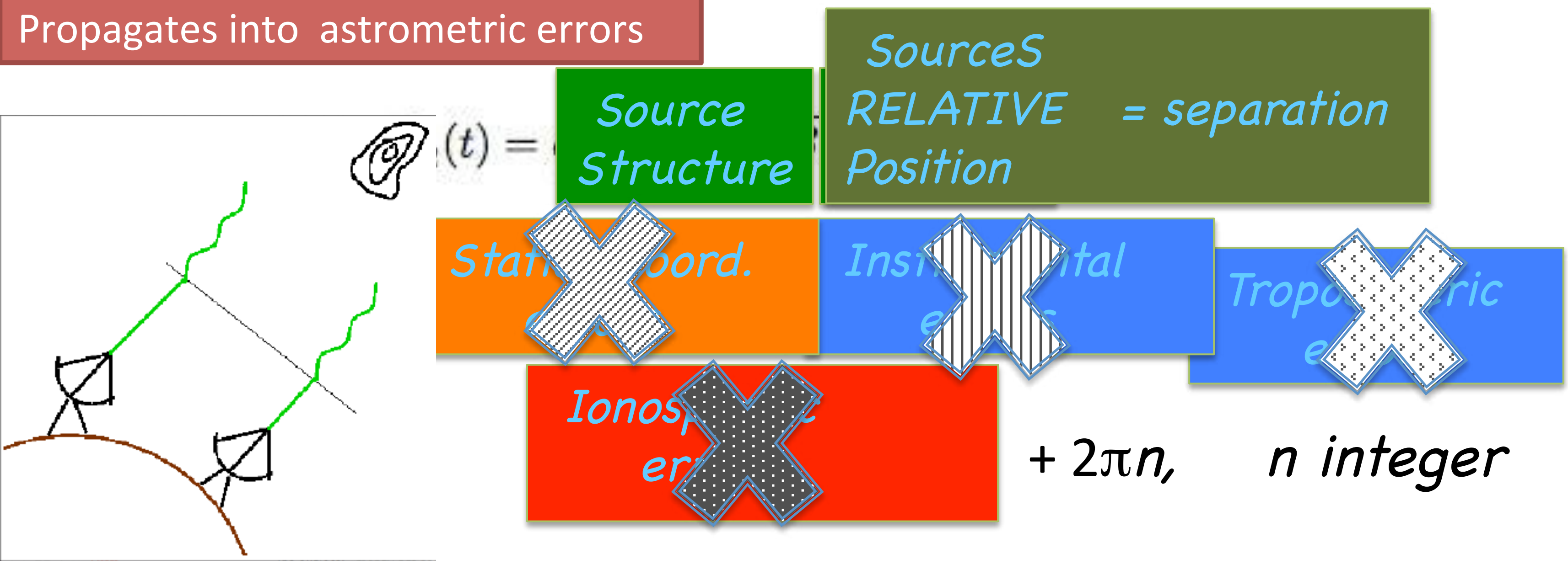
Obs. Freq.: wide range

ONLY STRONG SOURCES & NO ASTROMETRY

Calibration Technique (2): Phase Referencing

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

Imperfect compensation of PM
Propagates into astrometric errors



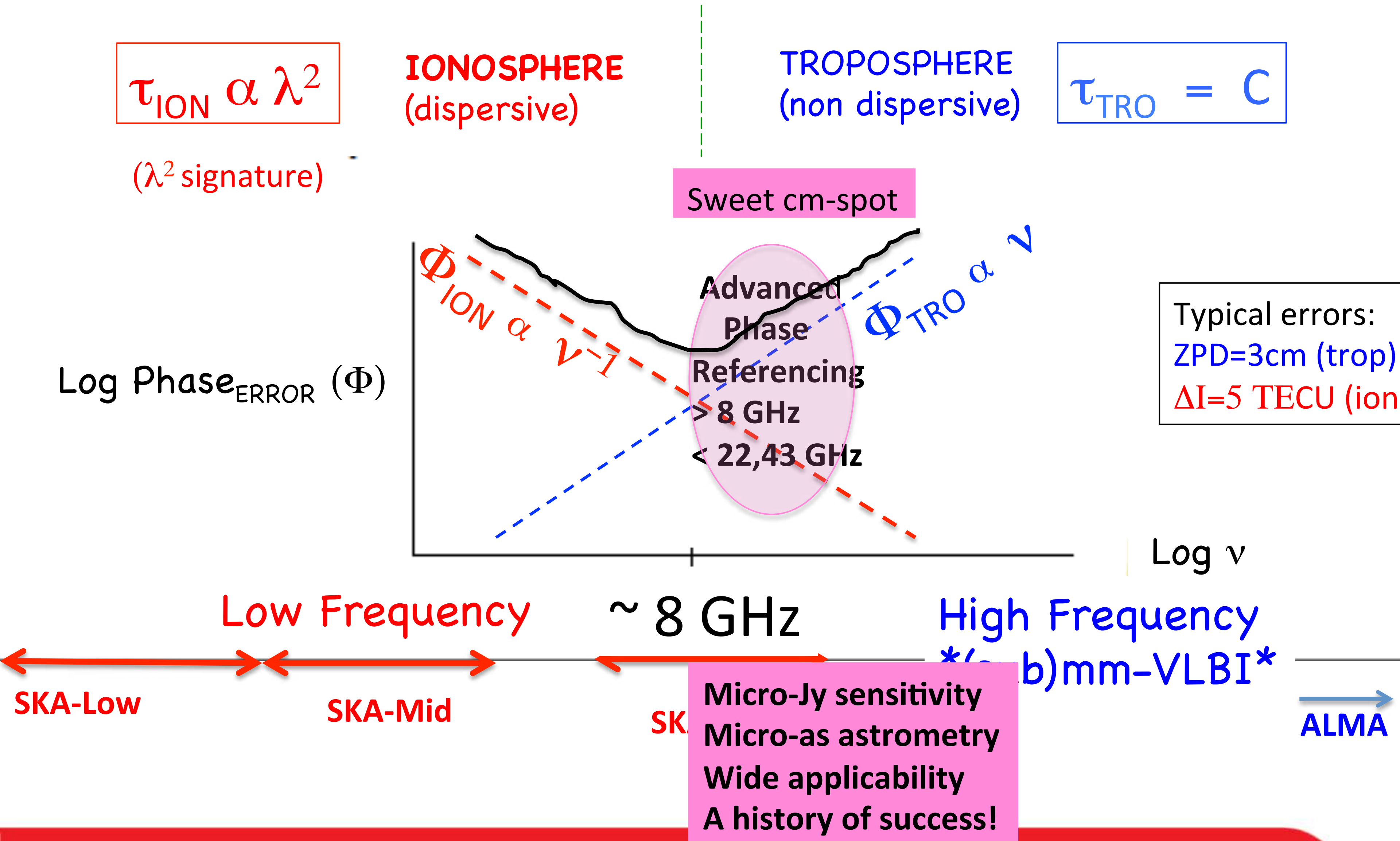
Goal: **IMAGING weak (and strong) precise ASTROMETRY**

Obs. strategy: Alternate fast btw 2 nearby sources

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

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

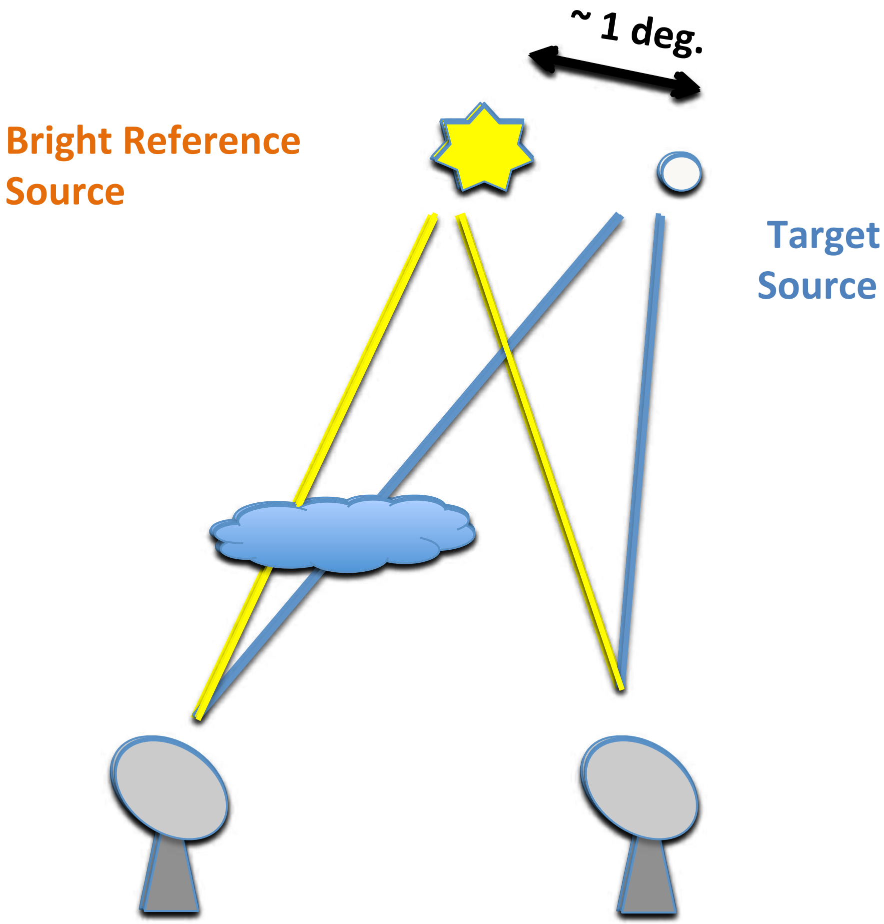
The Many Faces of the Propagation Medium



High Frequencies (> 22 GHz)
&
Troposphere

GOAL: Precise Astrometry → wider applicability

Phase Referencing *"trans-source"*

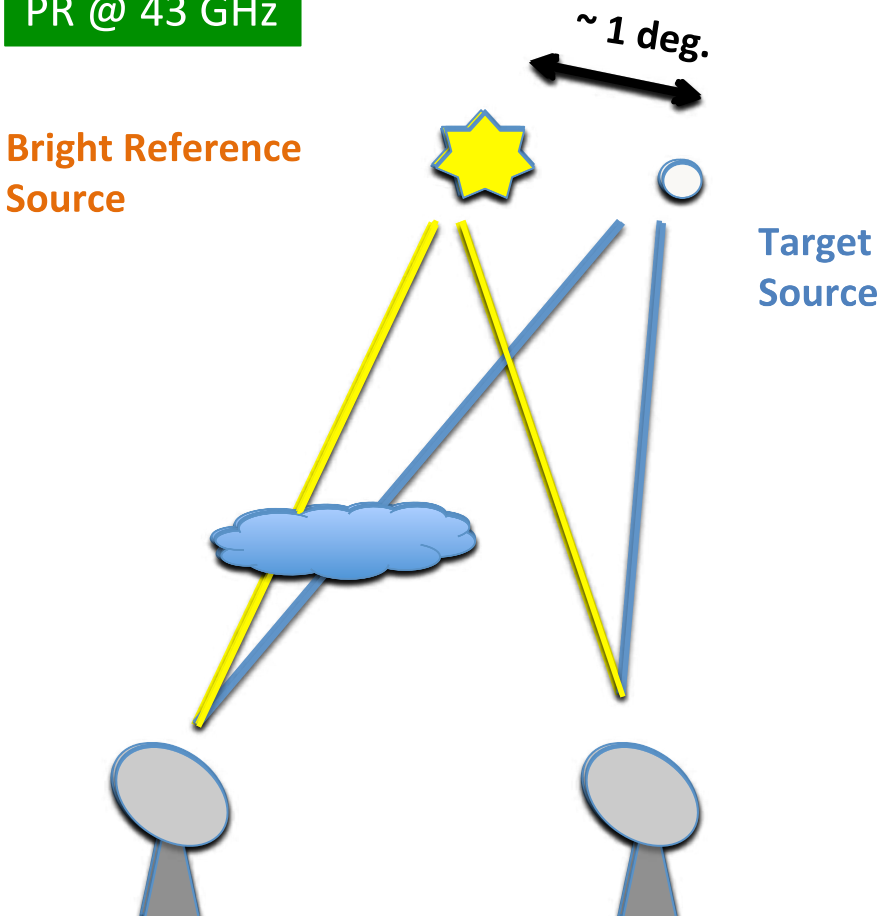


Phase Referencing *"trans-source"*

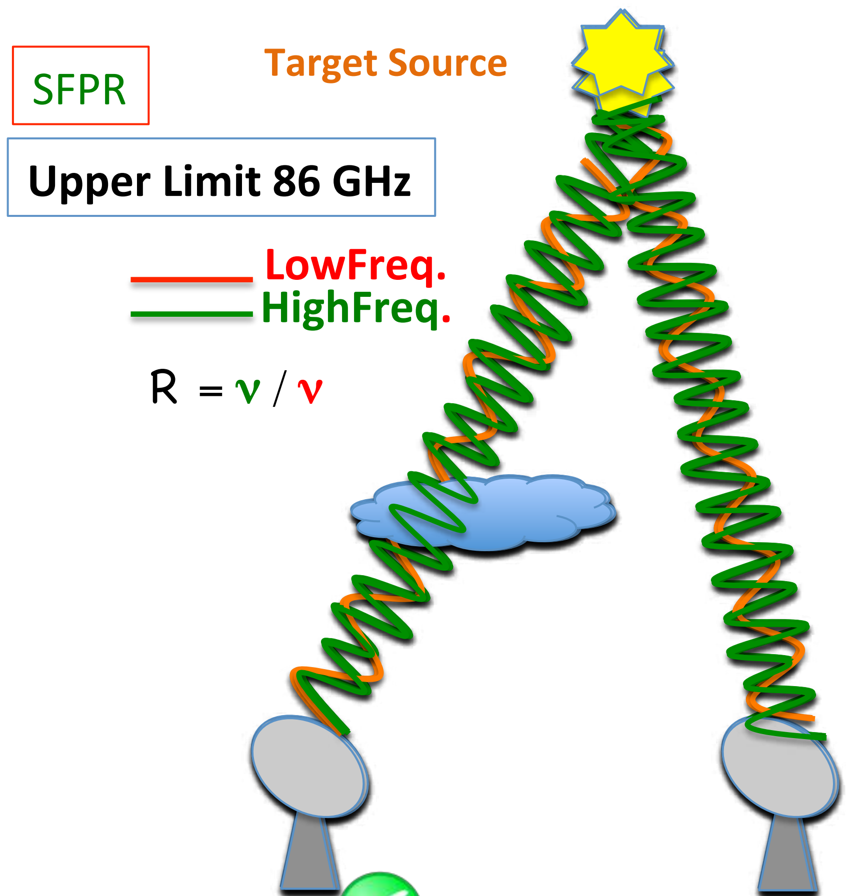
Paradigm Shift: "trans-frequency" calibration

"fast-frequency switching" with VLBA

PR @ 43 GHz



WEAK SOURCES ✓
ASTROMETRY ✓



WEAK SOURCES ✓
ASTROMETRY ✓

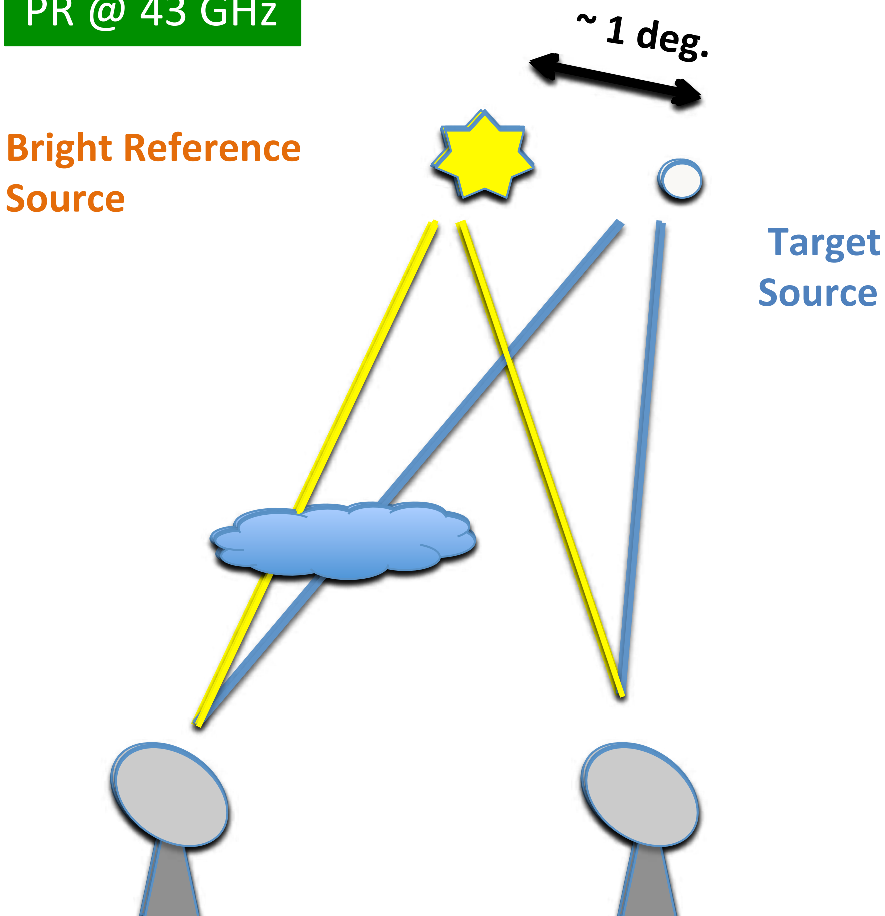
Rioja&Dodson 2008,2011

Phase Referencing *"trans-source"*

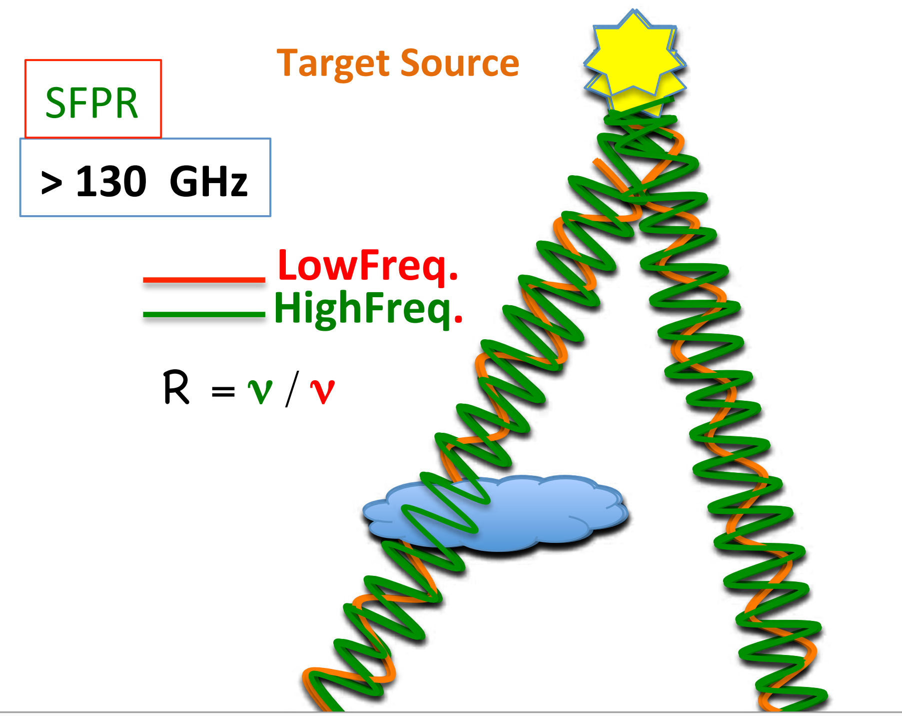
Paradigm Shift: "trans-frequency" calibration

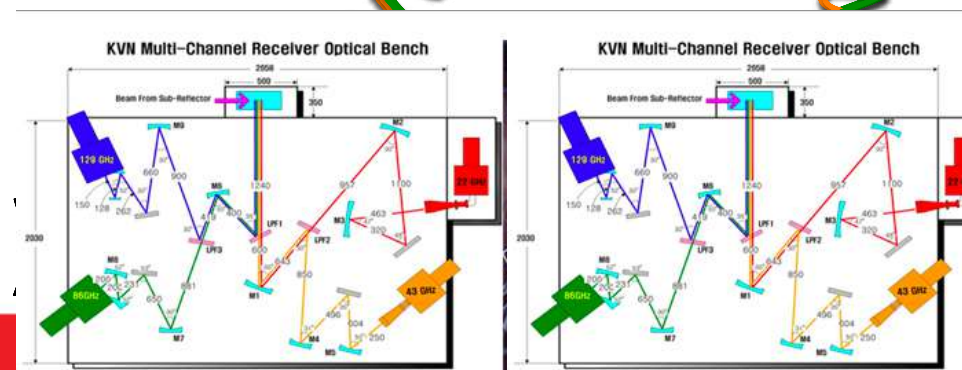
"Simultaneous Multi-channel receivers" with KVN

PR @ 43 GHz



WEAK SOURCES ASTROMETRY



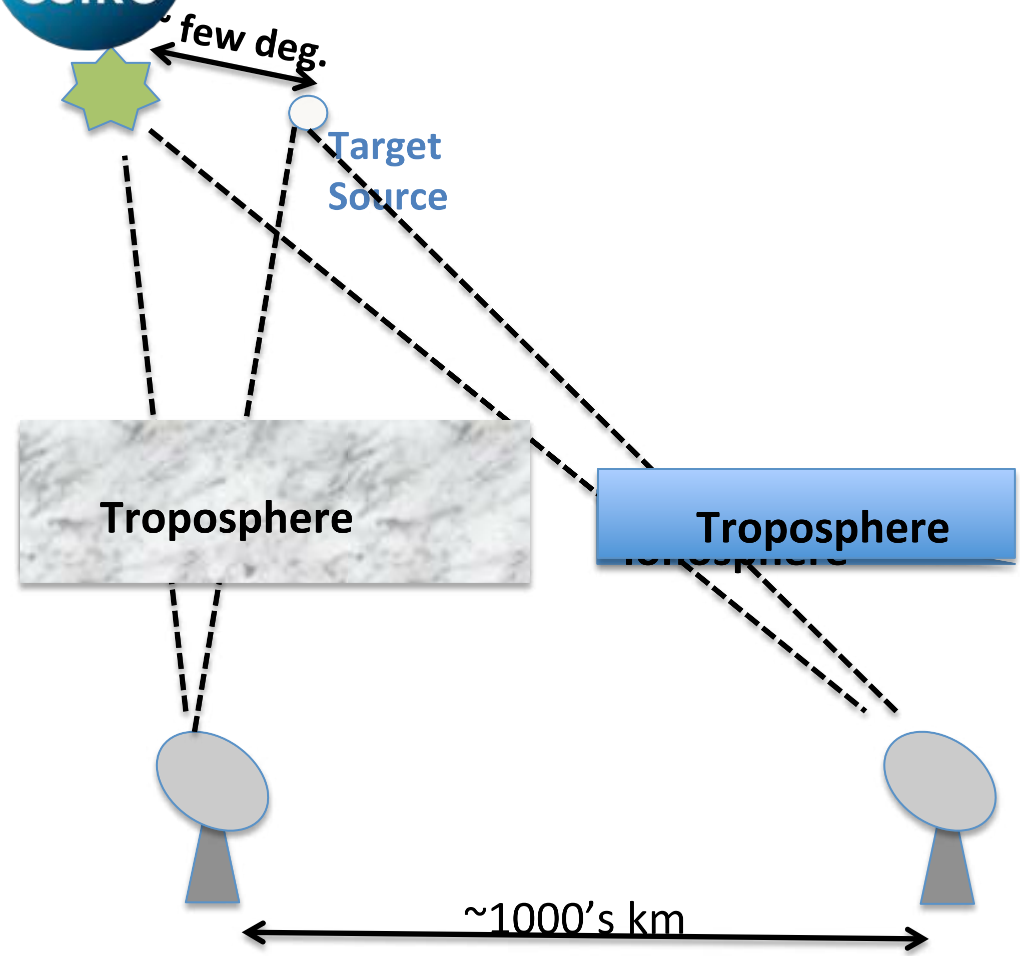


Low Freq VLBI also very interesting.
**Steep Spectrum sources (pulsars)
** SKA era

Low Frequencies (< 8 GHz)
&
Ionosphere

GOAL: Precise Astrometry → wider applicability

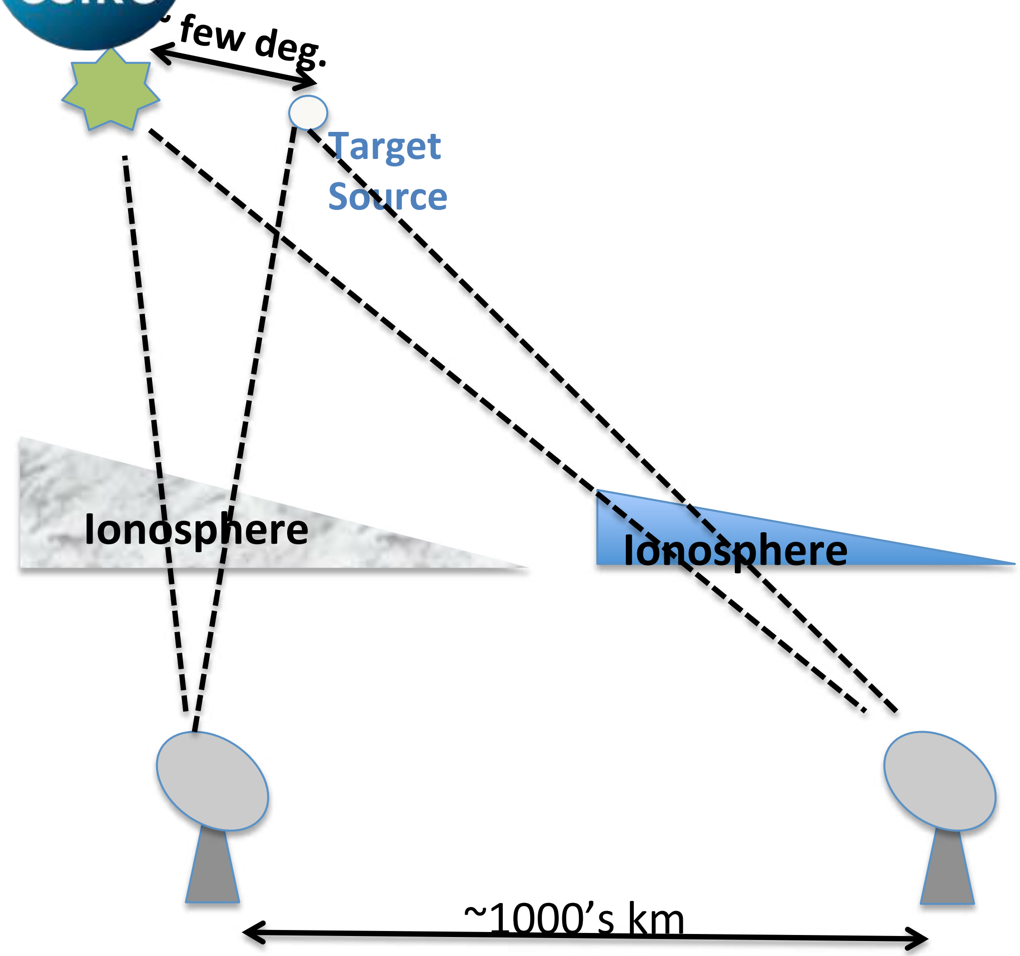
Low Frequencies & Ionosphere



Sketch representing ionospheric direction dependent effects

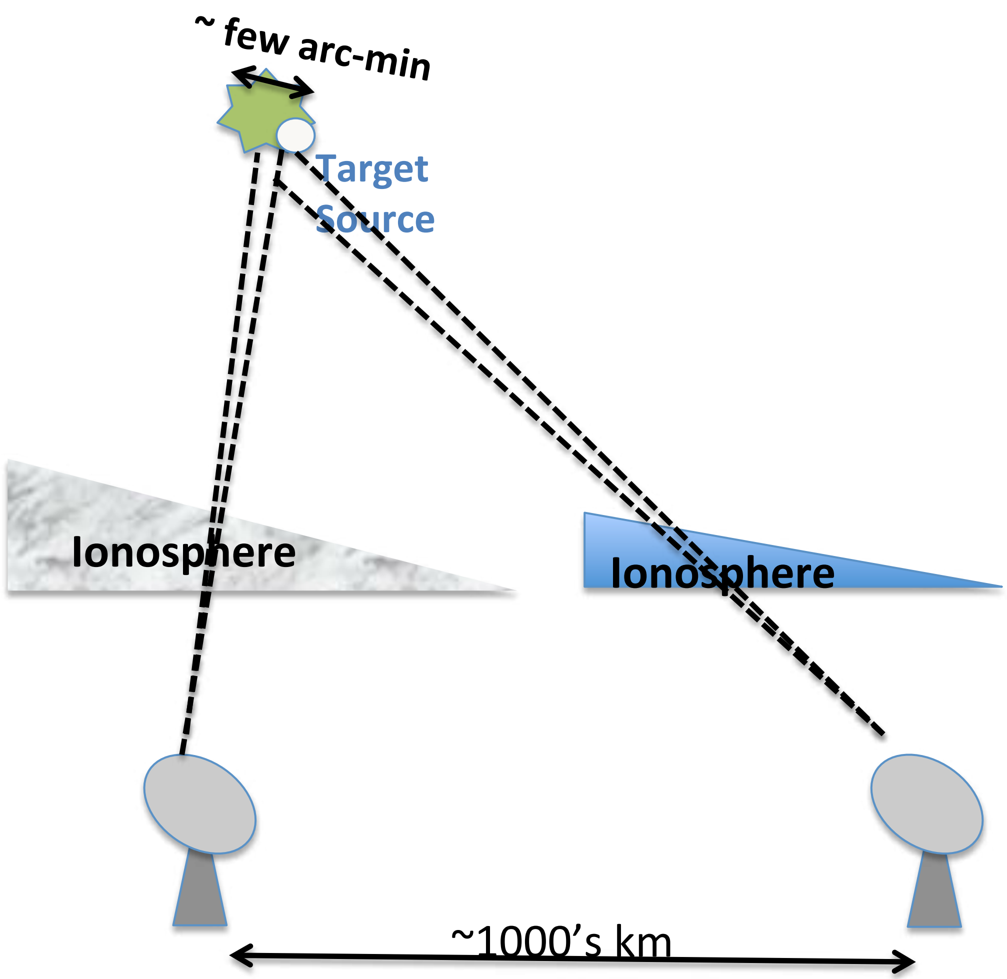
Low Frequencies & Ionosphere

<u>THE PROBLEM:</u>
"IONOSPHERIC WEDGE"
Spatial structure
Direction Dependent Effects



Sketch representing ionospheric direction dependent effects

Low Frequencies & Ionosphere



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Spatial structure
Direction Dependent Effects

Sketch representing ionospheric direction dependent effects

Low Frequencies & Ionosphere

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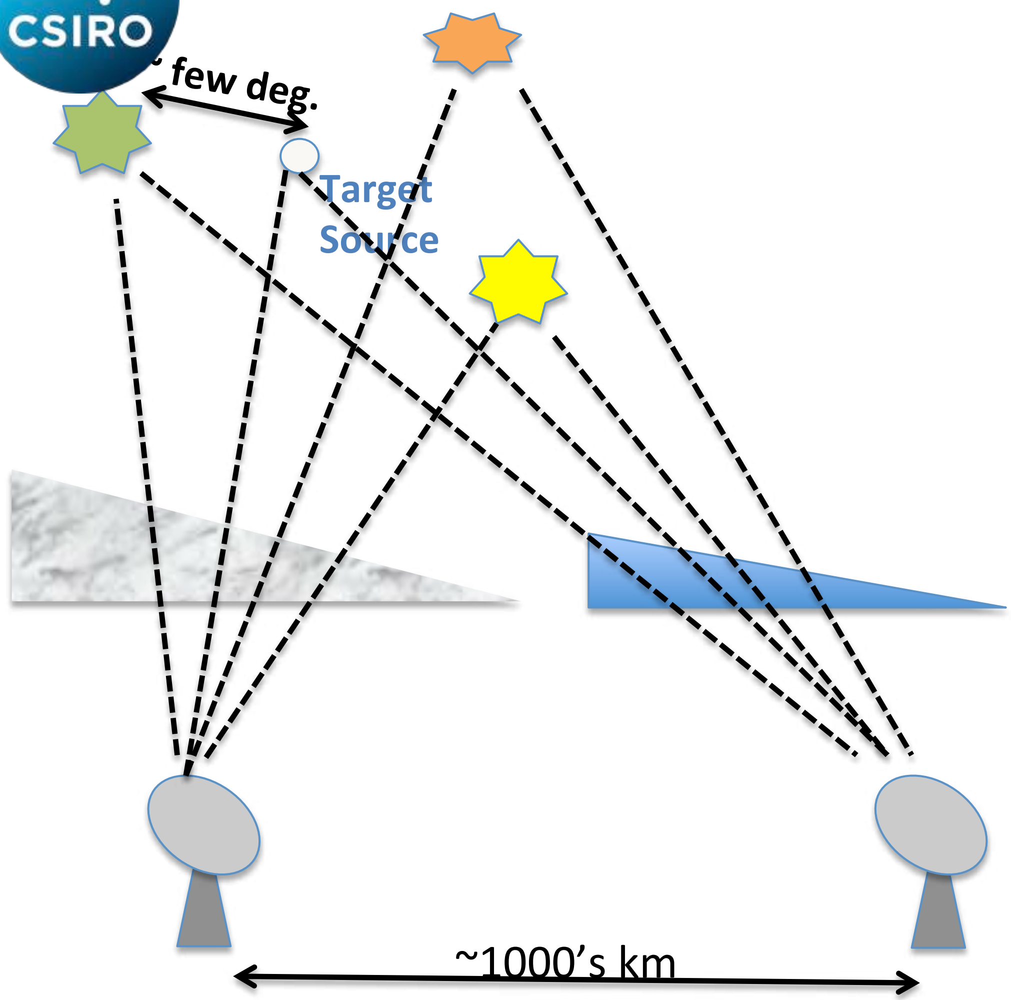
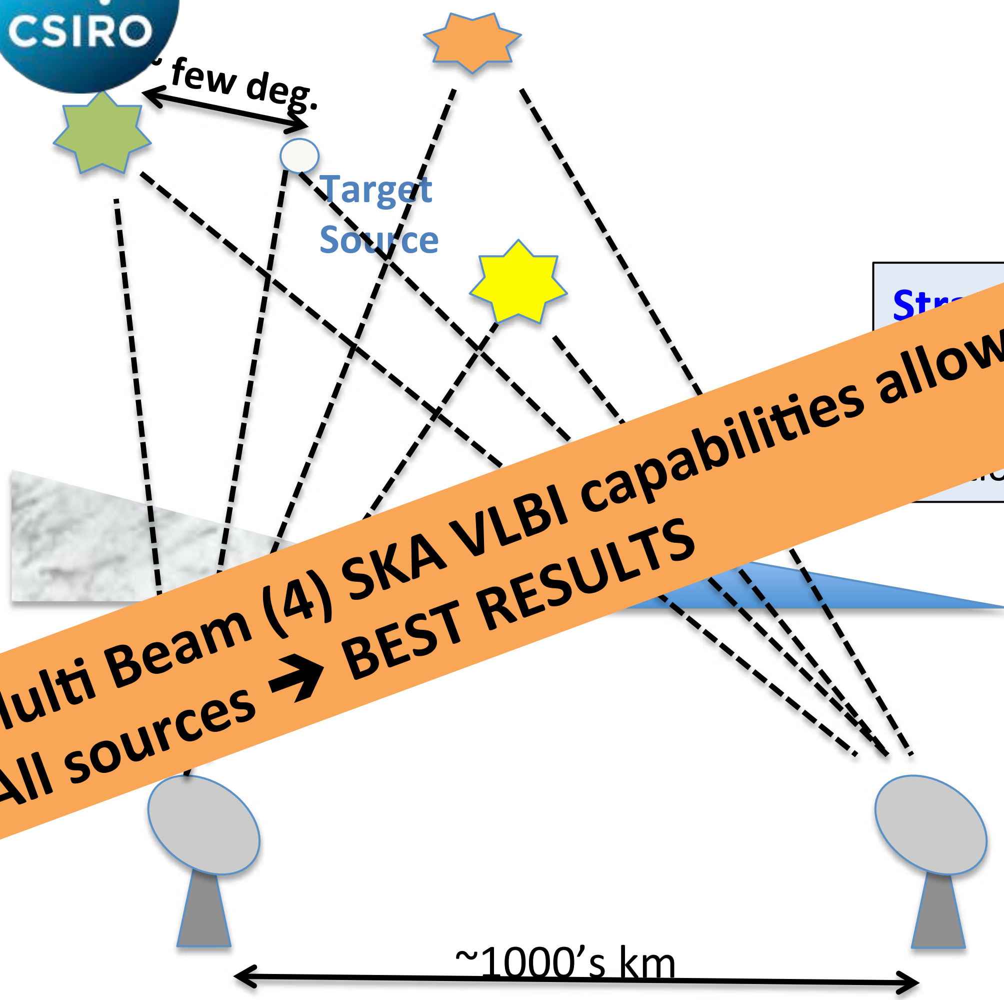
Spatial structure
Direction Dependent Effects



MultiView

Sketch representing ionospheric direction dependent effects

Low Frequencies & Ionosphere



THE PROBLEM:
"IONOSPHERIC WEDGE"
Spatial structu…
Directio…

Str… …tors around the target
…ultiple calibrators
…rpolation of the calibrator
…ions to the line of sight for the target.

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

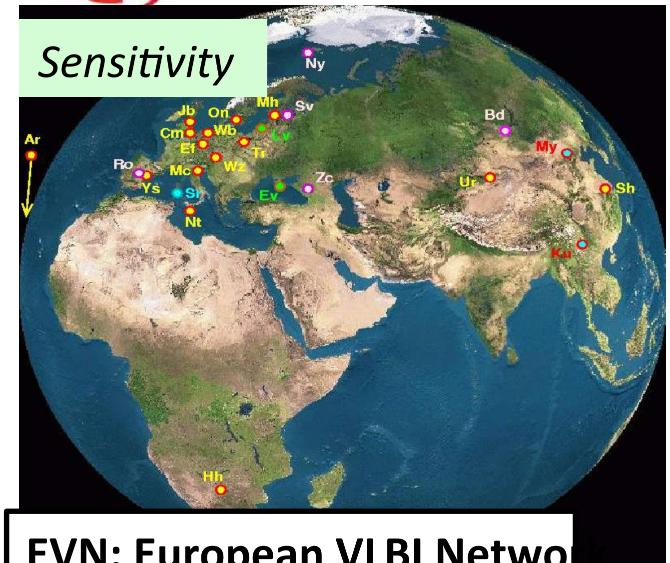
Outcome:
Now the spatial structure is accounted for,
Resulting in high precision astrometry
achievable at low frequencies..

(Rioja et al. 2017)

Sketch representing ionospheric direction dependent effects

VLBI NETWORKS

Sensitivity



EVN: European VLBI Network

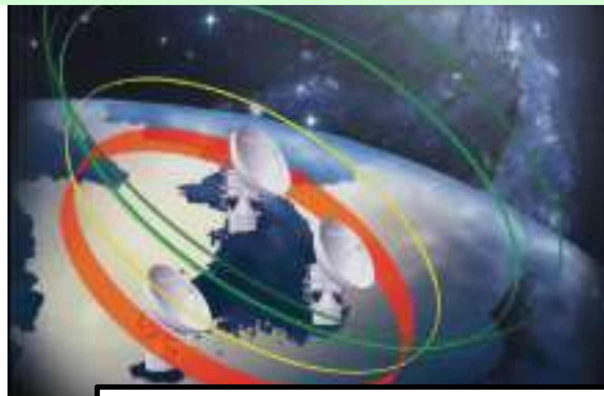
<~ 22GHz

General Purpose

VLBA Very Long Baseline Array

<~ 86GHz

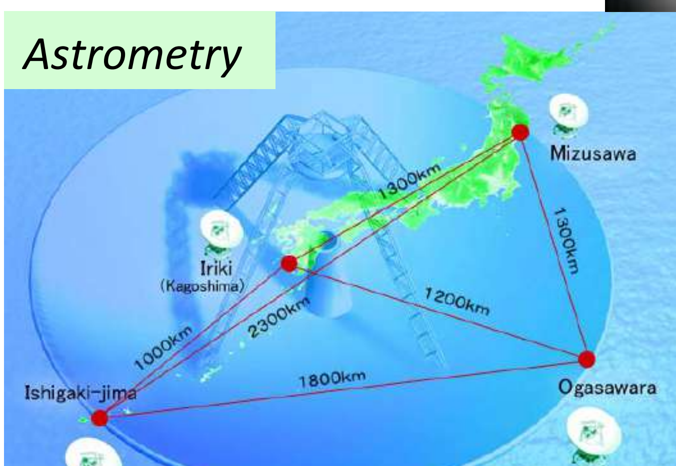
Highest Frequency Astrometry



KVN Korean VLBI Network

22/43/86/129 GHz

Astrometry



VERA VLBI for Earth Rotation and Astrometry

22/43 GHz

Southern Hemisphere

LBA Long Baseline Array

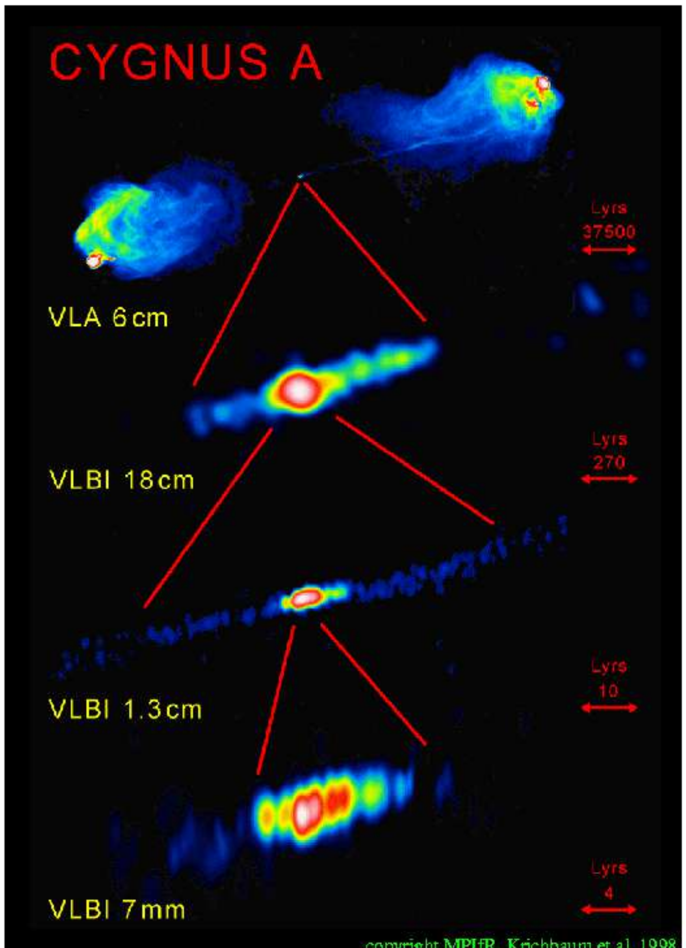
<~ 22GHz

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.

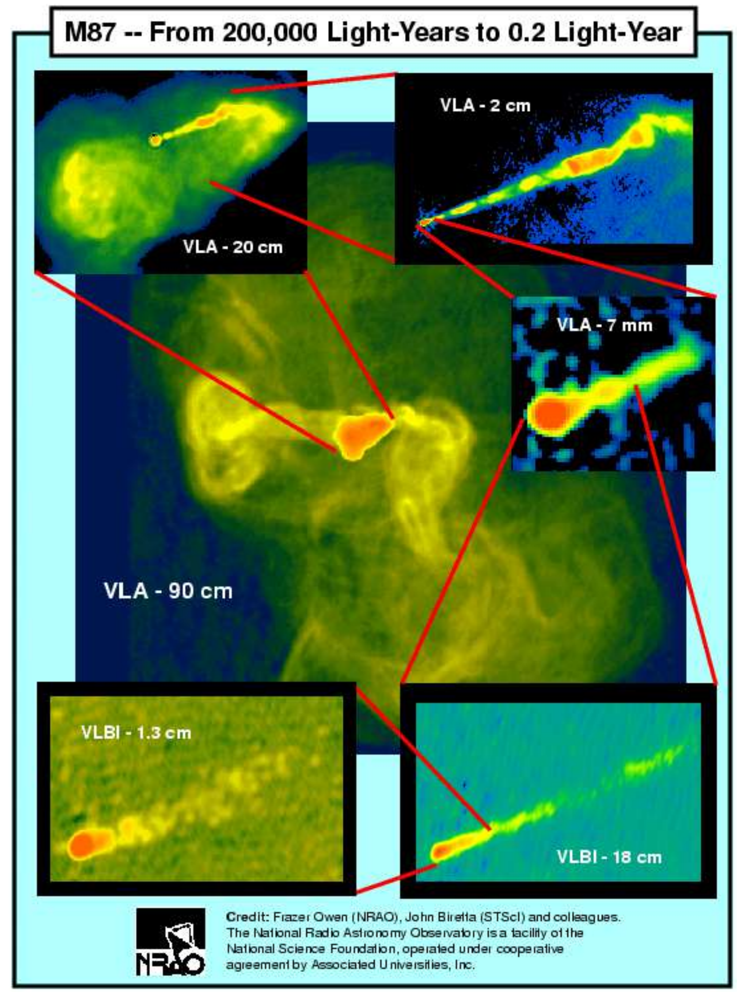
Radio sources can show emission on scales of arcminutes --> arcseconds --> milliarcseconds...



arcminutes

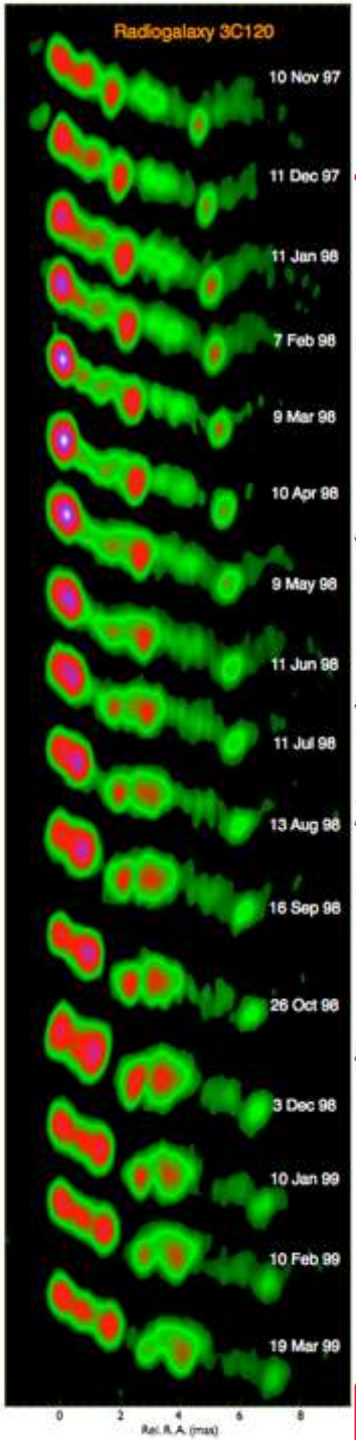
arcseconds

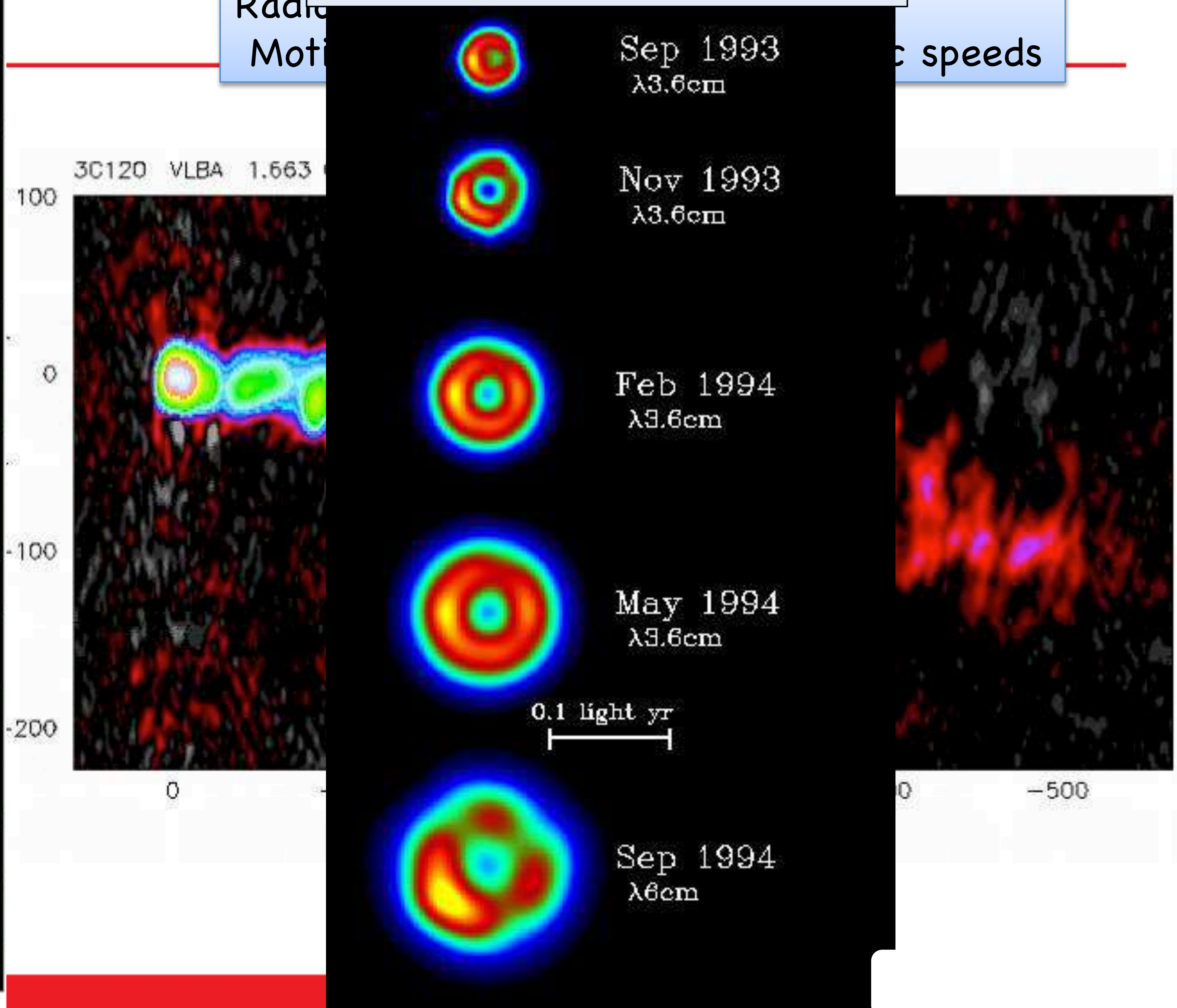
milliarcseconds



Radi
Moti c speeds

Movie of the Expansion of SN 1993J

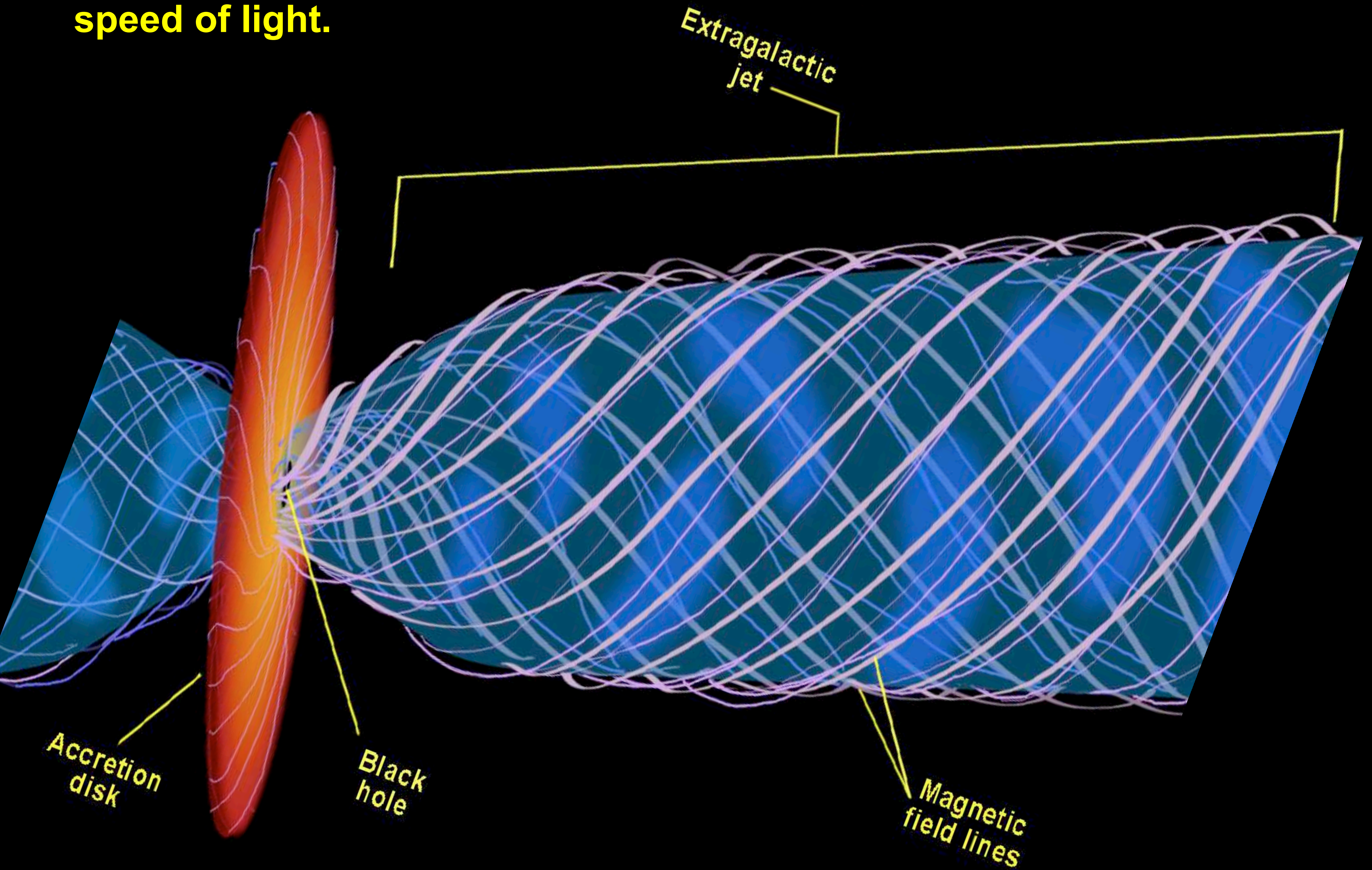




AGN Jet Studies

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

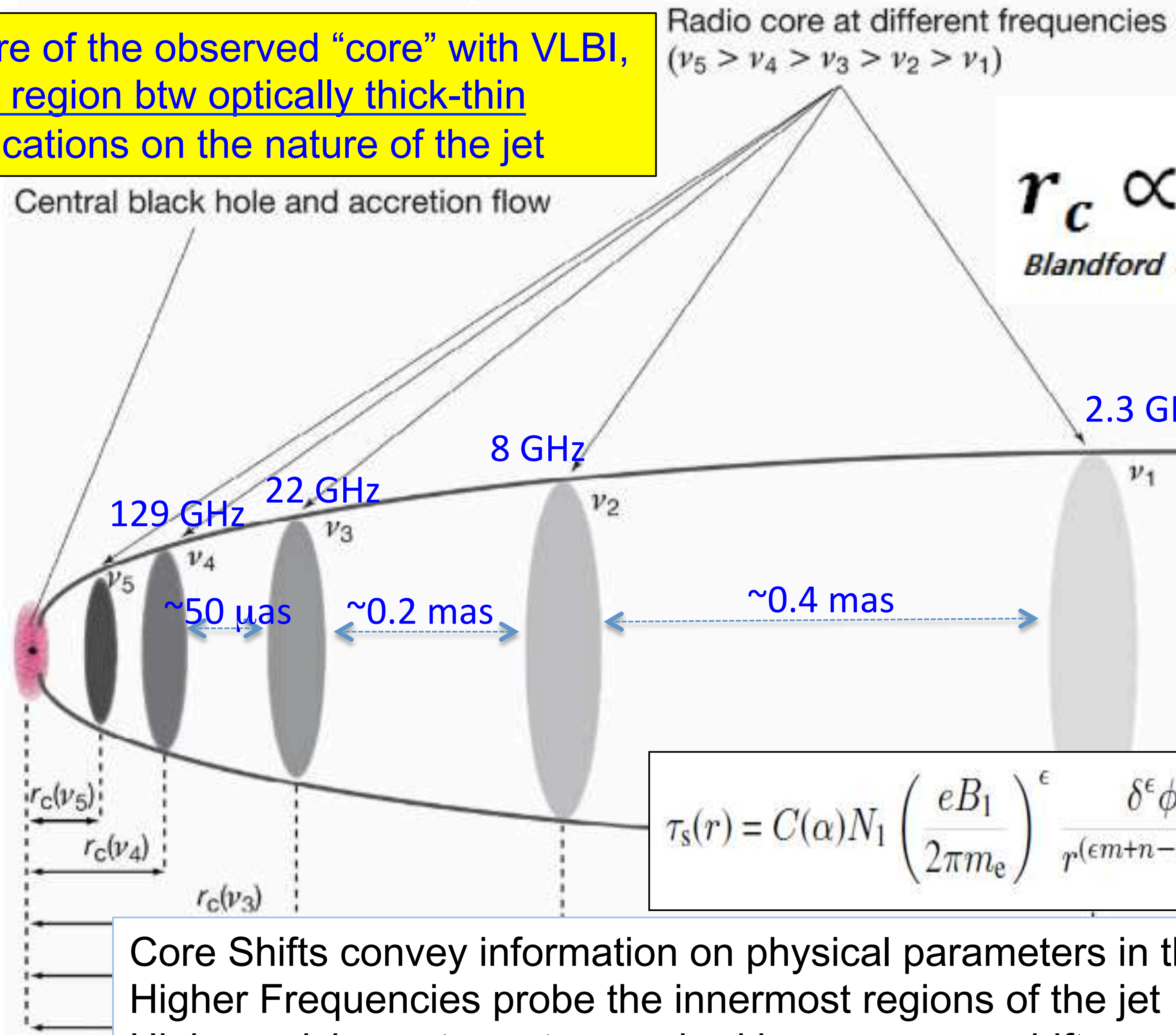
Magnetic field collimates outflow and accelerates particles to close to the speed of light.



AGN Jet Studies

Optical Depth & "Core Shift"

The nature of the observed "core" with VLBI,
<u>transition region btw optically thick-thin</u>
And implications on the nature of the jet



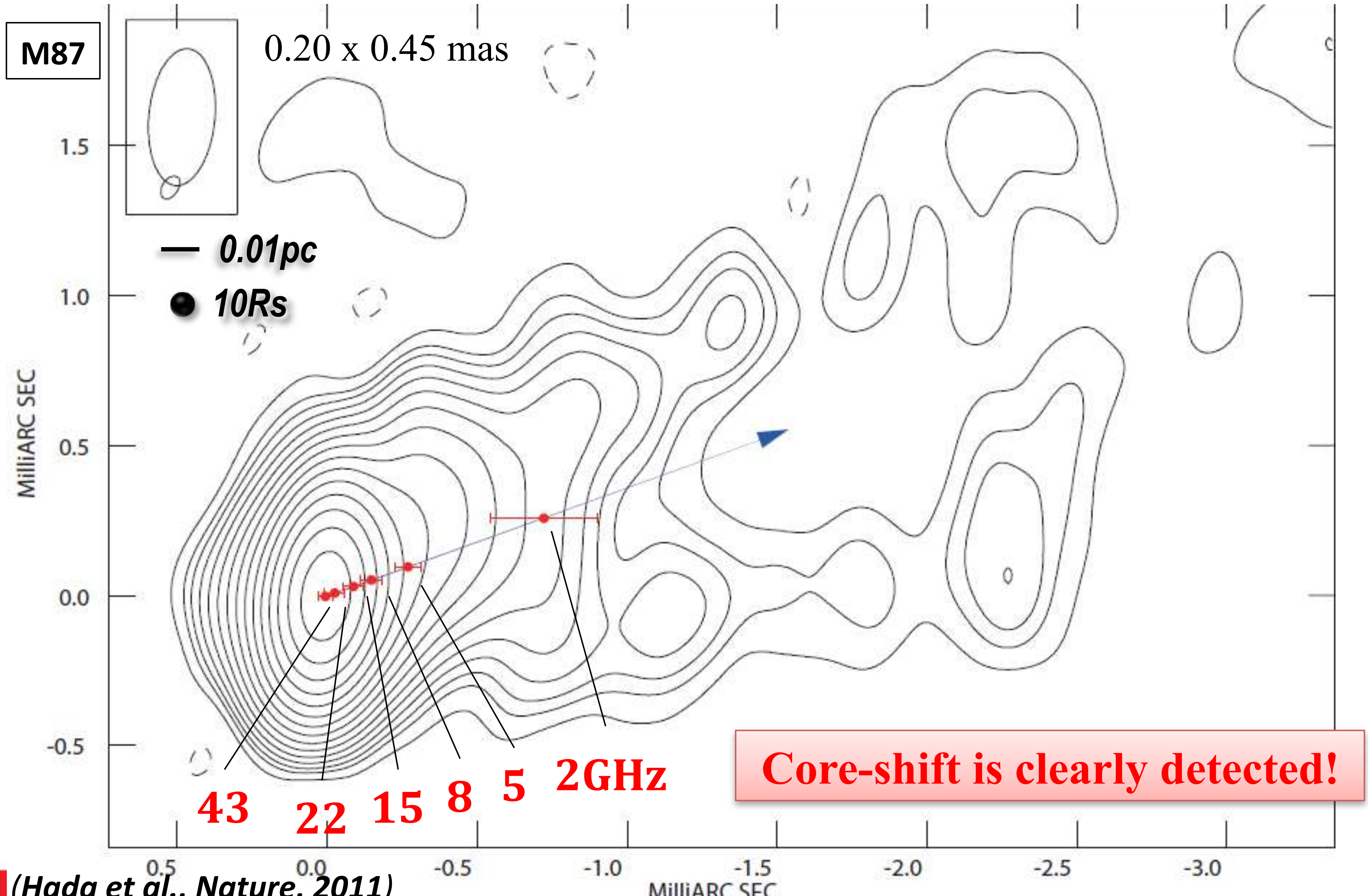
$$r_c \propto \nu^{-1/k_r}$$

Blandford & Konigl 1979

$$\tau_s(r) = C(\alpha) N_1 \left(\frac{eB_1}{2\pi m_e}\right)^{\epsilon} \frac{\delta^{\epsilon}\phi_o}{r^{(\epsilon m+n-1)}\nu^{\epsilon+1}}.$$

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 (➔ SFPR)

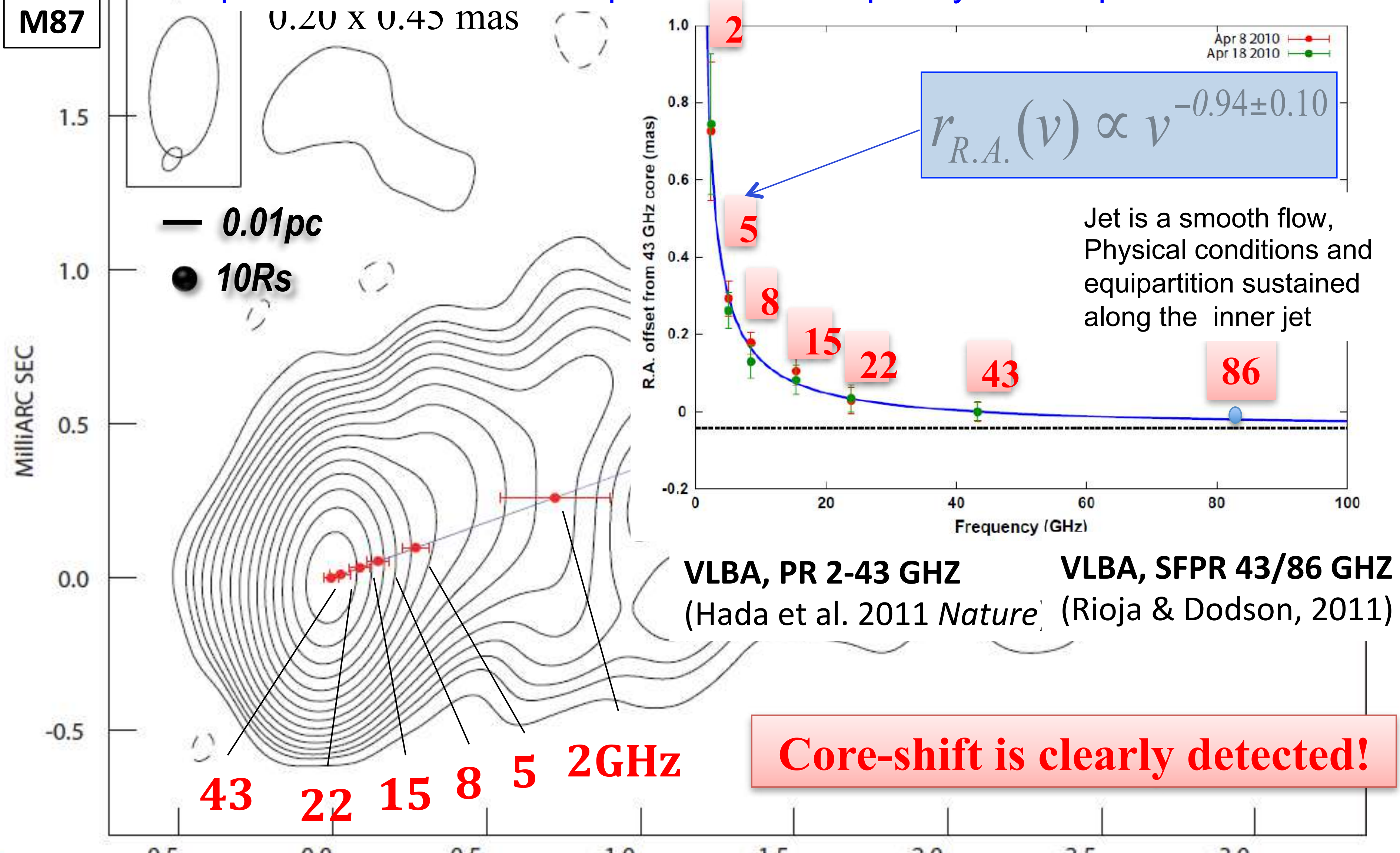
AGN Jets – Measured "Core shifts" in M87



(Hada et al., Nature, 2011)

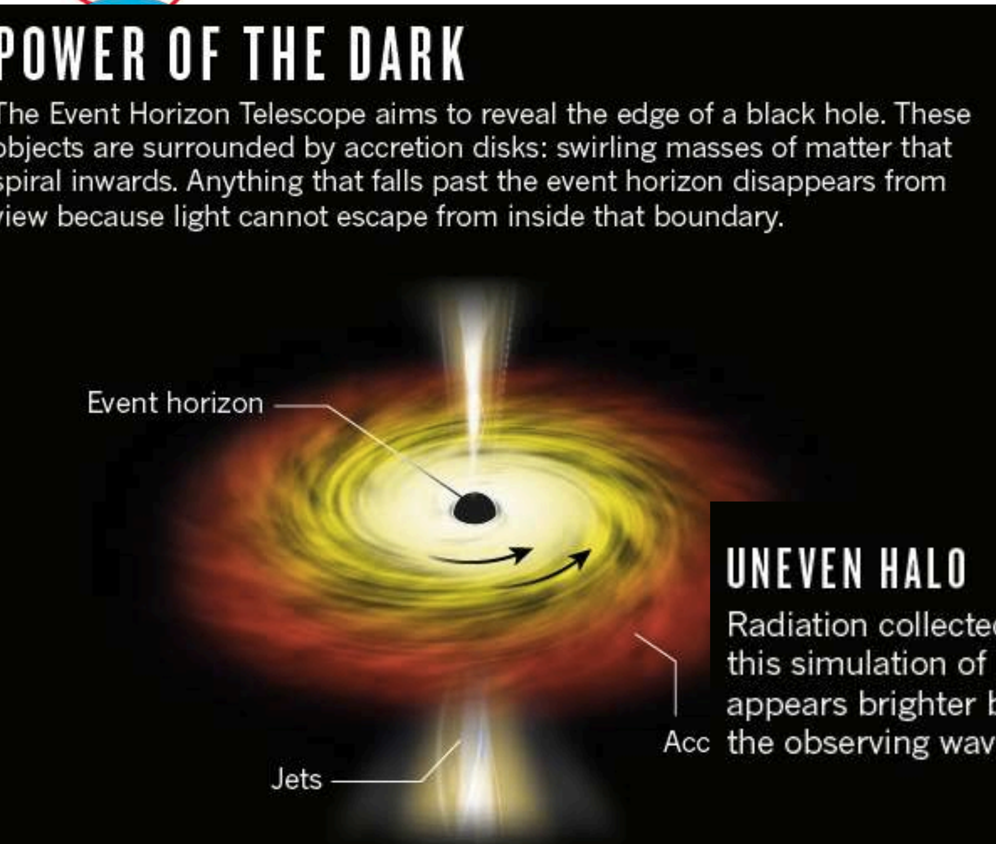
AGN Jets – Measured "Core shifts" in M87

Spectral evolution of core positions vs. frequency follows predictions of BK



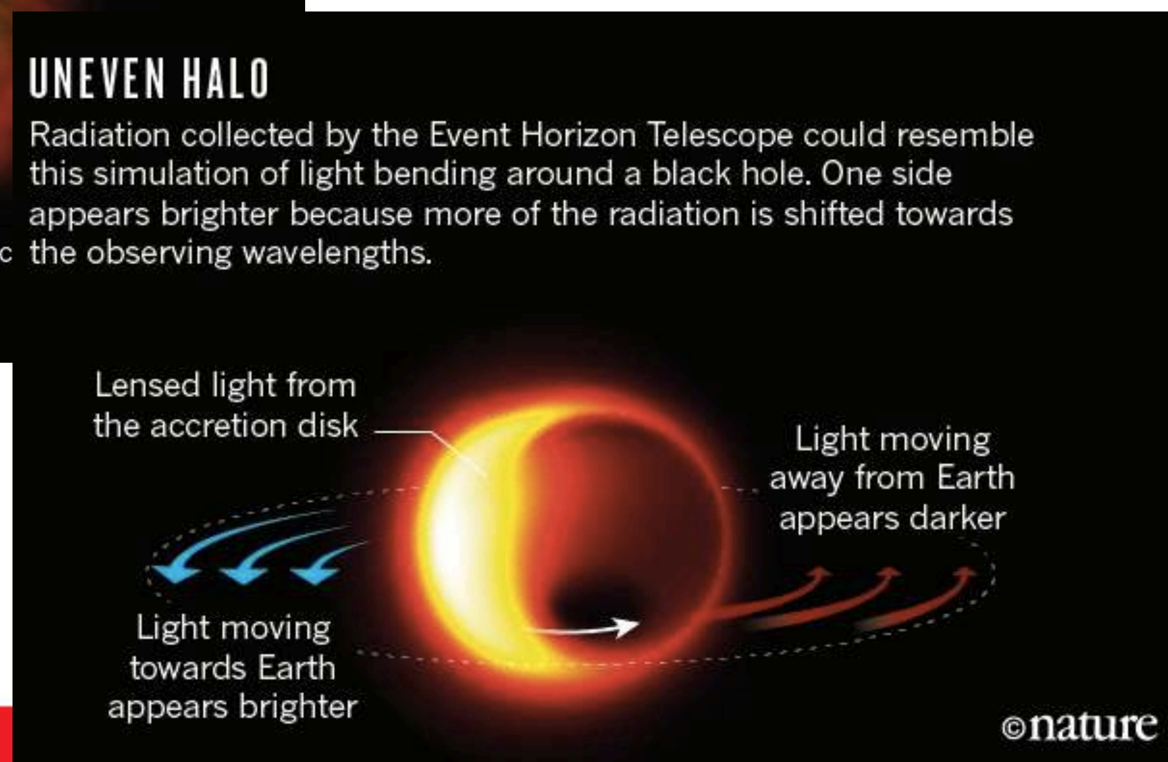
(Hada et al., Nature, 2011)

Event Horizon Telescope



"How to hunt for a black hole with a telescope the size of the Earth… "

VLBI with ALMA
λ~ 1mm; Resolution ~ 35 μas



Astrophysical Applications

Masers and VLBI:
Extragalactic and Galactic

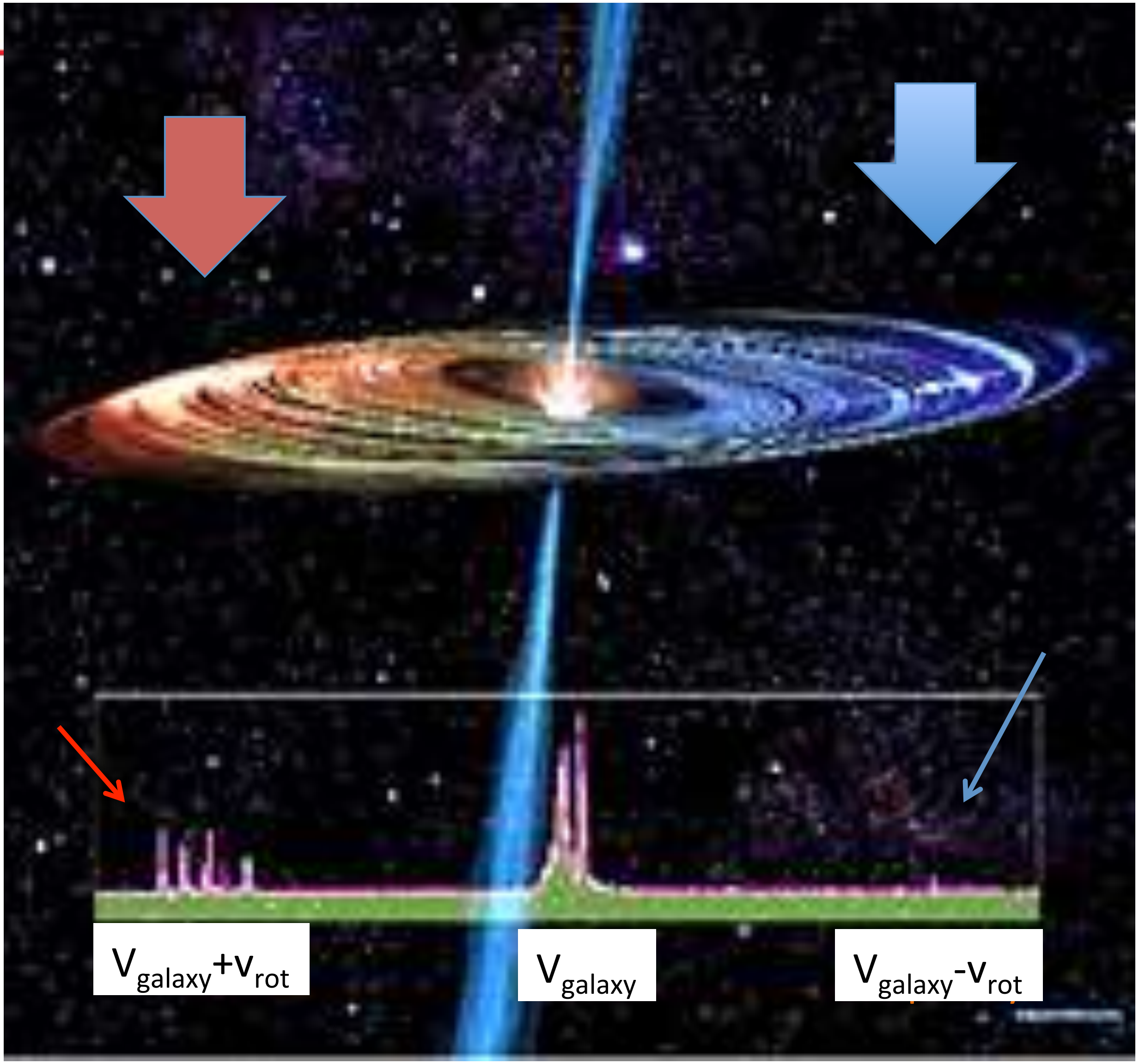
To measure geometric distances, BH masses, cosmology…

NGC 4258: The Maser Disk Archetype

H_2O 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.

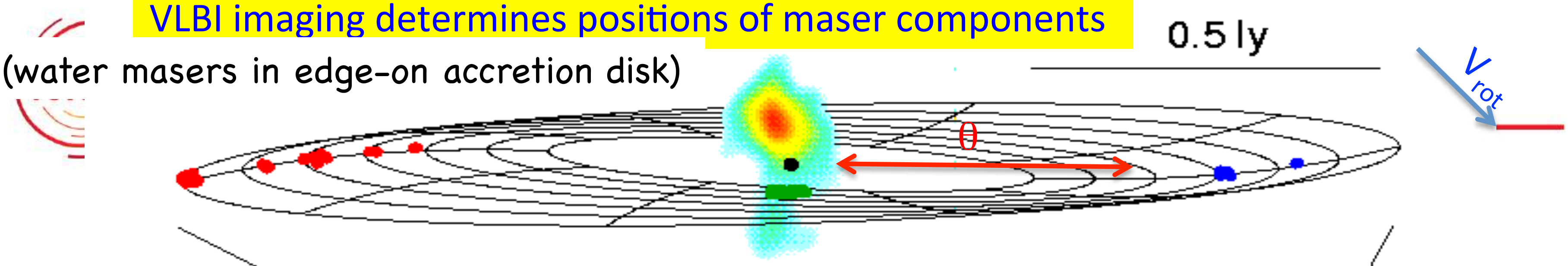


H_2O Megamasers in Active Galactic Nuclei

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

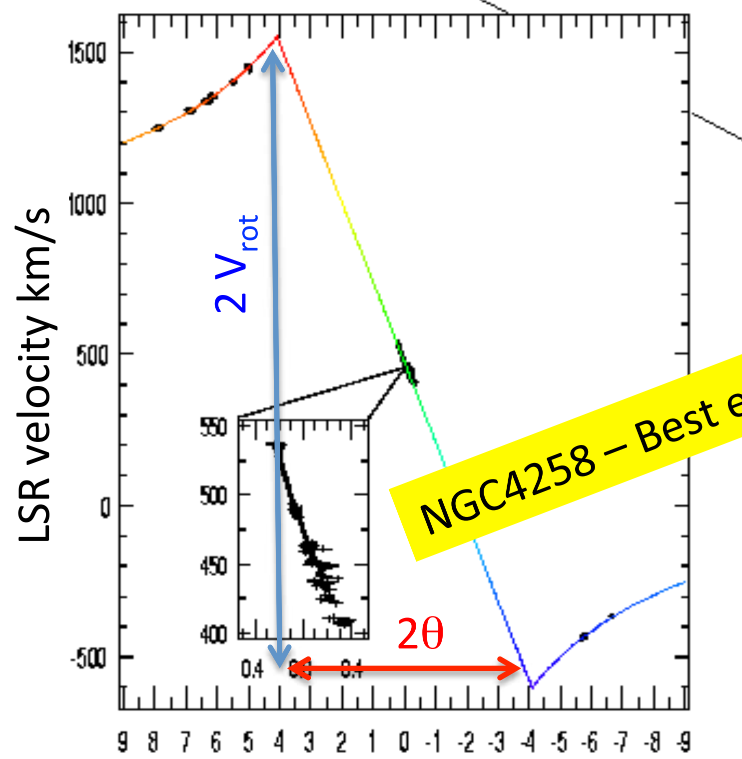
VLBI imaging determines positions of maser components

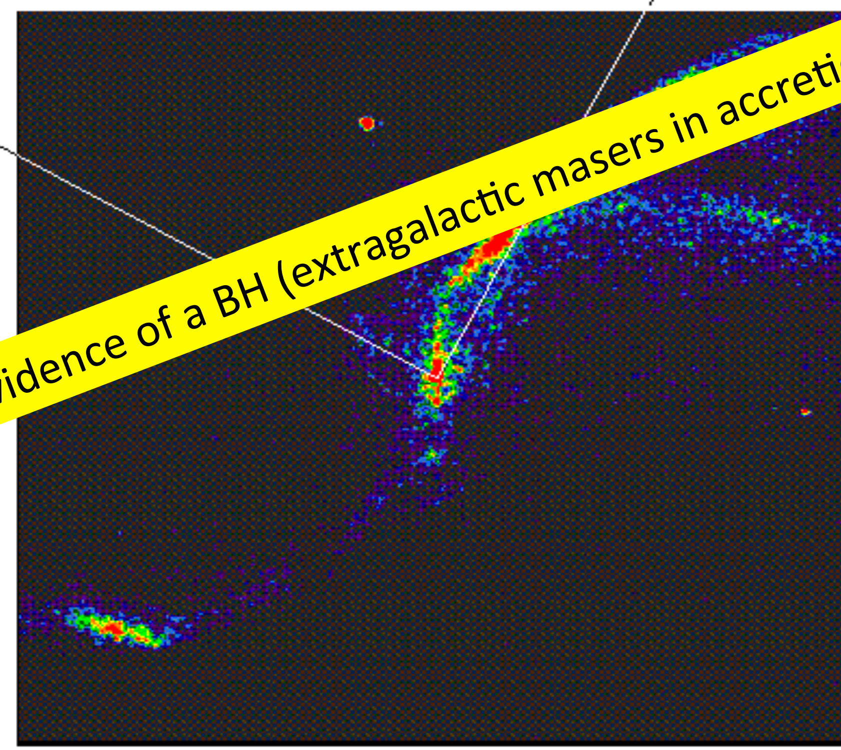
(water masers in edge-on accretion disk)



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

DISTANCE = Orbital velocity / Transverse Angular velocity





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

Central mass = 3.6 × 10^7 solar mass (Miyoshi et al. Nature 373, 127) (size < 0.13pc radius)
Distance = 7.2 ± 0.3 ± 0.5 Mpc (Herrnstein et al. Nature 400, 539)

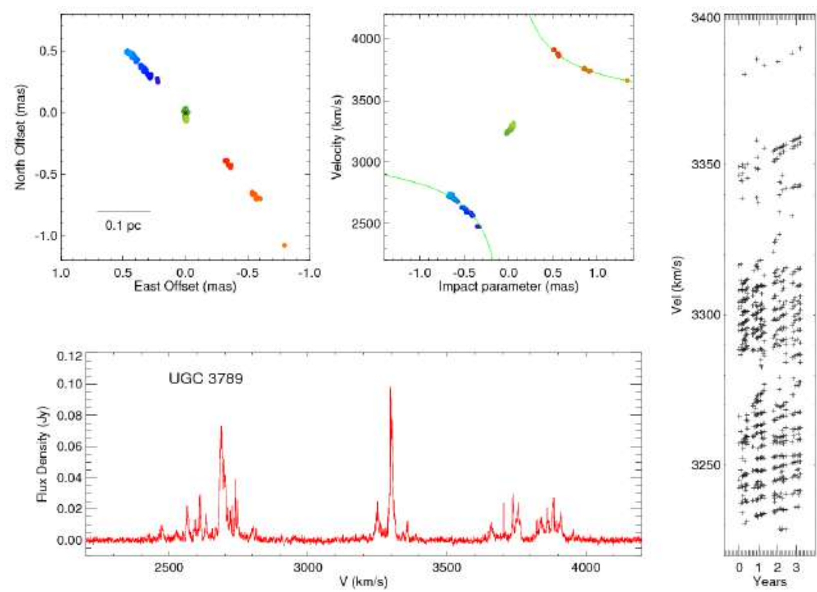
using the technique pioneered on the nearby galaxy NGC 4258…

Extragalactic Maser Surveys: Megamaser Cosmology Project (MCP)

The MCP is a multi-year VLBA “Key Project”
With the goal of determining H_o 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).

$$\boxed{V = H_o D}$$

UGC 3789

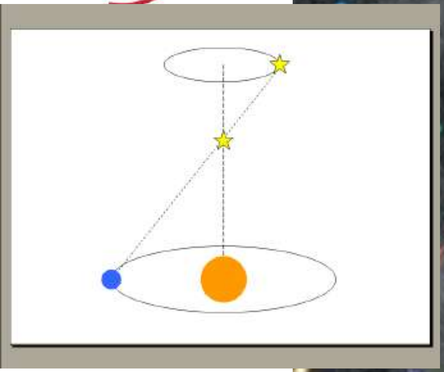


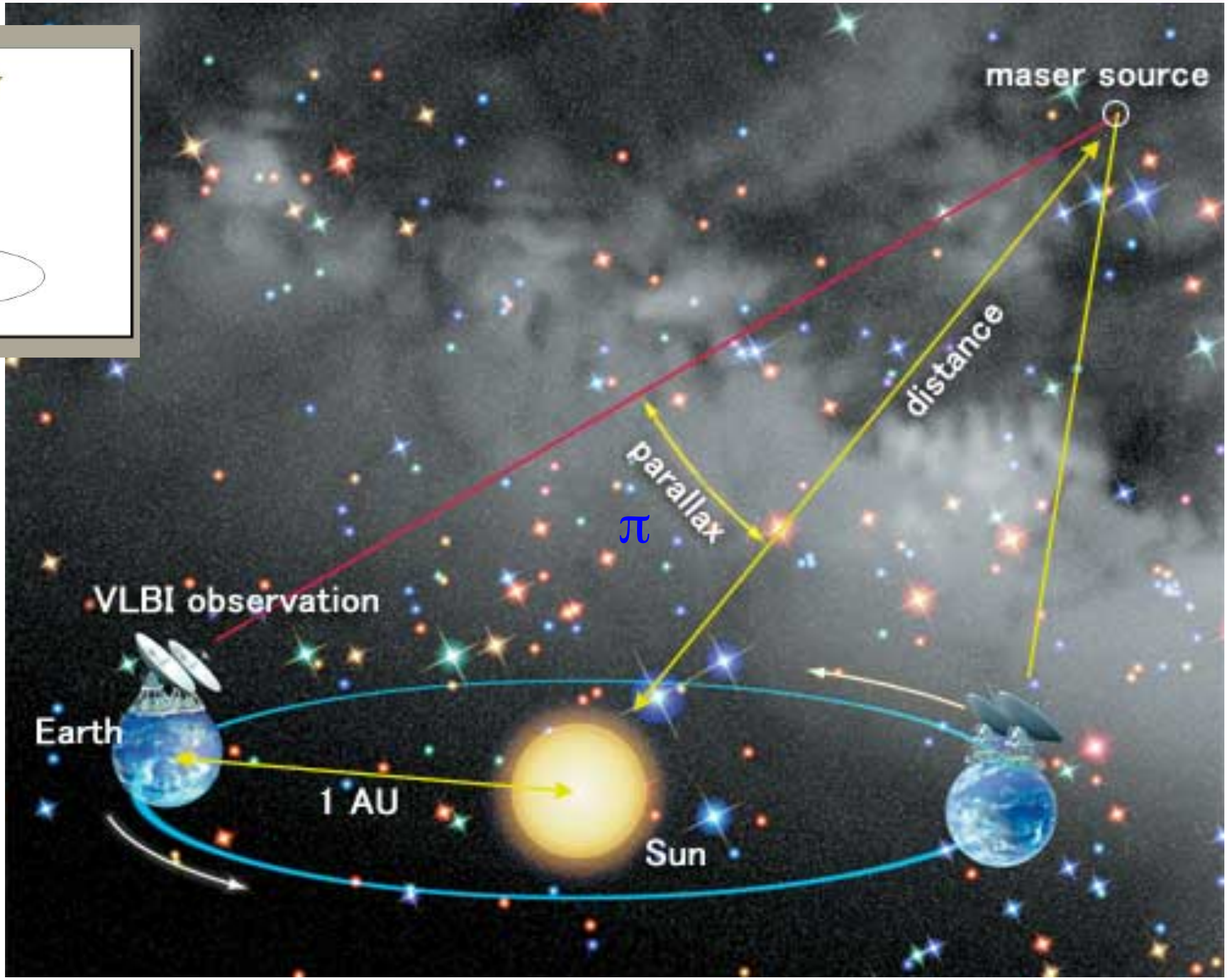
H0 = 69.3 ± 4.2 km/s/Mpc

Current estimate (from 4 sources).
Expect to achieve ~4% total uncertainty next year

https://safe.nrao.edu/wiki/bin/view/Main/MegamaserCosmologyProject

Astrometry is the most precise way to Measure Distances

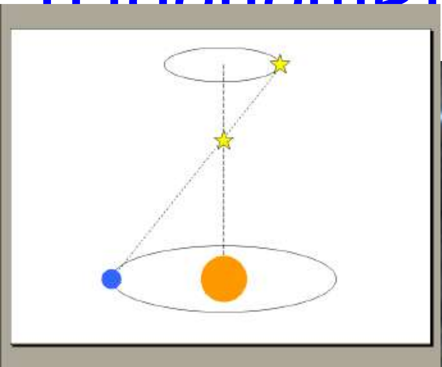




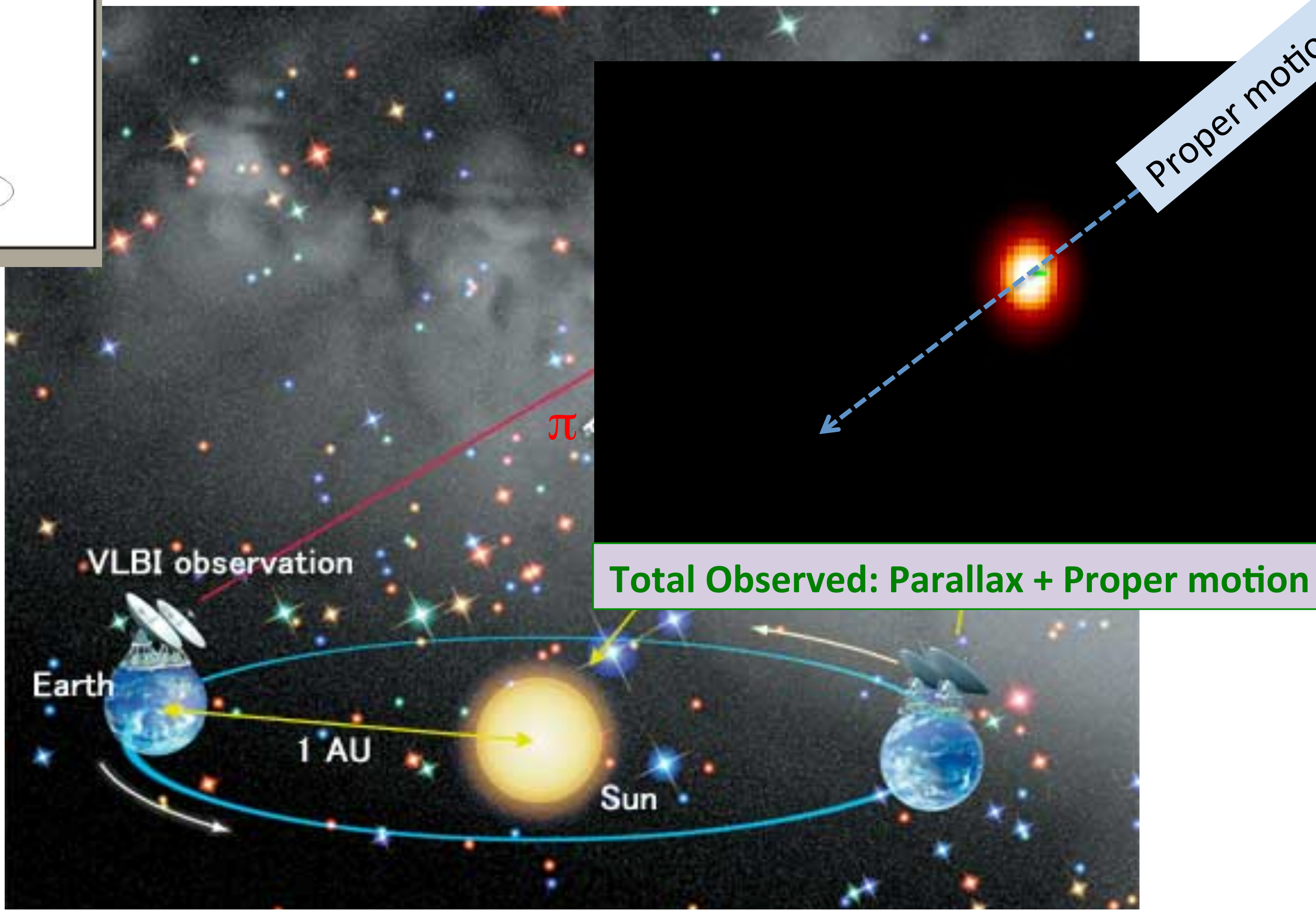
TRIGONOMETRIC PARALLAX: π (mas) = 1 / D (Kpc); 10 Kpc away, Parallax 0.1mas =100 micro-as

3D Structure and Kinematics of the Milky Way

Trigonometric Parallax – Measure Distances



Source parallax

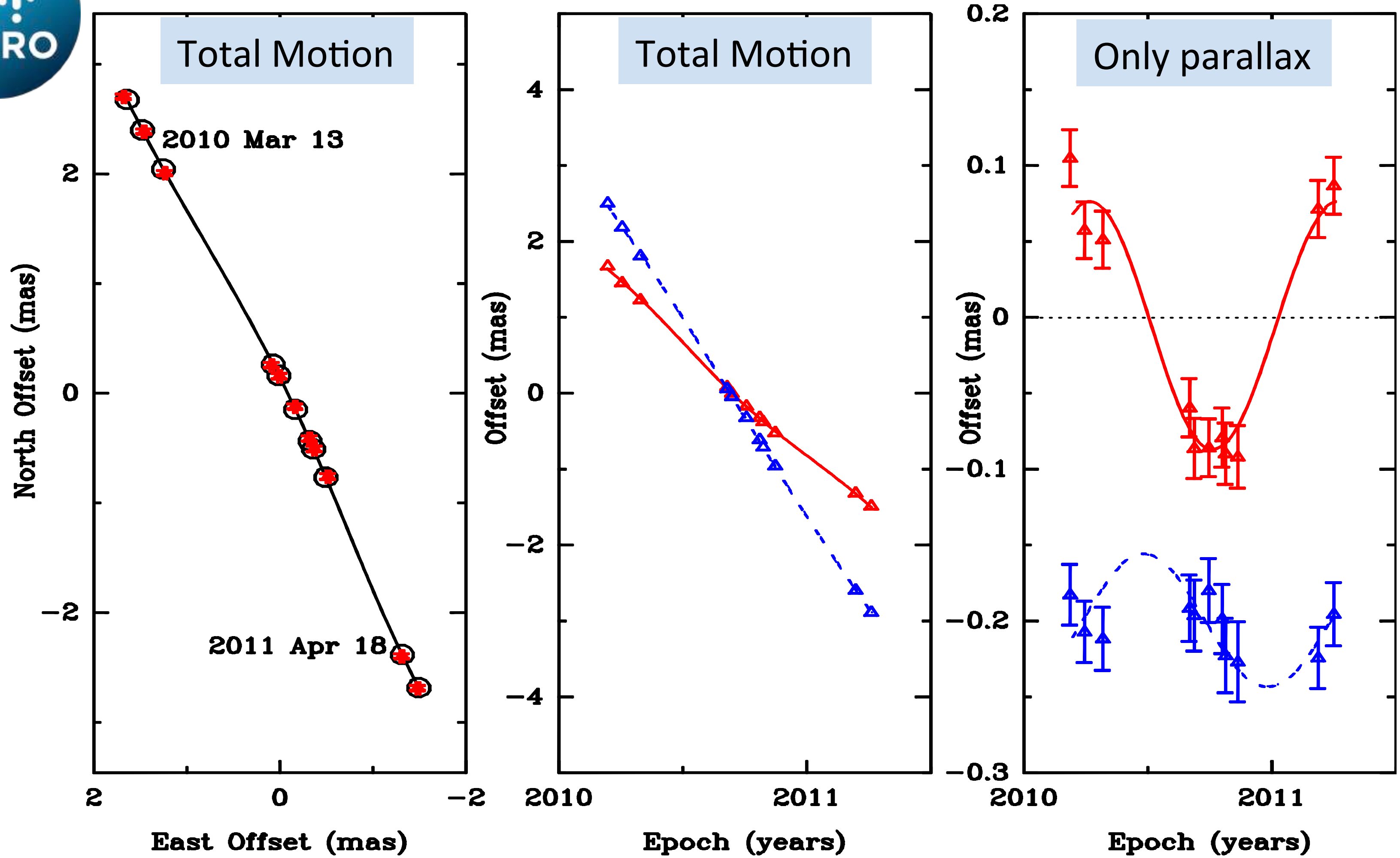


Total Observed: Parallax + Proper motion

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

Parallax for W 49N H_2O masers

$\pi = 90 \pm 7\ \mu as$ (D=11.1 ± 0.9 kpc)

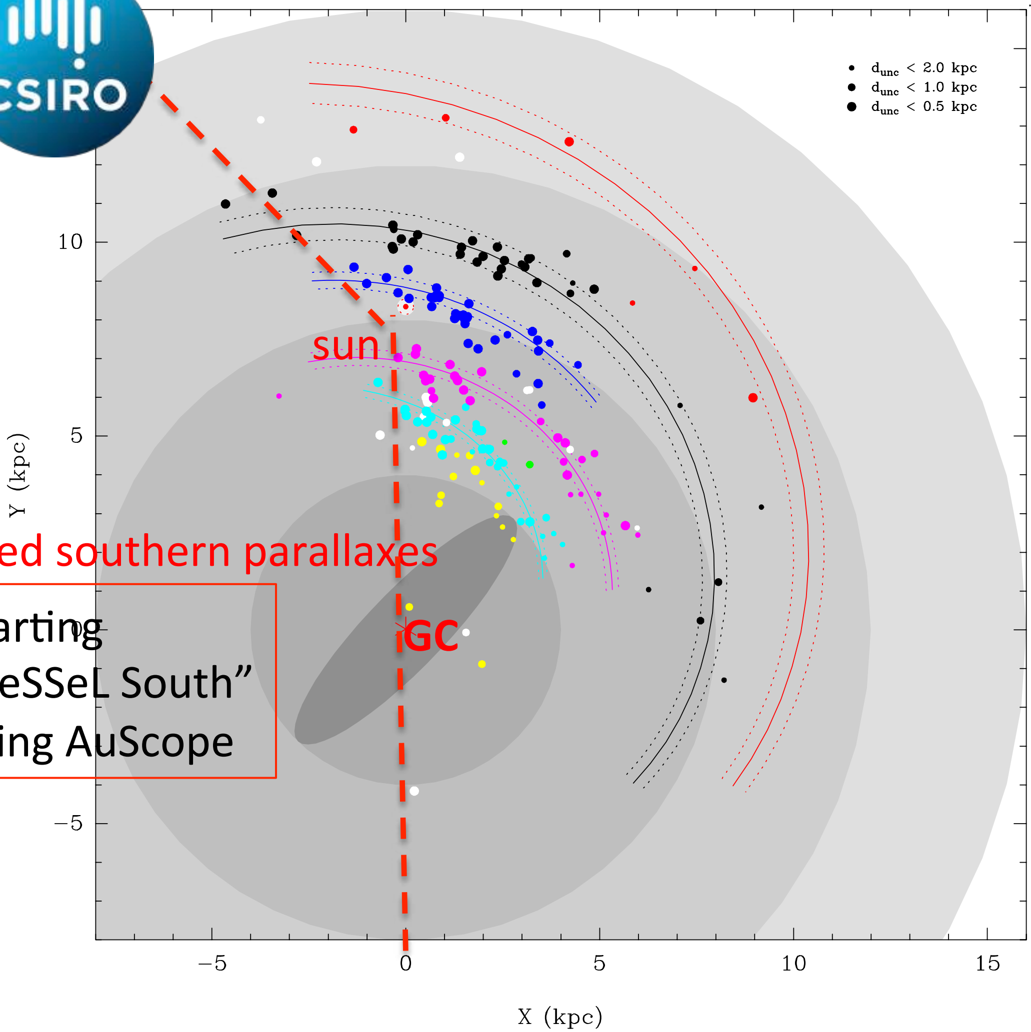


Zhang+ 2013

Red: East Offset
Blue: North Offset

Mapping Spiral Structure

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



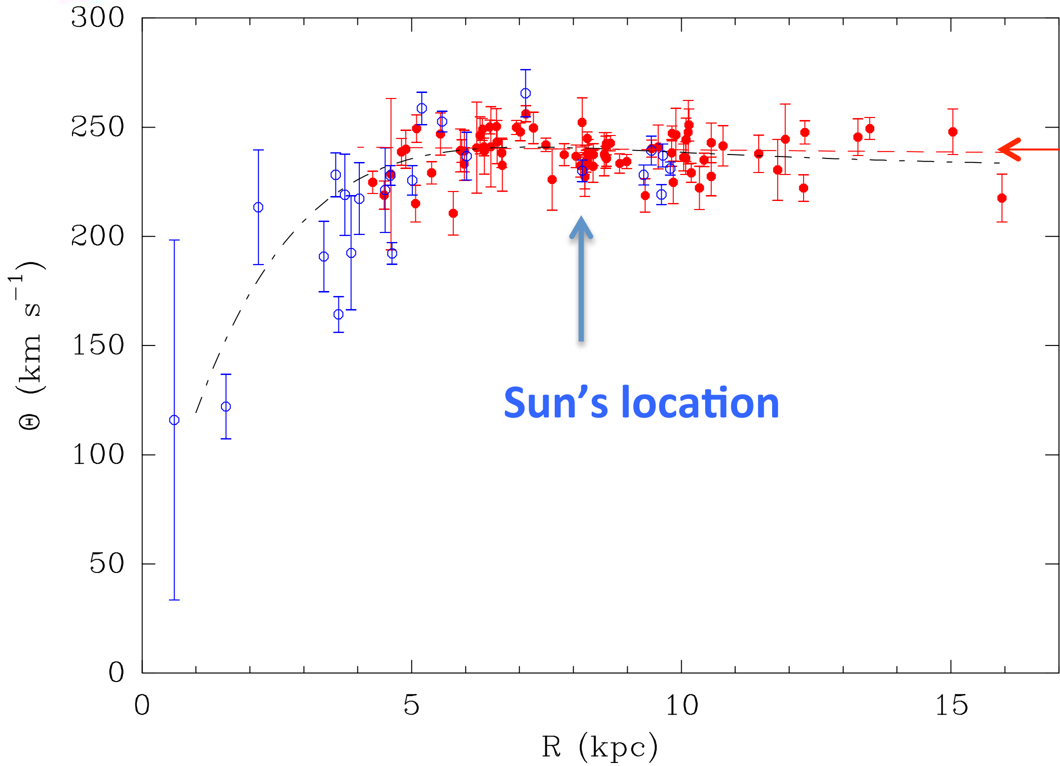
Starting “BeSSeL South” using AuScope

- 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:

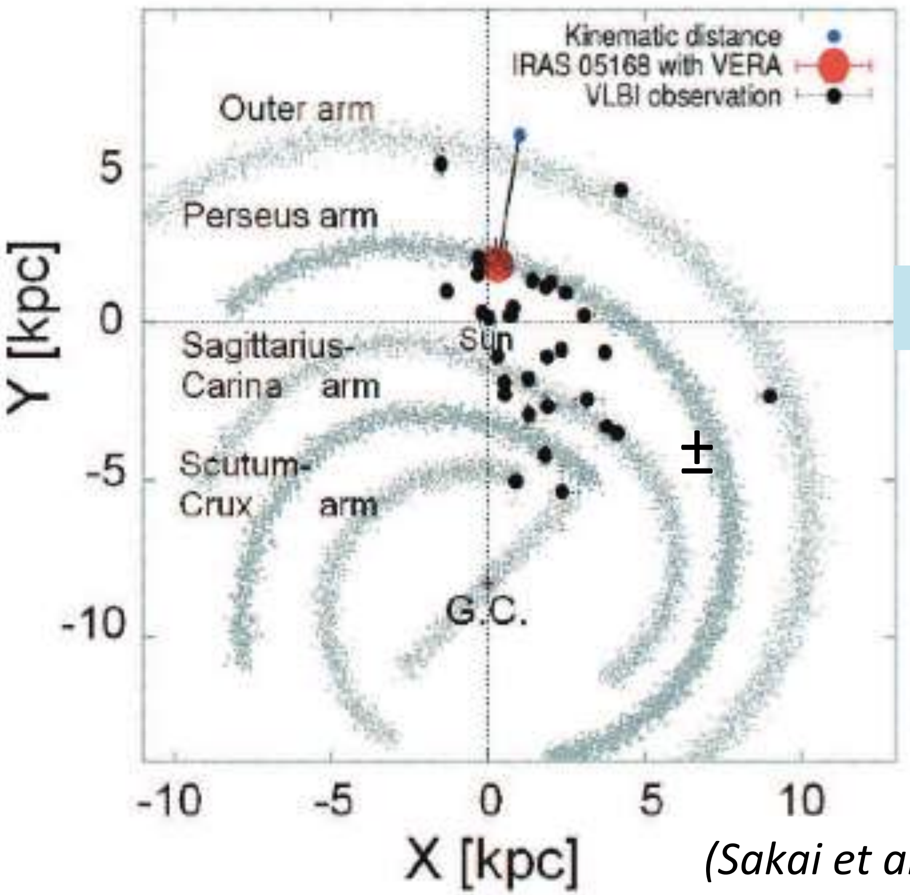
Θ_0 = ~240 km/s and nearly flat based on 3-D motions and "gold standard" distances

Replacing

Gunn, Knapp & Tremaine (1979) for a flat rotation curve… slope = Θ_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 ±0.2 Kpc

±

±

(Sakai et al, 2012, VERA H_2O Masers, 22 GHz)

Physical Parameter	Kinematic distance of 6.08 kpc (Molinari et al. 1996)	Our parallax measurement of 1.88 kpc
Virial mass ($M_\odot$)	2.4×10^3	7.4×10^2
LTE mass ($M_\odot$)	$>1.2\times10^4$	$>1.1\times10^3$
$\alpha=M_{vir}\ /\ M_{LTE}$	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 μJy sources, VLBA+GB+Arecibo+Eff
  Hipparcos parallax 120.2 ± 1.5 pc vs. VLBI parallax 133.5 ± 1.2 pc

(Melis et al. 2014, Science)

RELEVANCE:

- Model-independent distance ➔ massive revision of physical parameter
- Distance to prototypical cluster → underpin stellar population studies.

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*Panagia, 1973.

Summary

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 (μas) 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 Ho
- Parallax distances, 3D structure of Milky Way