The Power of Simultaneous Multi-Frequency Observations for mm-VLBI and Astrometry

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Overview

- **Limitations imposed by the propagation medium on (sub)mm-VLBI observations.**

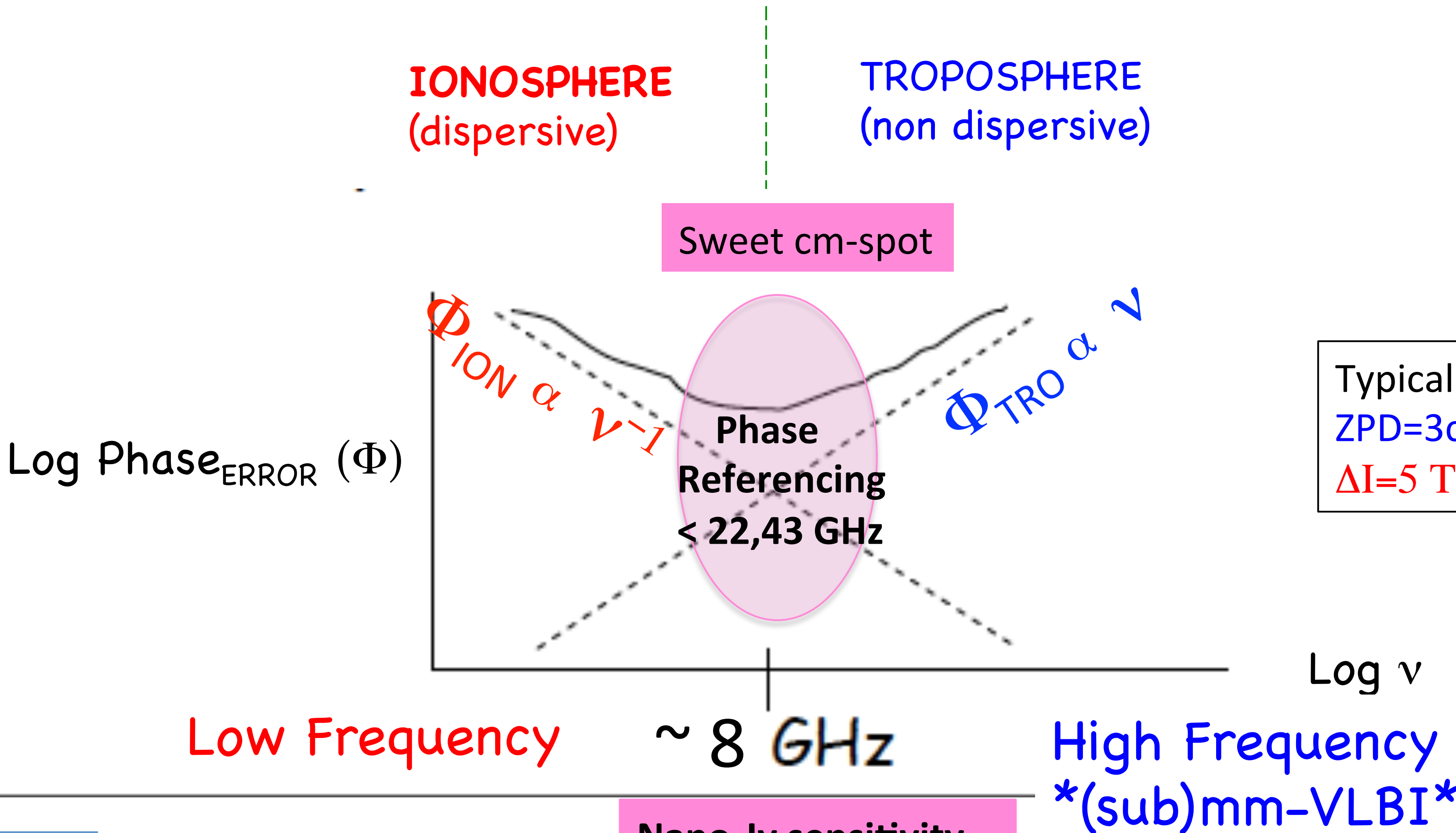
- **Multi-Frequency Calibration techniques to overcome them and widen the applicability of mm-VLBI.**

  1) SOURCE FREQUENCY PHASE REFERENCING (SFPR)
  2) MULTI FREQUENCY PHASE REFERENCING (MFPR)

- **Observational Demonstration and Measurements made possible by those techniques**

- **Instruments for multi-frequency observations**

The Many Faces of the Propagation Medium



Typical errors:
ZPD=3cm (trop)
ΔI=5 TECU (ion

← MWA/LOFAR
SKA-Low

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

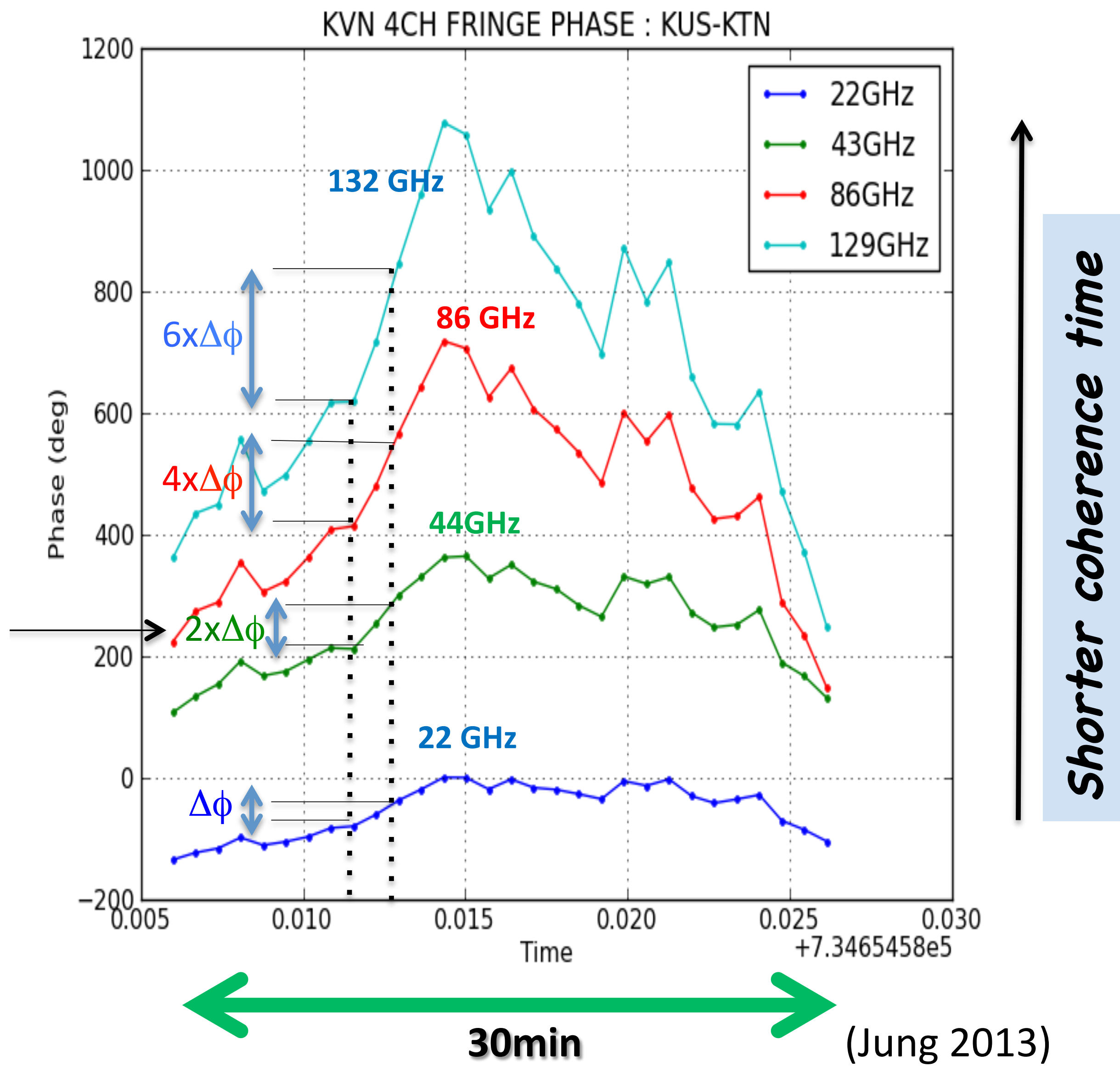
→ ALMA

Troposphere "in action"

Fluctuations in water vapor component (=turbulences) ➔phase fluctuations

TROPOSPHERE
(non dispersive)

$\tau_{TRO} = C$
$\Phi_{TRO} \propto \nu$



(Jung 2013)

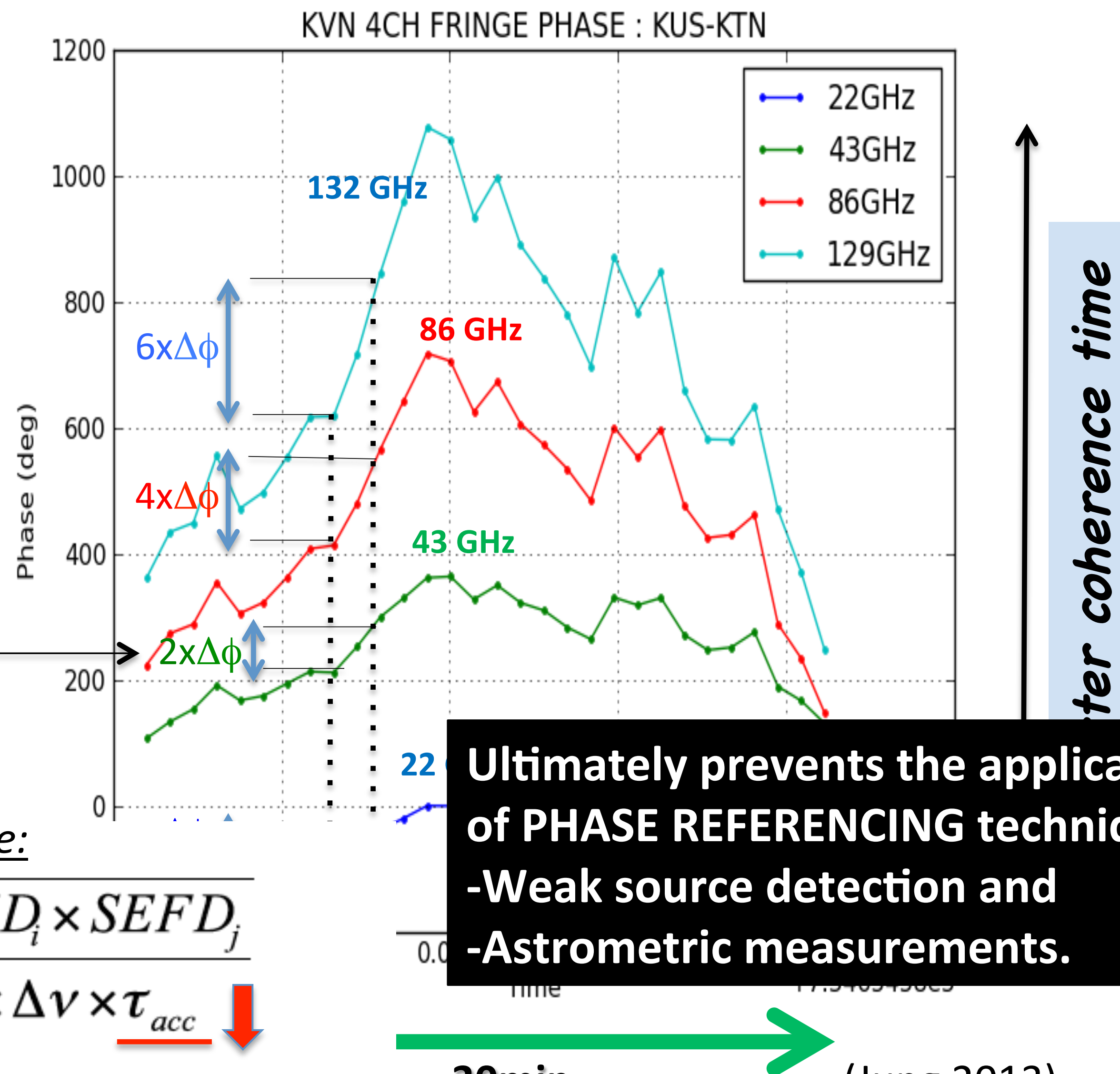
Troposphere "in action"

Fluctuations in water vapor component → phase fluctuations

TROPOSPHERE
(non dispersive)

$$\tau_{TRO} = C$$
$$\Phi_{TRO} \propto \nu$$

R = 44 / 22



Ultimately prevents the application of PHASE REFERENCING techniques for
-Weak source detection and
-Astrometric measurements.

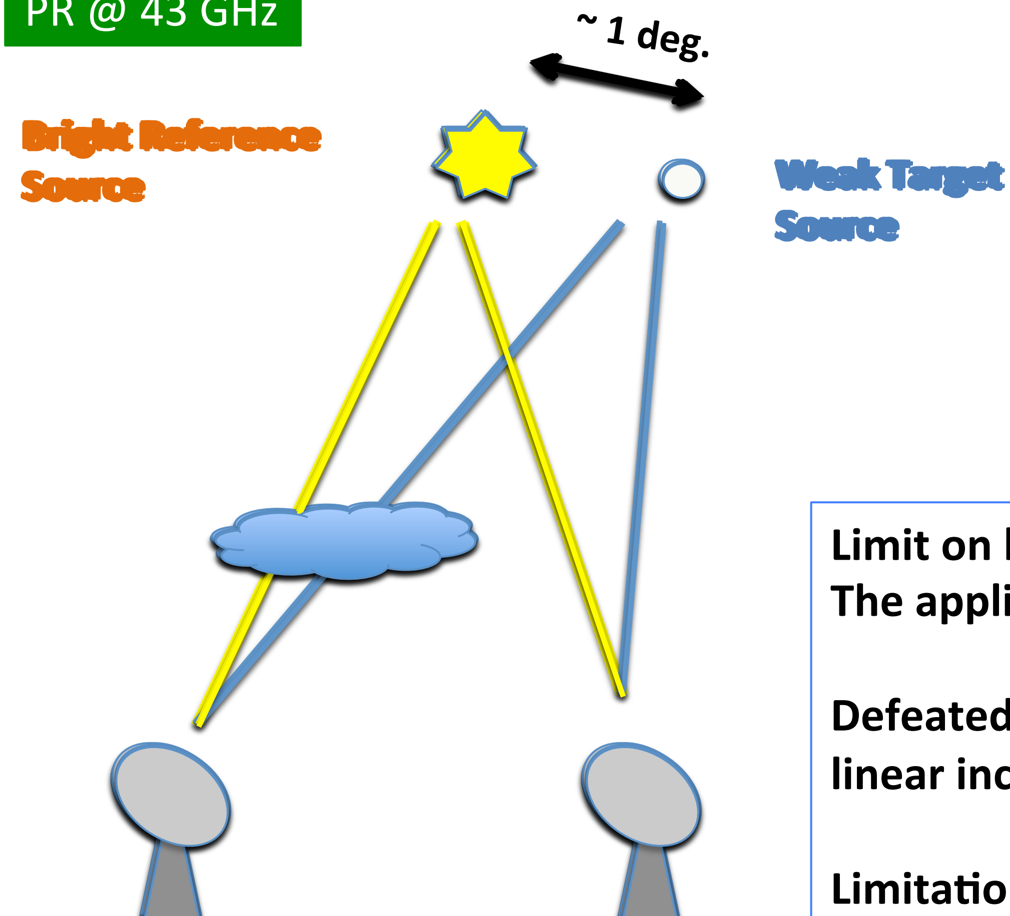
(Jung 2013)

Minimum Flux Detectable:

$$\Delta S_{ij} = \frac{1}{\eta_s} \times \sqrt{\frac{SEFD_i \times SEFD_j}{2 \times \Delta\nu \times \tau_{acc}}}$$

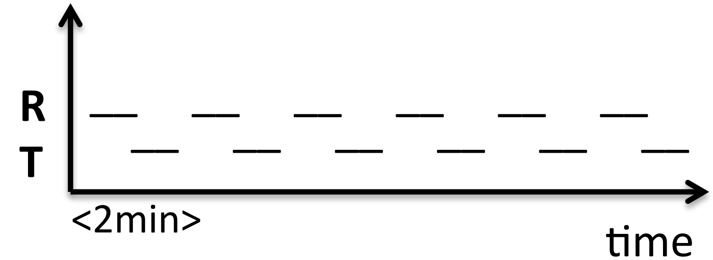
Phase Referencing
"trans-source"

PR @ 43 GHz

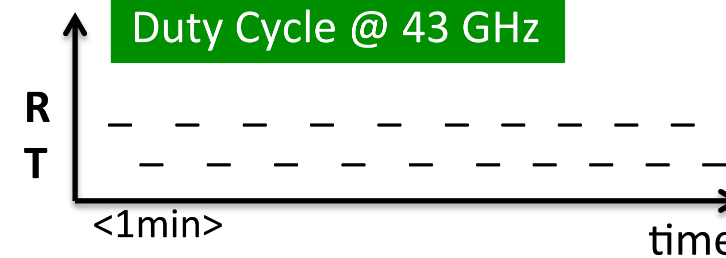


WEAK SOURCES
ASTROMETRY

Duty Cycle @ 22 GHz



Duty Cycle @ 43 GHz



Limit on how fast a telescope can move constrains The application to 43 GHz or below (in general).

Defeated by rapid phase tropospheric fluctuations, linear increase with frequency (non-dispersive)

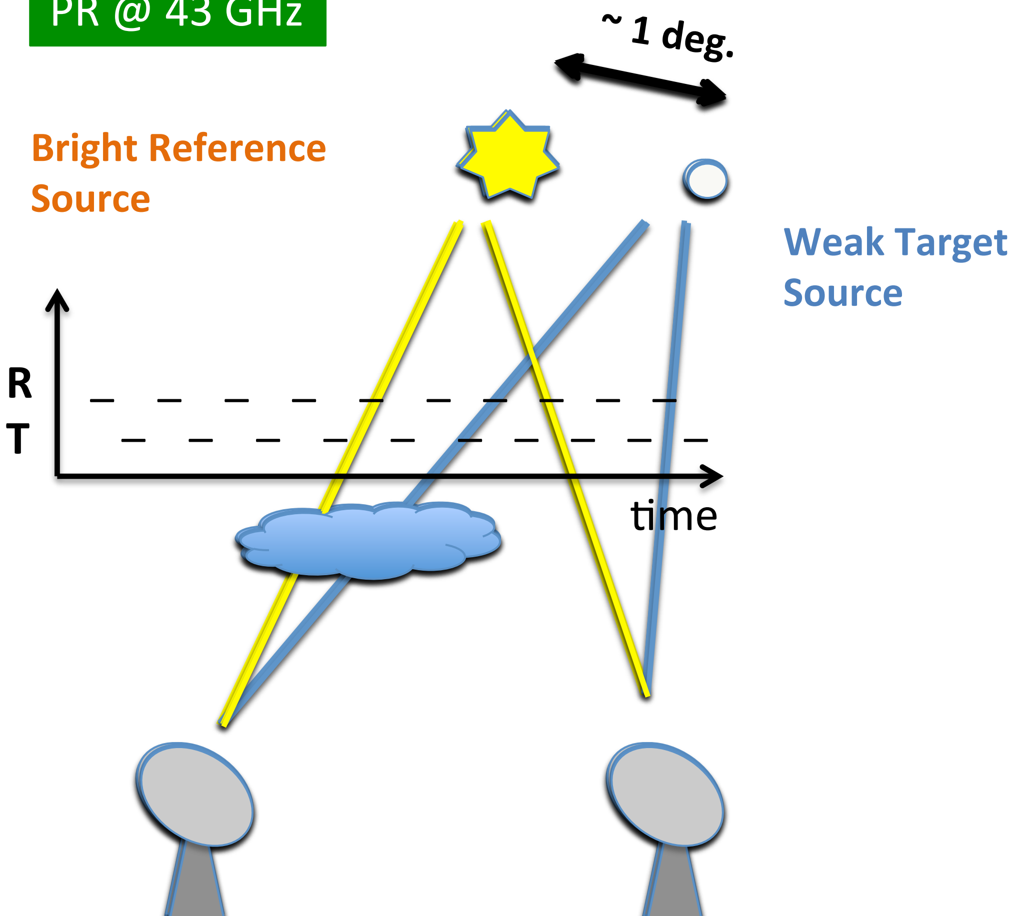
Limitations in performance start at freq. > 43 GHz

Phase Referencing *"trans-source"*

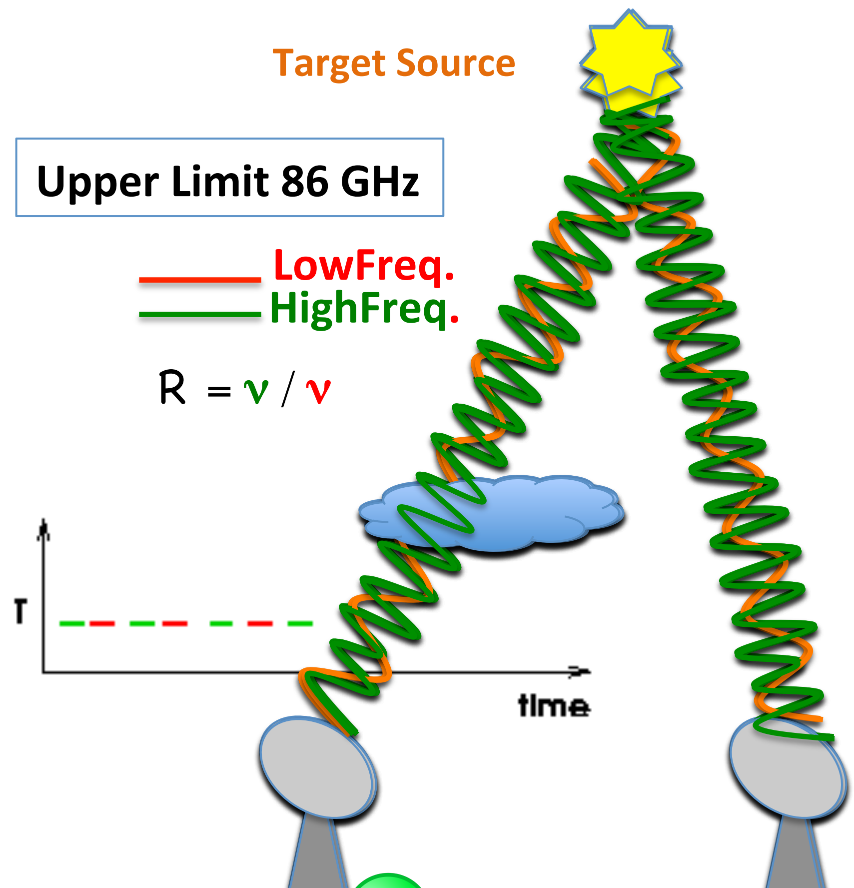
Paradigm Shift: "trans-frequency" calibration

"fast-frequency switching" with VLBA

PR @ 43 GHz



Upper Limit 86 GHz



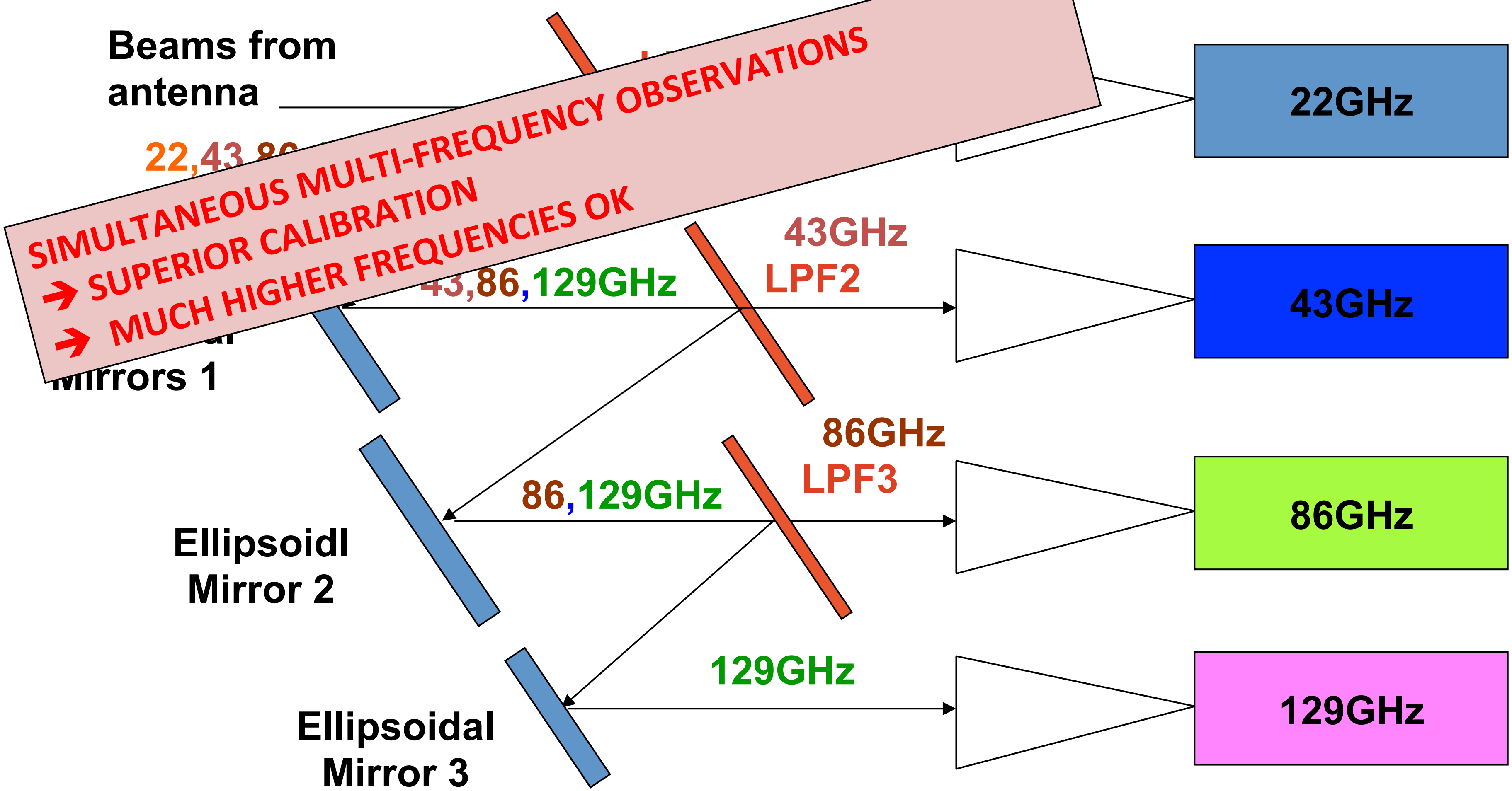
WEAK SOURCES ✓
ASTROMETRY ✓

WEAK SOURCES ✓
ASTROMETRY ✗

Middelberg et al. 2005
Rioja&Dodson 2008,2011

Multi-frequency receiving system of Korean VLBI Network (KVN)

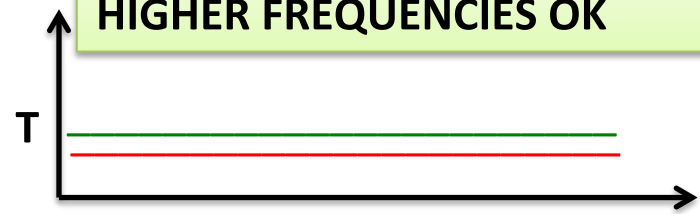
- Conceptual design came out in April 2003
- It is firstly proposed in VLBI application.



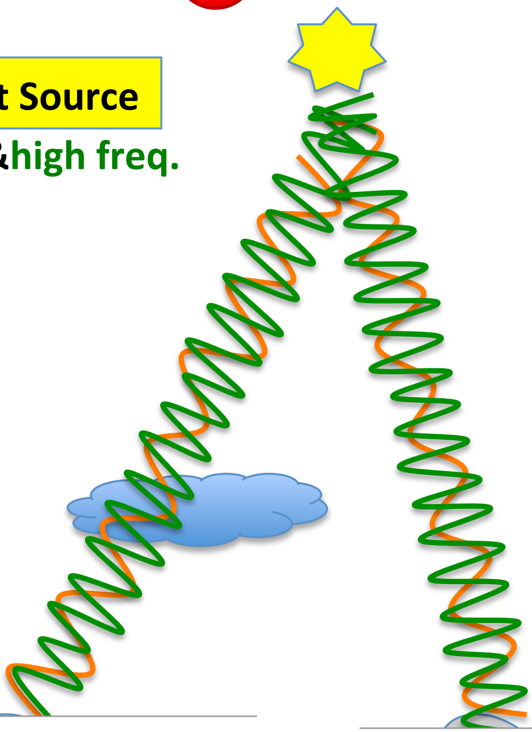
Frequency Phase Transfer (FPT)

WEAK SOURCES ASTROMETRY

BETTER (near) SIMULTANEOUS!
HIGHER FREQUENCIES OK



Target Source
@low&high freq.



$R = \nu / \nu$

Fast Slow Slow

$\phi_A^{FPT} = \phi_{GEO} + \phi_{TRO} + \phi_{ION} + \phi_{INST} + \phi'_{A,STR} + 2\pi n_A$

$R * \phi_A = R * (\phi_{A,GEO} + \phi_{A,TRO} + \phi_{A,ION} + \phi_{A,INST} + 2\pi n_A)$

Non-dispersive Errors:

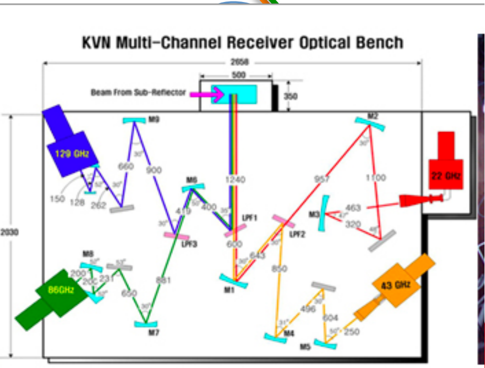
$\phi_{A,TRO} - R * \phi_{A,TRO} = 0$

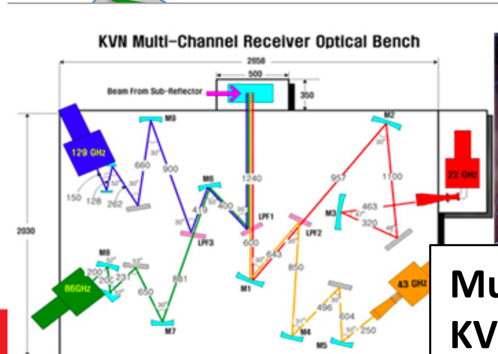
$\phi_{A,GEO} - R * \phi_{A,GEO} = 0$

Dispersive Errors:

$\phi_{A,ION} - R * \phi_{A,ION} = (R-1/R) * \phi_{A,ION}$

ϕ_{INST} … Anything!





Multi-channel KVN receivers

Frequency Phase Transfer (FPT)

<u>OUTCOME:</u> **PRECISE CALIBRATION OF THE TROPOSHERE**
(and in general any non-dispersive residuals)

<u>ENABLES</u>: **EXTENDED COHERENCE TIME**

- ➔ **WEAK SOURCE DETECTION <u>AT HIGH FREQUENCIES</u>**
- ➔ **~~ASTROMETRY~~**

**** (near) SIMULTANEOUS multi-frequency observations required for high freqs.***

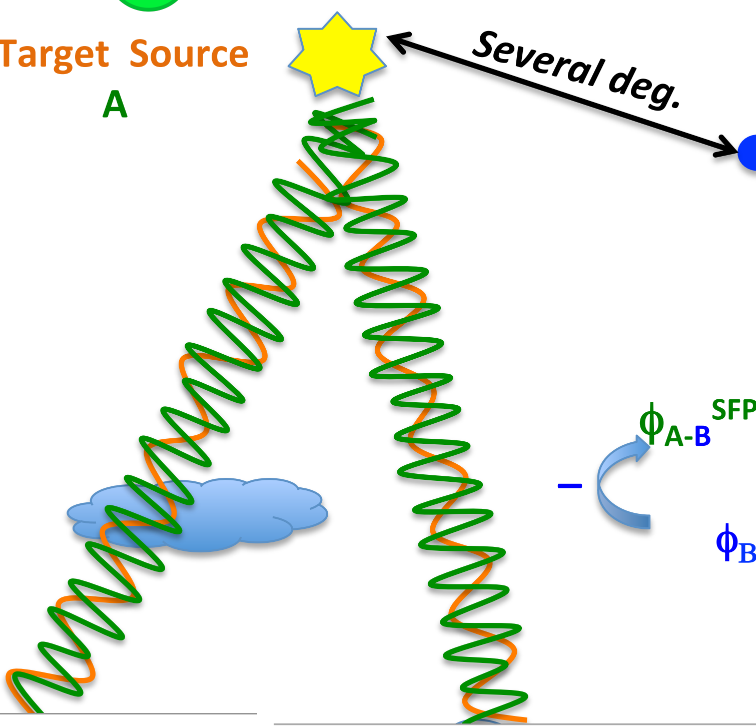
The Quest of Astrometry…
Source Frequency Phase Referencing (SFPR)

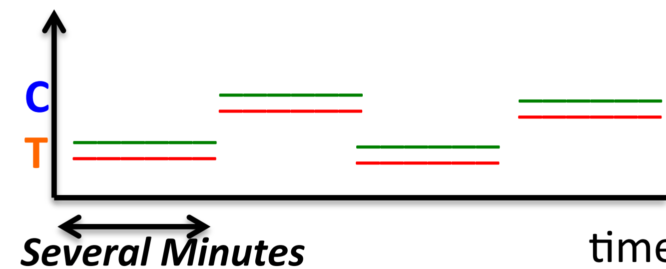
ICRAR

WEAK SOURCES ✓
ASTROMETRY ✓

SFPR: Rioja & Dodson '08,'11,'14,'15

(TWO SOURCES)





$R = \nu / \nu$

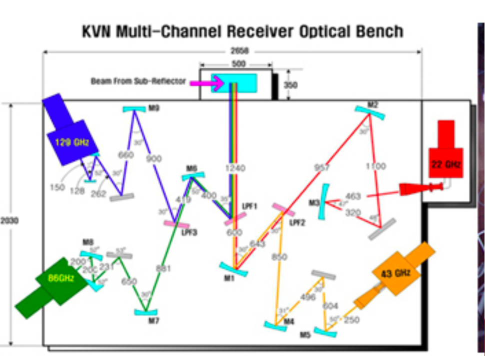
Fast Slow Slow

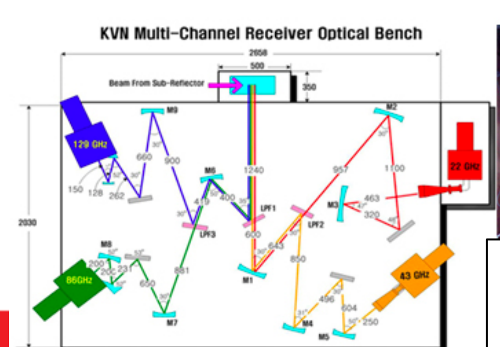
$\phi_{A-B}^{SFPR} = \ldots + \phi''_{A,STR} + 2\pi n_A$

$-\ \phi_B^{FPT} = \ldots + \phi_{B,ION} + \phi_{B,INST} + \phi'_{B,STR} + 2\pi n_B$

$\phi_{A,ION} - \phi_{B,ION} = 0$

$\phi_{A,\ldots} - \phi_{A,INST} = 0$





KVN

VLBA with freq. Switch

Astrometry:

ϕ_{A-B}^{SFPR} $\xleftrightarrow{FFT}$ **SFPRed A-Map at high freq.**

Source Frequency Phase Referencing (SFPR)

OUTCOME: PRECISE ATMOSPHERIC & INSTR. CALIBRATION, WHILE KEEPING ASTROMETRIC SIGNATURE

ENABLES: EXTEND COHERENCE TIME & ASTROMETRY AT HIGH FREQS

TARGET SCIENCE:

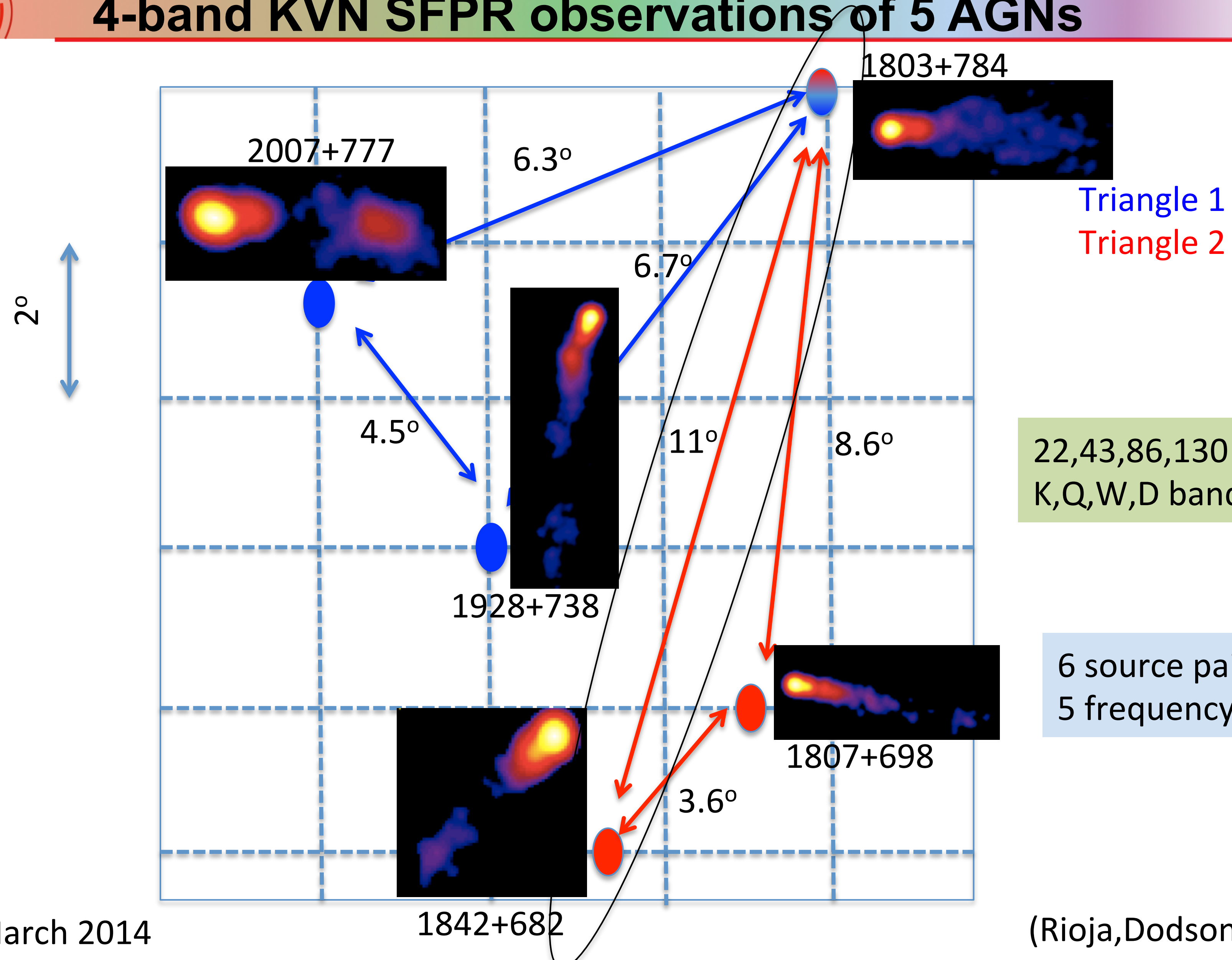
- ➔ WEAK SOURCE DETECTION
- ➔ ASTROMETRY (chromatic astrometry: continuum & line
  Registration of images at multiple frequencies:
  Spectral index maps,
  AGN "core-shifts";
  Faraday Rotation (polarization))

*Slow antenna switching OK

*Several degrees source separation OK

** (near)SIMULTANEOUS multi-frequency observations required for high freqs.*

Empirical Demonstration:
4-band KVN SFPR observations of 5 AGNs

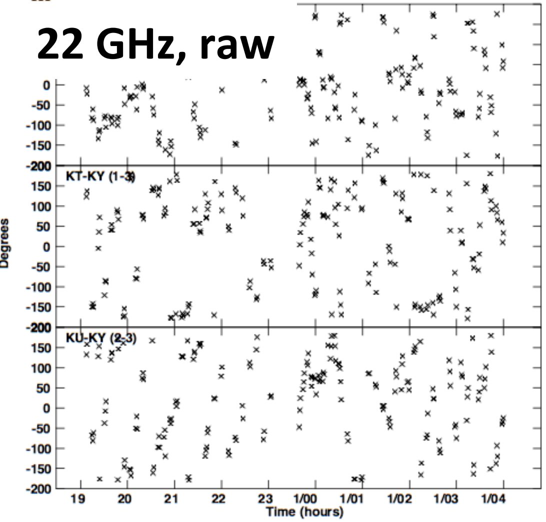


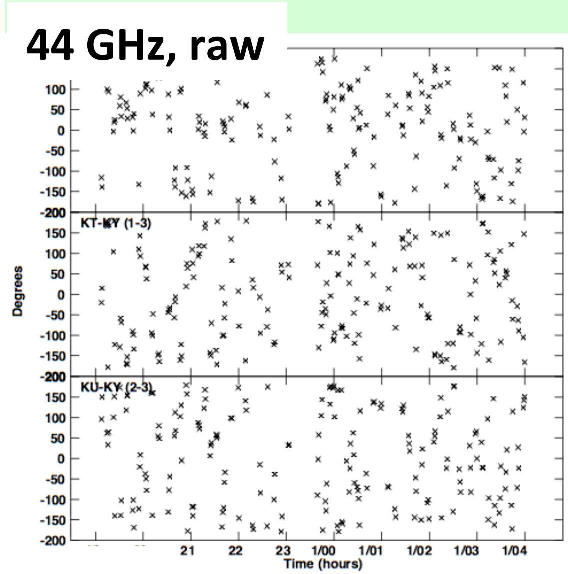
22,43,86,130 GHz
K,Q,W,D bands

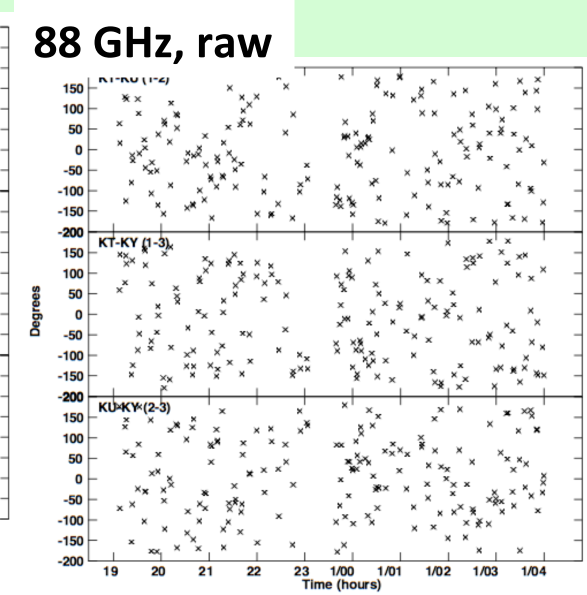
6 source pairs
5 frequency pairs

Epoch: March 2014

(Rioja,Dodson+'15)

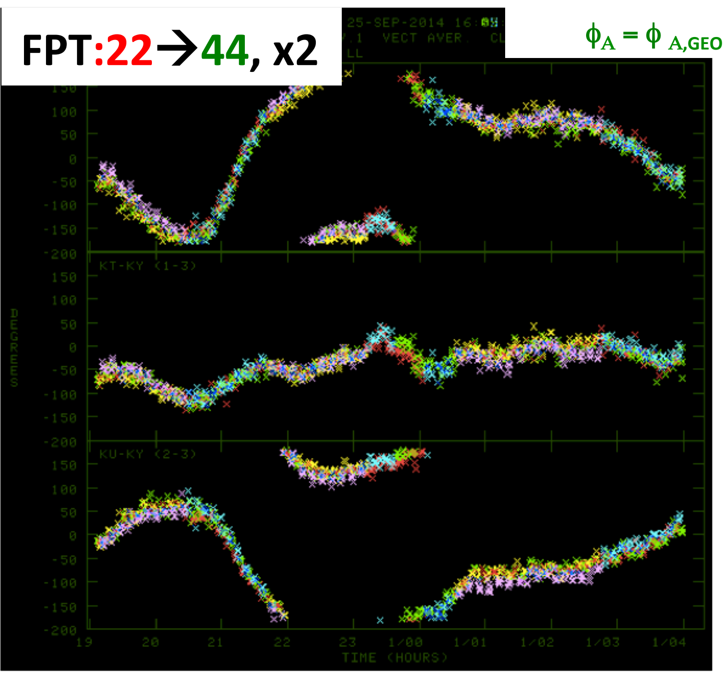


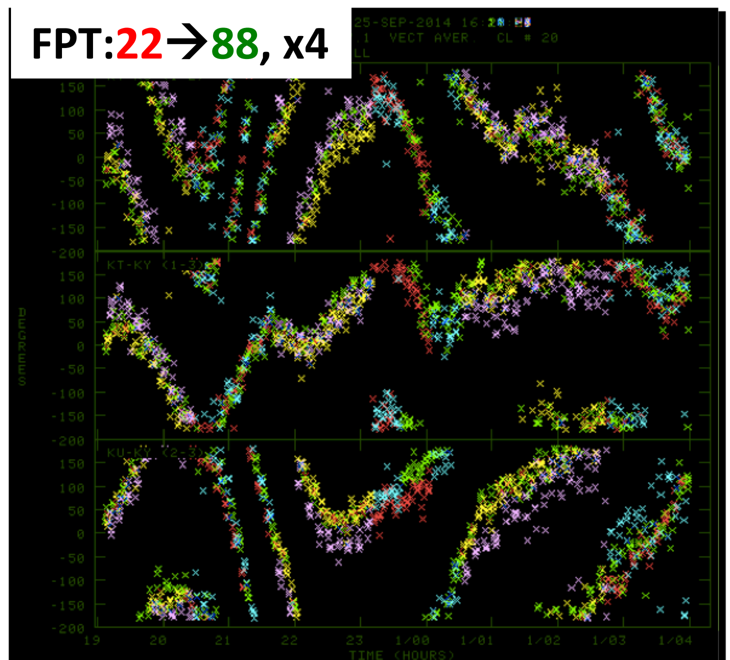




$\phi_A = \phi_{A,GEO} + \phi_{A,TRO} + \phi_{A,ION} + \phi_{A,INST} + 2\pi n_A$

$\phi_A = \phi_{A,GEO} + \phi_{A,TRO} + \phi_{A,ION} + \phi_{A,INST} + 2\pi n_A$

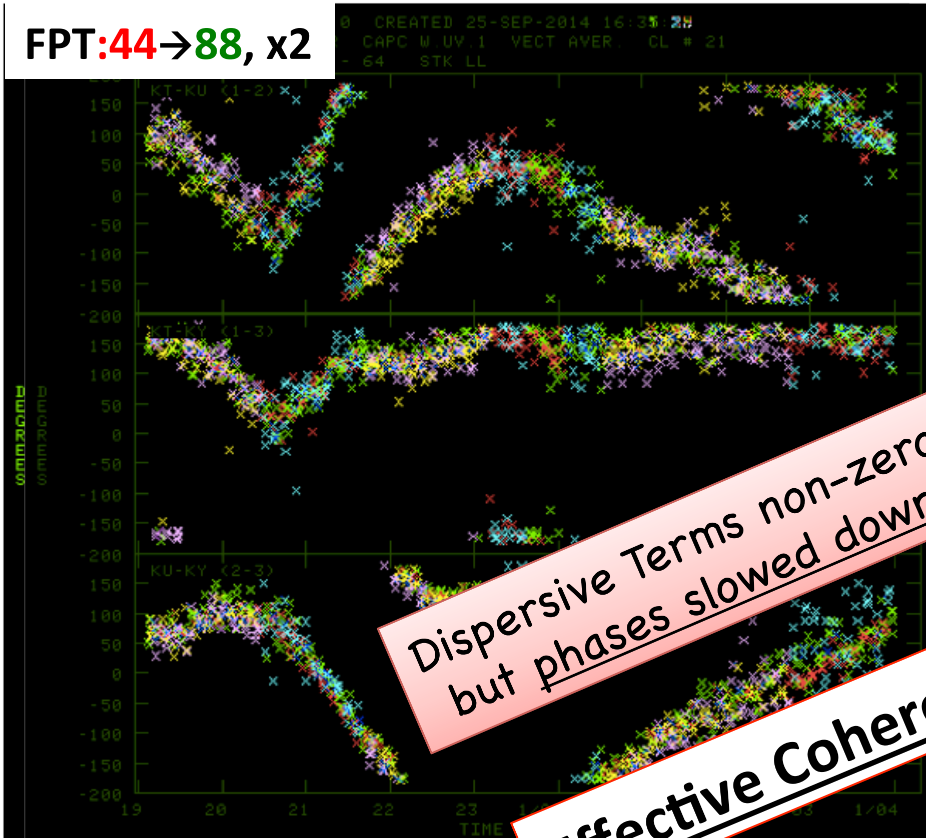


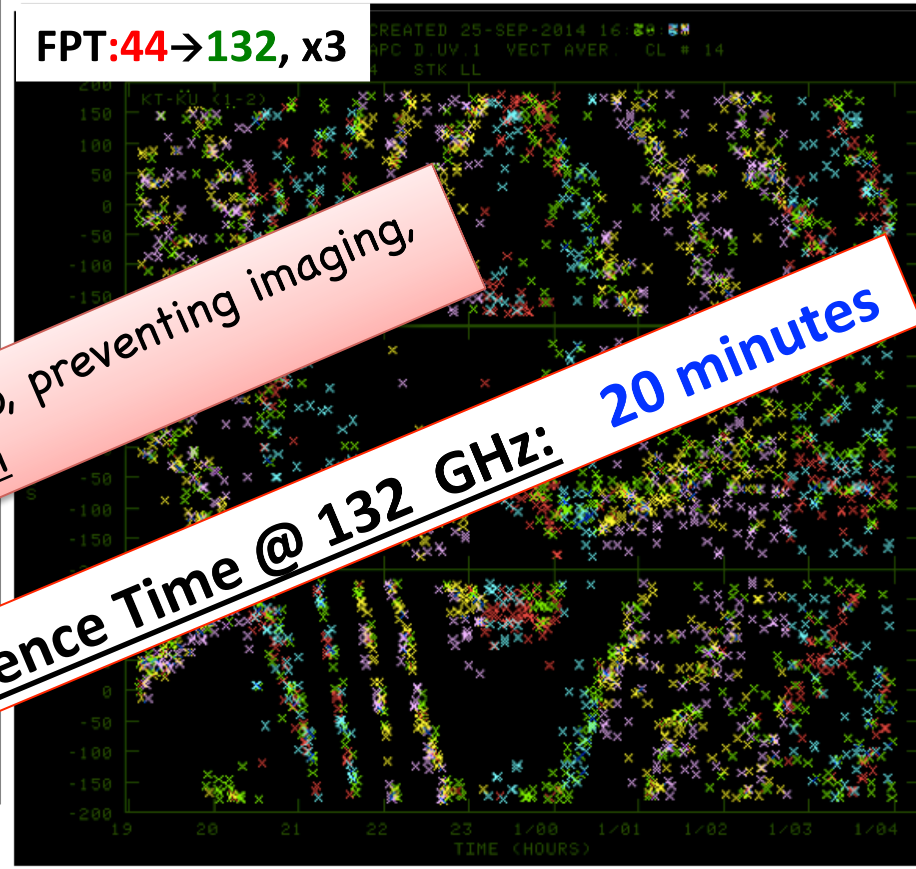


$\phi_A - 2 * \phi_A$

$\phi_A - 2 * \phi_A$

FPT analysis – "2-frequencies"
Residuals increase with R, for a given ν_{low} (44 GHz)





Dispersive Terms non-zero, preventing imaging, but phases slowed down

Effective Coherence Time @ 132 GHz: 20 minutes

$R = \nu / \nu$

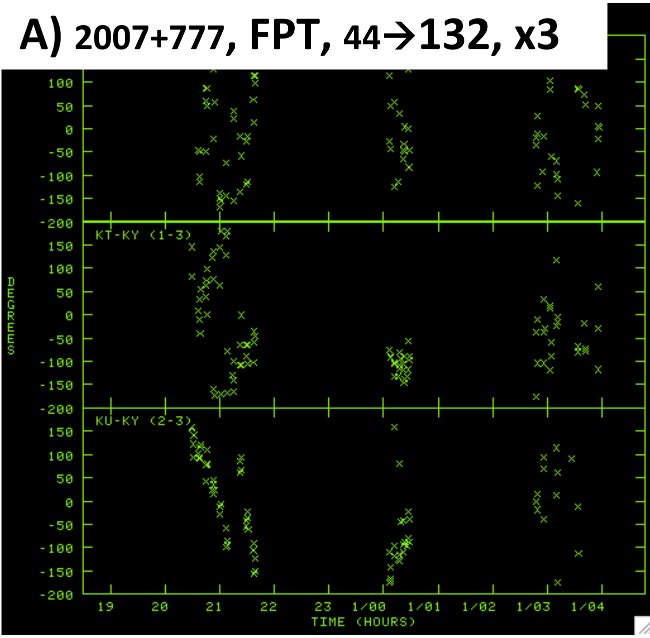
Fast Slow Slow

$\phi_A^{FPT} = \phi_{GEO} + \phi_{TRO} + \phi_{ION} + \phi_{INST} + \phi'_{A,STR} + 2\pi n_A$

$R*\phi_A = R*(\phi_{A,GEO} + \phi_{A,TRO} + \phi_{A,ION} + \phi_{A,INST} + 2\pi n_A)$

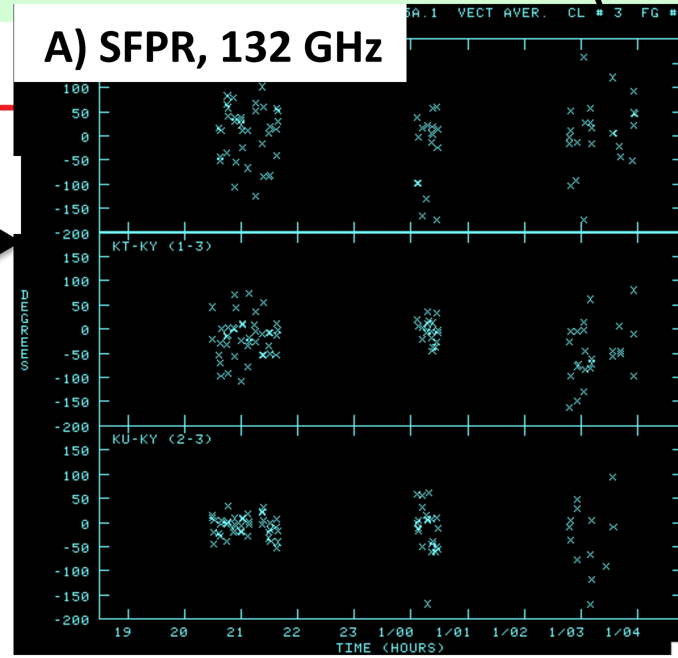
SFPR analysis – 132 GHz with 43GHz: 2007+777 (ref. 6.3° away)

A) 2007+777, FPT, 44→132, x3



A) – B) →

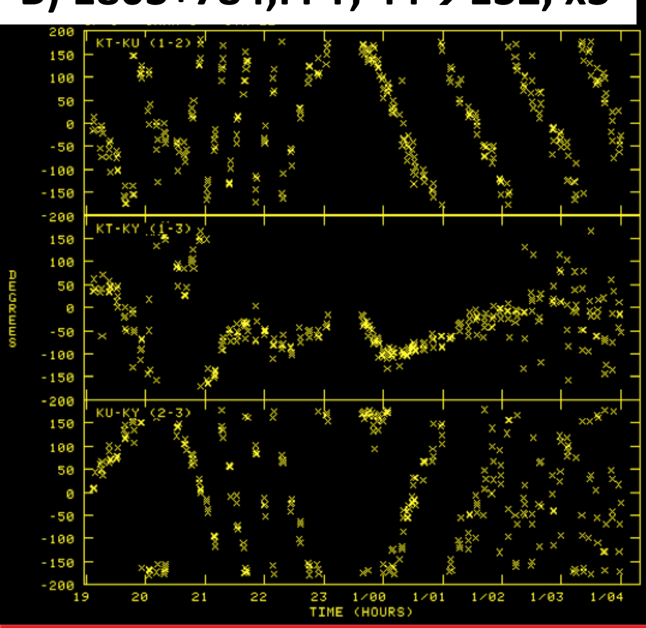
A) SFPR, 132 GHz



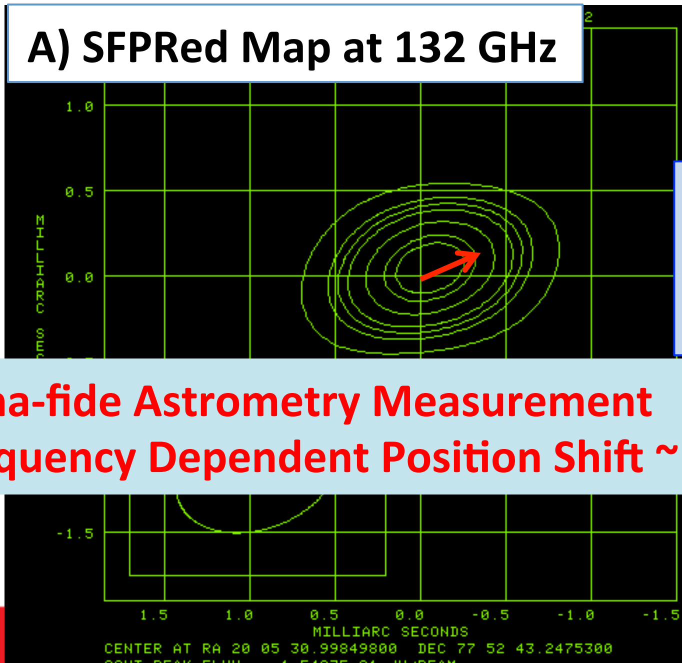
Effective Coherence Time @132 GHz:
8 hours

↕ **FFT**

B) 1803+784,FPT, 44→132, x3



A) SFPRed Map at 132 GHz

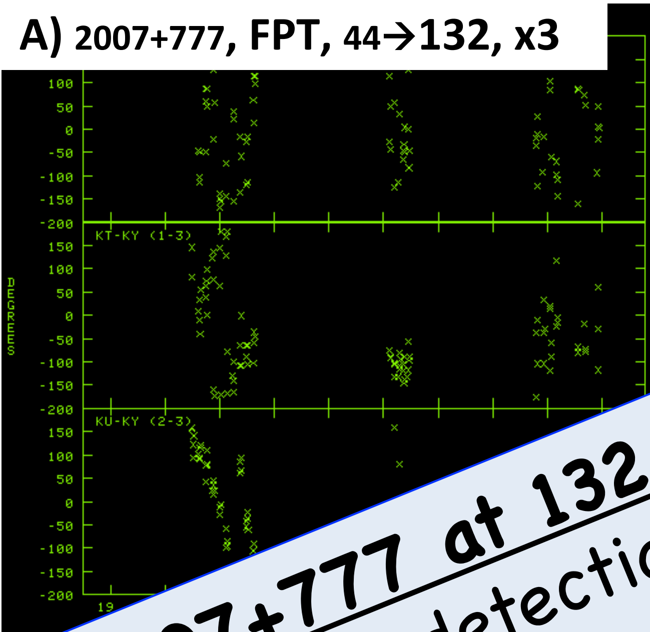


Peak Flux ~ 150 mJy
rms ~ 5mJy/beam
85-90% Flux Recovery

Bona-fide Astrometry Measurement
Frequency Dependent Position Shift ~ (-50,+50) µas

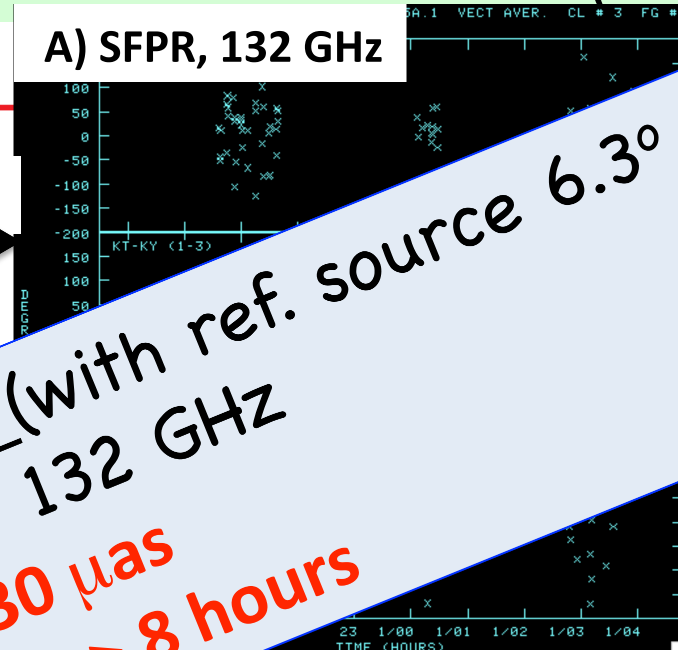
SFPR analysis – 132 GHz with 43GHz: 2007+777 (ref. 6.3° away)

A) 2007+777, FPT, 44→132, x3



A) – B)

A) SFPR, 132 GHz



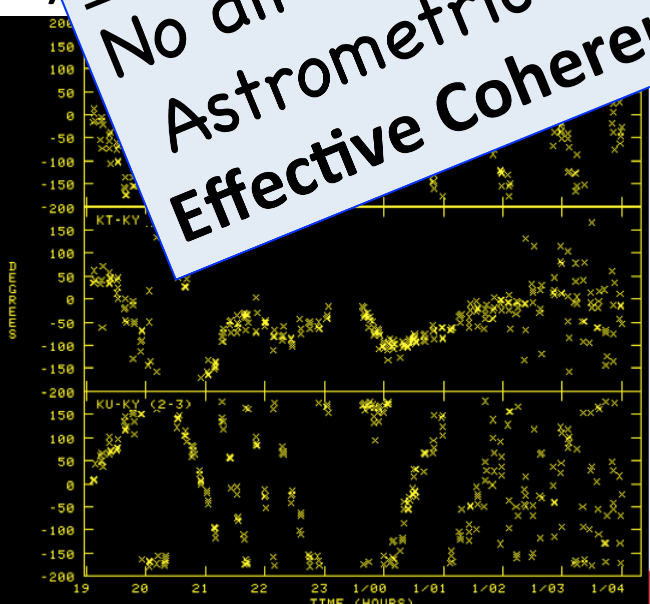
2007+777 at 132 GHz (with ref. source 6.3° away)

No direct detections at 132 GHz

Astrometric Error ~ **30 μas**

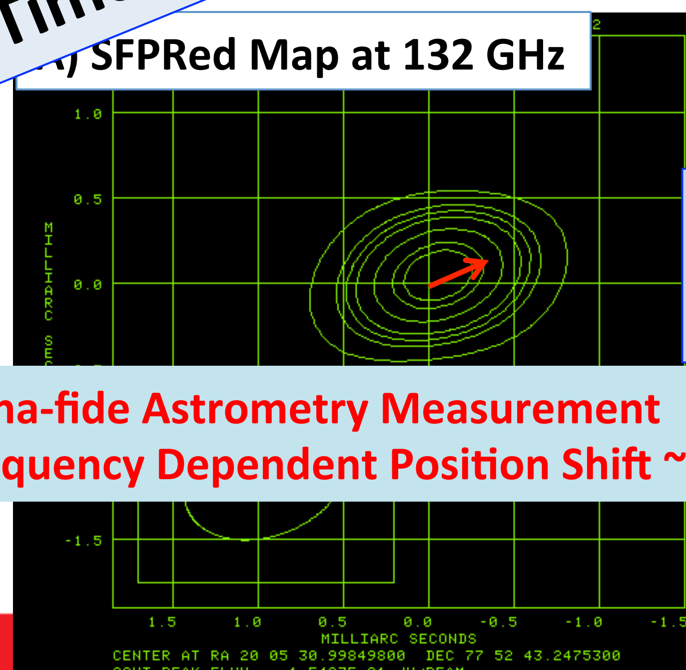
Effective Coherence Time > 8 hours

B)



FFT

SFPRed Map at 132 GHz

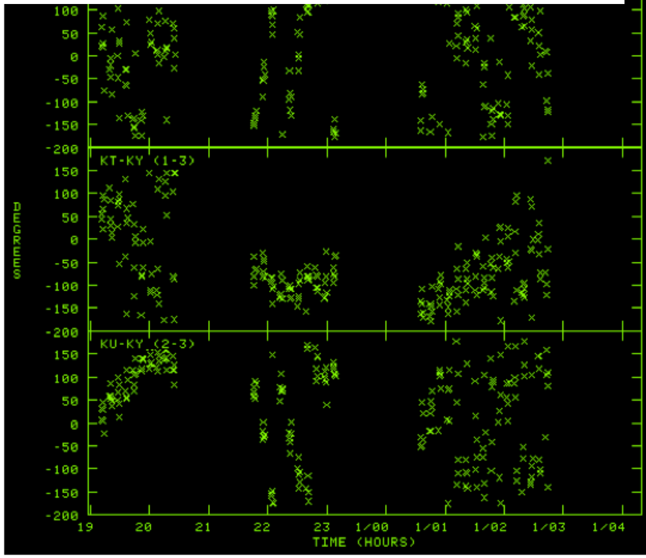


Peak Flux ~ 150 mJy
rms ~ 5mJy/beam
85-90% Flux Recovery

Bona-fide Astrometry Measurement
Frequency Dependent Position Shift ~ (-50,+50) μas

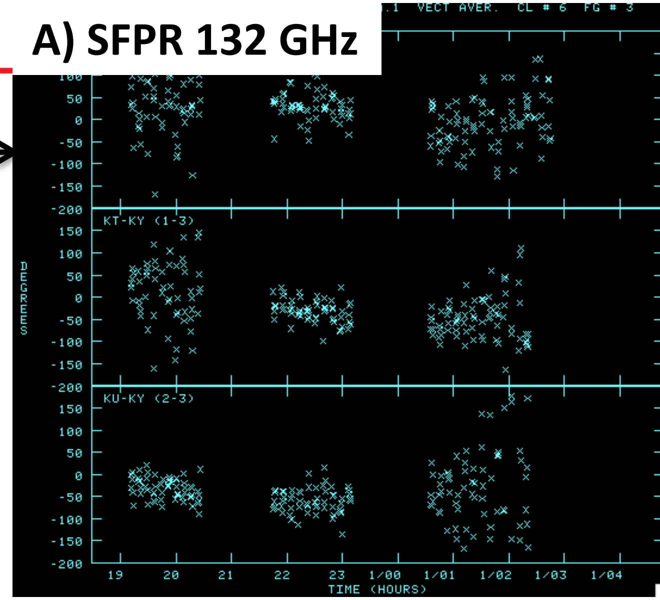
SFPR analysis – 132 GHz with 43GHz: 1842+681 (ref. 11° away)

A) 1842+681 FPT,44→132, x3



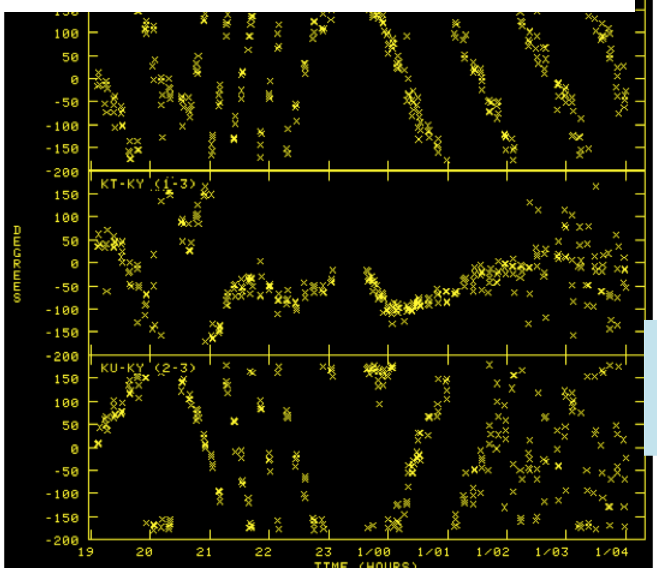
A) – B)

A) SFPR 132 GHz

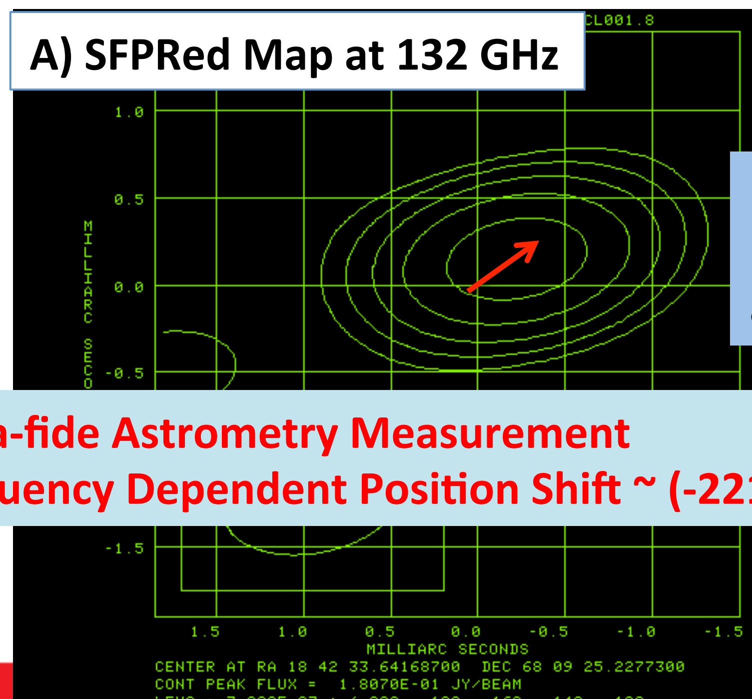


FFT

B) 1803+784, FPT,44→132, x3



A) SFPRed Map at 132 GHz

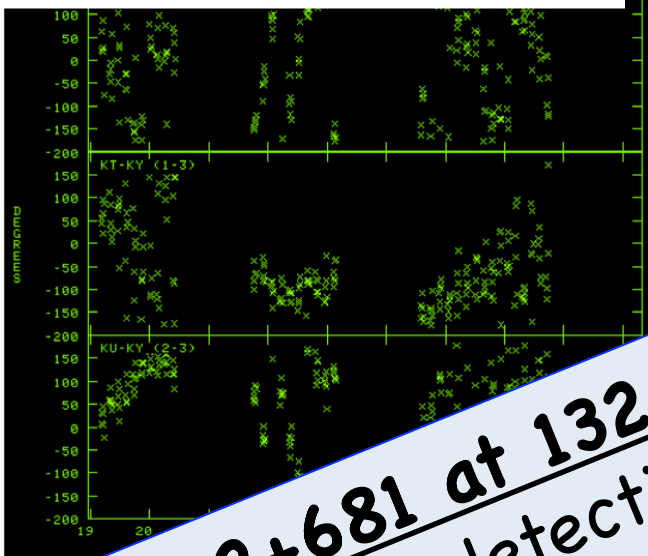


Peak Flux ~ 100 mJy
rms ~ 5 mJy/beam
87% Flux Recovery

Bona-fide Astrometry Measurement
Frequency Dependent Position Shift ~ (-221,+150) μas

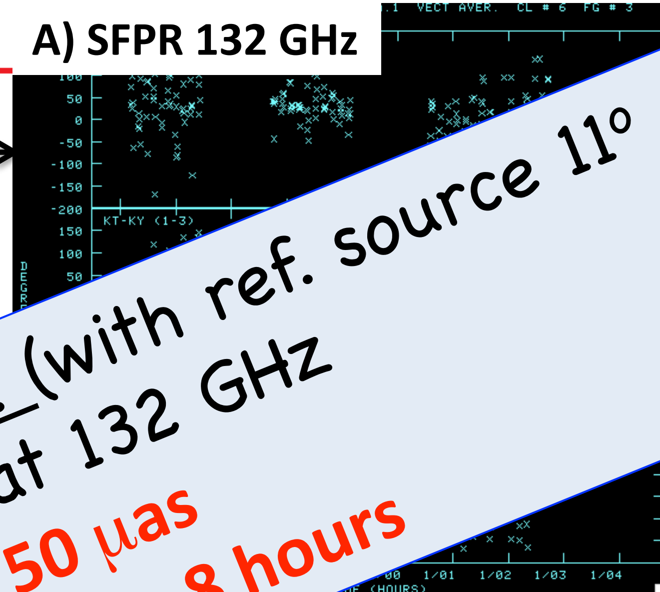
SFPR analysis – 132 GHz with 43GHz: 1842+681 (ref. 11° away)

A) 1842+681 FPT,44→132, x3



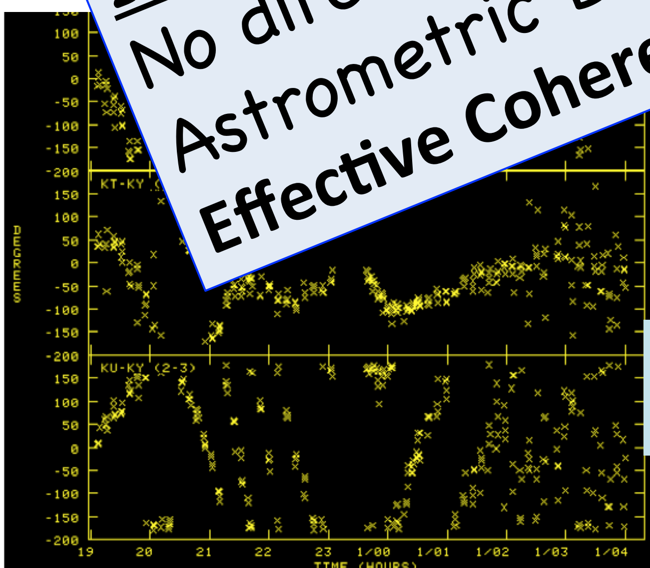
A) – B) →

A) SFPR 132 GHz

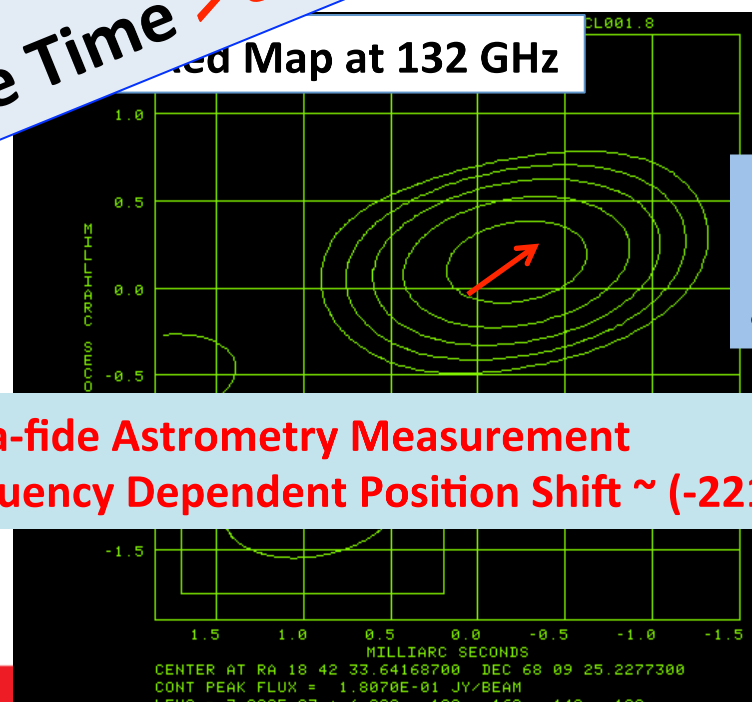


↕ FFT

B)



...ed Map at 132 GHz



1842+681 at 132 GHz (with ref. source 11° away)

No direct detections at 132 GHz

Astrometric Error ~ **50 μas**

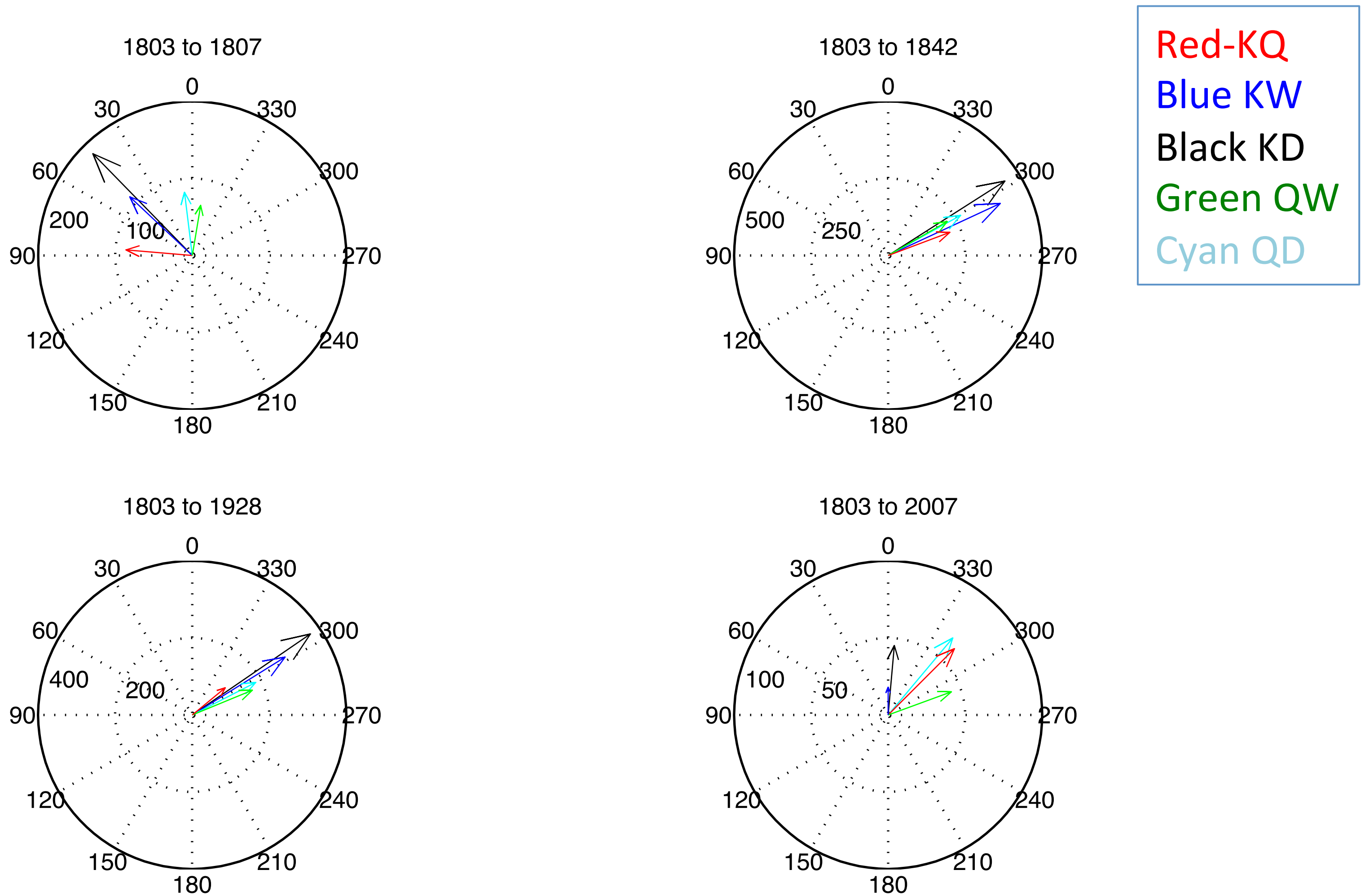
Effective Coherence Time > 8 hours

Peak Flux ~ 100 mJy
rms ~ 5 mJy/beam
87% Flux Recovery

Bona-fide Astrometry Measurement

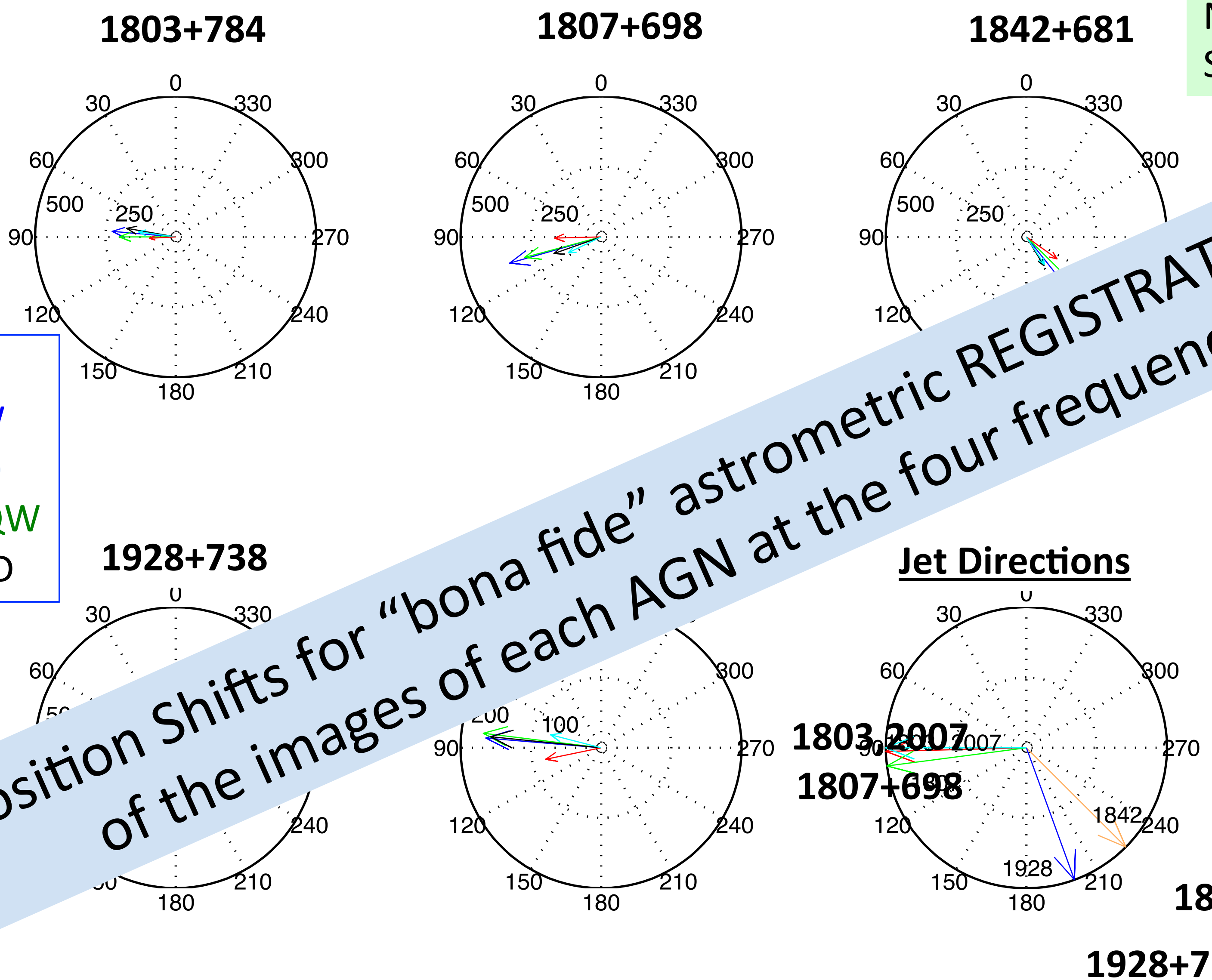
Frequency Dependent Position Shift ~ (-221,+150) μas

SFPR Astrometric RELATIVE Measurements: between TWO frequencies & TWO sources



Individual Source Shifts: Singular Value Decomposition Method PLUS Alignment with Jet Direction Constraint

Non-Degenerate Solution

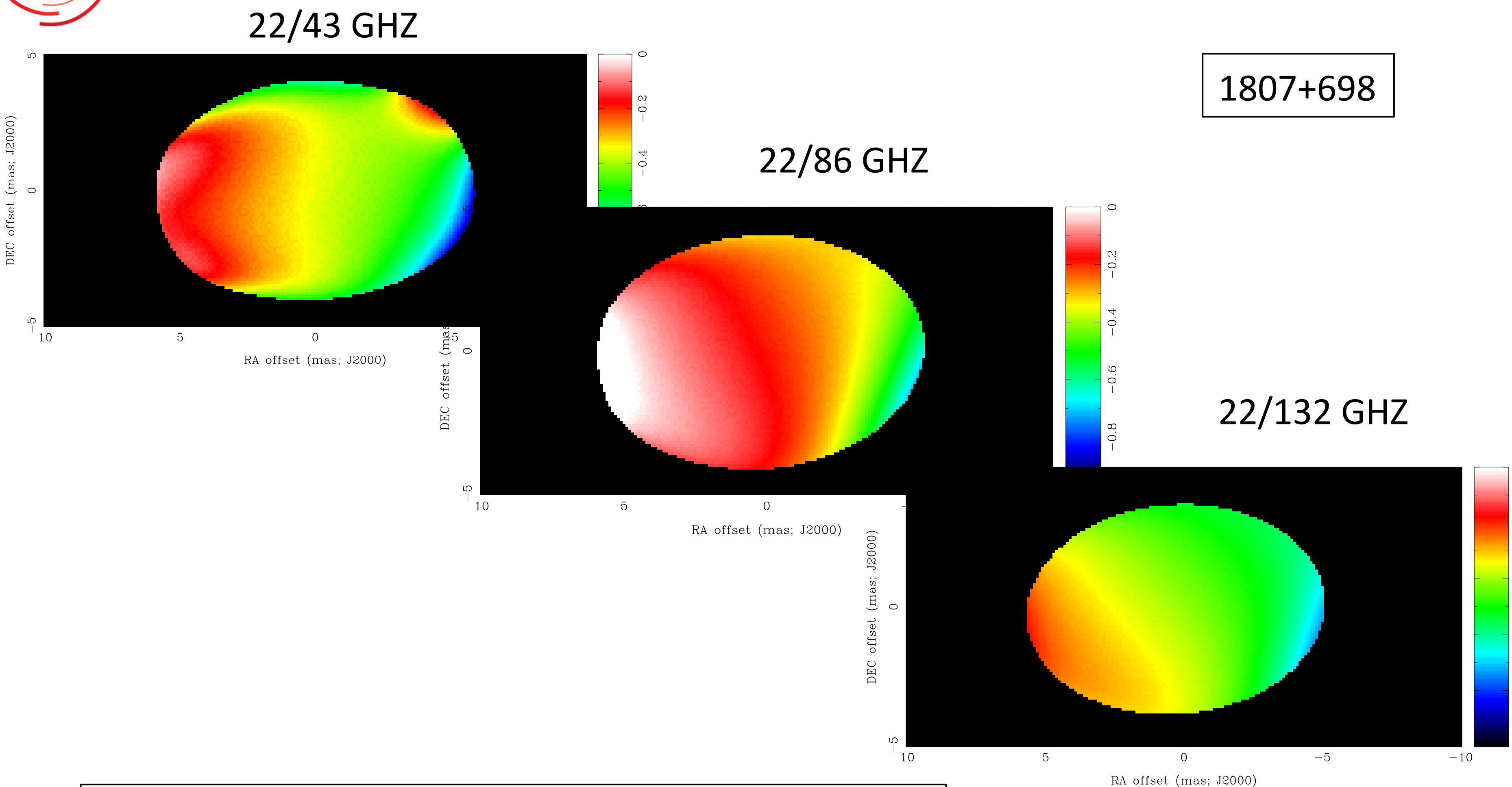


Red KQ
Blue KW
Cyan KD
Green QW
Black QD

Position Shifts for "bona fide" astrometric REGISTRATION of the images of each AGN at the four frequency bands.

(Rioja,Dodson+'15)

Spectral Index Maps: Astrometrically Aligned Images

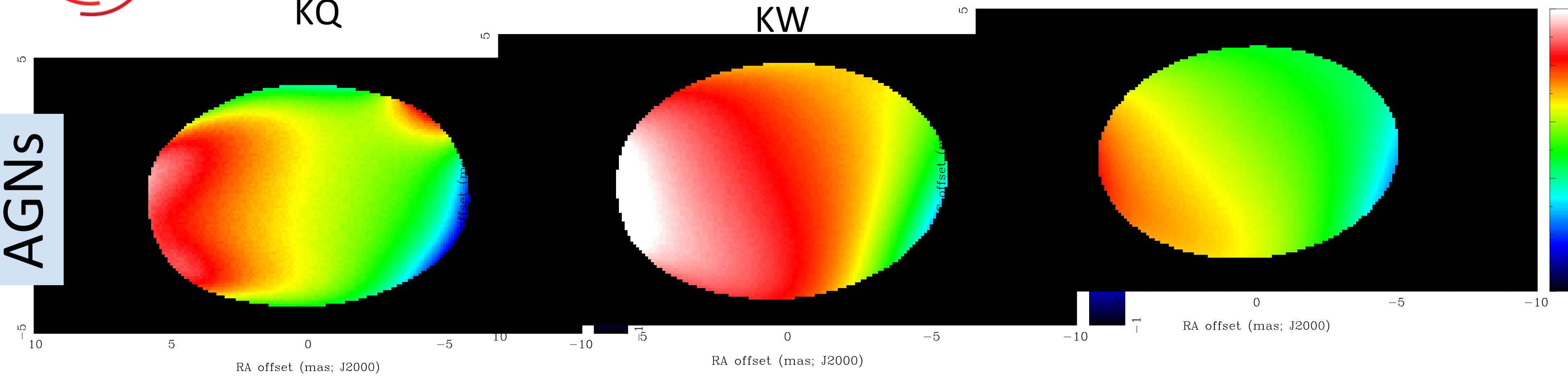


First Time "bona fide" Astrometry at 132 GHz, Made possible by SFPR

On-going developments towards a high resolution multi-freq array (x-KVN)

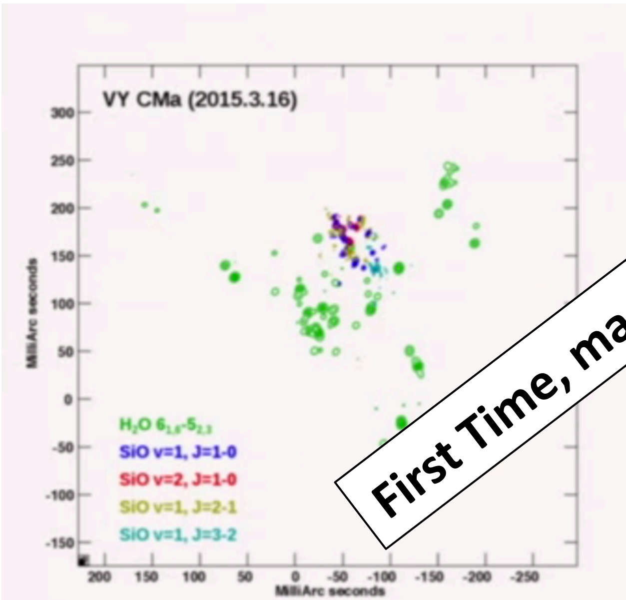
Spectral Index Maps: Astrometrically Aligned Images

AGNs



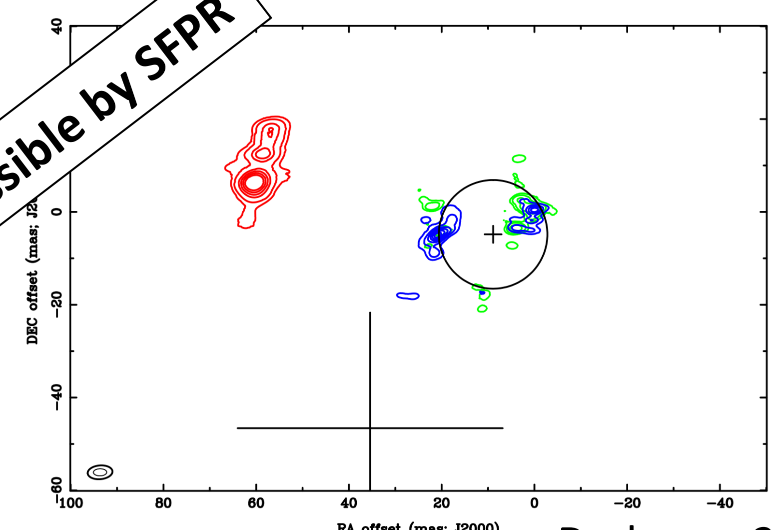
Registration of multi-transition masers

Evolved Stars



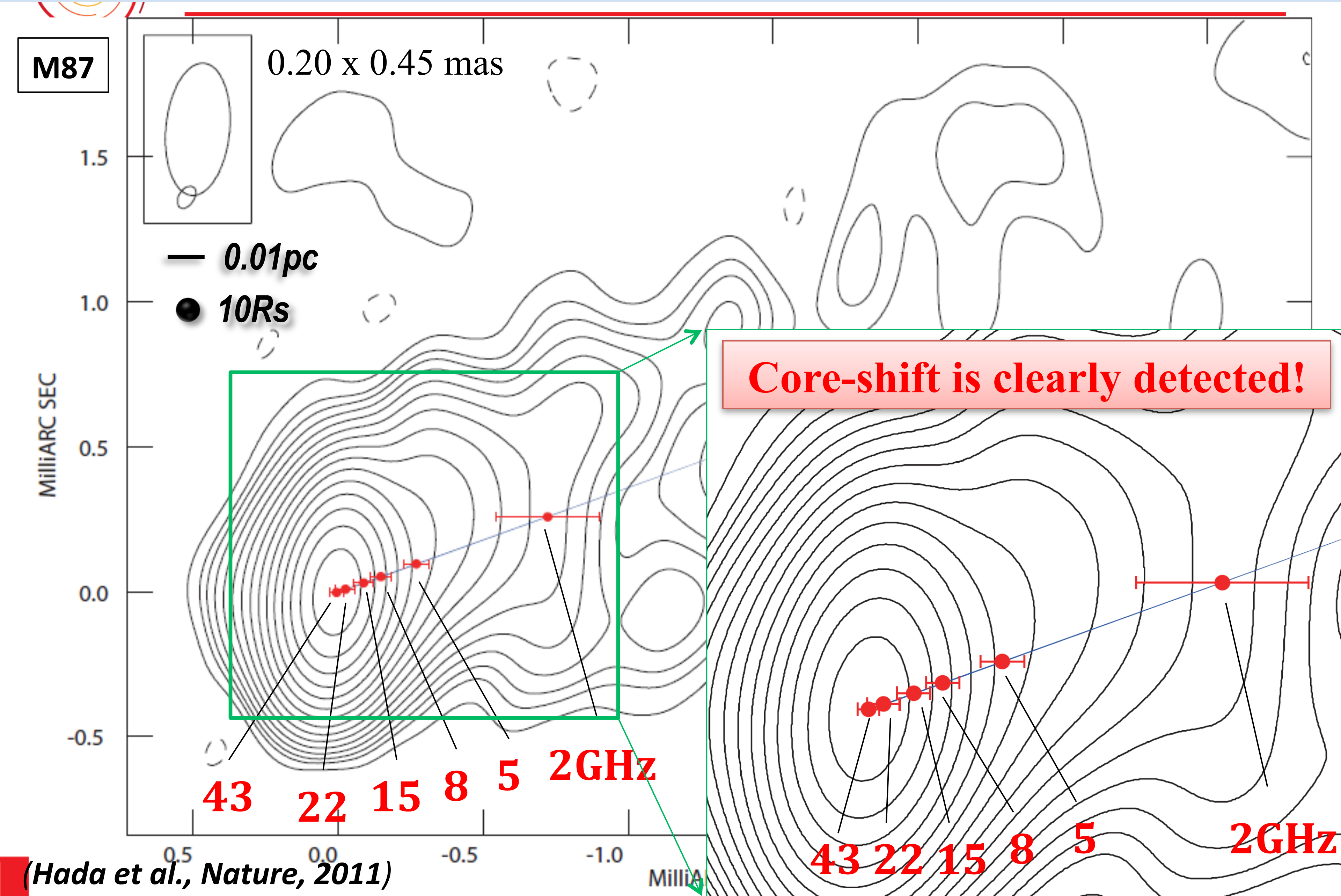
Cho et al. in Prep

First Time, made possible by SFPR



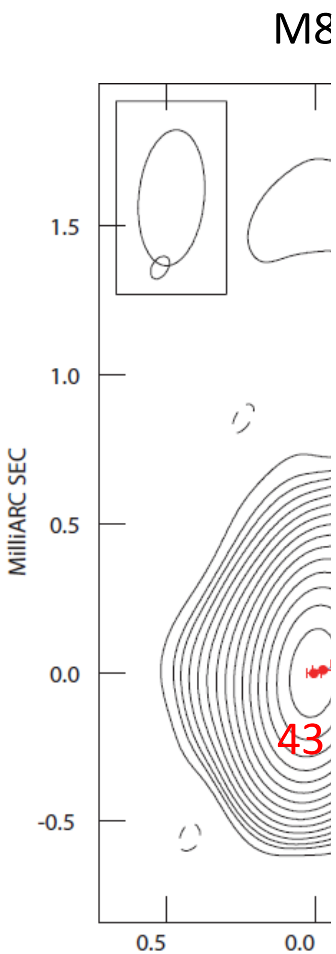
Dodson + 2014

AGN **Core-Shift** Measurements (Optical Depth)

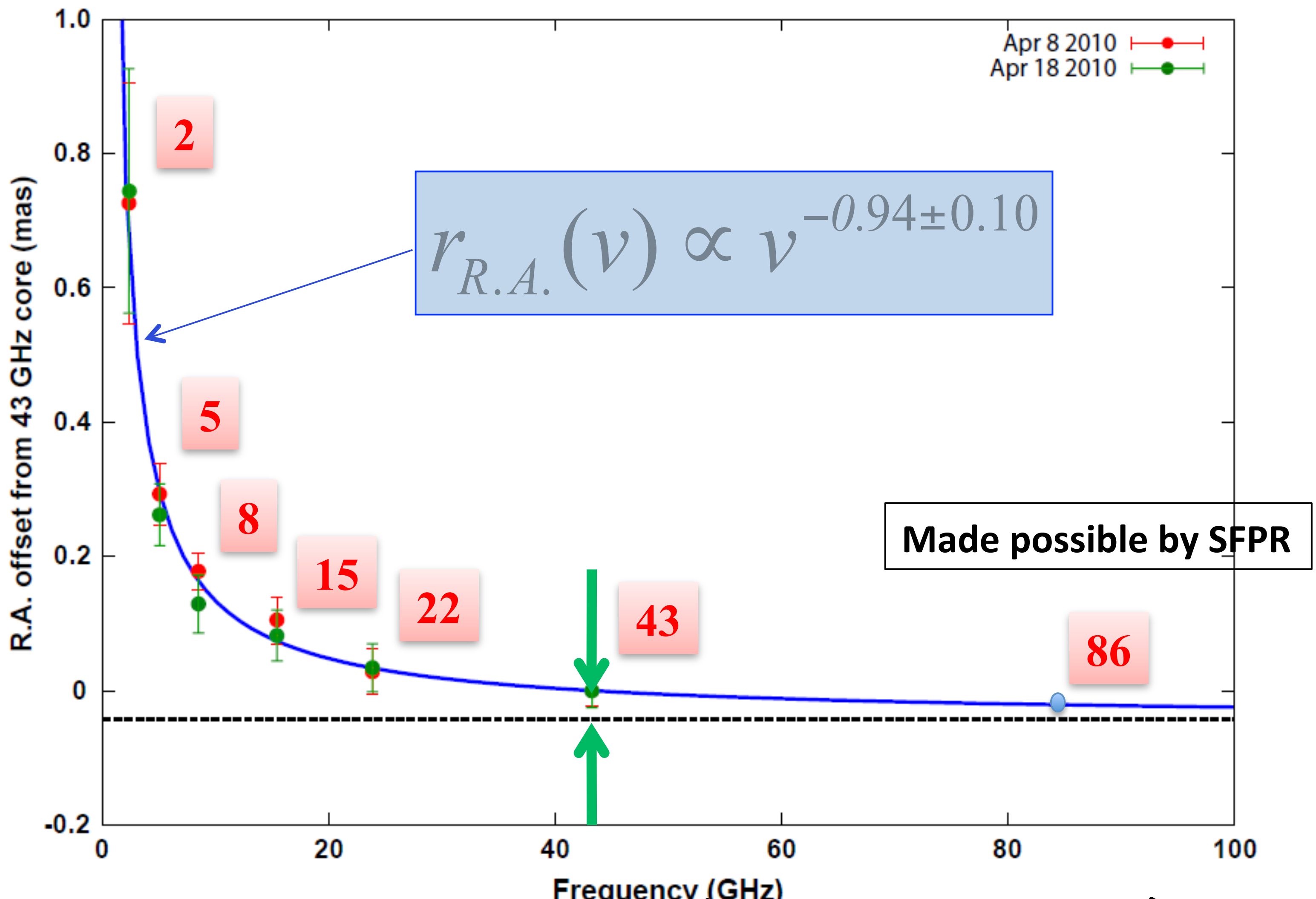


(Hada et al., Nature, 2011)

AGN: Multi Frequency astrometry



VLBA, PR
2-43 GHz



VLBA, PR 2-43 GHZ
(Hada et al. 2011 *Nature*)

VLBA, SFPR 43/86 GHZ
(Rioja & Dodson, 2011)

Developments for mm-VLBI continue…. ICE blocks

ICE = Ionospheri**C E**xtraction

Multi Frequency Phase Referencing (MFPR) Technique*: a variation of SFPR, with a* ***SINGLE*** *source*

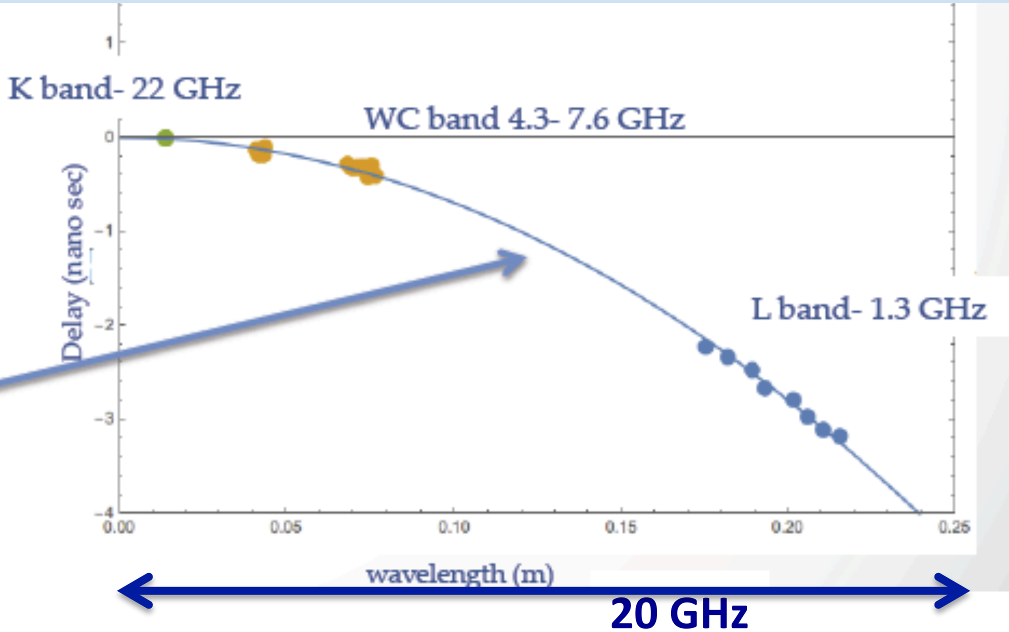
ICE Blocks: Fast-alternating multi frequency observations **at low frequencies**, of the target source.

Trop. Delay is same at all λ's (non-dispersive)

$$\delta\tau = c + 1.34\ \Delta TEC\ .\ \lambda^2$$

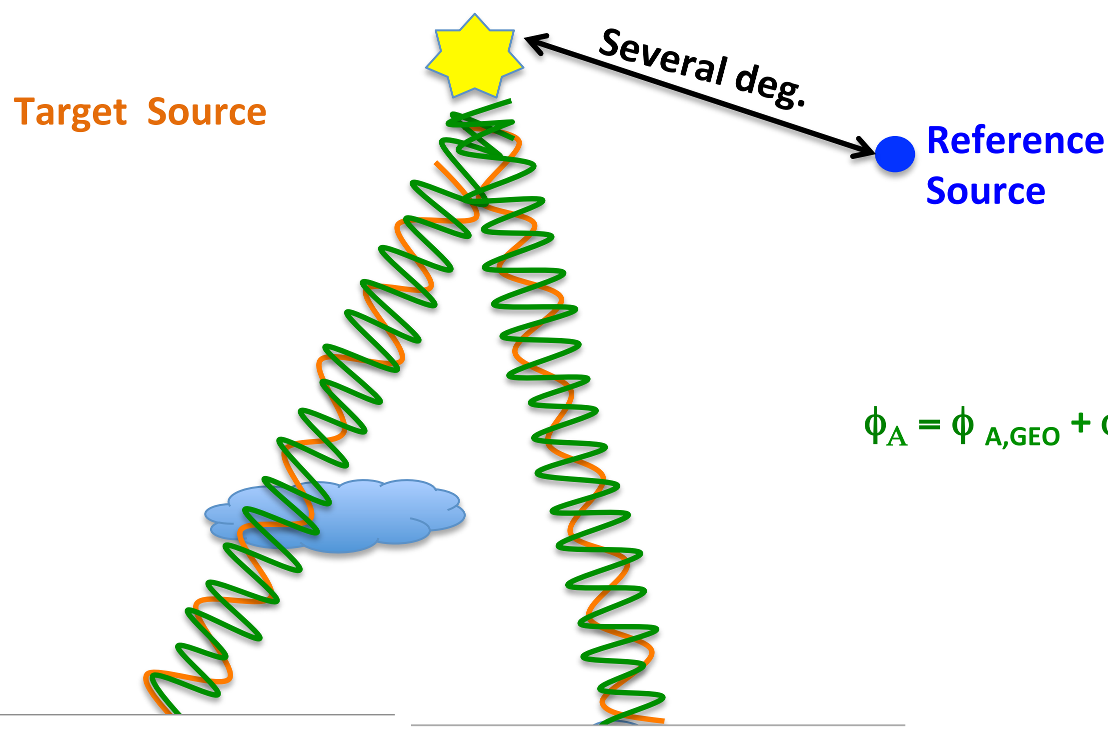
Tec (Total electron content)

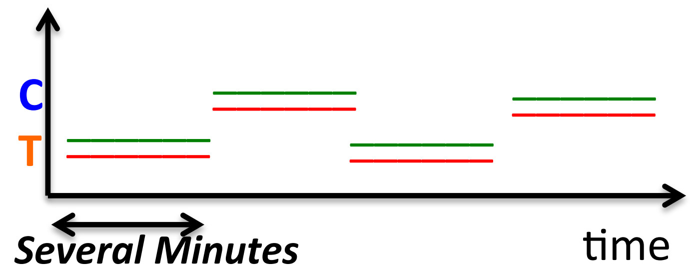
We have developed a program to fit the data.



Source Frequency Phase Referencing

Two Sources, Two Frequencies

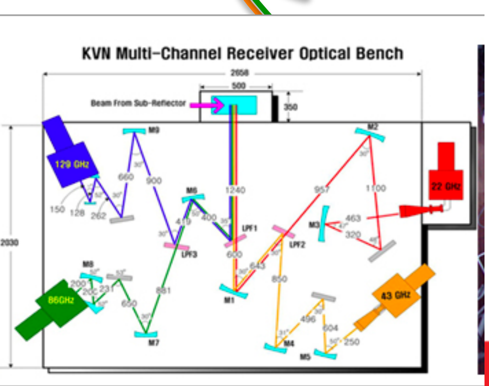


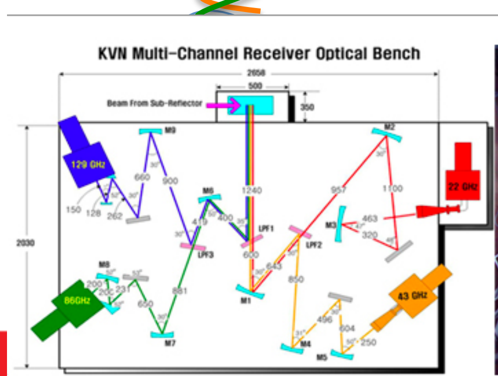


$R = \nu / \nu$

Fast Slow Slow

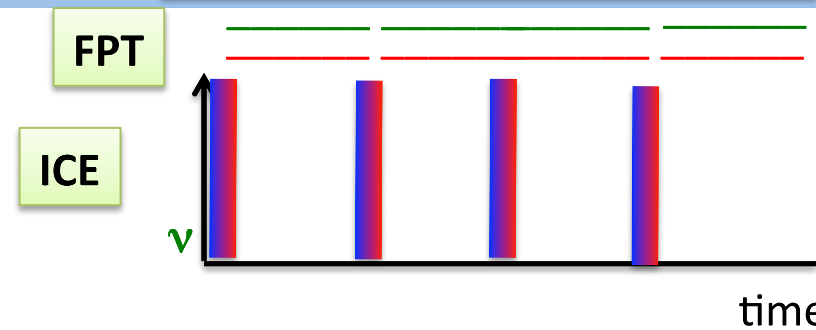
$\phi_A = \phi_{A,GEO} + \phi_{A,TRO} + \phi_{A,ION} + \phi_{A,INST} + \phi_{A,STR} + 2\pi n_A$



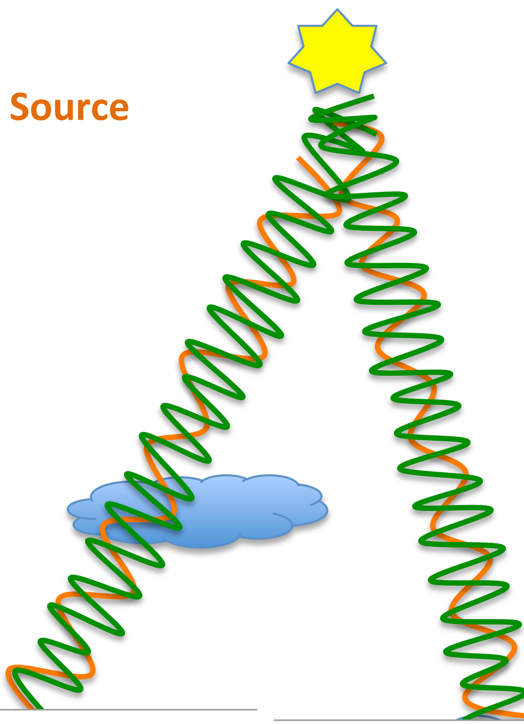


Multi-Frequency Phase Referencing (MFPR)

Single Source, Multi-Frequency



Target Source



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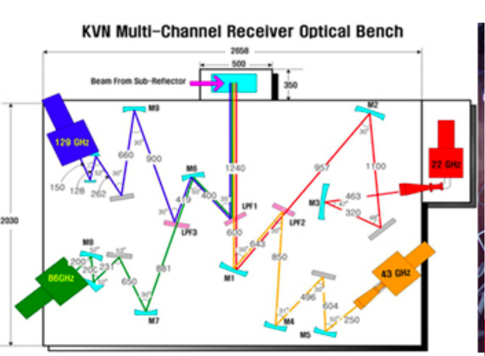
Fast Slow Slow

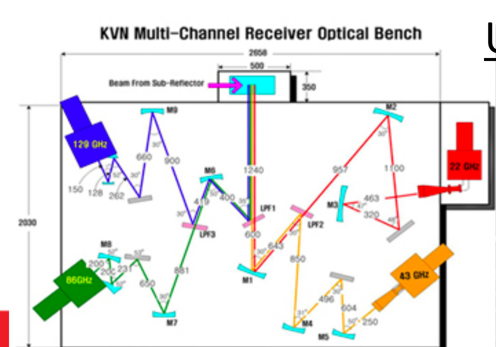
$\phi_A = \phi_{\ldots O} + \phi_{A\ldots} + \phi_{A\ldots N} + \phi_{\ldots T} + \phi_{A,STR} + 2\pi n_A$

FPT ICE

$\phi_{A,ION}$ = fTEC(ν) ➔ ΔTEC

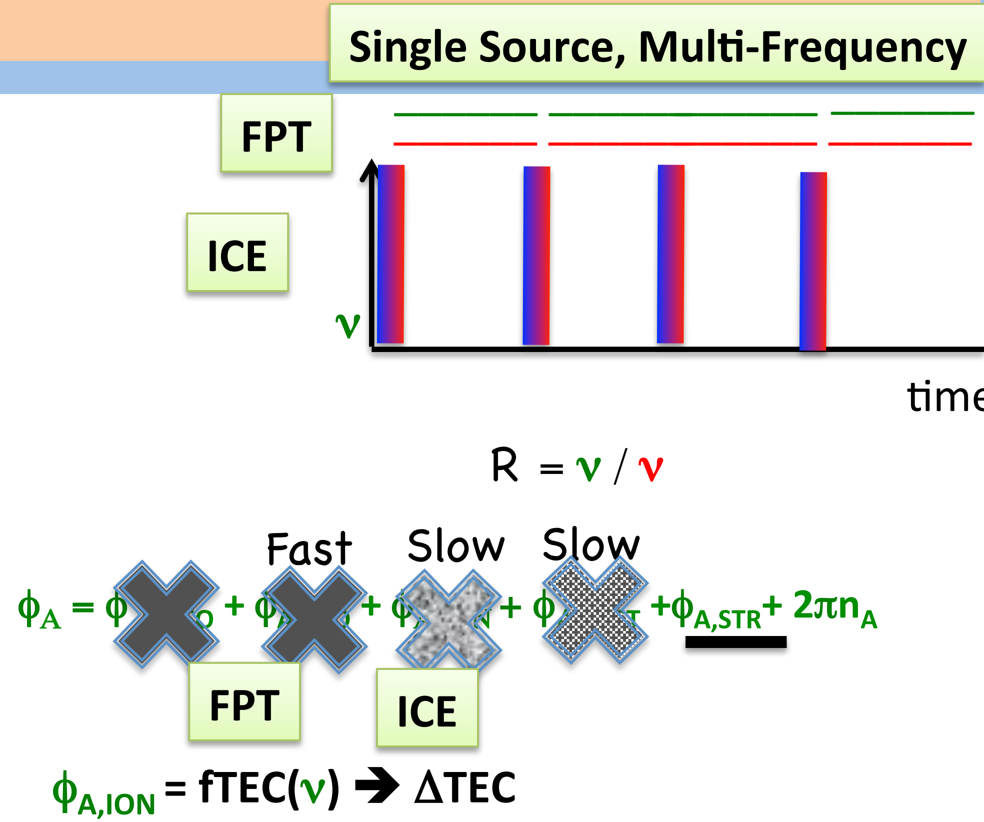
Use primary calibrator for $\phi_{A,INST}$ = stable (cte).





Multi-Frequency Phase Referencing (MFPR)

Basics of Multi-Frequency Phase Referencing (single source)



Use multi-frequency observations to derive TEC, i.e. the Ionospheric contribution

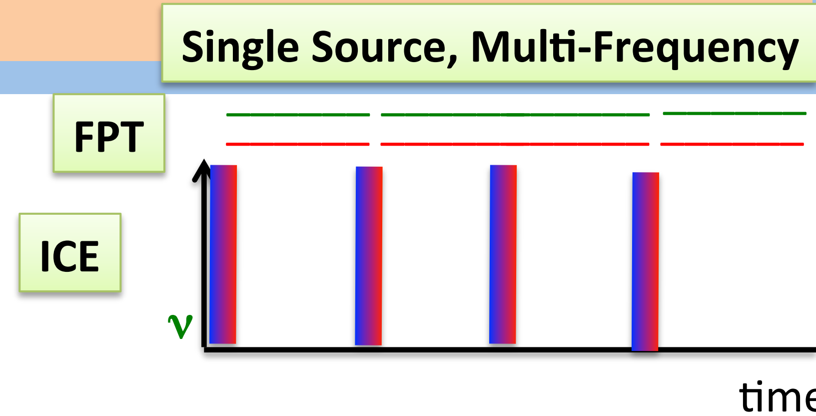
- `Curvature' of delay as a function of freq. allows determination of ΔTEC

Use fast frequency-switching to derive non-dispersive terms, i.e. the Tropospheric contribution

- Use solutions from `easy' low freq.
- Scale phase by freq ratio

Use primary calibrator for $\phi_{A,INST}$ = stable (cte).

Multi-Frequency Phase Referencing (MFPR)



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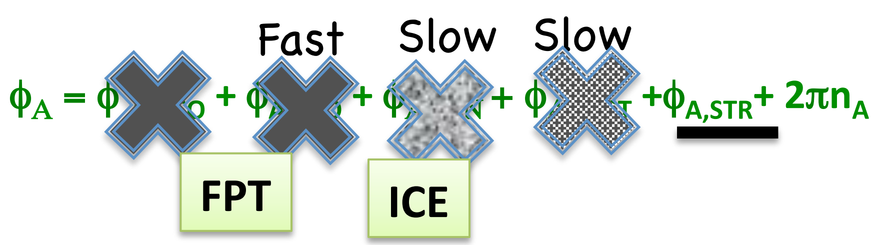

$\phi_{A,ION} = fTEC(\nu) \rightarrow \Delta TEC$

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Blazar "Core Shifts" at mm-wavelengths (Optical Depth, Standing Schocks?)

There are many reasons (particularly the association of gamma ray & radio flares Marscher, Nature '12) to believe that in Blazars there are standing shocks at which the B&K model breaks-down

And these should be revealed at the higher frequencies where conventional PR is not possible.

Blazar "Core Shifts" at mm-wavelengths (Optical Depth, Standing Schocks?)

<u>High precision astrometry at high frequencies</u> could distinguish between both

→ VLBA program of observations of blazars to ellucidate the nature of the radio core in AGNs

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Marscher,

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And these

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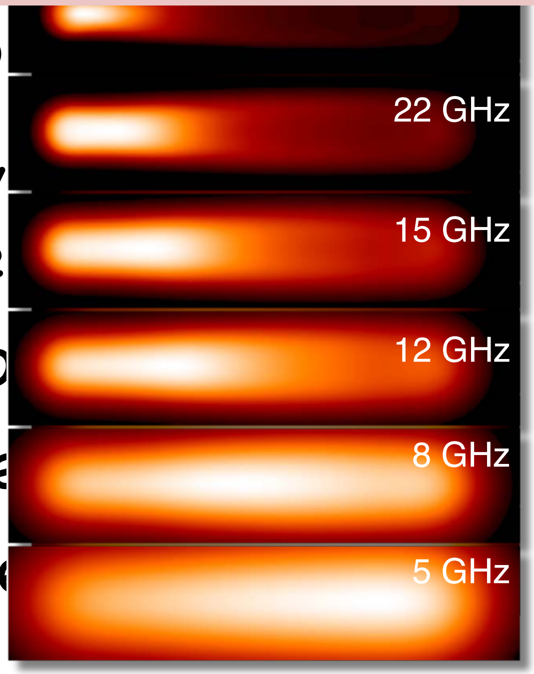
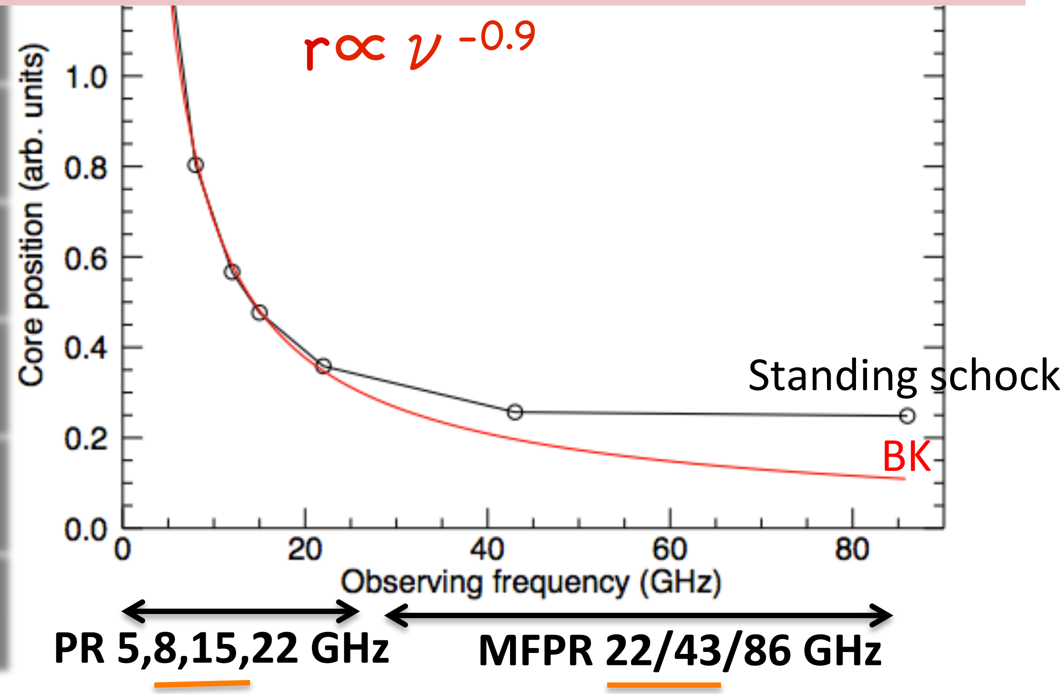




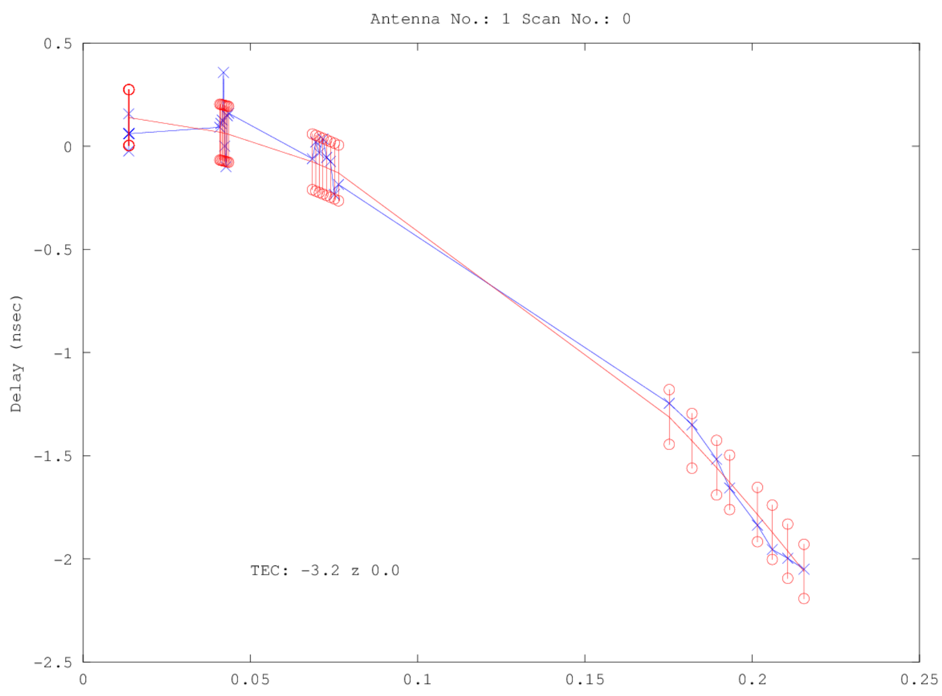
Left: Sync. emission from RMHD models (JLGomez;J.Marti)

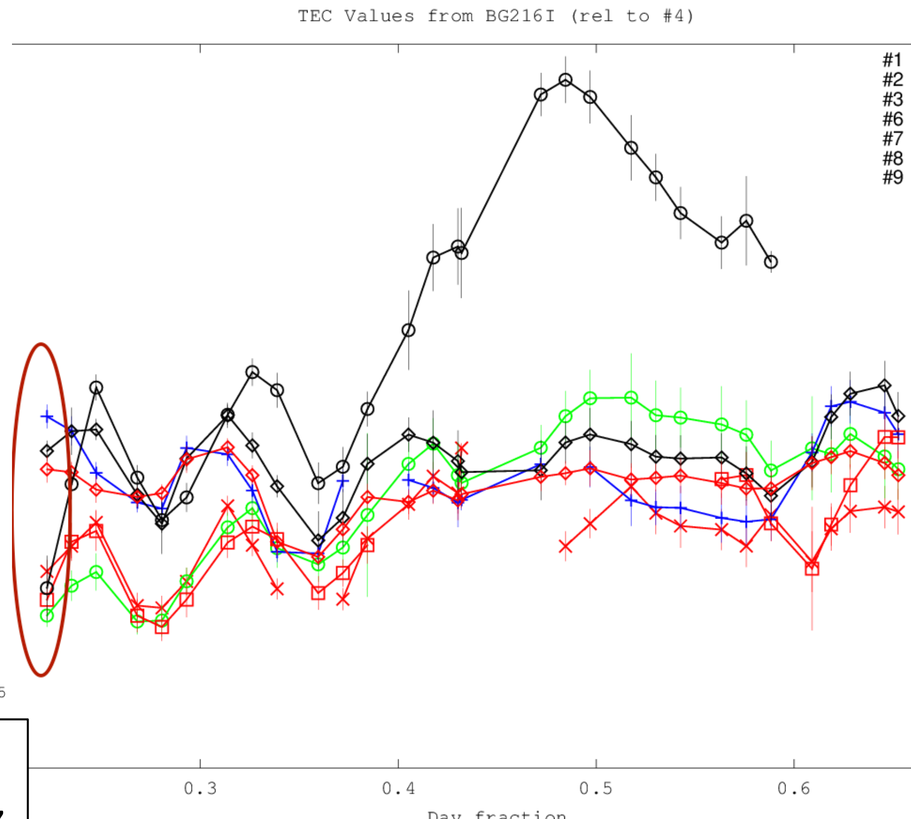
Right: Expected core-shifts for this class of AGN (black) vs BK (red

Experiment BG216I – BL Lac

Solve for delays (per IF) across all frequencies

TEC from $\tau = 1.34\,\Delta TEC\ \nu^{-2} + \Delta l/c$





K band
21.8-22 GHz

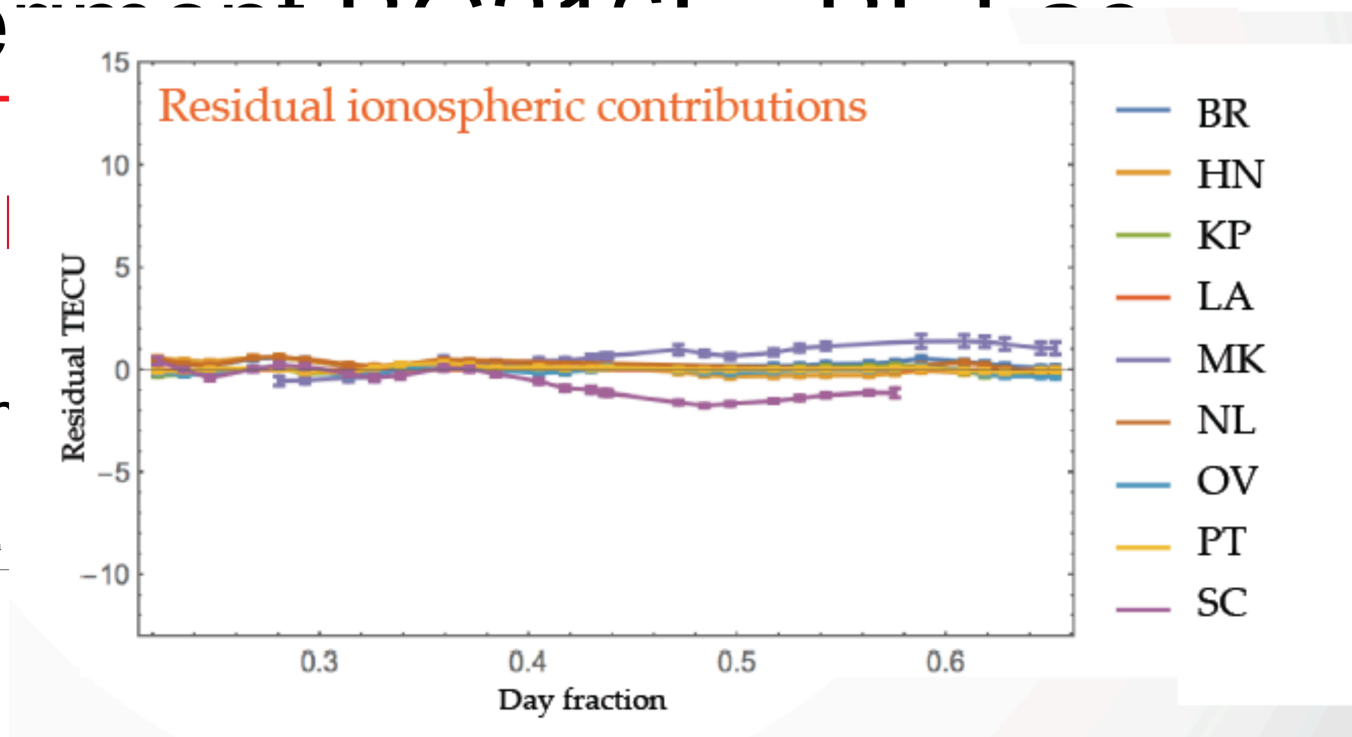
Wide C band
3.9 - 7.9 GHz

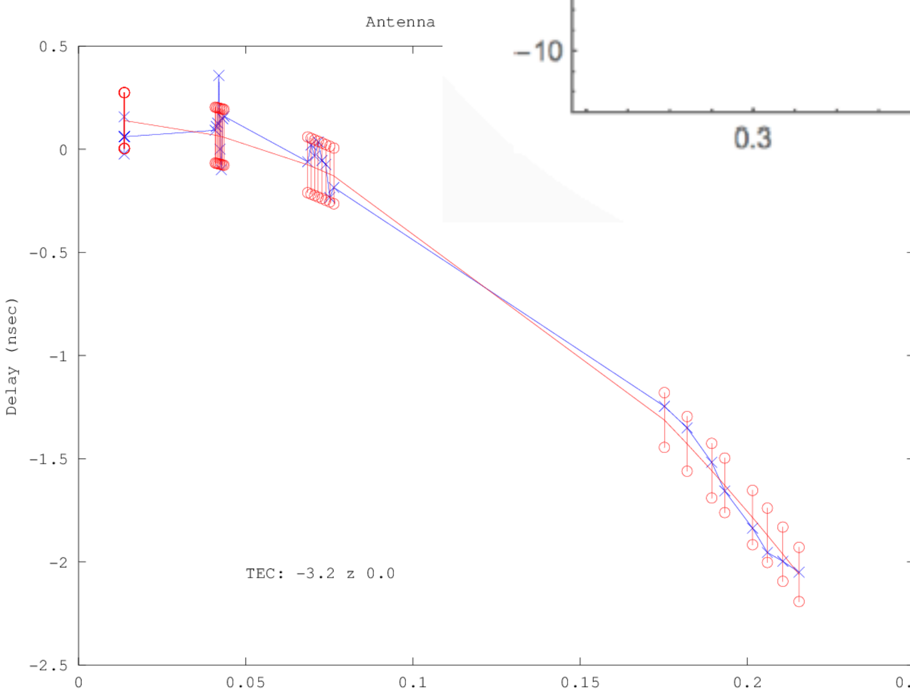
L band
1.4 -1.7 GHz

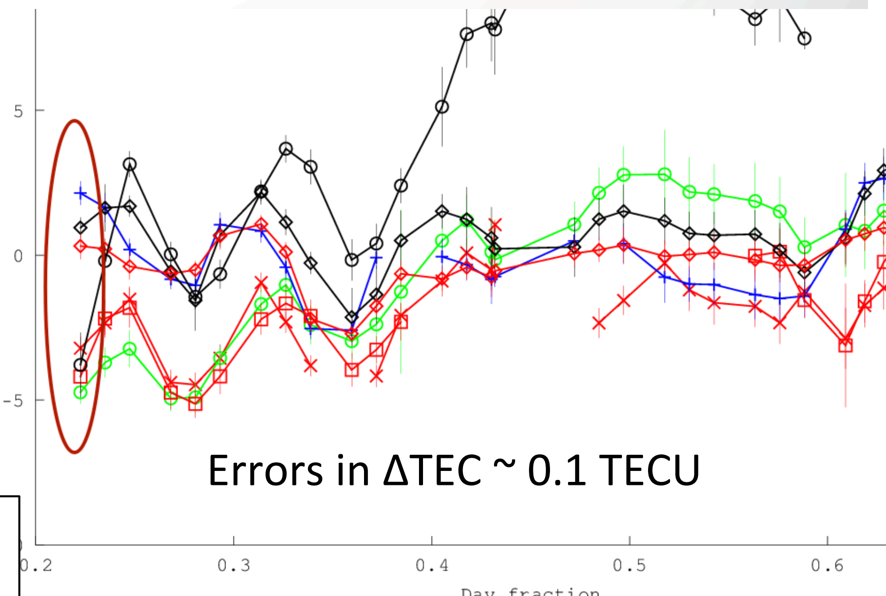
Expe

Solve for de

TEC fror







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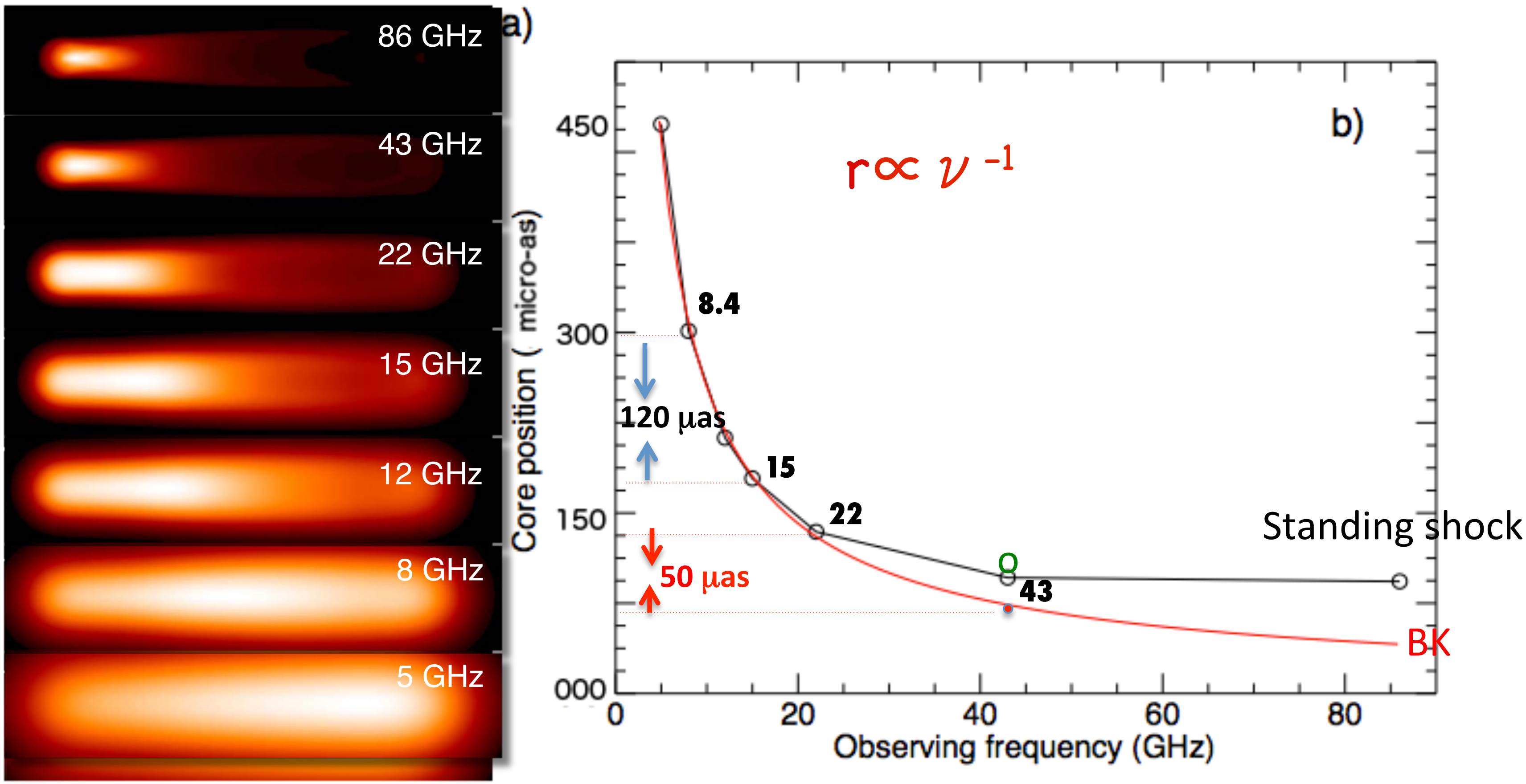
Preliminary Results on BL-Lac

Use cm-results to provide scale. 8.4/15 GHz, 120 μas

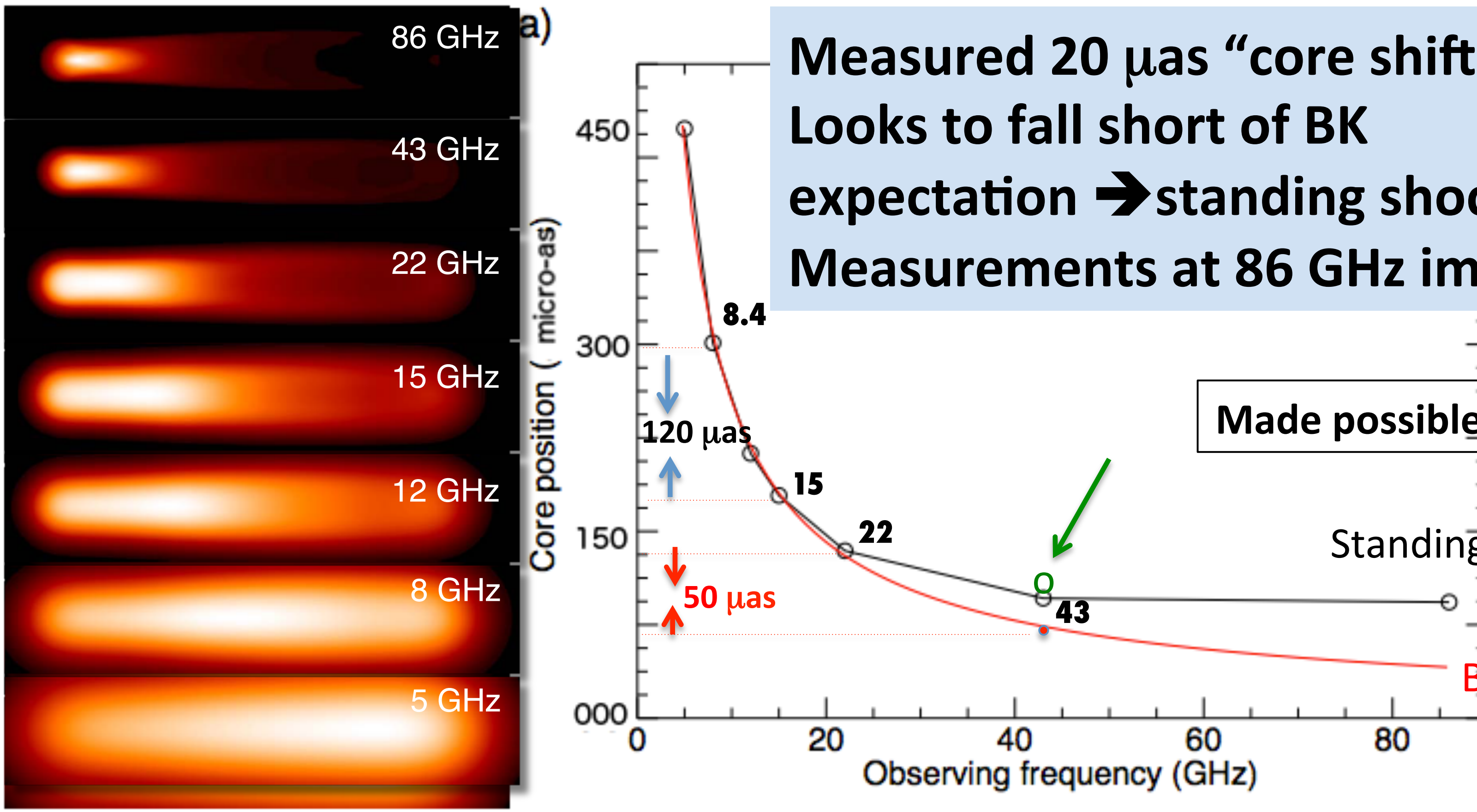


22/43 GHz *BK Predict* : $50^{+}_{-}40$ μas

"core-shift"

Preliminary Results on BL-Lac

Use cm-results to provide scale. 8.4/15 GHz, 120 μas



Measured 20 μas "core shift"
Looks to fall short of BK expectation → standing shock?
Measurements at 86 GHz important

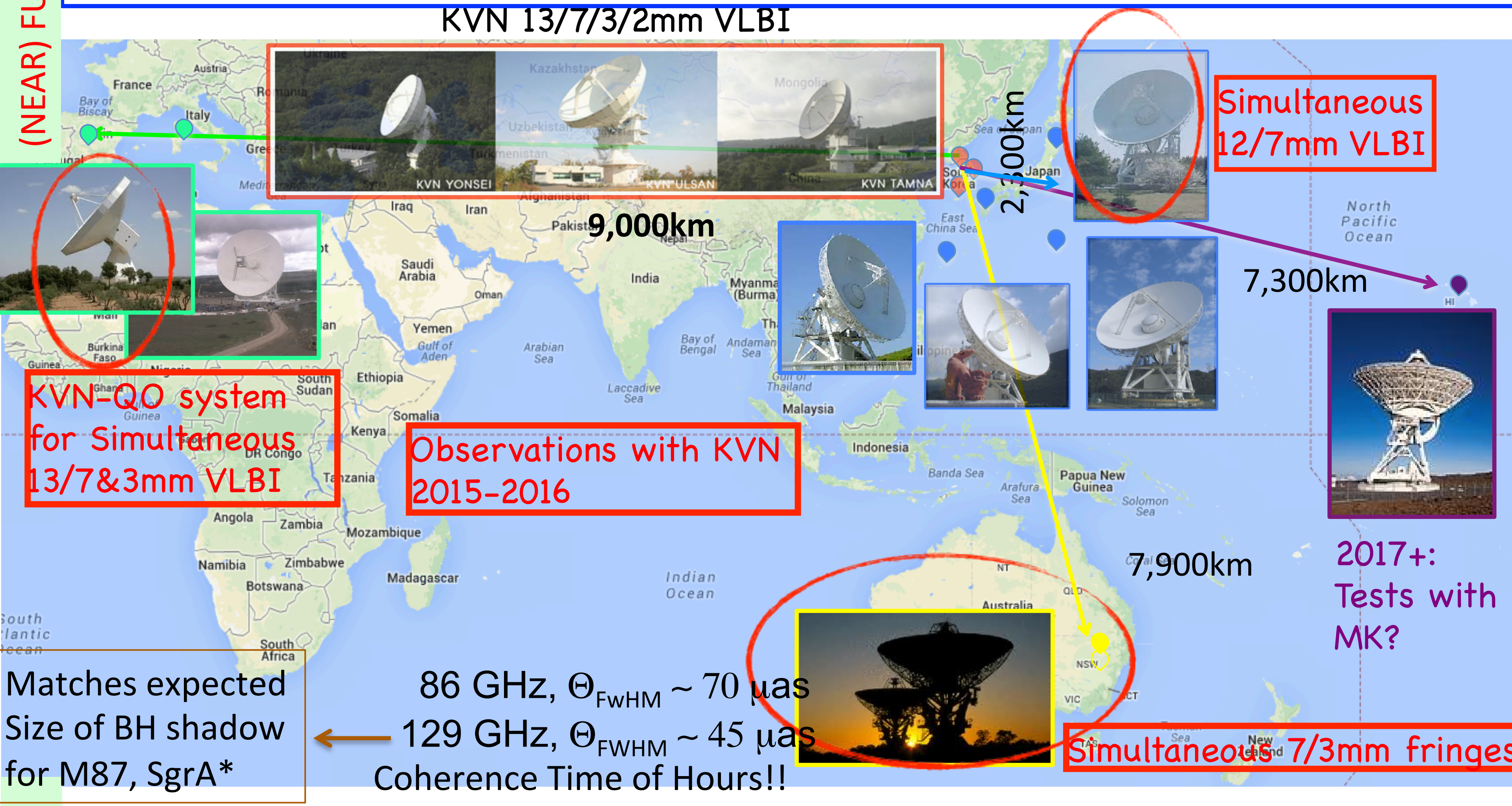
Made possible by MFPR

22/43 GHz "core-shift" *BK Predict* : 50 ± 40 μas *Measured*: 20 ± 6 μas with MFPR

(NEAR) FUTURE

The quest for largEST angular resolution (=highEST astrometric accuracy):

A Global "Multi-Frequency" mm-VLBI array



FUTURE

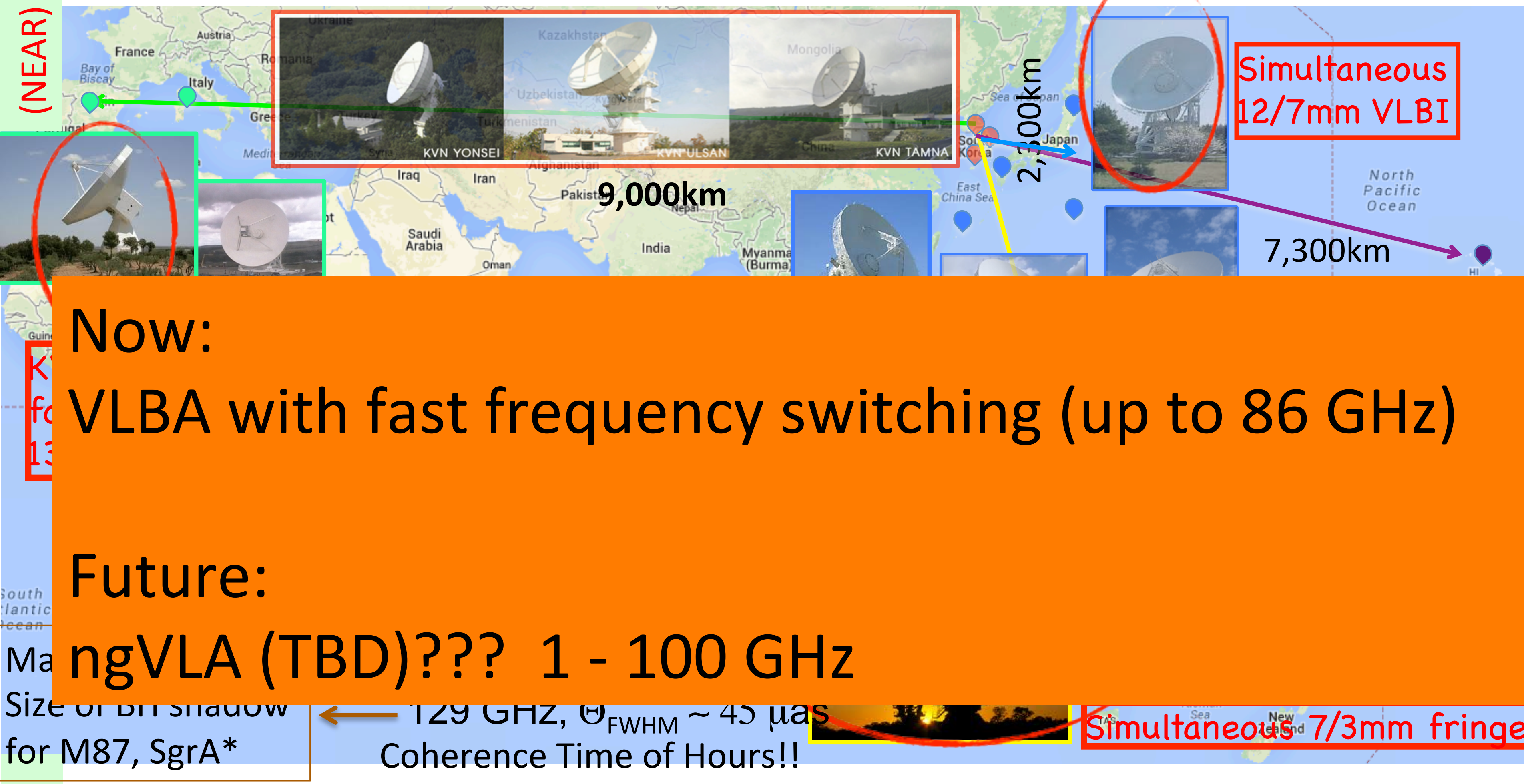
Techniques relevant for ALMA (long baselines)

(NEAR) FUTURE

The quest for largEST angular resolution (=highEST astrometric accuracy):

A Global "Multi-Frequency" mm-VLBI array

KVN 13/7/3/2mm VLBI



Now:

VLBA with fast frequency switching (up to 86 GHz)

Future:

ngVLA (TBD)??? 1 - 100 GHz

FUTURE

Techniques relevant for ALMA (long baselines)

Summary

Potential of multi-frequency observations to improve the performance of mm-VLBI with new capabilities.

SFPR / MFPR enable:

- Superior tropospheric compensation, boost array with increased sensitivity.
- High precision "bona fide" astrometry at (sub-)mm-VLBI
- No upper frequency limit (B2B mode in ALMA at ca. 650 GHz)

Widely applicable, to many sources, enables new applications
Very effective use of observing time with simultaneous multi-freq. observations.
Technology ready, Slow telescope switching / Single source OK

Science made possible by SFPR /MFPR – widen applicability, beyond scope of PR:

SFPR: "Core-shift" VLBA "bona fide" astrometric measurements of M87 at 86-GHz
Spectral Index maps astrometrically aligned up to 130-GHz, for 5 sources

MFPR: "Core-shift" VLBA "bona fide" astrometric measurements of BL Lac at 43-GHz

Coherence time @ 132 GHz extended to 20 minutes (FPT) and > 8 hours (SFPR)

END