International
Centre for
Radio
Astronomy
Research

High Accuracy Astrometry
&
New Methods with New Instruments

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ICRAR (Australia), OAN (Spain)

Curtin University

THE GOVERNMENT OF WESTERN AUSTRALIA

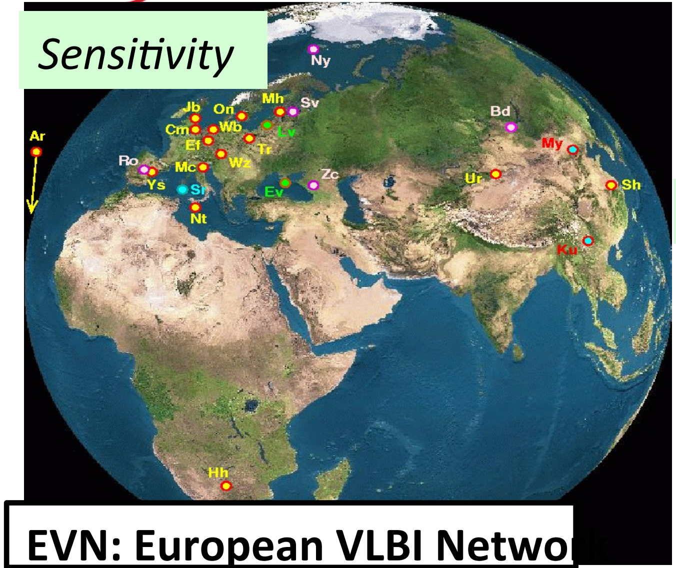
THE UNIVERSITY OF
WESTERN AUSTRALIA

Overview

- How and when does one get high accuracy (~ μas) astrometry?
- Sample of Astrophysical Applications of precise astrometry in a variety of fields
- Alternative Calibration Methods to open a new window into astrometry
- Astrometry with the Korean VLBI Network (KVN) up to 132 GHz.

VLBI NETWORKS

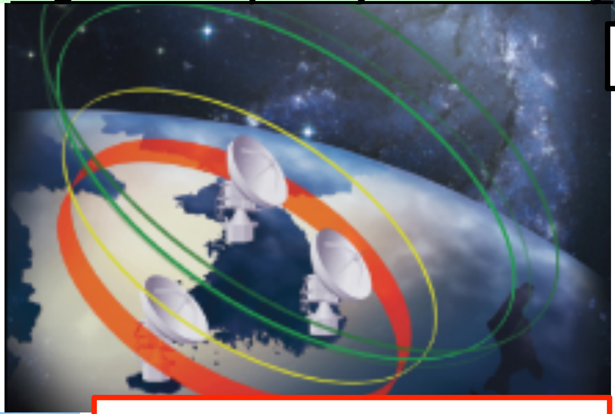
Sensitivity



EVN: European VLBI Network

<~ 22GHz

Highest Frequency Astrometry



KVN Korean VLBI Network

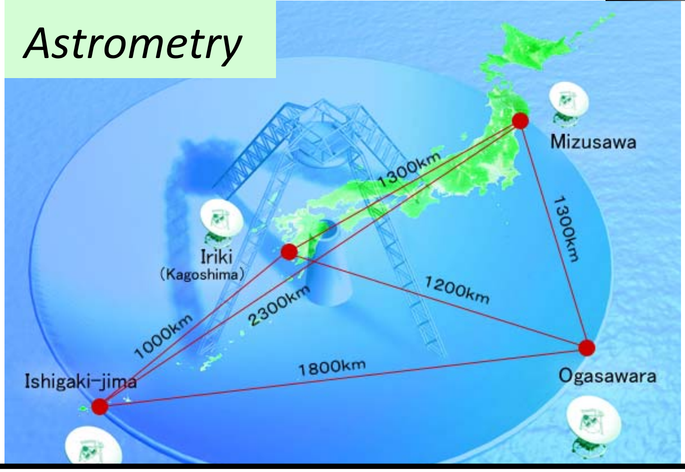
22/43/86/129 GHz

General Purpose

VLBA Very Long Baseline Array

<~ 86GHz

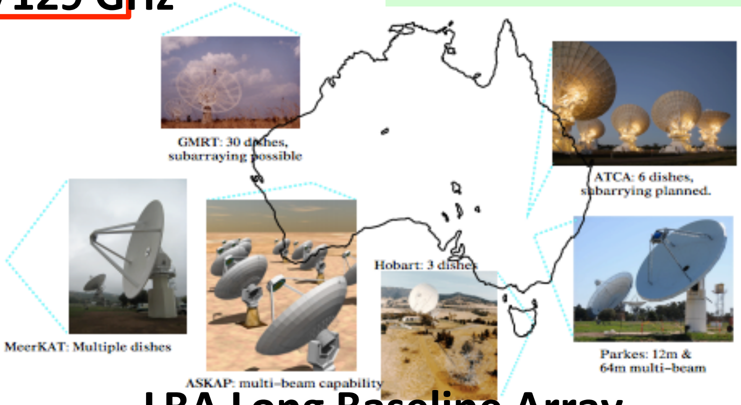
Astrometry



VERA VLBI for Earth Rotation and Astrometry

22/43 GHz

Southern Hemisphere

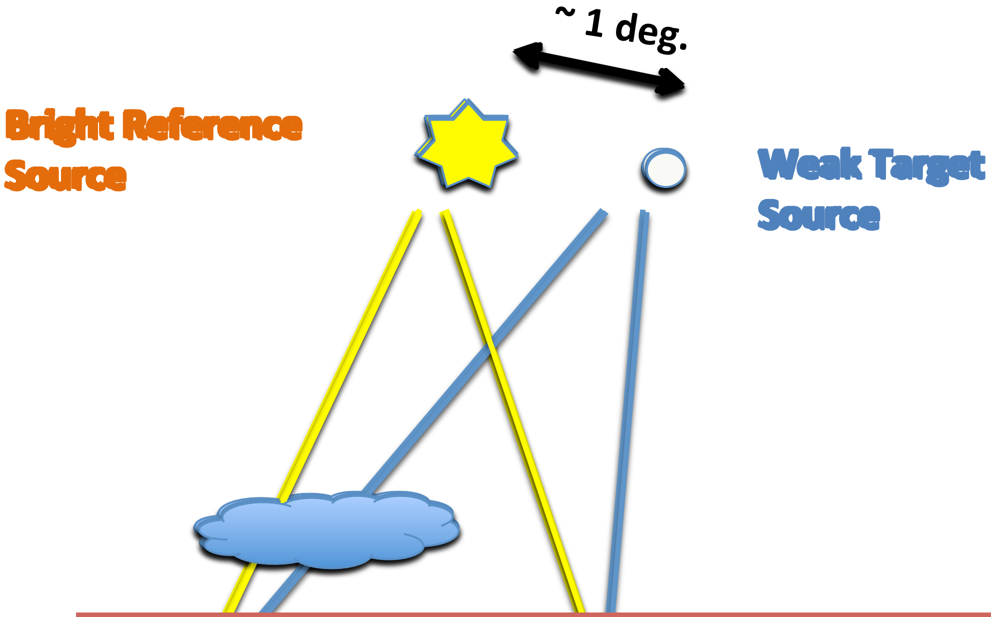


LBA Long Baseline Array

<~ 22GHz

ASTROMETRY with Phase Referencing

@ 22 GHz



AIM: Isolate geometric signature in interferometric phase

STRATEGY:

Use analysis of interleaving Observations of reference source as a GUIDANCE to calibrate out non-geometri contributions in target observations.

Ways to get accurate (μas) astrometry:

1) **Closer calibrator, to compensate for differential residual errors in "a priori" models.**
2) **Improve "a priori" models.**

CURRENT BEST PRACTISE

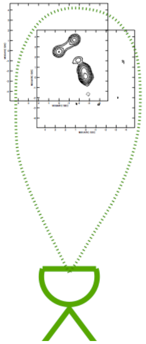
1)Very Close Calibrator

2) Improve "a priori" model

"in-beam"→ **Limited Application**

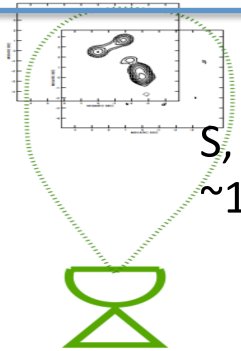
Error **Obs. Freq**

TROP Moderate Freq.



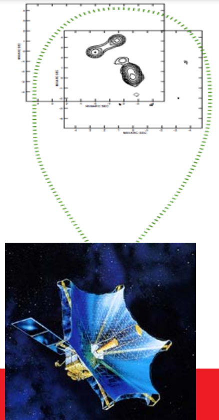
Ang. Sep. 33"
Dilution factor 10^{-4}
~10 micro-as

ION Low Freq.



S, L-band
~100 micro-as

Orbit Space VLBI



VSOP @ L-band: 14', 33",
Guirado et al 2001
Porcas&Rioja 2000

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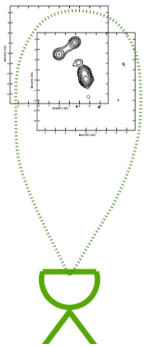
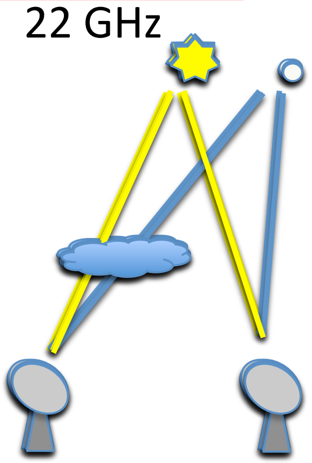


"ATC"→ **Wider Application**



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Advanced
Tropospheric
Calibration
Reid & Brunthaler 2004
Honma et al. 2008

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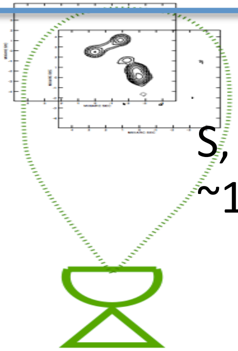

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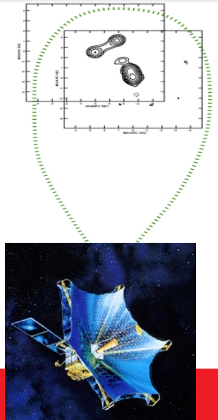

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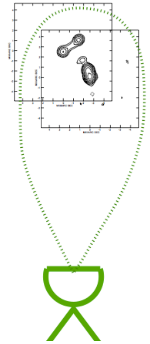

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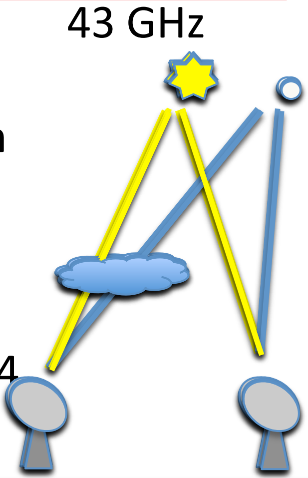

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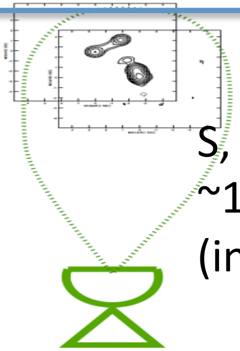
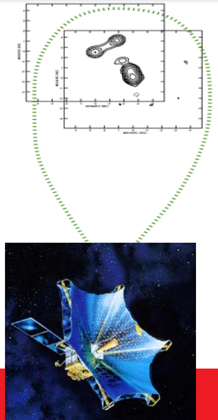


S, L-band
~100 micro-as
(in talk)

Orbit Space VLBI



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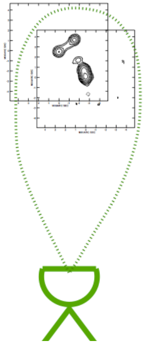

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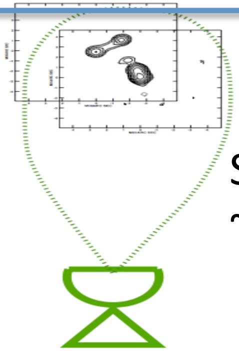

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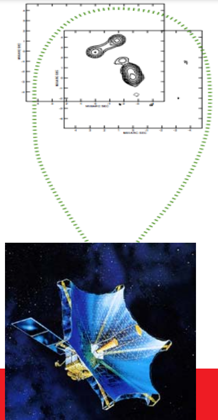
Orbit Space VLBI



VSOP @ L-band: 14', 33",
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"ATC"→ **Wider Application**

Advanced
Tropospheric
Calibration
Reid & Brunthaler 2004
Honma et al. 2008

Ang. Sep:
2-1 deg
Freq range:
5-43 GHz
~10 micro-as
1 @86 GHz

Just for fun….

Looking at references in Reid & Honma, Annu. Rev. Astron. Astrophysics, 2014

Time Interval	# Pub.	# Pub./year
-- 1990	24	
1991 – 2000	24	2.4 / year
2001 --2010	99	9.9 / year
2001 -2005	26	5.2 / year
2006 -2010	73	14.6 / year
2011 – 2013	63	21 / year

Annual Trigonometric Parallax, π

π (mas) = 1 / D (Kpc); 10 Kpc away, Parallax 0.1 mas

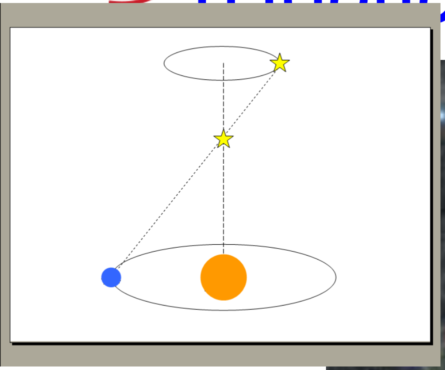
PARALLAX DISTANCE IS THE “GOLDEN STANDARD” OF DISTANCES.

Direct and geometric method, with no assumptions about luminosity, extinction, metallicity, crowding, etc.

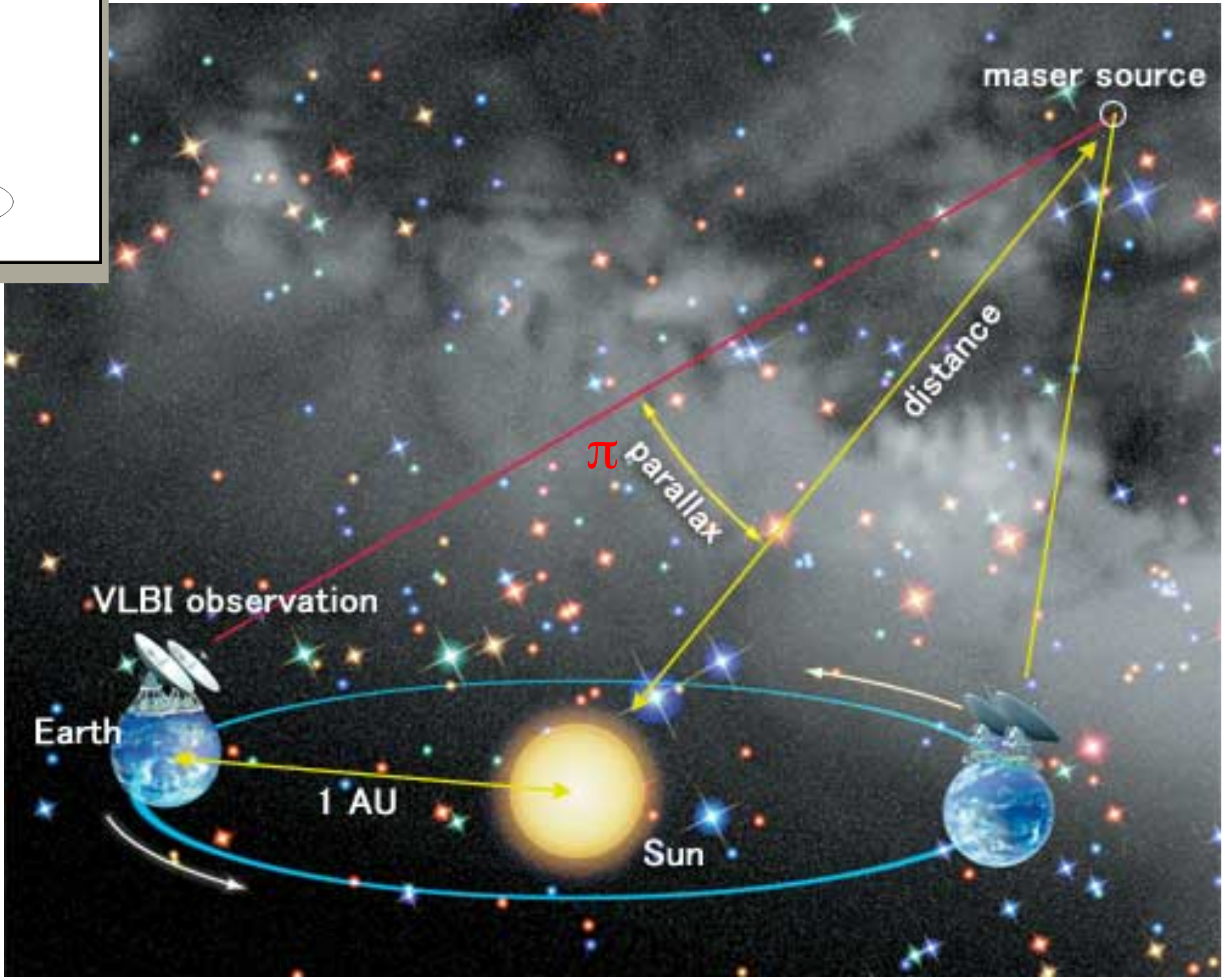
Major Key Science Projects for VERA and VLBA (BeSSeL survey)

3D Galactic Structure and Kinematics

Trigonometric Parallax – Measure Distances



Source parallax



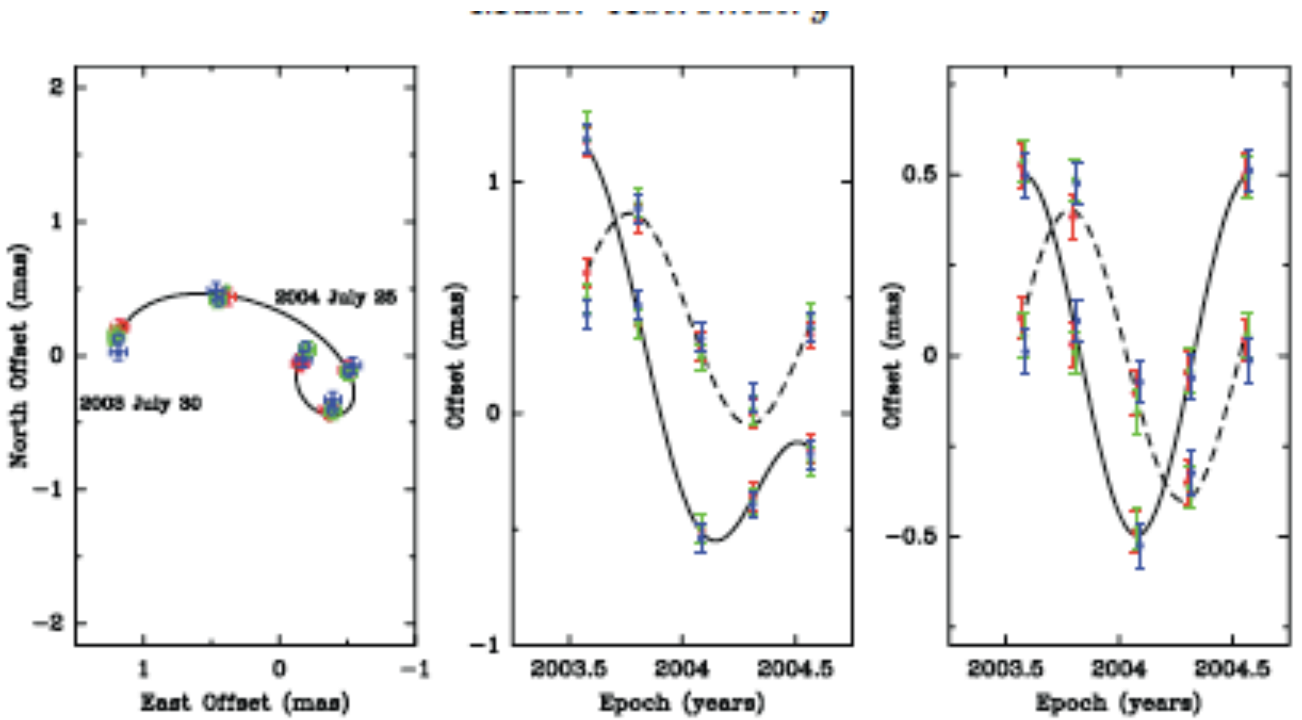
π (mas) = 1 / D (Kpc); 10 Kpc away, Parallax 0.1mas

Parallax Measurement for W3(OH)

Optical Photometric Distance 2.2 Kpc
Kinematic Distance 4.3 Kpc

π = 0.512 ± 0.010 mas ➔ D = 1.95 ± 0.04 Kpc , CH_3OH masers, VLBA, Xu et al. 2006

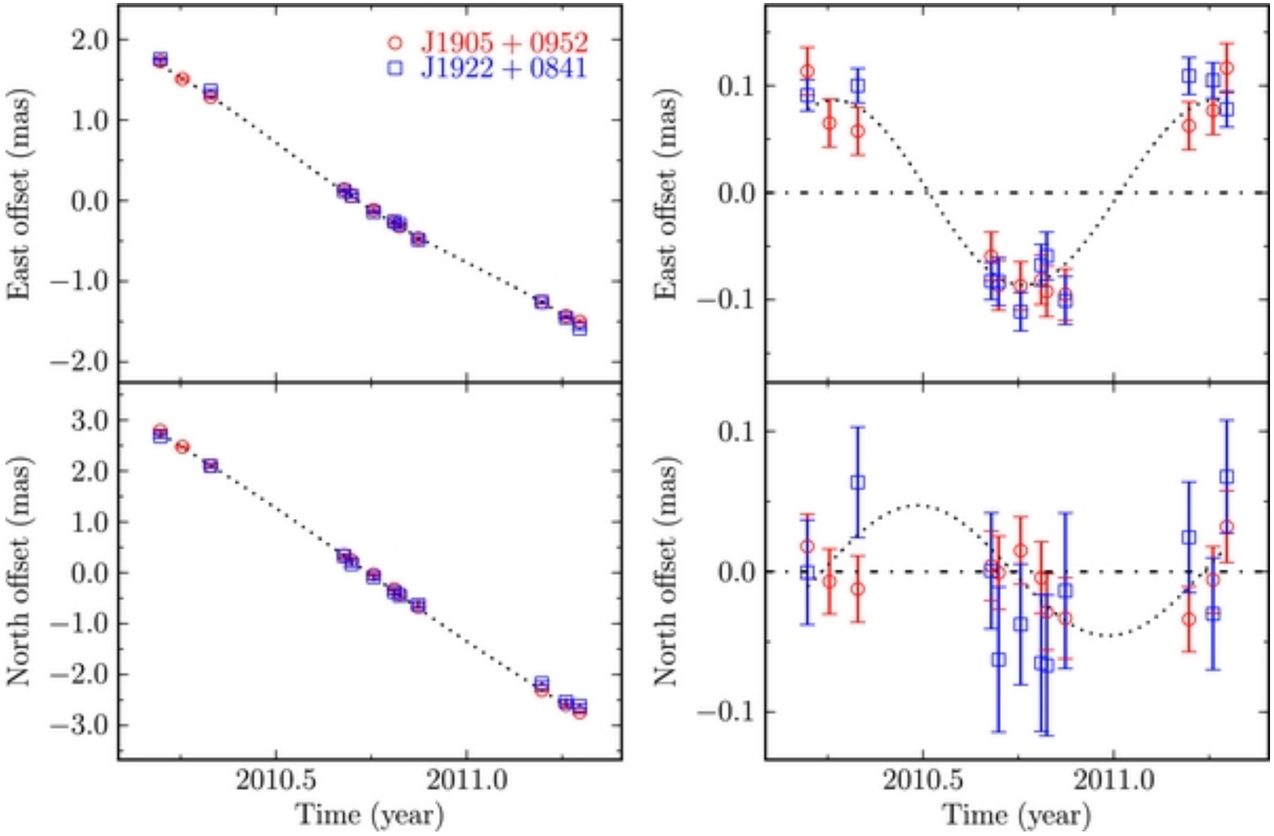
H2O masers, Hachisuka et al. 2006



Using Least Squares minimization estimate the standard 5 astrometric parameters: 1 Parallax, 2 position, 2 proper motions

W 49N – record distance

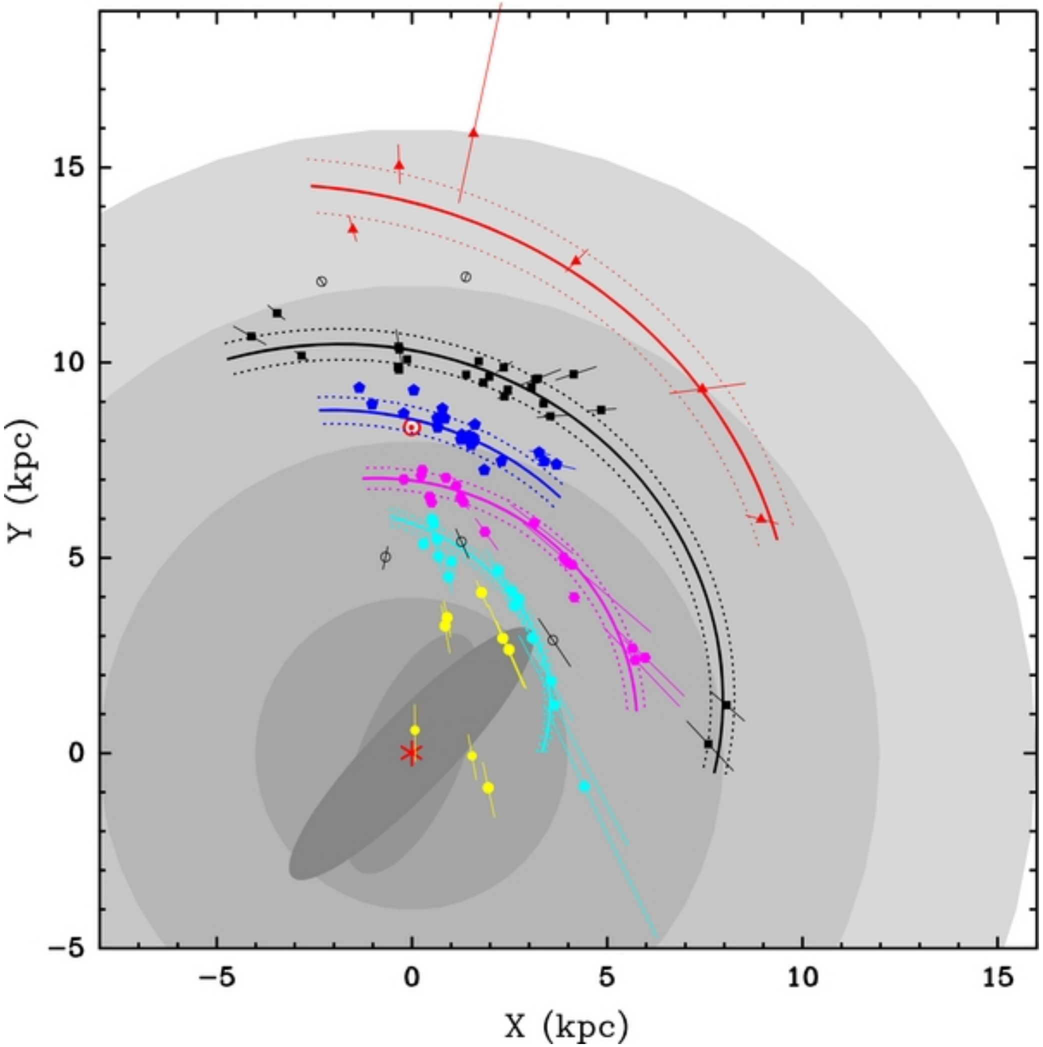
D = 11.1 ± 0.8 Kpc, H_2O masers, VLBA



Distant Star Forming Regions in the Perseus Spiral Arm (Zhang et al. 2013)

Galactic Structure

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

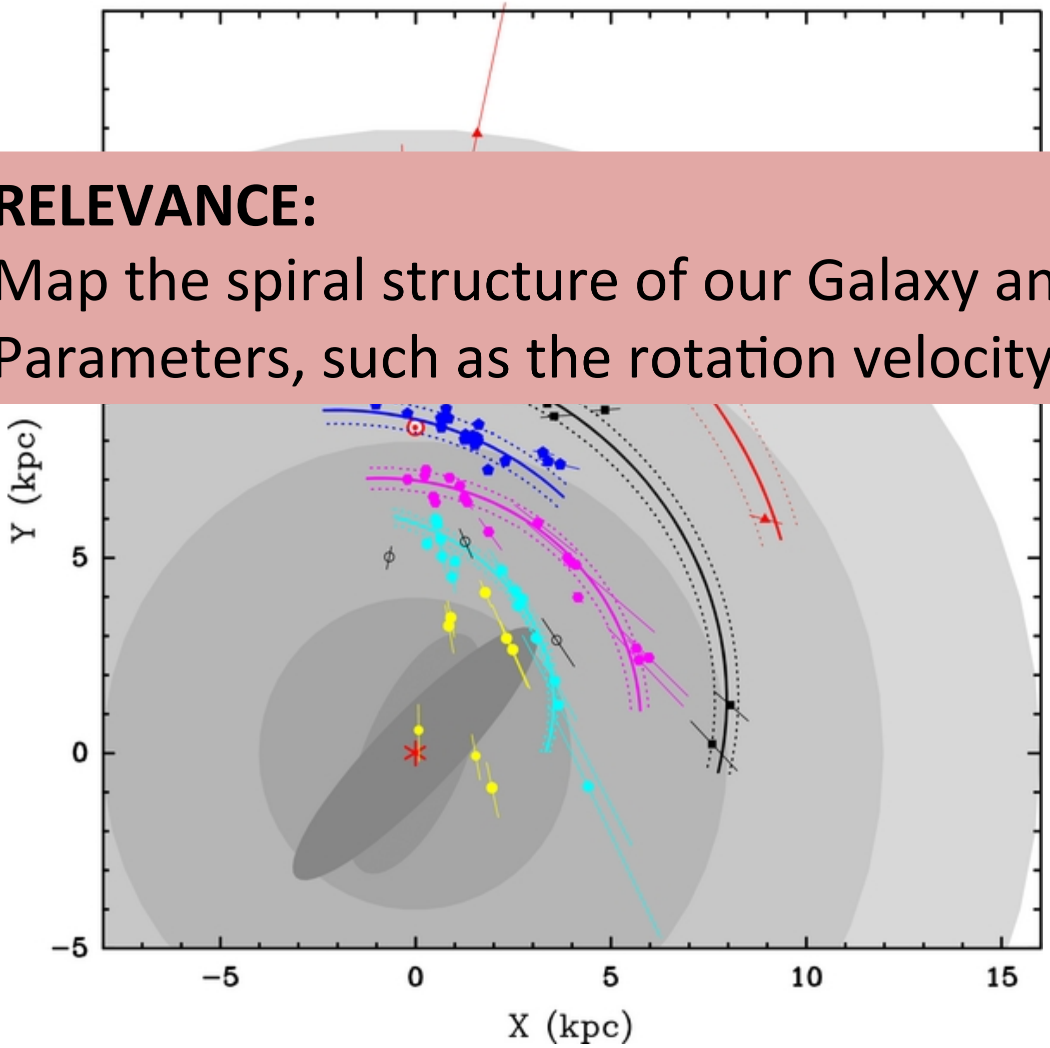


Reid et al 2009
Honma et al 2012
Reid et al 2014

➔ Honma's talk tomorrow

Galactic Structure

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

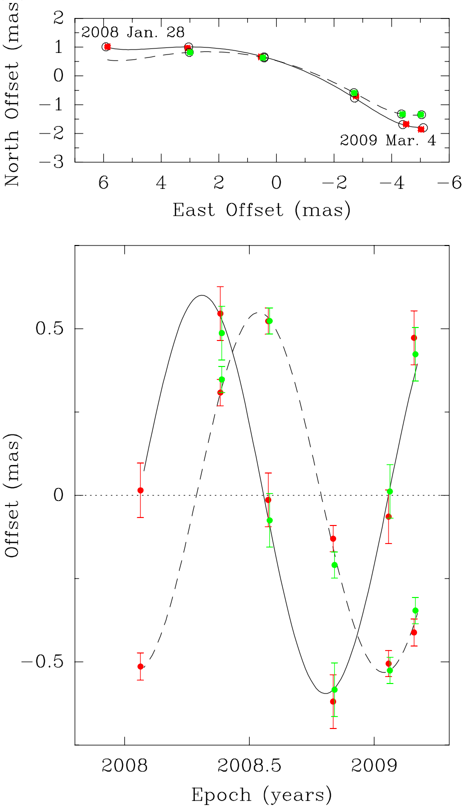


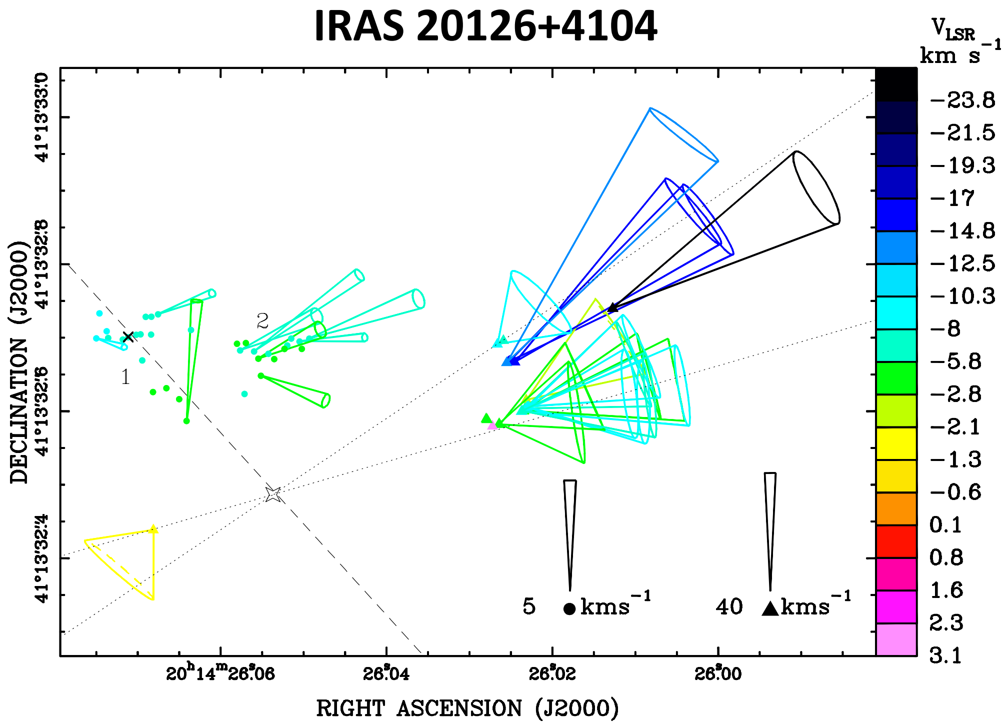
RELEVANCE:
Map the spiral structure of our Galaxy and to determine fundamental Parameters, such as the rotation velocity and distance to the GC.

Reid et al 2009
Honma et al 2012
Reid et al 2014

➔ Honma's talk tomorrow

High Mass Proto Stars – Outflow/Disk



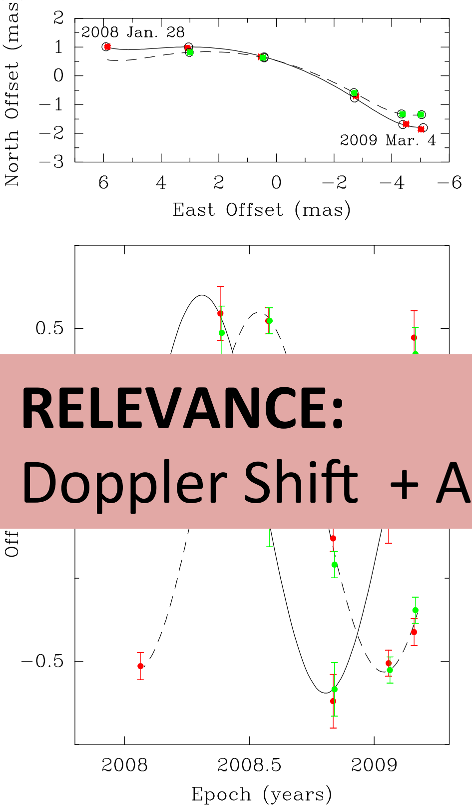


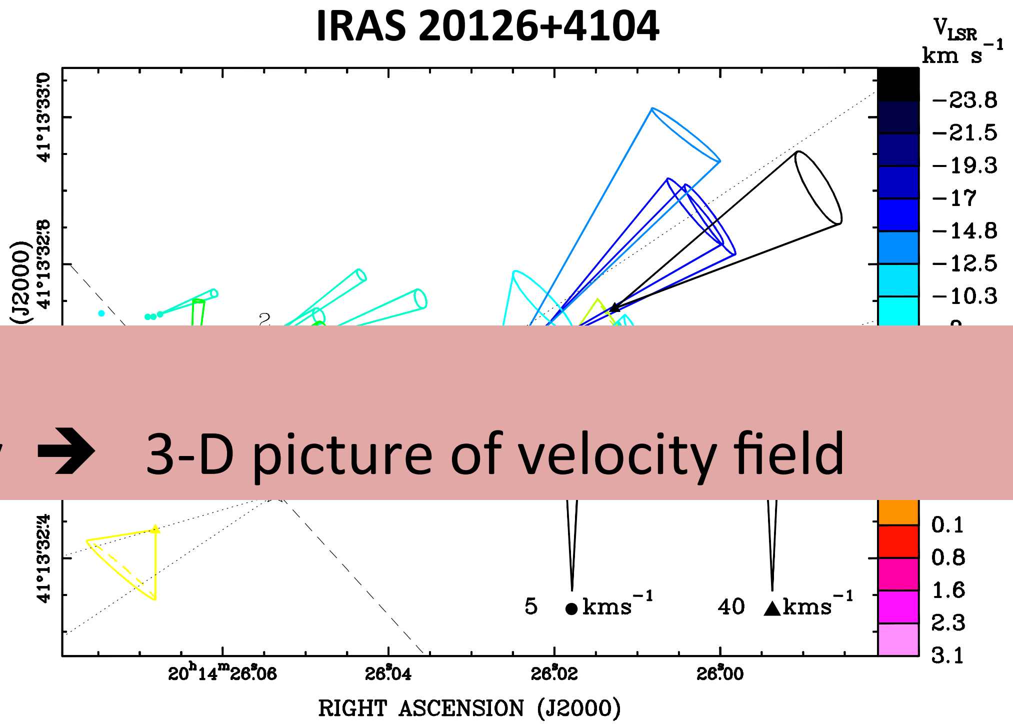
Moscadelli et al. 2011

D = 1.64±0.05 Kpc, H_2O masers (jet)/CH_3OH (disk), VLBA/EVN

Parallax, attemp to measure/separate jet motion from star motion using CH_3OH (disk) and H_2O masers (outflow)

High Mass Proto Stars – Outflow/Disk





RELEVANCE:

Doppler Shift + Astrometry ➔ 3-D picture of velocity field

Moscadelli et al. 2011

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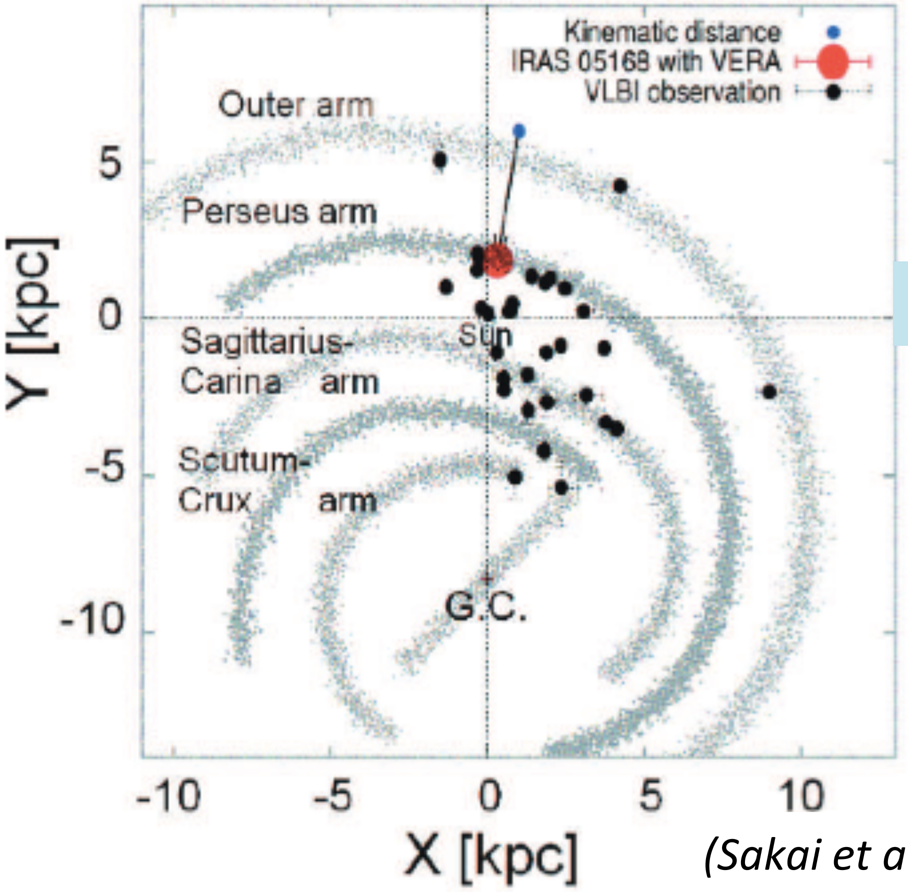
Parallax, attemp to measure/separate jet motion from star motion using CH_3OH (disk) and H_2O masers (outflow)

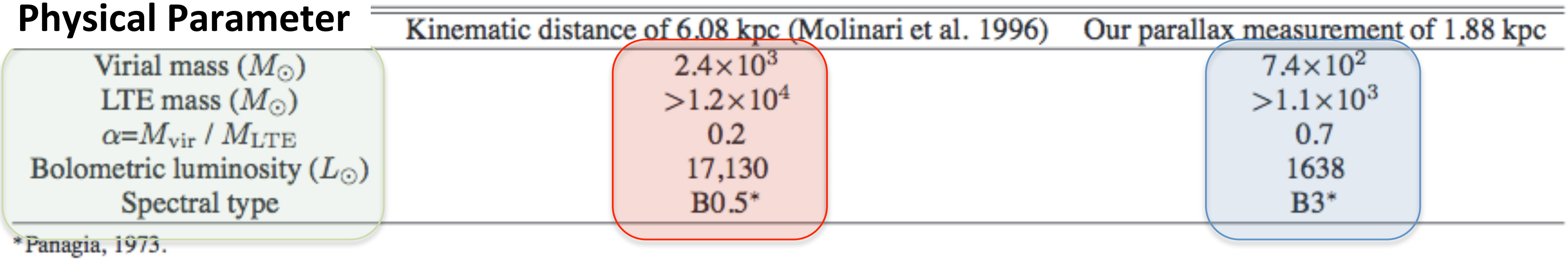
REVISING DISTANCES



Kinematic Distance 6.08 Kpc

VLBI Trigonometric Parallax 1.88 ±0.2 Kpc

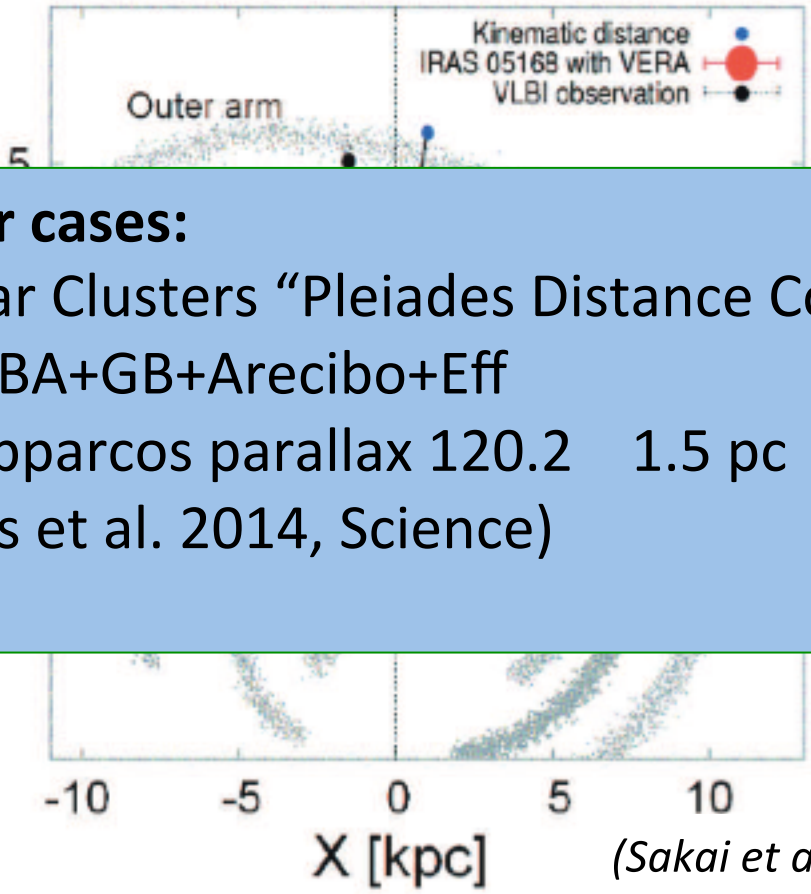
(Sakai et al, 2012, VERA H_2O Masers)



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 ($M_\odot$)	$>1.2\times10^4$	$>1.1\times10^3$
$\alpha = M_{\rm vir} / M_{\rm LTE}$	0.2	0.7
Bolometric luminosity ($L_\odot$)	17,130	1638
Spectral type	B0.5*	B3*

*Panagia, 1973.

REVISING DISTANCES

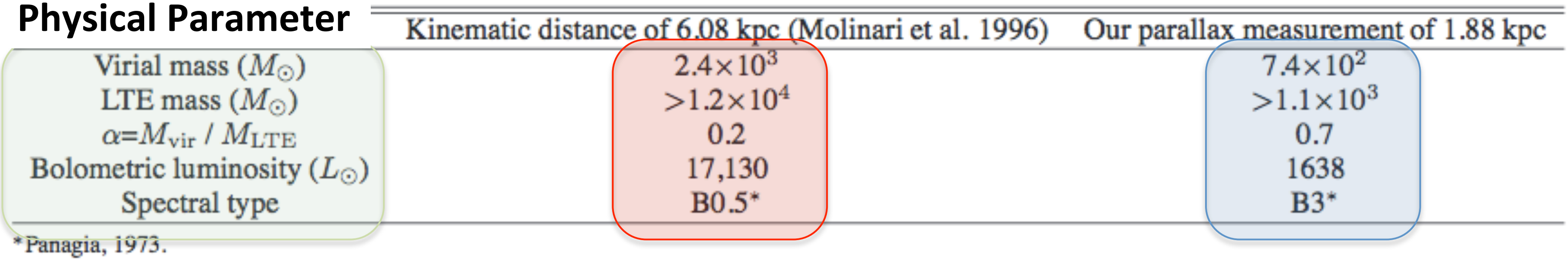


Other cases:

- 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)

(Sakai et al, 2012, VERA H_2O Masers)



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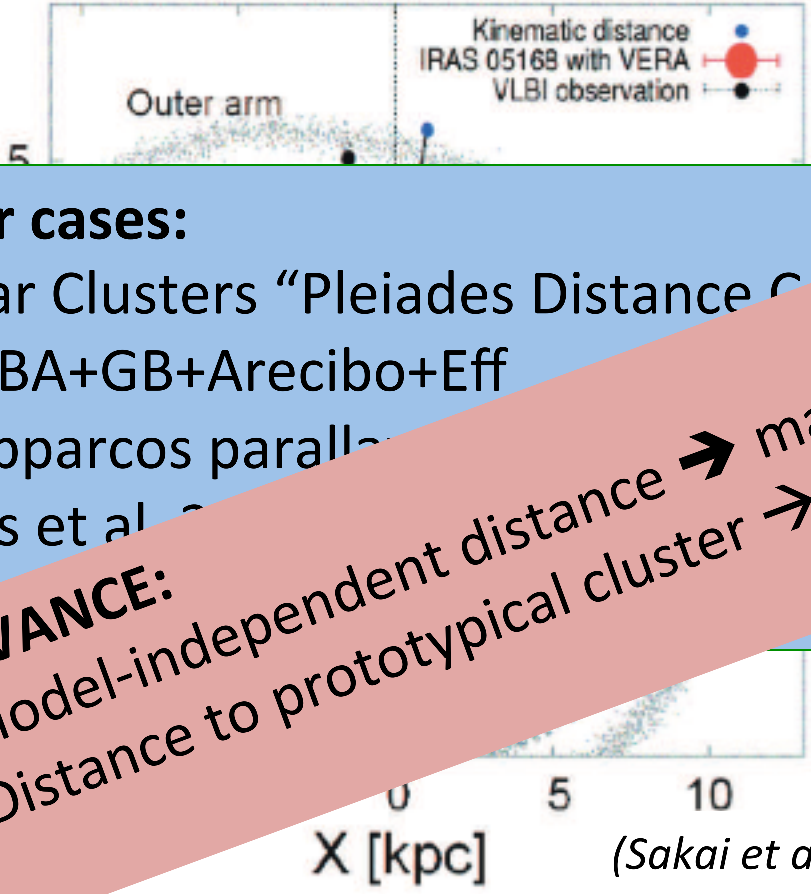

(Sakai et al, 2012, VERA H_2O Masers)

Other cases:

- Star Clusters “Pleiades Distance C
  VLBA+GB+Arecibo+Eff
  Hipparcos paralla
  lax 133.5 ± 1.2 pc
(Melis et al. 2

RELEVANCE:

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

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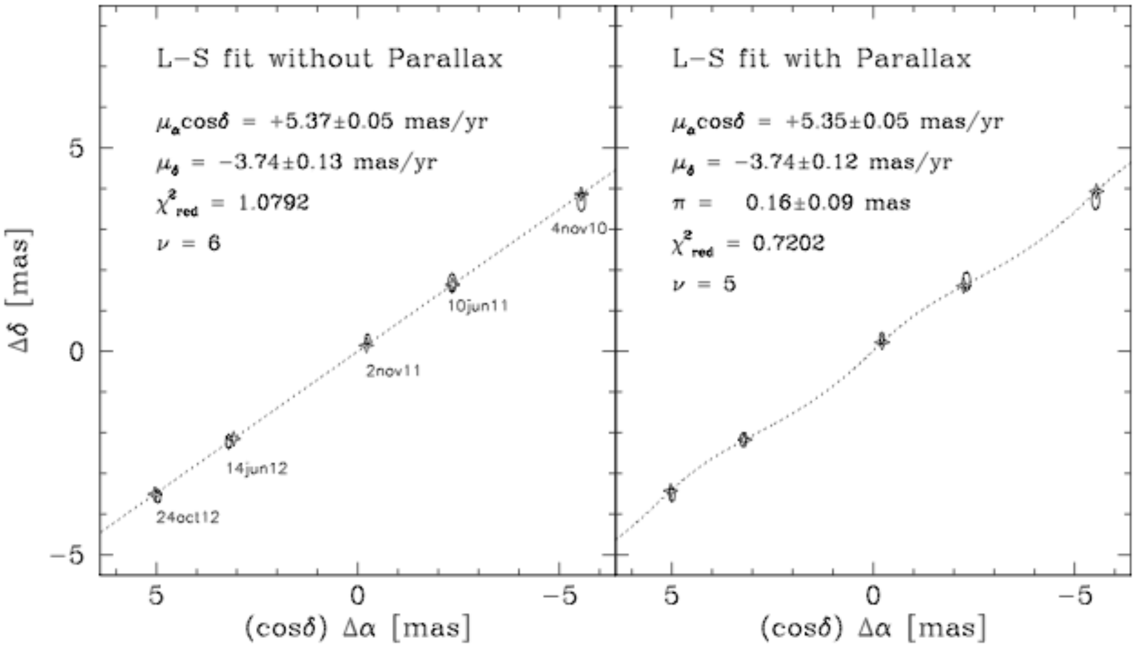
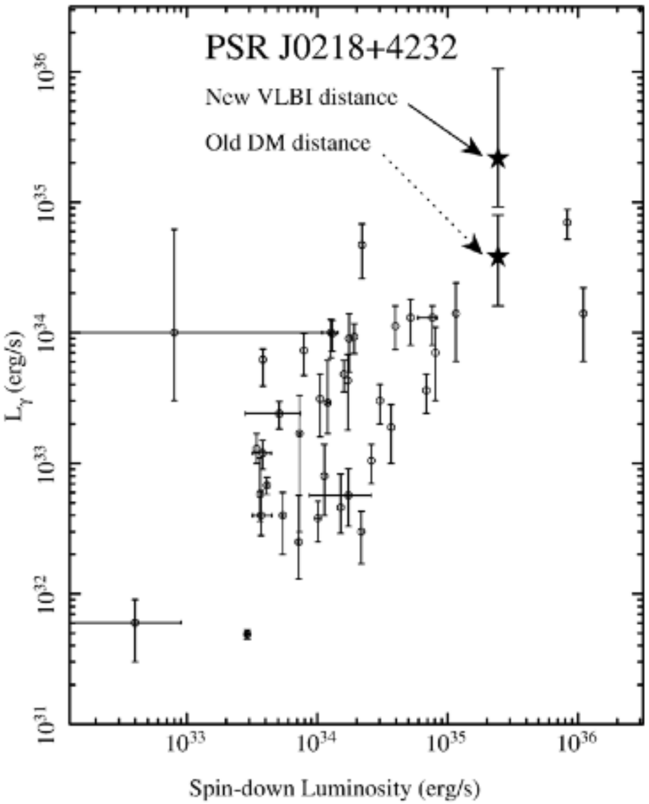
PULSARS @ L-BAND

J0218+4232 First trigonometric parallax pulsar based solely on EVN observations.



(Du et al. 2014)



DM Distance: 5.75 kpc – 2.7 kpc

$D = 6.3_{-2.3\text{Kpc}}^{+8.0\text{ Kpc}}$

$\mu_{\text{Tot}} = 6.53 \pm 0.08 \text{ mas yr}^{-1} = 195^{+249}_{-71} \text{ km s}^{-1}$

Most energetic γ –ray MSP known to date.

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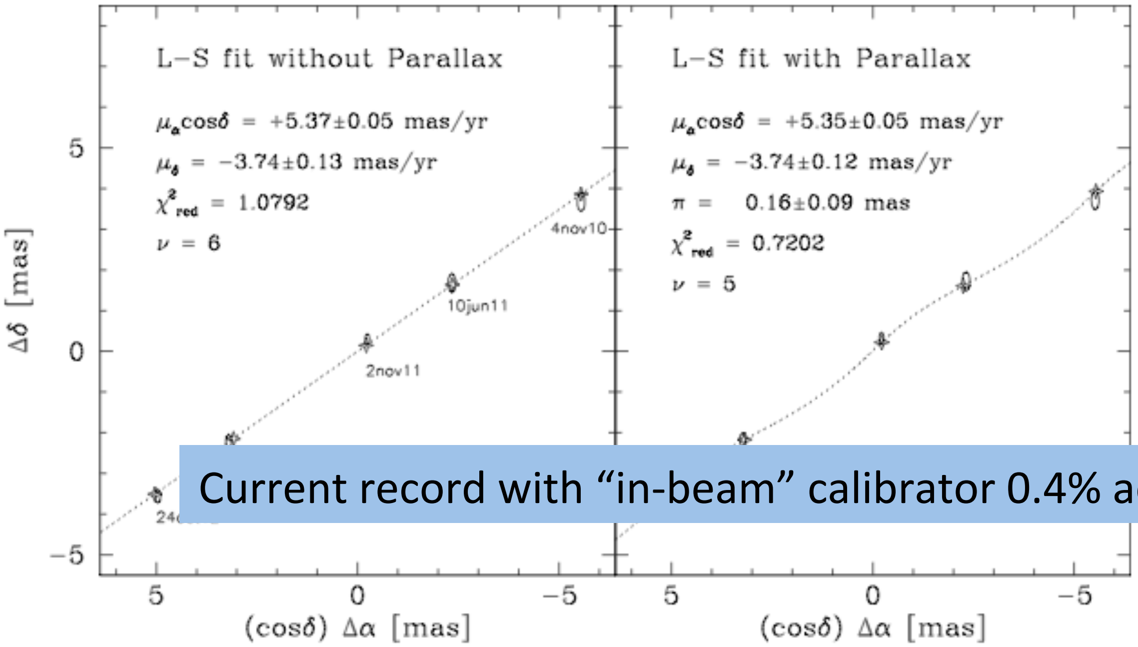

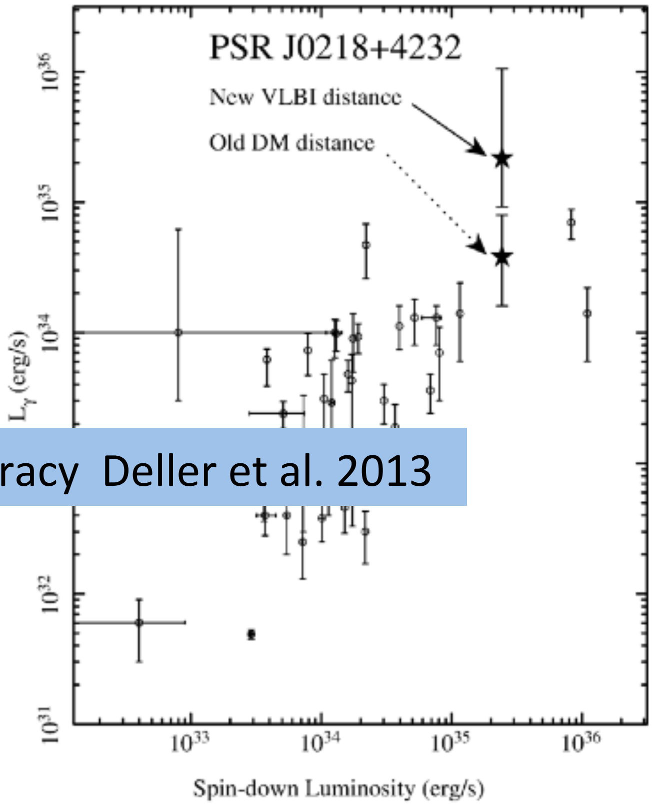

Current record with “in-beam” calibrator 0.4% accuracy Deller et al. 2013

(Du et al. 2014)

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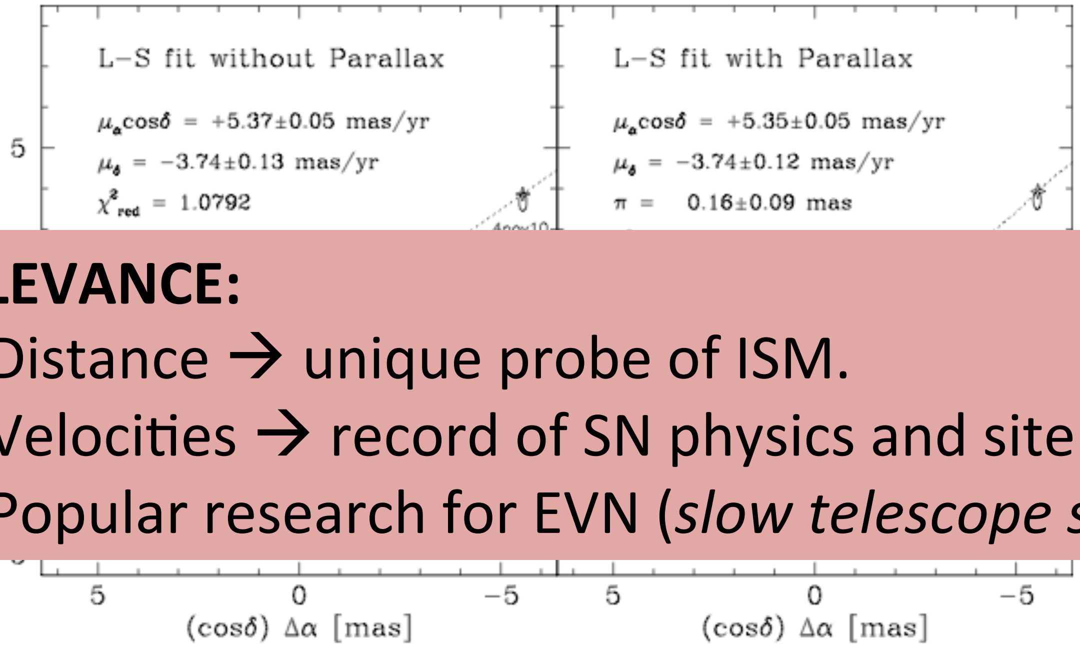

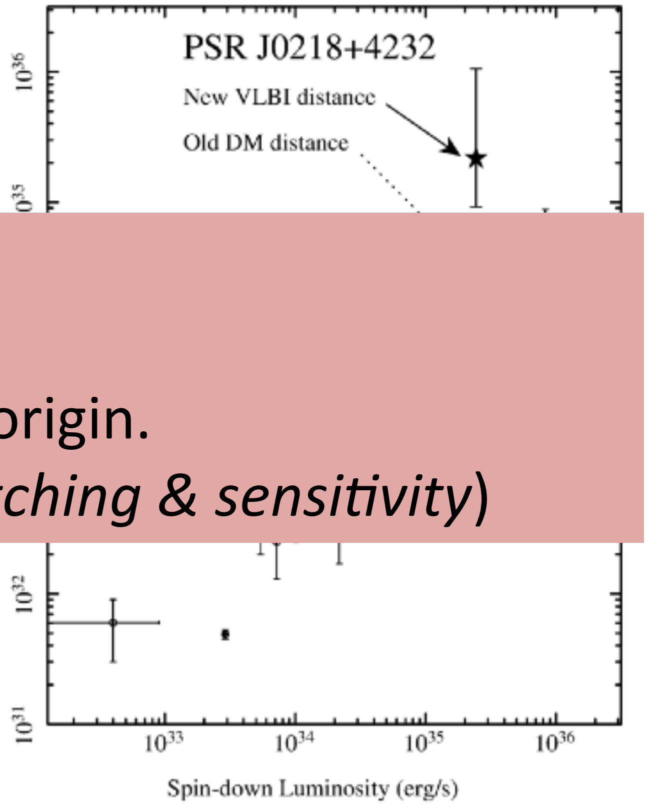

RELEVANCE:

Distance → unique probe of ISM.

Velocities → record of SN physics and site of origin.

Popular research for EVN (*slow telescope switching & sensitivity*)

(Du et al. 2014)

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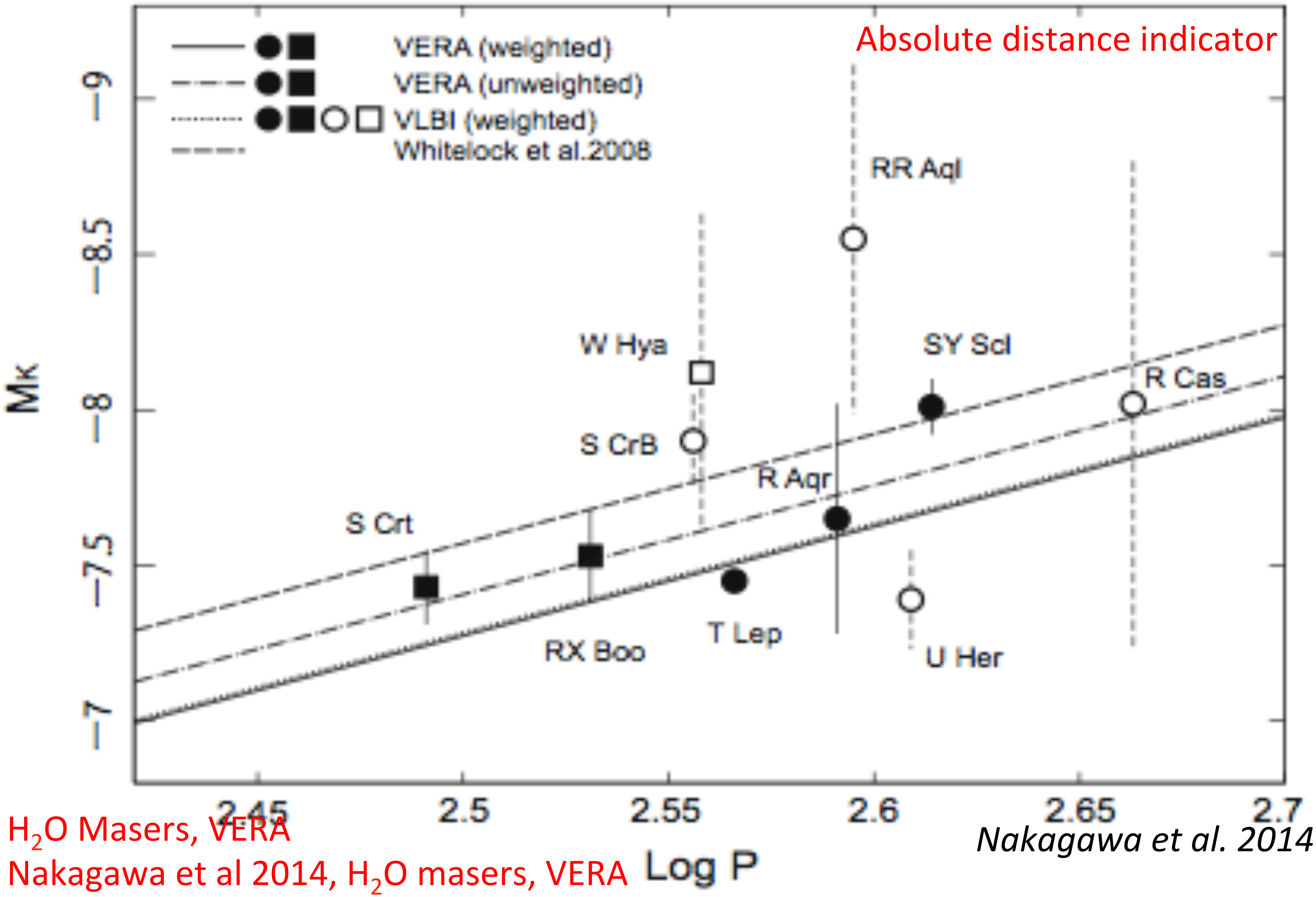
Mira-Variables - Period-Luminosity relation



Absolute distance indicator

Nakagawa et al. 2014

H_2O Masers, VERA
Nakagawa et al 2014, H_2O masers, VERA
OH Masers,
Vlemmings & van Langevelde, 2007

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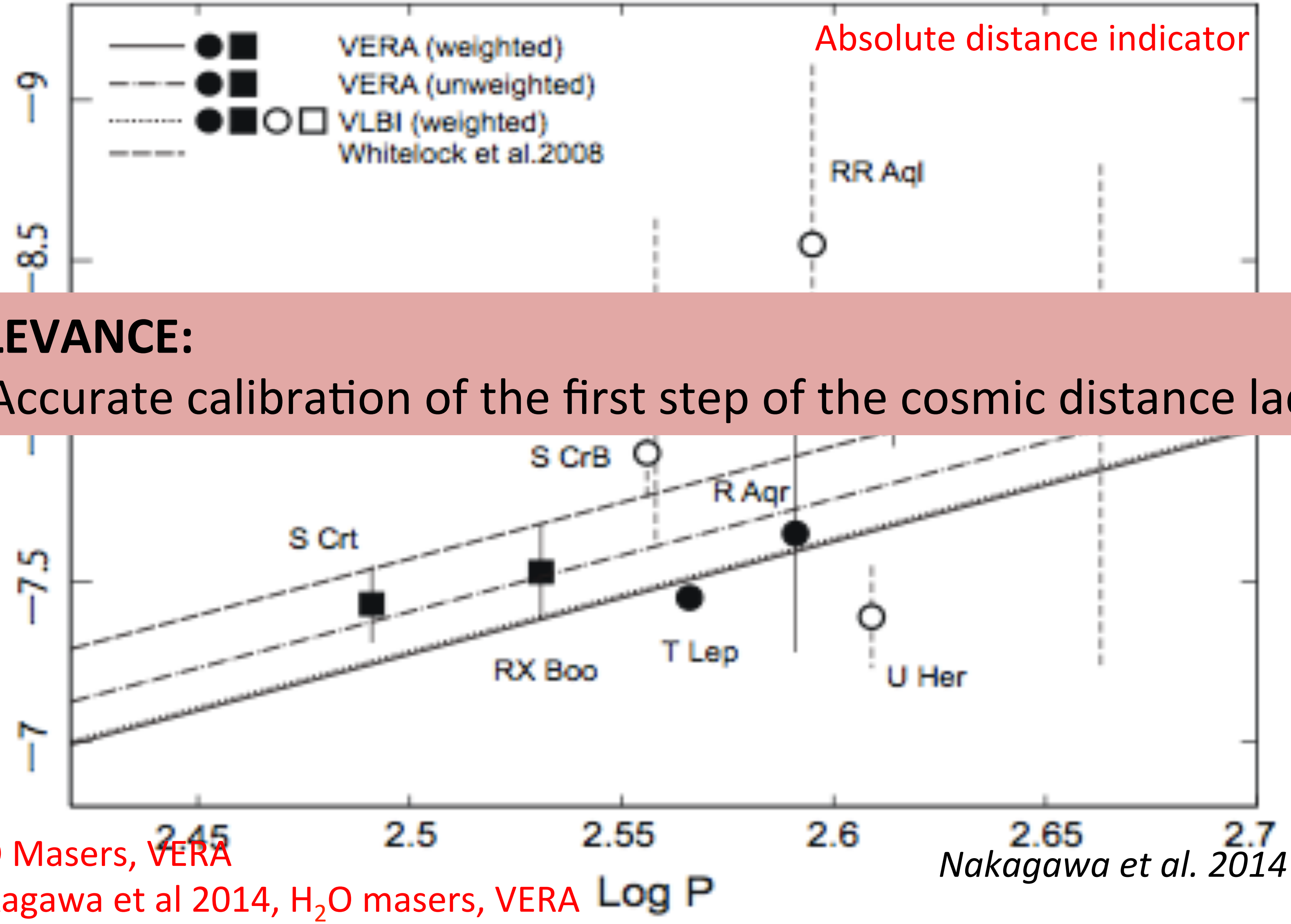


Absolute distance indicator

RELEVANCE:

- Accurate calibration of the first step of the cosmic distance ladder

Nakagawa et al. 2014

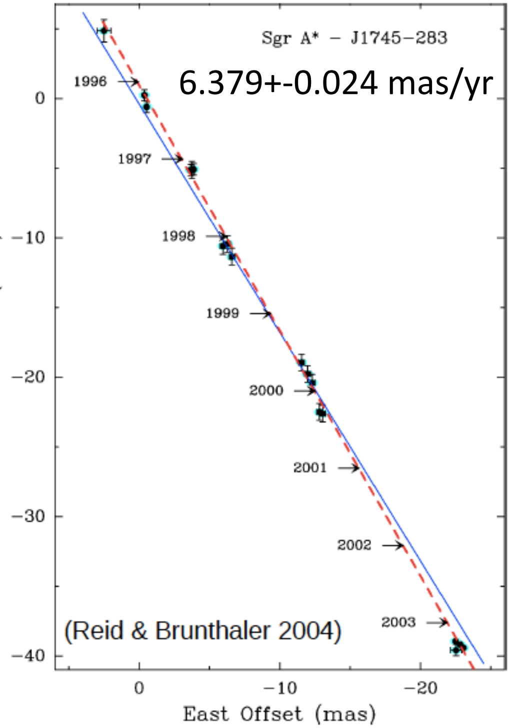
H_2O Masers, VERA

Nakagawa et al 2014, H_2O masers, VERA

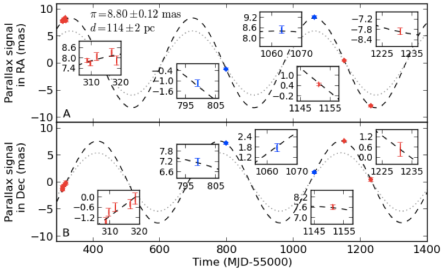
OH Masers,

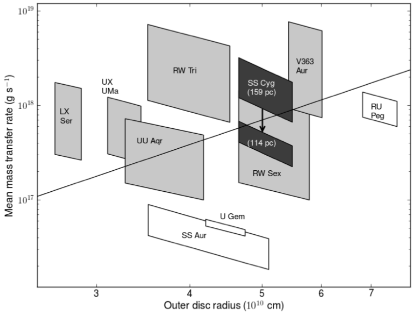
Vlemmings & van Langevelde, 2007

Proper Motion of SgrA*



X-ray-binaries

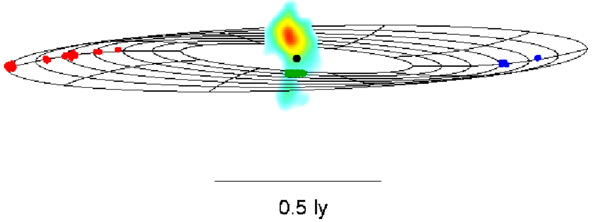




Miller-Jones et al 2013

Local Group Dynamics & "Hubble Flow…"

H_2O masers in edge-on accretion disk

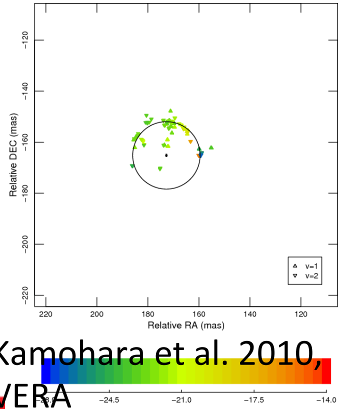


4% Distance Determination = 7.2 ± 0.3 ± 0.5 Mpc

(Herrnstein et al. Nature,1999)

Direct Geometric Method

CSEs in Evolved Stars



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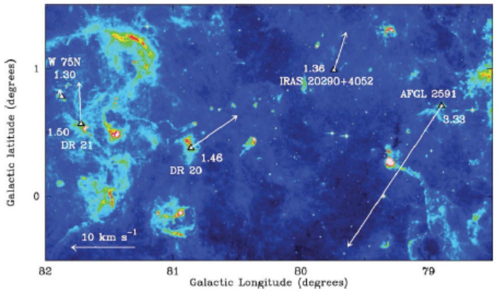

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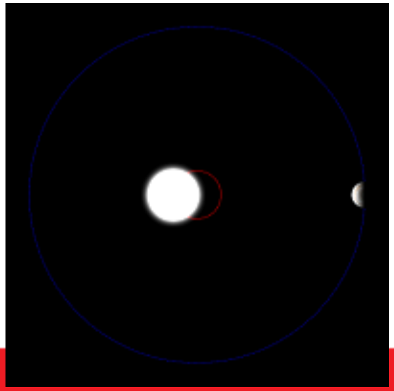
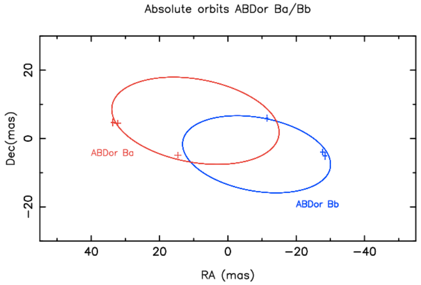
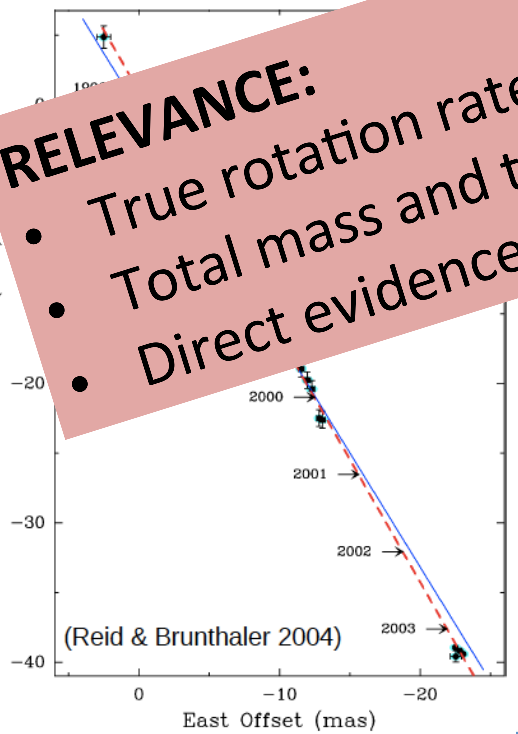




Azulay talk tomorrow

Guirado et al.

Proper Motion of SgrA*



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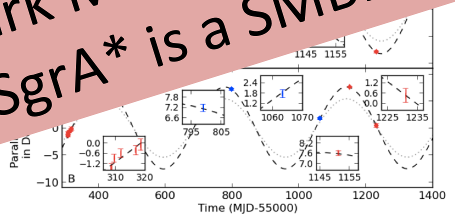

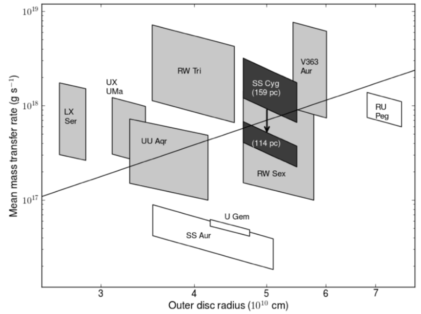

Miller-Jones et al 2013

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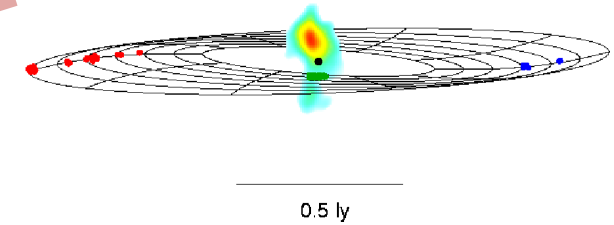

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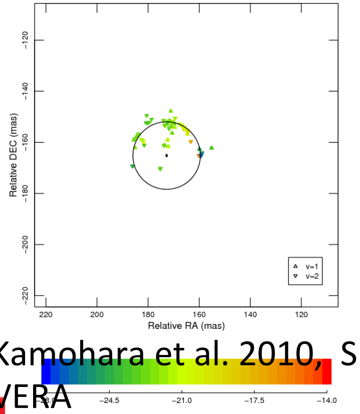

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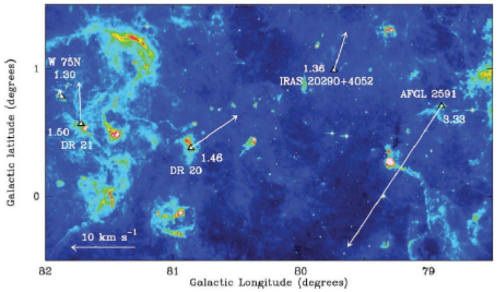

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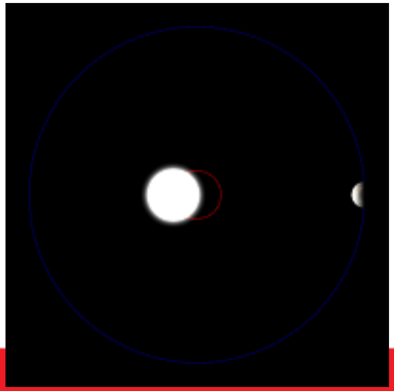

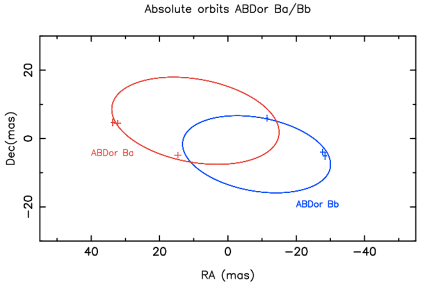

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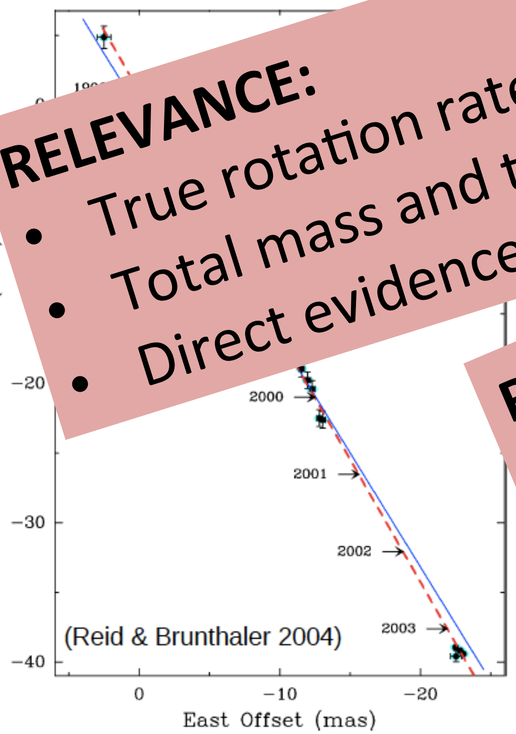

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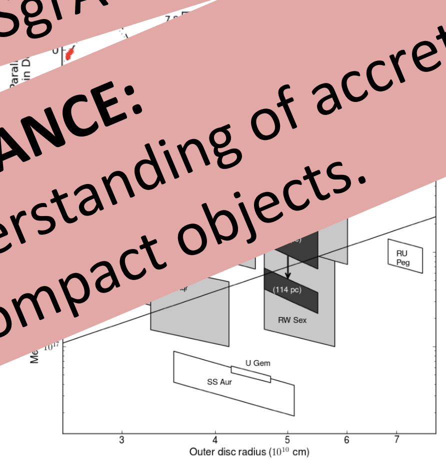
X



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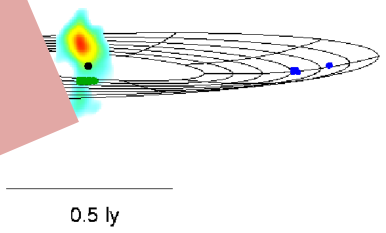

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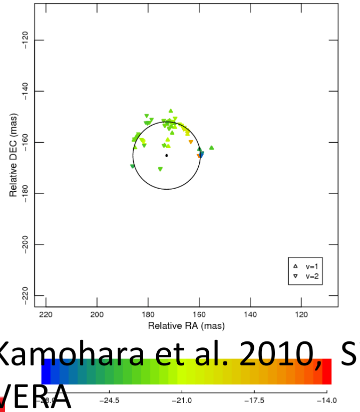

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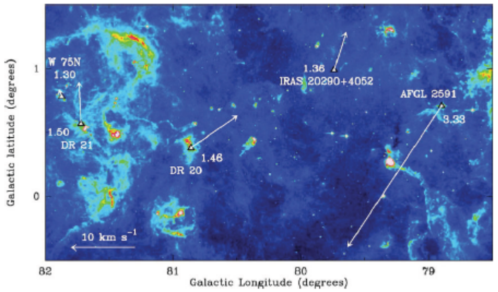

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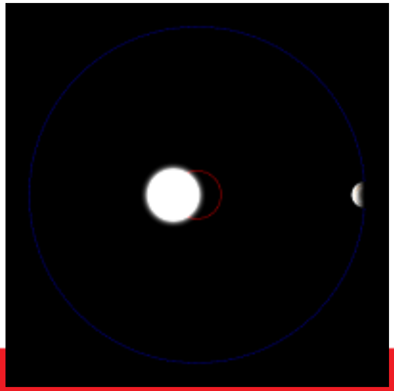

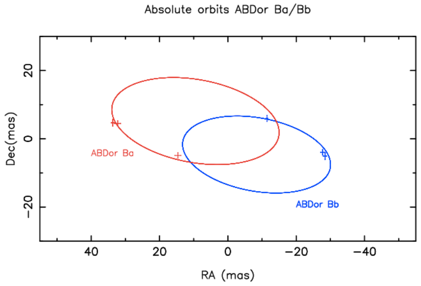

Azulay talk tomorrow

Guirado et al.

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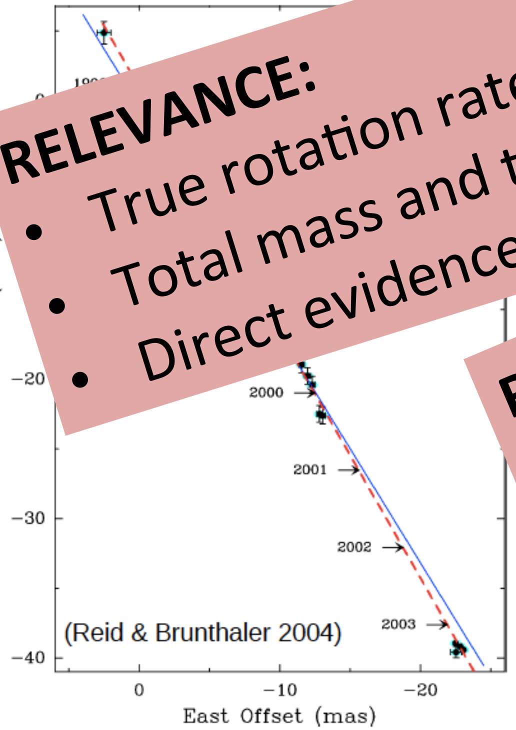

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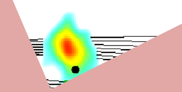

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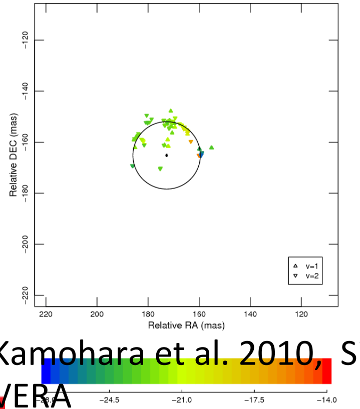

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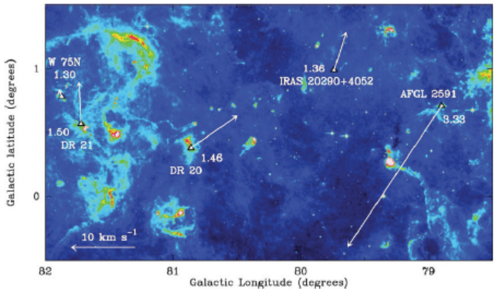

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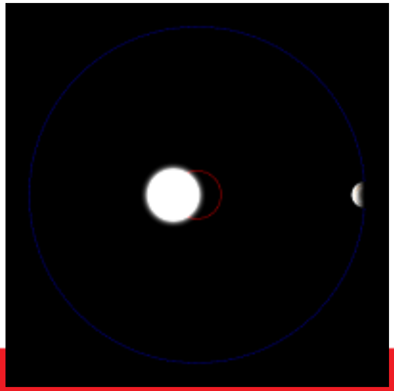

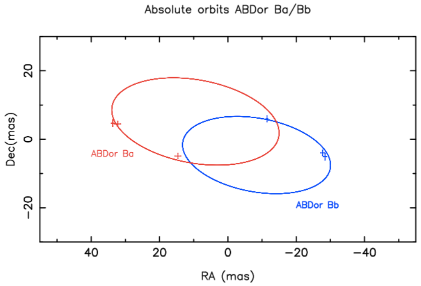

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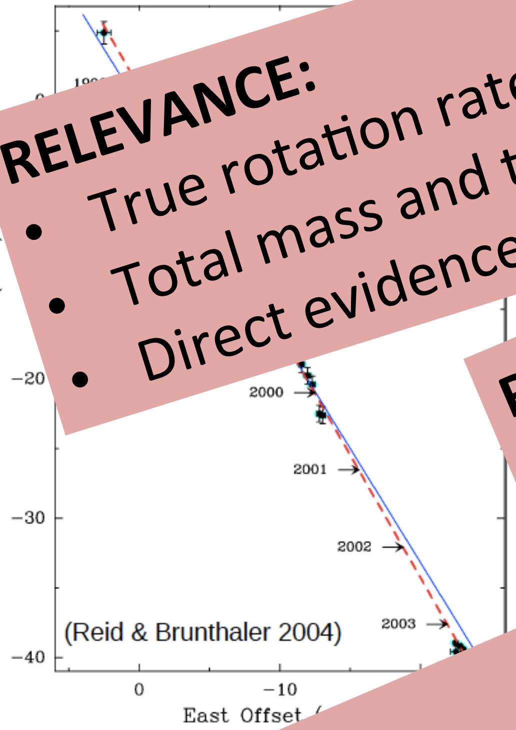

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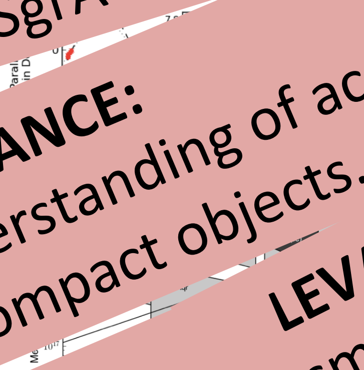

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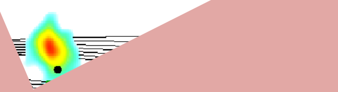

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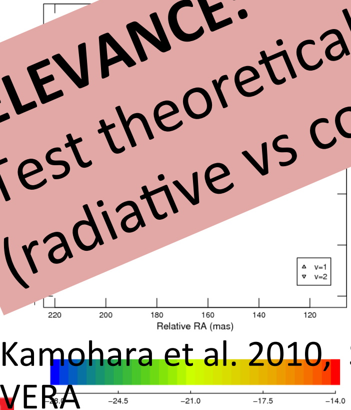

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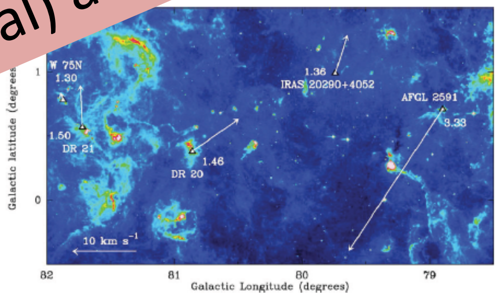

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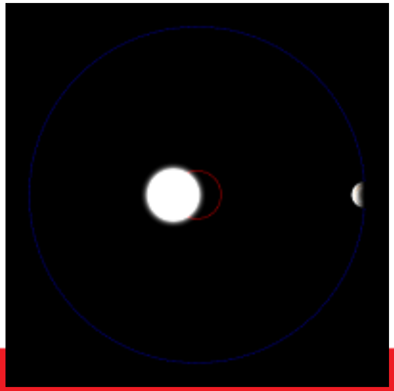

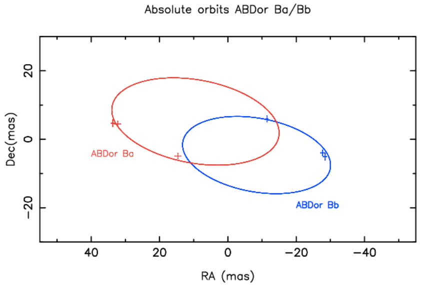

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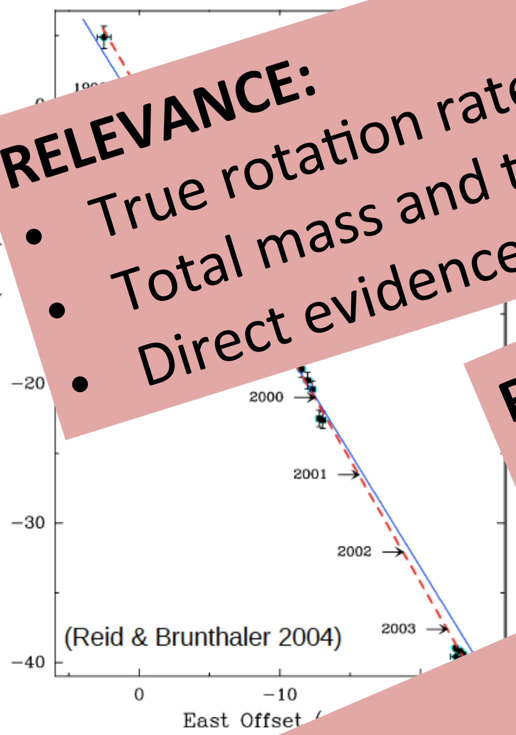

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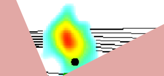

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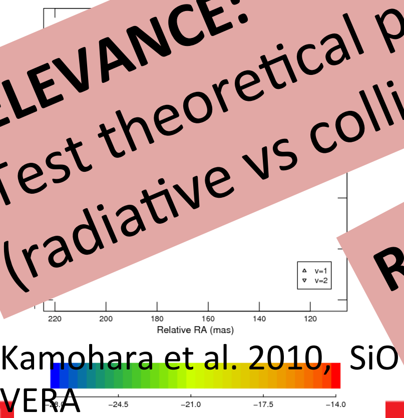

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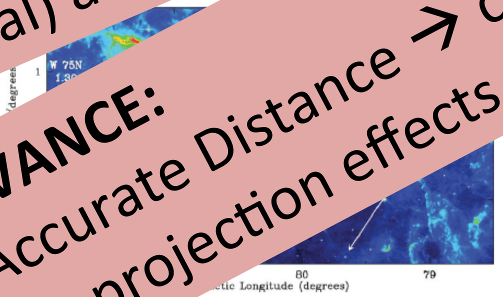

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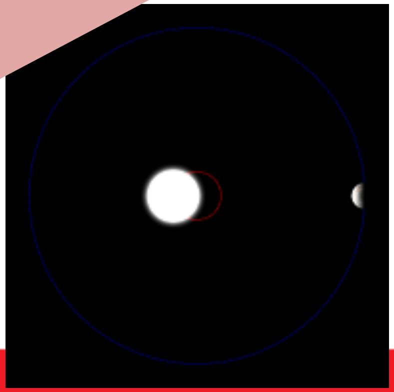
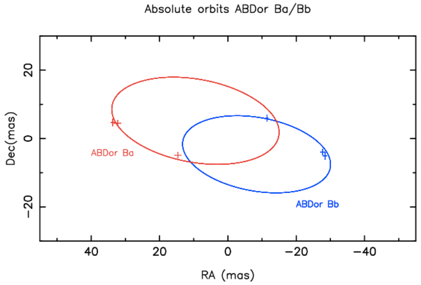
- Accurate Distance → confirm physical association, vs. projection effects.

Search/Dynamical mass





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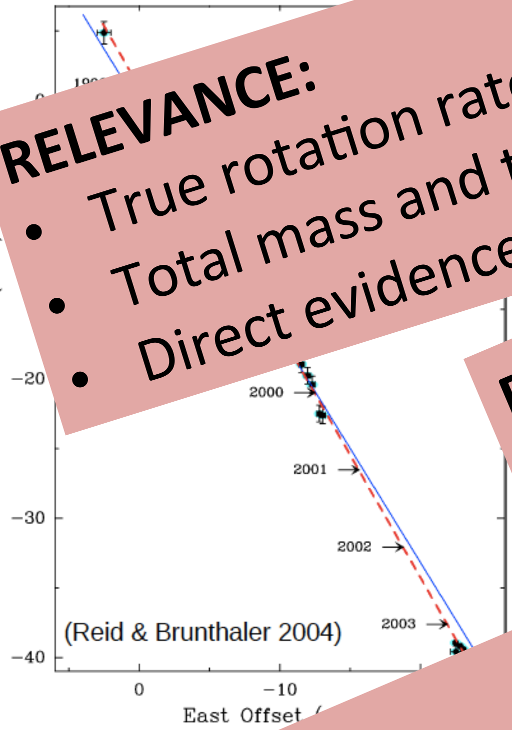

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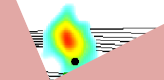

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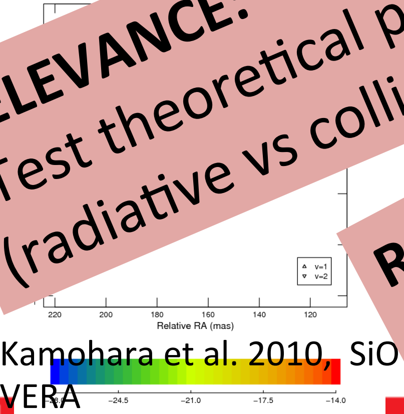

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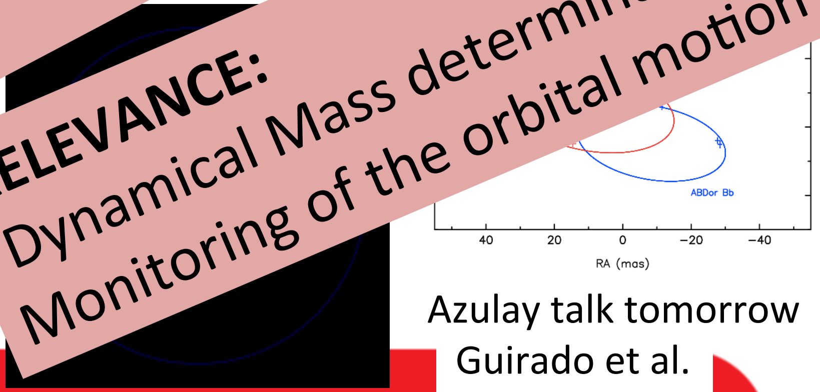
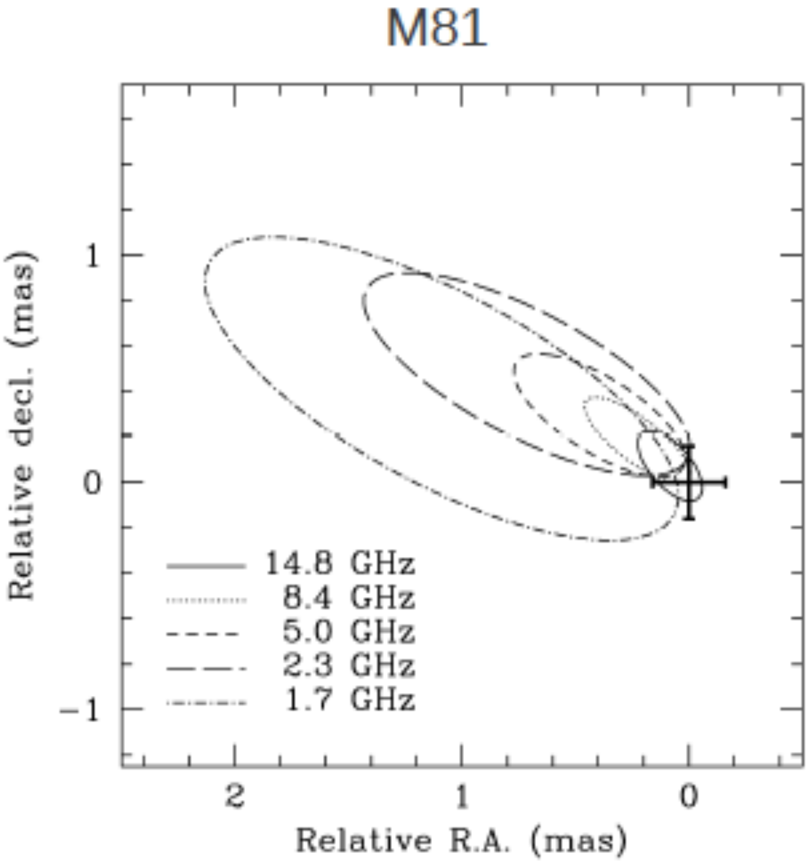


RELEVANCE:
Dynamical Mass determination wit Monitoring of the orbital motion

Azulay talk tomorrow
Guirado et al.

AGN: Multi Frequency astrometry



Bietenholz 2004	Global VLBI
Marti-Vidal et al. 2011	1.7-14.8 GHz

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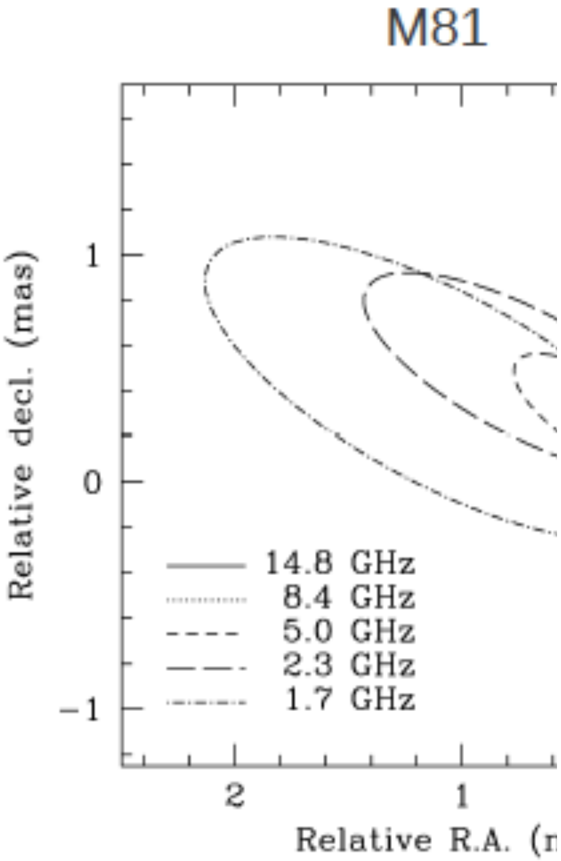
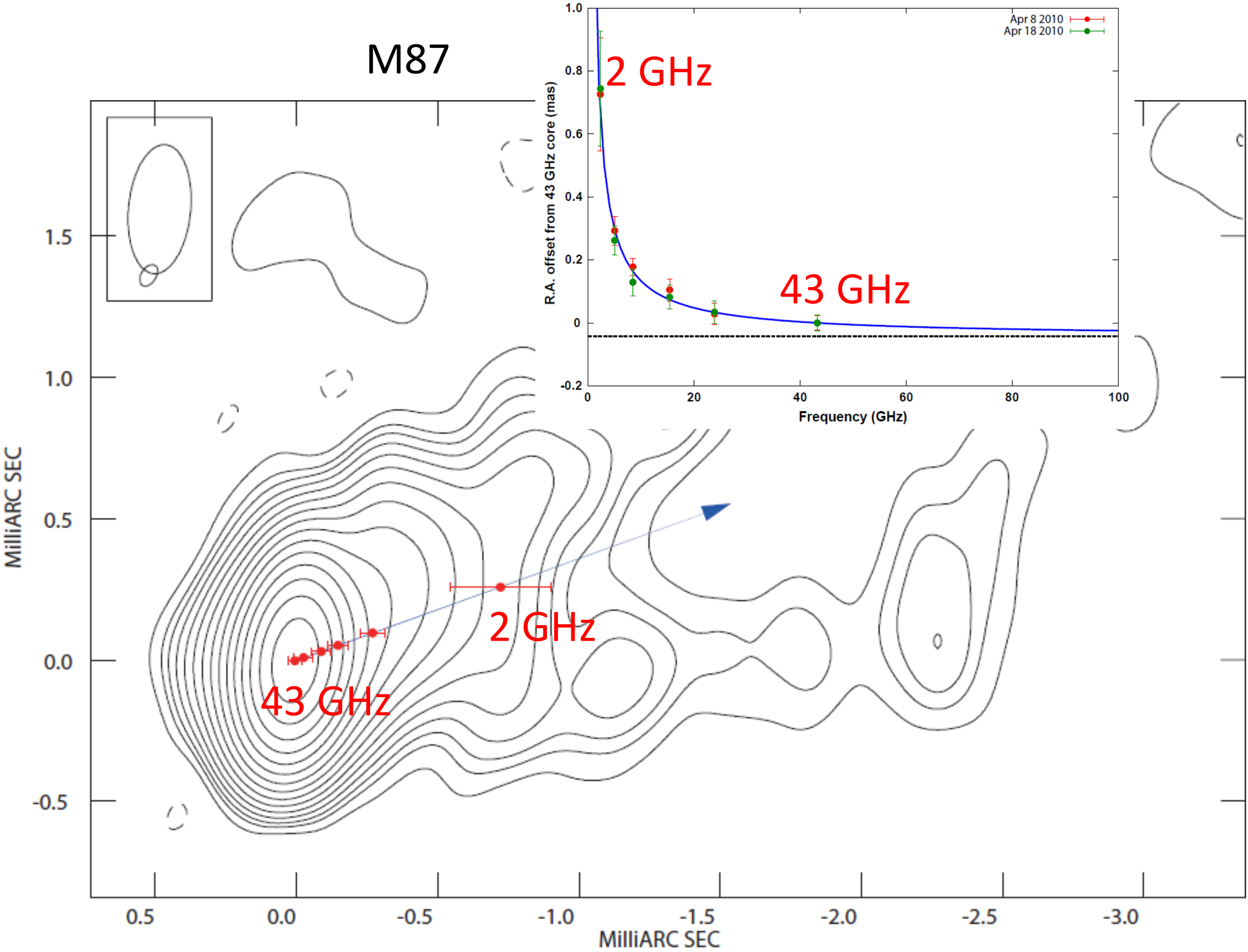

M81


M87

Bietenholz 2004

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Gl

1.7-14.8 GHz

VLBA

2-43 GHz

(Hada et al., Nature, 2011)

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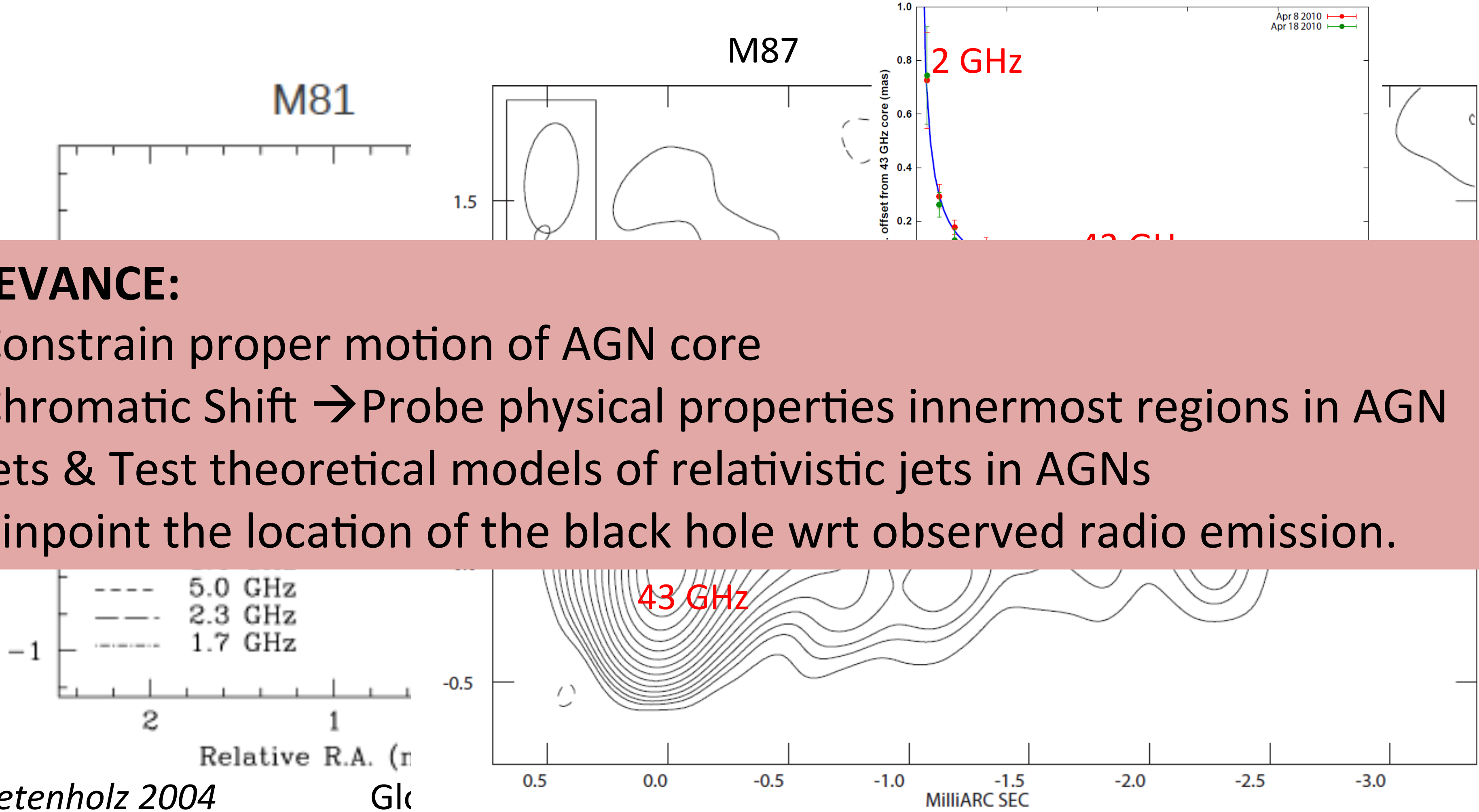


RELEVANCE:

- Constrain proper motion of AGN core
- Chromatic Shift →Probe physical properties innermost regions in AGN jets & Test theoretical models of relativistic jets in AGNs
- Pinpoint the location of the black hole wrt observed radio emission.

Bietenholz 2004

Marti-Vidal et al. 2011

Gl

1.7-14.8 GHz

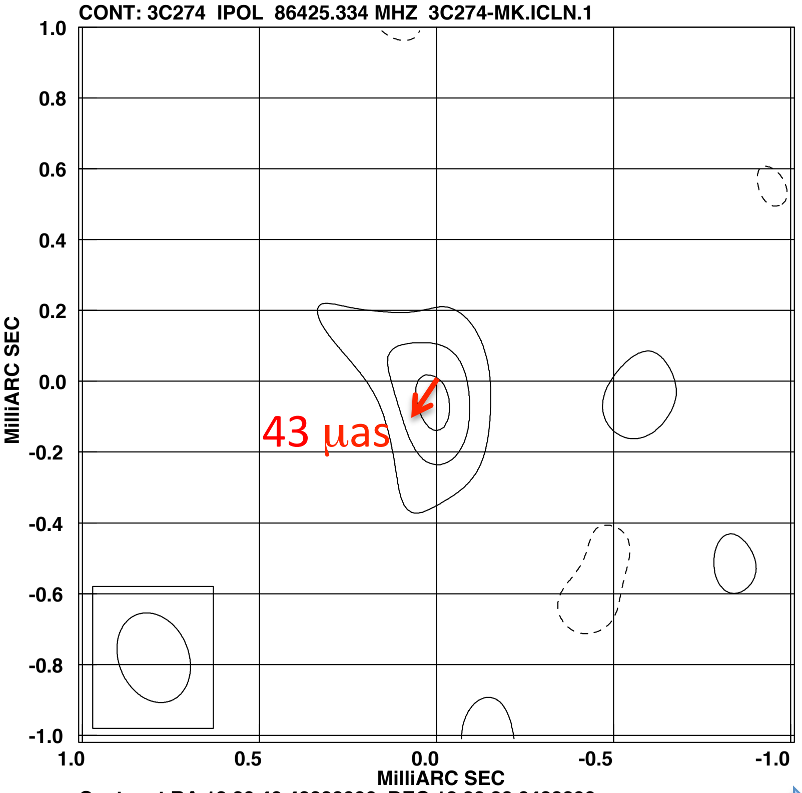
VLBA

2-43 GHz

(Hada et al., Nature, 2011)

M87: Core-Shift Measurement between 43 and 86 GHz

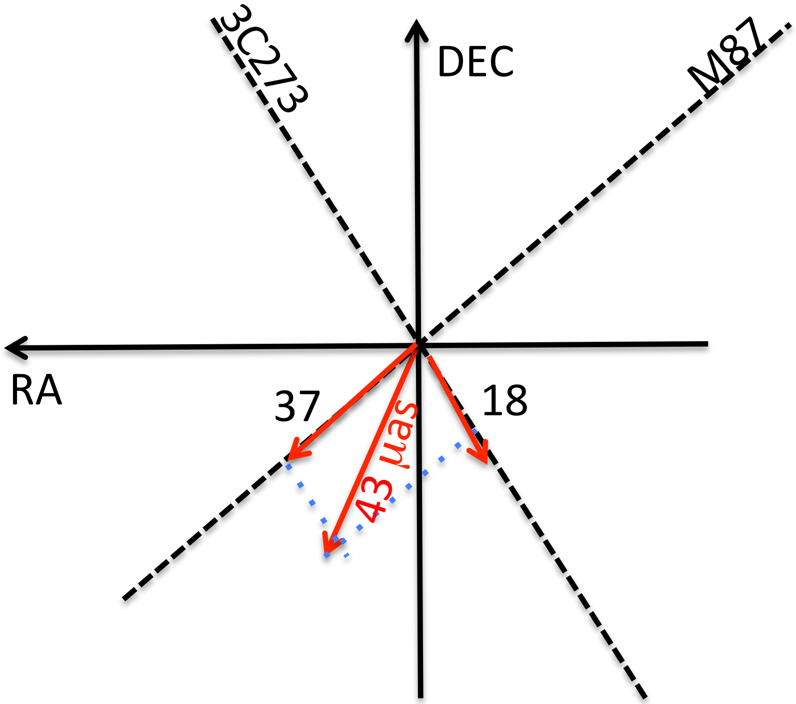
Obs. 2007, M87 wrt. 3c273, 10^{o} apart, VLBA SFPR



```
Center at RA 12 30 49.42338096  DEC 12 23 28.0438299
Cont peak flux =  1.5002E-01 JY/BEAM
Levs = 1.500E-02 * (-3, 3, 6, 9)
```

Vector Decomposition:

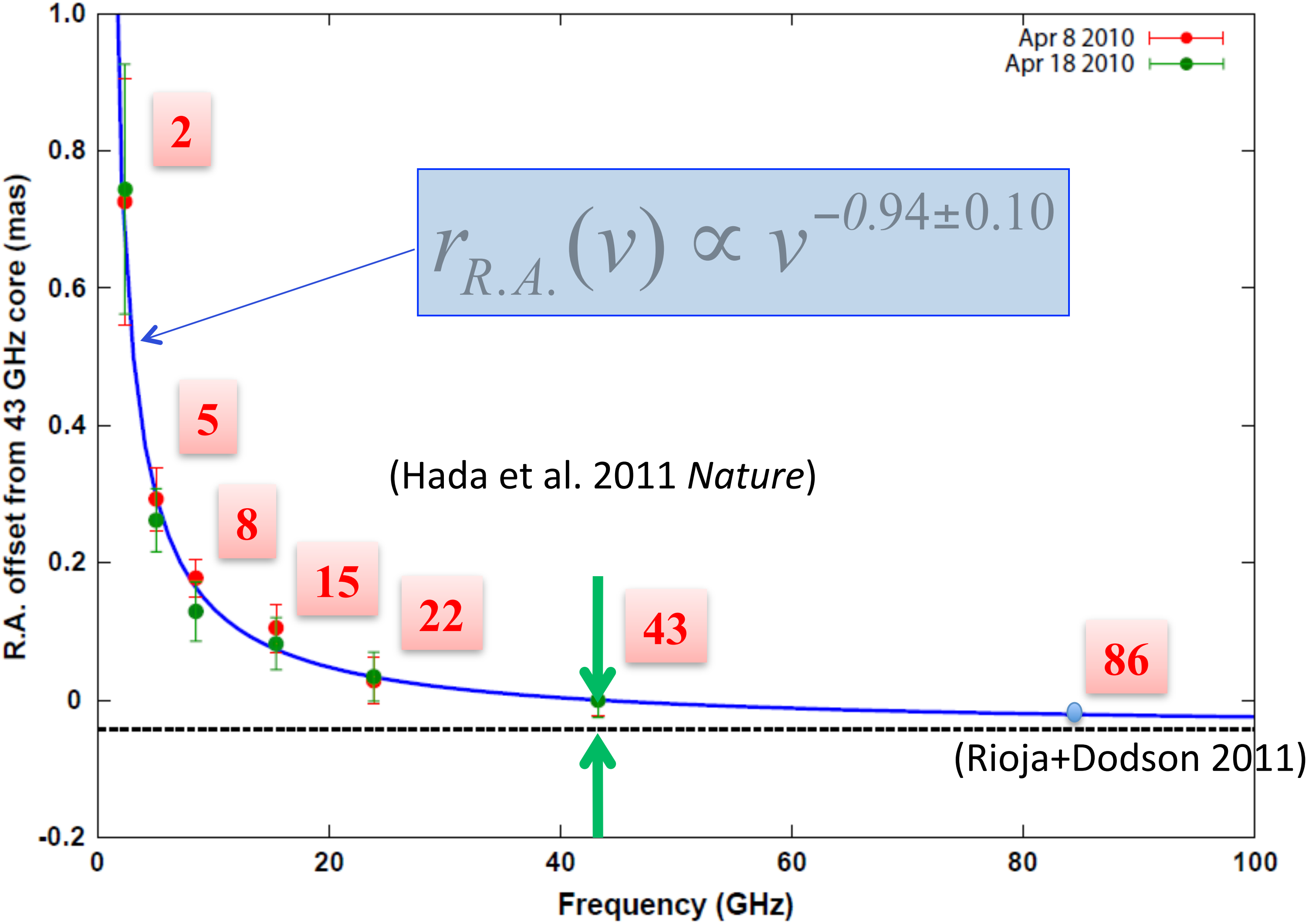
Larger Scale jet M87 PA ~ 290^{o}



Along RA ➔ M87 86-43 GHz $_{\_RA}$ ~ 30 micro-as

(Rioja + Dodson, 2011)

M87: Core positions vs frequency



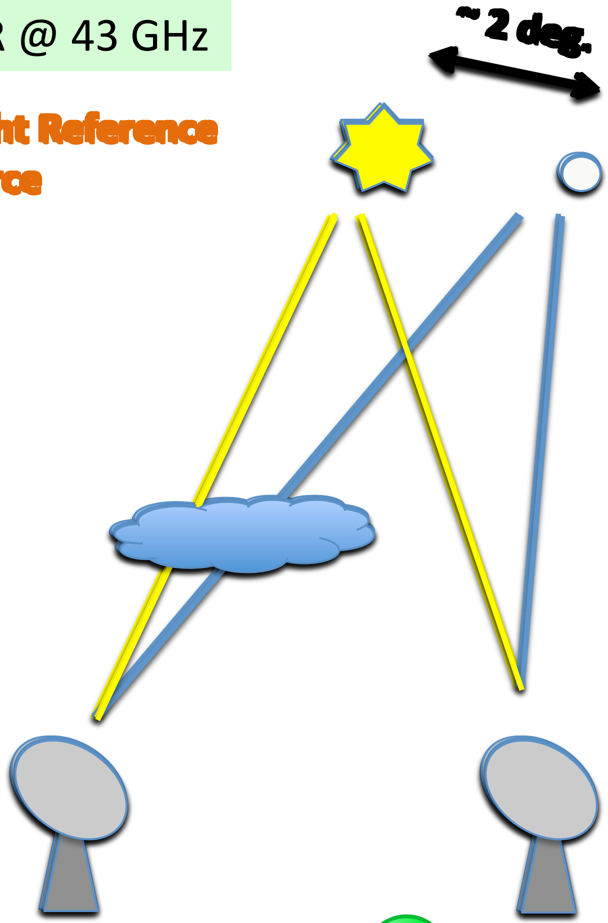
$$r_{R.A.}(\nu) \propto \nu^{-0.94\pm0.10}$$

(Hada et al. 2011 *Nature*)

Core positions converge to ～40μas (6*Rs*) east of the 43GHz core

ALTERNATIVE APPROACH FOR TROPOSPHERIC (non-dispersive) COMPENSATION

PR @ 43 GHz



Bright Reference Source

Weak Target Source

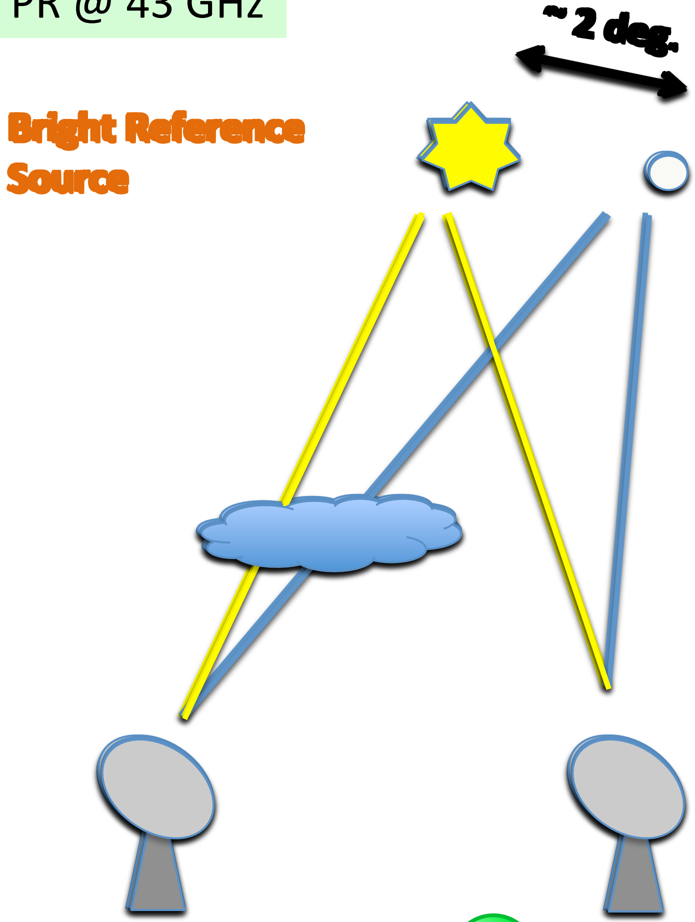
WEAK SOURCES ✓
ASTROMETRY ✓

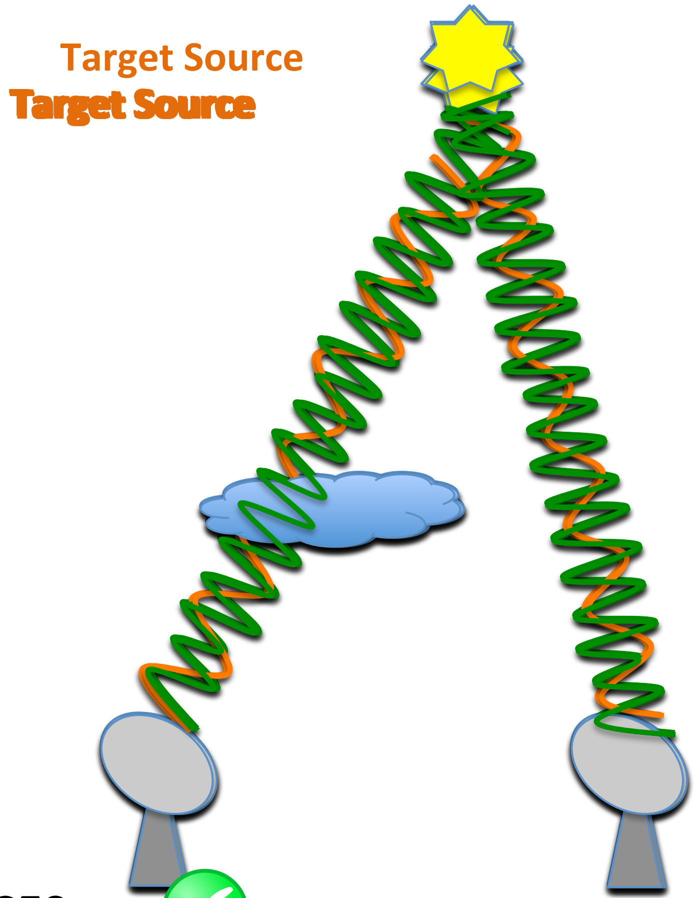
ALTERNATIVE APPROACH FOR TROPOSPHERIC (non-dispersive) COMPENSATION

Middelberg et al. 2005
Rioja&Dodson 2008,2011

“fast-frequency switching”
@ 22/43 GHz

PR @ 43 GHz



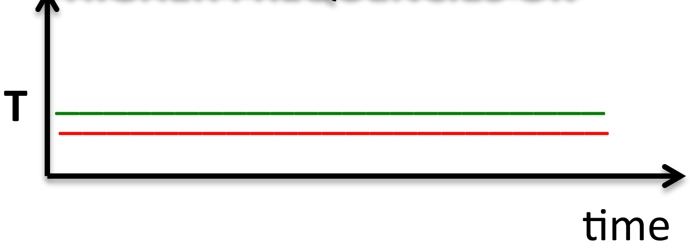


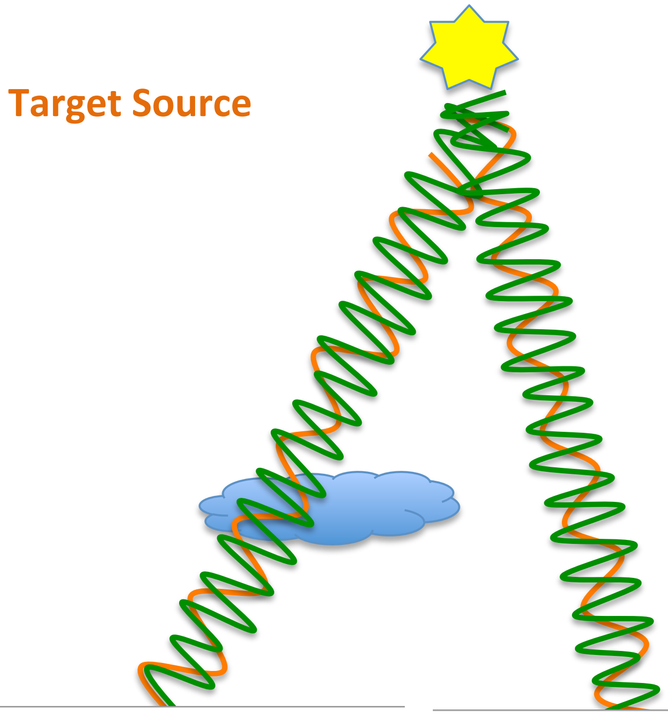
WEAK SOURCES ✓
ASTROMETRY ✓

WEAK SOURCES ✓
ASTROMETRY ✗

ALTERNATIVE APPROACH FOR TROPOSPHERIC COMPENSATION

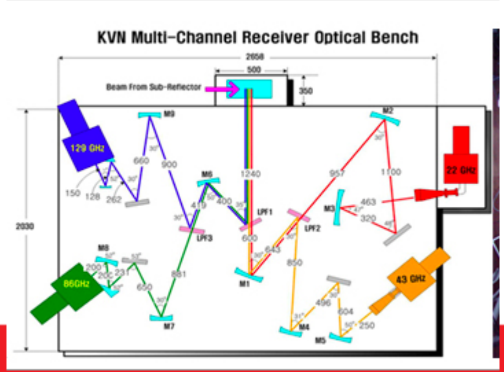
BETTER SIMULTANEOUS!
HIGHER FREQUENCIES OK

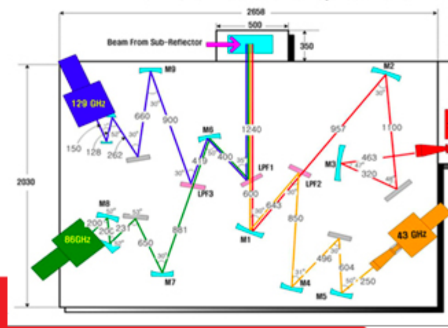




Superior Tropospheric Calibration!
(see poster T. Jung)

Multi-Channel KVN receivers





WEAK SOURCES ✓
ASTROMETRY ✗

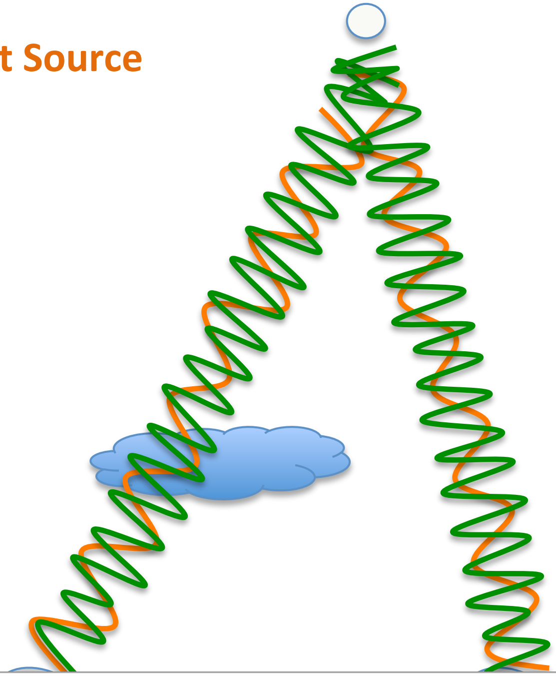
ASTROMETRY with Source-Frequency-Phase-Referencing *(SFPR)*

(2 frequencies, 2 sources)

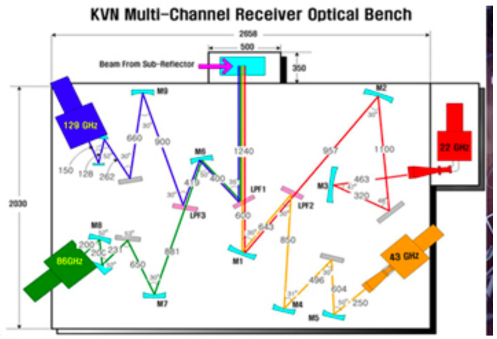
SFPR: Rioja & Dodson 2008,2011

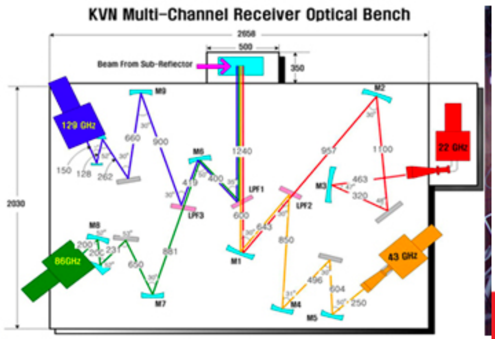
WEAK SOURCES ✓

ASTROMETRY ✓



Target Source





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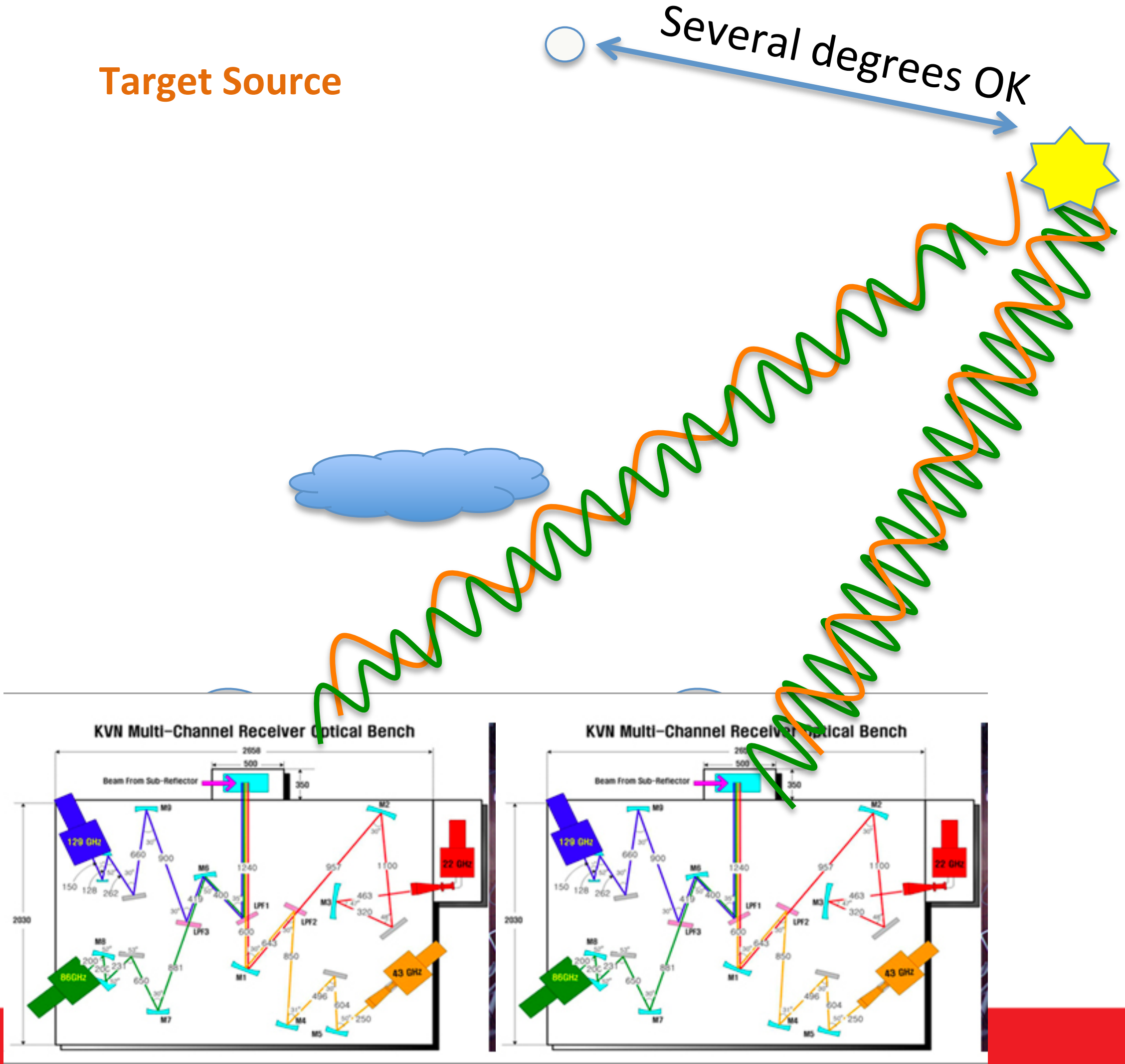
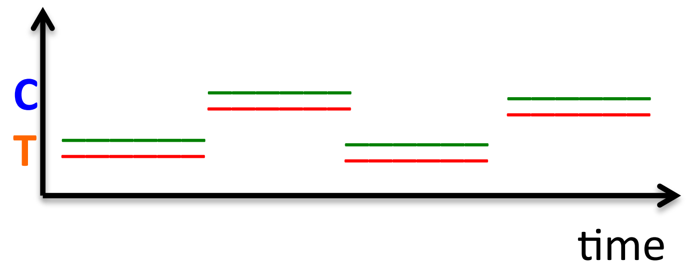
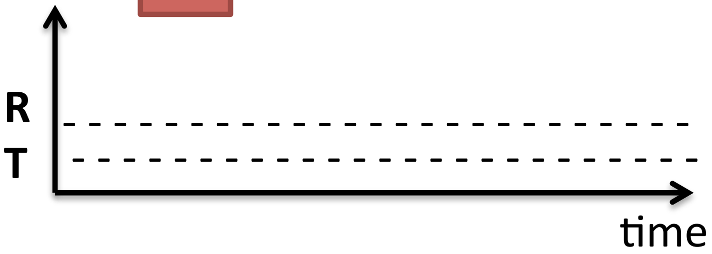


SFPR



PR



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ASTROMETRY with Source-Frequency-Phase-Referencing *(SFPR)*

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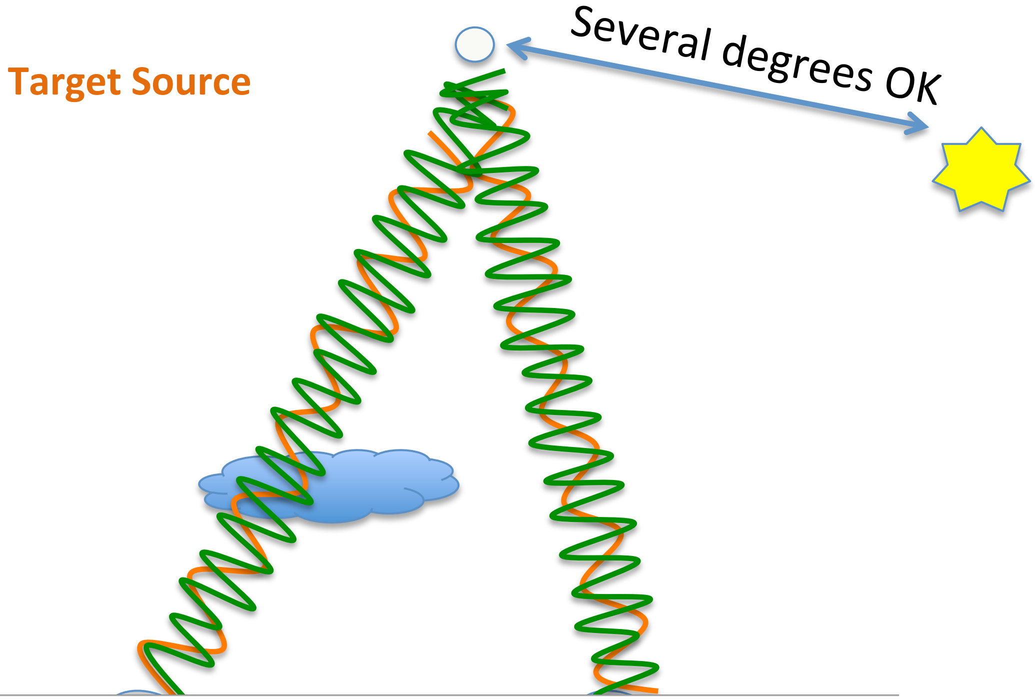
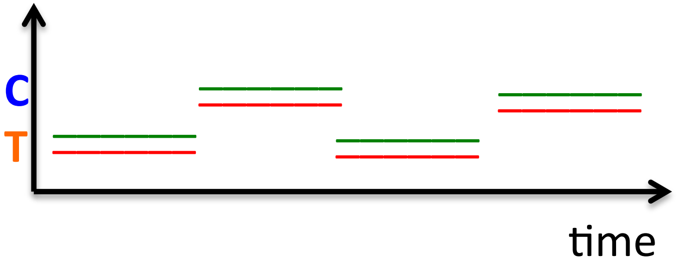
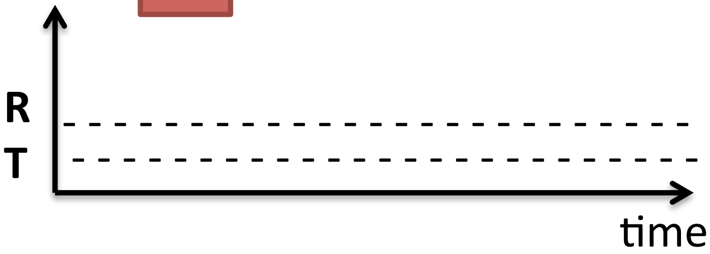
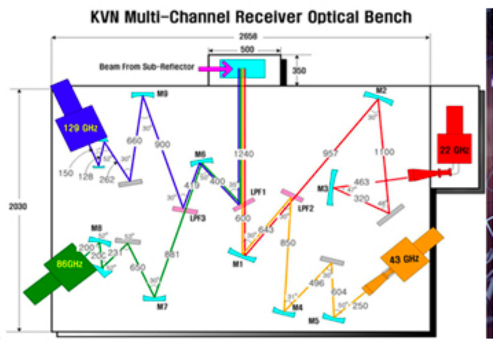


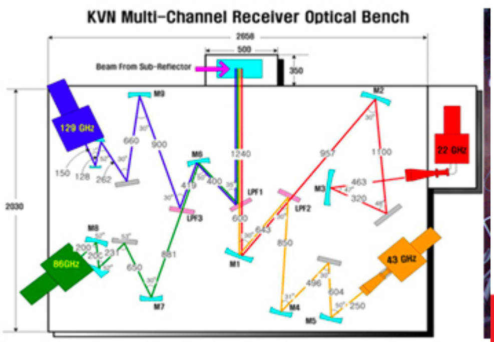
SFPR



PR







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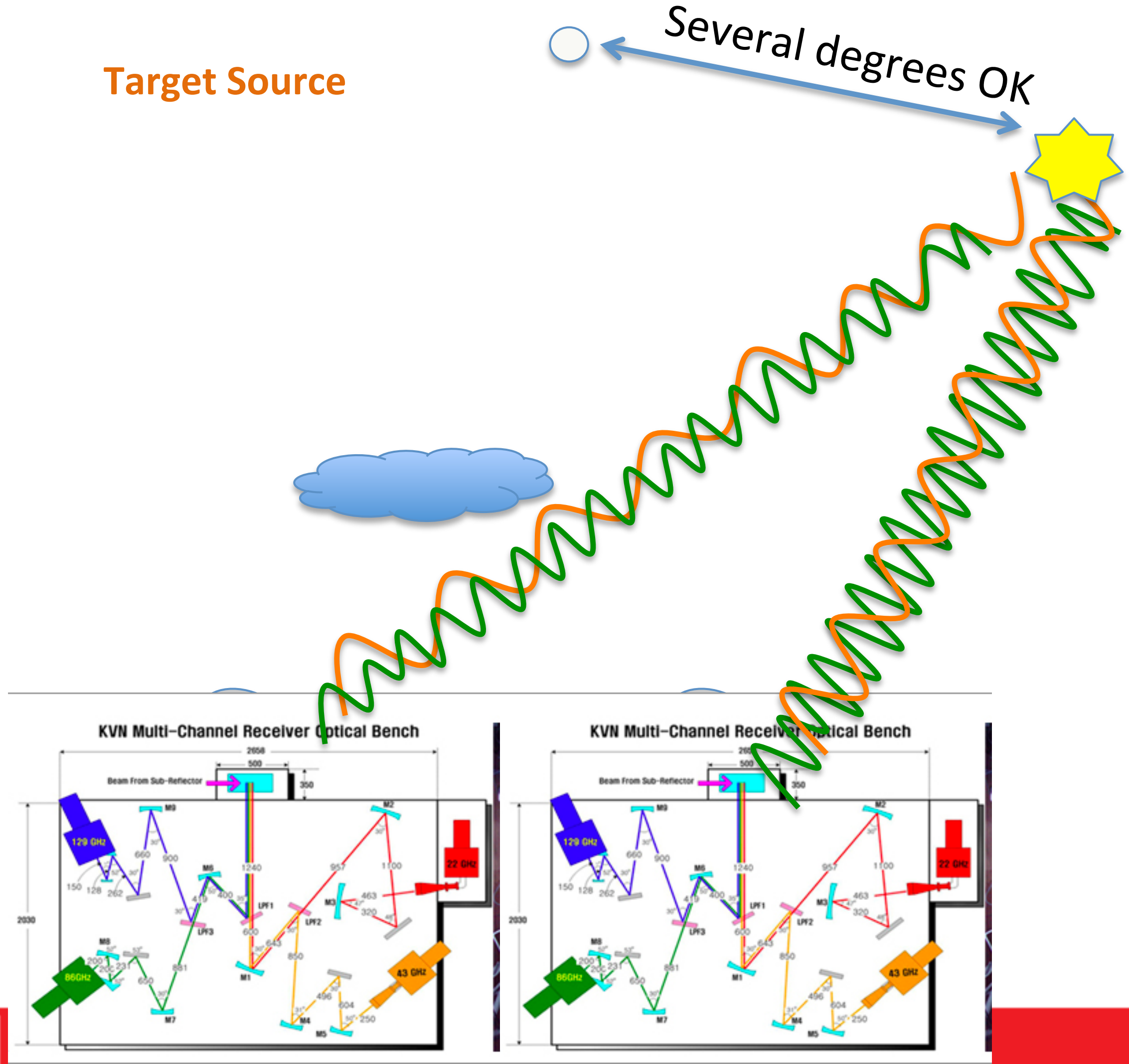
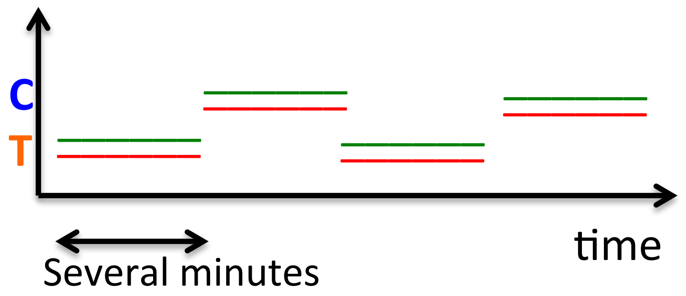
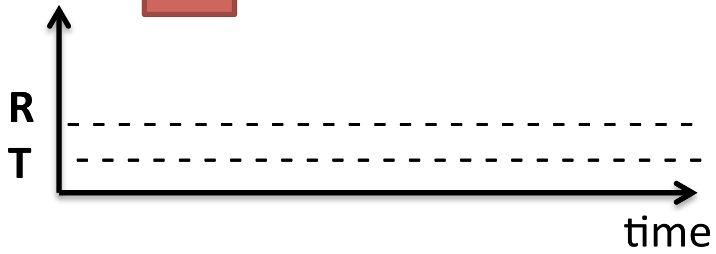


SFPR



PR



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OUTCOMES OF SOURCE-FREQUENCY-PHASE-REFERENCING

OUTCOME:

Precise calibration of the atmosphere

ENABLES:

Astrometry between frequencies (*e.g. core shift, molecular transitions spectral line*) at very high frequencies

&

also space VLBI

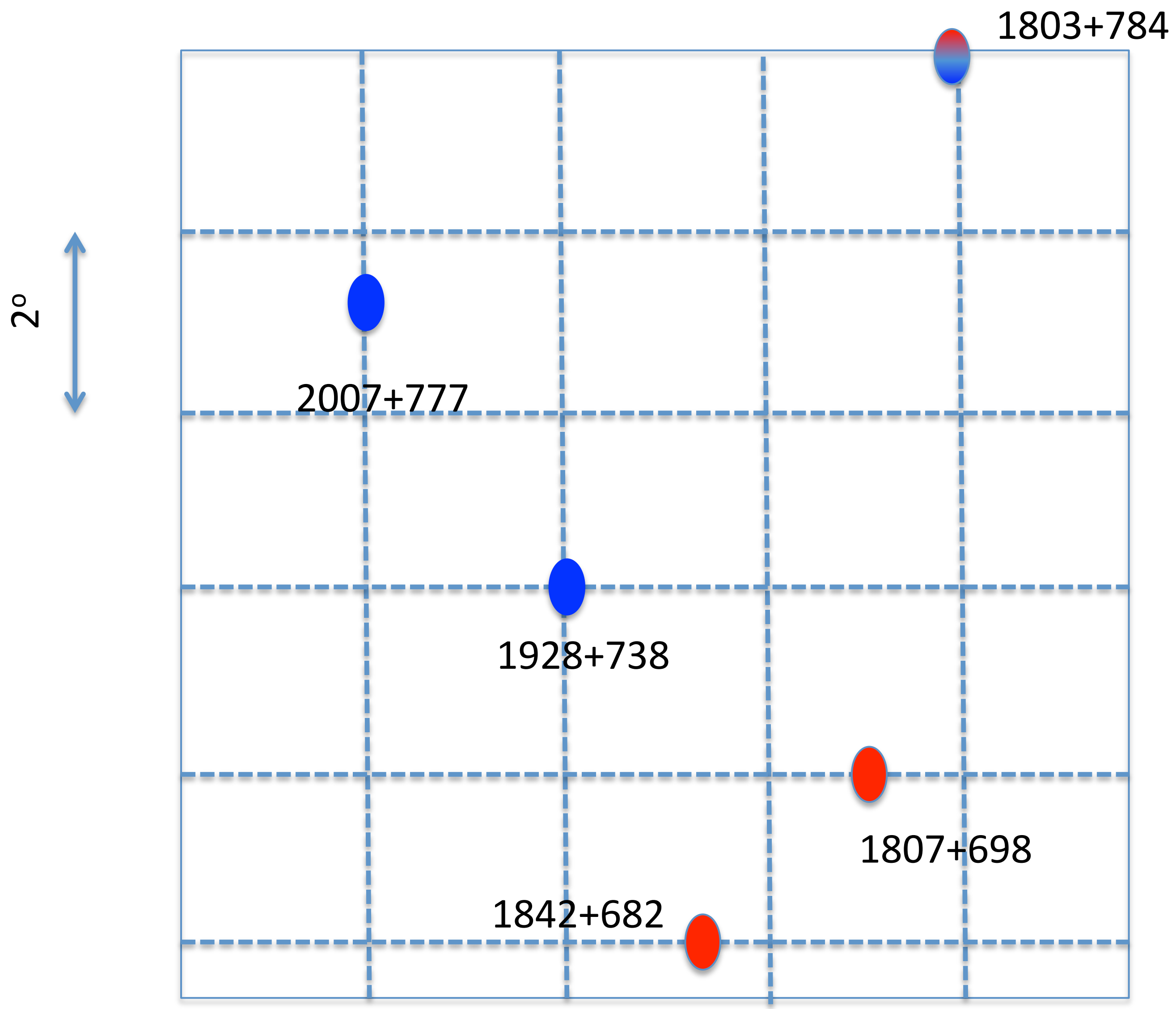
&

Weak Source Detection at High Frequencies

Slow switching OK

Several Degrees away OK

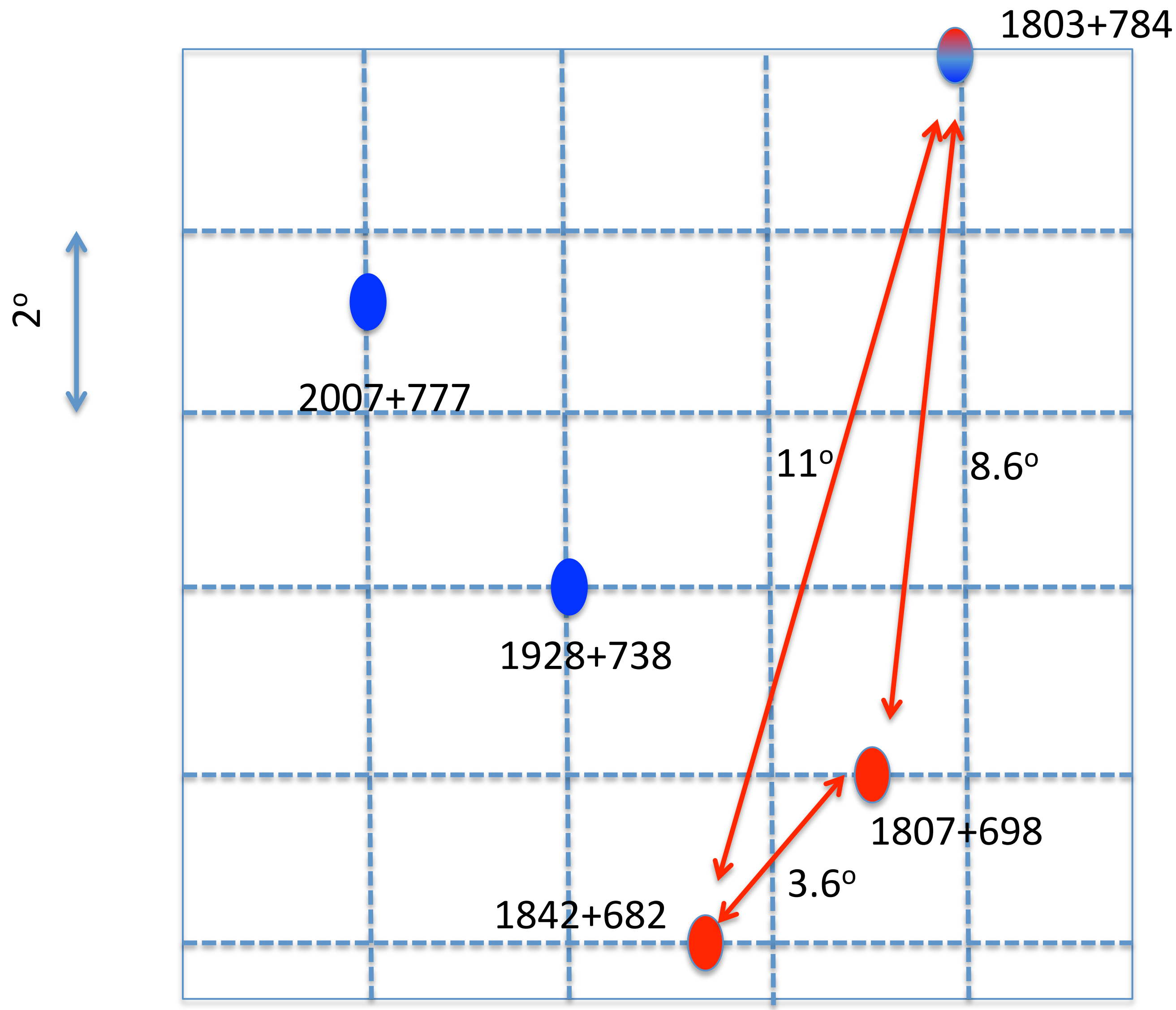
Latest SFPR results on sources from Polar Cap sample with KVN



Triangle 1
Triangle 2

22,43,86,129 GHz

Latest SFPR results on sources from Polar Cap sample with KVN



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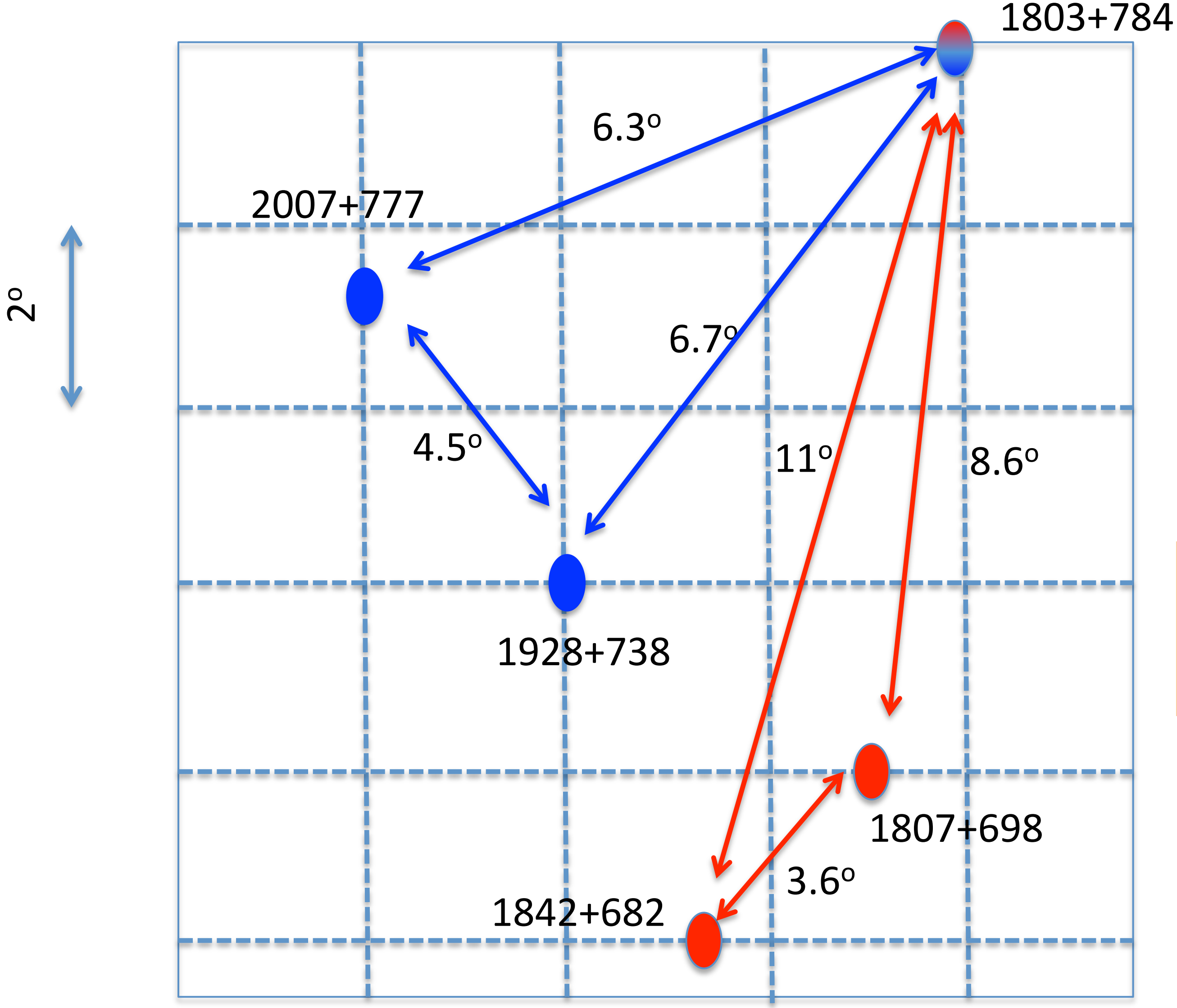
Latest SFPR results on sources from Polar Cap sample with KVN



Triangle 1
Triangle 2

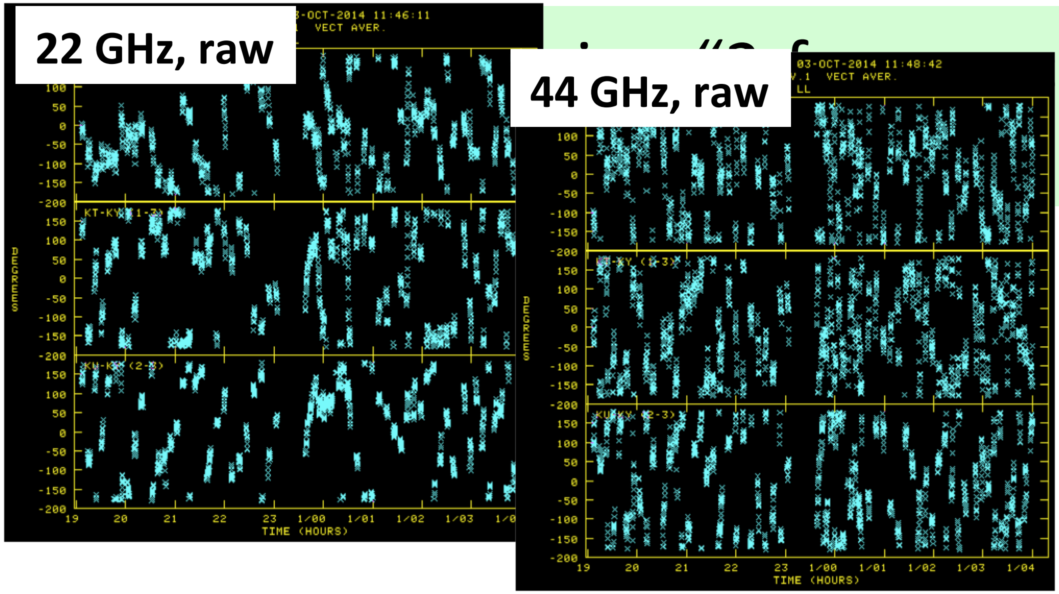
22,44,88,132 GHz

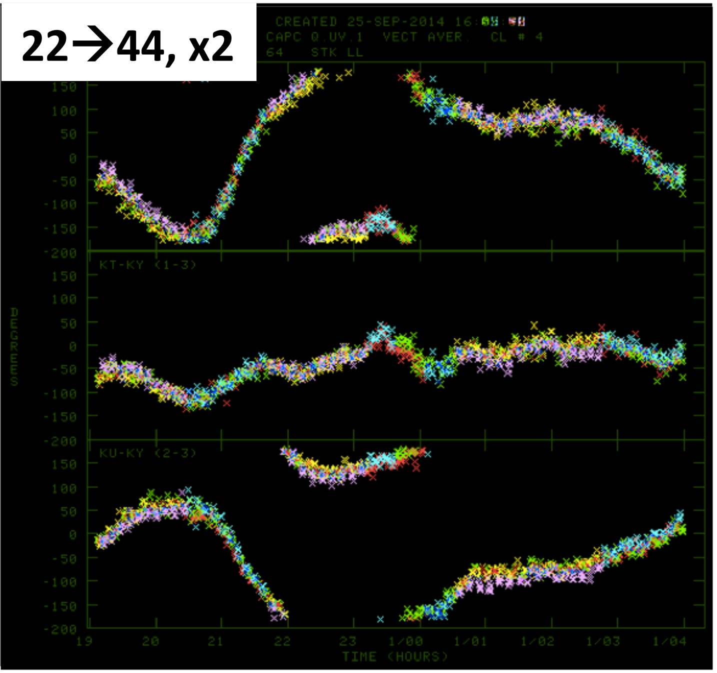
KVN Obs.:
Duration 8 hours
3 min scan/source

FPT analysis – “2-frequencies”
Residuals increase with R, for a given ν_{low} (22GHz)

ies”

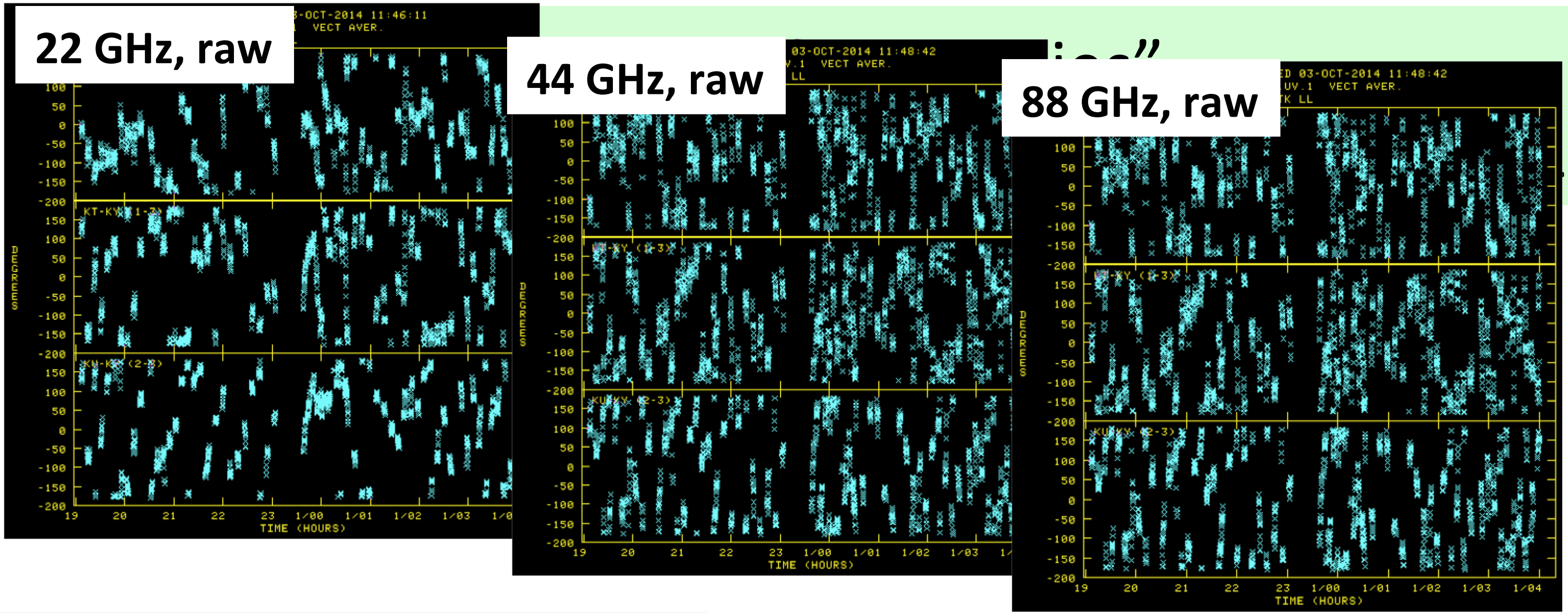
for a given ν_{low} (22GHz)





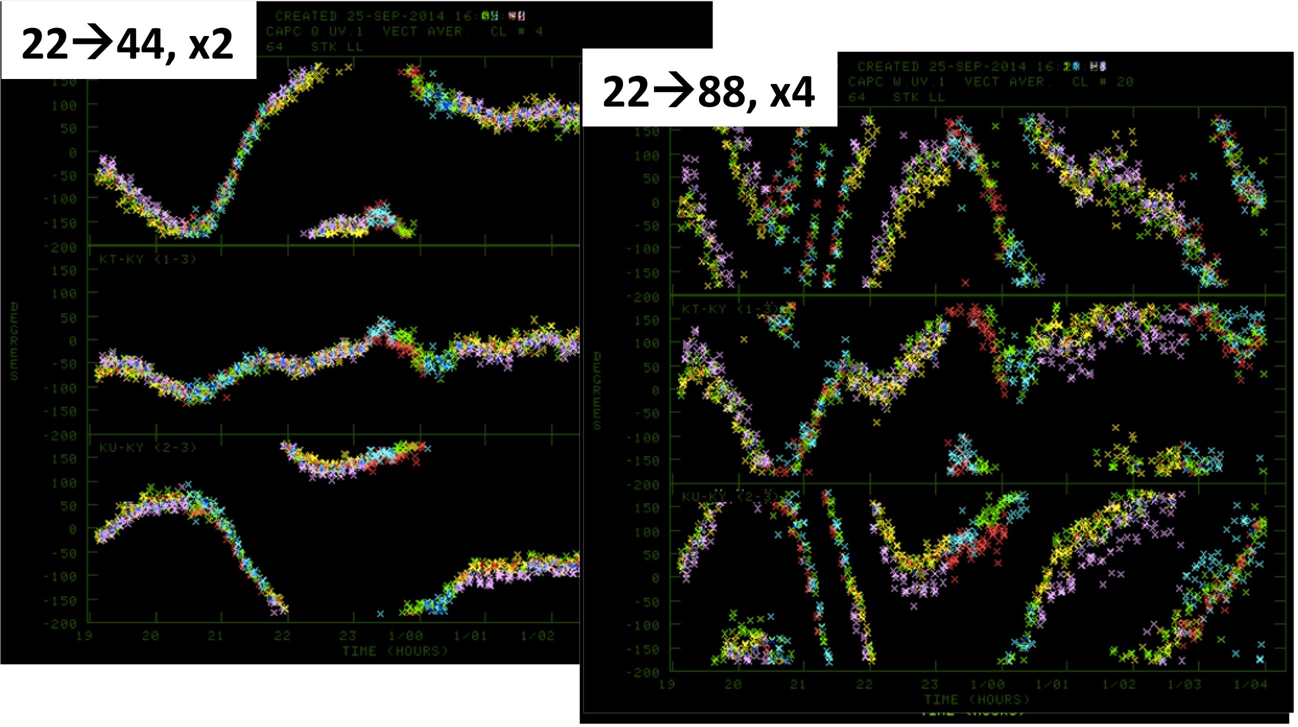
ies”

2GHz)

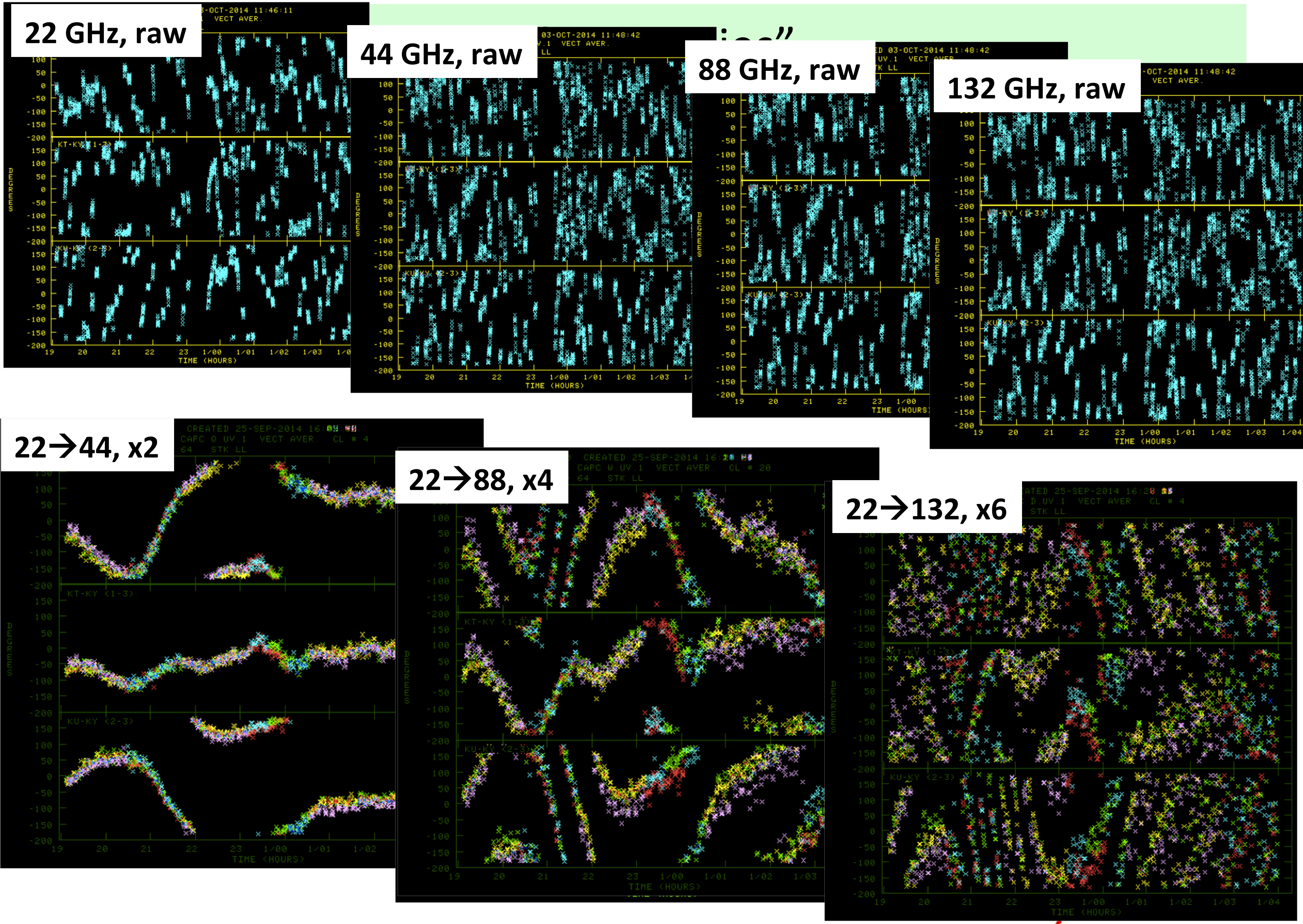

22 GHz, raw

44 GHz, raw

88 GHz, raw

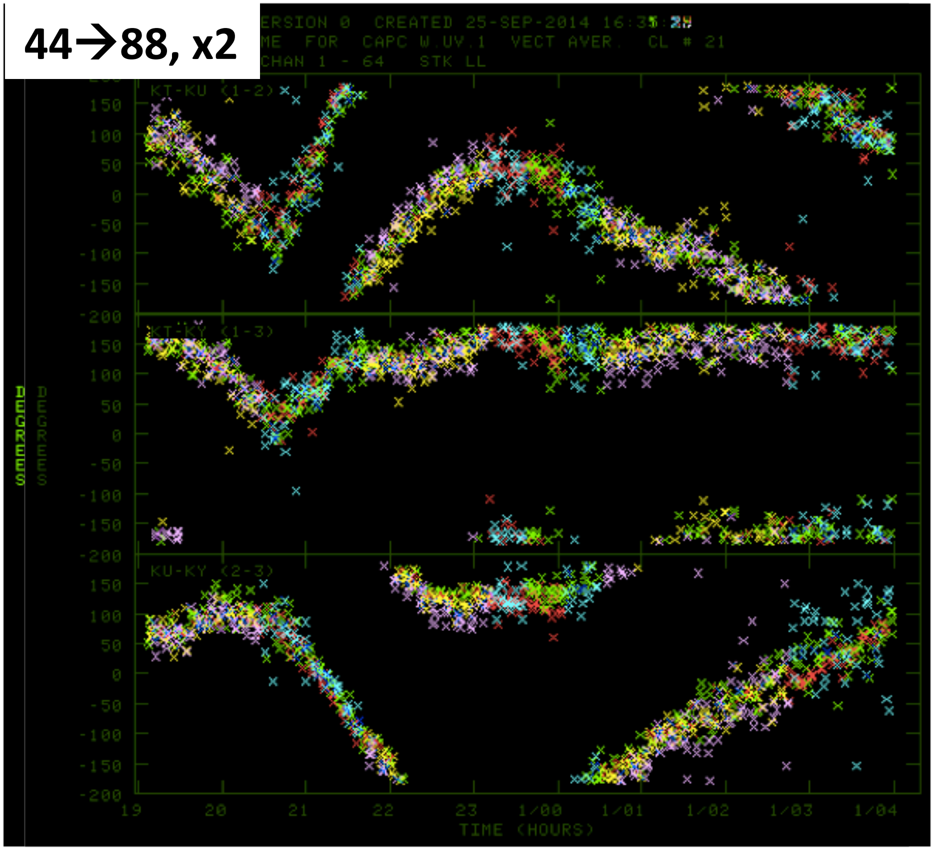

22→44, x2

22→88, x4

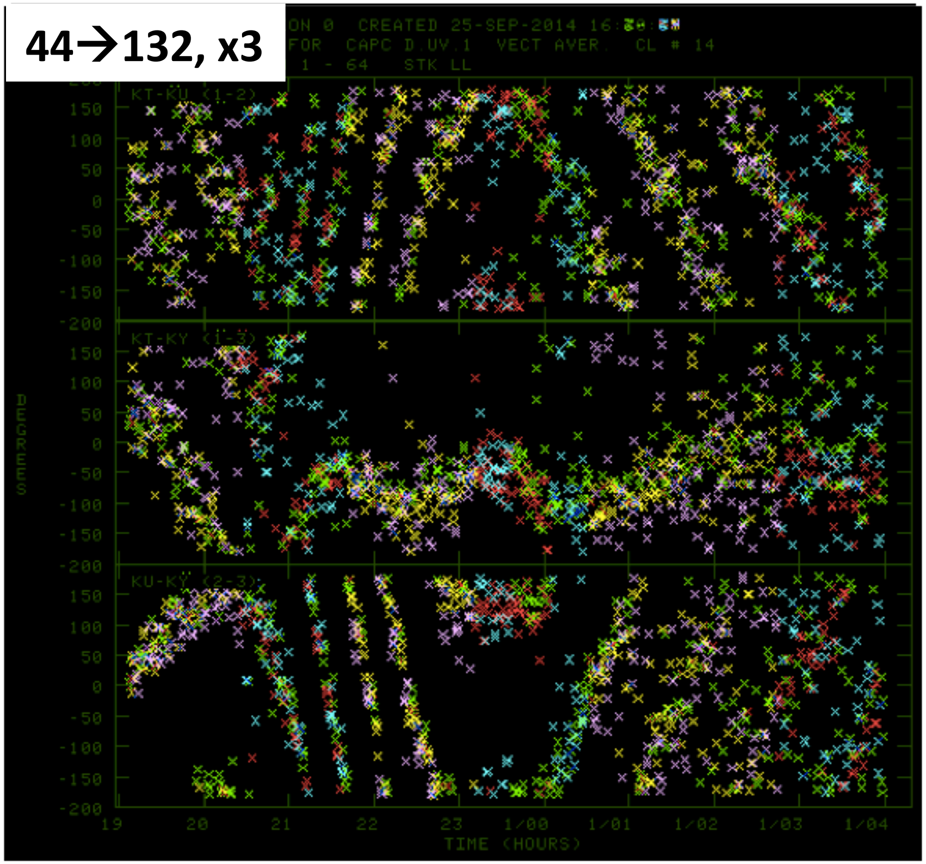

22 GHz, raw
44 GHz, raw
88 GHz, raw
132 GHz, raw
22→44, x2
22→88, x4
22→132, x6
03-OCT-2014 11:46:11
VECT AVER.
03-OCT-2014 11:48:42
CREATED 25-SEP-2014
KT-KY (1-3)
KU-KY (2-3)
DEGREES
TIME (HOURS)

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

44→88, x2

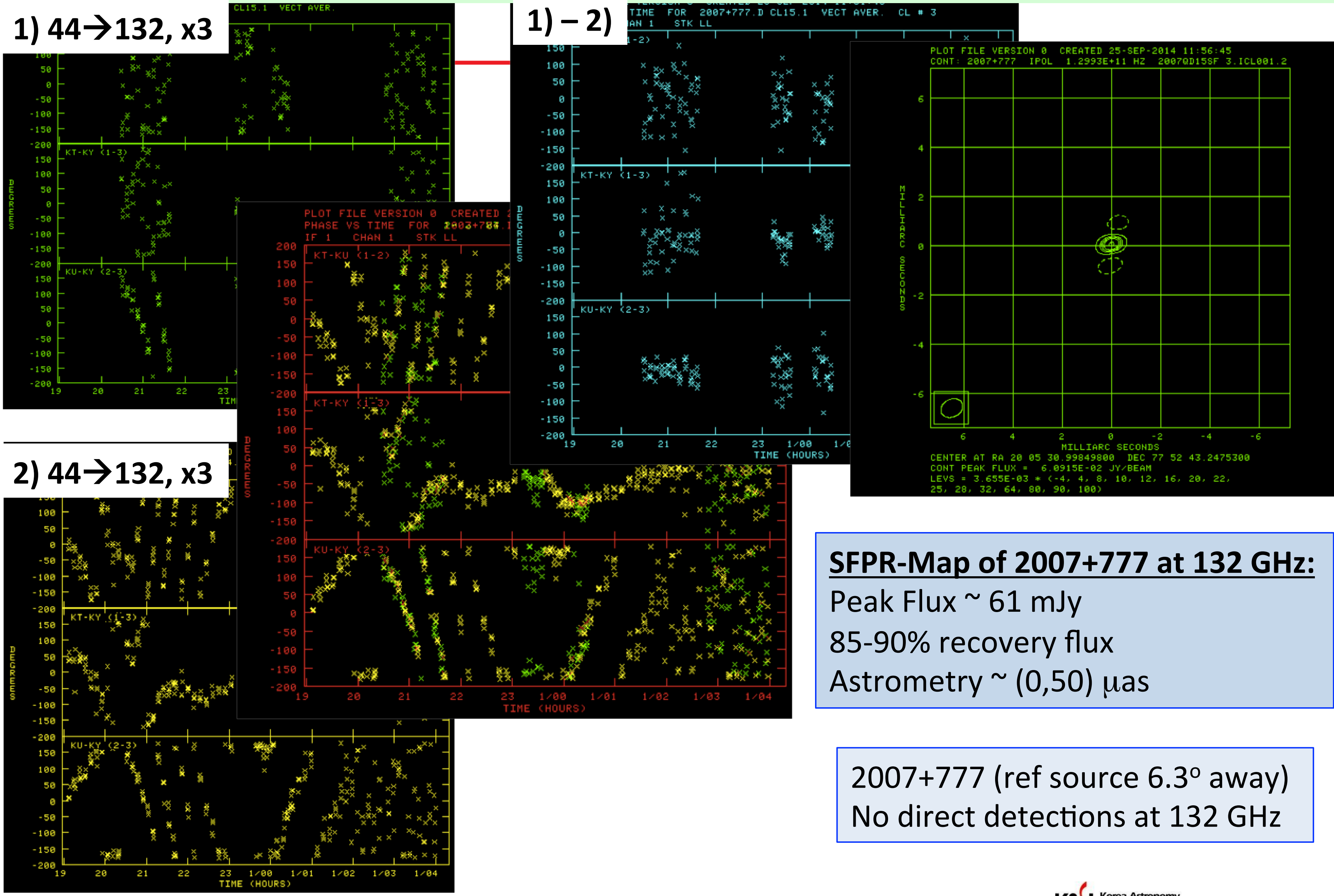


44→132, x3



SFPR analysis –
“2-frequencies” 44 GHz ,132 GHz
&
“2 sources” 1), 2)

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



SFPR-Map of 2007+777 at 132 GHz:

Peak Flux ~ 61 mJy

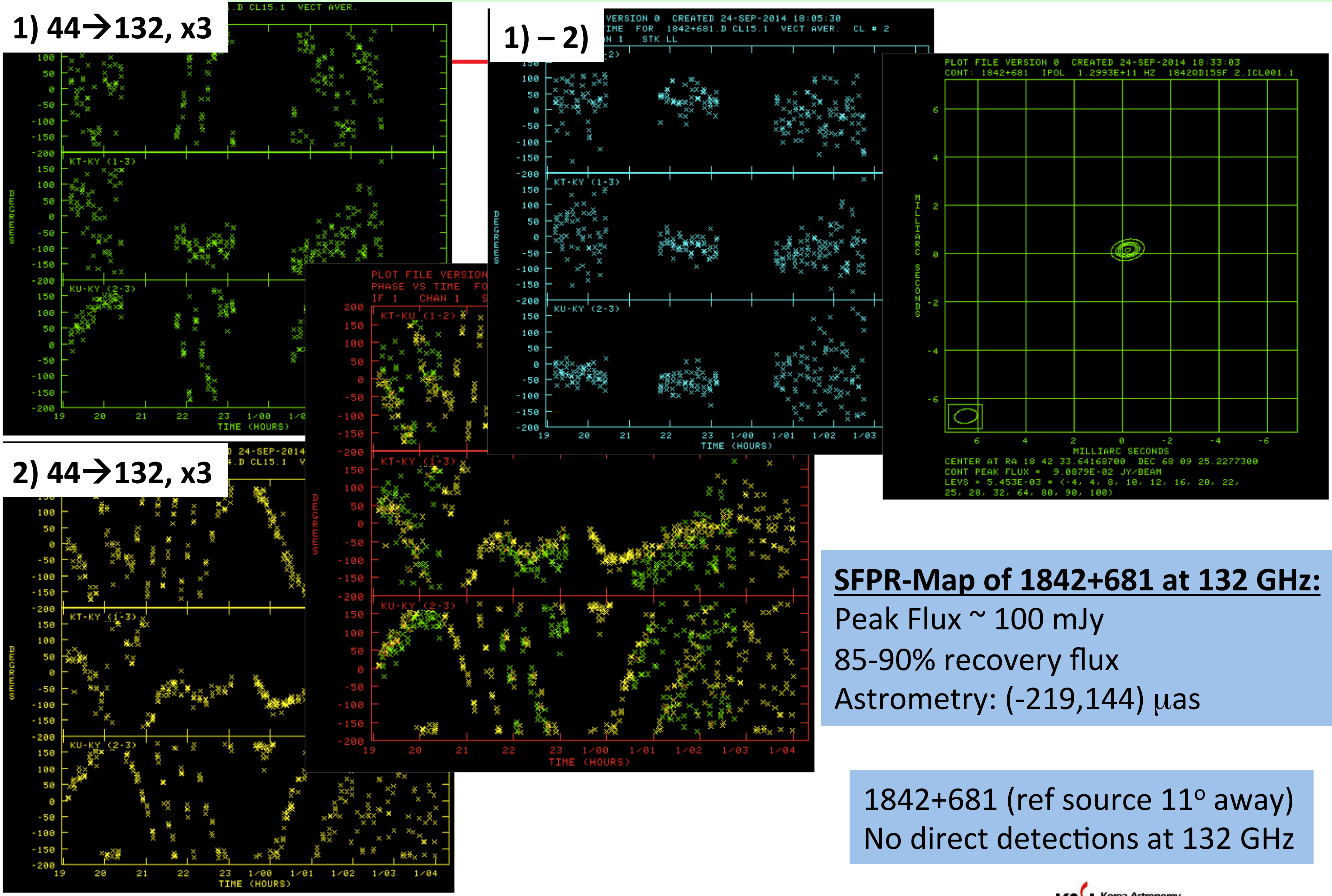
85-90% recovery flux

Astrometry ~ (0,50) μas

2007+777 (ref source 6.3° away)

No direct detections at 132 GHz

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



SFPR-Map of 1842+681 at 132 GHz:

Peak Flux ~ 100 mJy

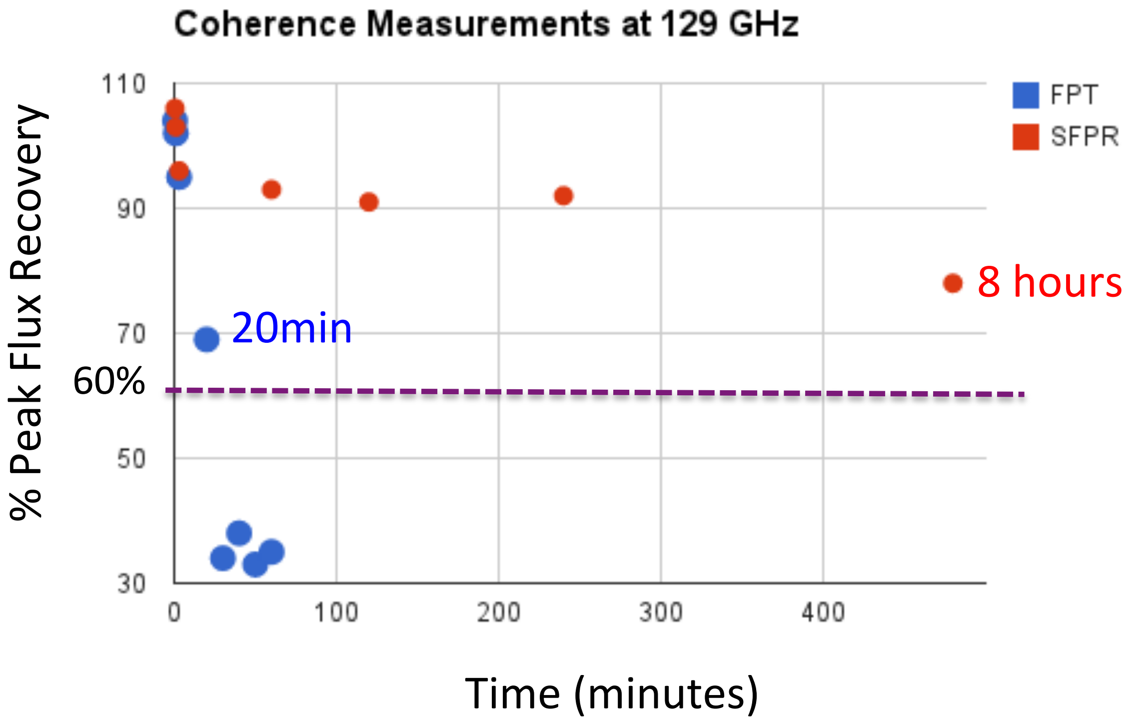
85-90% recovery flux

Astrometry: (-219,144) μas

1842+681 (ref source 11° away)

No direct detections at 132 GHz

Coherence Studies using KVN Observations, for FPT & SFPR analysis



FPT for 44 GHz → 132 GHz increases coherence up to 20 min integration time
SFPR for 44 GHz—> 132 GHz, plus 11^0 ref source, increases coherence up to many hours

More KVN SFPR astrometry

Continuum:

- **OJ287 – 22-43 GHz**
- **(Verification of astrometry using comparative VLBA, Rioja et al. 2014)**
- **3C 66A & 3C 66B, 22-43 GHz**
- **(See poster Zhao et al.)**
- **Polar cap 22-43-86-129 GHz**

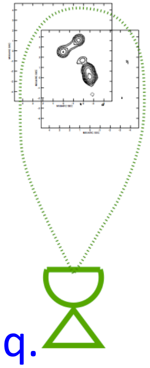
Spectral Line:

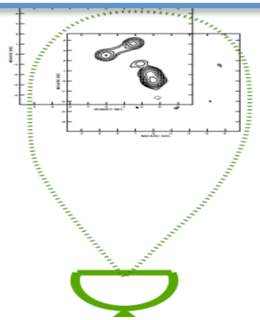
- **RLMi 22 (H_2O masers) / 44 (SiO masers) GHz + relative astrometry**

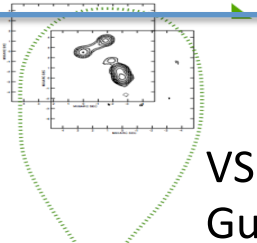
(Dodson et al. 2014)

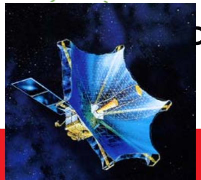
SUMMARY

“in-beam”









Error	**Obs. Freq**	**Limited Application**	**Wider Application**	**EXTRA Wider Application**	
TROP	~~Mode[illegible]e Freq.~~ Up to Very High Freq.	Ang. sep 33” Dilution factor 10^{-4} ~10 micro-as	*ATC* (Reid+Brunthaler 2004) **Ang. Sep** 2-1 deg **Freq Range:** 5-43 GHz 10 micro-as	*SFPR* (Rioja+Dodson 2011) **Ang. Sep** Several deg **Freq Range:** 22 - --- GHz < 10 micro-as	*In ALMA, EHT era*
ION	Low Freq.	S, L-band ~100 micro-as		*“Multi-view”*	*In SKA era*
Orbit	Space VL	VSOP@C,L band: 14’, 33” Guirado et al 2001 Porcas&Rioja 2000		*SFPR* **Ang. Sep** Several deg **Freq Range:** 22 - --- GHz << 10 micro-as	*In Chinese Space VLBI era?*

SUMMARY

ATC accelerated the use of astrometry, but still limited in frequency range.
A wide range of science has been carried out with astrometry and ATC.

In addition I have presented:
New ways of doing astrometry outside of comfort zone of PR, i.e. SFPR
- → high precision astrometry with mm-VLBI

SFPR enables:
- **Superior tropospheric compensation, boost array with increased sensitivity.**
- **High precision astrometry at (sub-)mm-VLBI**
- **No upper frequency limit (?)**

Astrophysical applications:
- Multi-frequency **studies with "bona fide" astrometric registration, in continuum and spectral line observations.**
- **Weak Sources**

Widely applicable, to many sources
Very effective use of observing time
Technology ready, Slow telescope switching

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What about a new capability for the EVN?