International Centre for Radio Astronomy Research

Precise Astrometry today and tomorrow with Next-Generation Observatories

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Curtin University

The University of Western Australia

Overview

Sample of Astrophysical Applications in a variety of fields
Bona fide astrometric measurements with VLBI 2016-2018

① SKA and methods for high precision (~ μas) astrometry
    MultiView and Pathfinder demonstration

② VLBI in Gaia era
    Comparisons and comments

③ Galactic Structure
    Updates on BeSSeL /VERA project

④ Evolved Stars and chromatic-Astrometry
    Results from the KVN

⑤ AGN core-shifts & alternative Calibration Methods
    UVPAP, MFPR

⑥ Technological Developments relevant to astrometry
    BRAND, PAFs, Global multi-freq. mm-VLBI array

The quest for accurate astrometry…

sure_colored.jpeg (JPE... http://upload.wikimedia.org/wikipedia/co...

$\sigma_{POS} \sim \theta_B$ / SNR **(Thermal Noise Limit)**

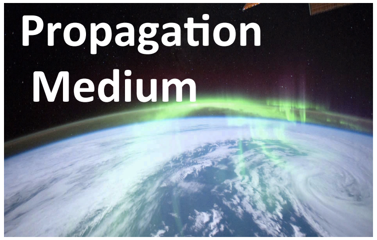
VLBI ➔ micro-as (μas) astrometry

IF you can remove SYSTEMATICS

1) Long baselines, large collecting areas to reduce *thermal errors*

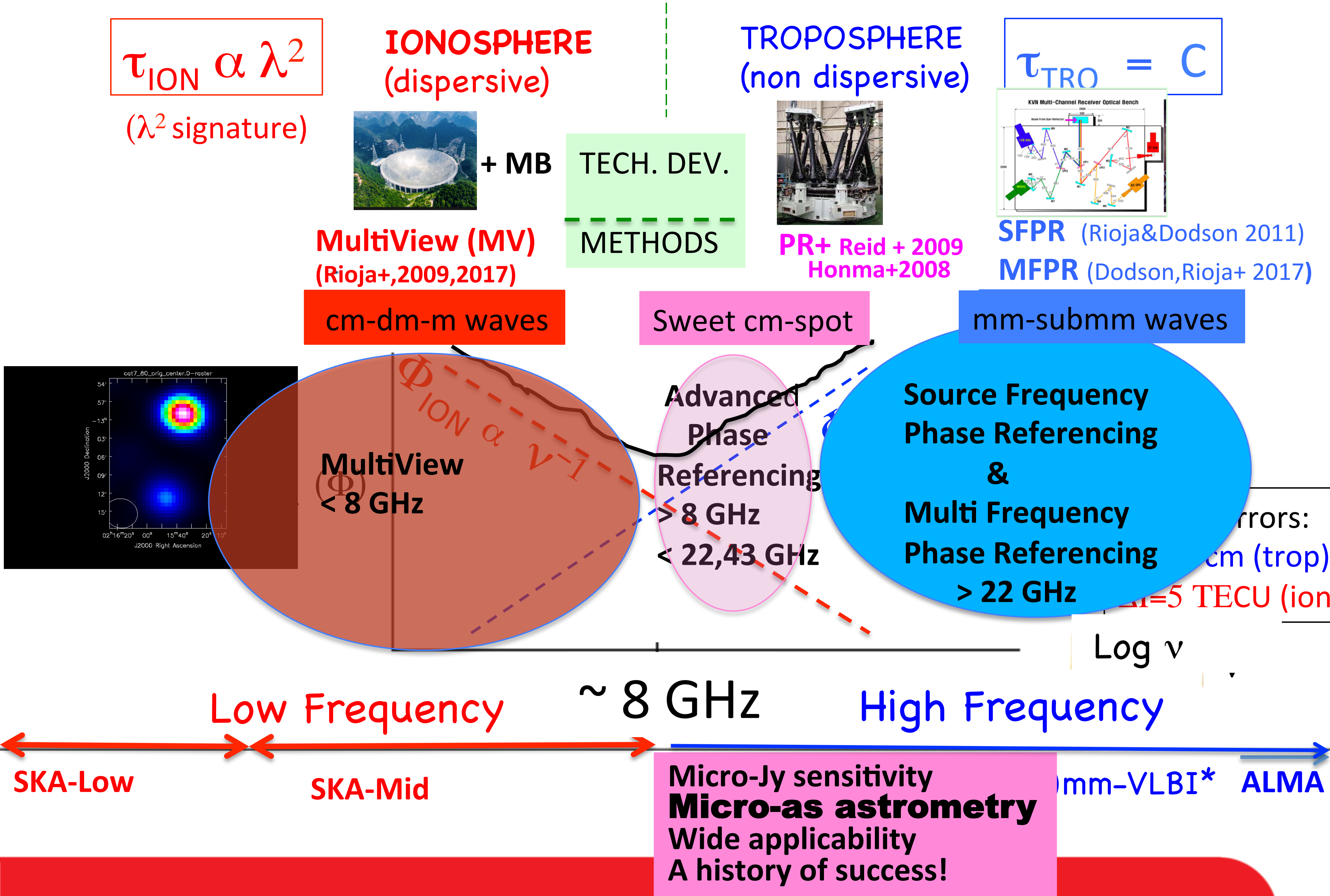
23/03/14 10:32 PM

2) Requires a matching improvement in **methods** to calibrate out *systematic errors*.

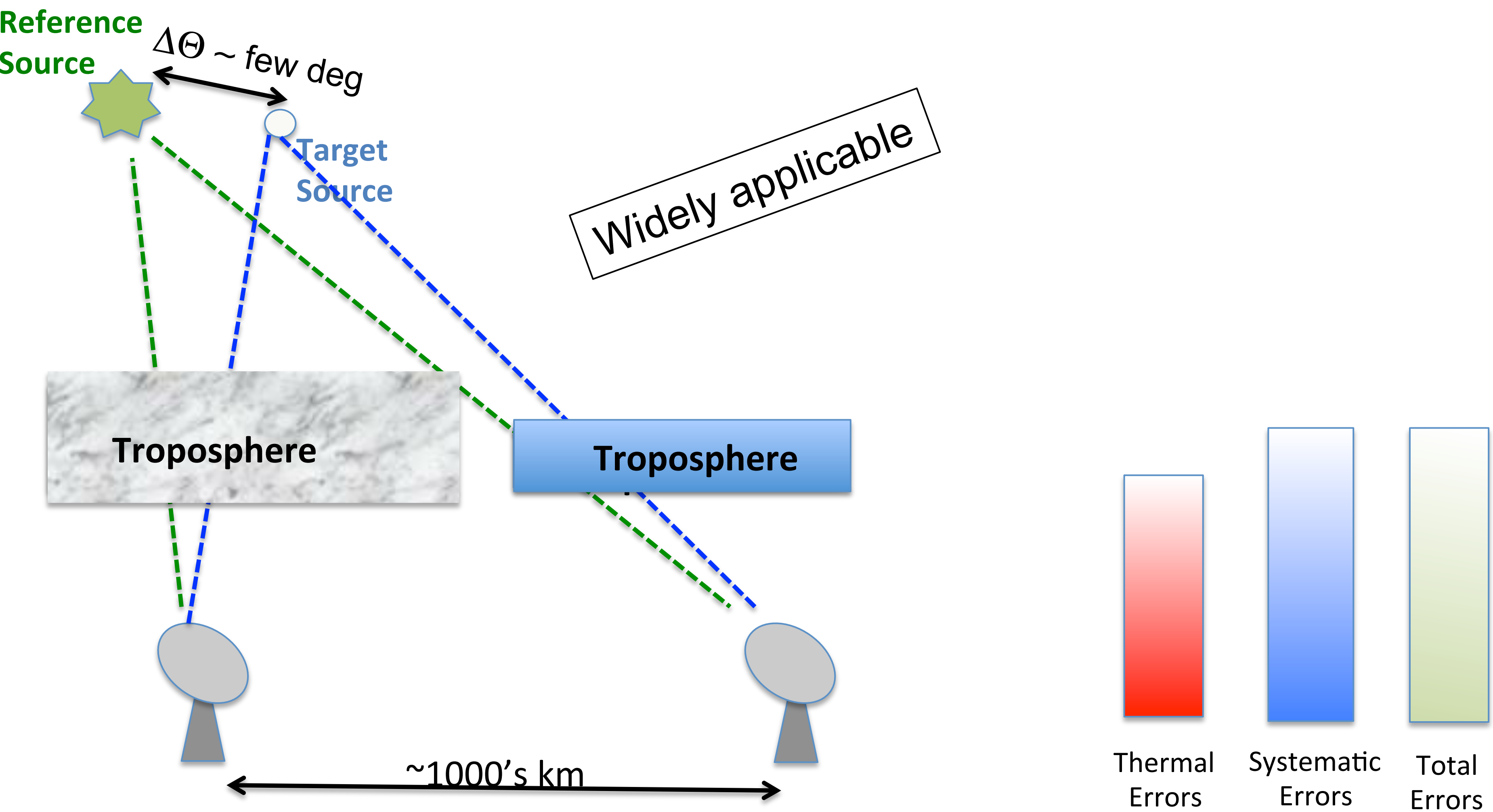


(independent atmospheres)

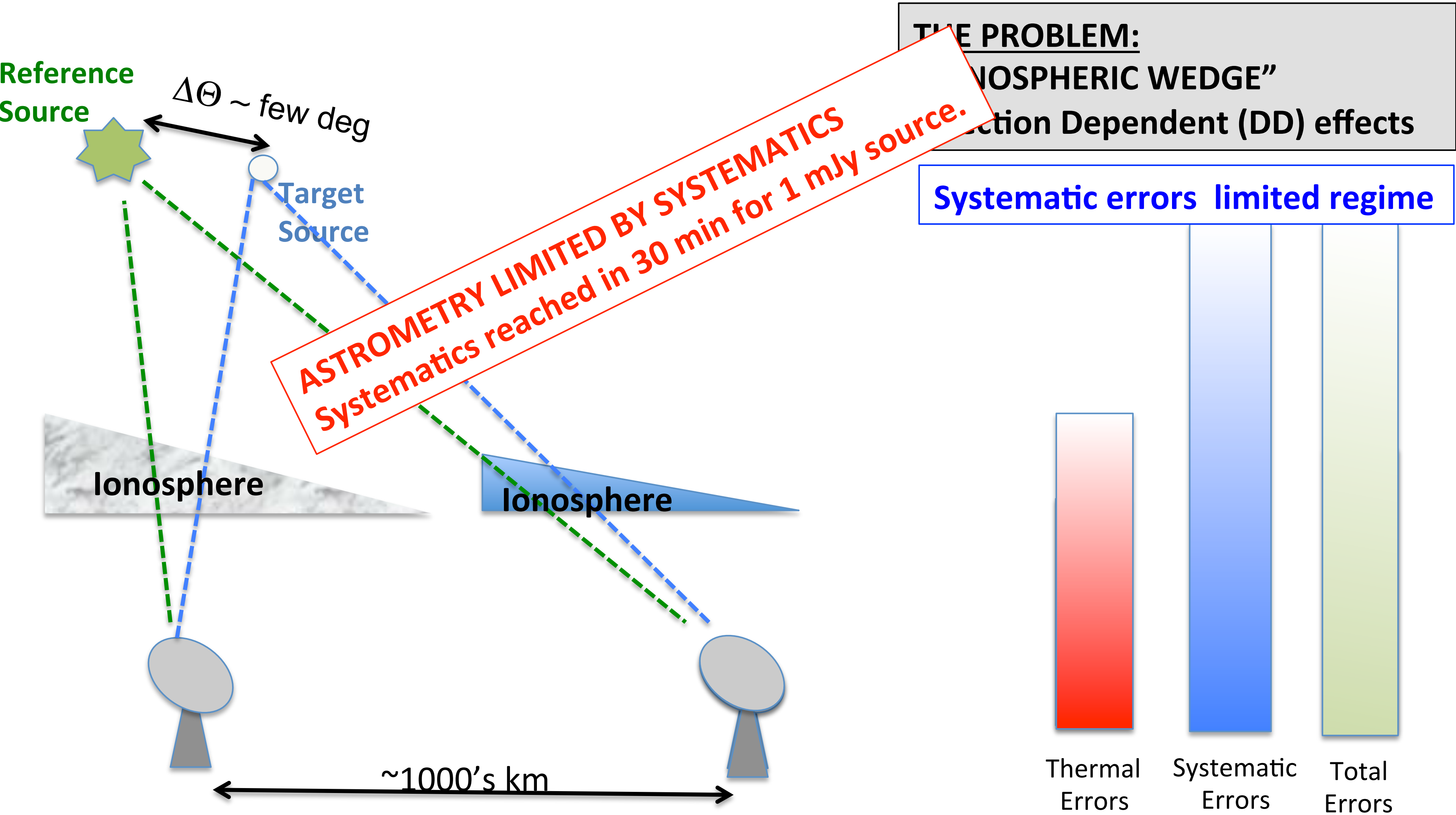
The Many Faces of the Propagation Medium



High Frequencies & Troposphere



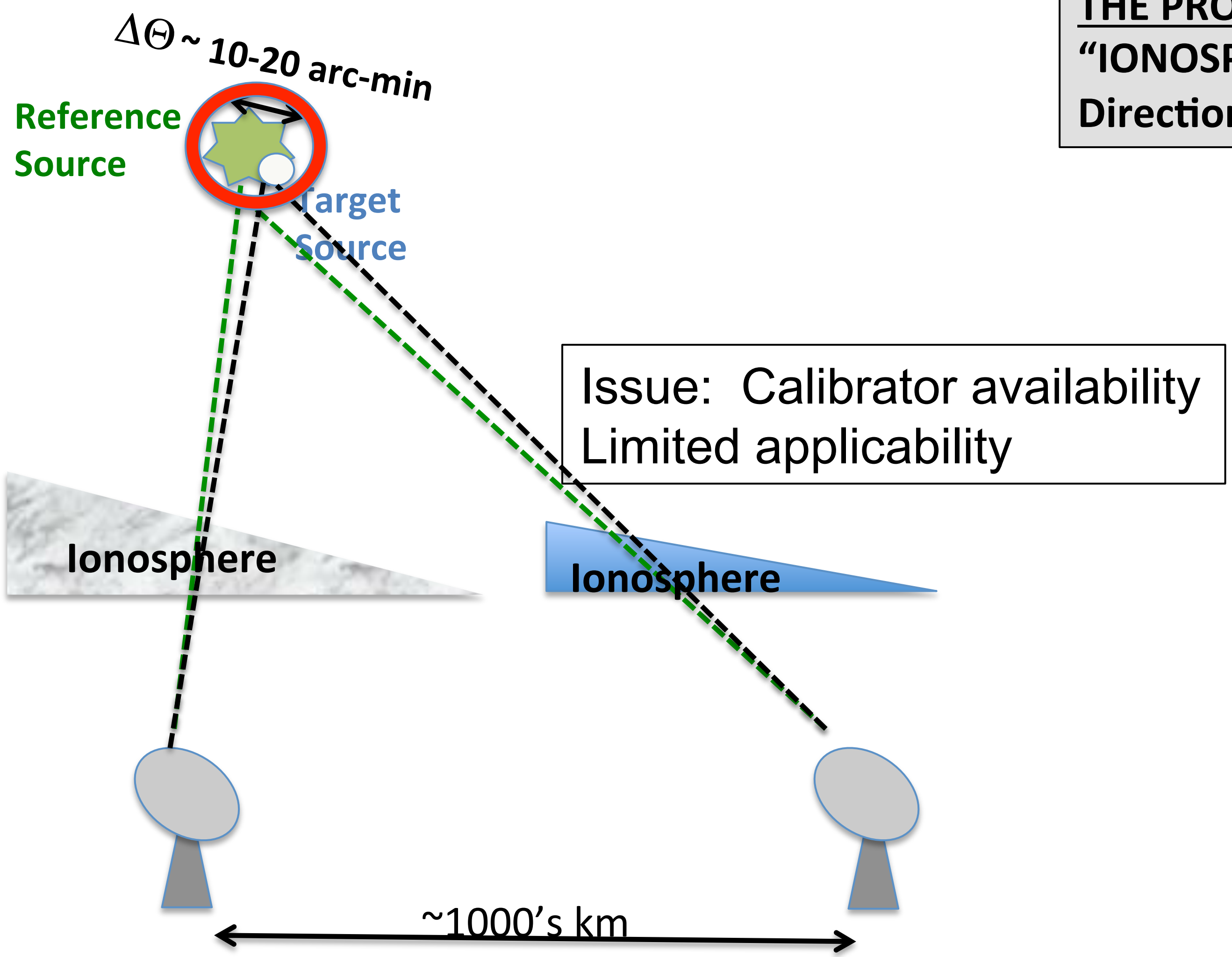
Low Frequencies & Ionosphere

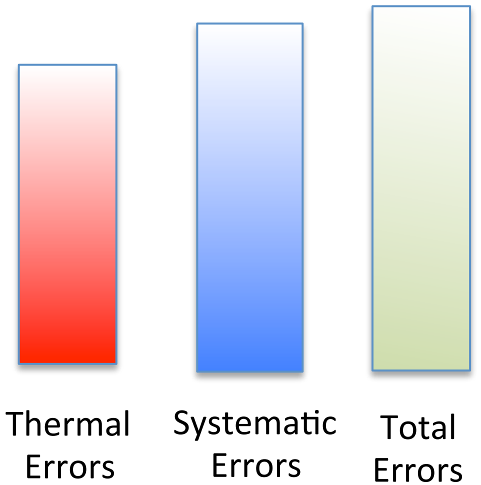


Sketch showing the limitations of general PR at low frequencies

Low Frequencies & Ionosphere

THE PROBLEM:
"IONOSPHERIC WEDGE"
Direction Dependent (DD) effects

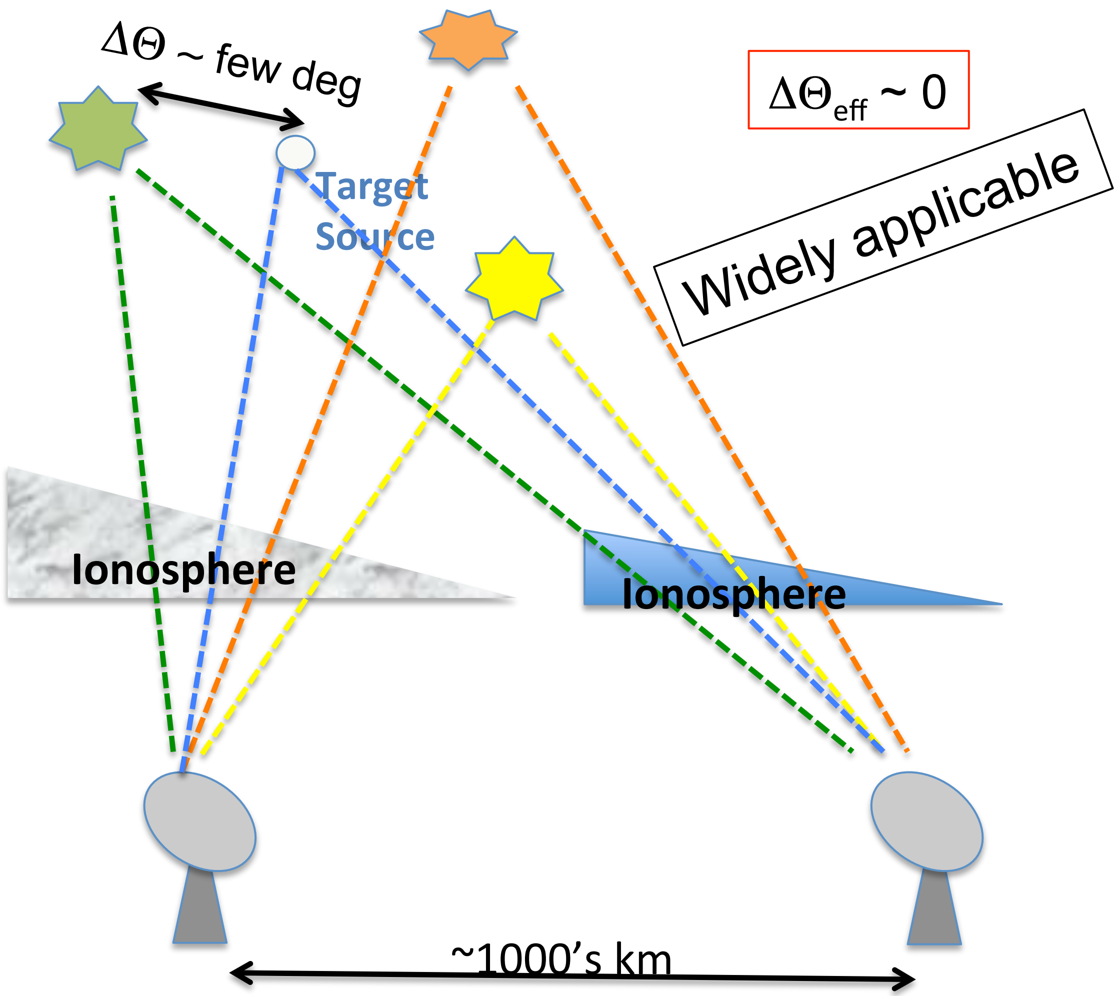




OPTIONS to overcome DDEs:

One VERY close reference source and use conventional PR *(in-beam)*

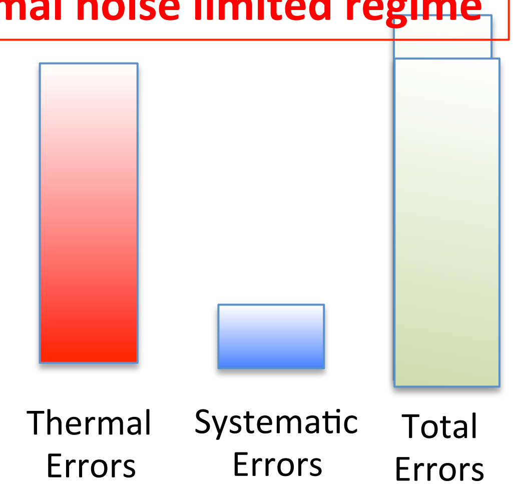
Low Frequencies & Ionosphere



THE PROBLEM:
"IONOSPHERIC WEDGE"
Direction Dependent (DD) effects

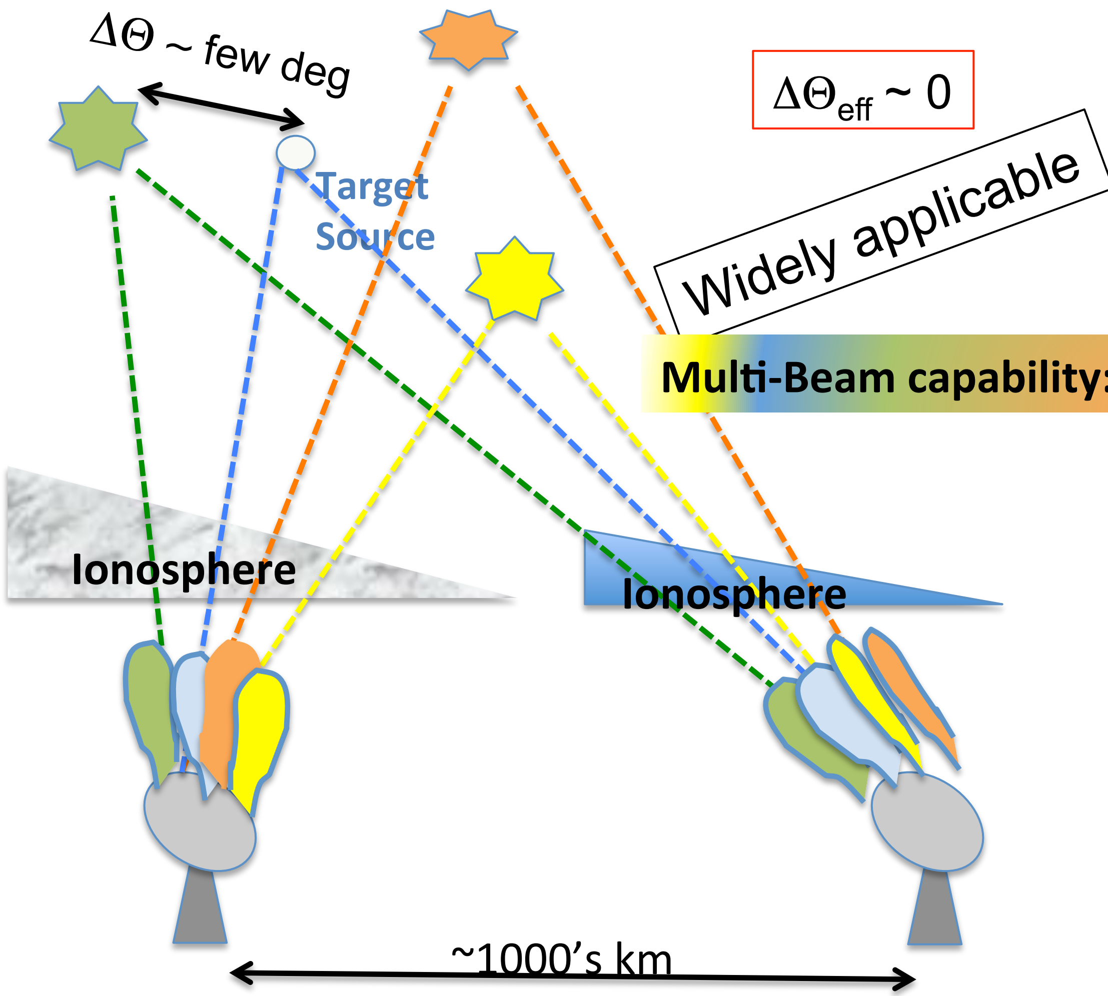
obs. strategy: **switching**
fast slewing

Thermal noise limited regime



Our hypothesis to overcome DDEs with: *Multiple (3) reference sources, **further away**, 2D interpolation in visibility domain ➔ MultiView* *(Rioja, Dodson+, 09,17)*

Low Frequencies & Ionosphere

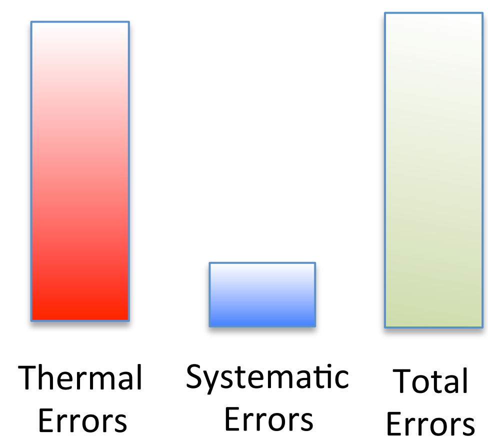


THE PROBLEM:
"IONOSPHERIC WEDGE"
➔Spatial structure

obs. strategy: **switching**
fast slewing - - much less efficient

*obs. strategy: **simultaneous***
minimum 4 (tied array) beams

Thermal noise limited regime



Our hypothesis to overcome DDEs with: *Multiple (3) reference sources, **further away**,*
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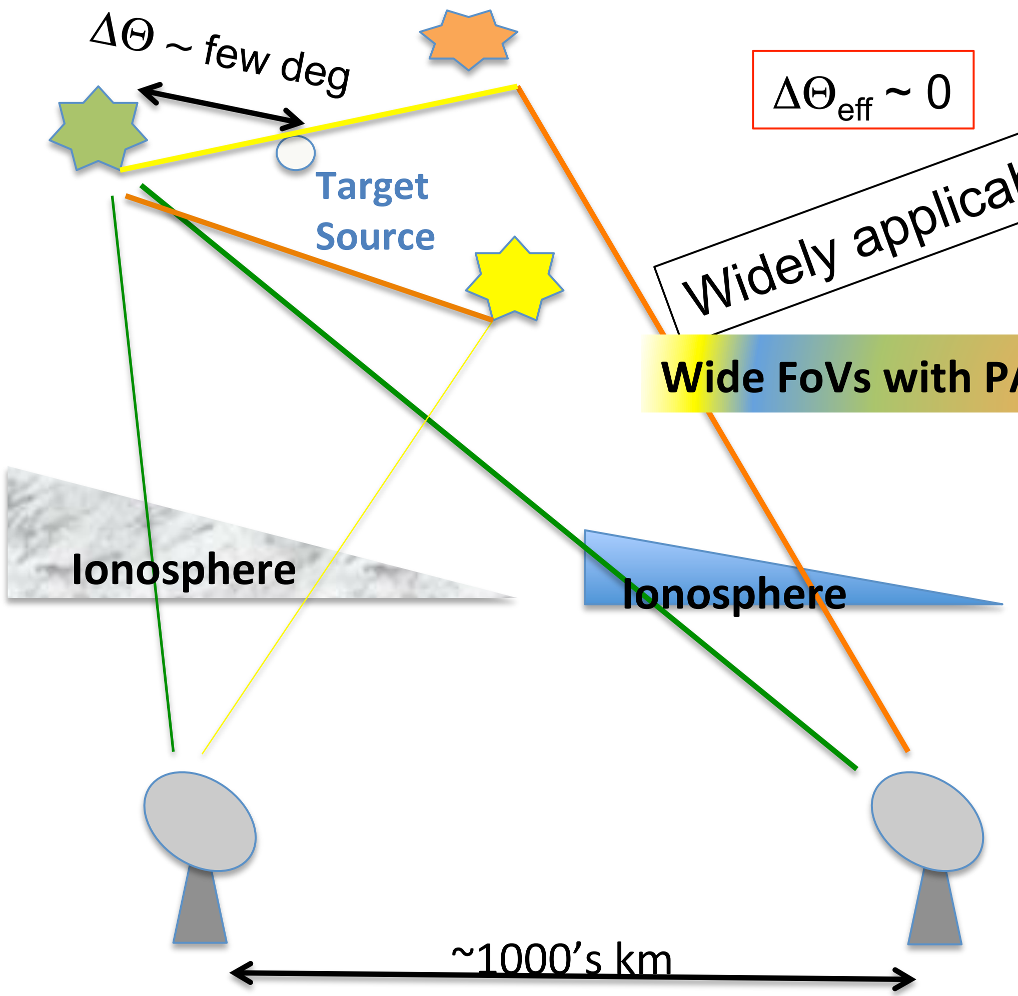
Low Frequencies & Ionosphere



ΔΘ$_{eff}$ ~ 0

Widely applicable

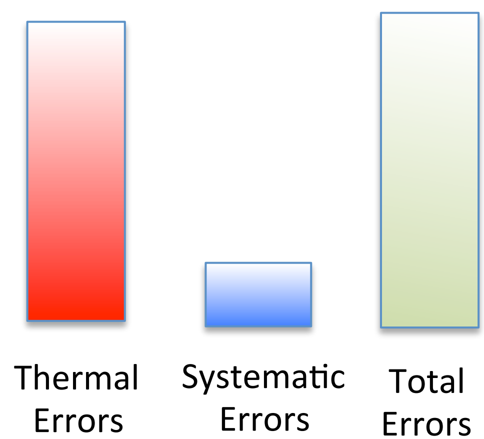
Wide FoVs with PAFs:

<u>THE PROBLEM:</u>
"IONOSPHERIC WEDGE"
➔Spatial structure

obs. strategy: **<u>switching</u>**
fast slewing - - much less efficient

*obs. strategy: **<u>simultaneous</u>***

Thermal noise limited regime

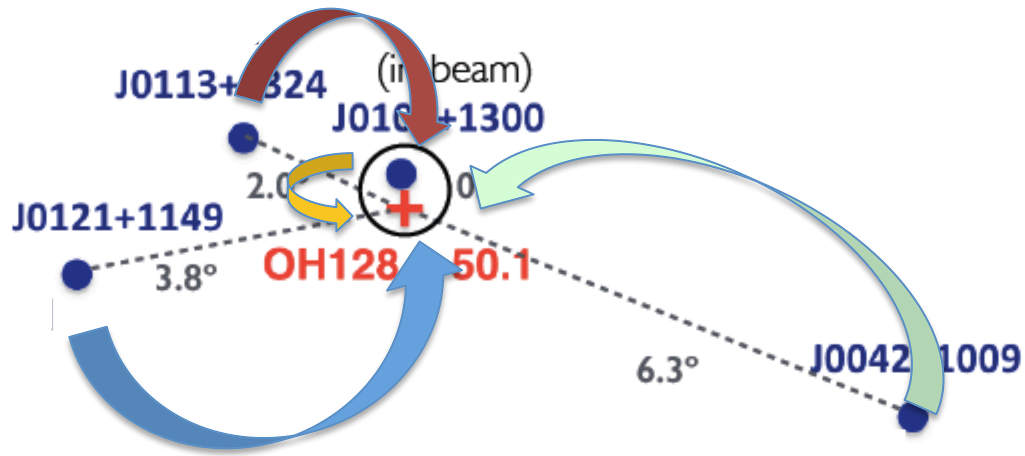


Our hypothesis to overcome DDEs with: *Multiple (3) reference sources, **further away**, 2D interpolation in visibility domain ➔ MultiView (Rioja, Dodson+, 09,17)*

Demonstration of MultiView: Comparative Astrometric Analysis

(*Rioja+ 2017; Orosz+ 2017*)

VLBA observations at L-band, AGNs / OH maser.
2 epochs, 1 month apart



<u>ANALYSIS METHODS</u>:

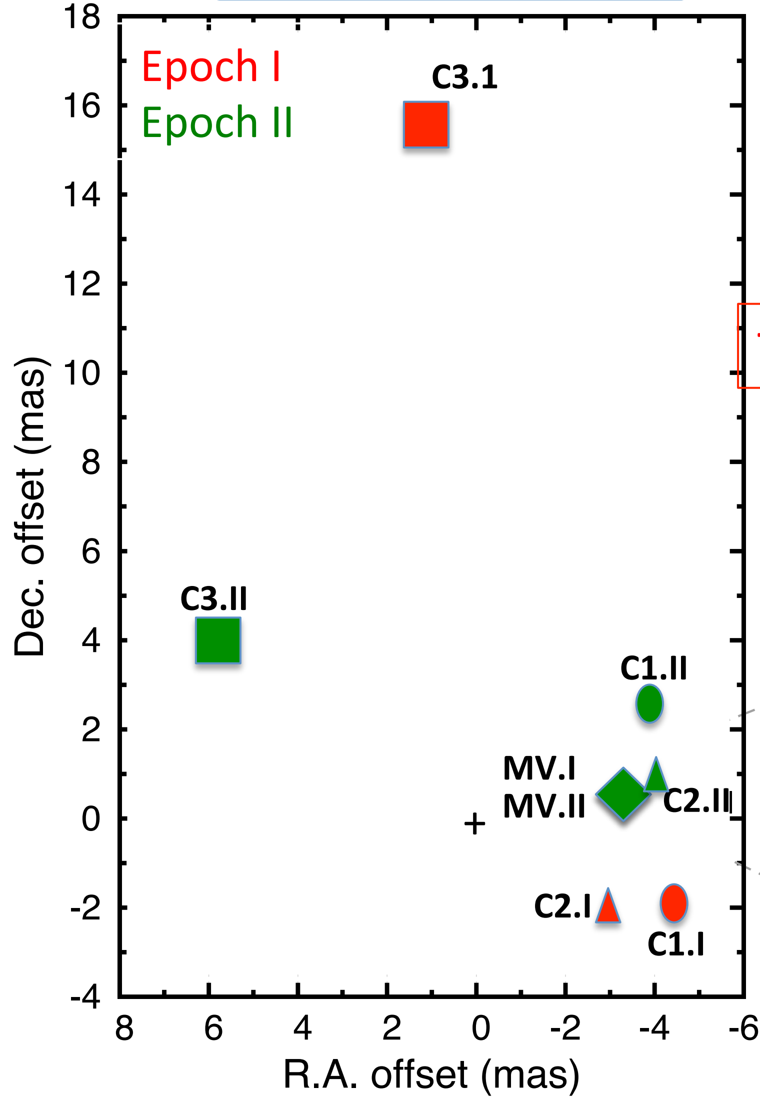
➔Phase Referencing (PR) : Single Calibrator (no spatial interpolation), range of angular separations ($\Delta\Theta$ =2° ,4° ,6° ,0.4°)

➔MultiView (MV) : Three Calibrators together + 2 D interpolation to position of target.

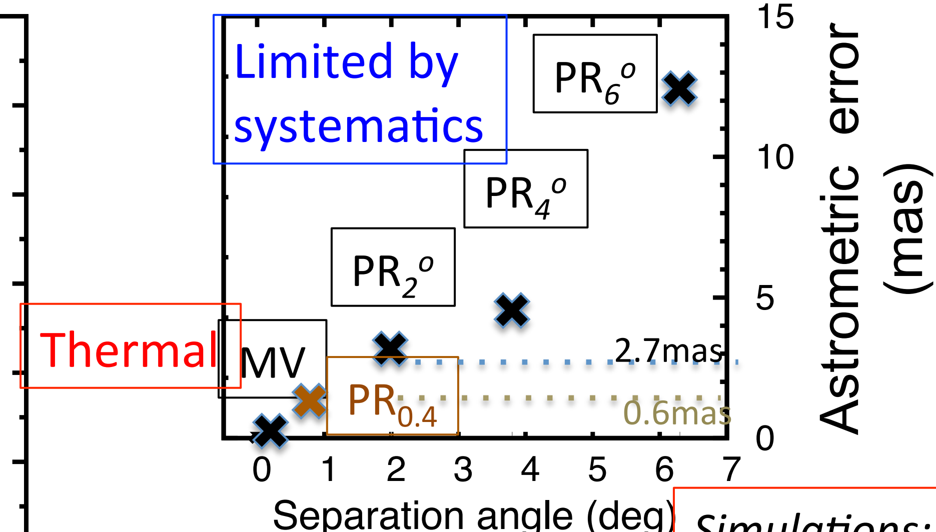
FoM: Use astrometric repeatability at both epochs as empirical estimate of systematics.

Comparative Astrometry (PR 2°; 4°; 6° vs. MV 2°+4°+6°): Position Accuracy

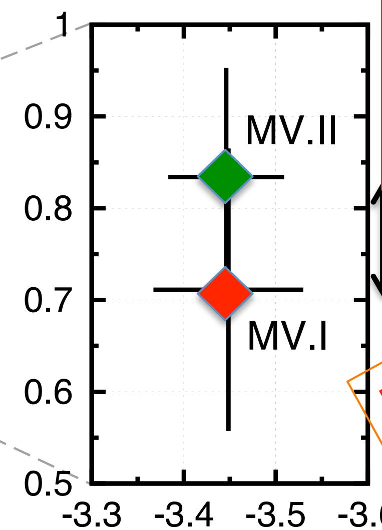
Astrometric Results



Repeatability between Epochs → Systematics



Simulations:
Equiv. Sep ~ 2°/10
0.2 deg = 12arcmin
[Jimenez, Rioja+2010]



~130 μas

Reach theoretical Thermal noise limit!

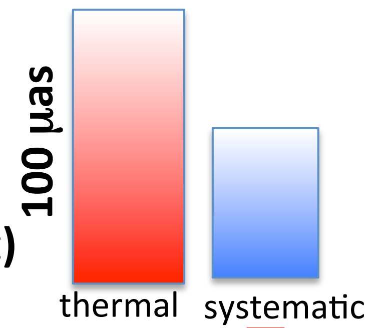
Astrometric Error per measurement
~ 100 μas

[Rioja et al. 2017] The higher repeatability of MV illustrates the gain using

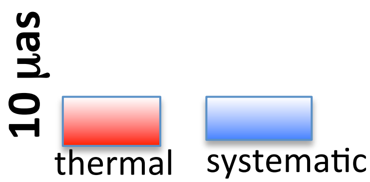
Ultra Precise Astrometry with SKA-VLBI

Huge increase in sensitivity (very small thermal noise errors)
Potential for 10 micro-arcsecond astrometric accuracy at L-band
Requires matching calibration of ionospheric systematic effects

Current Instruments:
(per measurement)



FAST MB-VLBI with MV



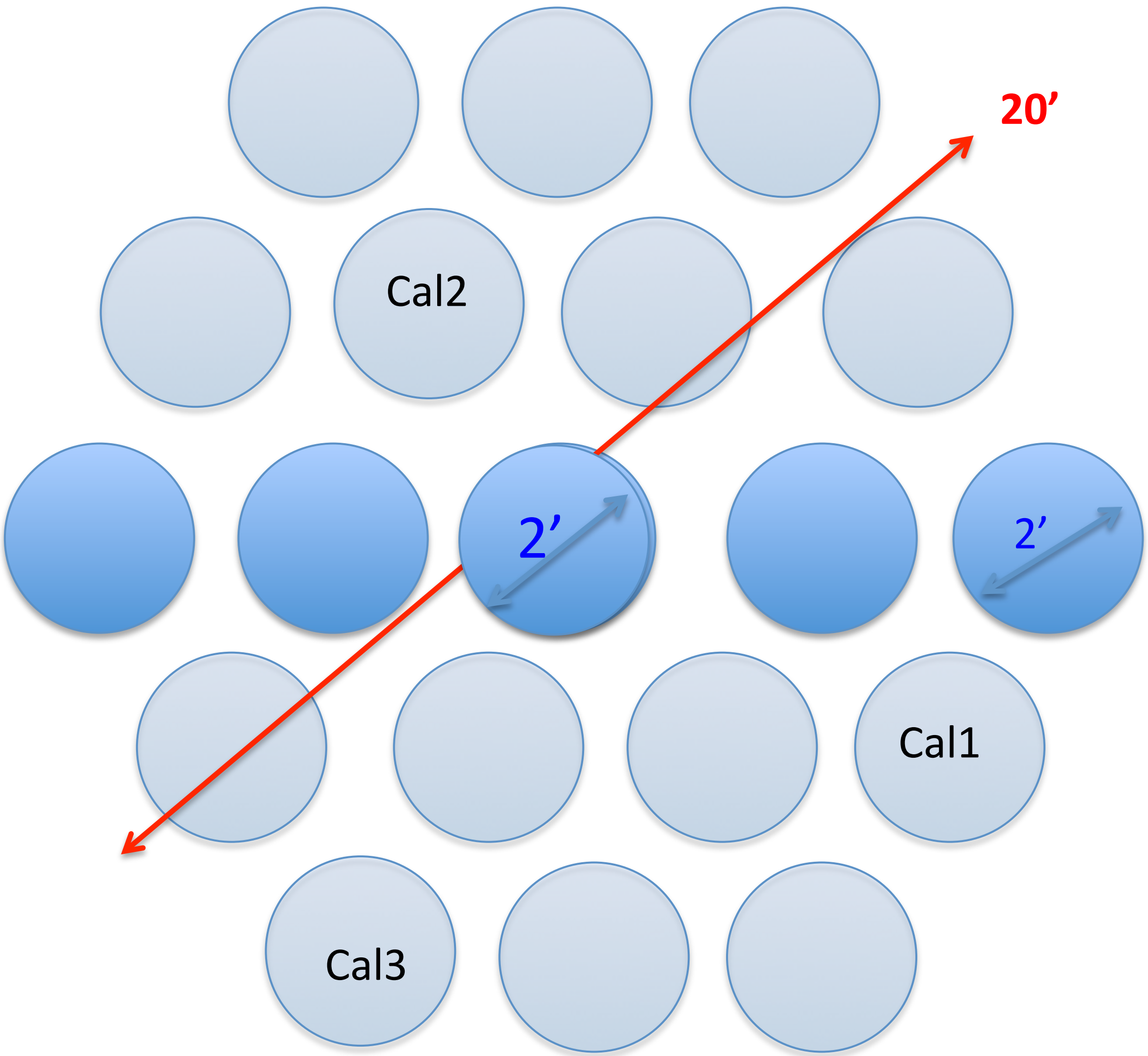
Calibration	Target-Cal Separation	Probability
PR (1 cal.)	$\Delta\Theta \sim 1'$	Unlikely
MV (3 cals.)	$\Delta\Theta \sim 10' - 30'$ **NEW**	OK

MultiView drives the requirement for a minimum of 10 SKA tied array beams.

Beams for MultiView Observations

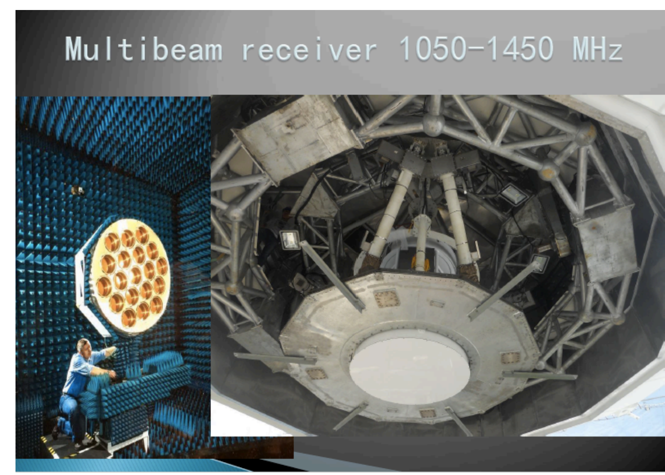
FAST: 300m

FAST19-beams array receiver for MultiView



FAST MB: 300m

Single-pixel 30m
Matches FAST FoV



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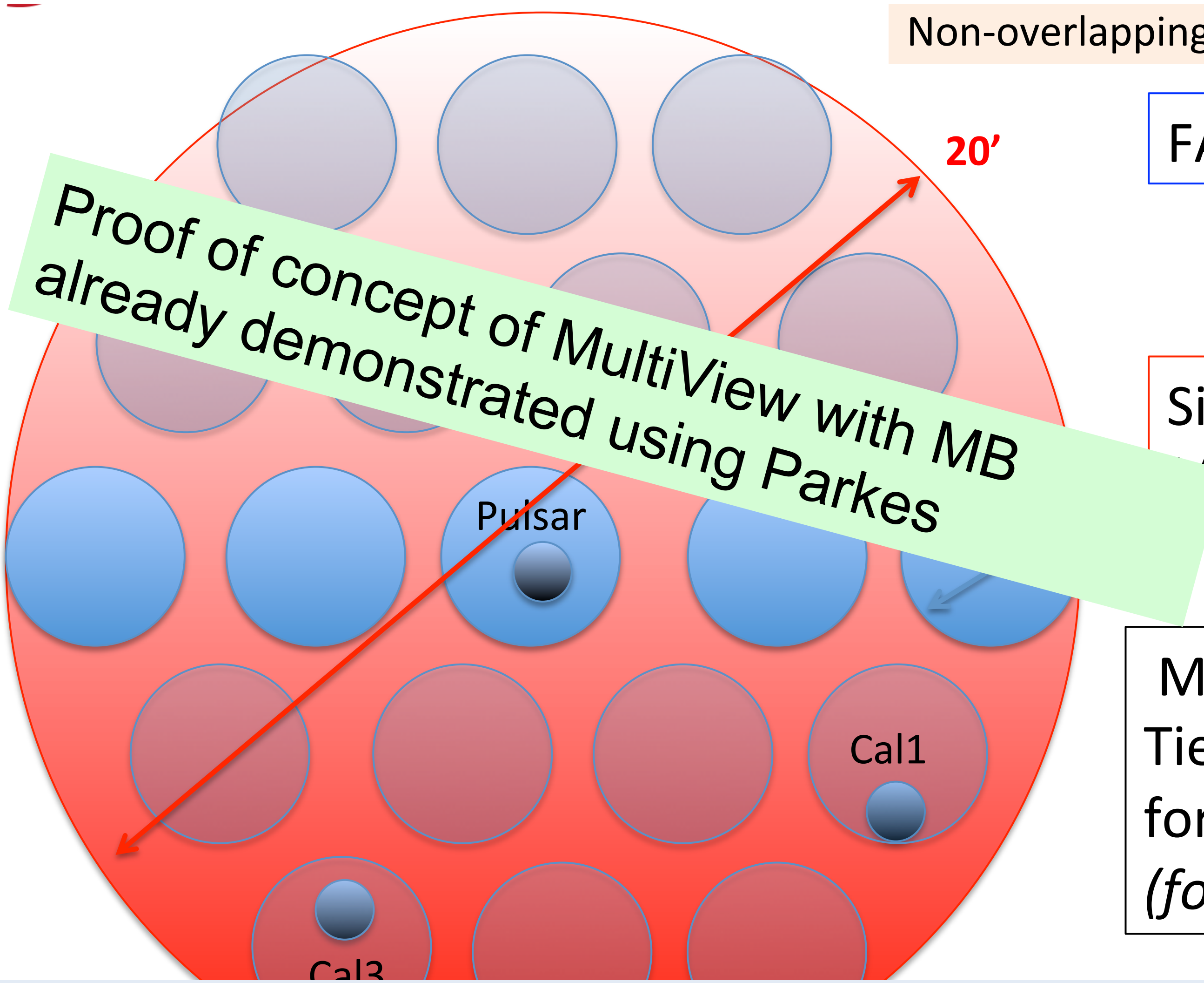


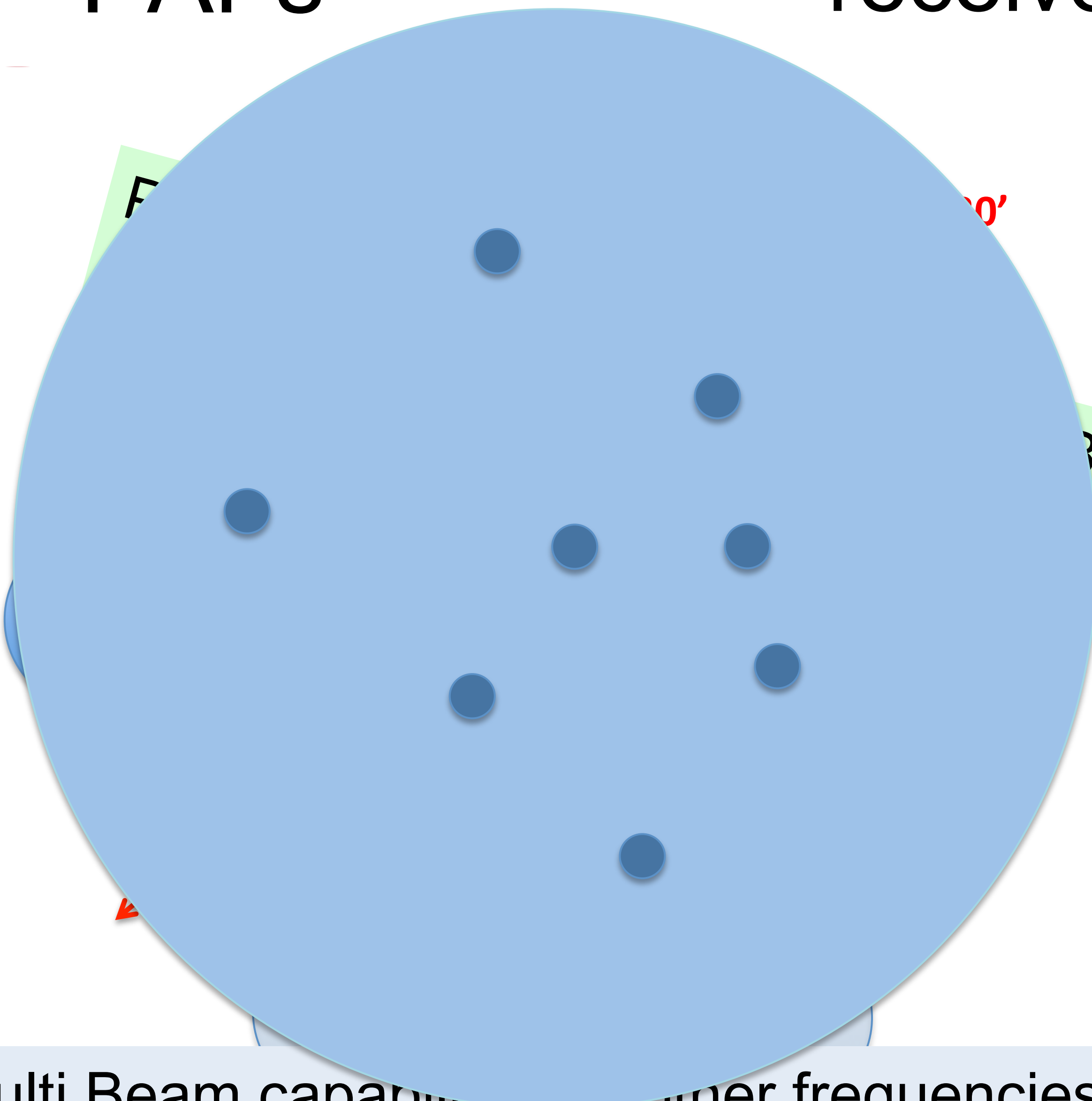
FAST MB: 300m

Single-pixel 30m
Matches FAST FoV

MeerKAT/SKA:
Tied-array beams
for 6km baseline
(for future)

Multi Beam capabilities at other frequencies (i.e. 1.6 GHz) would enable other science (OH-maser ultra precise astrometry)

PAFs receiver for MultiView



FAST MB: 300m

le-pixel 30m
ches FAST FoV

MeerKAT/SKA:
Tied-array beams for 6km baseline
(for future)

Multi Beam capabilities at other frequencies (i.e. 1.6 GHz) would enable other science (OH-maser ultra precise astrometry)

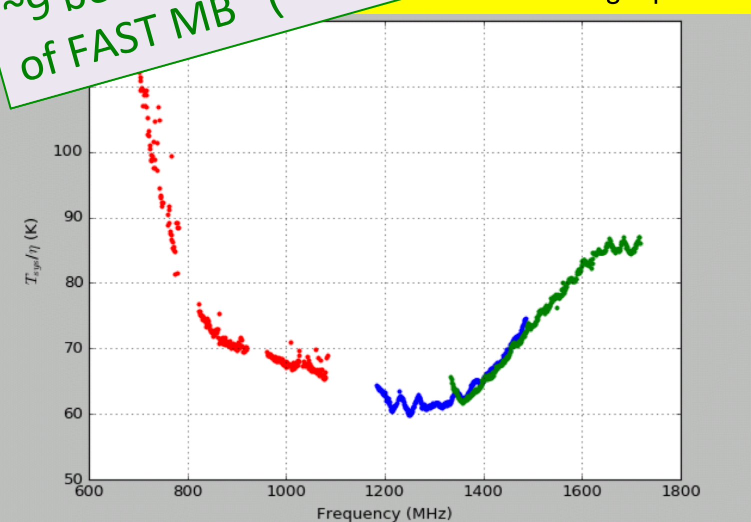
Wide FoV Technologies in large European telescopes

Effelsberg & Lovell – CSIRO MKII PAF

0.7-1.7 GHz

~9 beams for VLBI with MV to match the 20’ FOV of FAST MB (~ 4 beams for Lovell)

…oV = 36 x single pixel FoV



WSRT - Apertif

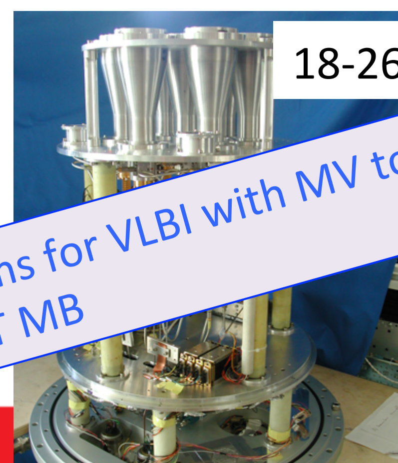
Multiple independent steerable tied -rray beams across the central 25-m disk equivalent beam for VLBI with MV

1.1-1.7 GHz

PAF FoV = 25 x single pixel FoV

SRT – Multi Beam

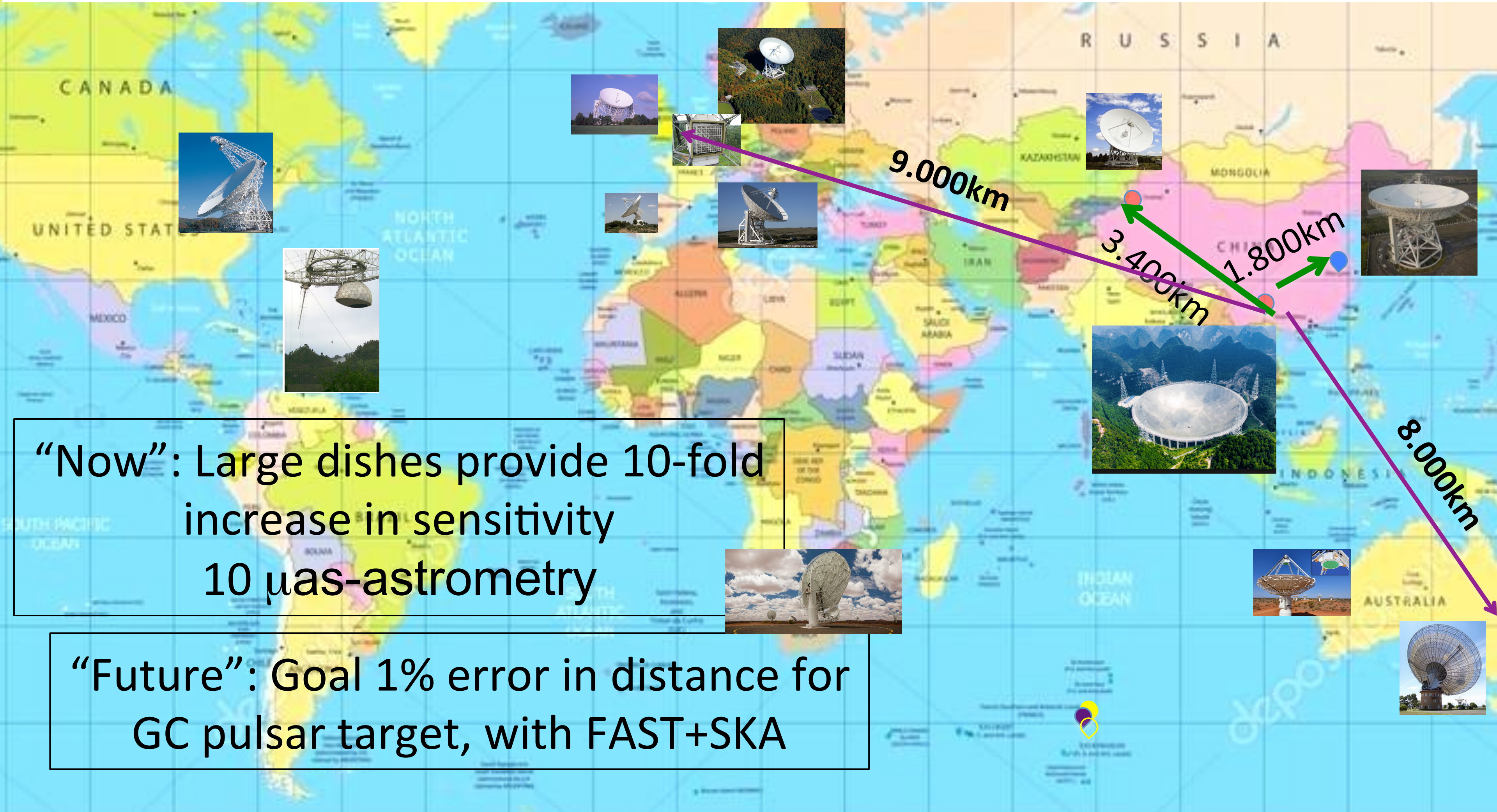
18-26 GHz



~4 beams for VLBI with MV to match the 20’ FOV of FAST MB

3- 4.5 GHz 7-feed under development

Early Science Case for FAST – VLBI:
Ultra Precise Pulsar Astrometry
Improve parallax/proper motion to enhance timing results



"Now": Large dishes provide 10-fold increase in sensitivity
10 μas-astrometry

"Future": Goal 1% error in distance for GC pulsar target, with FAST+SKA

- Many suitable targets.
- Proof of concept of MultiView with MB already demonstrated using Parkes

MultiView SUMMARY

Astrometry rapidly reaches systematic limits; increased sensitivity does not improve accuracy

Ultra Precise Astrometry with SKA-VLBI requires new experimental methods:
MultiView addresses these requirements.

FAST, like SKA, provides increased sensitivity. FAST has a MultiBeam receiver, so can perform MultiView-VLBI

FAST can provide an early science demonstrator for ultra precise astrometry in SKA-era.

Review of Recent Advances

Constrained by Selection Effects and Biases

Astrometry continues to demonstrate wide applicability
⇒ Many many results to cover!

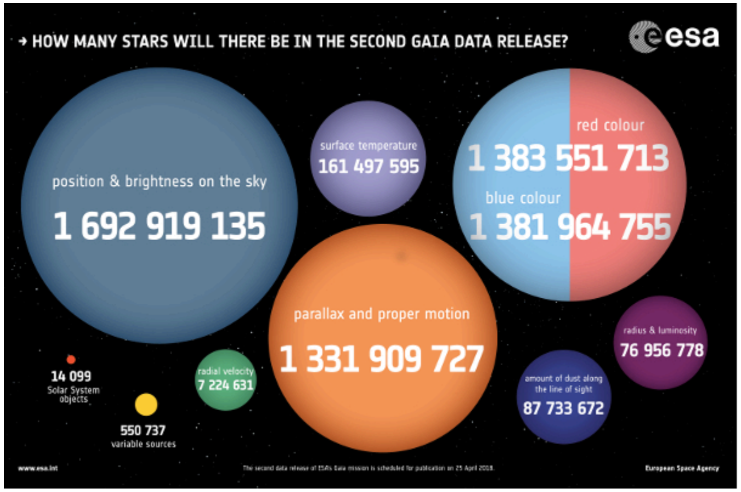
Limited to:
`bona-fide' astrometric measurements with VLBI 2016-2018

Attempt to break down by technique (e.g. *in-beam, SFPR, MV*)

Link to new technological developments that facilitate techniques
(e.g. *increased sensitivity, simultaneous freq., multiple beams*)

1. Radio Astrometry in the Gaia Era
Gaia DR2 vs VLBI

Gaia DR2 – data collected the first 22 months (Gaia Collaboration + 2018)



Comparison between Gaia and Accurate VLBI astrometry to verify Gaia results.

Very active field!

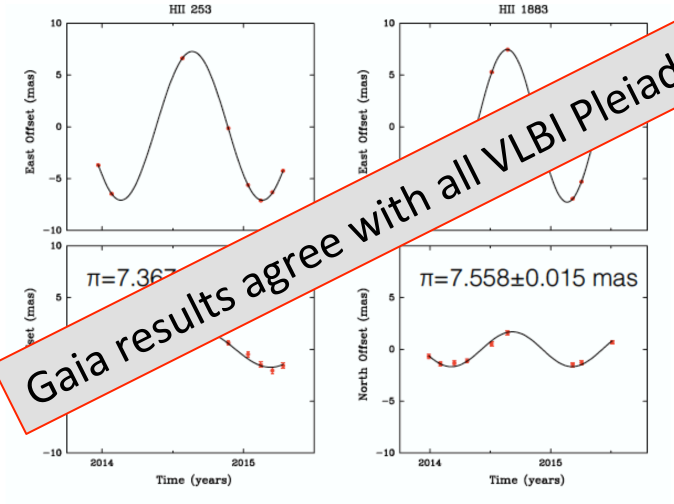
<u>Parallax</u> uncertainties: 0.04 mas (G<15); 0.1 mas (G=17); 0.7 mas (G=20)
All sources treated as single stars.
Systematics < 0.1 mas depend on position, magnitude, colour
Bias ~ 30 μas (Lindegren+ 2018)

VLBI
Phase referencing
Accuracy ~ 10 μas
Comparable to, or better than Gaia's target accuracy

1. Radio Astrometry in the Gaia Era

VLBA Pleiades LP: 4 new parallaxes (tot

Gaia results agree with all VLBI Pleiades astrometry

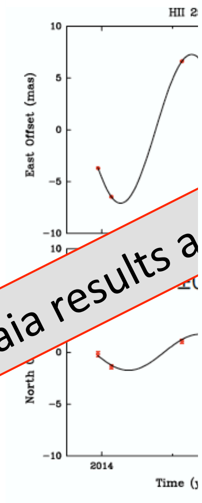


Mellis + 2018
https://osf.io/byrcf/

Remember…
Hipparcos Pleiades
Distance controversy

1. Radio Astrometry in the Gaia Era

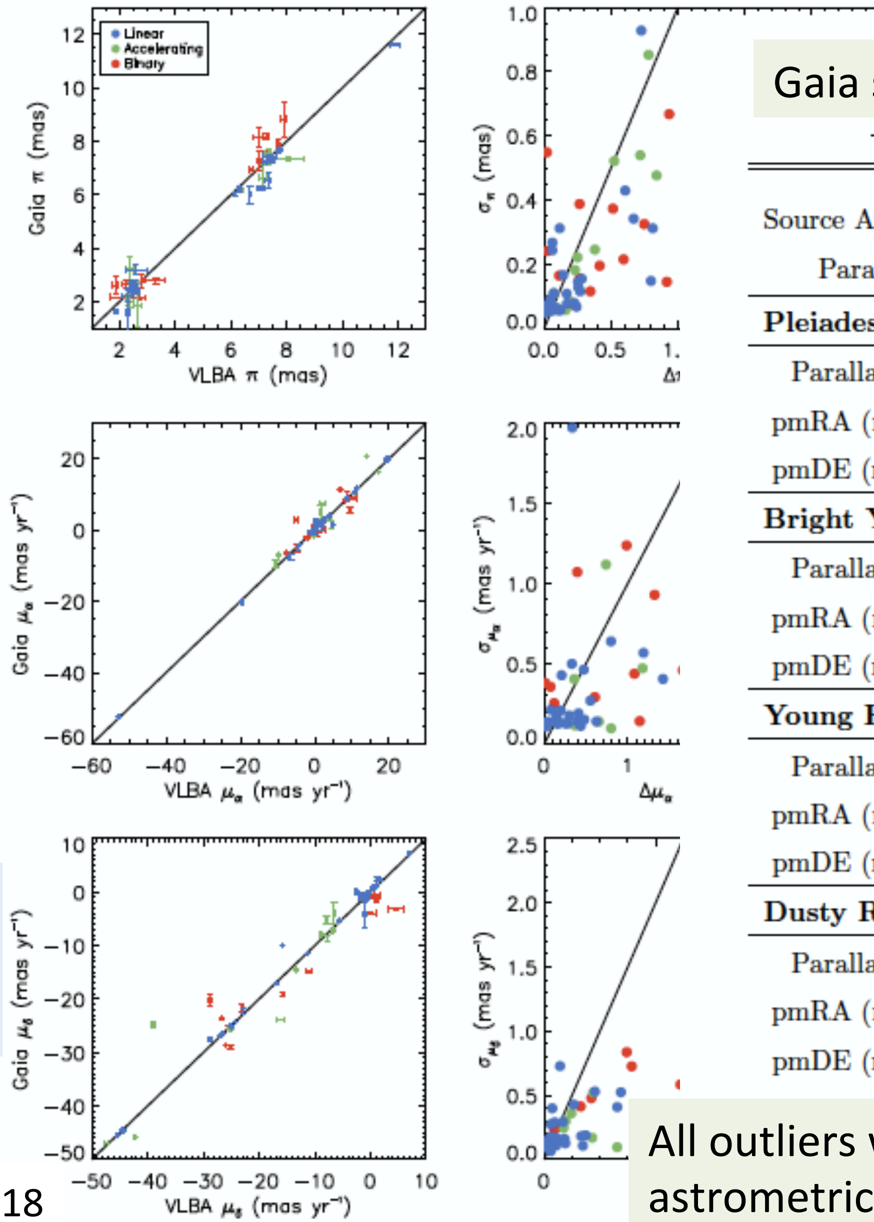
VLBA Ple



aia results a

Orion Star Forming Complex

Kounkel + 2018



Comparison of astrometric Solutions btw Gaia and VLBA

Differe... Combined uncertainty

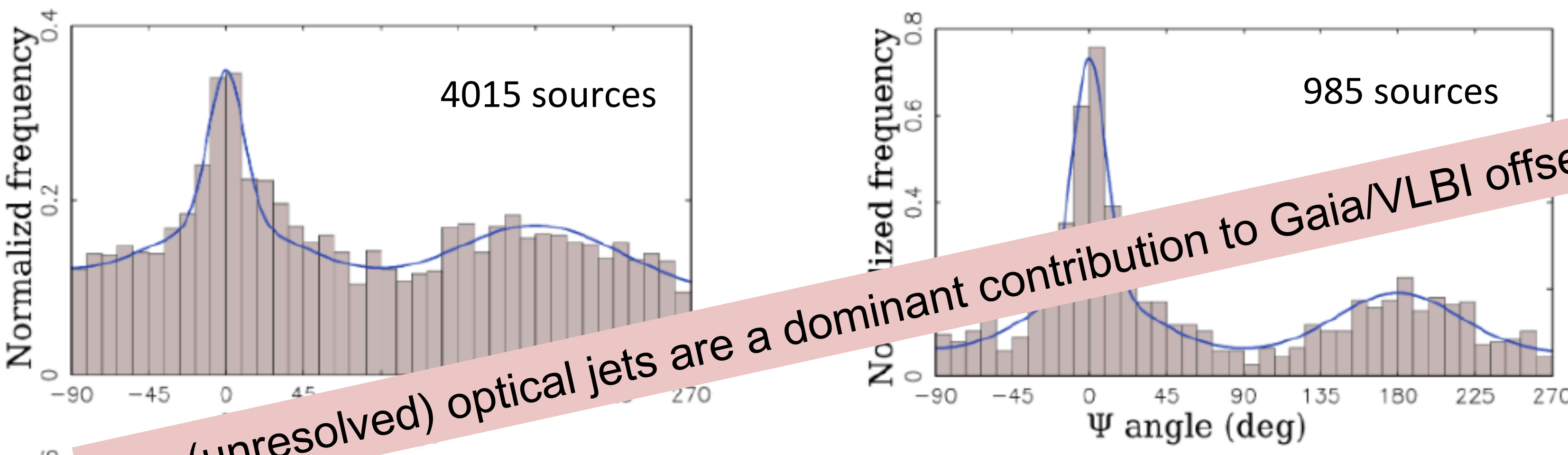
Gaia struggles with binaries and dusty stars

Source Astrometric Parameter	VLBI Value	*Gaia Value*	*Gaia* Astrometric Excess Noise (mas)
Pleiades Triple System HII 3197			
Parallax (mas)	7.27±0.08	2.22±0.71	2.56
pmRA (mas yr^{-1})	+18.0±0.8	+31.1±0.9	
pmDE (mas yr^{-1})	−42.5±1.8	−41.4±0.9	
Bright Young Binary System V1046 Ori			
Parallax (mas)	2.64±0.075	0.44±0.17	0.62
pmRA (mas yr^{-1})	+1.88±0.09	+0.45±0.39	
pmDE (mas yr^{-1})	+1.2±0.14	+2.5±0.38	
Young Embedded Binary System Oph S1			
Parallax (mas)	7.24±0.09	8.16±0.11	0.65
pmRA (mas yr^{-1})	−2.05±0.02	−2.17±0.25	
pmDE (mas yr^{-1})	−26.72±0.04	−23.55±0.16	
Dusty Red Supergiant Star VY CMa			
Parallax (mas)	0.855±0.057	−5.92±0.82	4.48
pmRA (mas yr^{-1})	−2.800±0.58	+0.93±1.77	
pmDE (mas yr^{-1})	+2.60±0.58	−6.47±1.75	

All outliers within 3σ agreement with VLBI when astrometric excess noise is added in quadrature to Gaia quoted uncertainties (whenever σ > 2!).

VLBI-Gaia AGN position offsets favor parsec-scale jet direction

Matches: 9081; radio images at mas scale for 8143; present for half data



The (unresolved) optical jets are a dominant contribution to Gaia/VLBI offsets

Histogram of the distribution of the Gaia/VLBI position angle offsets wrt VLBI jet directions (from analysis of VLBI images at mas scales).

- Preferable direction along the jet, and at a smaller extent in the direction opposite to the jet.

Anticipate that a study of VLBI/Gaia position offsets will become a power tool for probing properties of the accretion disk and the relativistic jet in the AGNs ➔ Talk by L. Petrov

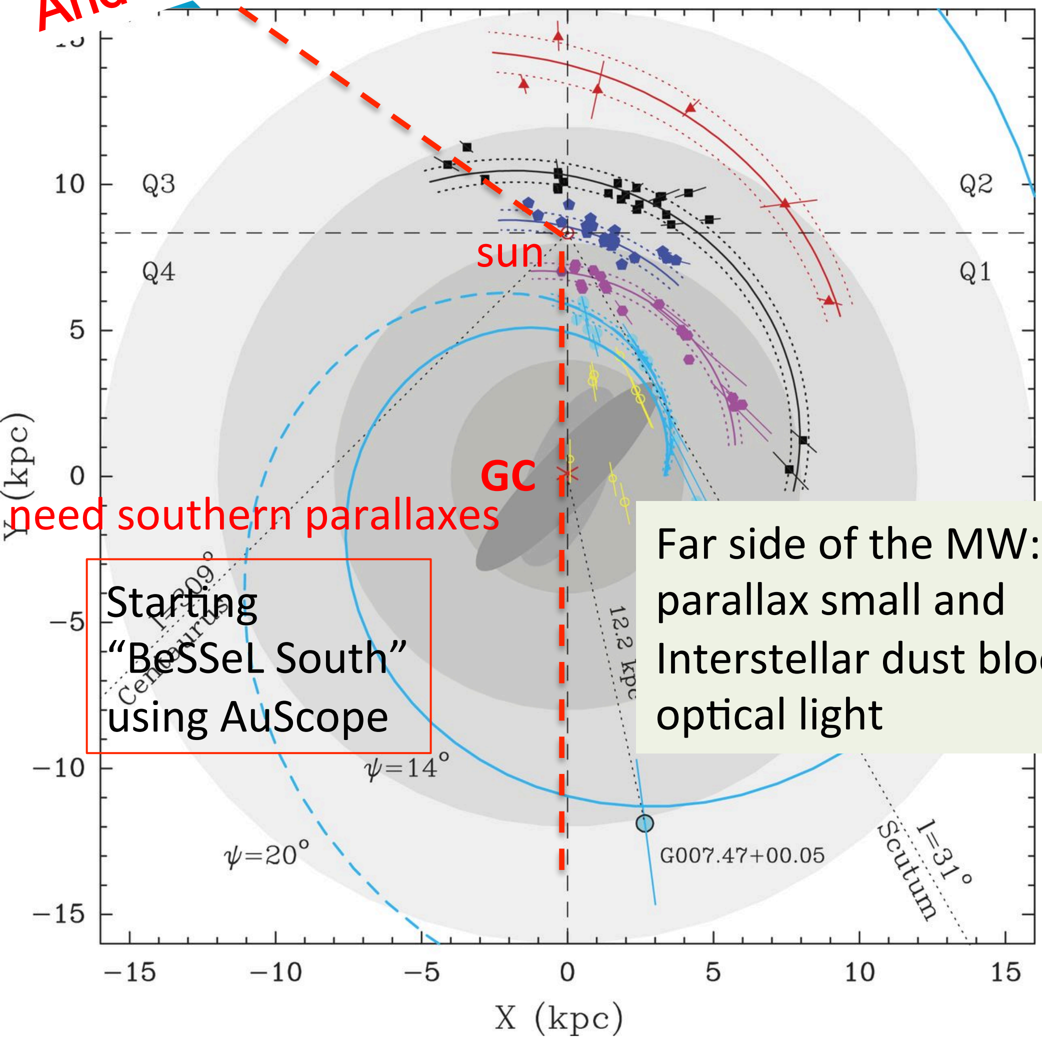
Petrov + 2017, 2018

Kovalev + 2017

Mapping Spiral Structure with VLBI

2. Maser astrometry And Galactic Structure

…ajor "Key Science" Projects for VERA and VLBA (BeSSeL survey), PR+



Starting "BeSSeL South" using AuScope

Far side of the MW: parallax small and Interstellar dust blocks optical light

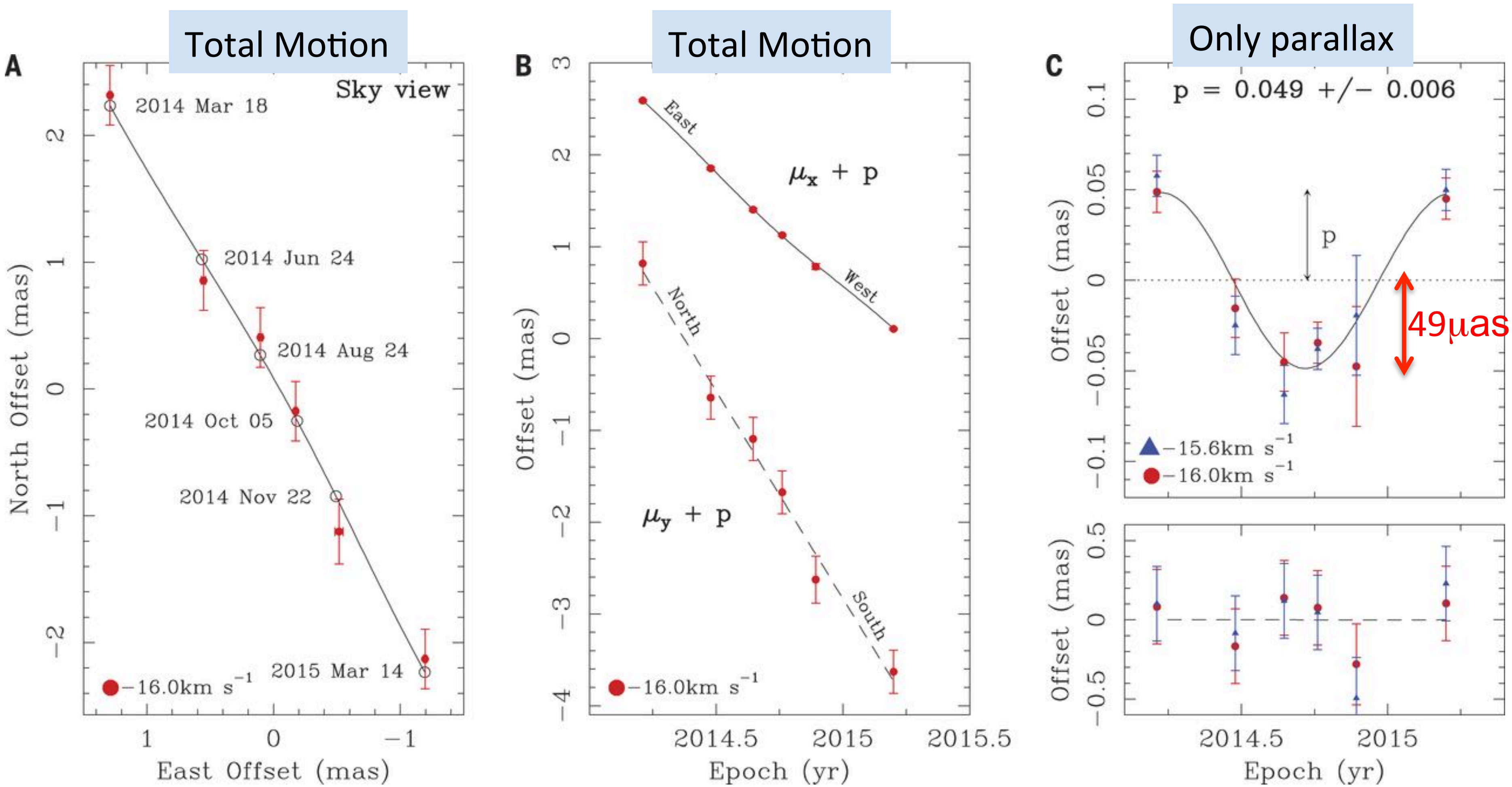
- Parallaxes: ~170 parallaxes for massive young stars
- Arms assigned by CO l-v plot
- Tracing most spiral arms, eg…
  - Outer arm traced
  - Perseus arm "gap"
  - Local arm significant
  - Sagittarius arm
- Inner, bar-region is complicated

Reid et al. 2014, 2016
Honma et al. 2012

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

Most distant parallax to date on the far side of the MW (H_2Omasers)

π = 49 ± 6 μas (D=20.4 ± 2.8 -2.2 kpc) G007.47+00.05



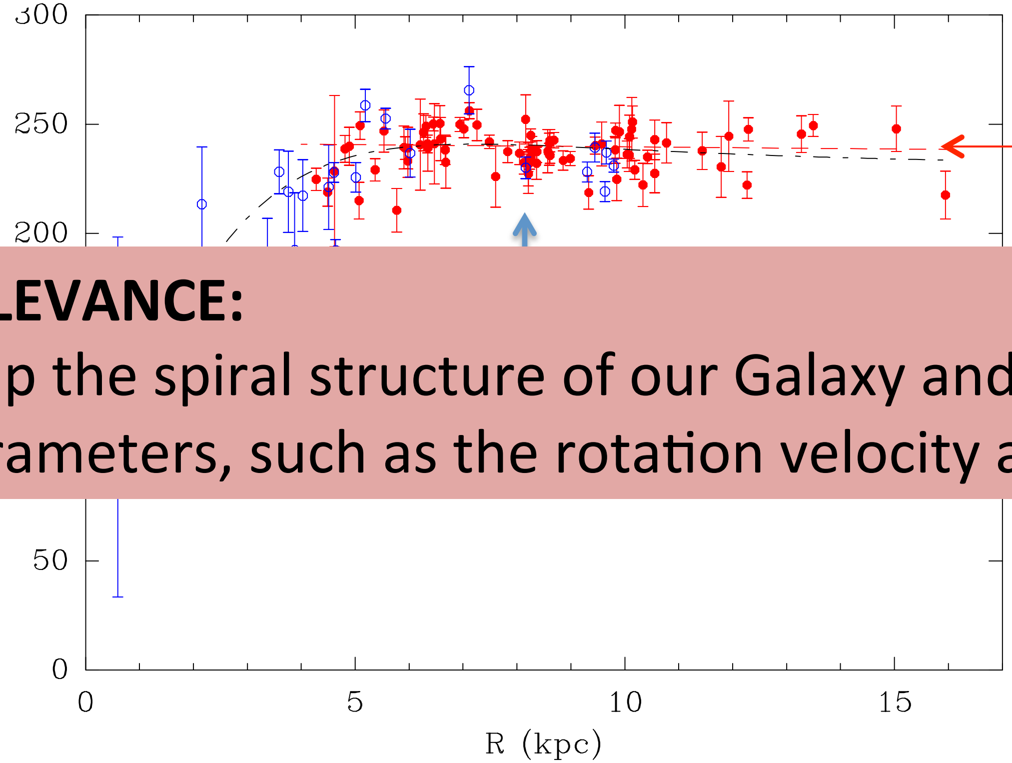
Sky Projected Motion

Decomposed offset position along the east and north directions vs. time

Sanna+ 2017 (Science)

2. Maser astrometry And Galactic Structure

The Milky Way's Rotation Curve



Revised IAU recommendation:

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

Replacing

Gunn, Knapp & Tremaine (1979) for a flat rotation curve… Slope, θ_0 = 220 km/s

RELEVANCE:

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

Widespread impact on astrophysics:

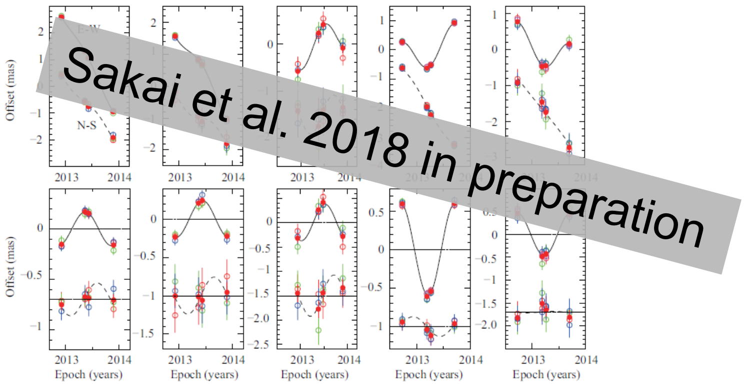
The increase in speed increases the Milky Way's mass by 50 percent, bringing it even with the Andromeda Galaxy

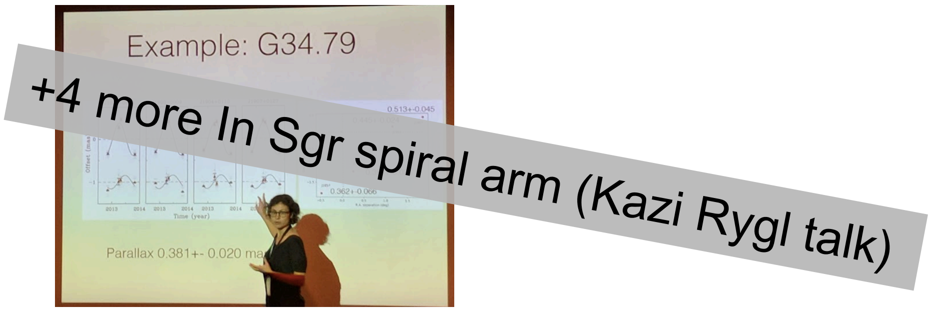
2.Maser astrometry And Galactic Structure

Includes high precision astrometry at 6.7 GHz (Methanol Masers)

Additions

Xu + 2016, Science

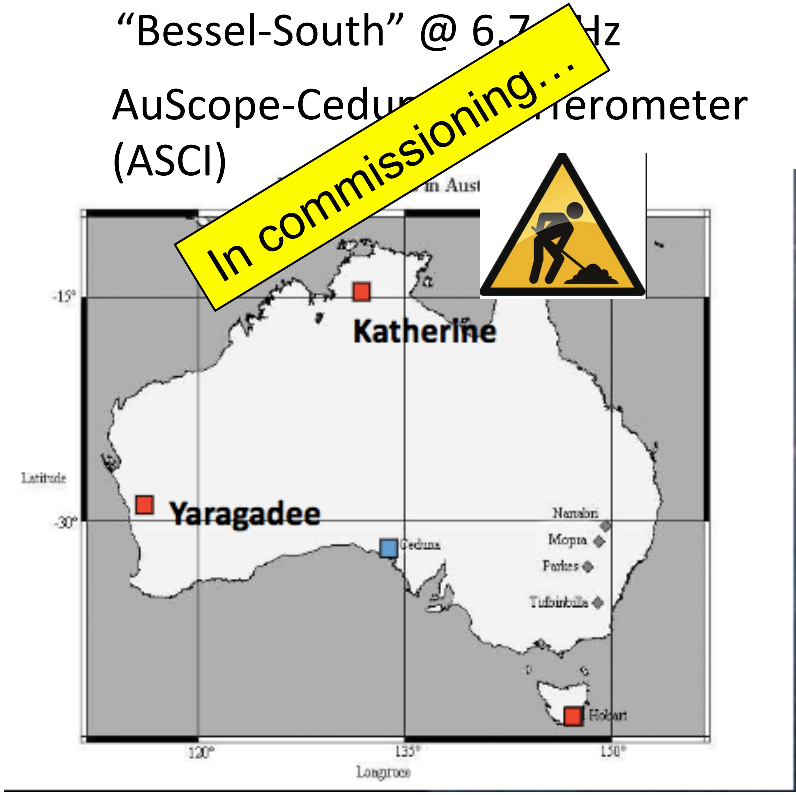




FUTURE

"Bessel-South" @ 6.7 GHz

AuScope-Ceduna Interferometer (ASCI)

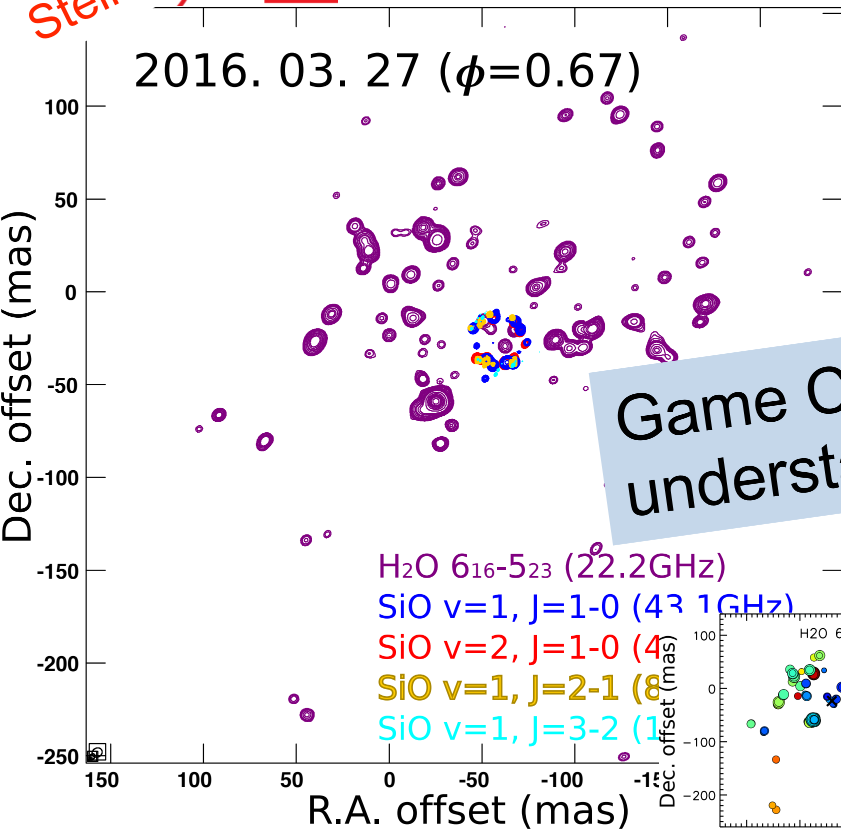


Different Astrometric calibration than for H_2O masers
Reid + 2017 *(similar to MultiView in Image Domain)*
"artificial quasar method"

Plan to use MultiView
Rioja,Dodson+ 2017

3.Late stages of Stellar Evolution

EVOLVED STARS STUDIES with the KOREAN VLBI NETWORK *(KVN, SFPR)*



O and 43.1/42.8/86.2/129.3 GHz SiO masers of a

y processes, mass loss and pumping mechanisms.

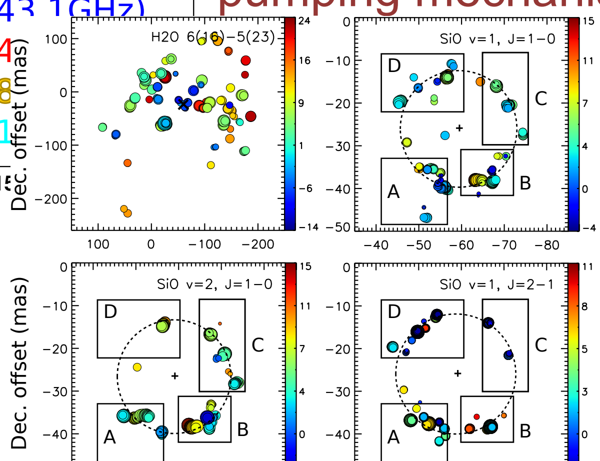
Bona fide astrometrically register

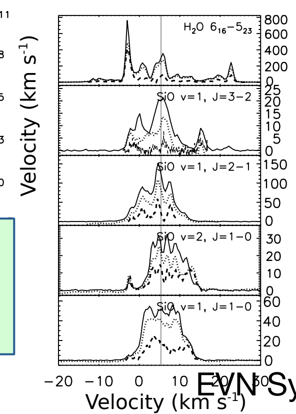
emission at all

Game Changer: Robust data set to advance understanding and theoretical models.

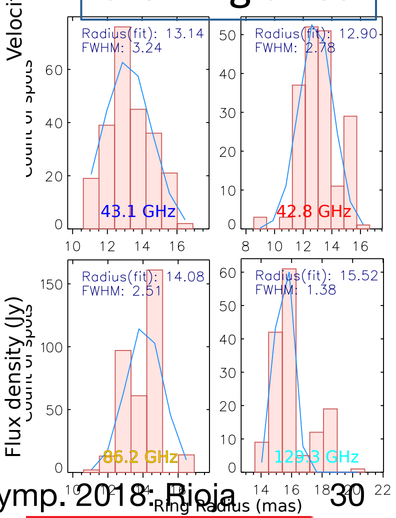
p/offset btw masers

transitions, ring sizes and temporal evolution to discriminate btw proposed maser pumping mechanisms (radiative / collisional)





SiO ring sizes

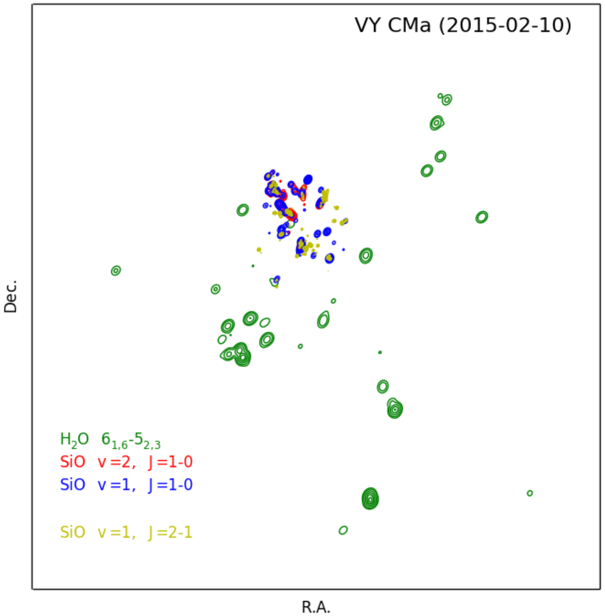


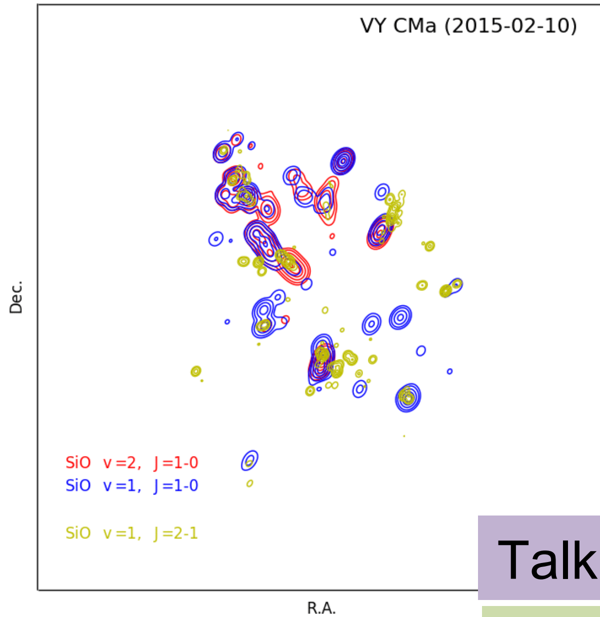
1st paper from ES KVN KSP
VX Sagittarii
Dong-Hwan Yoon +
Nature Comm., 2018

2nd paper on R Crateris
Dong-Jin Kim + Accepted

3.Late stages of Stellar Evolution

Temporal Evolution





VY CMa (Cho + in prep)

22 GHz (H_2O maser) to 42.8,43.1,42.9, 86.2 & 129.3 GHz (SiO masers) with full astrometric imaging, every few months.

Talk by Youngjoo Yun

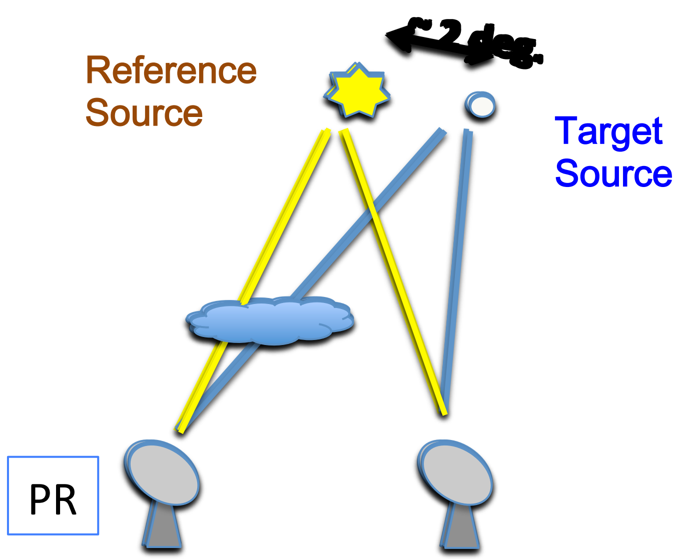
- Asymmetric spatial distribution of H_2O maser
- Typical spoke-like or snail trail features of SiO
- Gaps in emission for different transitions

See also posters by
Cho + for an overview of the ES KSP
Yoon+ VX Sgr dynamical development from the SiO to the H_2O maser regions.

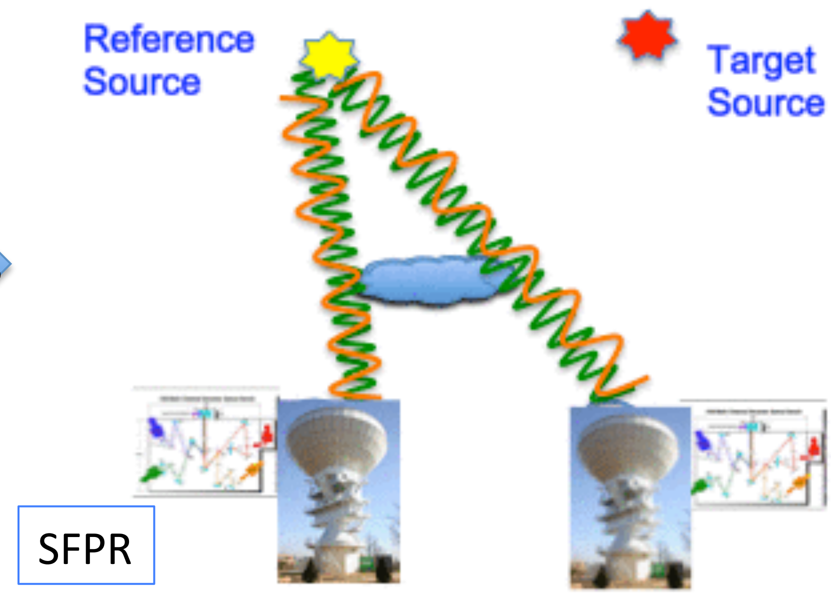
Work in progress …
KVN SFPR astrometry testing the pumping models & astro-chemistry

Enabled by the innovative KVN receiver system

Single Frequency Receiver → TECH → Simultaneous Multi-Frequency Receiver



METHODS →

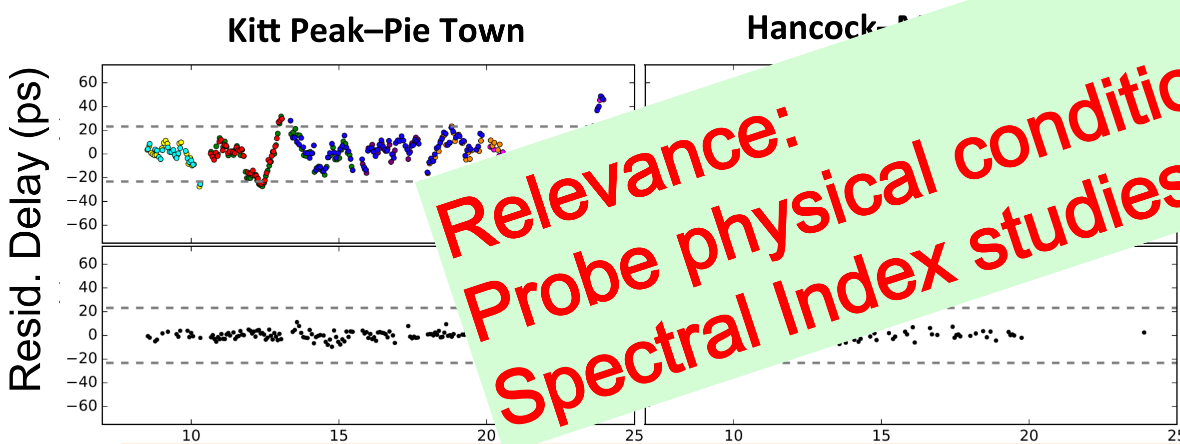


High-Precision wide-angle astrometry at 43 GHz *(VLBA, UV PAP)*

4. Jet Physics of AGN

Do we have to have close calibrators

Astrometry between pairs of sources up to ~ 15° separation ... sing a parametric approach.



Relevance:
Probe physical conditions in AGN jets
Spectral Index studies

... every
... n to the delays:
... eometric, Instrumental, Tropospheric, Ionospheric
along with source positions.

RECORD FREQUENCY 43 GHz

Abellan + 2018

“Core-shift” values agree with predictions from SSA effects
(Kovalev+ 2008, Lobanov 1998)

- Stud... al Pole
- Frequencies: 15 & 43 GHz
- First Global differential phase delay astrometry analysis at 43 GHz over such wide angles.
- Uses dedicated software (UVPAP) (highest frequency so far – probably the limit)
- Measured core-shift between U (15 GHz) and Q (43 GHz) bands & compared to SFPR

Revealing a recollimation Shocks in AGNs *(VLBA, MFPR)*

Going beyond the B&K core-shift to unveil the standing shock, for BL-Lac

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. These should be revealed at the higher frequencies.

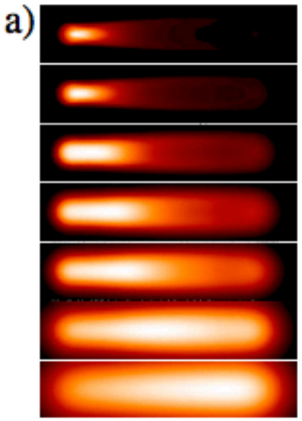
Jet Physics of AGNs

Revealing a recollimation Shocks in AGNs *(VLBA, MFPR)*

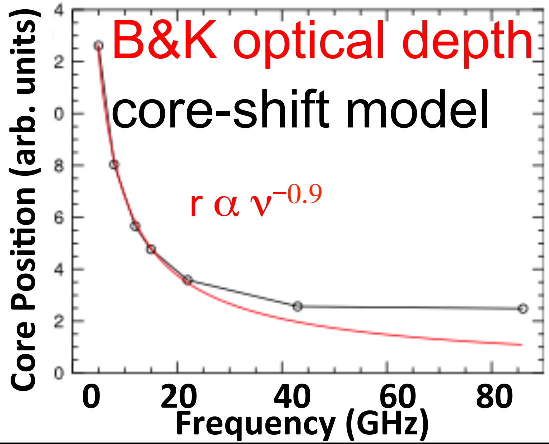
Going beyond the B&K core-shift to unveil the standing shock, for BL-Lac

SIMULATIONS

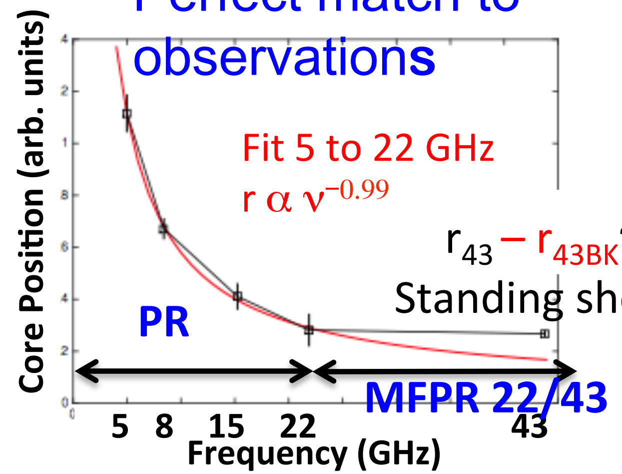
MHD Simulations



Predict deviation from



Perfect match to observations



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

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

Looks to fall short of BK expectation
➔standing shock?

(Dodson + 2017, Molina + 2017)

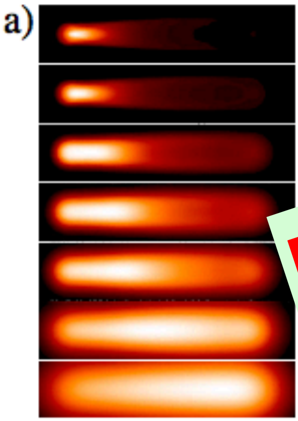
Revealing a recollimation Shocks in AGNs *(VLBA, MFPR)*

.Jet Physics of AGNs

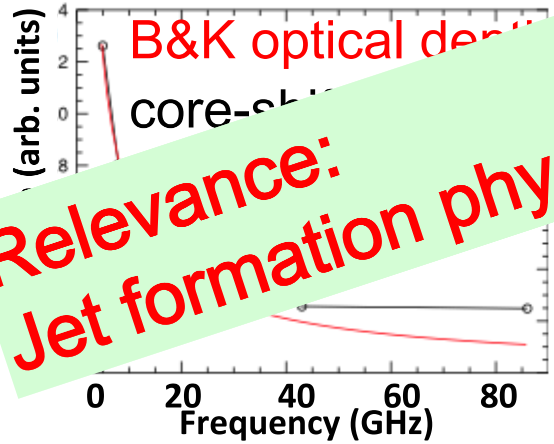
To uncover the transition from B&K core-shift to unveil the standing shock, for BL-Lac

SIMULATIONS

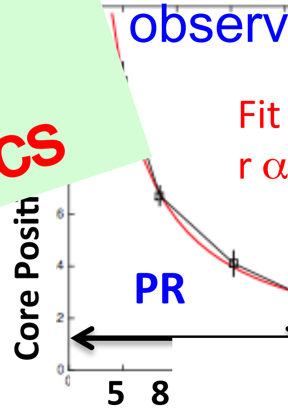
MHD Simulations



Predict deviation from

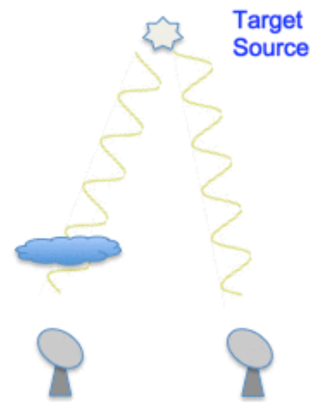


Perfect
observ



Relevance:
Jet formation physics

MFPR:
Single Source!
Alternate "ion blocks" *(L/C/K)*
&
fast frequency switching *(K/Q)*

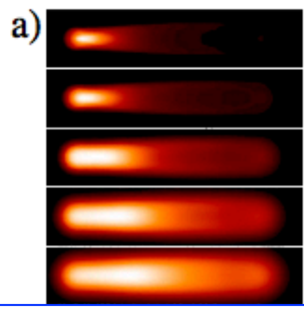


Revealing a recollimation Shocks in AGNs (*VLBA, MFPR*)

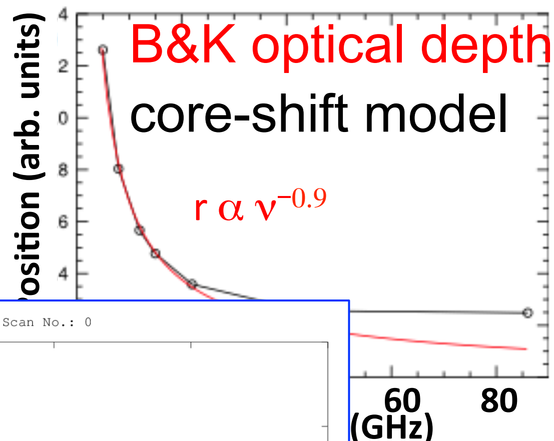
To uncover the transition from B&K core-shift to unveil the standing shock, for BL-Lac

SIMULATIONS

MHD Simulations

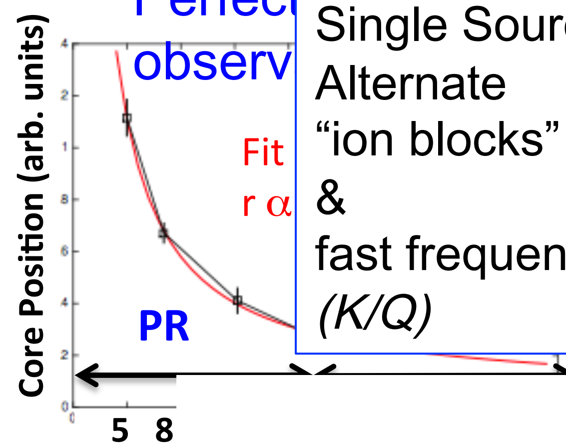


Predict deviation from



Perfect

observ



MFPR:
Single Source!
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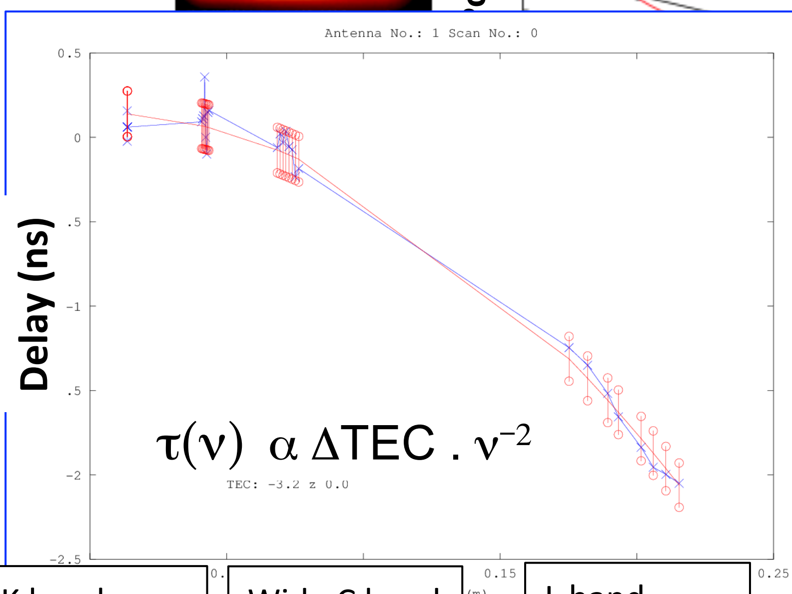
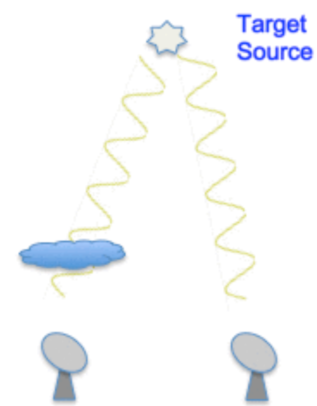
(K/Q)



K band
21.8-22 GHz

Wide C band
3.9 - 7.9 GHz

L band
1.4 -1.7 GHz



Revealing a recollimation Shocks in AGNs
(VLBA, MFPR)

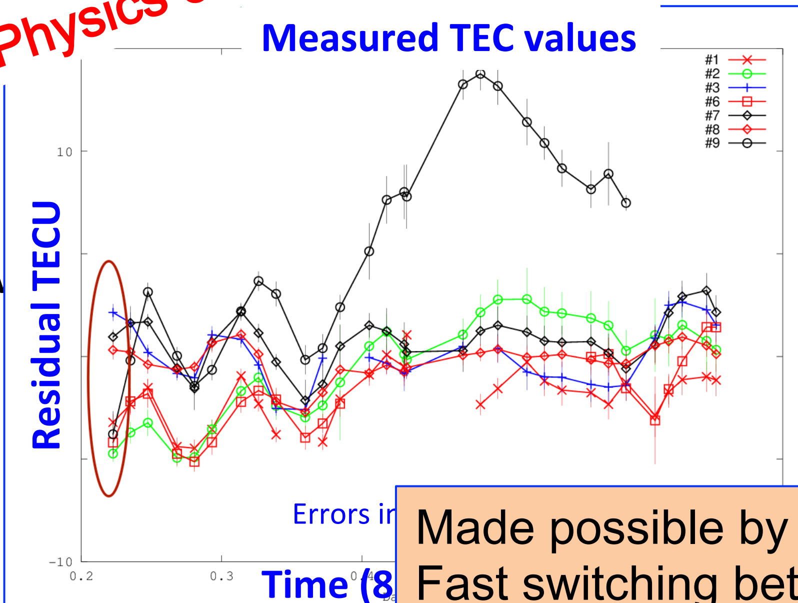
Jet Physics of AGNs

from

c

M

Posters on AGN "core-shift" measurements:
Ilje Cho + SgrA* (KVN, 22/43/86 GHz)
Voitsik + 24 AGNs (EVN, 1.7/2.3/5/8 GHz)



tion from
depth
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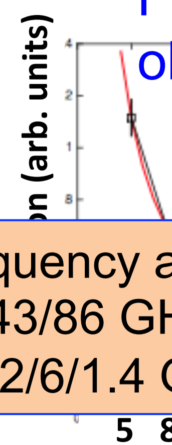
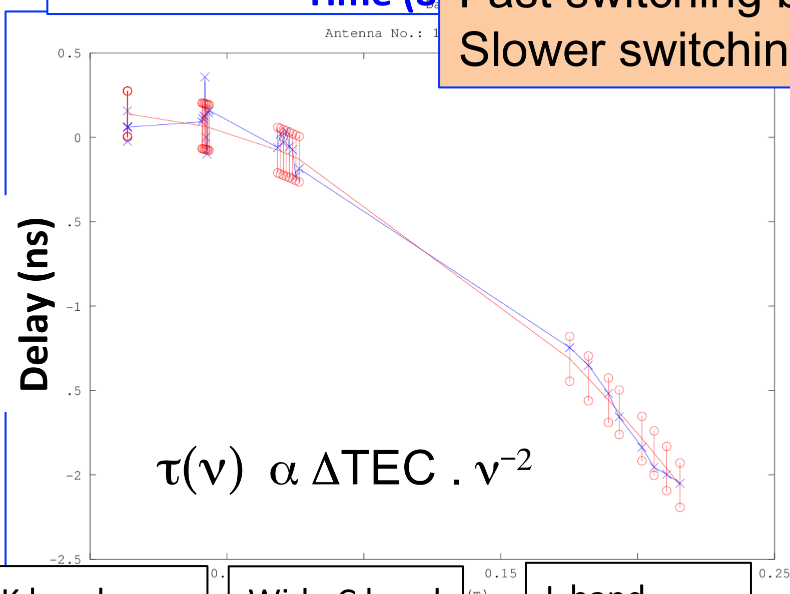


60 80
(GHz)

Perfect
observ

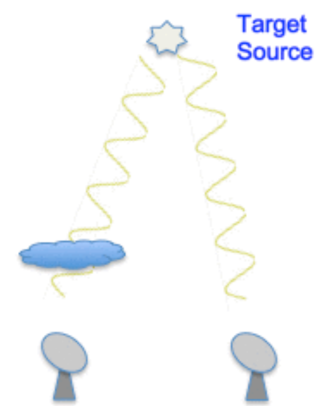
MFPR:
Single Source!
Alternate
"ion blocks" *(L/C/K)*
&
fast frequency switching
(K/Q)

Made possible by VLBA frequency agility:
Fast switching between 22/43/86 GHz
Slower switching between 22/6/1.4 GHz



$\tau(\nu)\ \alpha\ \Delta TEC\ .\ \nu^{-2}$

K band	Wide C band	L band
21.8-22 GHz	3.9 - 7.9 GHz	1.4 -1.7 GHz



SKA1 x10 more sensitive: Provide precise distances/pm to 10kpc

5.SKA science

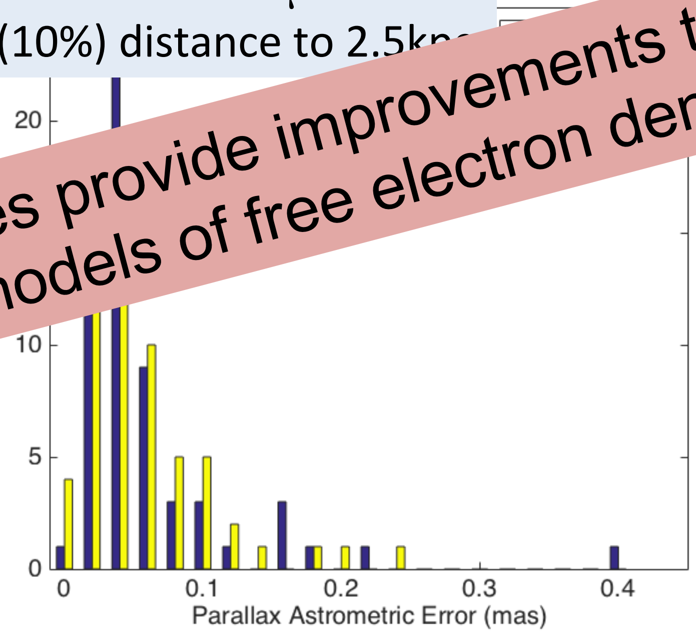
PSR-π is the large VLBA campaign to measure the parallax and proper motion of pulsars using VLBI.

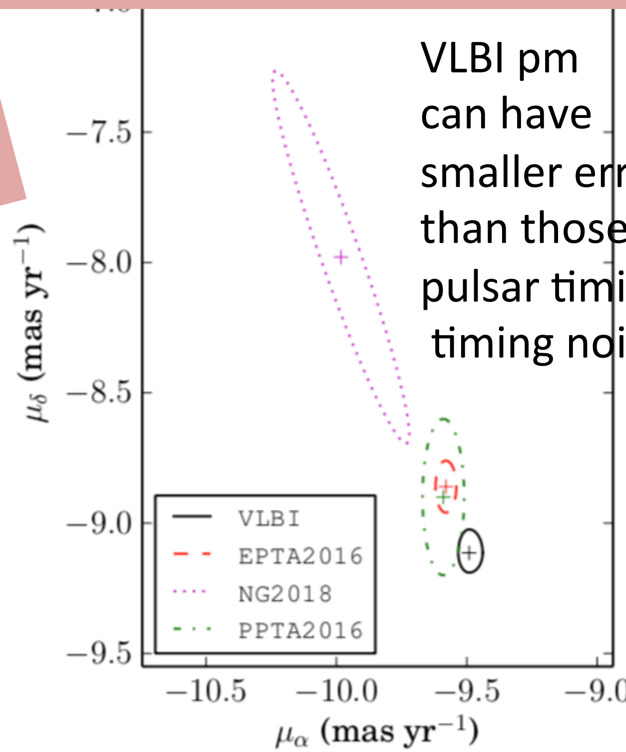
PSR-π paper II ("Data paper") has 1808.09046, Deller + 2018) listing searched) with in-beam calibrators.

VLBI precise proper motions can improve pulsar GW timing arrays.

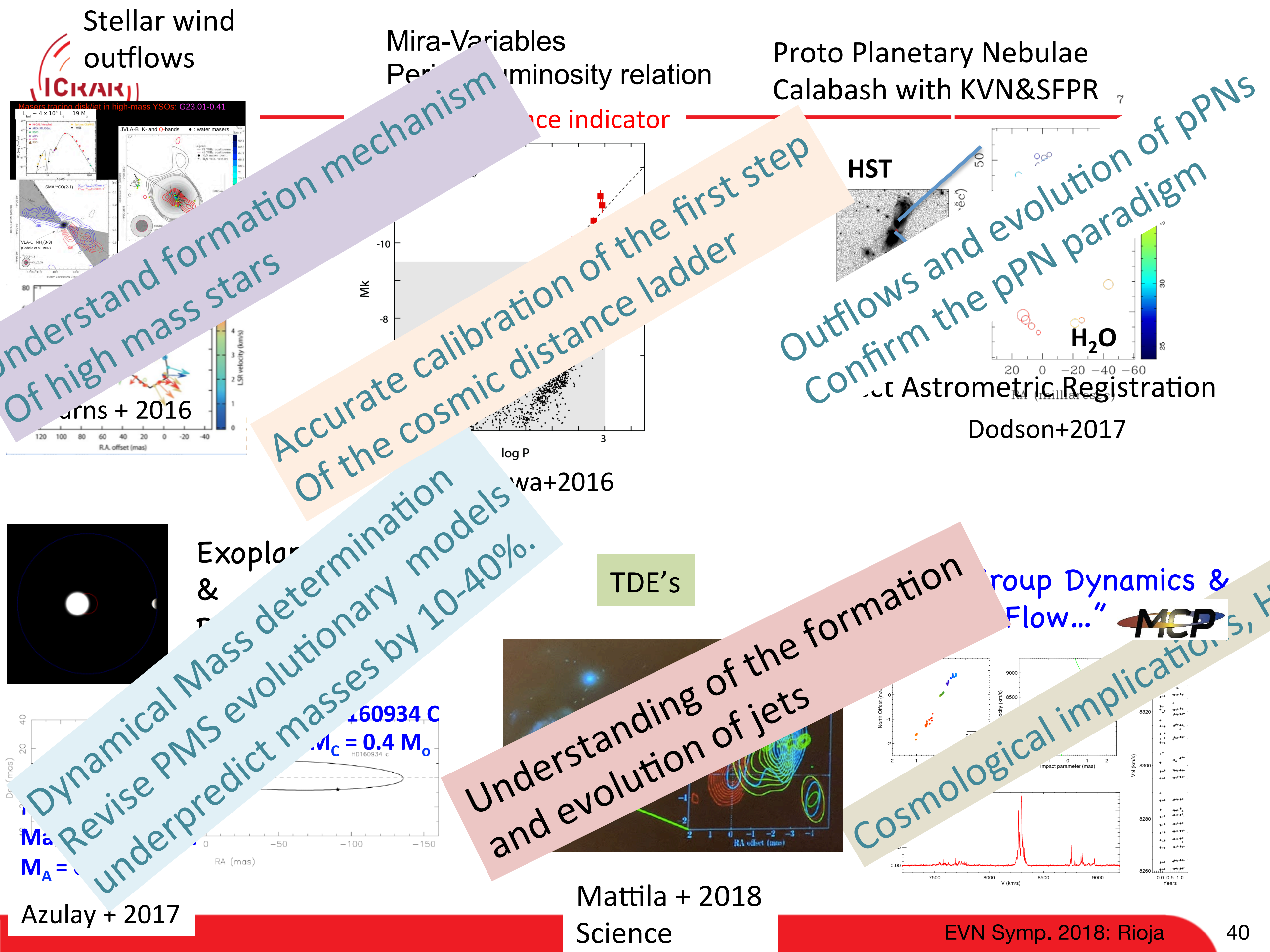
Median error 40 μas
Precise (10%) distance to 2.5kpc

Distances provide improvements to galactic models of free electron density





VLBI pm can have smaller errors than those from pulsar timing… timing noise?


Stellar wind
outflows
ICRAR
Masers tracing disk/jet in high-mass YSOs: G23.01-0.41
Mira-Variables
Period-Luminosity relation
Distance indicator
Proto Planetary Nebulae
Calabash with KVN&SFPR
HST
H_2O
Astrometric Registration
Dodson+2017
Mk
log P
Understand formation mechanism
Of high mass stars
Accurate calibration of the first step
Of the cosmic distance ladder
Outflows and evolution of pPNs
Confirm the pPN paradigm
Burns + 2016
Exoplanets
&
Dynamical Mass determination
Revise PMS evolutionary models
underpredict masses by 10-40%.
HD160934 C
M_C = 0.4 M_o
M_A =
RA (mas)
Azulay + 2017
TDE's
Understanding of the formation
and evolution of jets
Mattila + 2018
Science
Group Dynamics &
Flow…"
MCP
Cosmological implications, H
Impact parameter (mas)
V (km/s)
Years
EVN Symp. 2018: Rioja
40

TECHNOLOGICAL DEVELOPMENTS RELEVANT TO ASTROMETRY

1. BRAND EVN

- BRoad bAND EVN, a project to build a prototype primary focus receiver for the EVN (and other telescopes) with a very wide frequency range from

1.5 GHz to 15.5 GHz

- Innovative, very wide bandwidth.

- **To use full bandwidth** requires **coherent fringe-fitting** over the very wide frequency range,Including ν^{-2} term for ionosphere plus linear (ν) slope, carried out inside CASA with RINGS.

RELEVANT FOR ASTROMETRY AT CM-wavelengths:
With coherent fringe-fitting chromatic astrometry information between simultaneous images at different frequencies.

The BRAND EVN partners include Germany (MPIfR), Italy (INAF), Sweden (OSO), Spain (IGN), The Netherlands (ASTRON), and Latvia (VIRAC).
Project Engineer Gino Tuccari; Project Manager: Walter Alef

Wide FoV Te

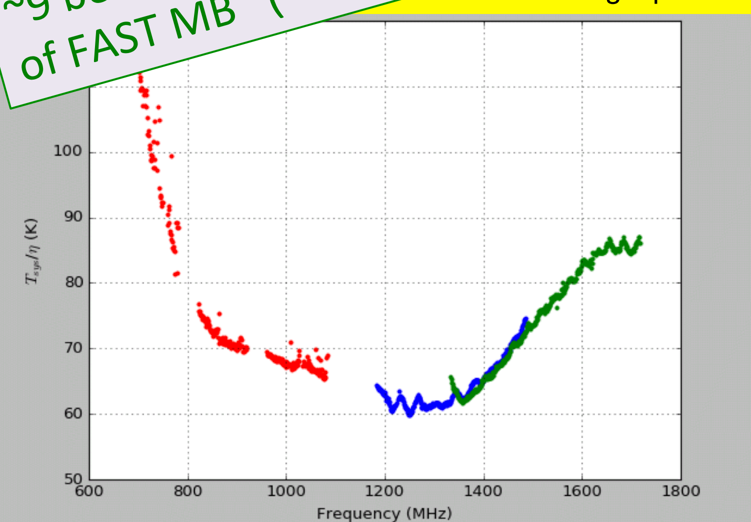
2. PAFs for SKA astrometry

Effelsberg & Lovell – CSIRO MKII PAF

0.7-1.7 GHz

~9 beams for VLBI with MV to match the 20’ FOV of FAST MB (~ 4 beams for Lovell)

…oV = 36 x single pixel FoV



WSRT - Apertif

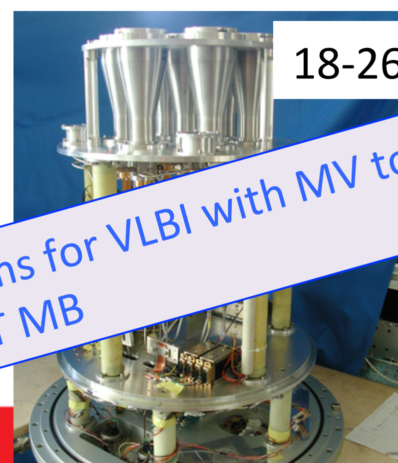
Multiple independent steerable tied -rray beams across the central 25-m disk equivalent beam for VLBI with MV

1.1-1.7 GHz

PAF FoV = 25 x single pixel FoV

SRT – Multi Beam

18-26 GHz

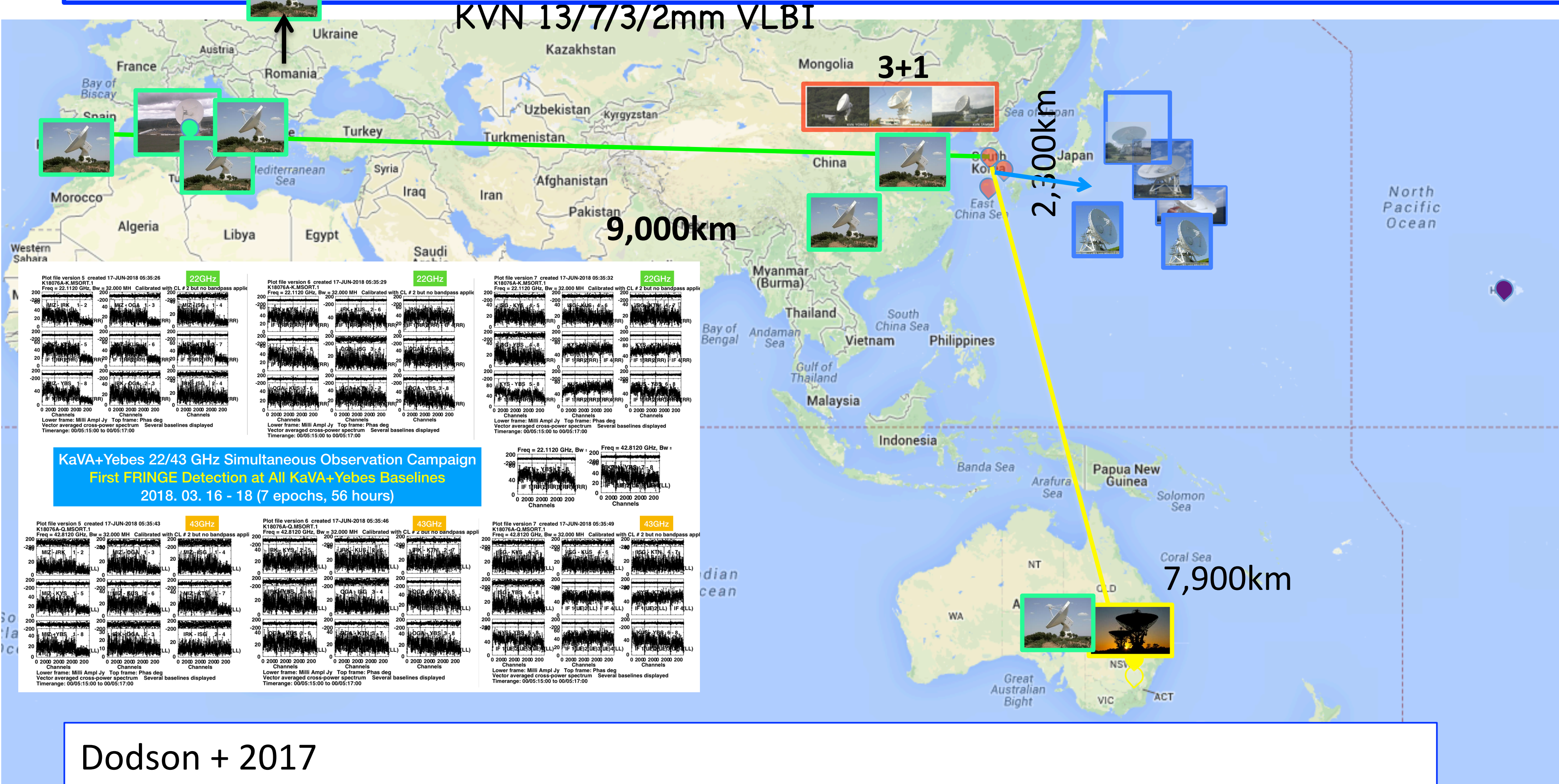


~4 beams for VLBI with MV to match the 20’ FOV of FAST MB

3- 4.5 GHz 7-feed under development

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

3. A Global "Multi-Frequency" mm-VLBI array



Dodson + 2017

"The science case for simultaneous mm-wavelength receivers in radio astronomy"

Outcome of ERATEC meeting held in Florence Oct. 2015

Techniques relevant for ALMA (long baselines)

Summary

- Bona fide Precise Astrometry adds a new dimension to your research,
  with positions, proper motion, distances, and
  direct registration of temporal and frequency monitoring.

- Fundamental contribution to many research fields in astrophysics: widely applicable to many targets and at a wide range of frequencies (m to (sub)mm waves) in conjunction with appropriate methods.

- All regimes, ground VLBI & Space VLBI

- Developments of new calibration methods and new instruments are providing a leap in the astrometric performance .

Acknowledgements:*This presentation has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730562 [RadioNet]*

MultiView SUMMARY

Astrometry rapidly reaches systematic limits; increased sensitivity does not improve accuracy

MultiView calibration results in superior ionospheric calibration with angular separations of a few degrees. **Simultaneous observations will improve results.**

General calibration method, for all frequencies.
Demonstration shown VLBA obs*. @* 1.6 GHz*;* also successful 6.7 GHz*;* trying at 0.3 GHz

MV is widely applicable right now, with:

- Simultaneous observations with PAFs /multi-beam
- Fast-source switching

For SKA-VLBI, with multiple in-beam calibrators, will deliver 10 micro-as astrometric accuracy.