Ultra-precise astrometry with the ~~next-generation~~ of radio instruments

International Centre for Radio Astronomy Research

Boosting astrometric performance, for metre to (sub-)mm-VLBI with atmospheric calibration

Now covering metrewave (SKA-Low),
cm (SKA-mid/ngVLA-Long),
mm (ngVLA-Long)
and sub-mm (ngEHT)

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In collaboration with
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Curtin University

The Government of Western Australia

The University of Western Australia
Achieve International Excellence

For (copious) details see Annual Review:
Rioja & Dodson 2020: A&ARv, 28, 6

Outline

- New horizons for VLBI astrometry in the era of next gen. instruments

  Next Gen Instruments are reducing the THERMAL noise

  COLLECTING AREA

- Next Gen. Tools: Instruments, METHODS, Key Enabling Technology

  Next Gen methods are reducing the SYSTEMATICS

  TECHNIQUES

- (Ultra) Precise Astrometry across the spectrum, even previously unthinkable domains

➢ MultiView (MV) strategies for m- and cm- radio astrometry

Provides angular separations between a source and a virtual reference point

➢ SFPR strategies for mm- and submm- radio astrometry

Provides angular separations between frequencies for a single source

➢ Combined strategies for relative astrometry at mm wavelengths

Applications of Radio Astrometry

Astrometry offers one of the few methods to determine the 3rd dimension, distance.

VLBI Absolute Astrometry (in Radio) has pro

Covered in FM7-3 & 4: Astrometry techni

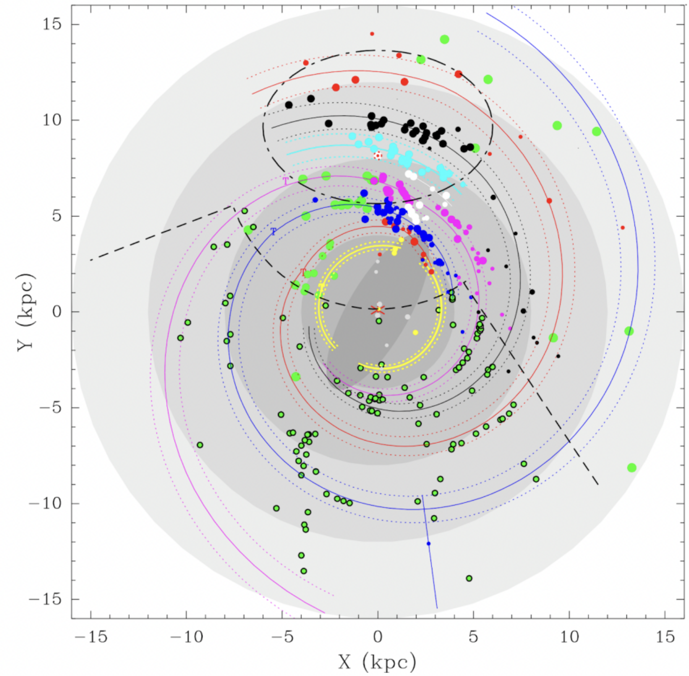
- The ICRF and deviations from this:

ICRF3 has 4536 sources in S/

bands

median error of 100 µas

- Comparisons with GAIA to ID offsets
- Secular Aberration Drift



VLBI Relative Astrometry has provided:

For our own Galaxy the parallax to H_2O mas

- the Sun distance to the Galactic Centre,
- the Galactic Rotation Curve,
- the location of the arms

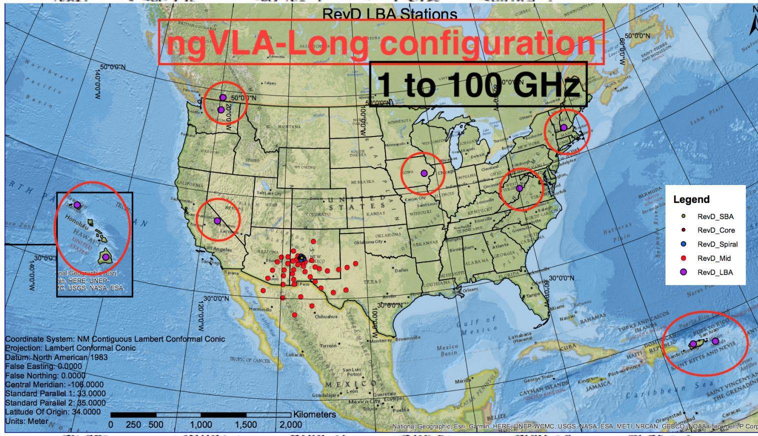
For pulsars their velocity, thus details of binary progenitors

Proof that GW170817 NS-NS inspiral was an off-axis short GRB Mooley '18

Ultra Precise Astrometry

Covered in FM7-1 & 2: Astrometry science

Key feature of multiple KSPs for the SKA.
E.g. Parallax of pulsars across the Galaxy, distance error < 1% up to 10 Kpc



<u>Some Unique targets:</u>

Pulsars, FRBs

Magnetism studies using RM

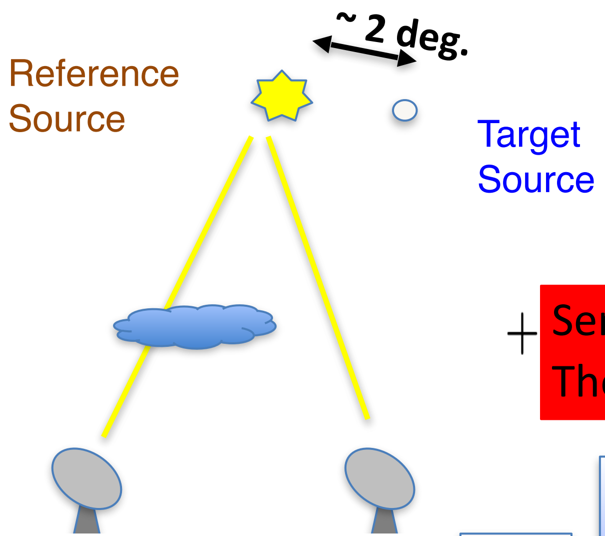
Emission at fixed frequencies,i.e. OH, Methanol Masers

Absorption

Common Framework for Methods

Where we come from:

Phase Referenced (PR) Relative Astrometric VLBI has been in use for ~50 years, since the beginning:



Astrometry Information

$$\phi_T(t,\nu) - \phi_R(t',\nu) = (\phi_{T,\mathrm{pos}} - \phi_{R,\mathrm{pos}}) + (\phi_{T,\mathrm{str}} - \phi_{R,\mathrm{str}})$$

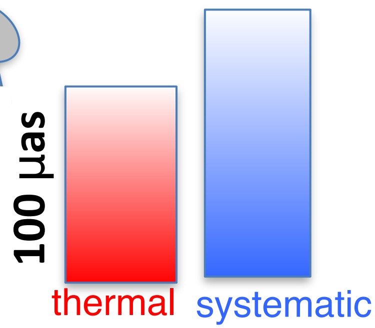
$$+ \ldots + (\phi_{T,\mathrm{tro}} - \phi_{R,\mathrm{tro}}) + (\phi_{T,\mathrm{ion}} - \phi_{R,\mathrm{ion}}) + \ldots)$$

$$\pm\sigma\phi_{\mathrm{thermal}} + 2\pi(n_T - n_R) \qquad n_T, n_R \in \mathrm{integer}$$

Sensitivity; Thermal error

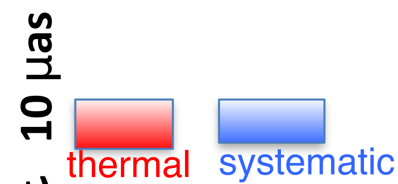
Calibration; Systematic error

Current Instruments & Methods: (per measurement)



Where we go:

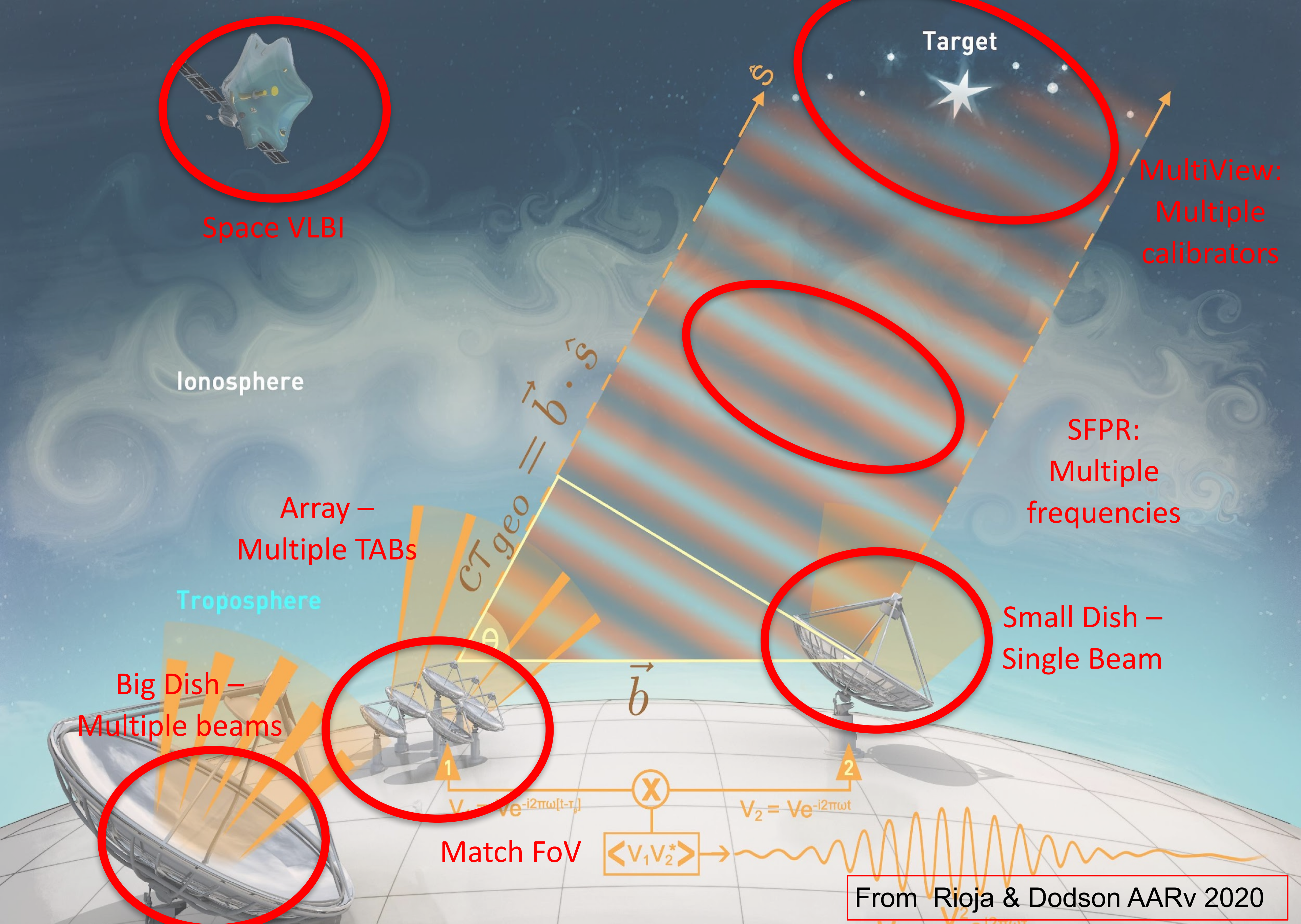
Next Gen. Instruments & Methods: (per measurement)



In AARv (2020) current and next-generation astrometric methods are synthesised into a common framework, governed by a simple relationship:

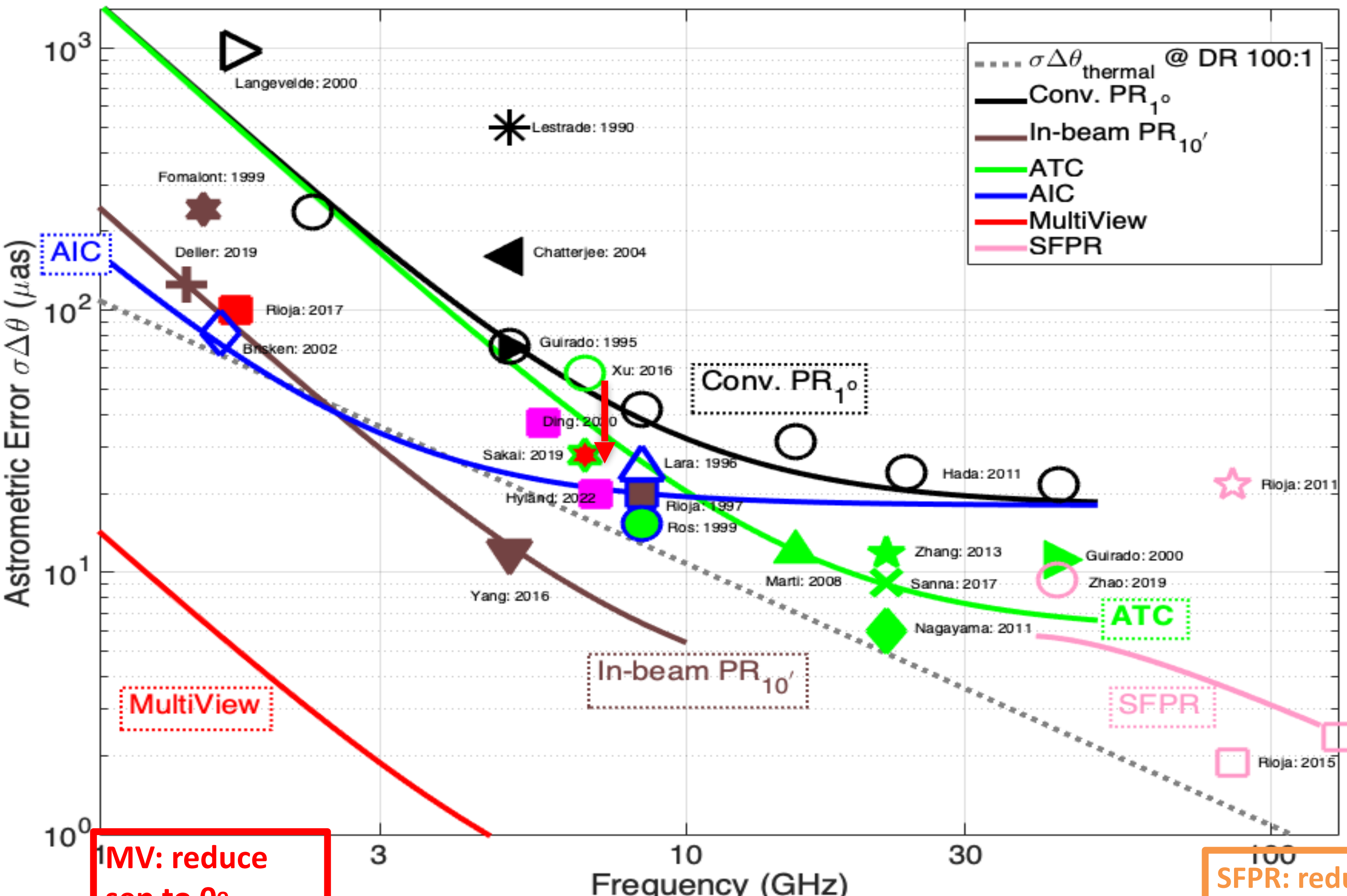
$$\phi_T(t,\nu_T) - \mathcal{R}\times\phi_R(t',\nu_R) = (\phi_{T,\mathrm{pos}} - \mathcal{R}\times\phi_{R,\mathrm{pos}}) \pm \sigma\phi^{\mathrm{cal}}$$

$$\pm\sigma\phi_{\mathrm{thermal}} + 2\pi(n_T - \mathcal{R}n_R)$$



From Rioja & Dodson AARv 2020

Historical values of $\sigma\Delta\theta_{cal}$



$\sigma\Delta\theta_{thermal}$

$\sigma\Delta\theta_{cal}$

MV: reduce sep to 0°

SFPR: reduce Trop 0cm

Ionosphere Dominant

Troposphere Dominant

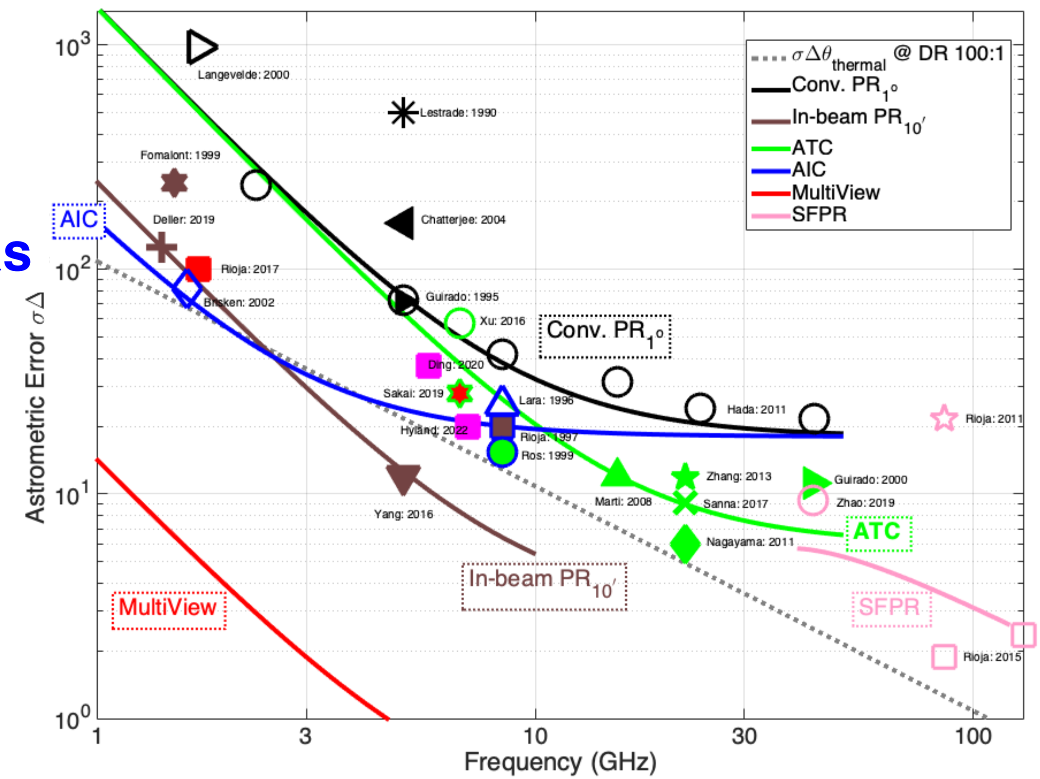
Slide Show of Astrometry

TODAY

Thermal noise matching with in-beam (at 10’)

but far greater than MultiView (at 30’)

100μas

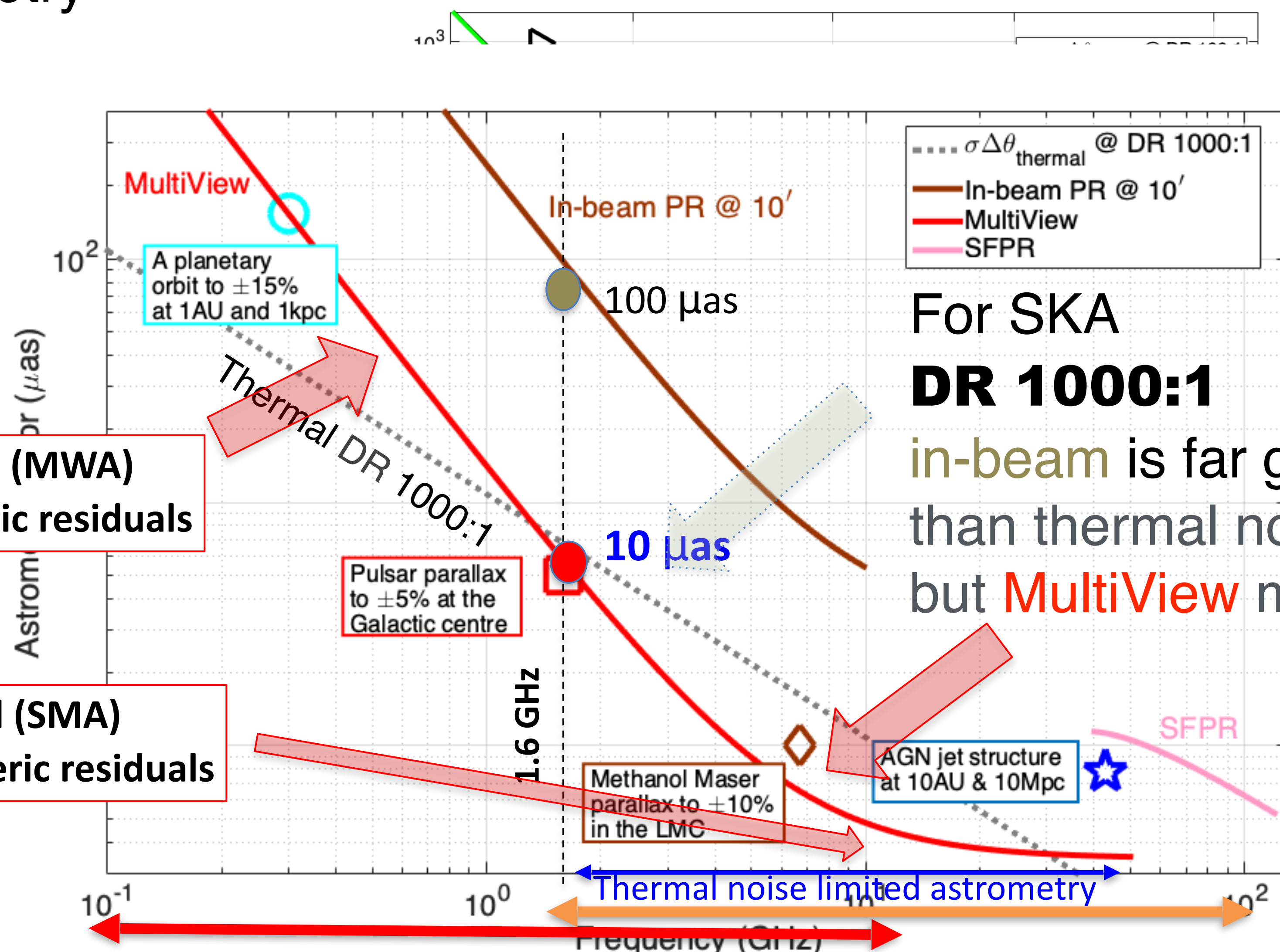


10μas

Slide Show of Astrometry

In NextGen telescope Era

Ther
with
but f
Multi'



For SKA

DR 1000:1

in-beam is far greater than thermal noise, but MultiView matches

Measured (MWA) ionospheric residuals

Measured (SMA) tropospheric residuals

1 µas

ngEHT

SKA-Low

SKA-Mid

ngVLA

Feasibility for ultra precise astrometry at SKA frequencies

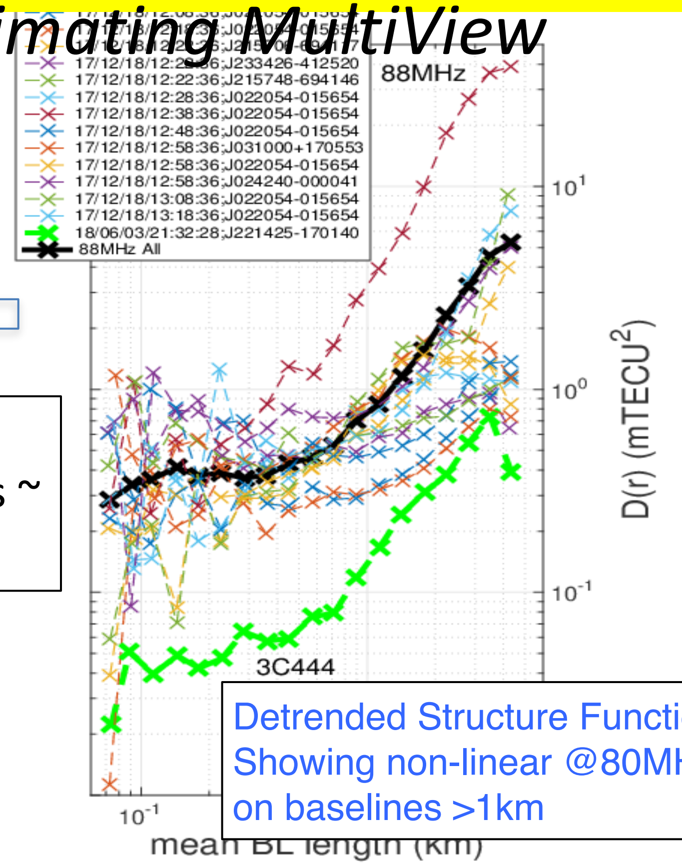
*Empirical ionospheric studies for estimating MultiView astrometry limits (*see JATIS SKA sp. Issue.*)*

Frequency ν (GHz)	MV error $\sigma\Delta\theta^{MV}$ (μas)	No. of in-beam sources
0.3	150	14†
0.9	17	15
1.6	6	5.5
5.0	~1	0.4 (6)
8.0	~1	0.1 (2)
15.0	~1	0.0 (0.4)

In-beam MV

Switched

MV Iono residuals ~ 1 mTEC



Detrended Structure Function Showing non-linear @80MHz on baselines >1km

Rioja Dodson 2021

\# sources within beam of 20-m antenna & <1 deg

With SKA-Phase 1 (Phase-2 in brackets) C. Garcia-Miro

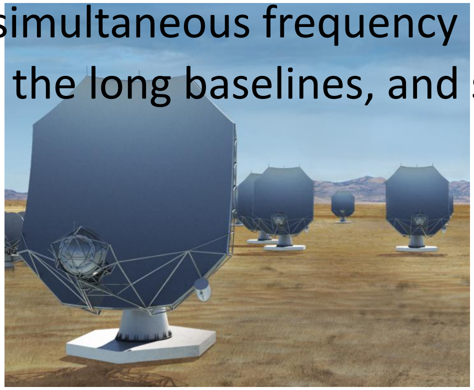
Many phase screens show significant curvature

Many showed fast (~10sec) changes in phase surface

Feasibility for ultra precise astrometry at ngVLA frequencies

ngVLA-Long has a large overlap with SKA-mid
But also frequencies above 22GHz

Design choices prevent the possibility of simultaneous frequency observations. But the paired antennas on the long baselines, and sub-arraying the core will allow this.



Potentially 3uas precision is possible for SFPR, up to 120GHz

Low Risk, based on KVN success

Potentially 1uas precision is possible for conventional astrometry, up to ~100GHz

Unknown Risk, needs investigating

Feasibility for ultra precise astrometry at ngEHT frequencies

Astrometry at ngEHT frequencies would be an __amazing__ extension of the technique – but why not?

Rioja Dodson Asaki 2022 (sub shortly)

SFPR astrometry between frequencies at 43 to 130GHz is now `standard' for KSPs on the KVN – we are only doubling the frequency to 80 to 240/320GHz

Low Risk, based on KVN success

Conventional astrometry at mm wavelengths (>43GHz) will require simultaneous multiple beams (VERA*2)
As need to remove Temporal and Spatial terms (VERA was temporal only)

No path for this with Current arrays, but ngVLA (and potentially ngEHT) has paired antennas on long baselines. Estimates are positive

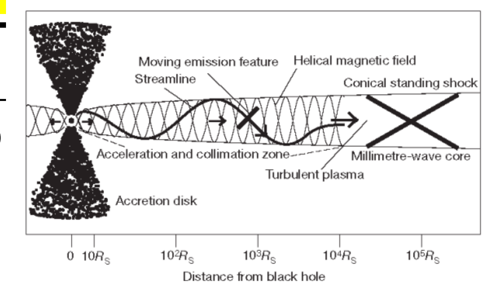
Unknown Risk, needs investigating

Science Drivers for astrometry at ngEHT frequencies

Offset between Foot of Jet and true Black H

SFPR-VLBI between 86 and 340GHz will provide *bona-fide* astro

- Low risk
- Long term quest



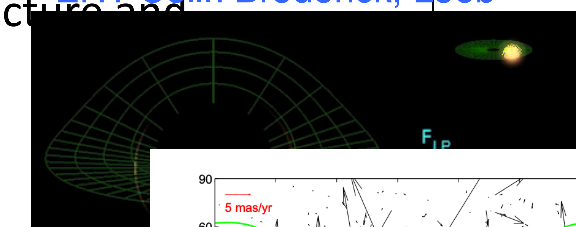
Marcher 1998

Structural Variability

Phase Referencing can break degeneracy between Source Structure and Atmospheric Variability

- Vital for SgrA*
- Does not need to be astrometric

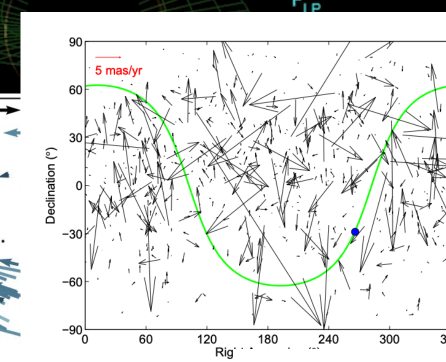
EHT Coll.: Broderick, Loeb



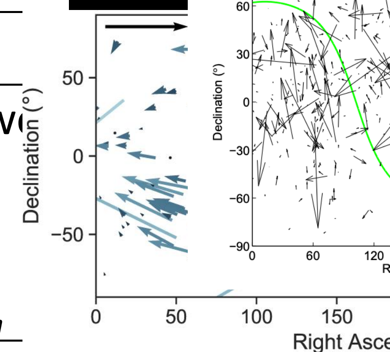
Cosmological Secular Parallax

MV-VLBI + SFPR-VLBI will provide *bona-fide* astrometry betw

- High(er) Risk
- Hubble Flow as a function of red-shift (z>>1)
- Jet Structure removed



Titov, O. 2013

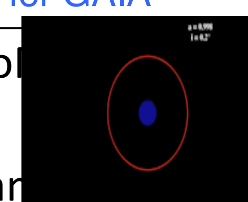


From Paine 2020 for GAIA

Spin shift between Photon Ring and CoM

MV-VLBI + SFPR-VLBI to measure shift between between BH photon ring and Co

- Direct BH Spin vector measurement
- Very hard! Optical measure of CoM + small errors between Optical/Radio fran



From Johnson, Younsi 2016

Key Tasks for Readiness

Simultaneous MultiView

Limited tests have been done.
MultiBeam Parkes-64m to Single Beam Parkes-12m for an ASKAP VLBI demonstration
PAFs or TABs would be able to demonstrate *simultaneous* MV-VLBI
Effelsberg is an ideal demonstrator

Paired Antennas

Paired antennas have not been investigated explicitly
although related studies of phase screen patterns have been reported.
Many sites would be suitable (eg ATCA, VLA) and data should be in the archive
we will follow this up

SFPR between 3mm and 1mm

Demonstrations are being planned
Tests between Pico Valeta (IRAM) and Yonsei (KASI) for this winter
Maybe Haystack, NOEMA and APEX can also join

Current Pathfinder Sites suitable for MV–VLBI
For Ultra Precise Astrometry

Parkes 64m: PAF
FAST 300m: MB
Effelsberg 100m: PAF
Jodrell 76m: PAF
WRST 14x25m: TAB
Sardinia 64m: MB
GMRT 30x45m: TAB

Proposed

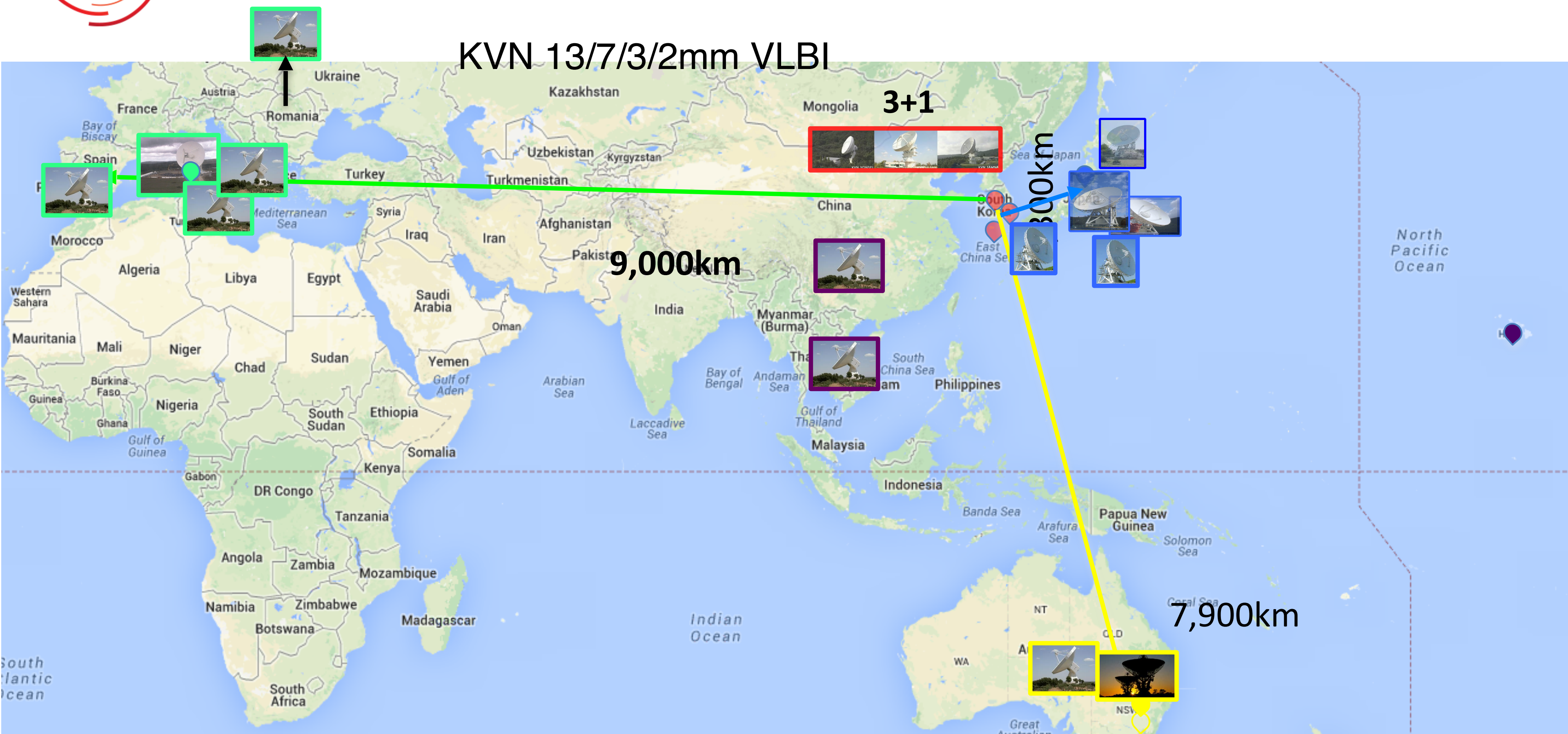
ASKAP 36x12m: TAB
MeerKAT 64x14m: TAB
ATCA 6x21m: TAB

"Goal Now": Use Large dishes & surpass systematic limits: 10 µas-astrometry @ L-band

"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

Current Pathfinder Sites suitable for SFPR–VLBI
For Ultra Precise Astrometry



Suitable Science Examples: See Dodson+, 2017

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

1st Long (2,000km) Baseline Demo: See Zhao+, 2019

"SFPR Observation of AGNS with KAVA"

SUMMARY

Science Goals drives the need for ultra-precise astrometry across the frequency spectrum. Next-Generation Radio telescopes will provide this – if systematics removed.

Ultra Precise Astrometry requires new methods:
MultiView/SFPR meets the requirements; from 0.1 to 300GHz
For Ground Arrays and Space VLBI

A good number of telescopes support multi-frequency mm-VLBI; many demonstrations of SFPR being performed.

Demonstrations are required:
Many aspects are suitable for testing now (eg PAFs & TABs)
Many issues to be settled, with current technologies/methods

Key demonstrations of technical issues to ensure ultra-precise astrometry can be done with pathfinders NOW

More details in Rioja&Dodson A&ARv (2020)

Thanks for your attention!