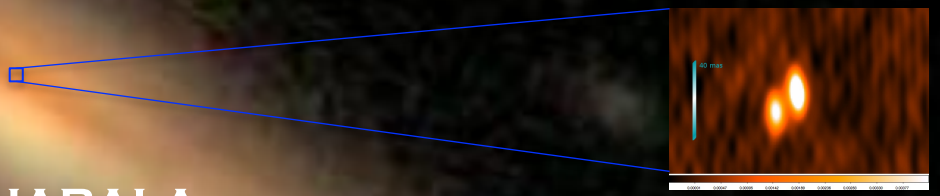
Using quasar physics to improve the VLBI reference frames



Stas Shabala
University of Tasmania

with: Lucia Plank, Jamie McCallum, Jim Lovell, Rob Schaap (UTAS)
Johannes Böhm, Hana Krásná (TU Wien)
Oleg Titov (Geoscience Australia)
Jing Sun (Shanghai Astronomical Observatory)

Outline

① What are these radio sources we look at ?

② Quantifying the effects of quasar structure

③ VieVS structure simulator

- Simulation strategy
- Effect on the reference frames

(Station positions : mm level

Source positions : above ICRF2 noise floor)

④ Mitigation strategies

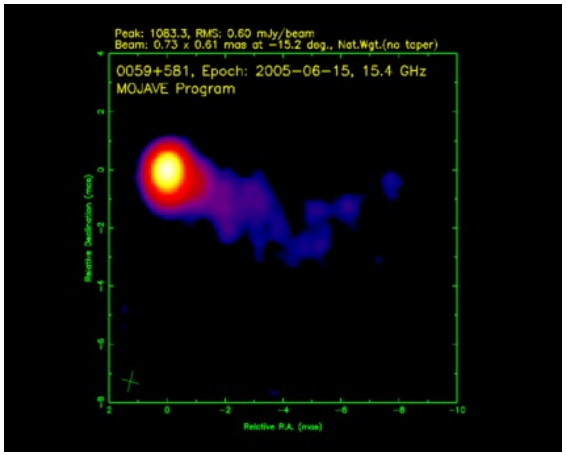
Uncooperative quasars

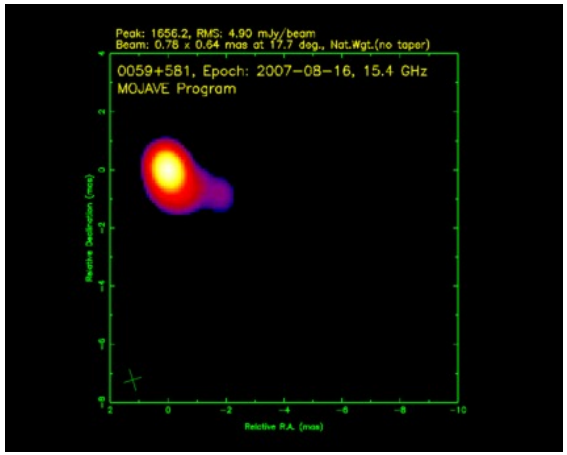
What you want them to be

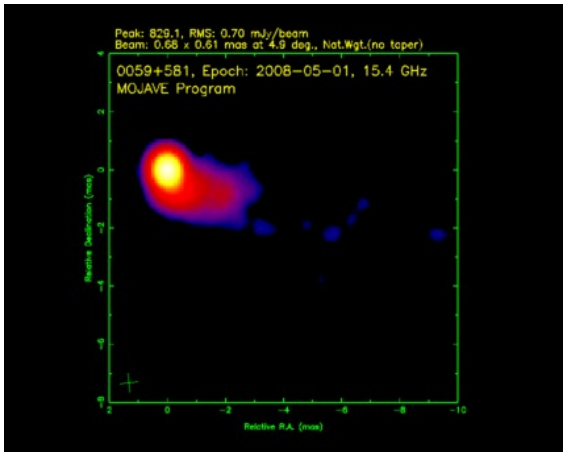
- ✧ Bright point sources
- ✧ Fixed in space and time

What they are

- ✧ Supermassive black holes
- ✧ Jets ➔ structure
- ✧ Evolve on human timescales



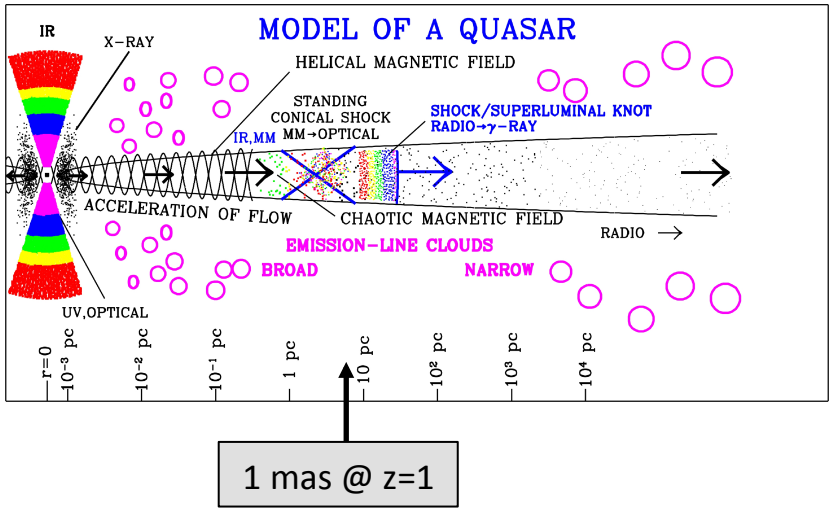


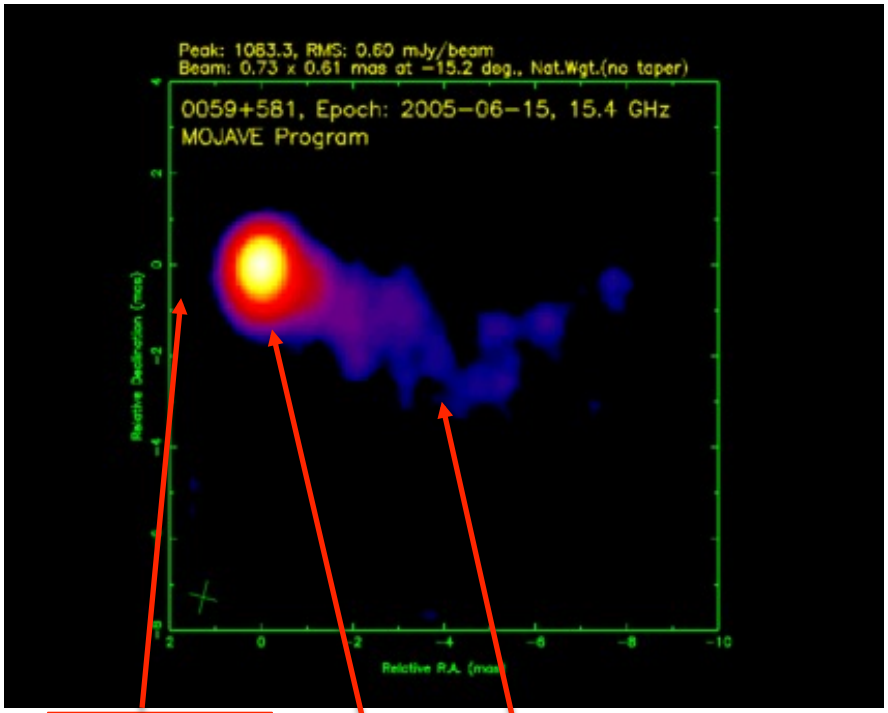


Lister et al. (2009)

Inner regions of an Active Galactic Nucleus

Image: BU / A. Marscher

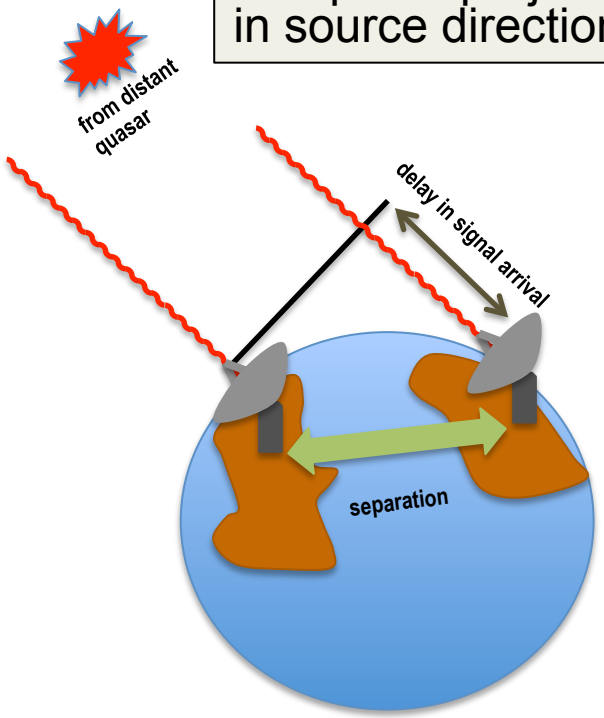




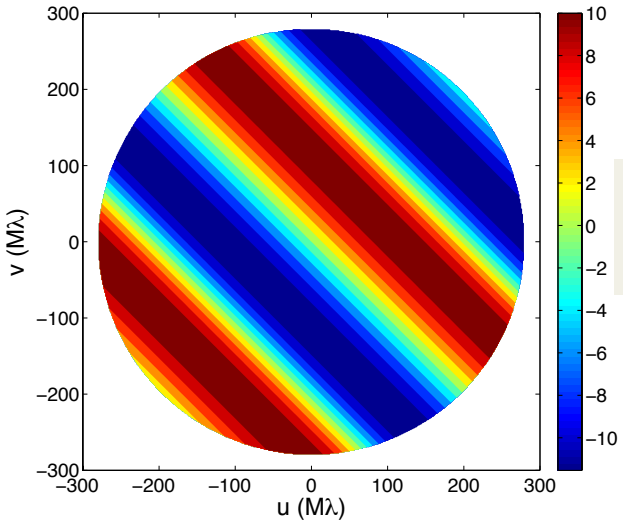
One jet towards us (Doppler boosted) -> seen
One jet away from us (D. deboosted) -> unseen

uv plane

N-E plane projected in source direction



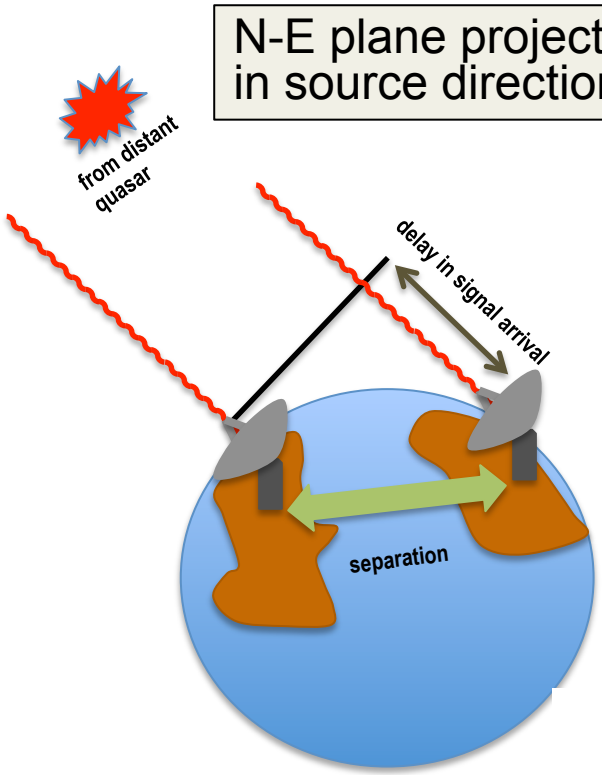
✧ interferometers measure correlated **amplitude** and **phase**



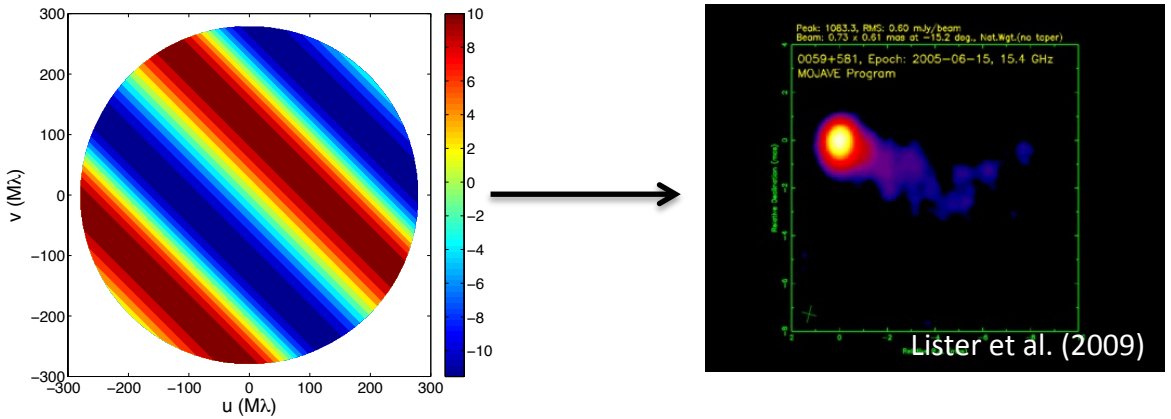
Visibility phase

distances measured in units of wavelength $\lambda = c/\nu$

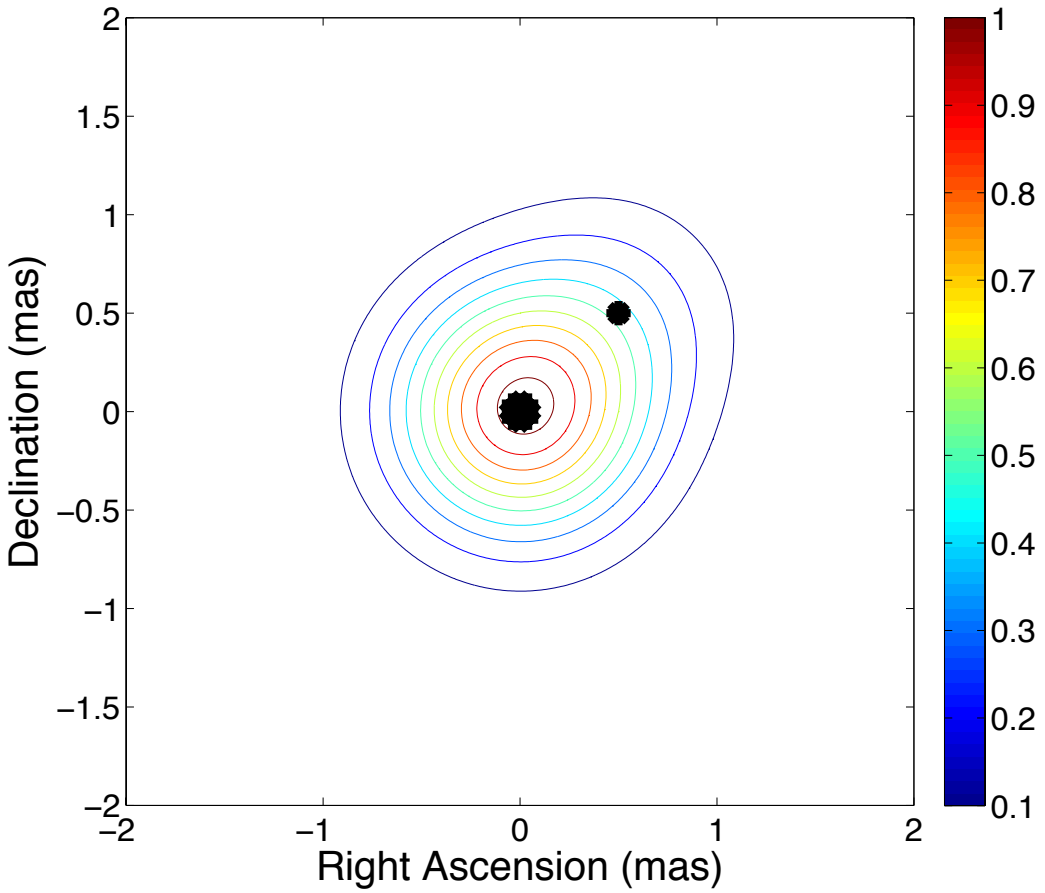
uv plane



- ✧ interferometers measure correlated **amplitude** and **phase**
- ✧ image
  ←FourierTransform→ amplitudes/phases in *uv* plane



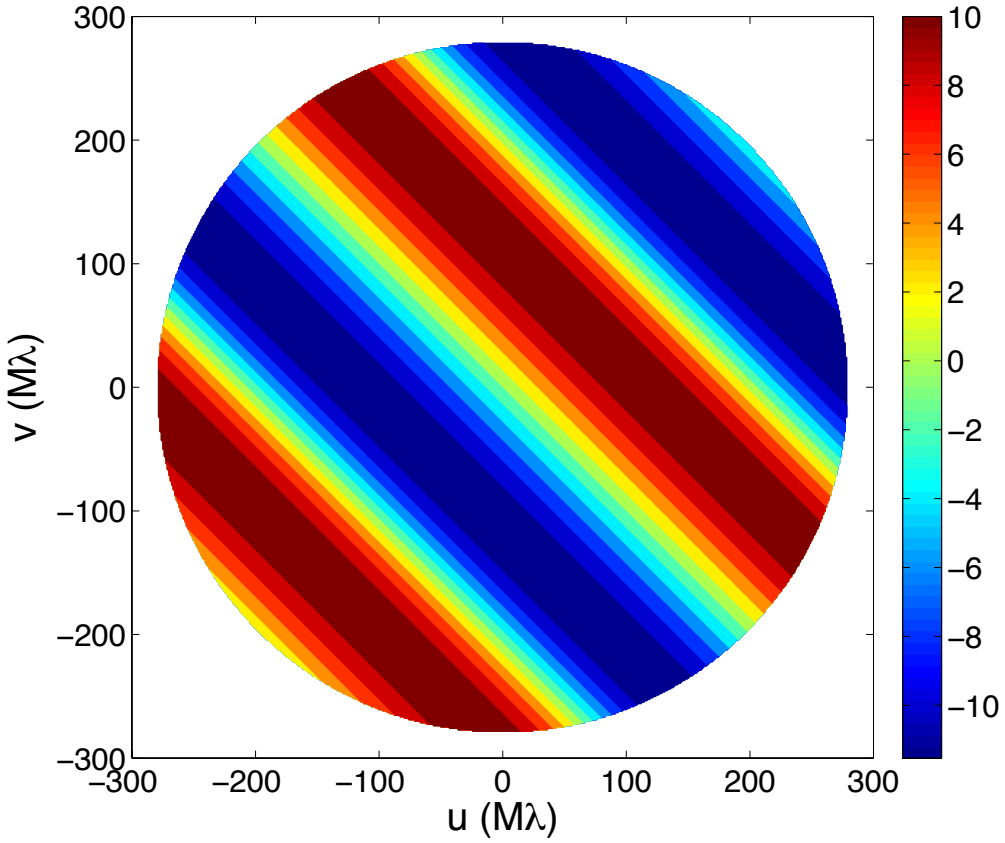
Simulated source



Visibility phase

N-E plane projected in source direction

different location in *uv* plane depending on **frequency** and **baseline**



distances measured in units of wavelength $\lambda = c/\nu$

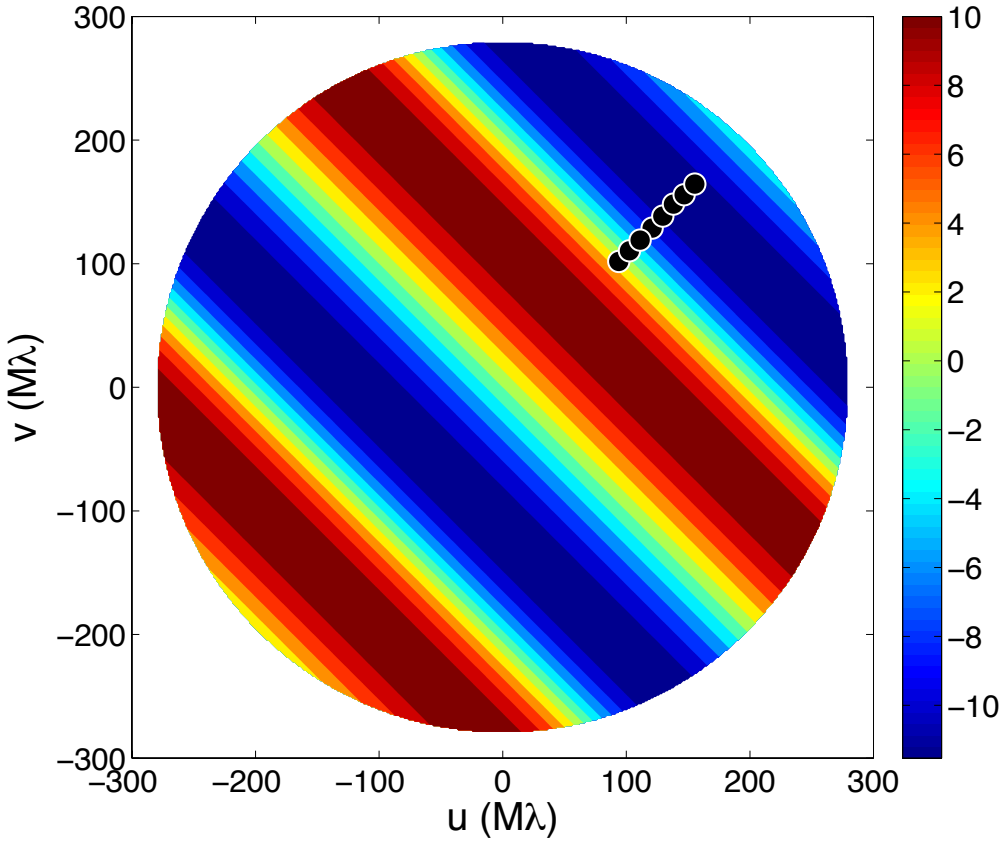
Source structure in geodetic VLBI

- Group delay = (1 / 2π) (Δ phase / Δ frequency)
  - phase depends on *projected* structure as seen by a given baseline
  - function of:
    - baseline
    - observing time
    - amount and direction of structure
  - effect is different at each of 8 sub-bands at X-band (because frequencies are slightly different)
- Hence group delay (= slope across band) changes

Visibility phase

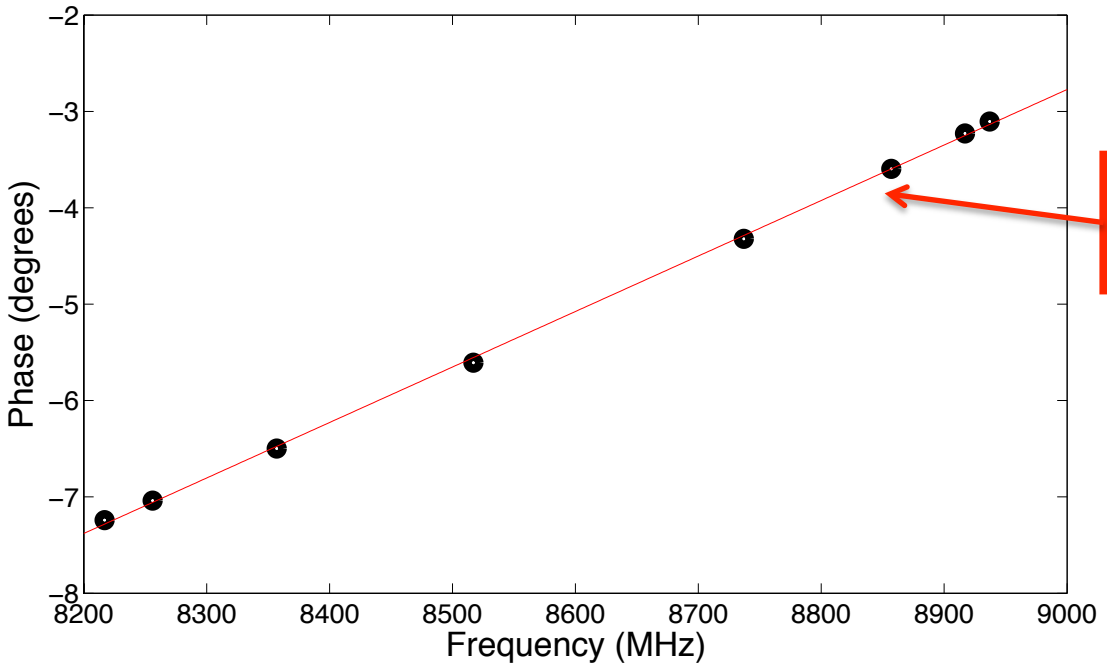
N-E plane projected in source direction

different location in *uv* plane depending on **frequency** and **baseline**



distances measured in units of wavelength $\lambda = c/\nu$

Structure phase on 9000 km baseline

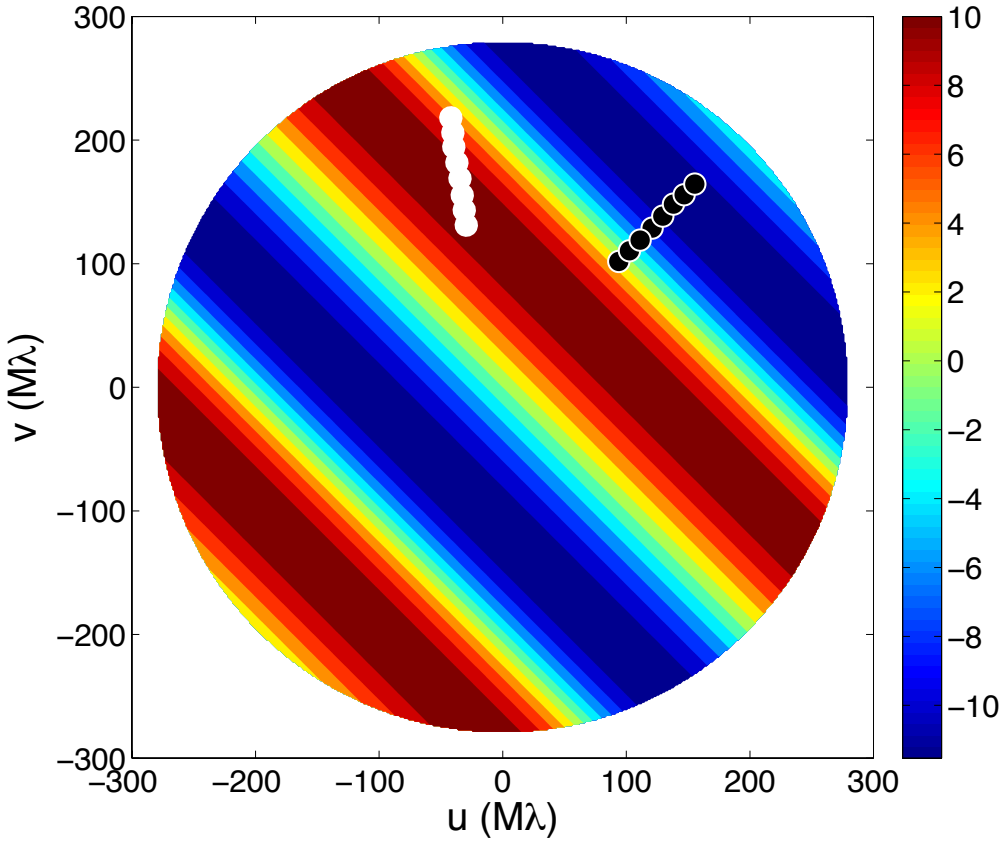


slope =
structure delay

Visibility phase

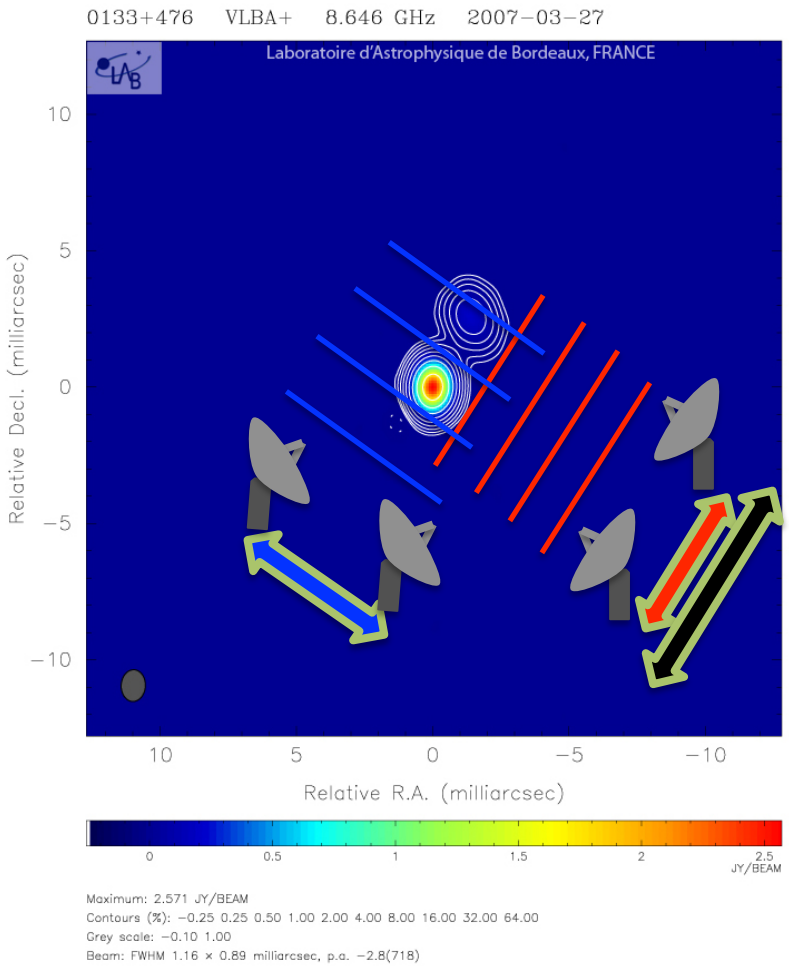
N-E plane projected in source direction

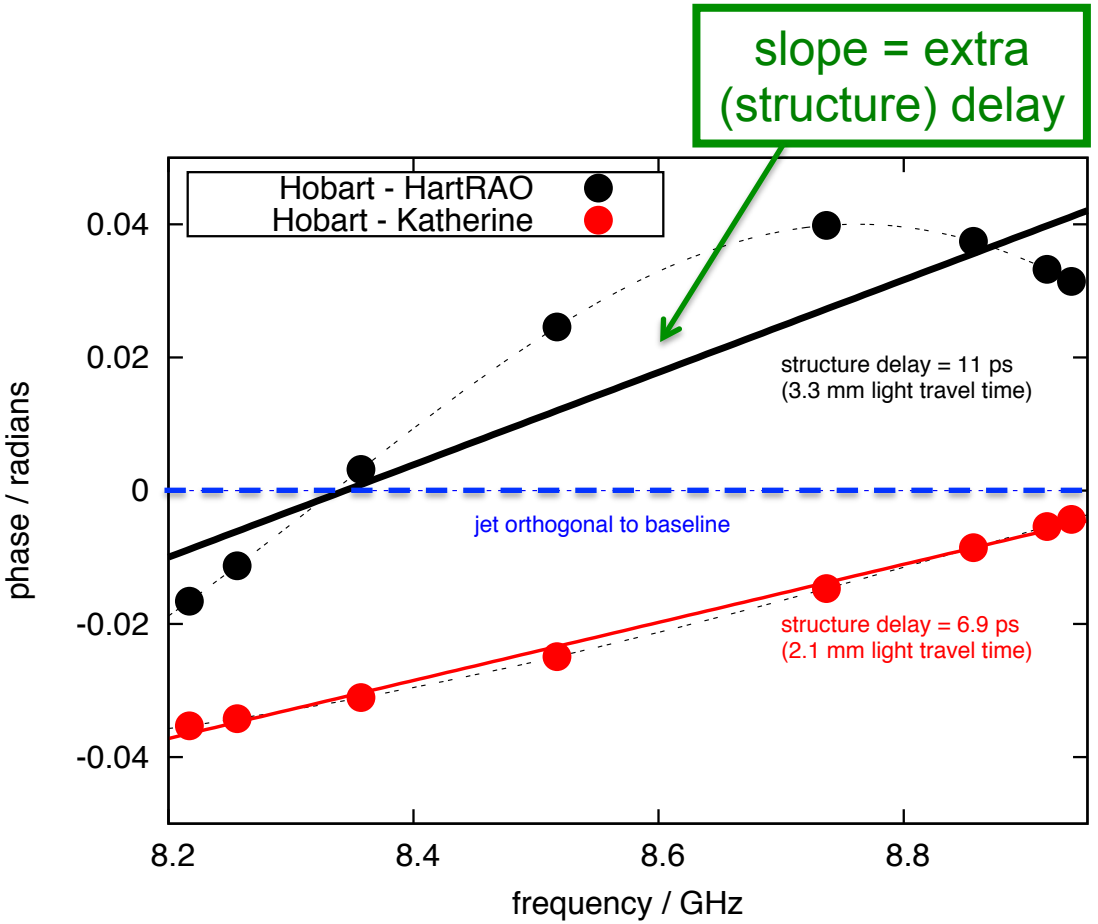
different location in *uv* plane depending on **frequency**, **baseline** and **time**



distances measured in units of wavelength $\lambda = c/\nu$

Jet – baseline orientation





How a source is observed is important

3 effects of quasar structure

slope ≠ 0

1. Measure incorrect position
   - Position offset (X, Y, Z) from "correct" value
2. Measure different positions for different schedules
   - Scatter in station positions for different baseline/ schedule combinations (even with same quasars)
     ➔ increased rms for positions derived from different schedules
3. Multiple observations inconsistent with each other
   - Larger formal uncertainties, within a single session

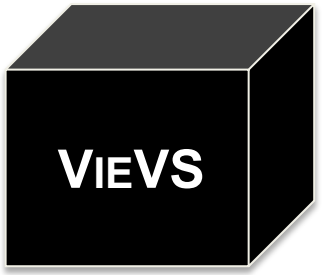
slope changes with projected structure

VieVS source structure simulator

Vienna VLBI Software (VieVS)

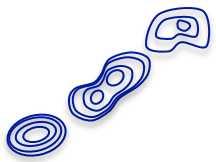
- Simulate geodetic observations
- Process simulated observations

➔ station / source positions, EOPs



Quasar structure simulations

- Quasars ≠ point-like
- Extra structure delay per observation
- (mostly) Mock source catalogues



Simulated catalogues

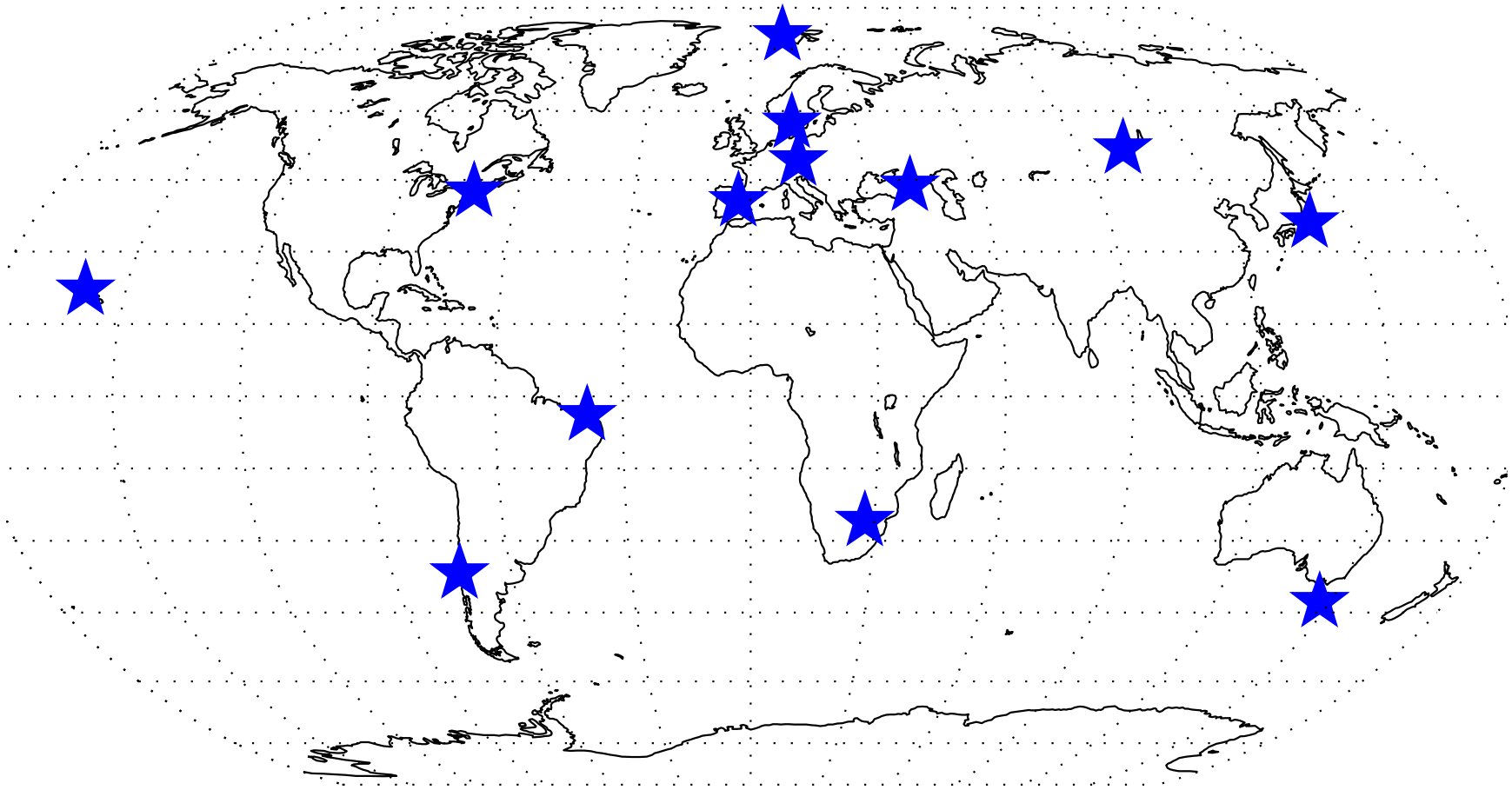
- Structure indices ➔ mock quasar images

  SI = 1 + 2 log (τ / ps)

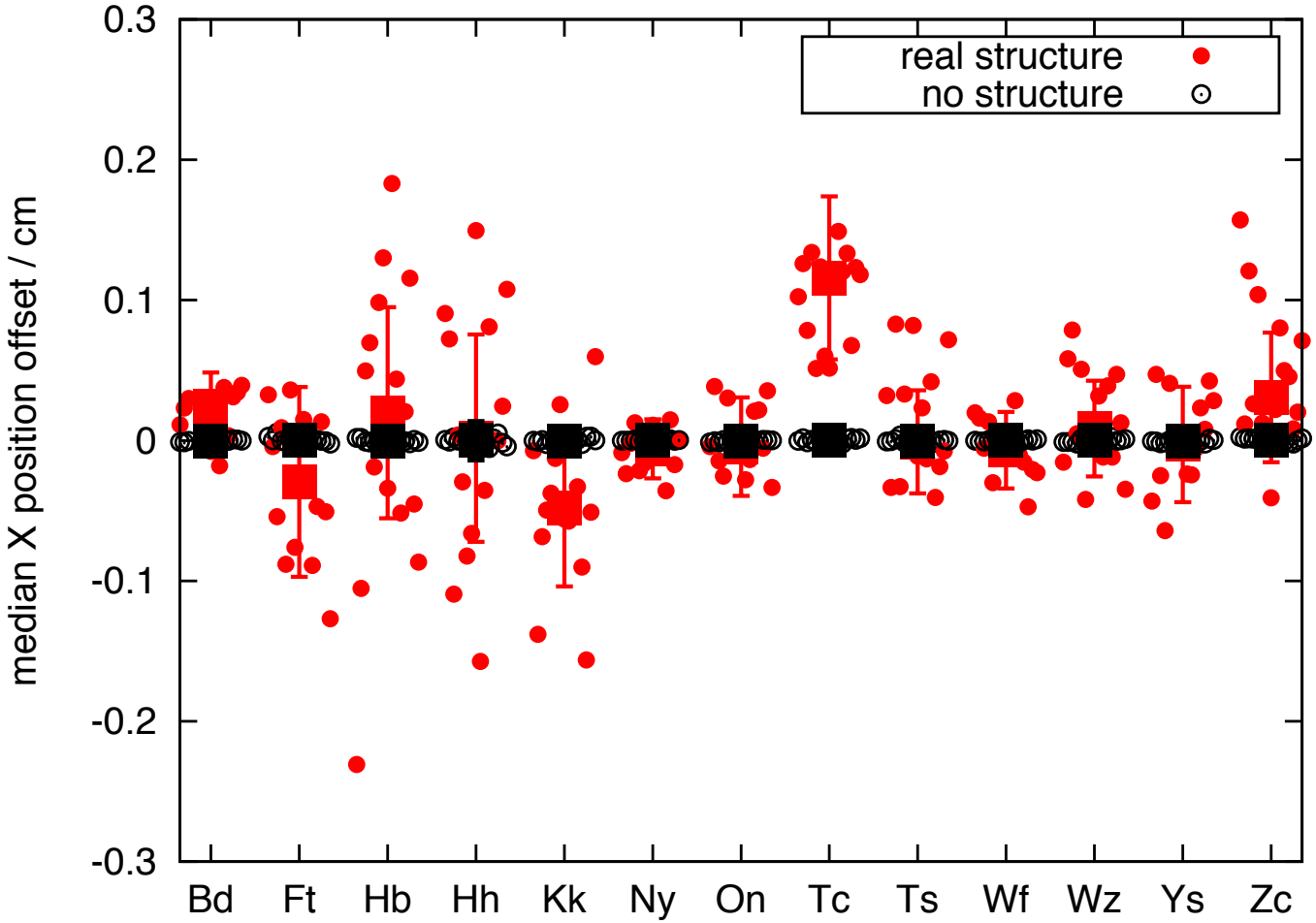
  - Choose SI (none, 1, 2, 3, 4, ICRF2 distribution)
  - 2-component sources
  - Also one “real” CONT11 catalogue

- Simulate realistic schedules with *VieVS*
  - CONT11
    - 15 – 29 September 2011
    - 13 stations
    - 30 realizations of each day
  - Additional delay term due to source structure

CONT11

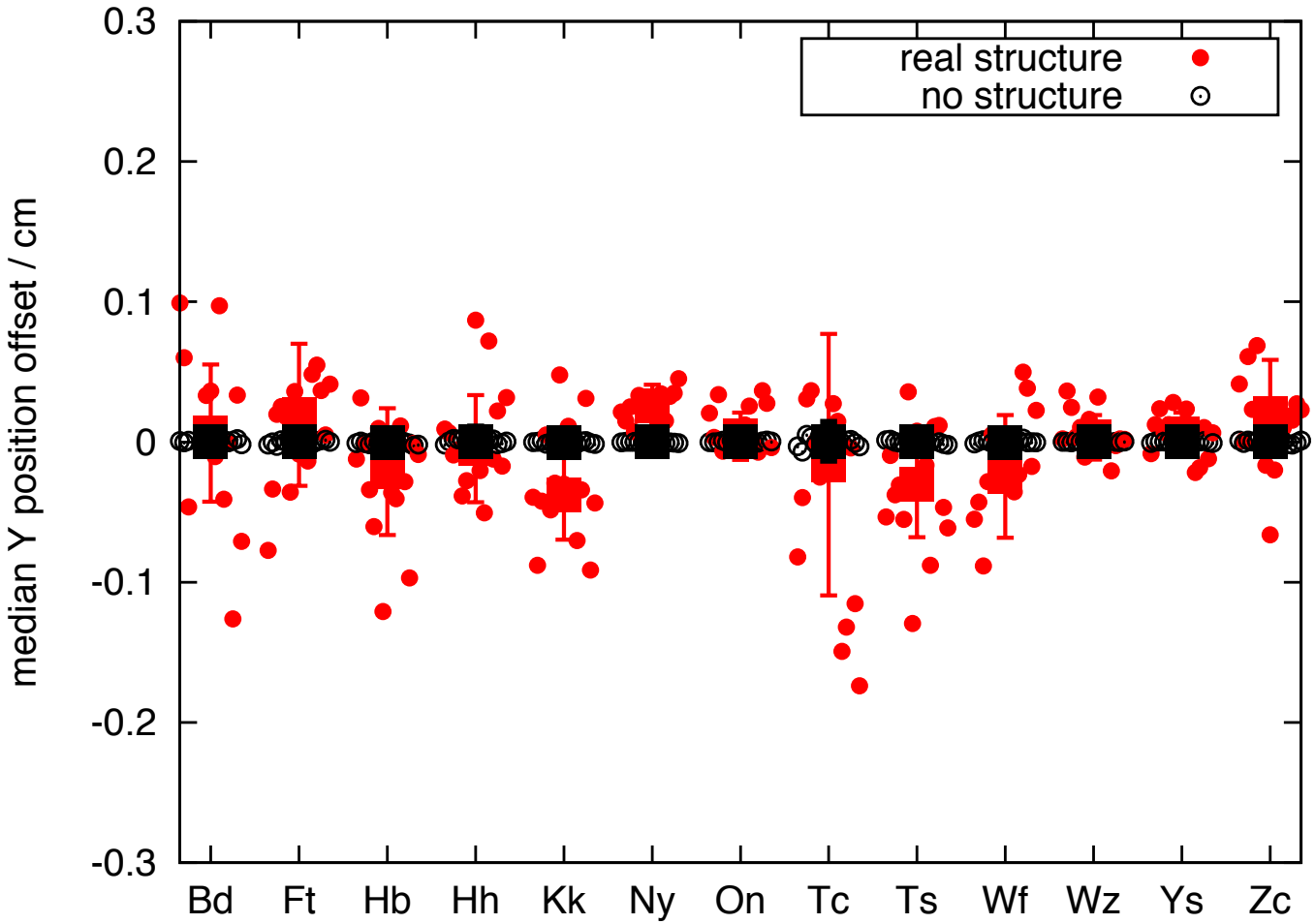


Station positions – X coord



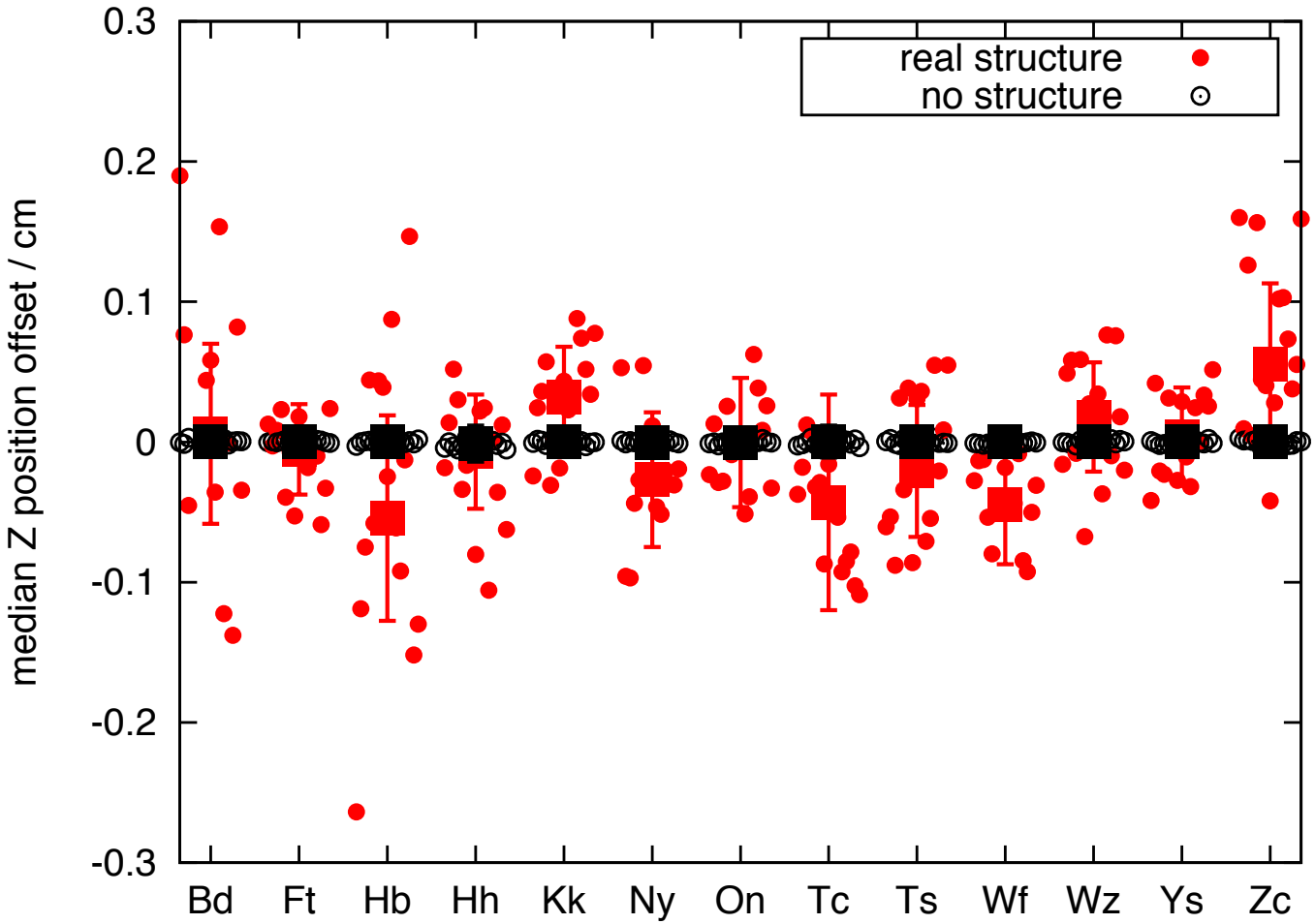
Shabala+15, J. Geodesy

Station positions – Y coord



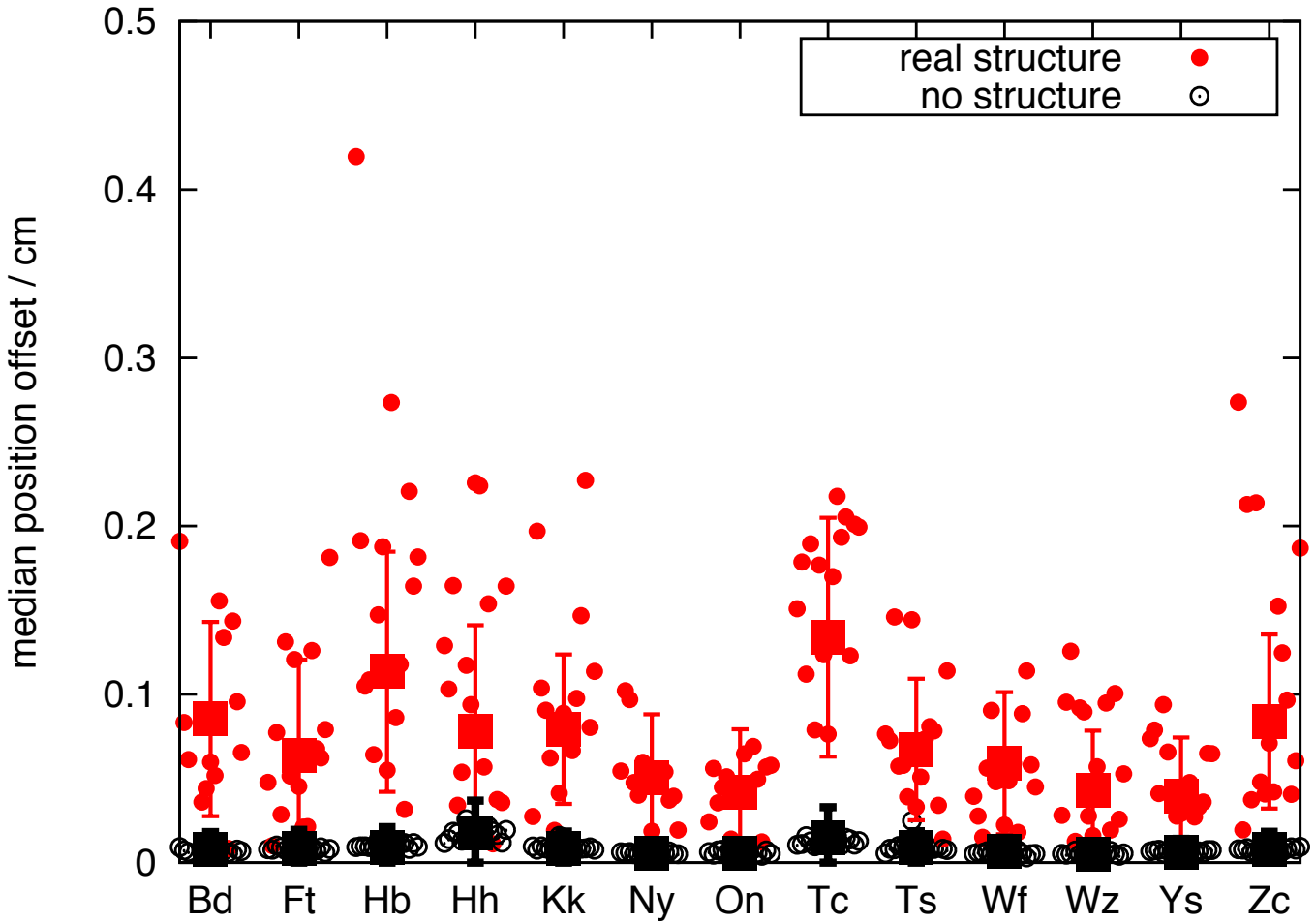
Shabala+15, J. Geodesy

Station positions – Z coord



Shabala+15, J. Geodesy

Station positions – 3D coord offset



Shabala+15, J. Geodesy

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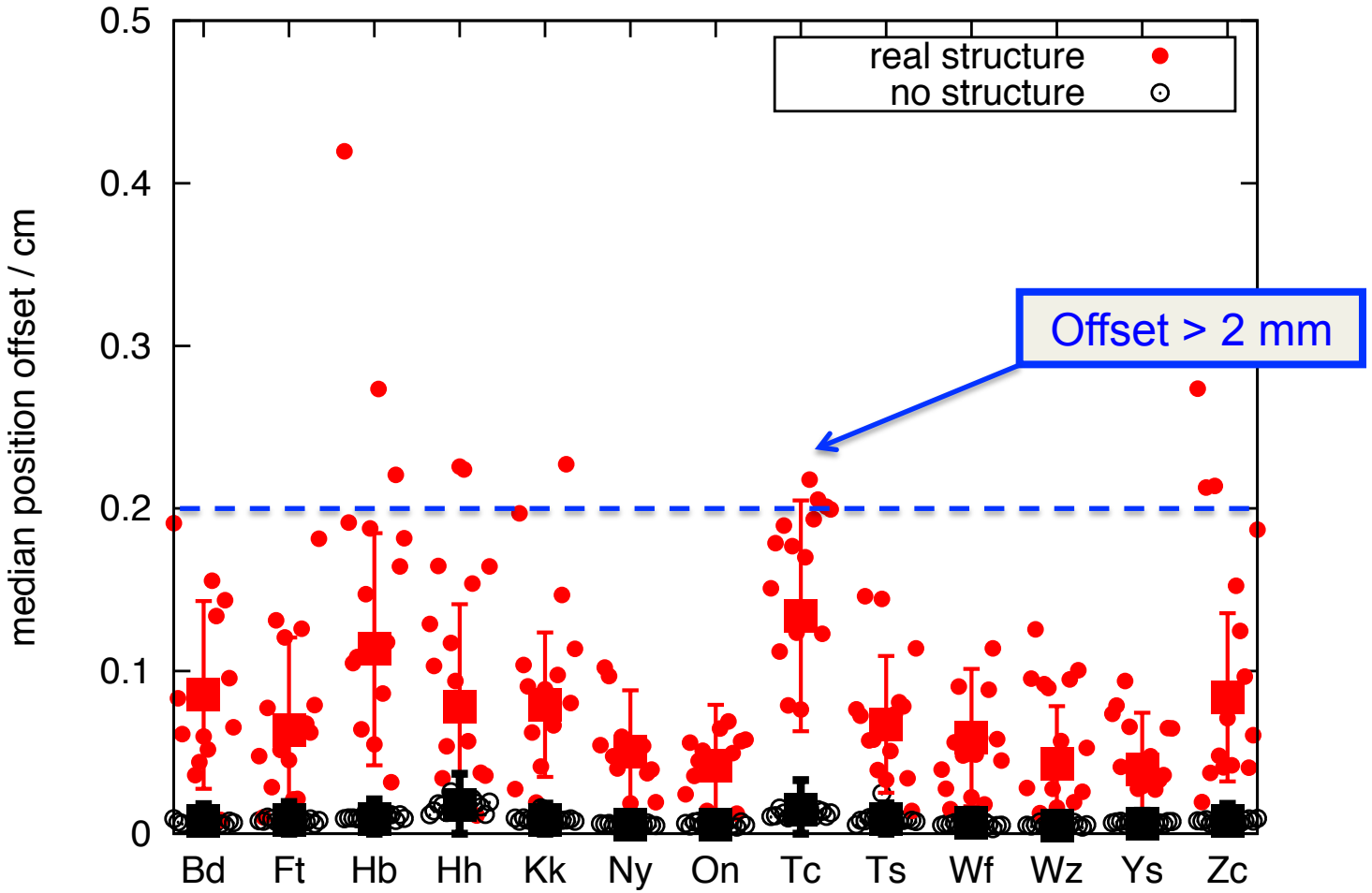
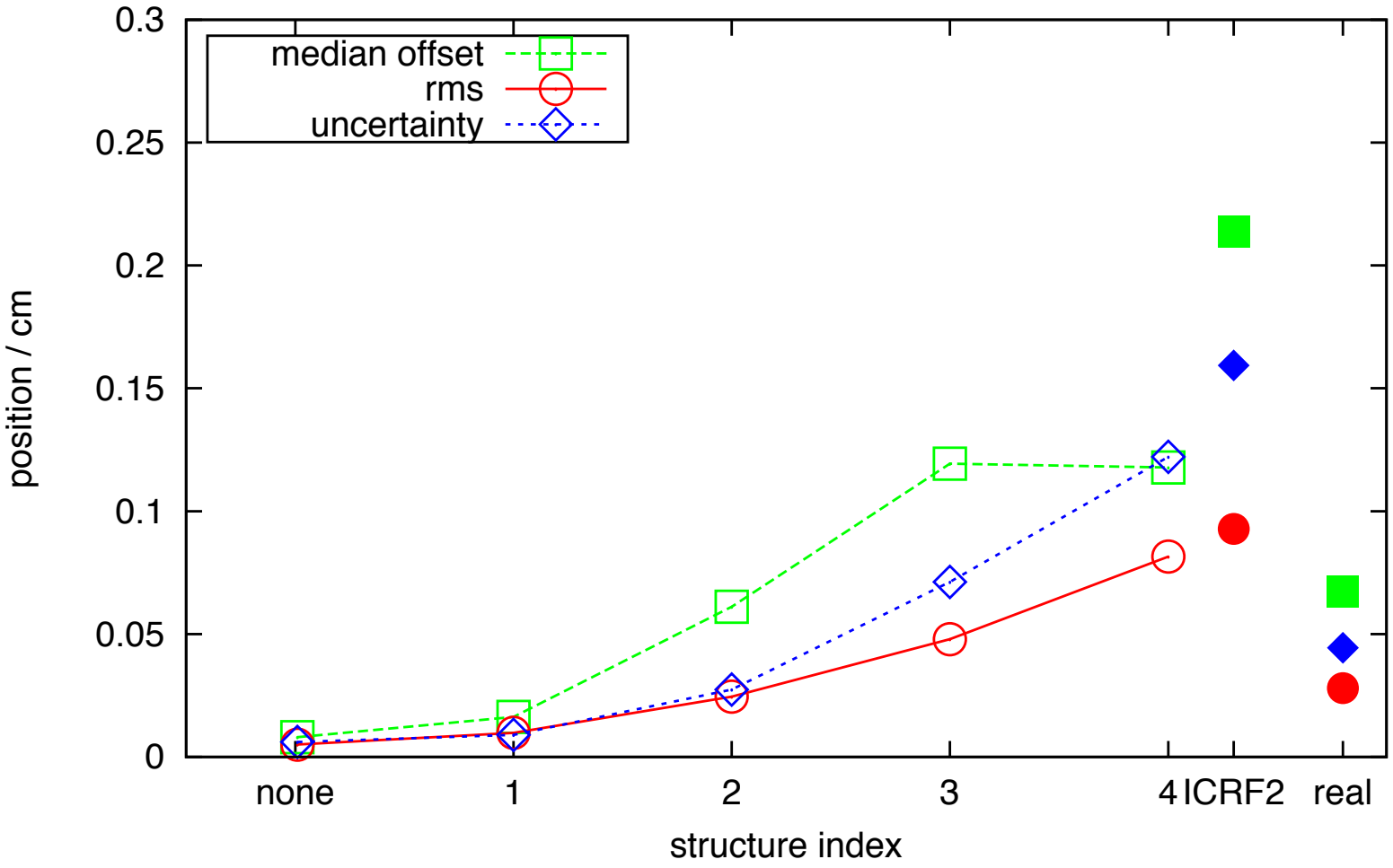


Shabala+15, J. Geodesy

How important is quasar structure ?



SI = 1 + 2 log (τ / ps)

Shabala+15, J. Geodesy

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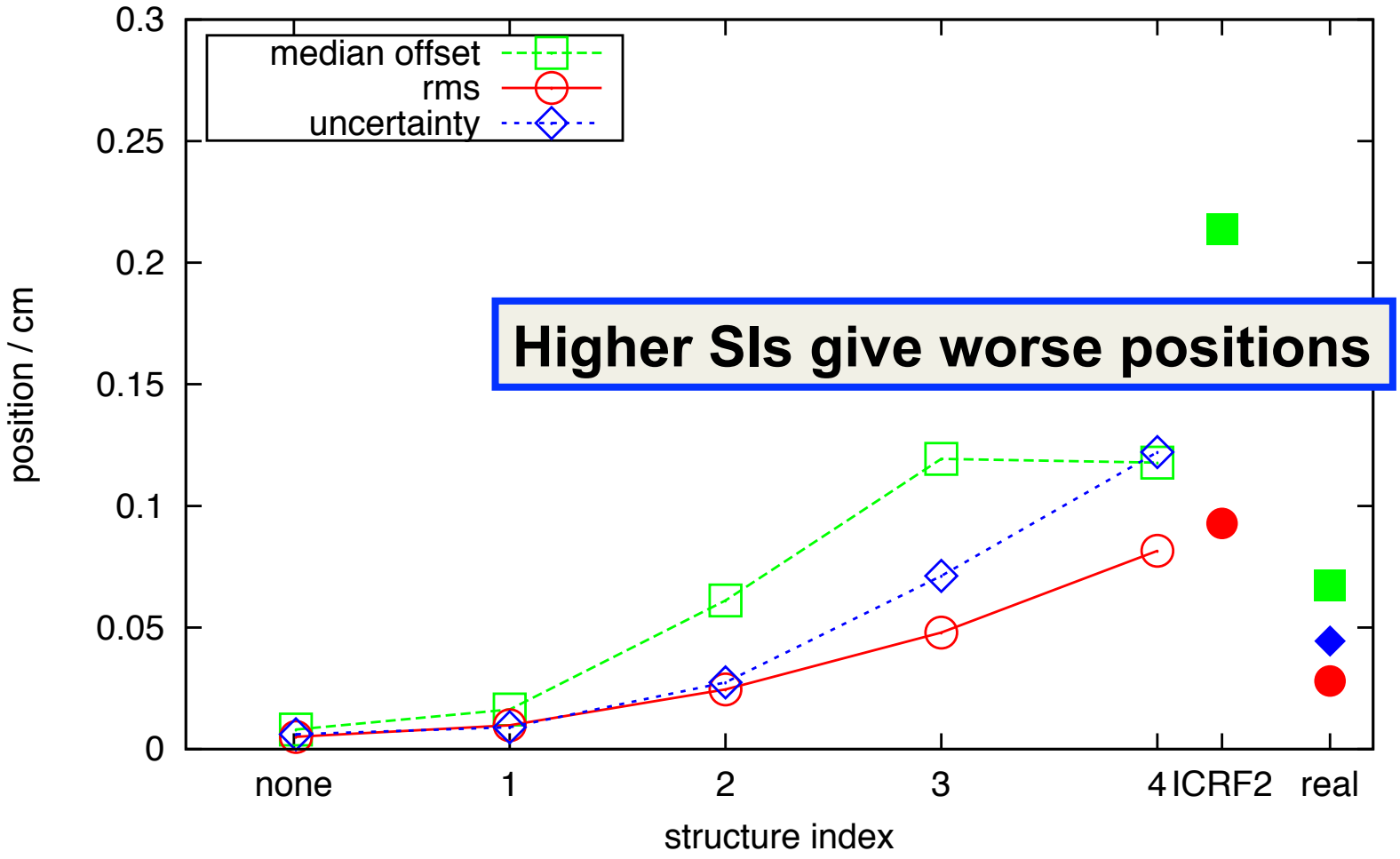

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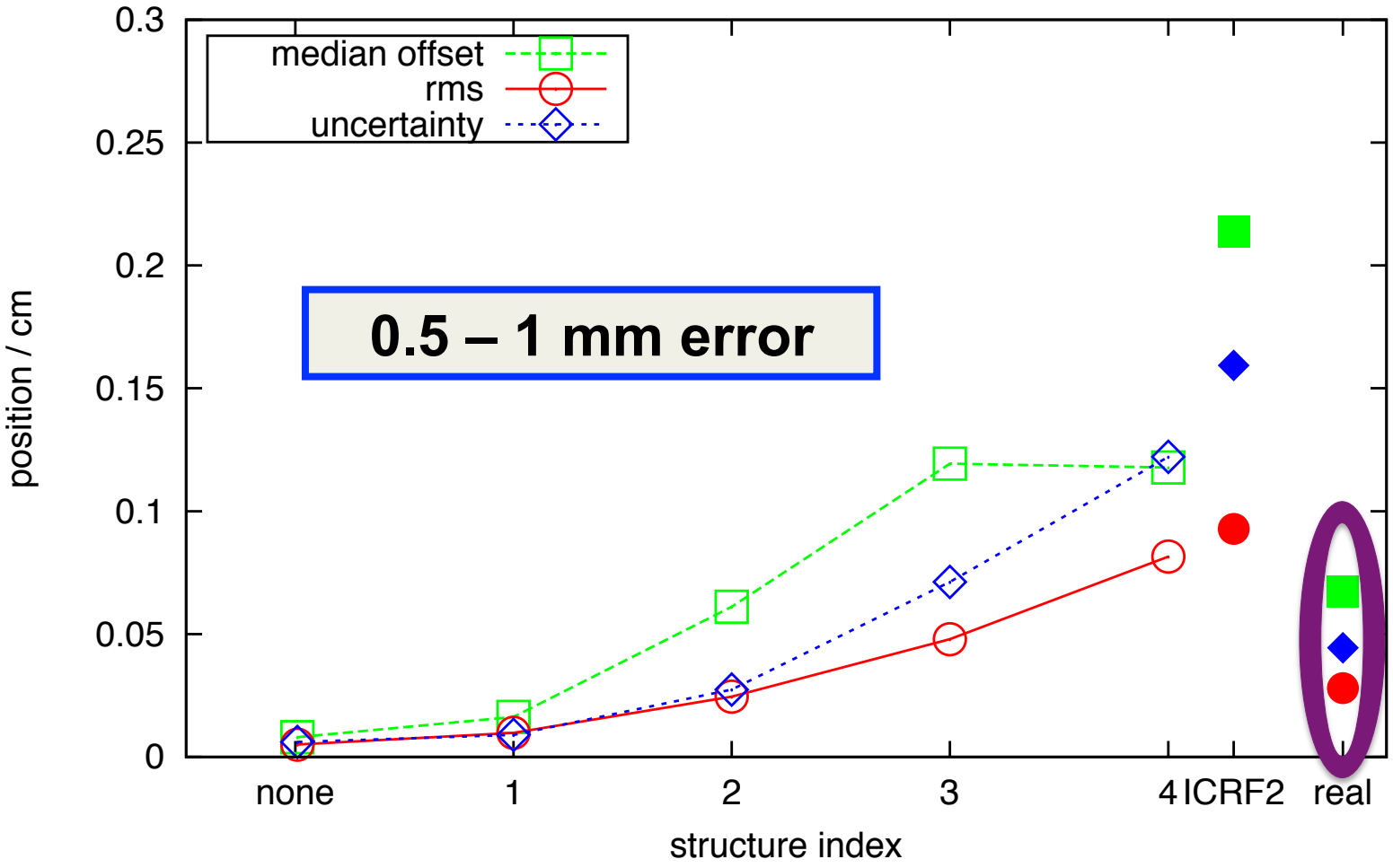

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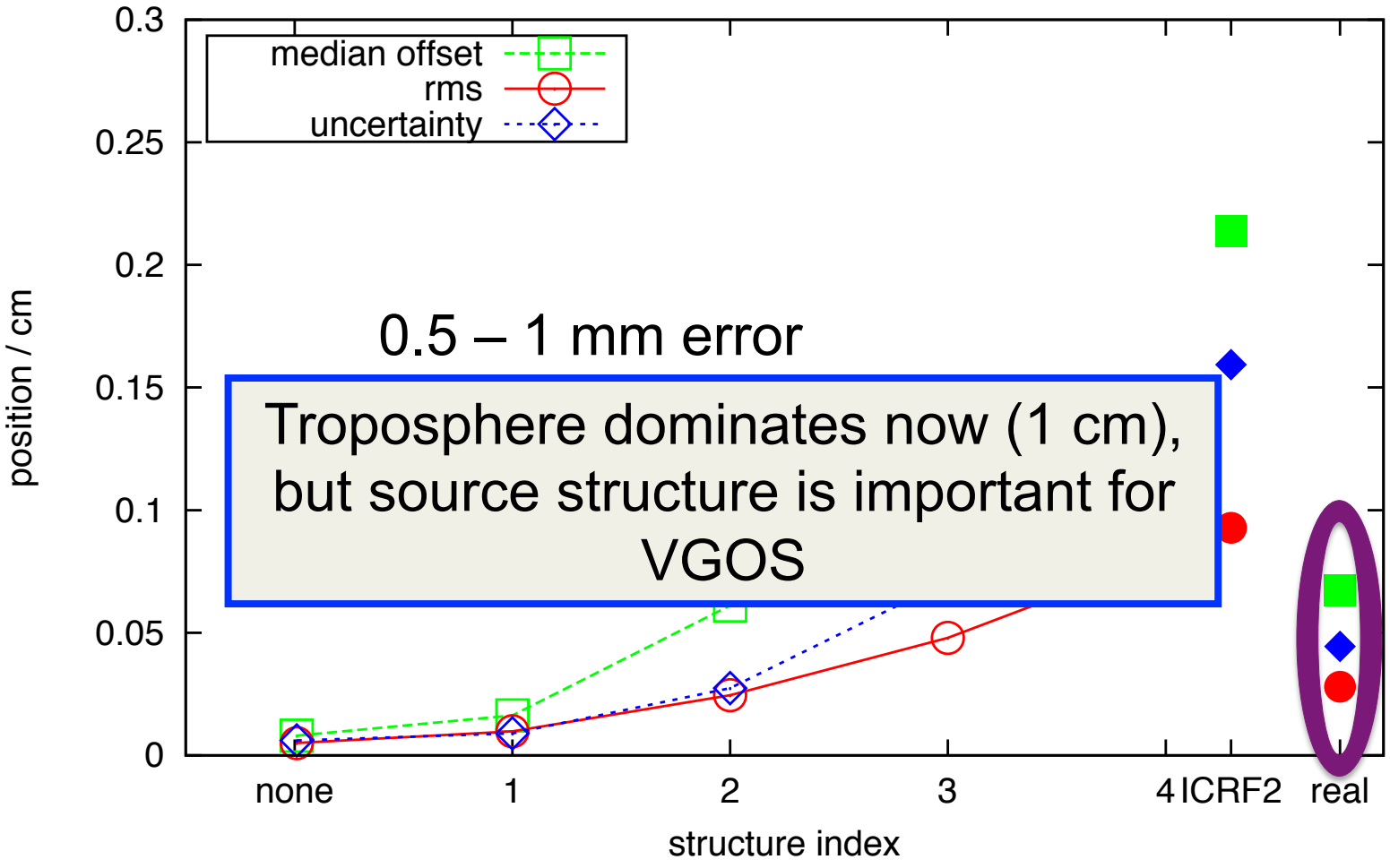

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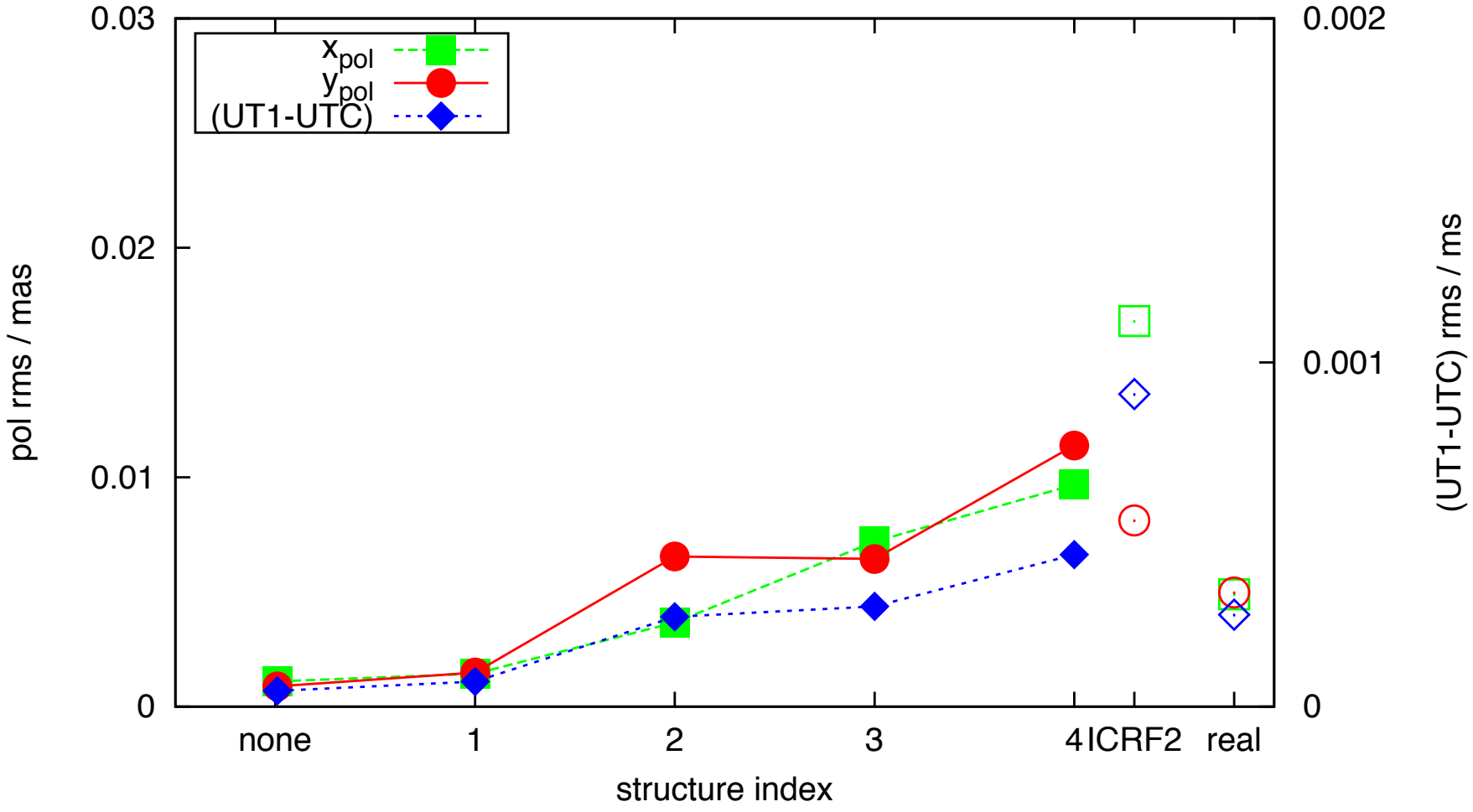
Shabala+15, J. Geodesy

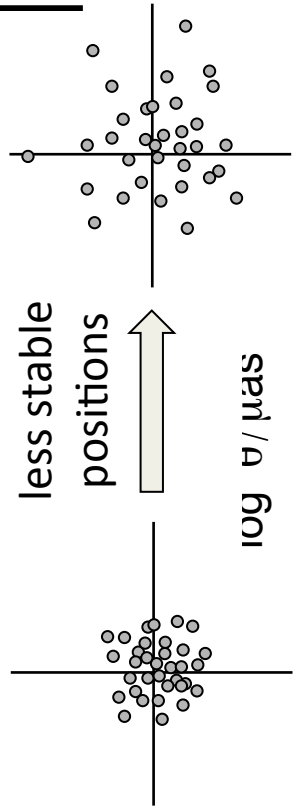
EOP rms

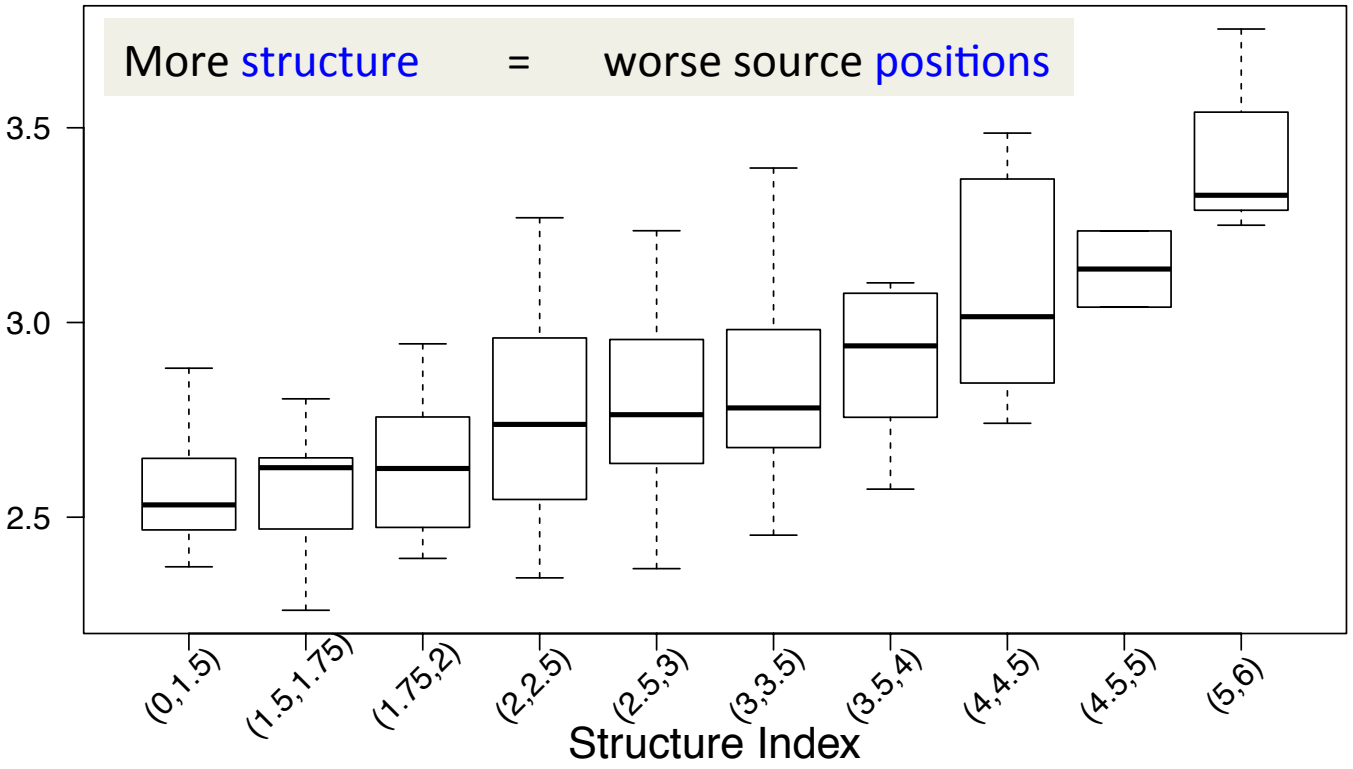


Shabala+15, J. Geodesy

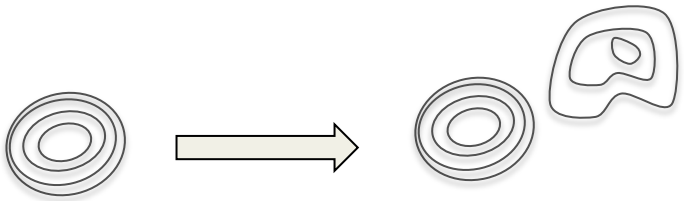
Source structure : effects on CRF

Schaap et al. 2013, MNRAS, 434, 585



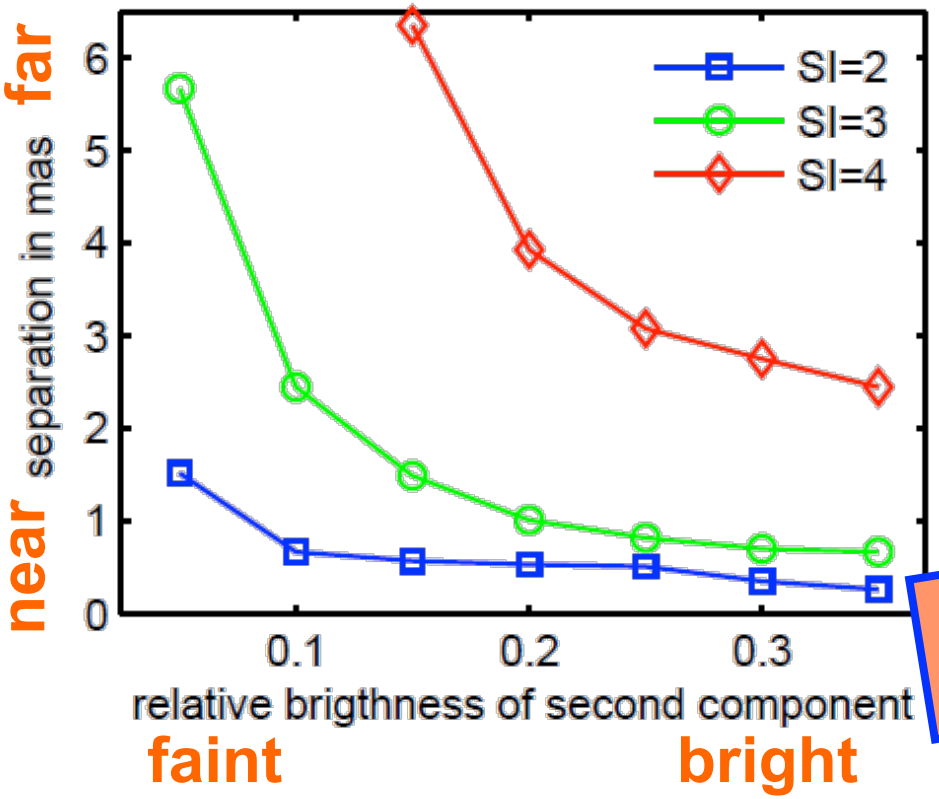


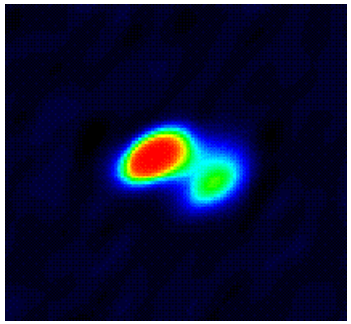
OBSERVED



Modeling structure

Plank, SS+16, MNRAS





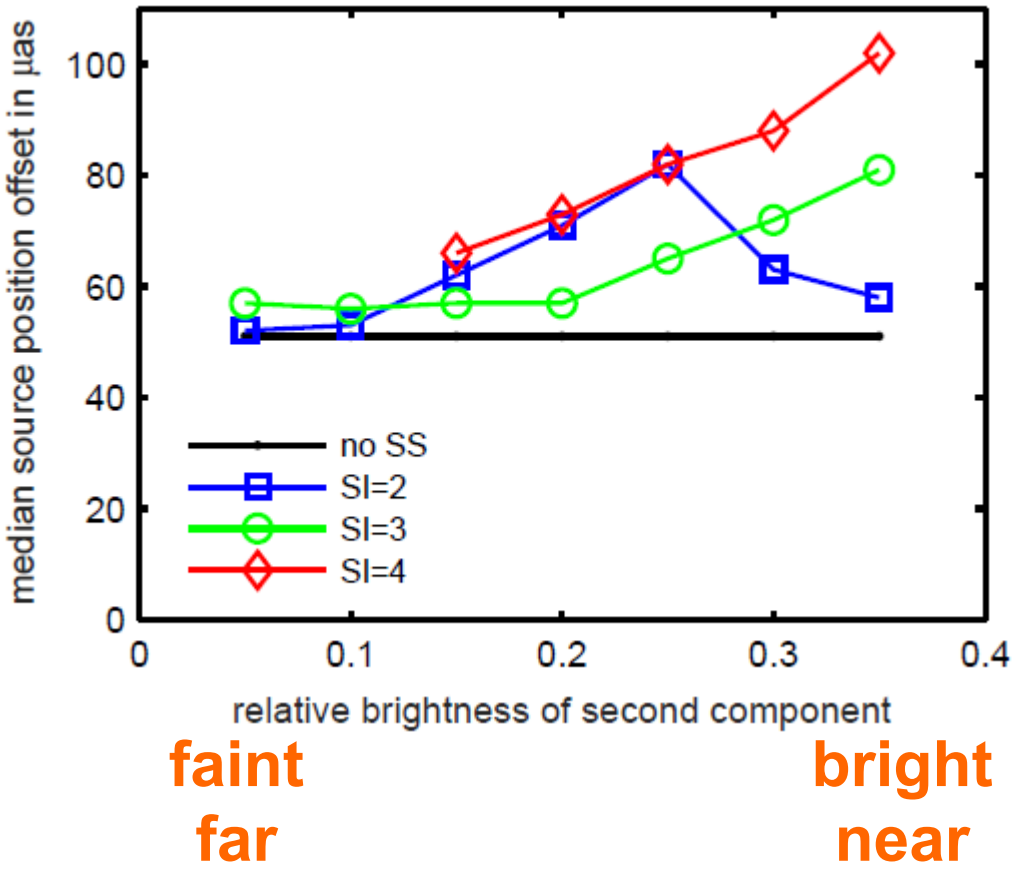
- Two-component models
- Flux density ratio *vs* separation

How do different levels of structure affect **source positions** ?

SI = 1 + 2 log (τ / ps)

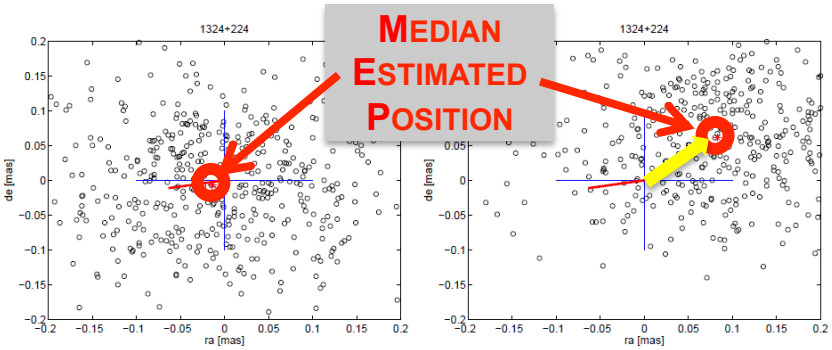
Displacement due to structure

Plank, SS+16, MNRAS



faint
far

bright
near

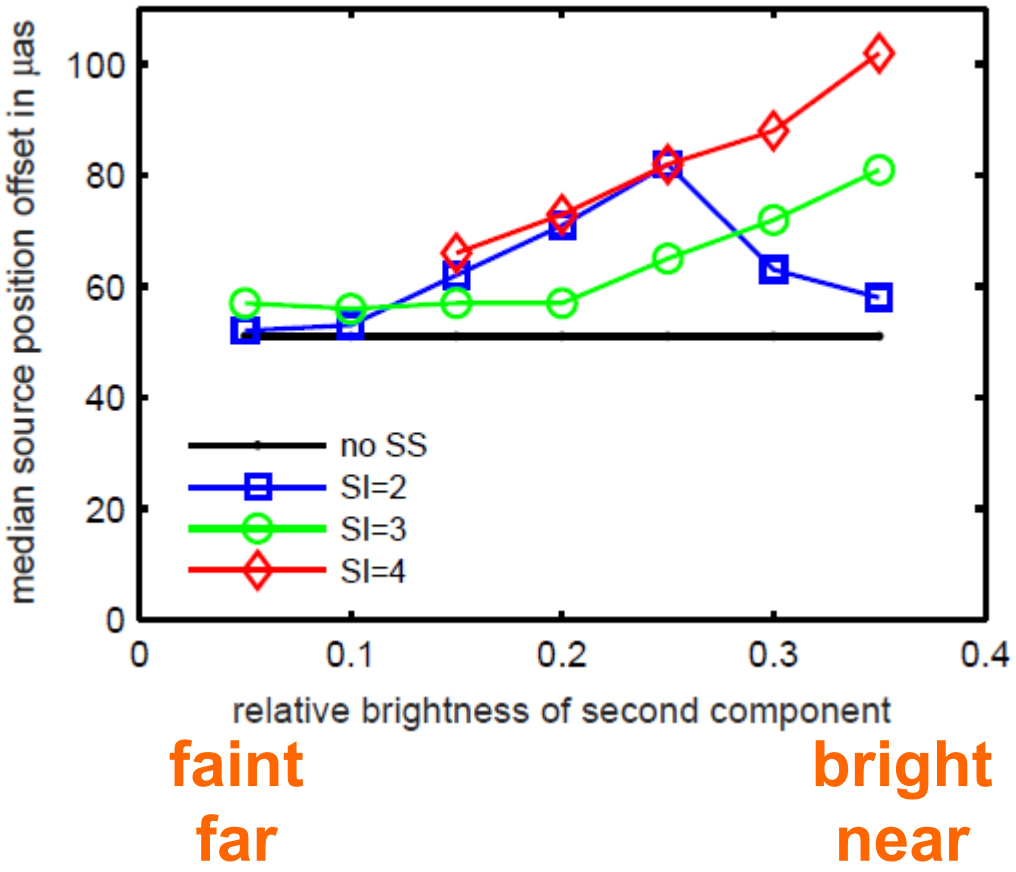


- 104 sim sessions in 2013
- Systematic
- Tens of μas
- Above troposphere
- "Good" (SI = 2) sources can be bad

$$SI = 1 + 2 \log (\tau / ps)$$

Displacement due to structure

Plank, SS+16, MNRAS



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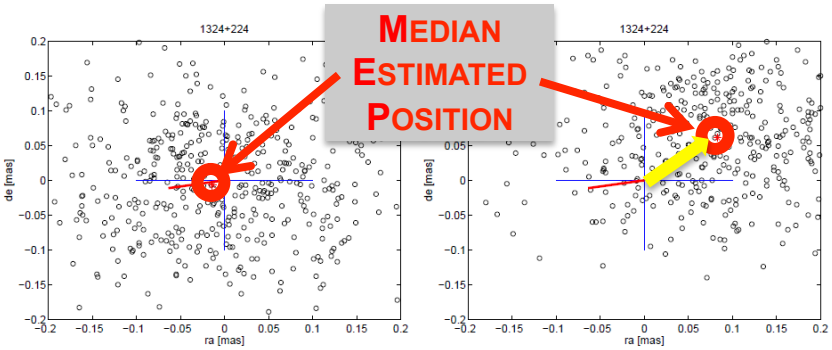

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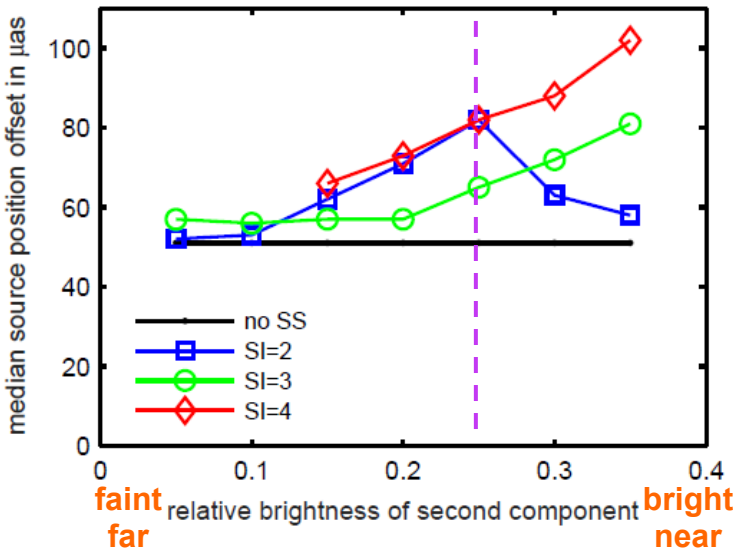
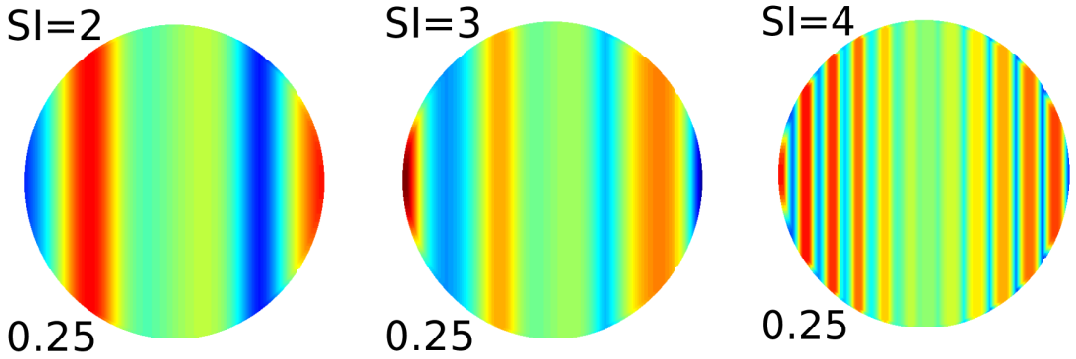
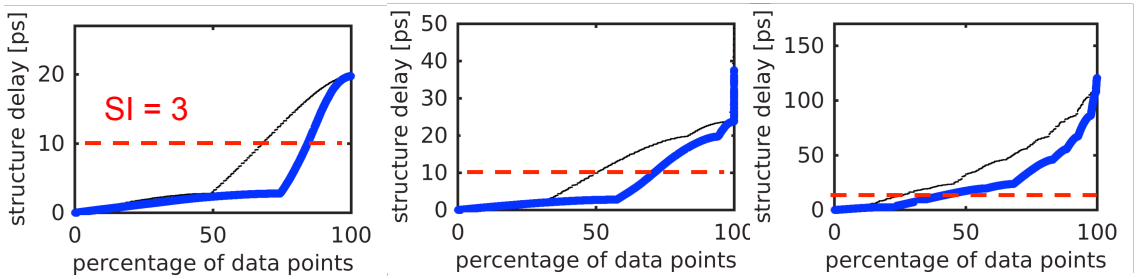
Delay maps





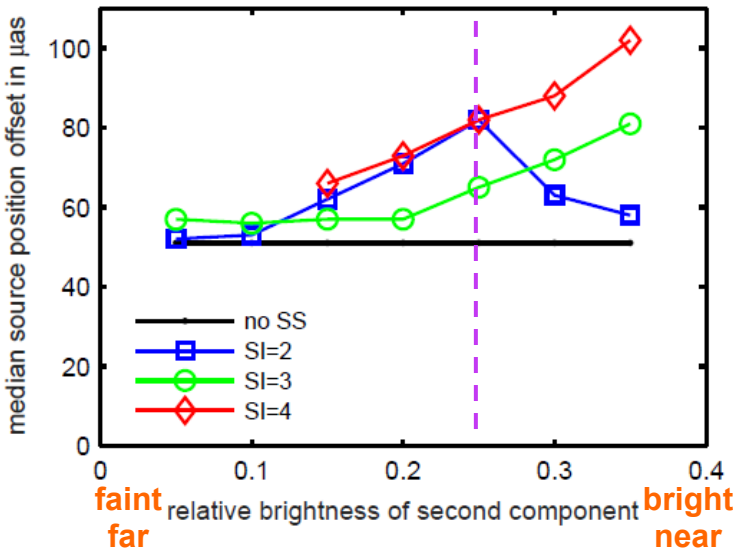


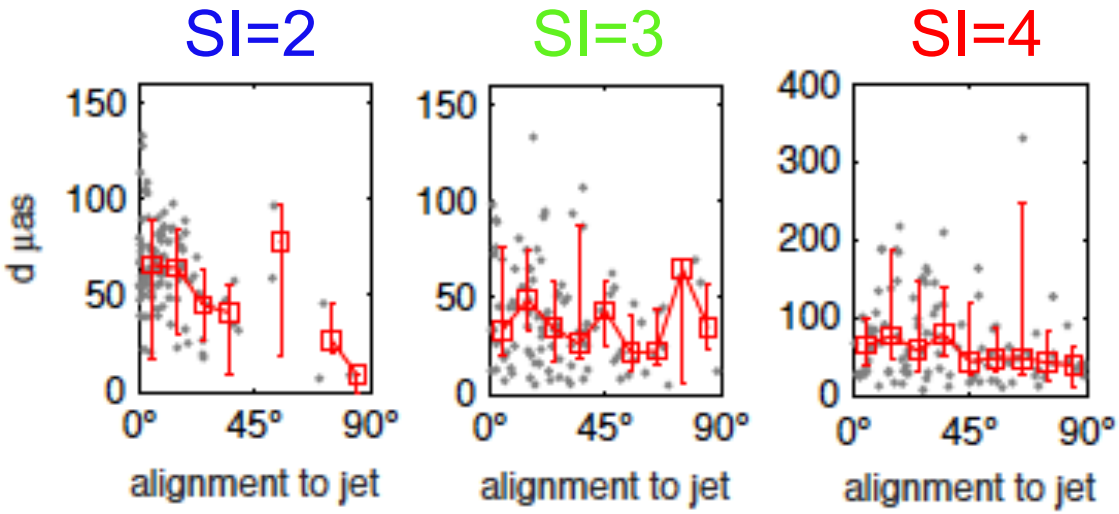
- **Structure delay** *vs* projected baseline
- SI=3 /4
  - delay changes rapidly with baseline

  → "noise" - like term
- systematic shift for SI=2

Plank+16, MNRAS

Systematic or noise ?

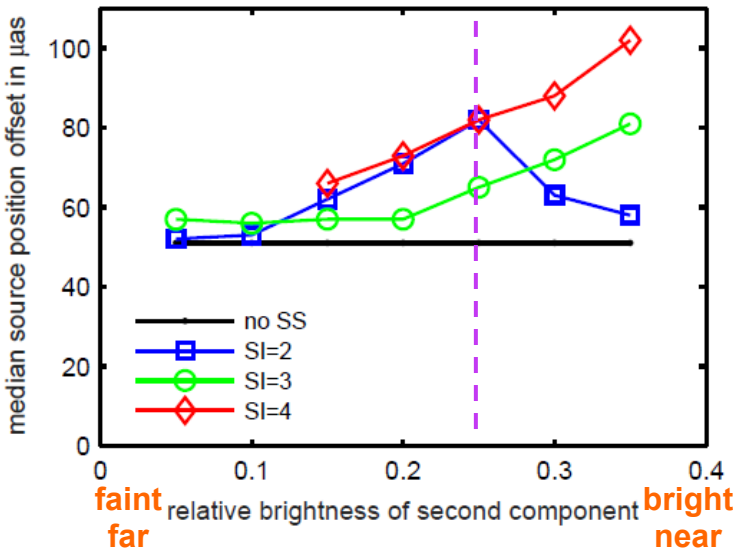


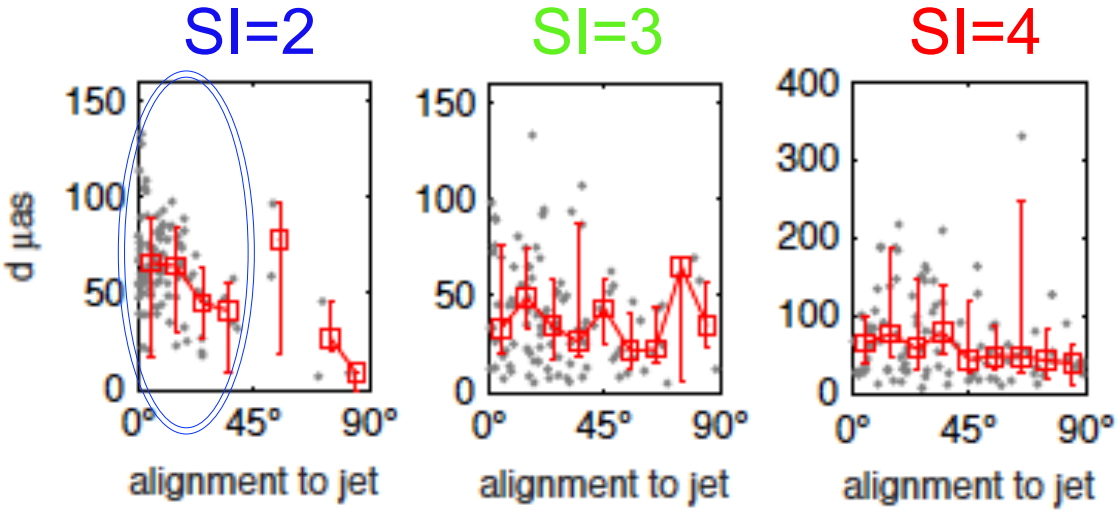


- direction of displacement *vs* jet direction
- 104 simulated sessions for year 2013

Plank+16, MNRAS

Systematic or noise ?





- direction of displacement *vs* jet direction

Plank+16, MNRAS

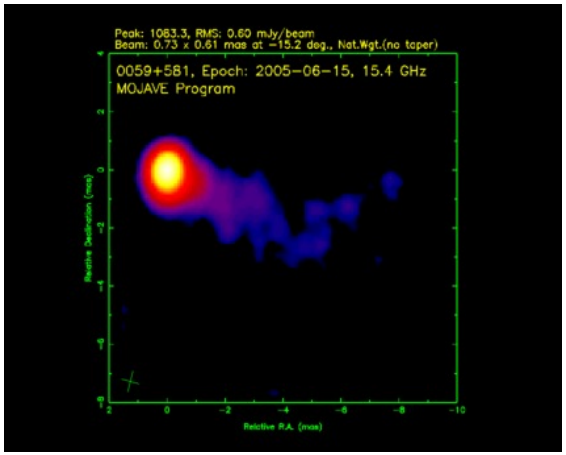
- 104 simulated sessions for year 2013
- SI = **2**: displacement preferentially in the jet direction
- SI = **3** / **4**: no relationship between jet and offset directions
  - effects of different baselines "cancel out"

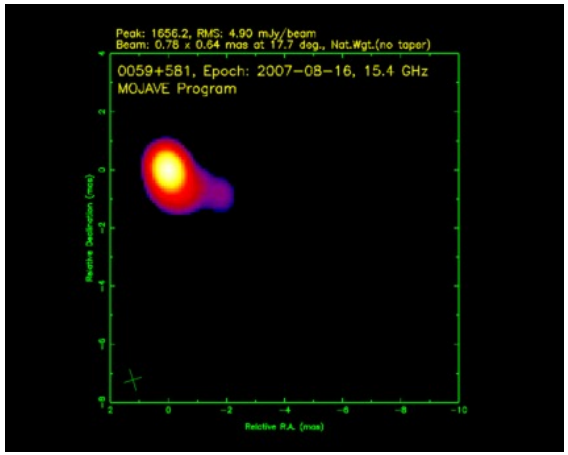
How do we improve the Reference Frames ?

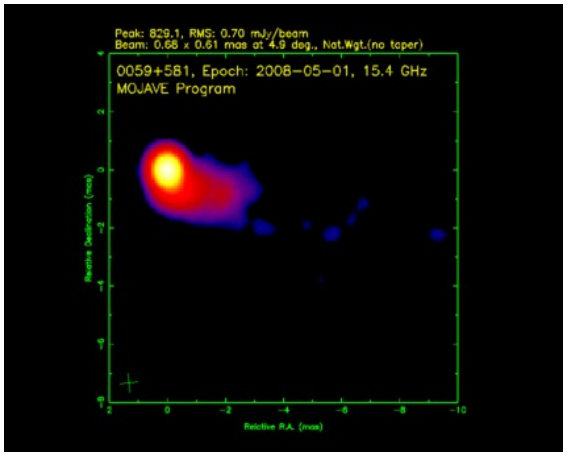
(with quasar physics)

Good news

① We can image quasar structure
(and make corrections)







Lister et al. (2009)

How do we improve the Reference Frames ?

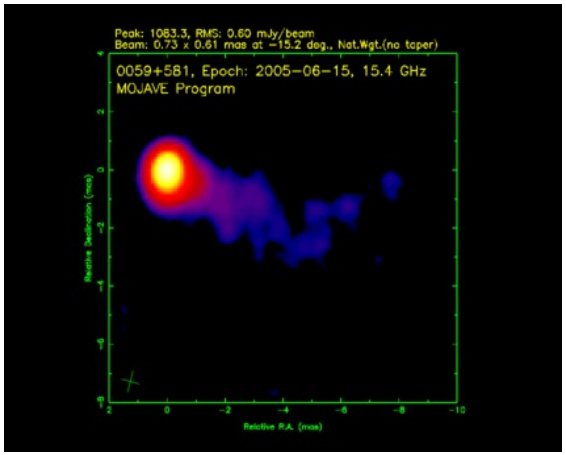
(with quasar physics)

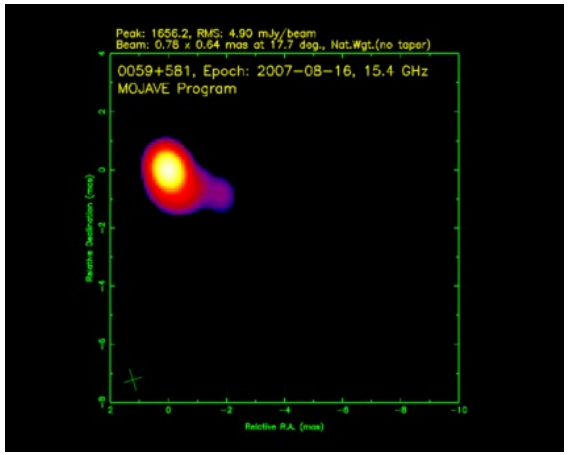
Good news

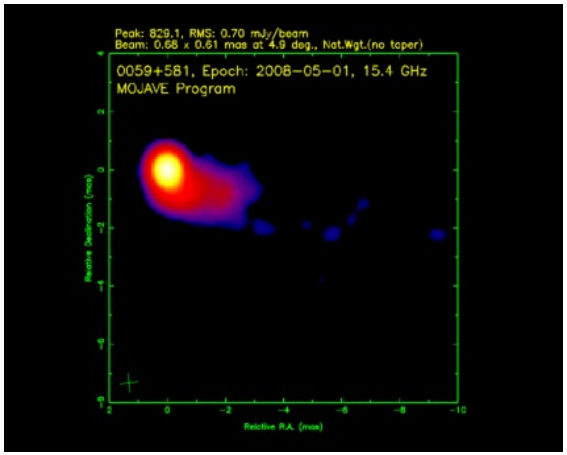
① We can image quasar structure
(and make corrections)

Bad news

Quasars evolve
(need to to this often)







Lister et al. (2009)

How do we improve the Reference Frames ?

(with quasar physics)

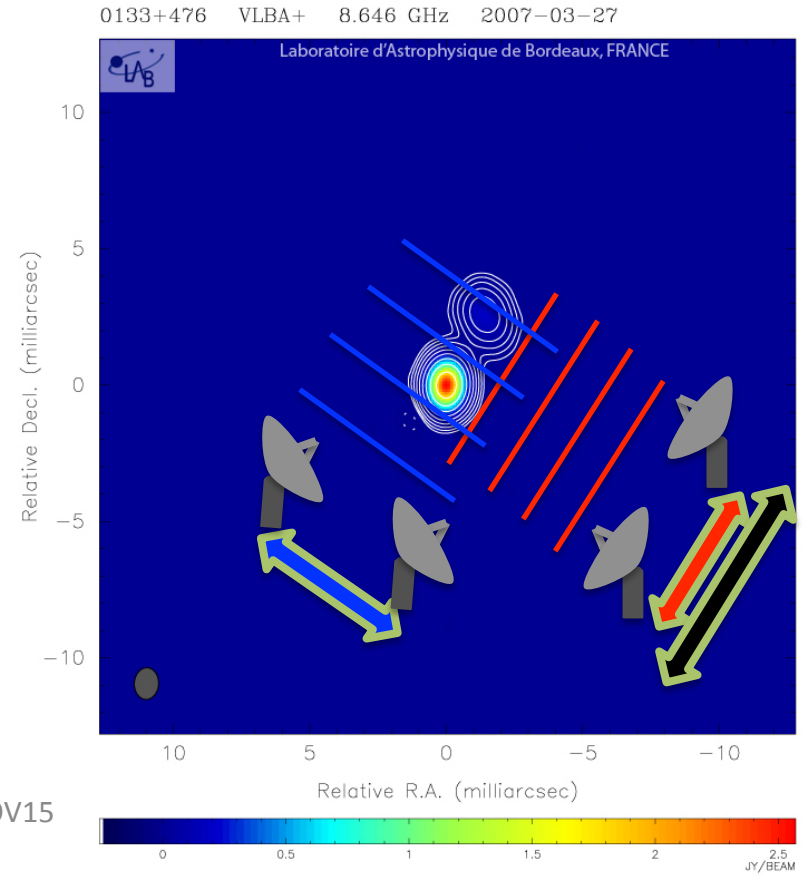
Good news

① We can image quasar structure

② Jet direction remains constant
(avoid unfavourable
baseline – jet orientation)

Bad news

Quasars evolve



How do we improve the Reference Frames ?

(with quasar physics)

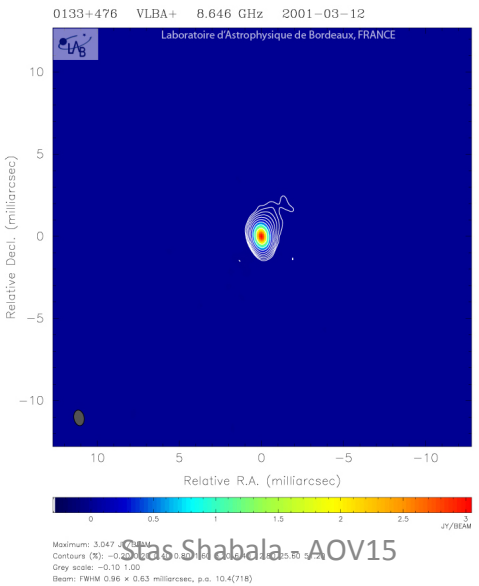
Good news

① We can image quasar structure

② Jet direction remains constant

③ Quasars evolve !
(observe quasars when they are "well behaved")

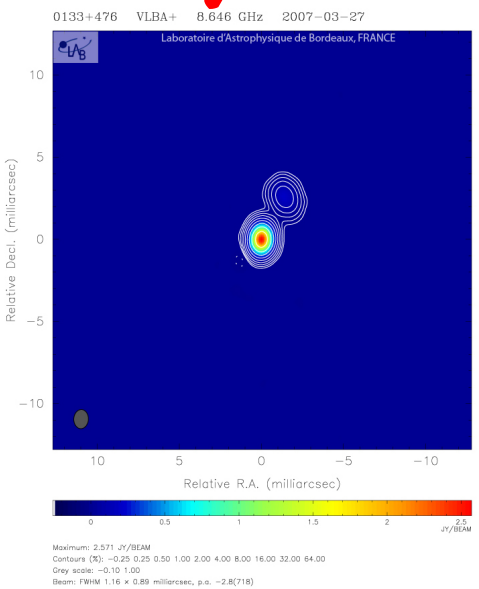
✓



Bad news

Quasars evolve

✗



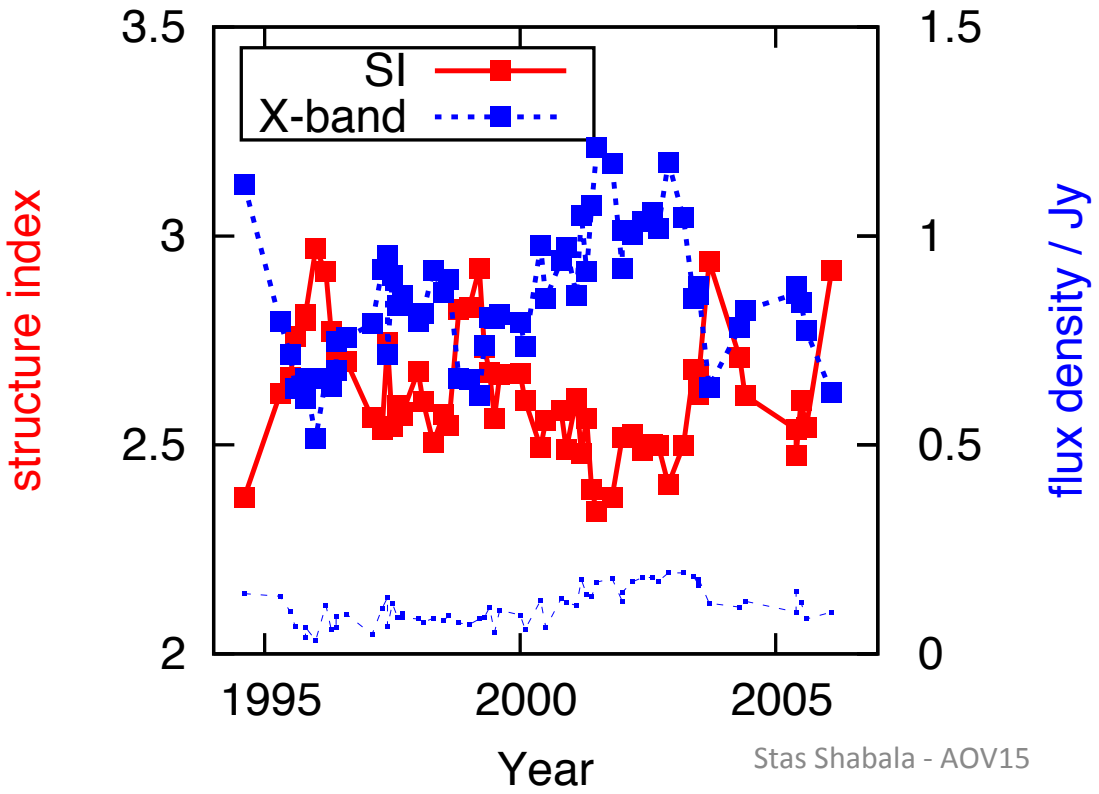
Quasar evolution

OBSERVED

- Structure anti-correlates with flux density

➔ Observe sources when flux density is high (and so structure is small)

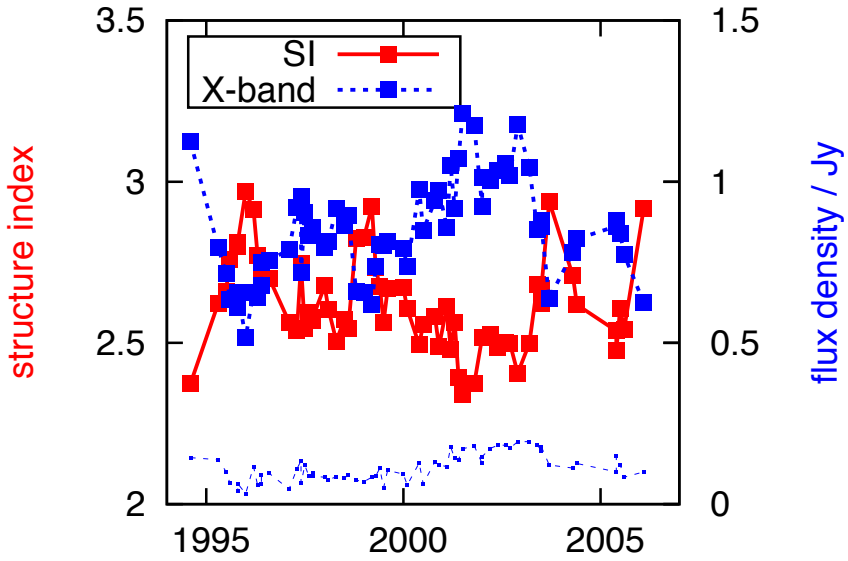
Source 1357+769



Shabala+16, REFAG proc., submitted

Quasar evolution

OBSERVED



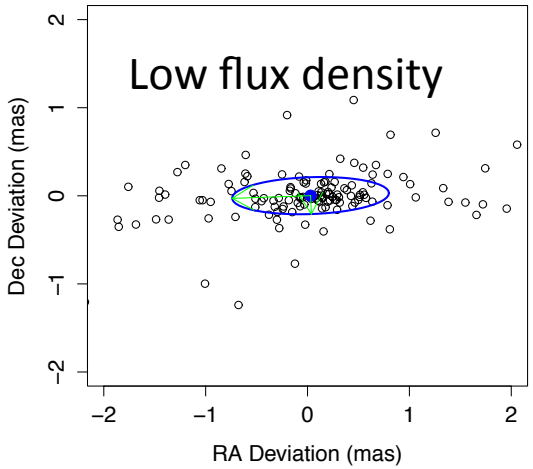
- Structure anti-correlates with flux density

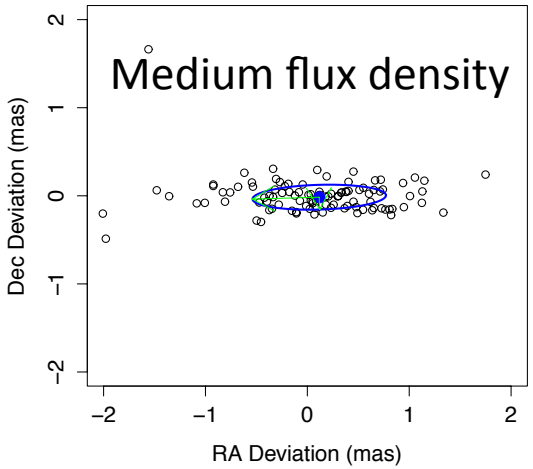
➔ Observe sources when flux density is high (and so structure is small)

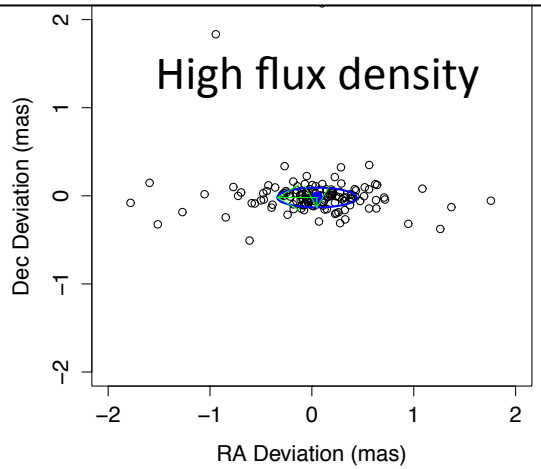
- Position scatter decreases for sources with high flux density

Source 1357+769

Shabala+16, REFAG proc., submitted



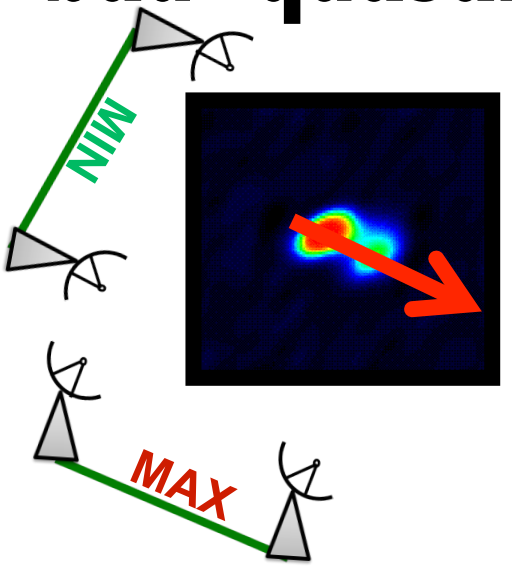


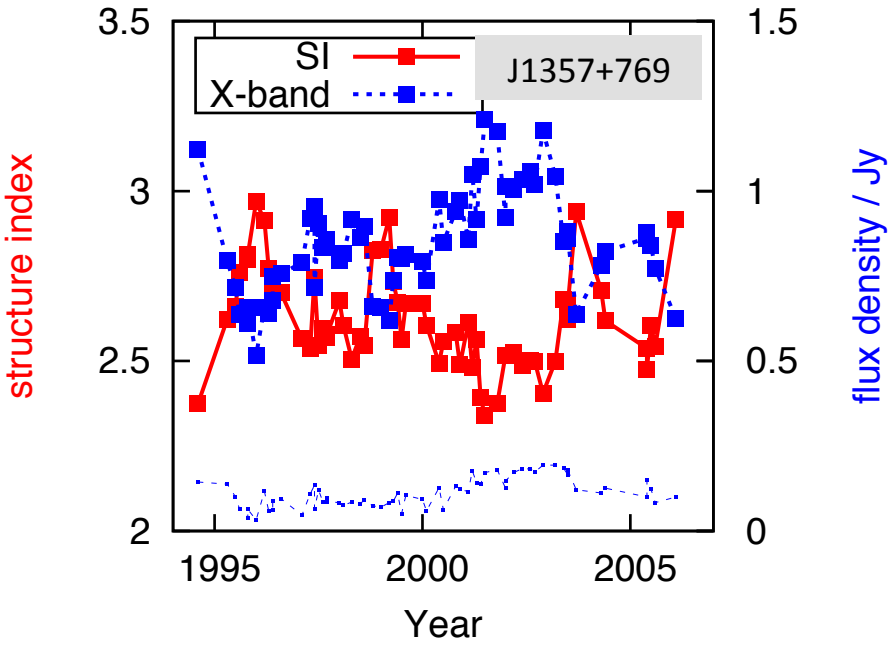


If we *have* to observed a 'bad' quasar…

1. Schedule with respect to jet direction

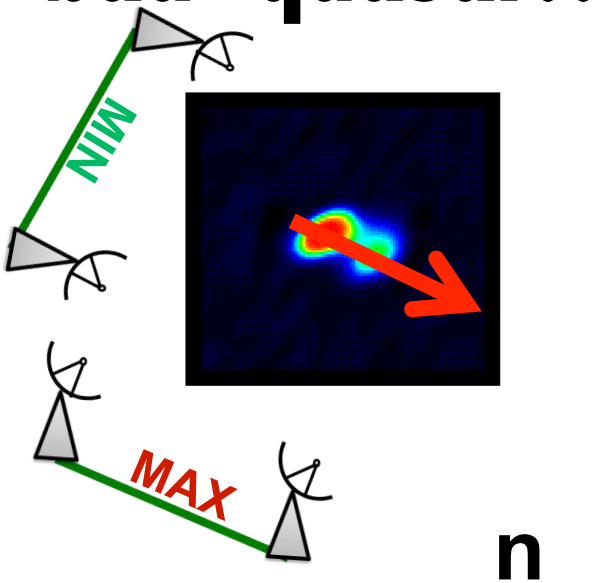
   - Optimise for given set of baseline / jets
   - Structure changes;
     jet direction (mostly) does not

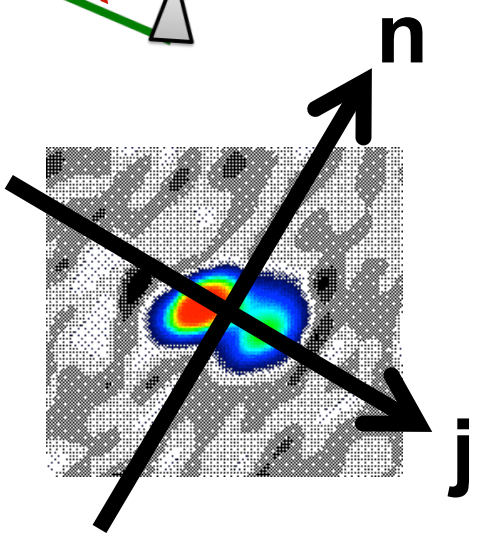




If we *have* to observed a 'bad' quasar…

1. Schedule with respect to jet direction
   - Optimise for given set of baseline / jets
   - Structure changes;
     jet direction (mostly) does not
2. Solve with respect to jet direction
   - Along / orthogonal to jet (instead of RA / Dec)
   - Position **along jet**: allowed to vary
     (nuisance parameter)
   - **Orthogonal**: well-defined single position
   - Improvement seen in simulations
     (Plank+ 2016)
   - Real test: VGOS observations





Summary

- **Quasars are not point sources**
  - extra group delay
    - ✧ Baseline-, time-, frequency- dependent
  - systematic error ➔ simply more observations won't help

- **Quasar structure simulations** with *VieVS 2.2*
  - ✧ new source structure simulator module
  - ✧ mock + real quasar catalogues
  - ✧ station positions affected at mm level
  - ✧ source positions at 50 uas level

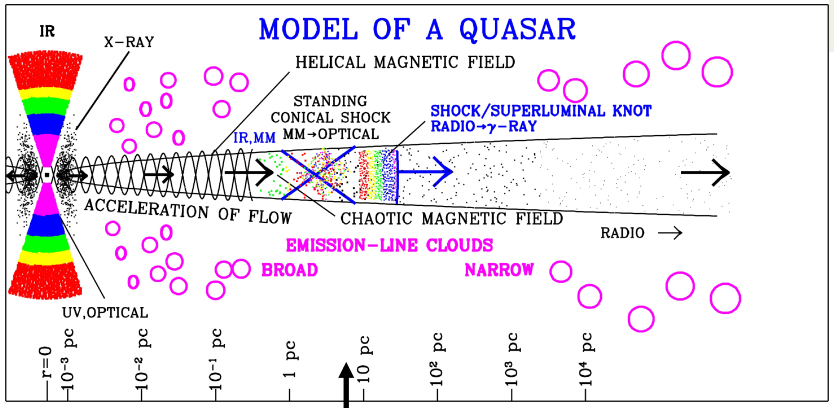
Shabala+15, J. Geod, 89, 873

Plank+16, MNRAS, 455, 343

- **Mitigation strategies**
  - ❖ corrections using source images in analysis (difficult)
  - ❖ not scheduling unfavourable jet / baseline combinations
    - ▪ avoid long baselines parallel to jet
  - ❖ source selection
    - ▪ radio sources vary in structure on year timescales
    - ▪ more compact when flaring (bright)

Inner regions of an Active Galactic Nucleus

Image: BU / A. Marscher



1 mas @ z=1

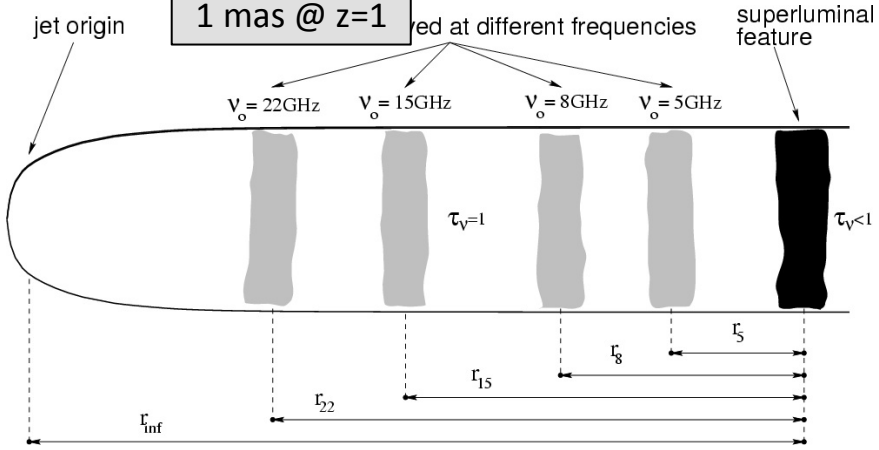
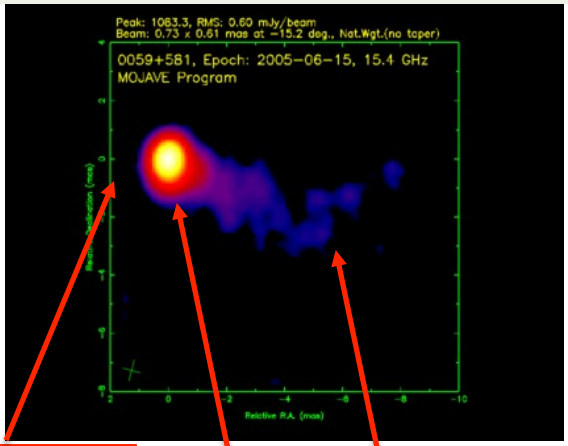


Image: Kovalev et al. (2008)

One jet towards us (Doppler boosted) -> seen
One jet away from us (D. deboosted) -> unseen



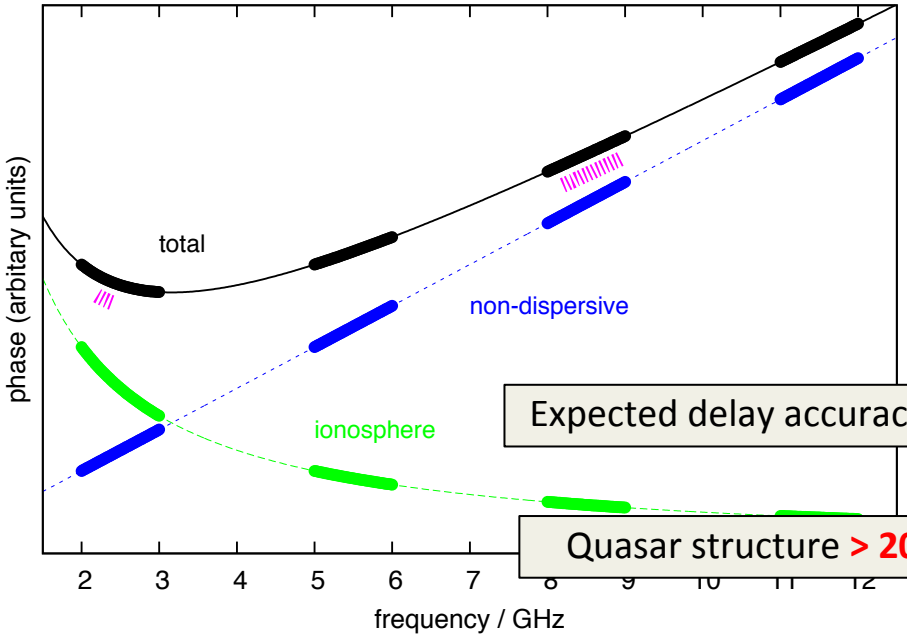
jet origin

core

jet

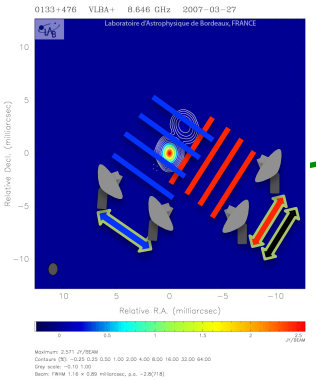
Synchrotron self-absorption
➔ core location depends on frequency
➔ "**Core Shift**"

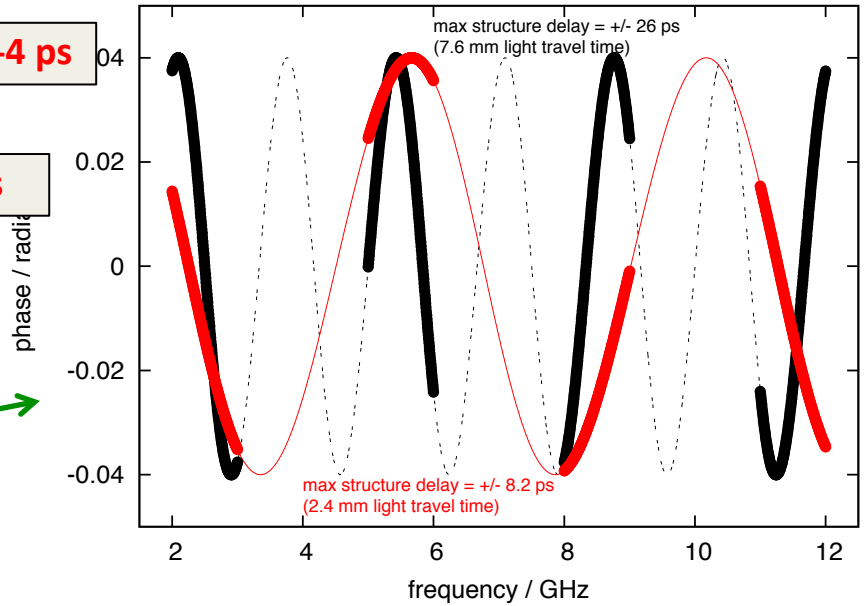
Quasar structure in VGOS



Expected delay accuracy **2-4 ps**

Quasar structure **> 20 ps**





How do we connect phases across 10 GHz?

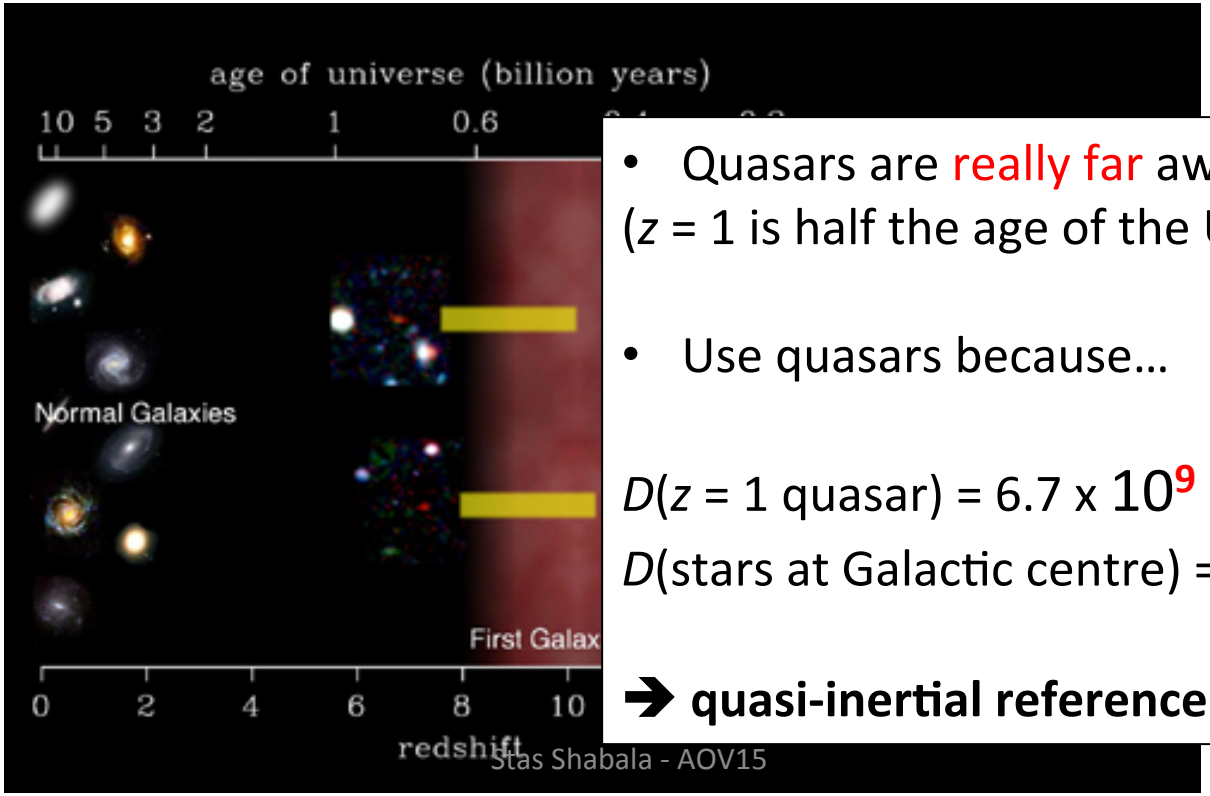
Quasars

What you want them to be

- ✧ Bright point sources
- ✧ Fixed in space and time

What they are

- ✧ Supermassive black holes
- ✧ 10^6 times more distant than stars



- Quasars are really far away (z >=1)

(z = 1 is half the age of the Universe)

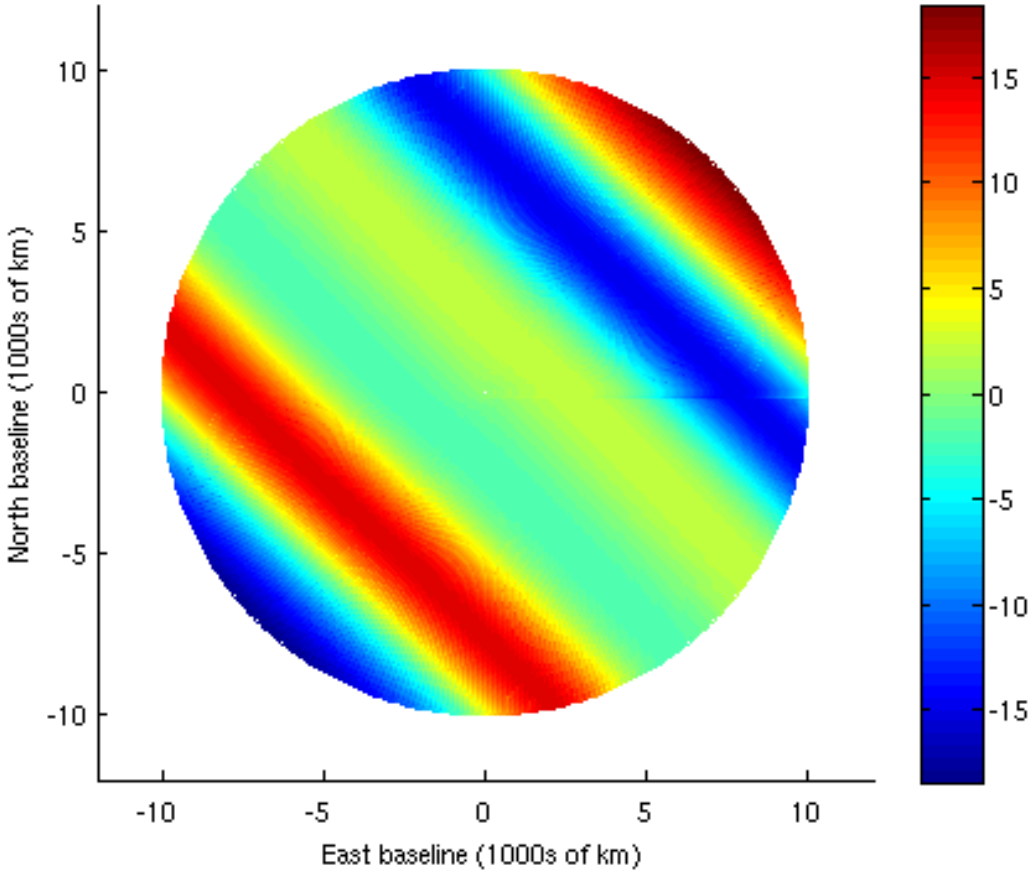
- Use quasars because…

$D(z = 1 \text{ quasar}) = 6.7 \times 10^9$ pc

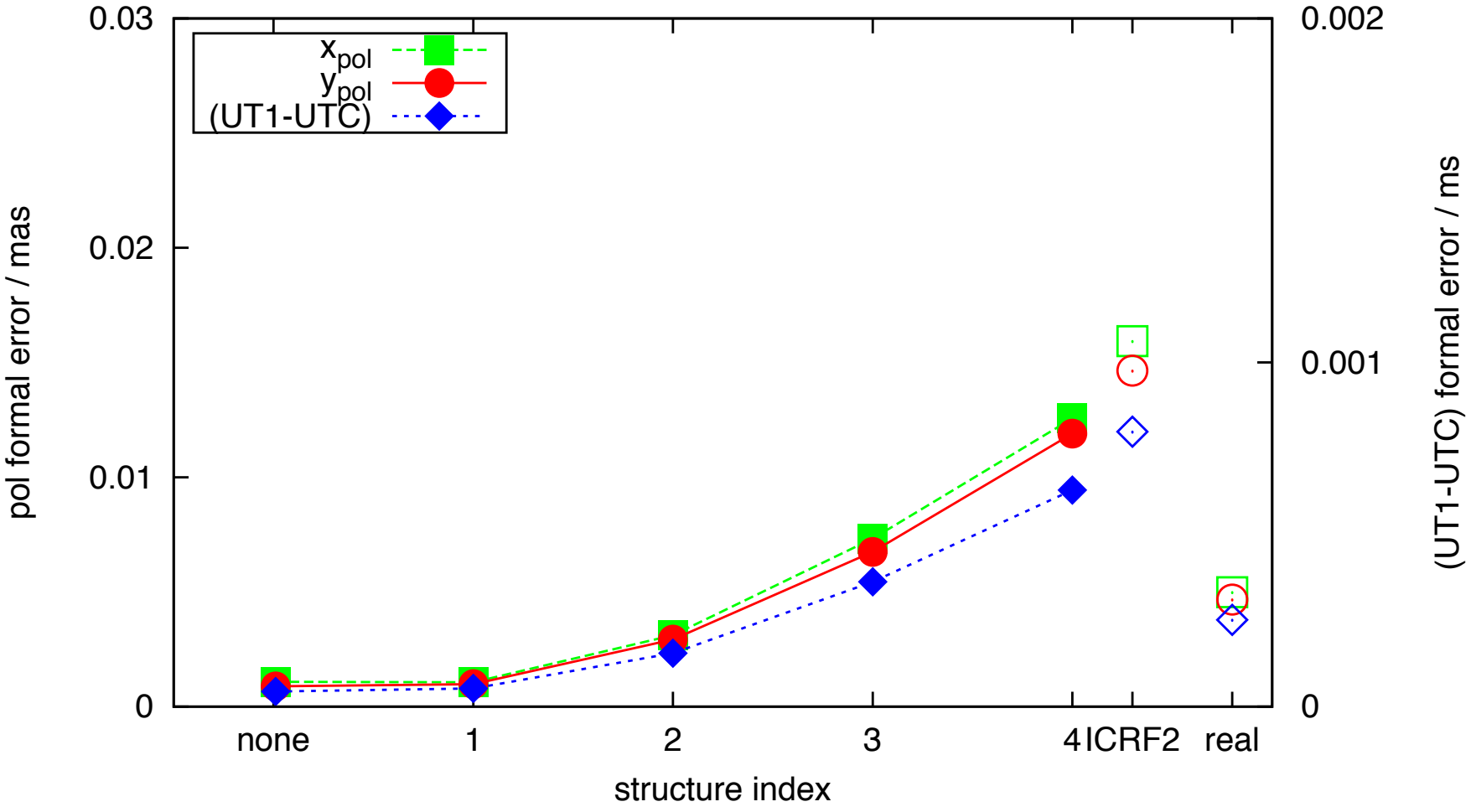
$D(\text{stars at Galactic centre}) = 8 \times 10^3$ pc

➔ **quasi-inertial reference frame**

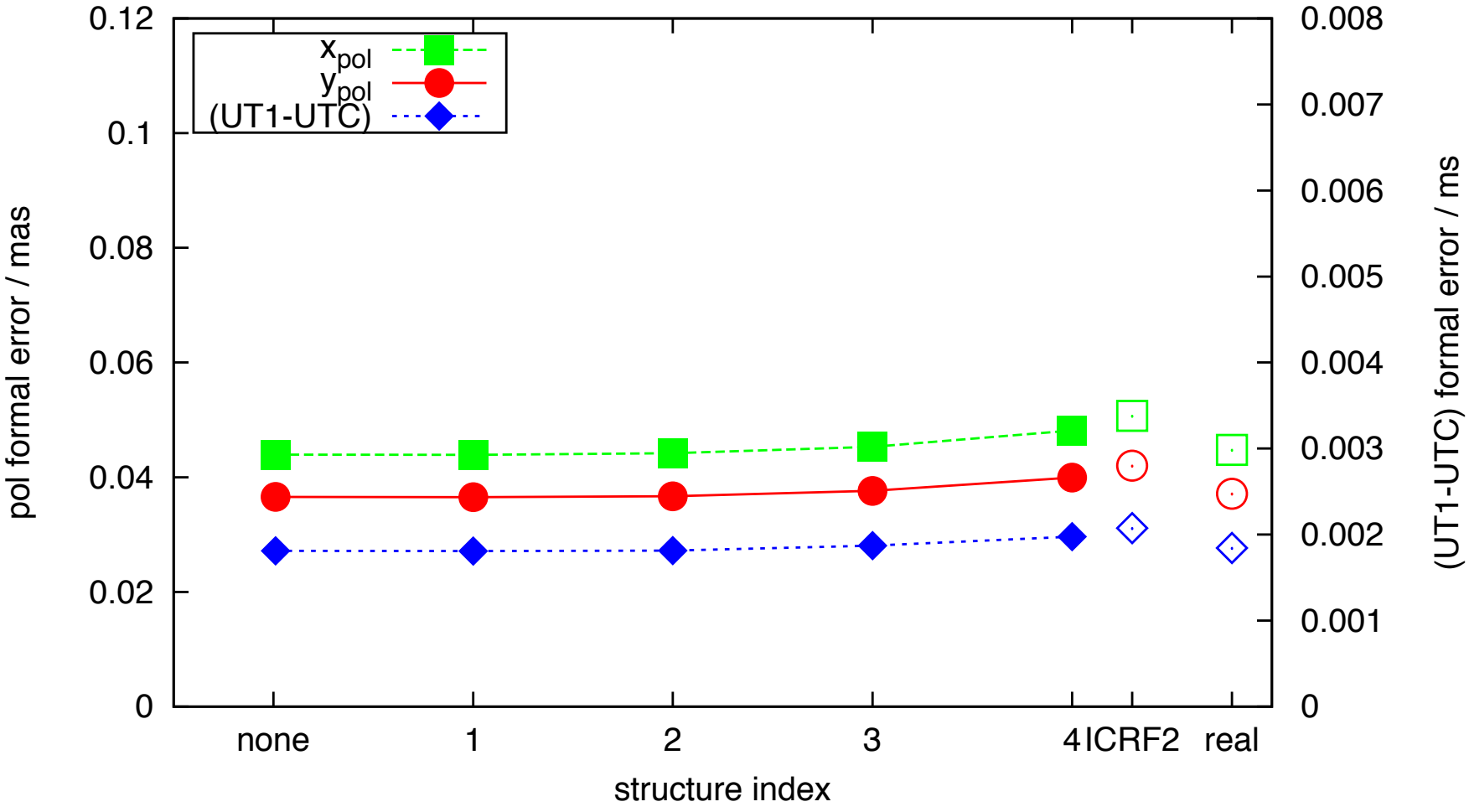
Structure delay (ps)



EOP formal error (structure only)

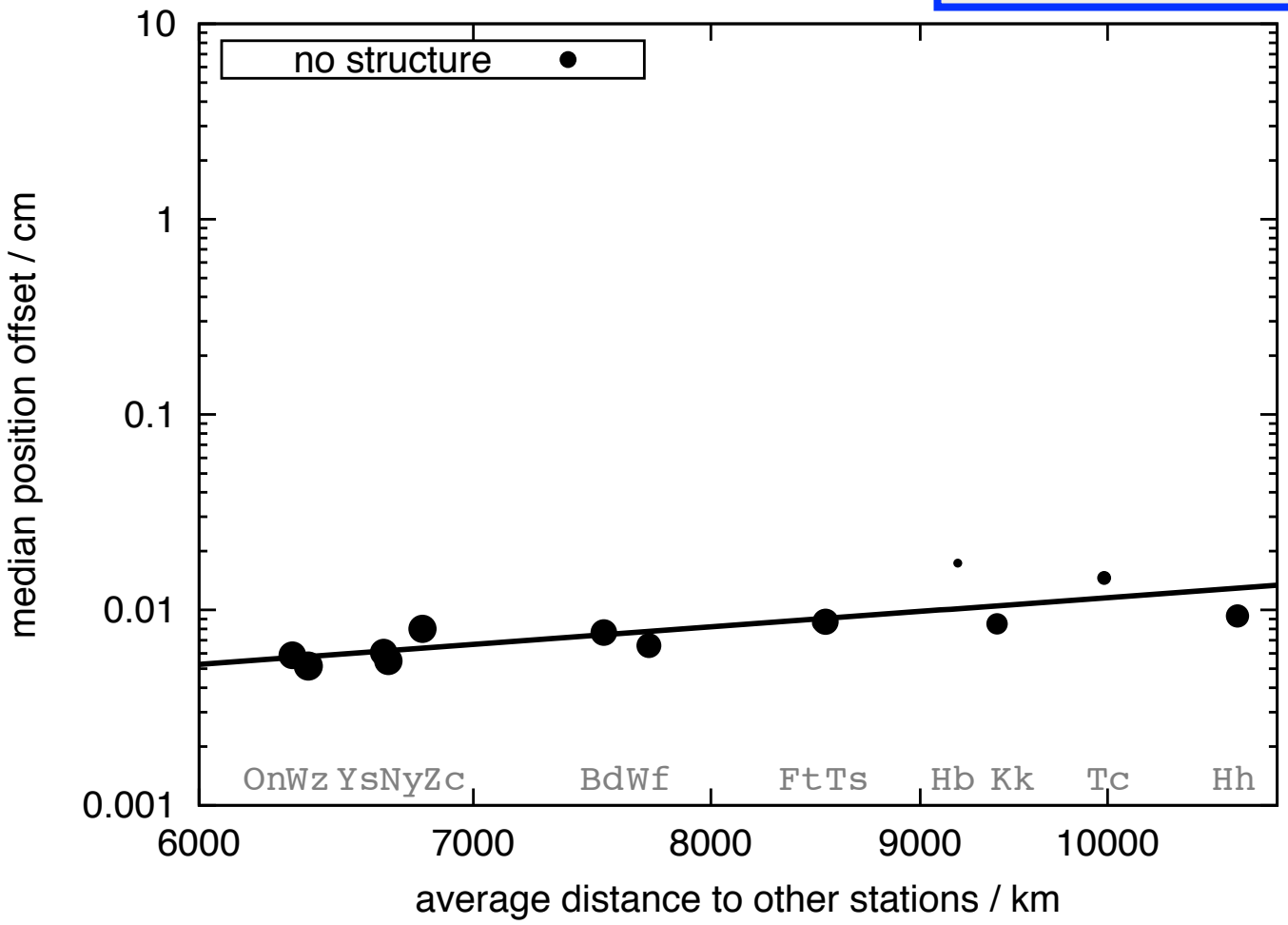


EOP formal error (with trop.)



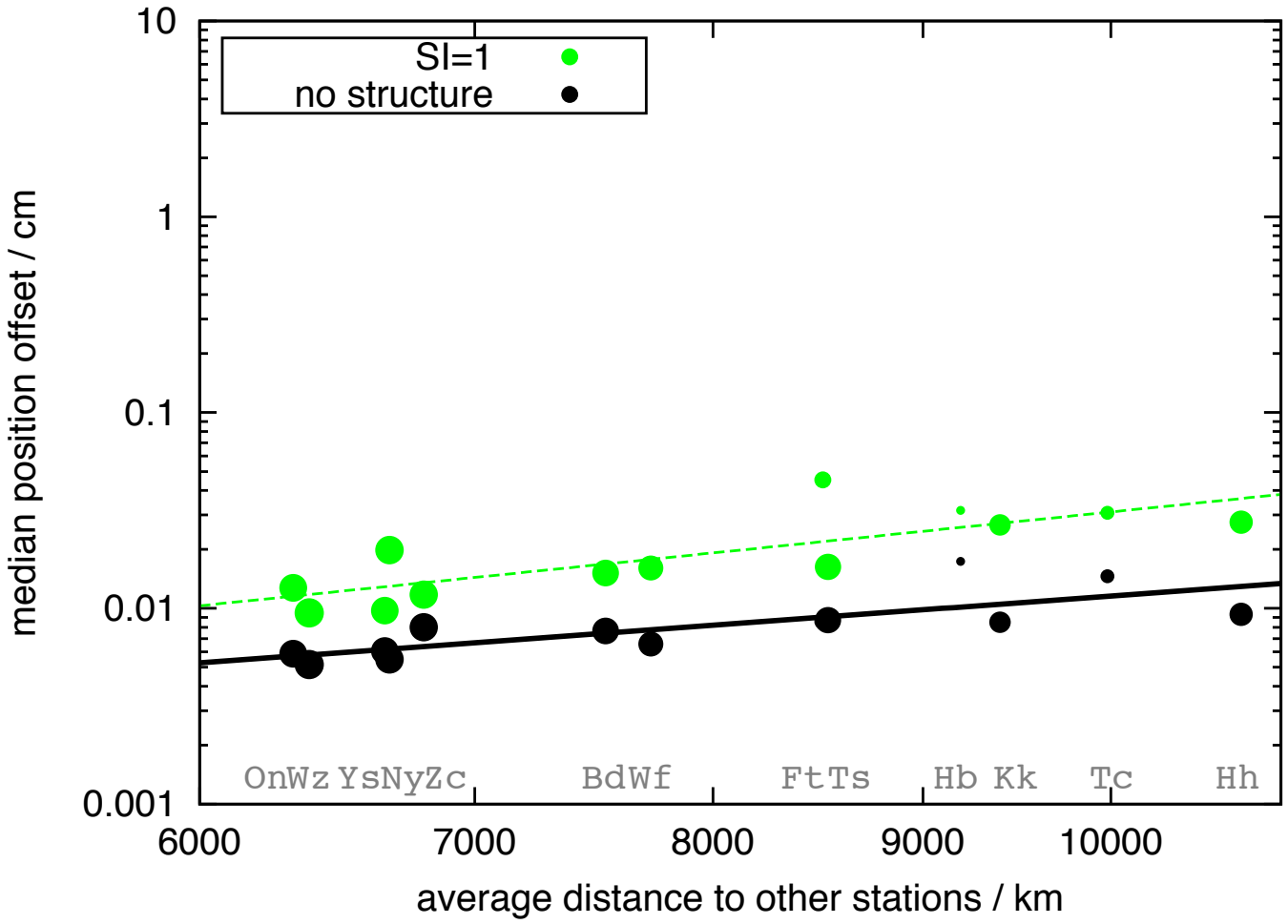
Median position offset

median of 15 x 30 realizations



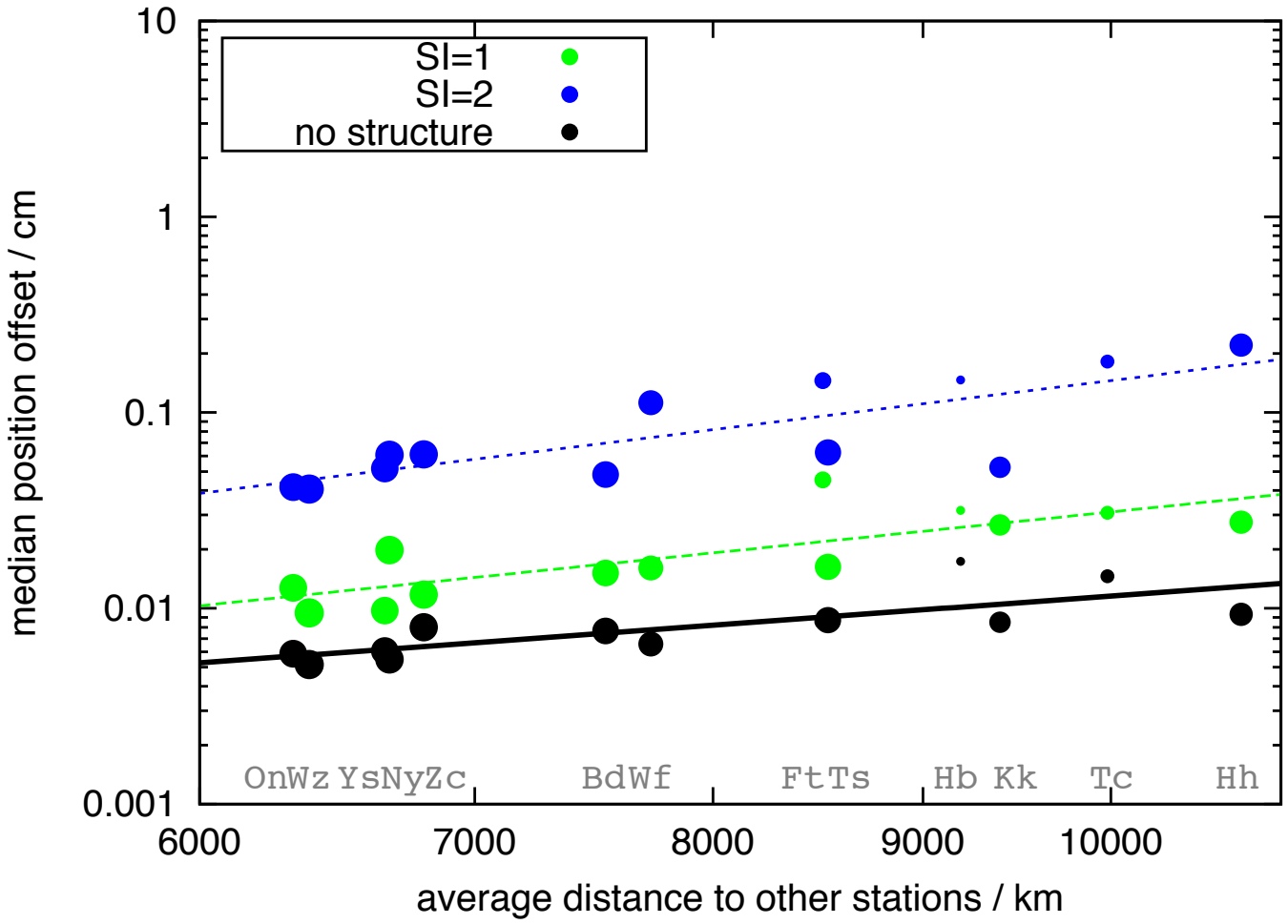
Shabala+15, J. Geodesy

Median position offset



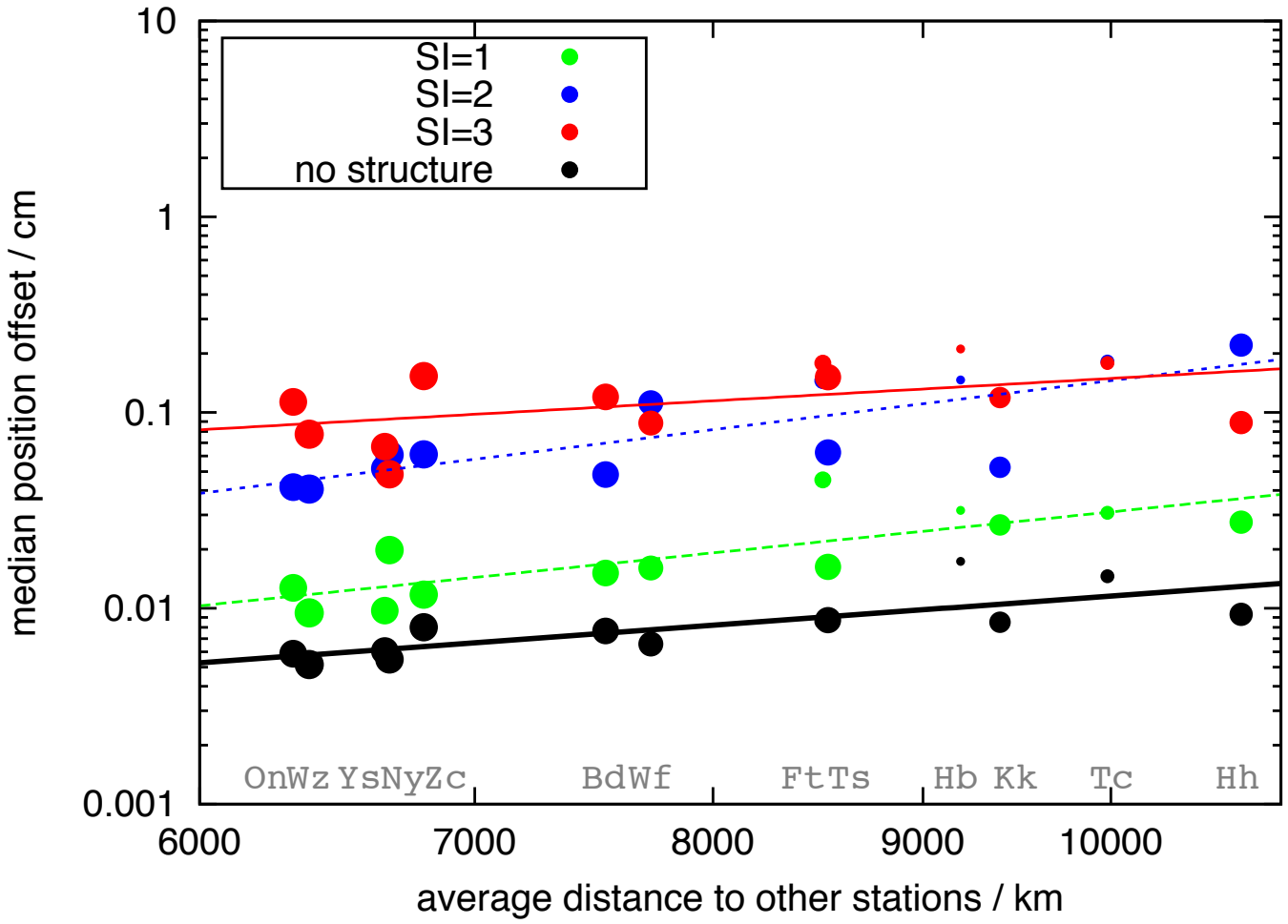
Shabala+15, J. Geodesy

Median position offset



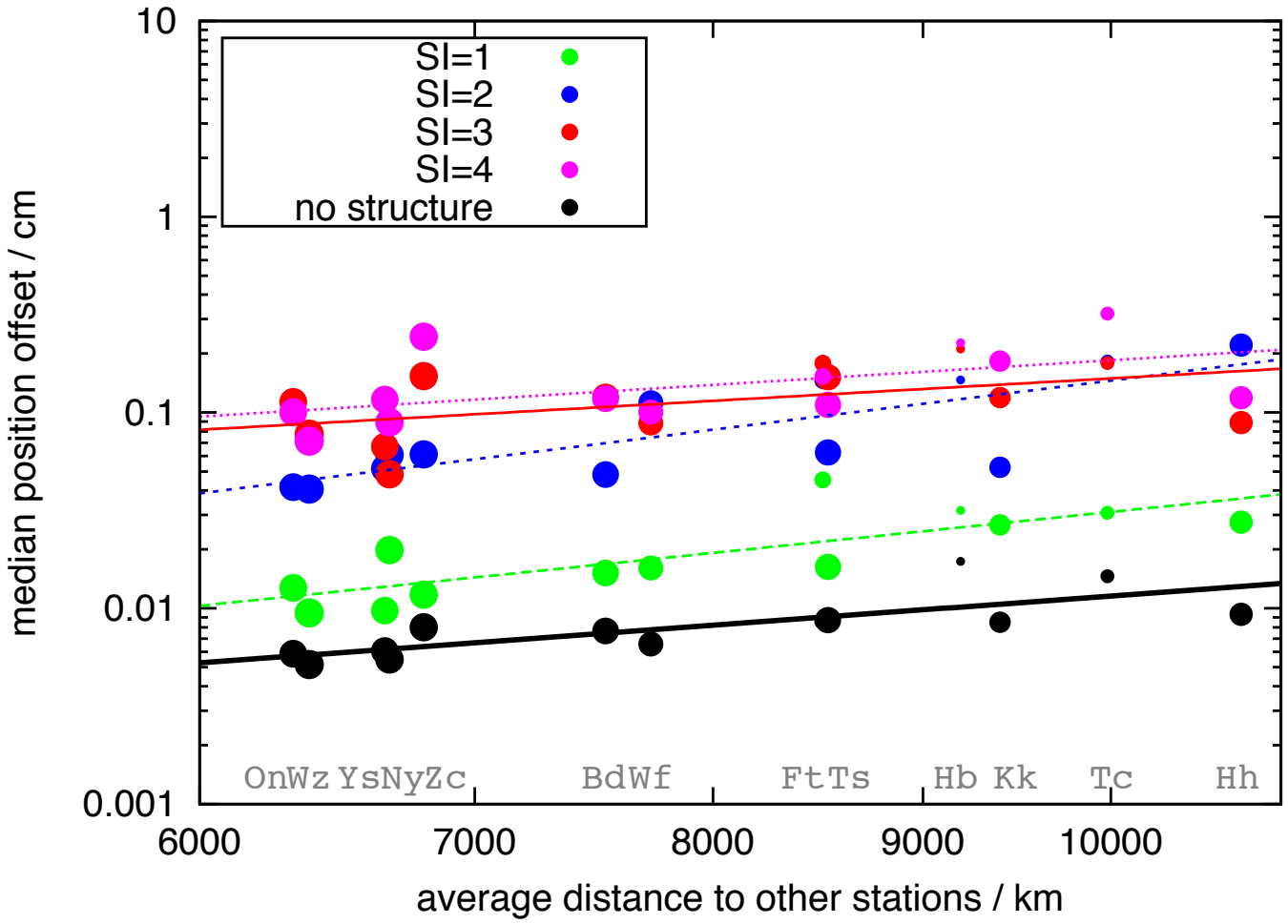
Shabala+15, J. Geodesy

Median position offset



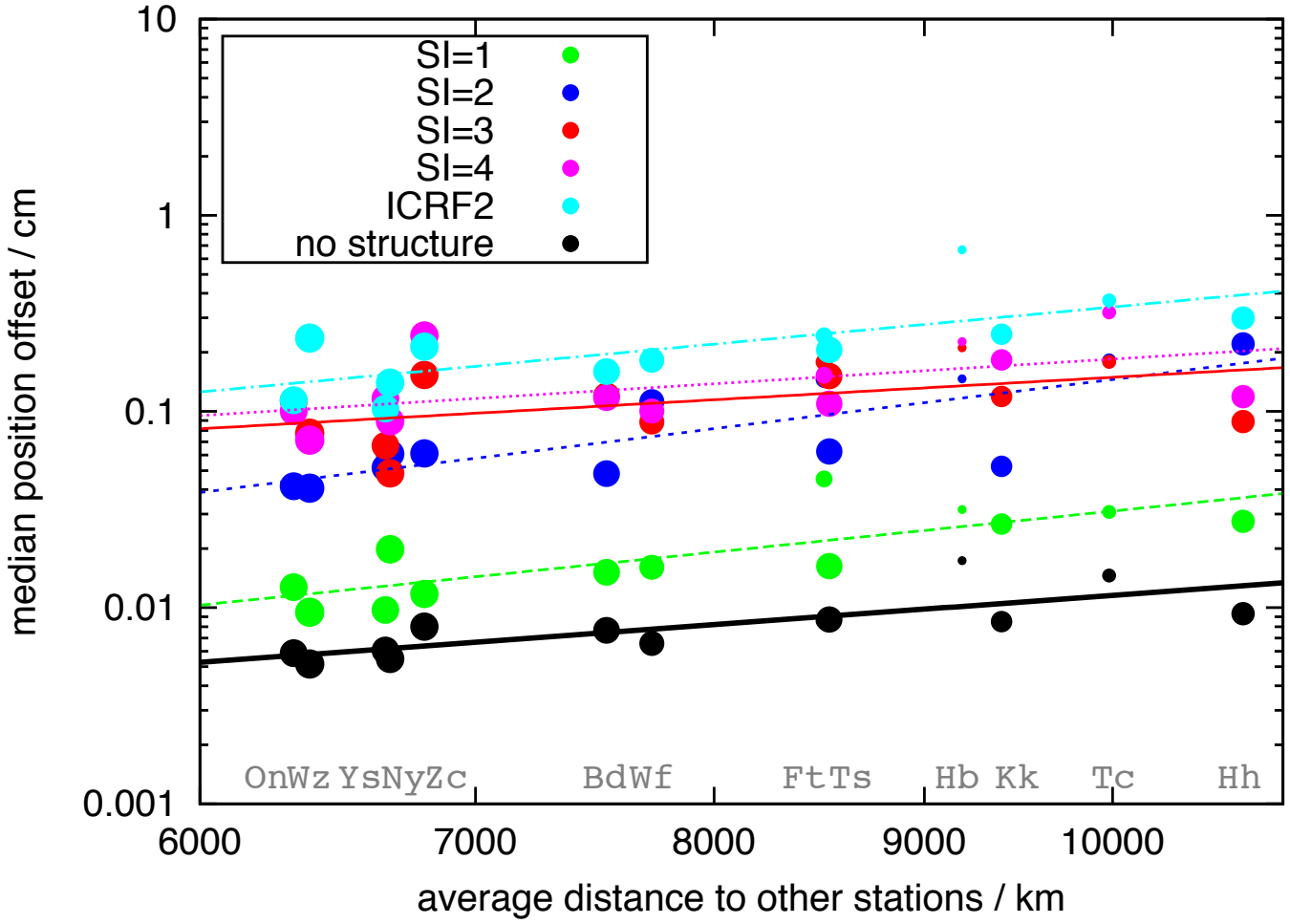
Shabala+15, J. Geodesy

Median position offset



Shabala+15, J. Geodesy

Median position offset



Shabala+15, J. Geodesy

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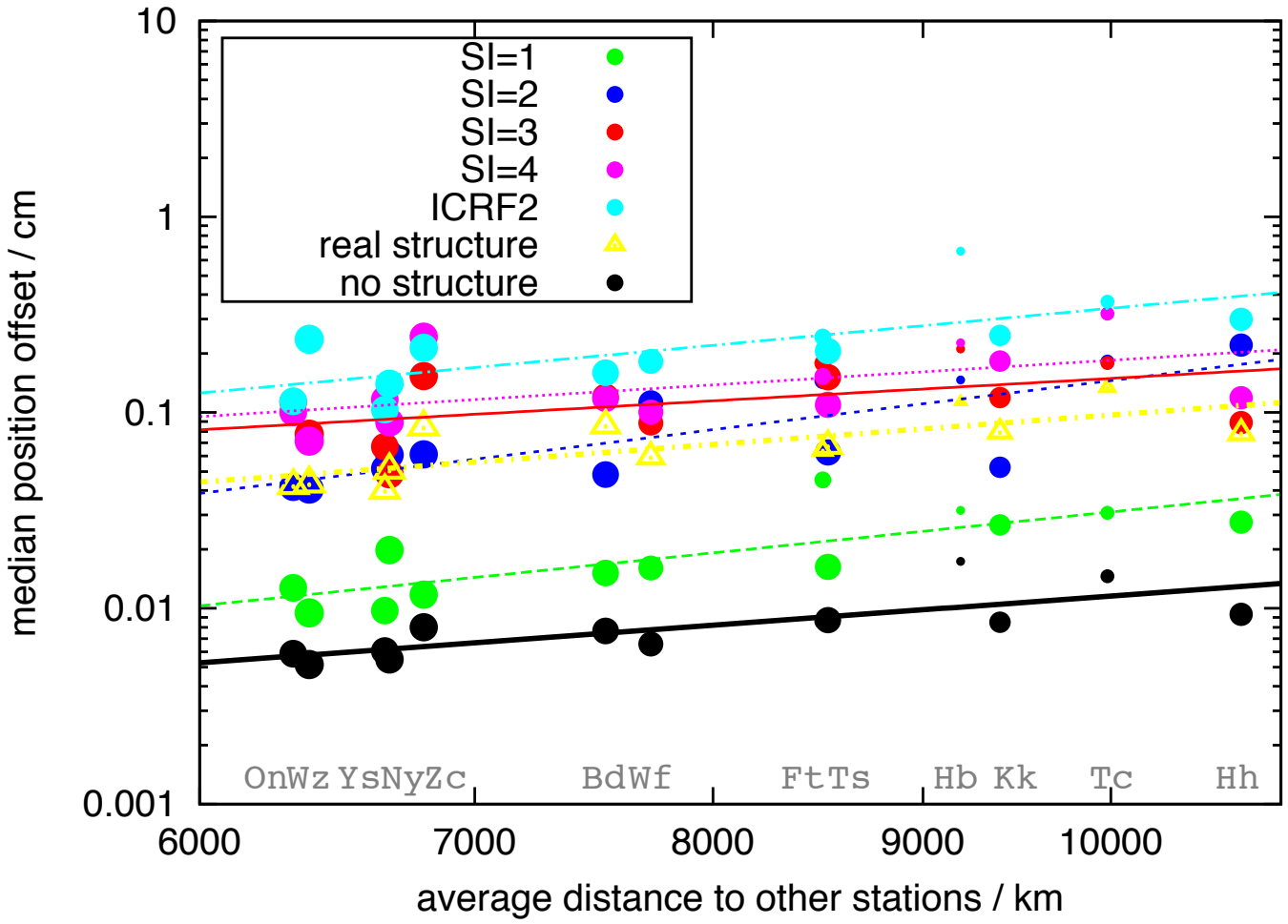

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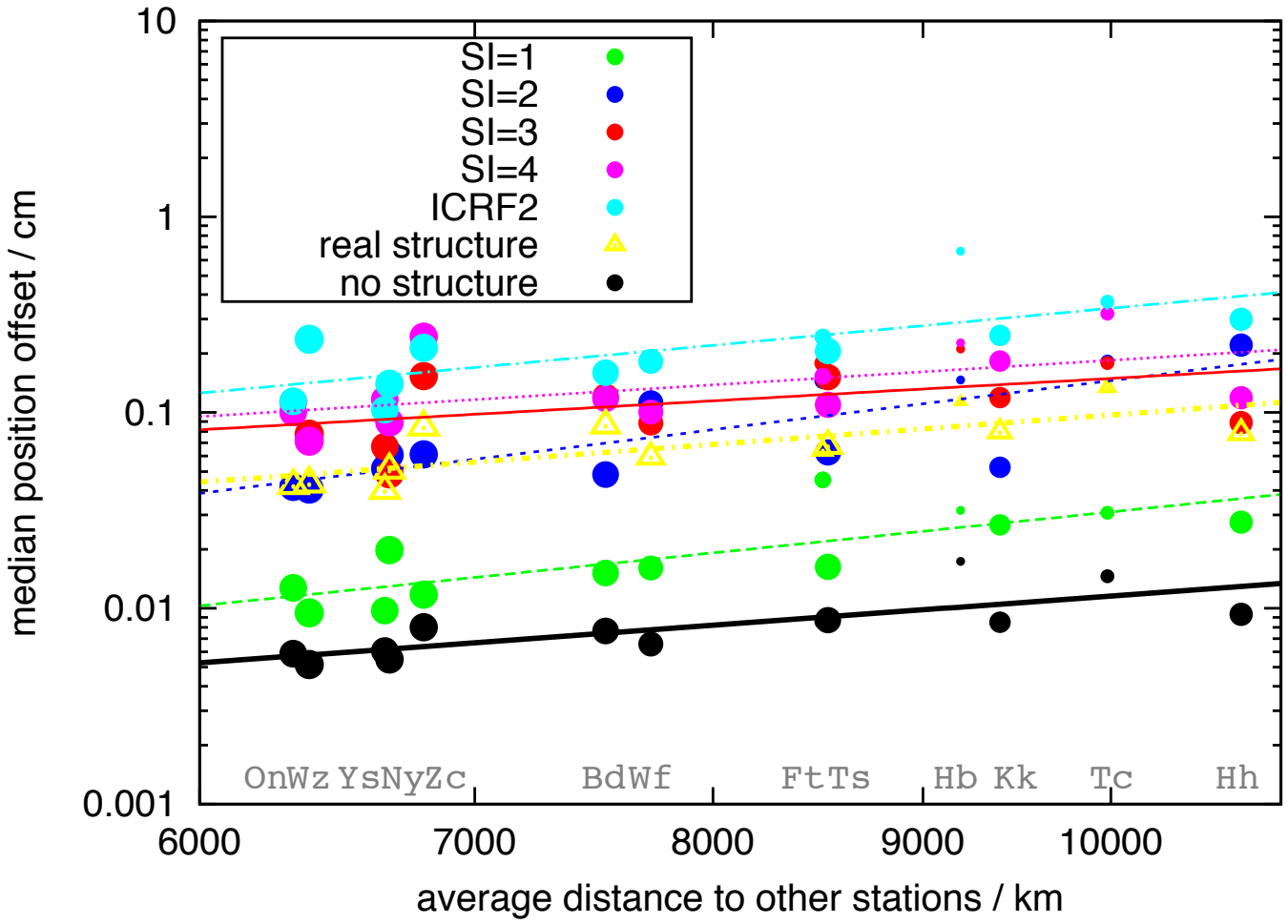

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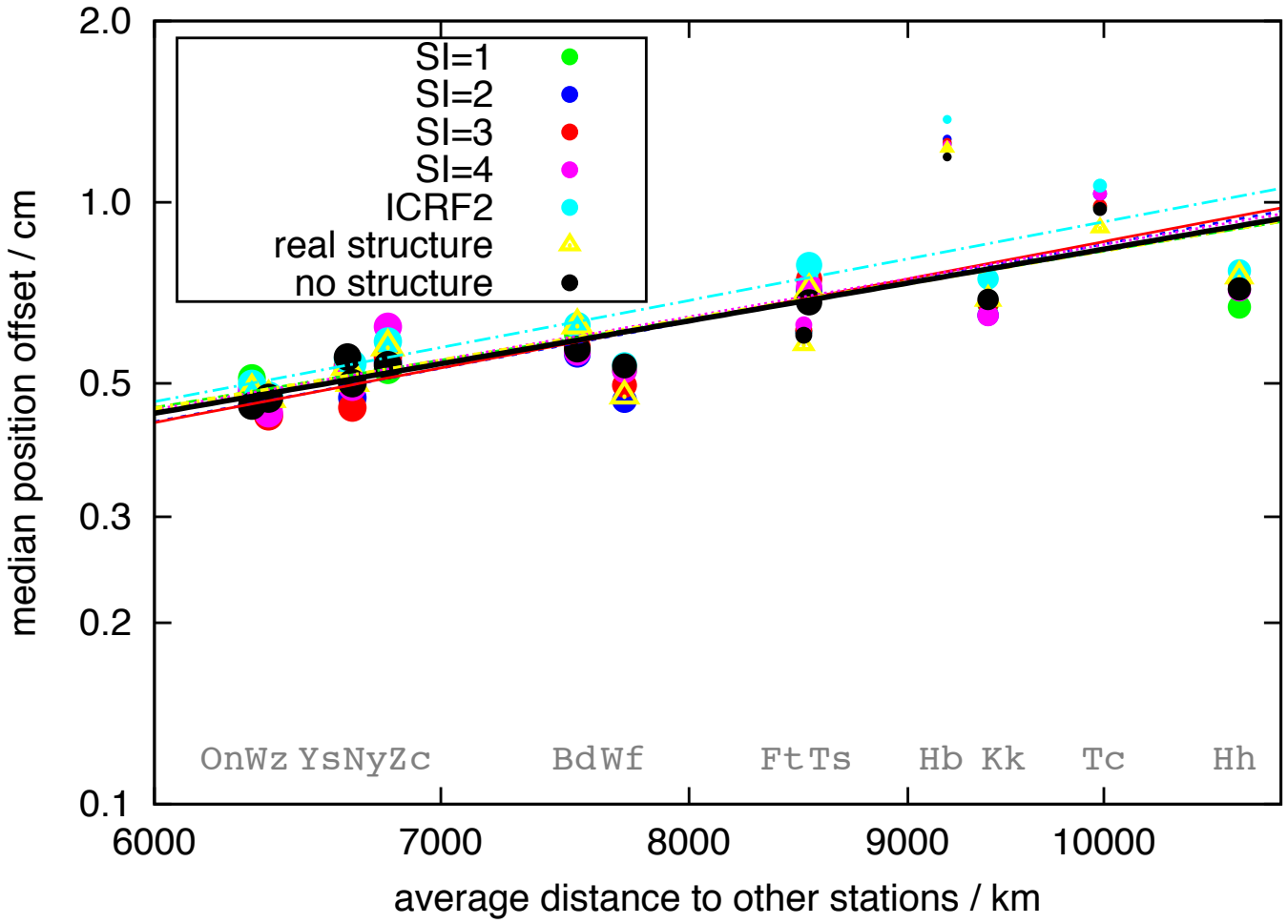

Shabala+15, J. Geodesy