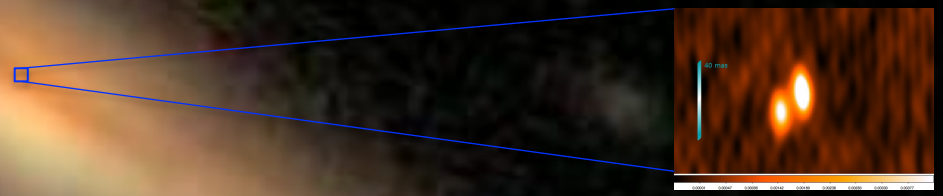
Using quasar physics to improve the VLBI reference frame



Stas Shabala
University of Tasmania

with: Lucia Plank, Jamie McCallum, Rob Schaap (UTAS)
Johannes Böhm, Hana Krásná (TU Wien)
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 frame
  (Station positions : mm level)

④ Mitigation strategies

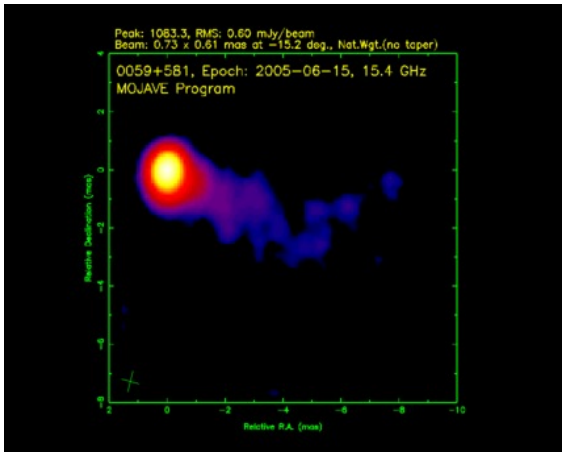
Uncooperative quasars

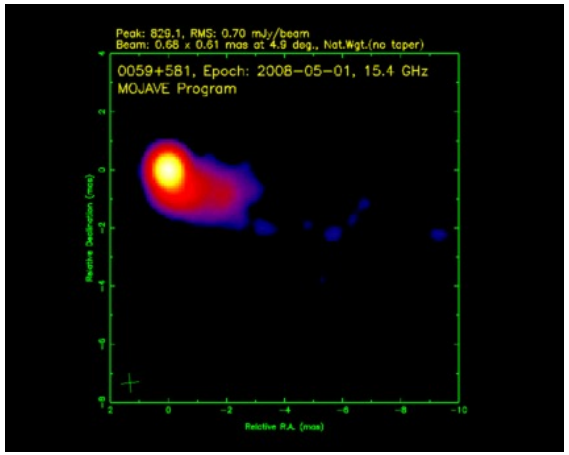
What you want them to be

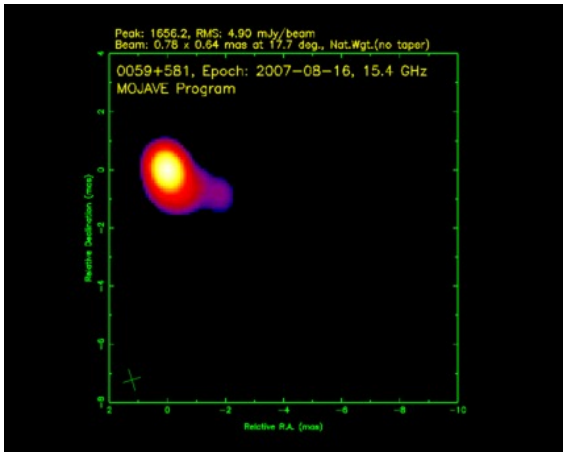
- ✧ Bright point sources
- ✧ Fixed in space and time

What they are

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



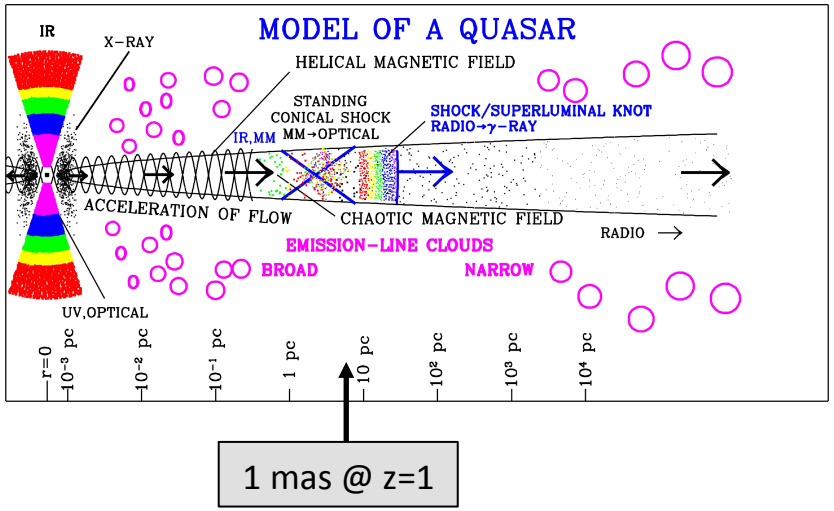


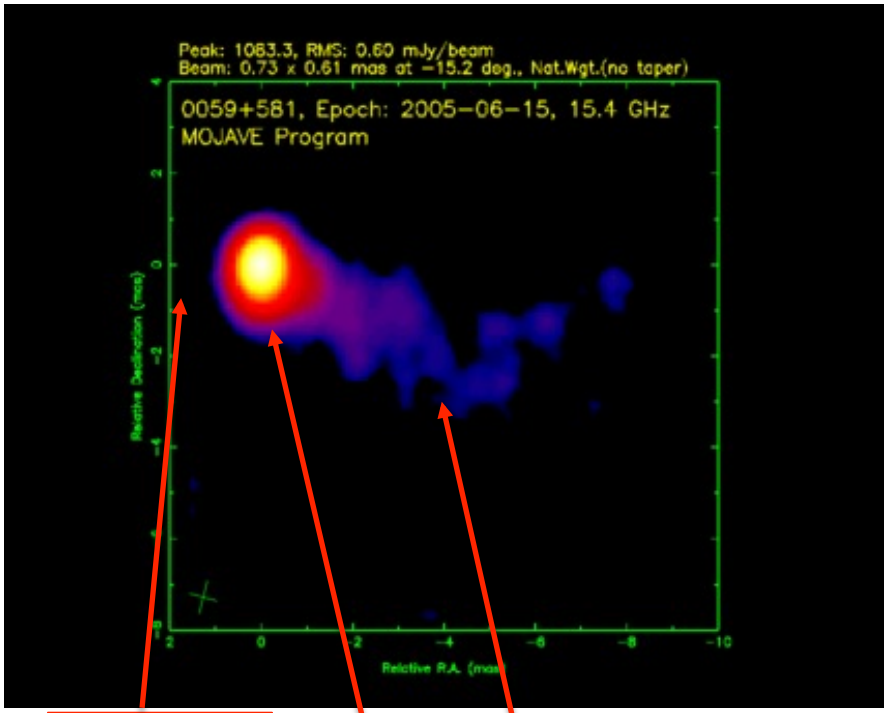


Lister et al. (2009)

Inner regions of an Active Galactic Nucleus

Image: BU / A. Marscher

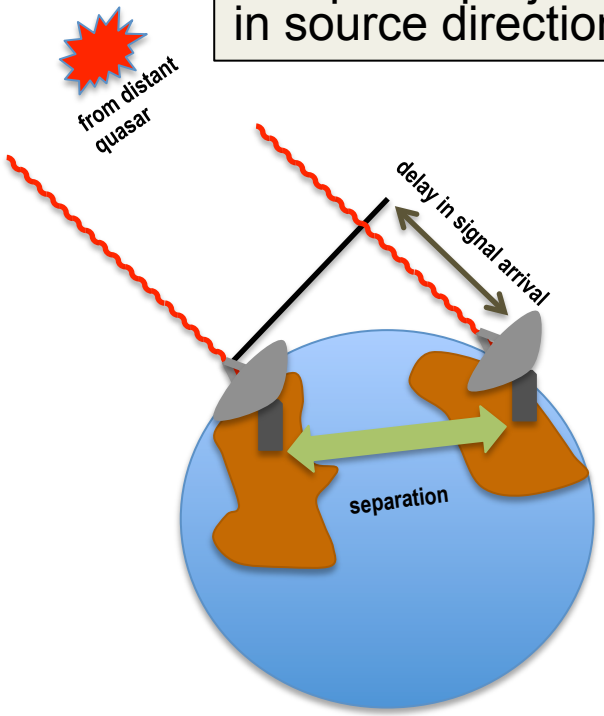




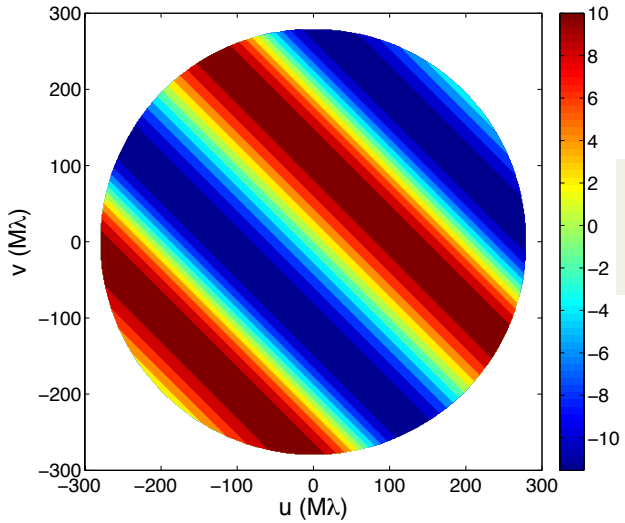
One jet towards us (Doppler boosted) -> seen
One jet away from us (D. deboosted) -> unseen

uv plane

N-E plane projected in source direction



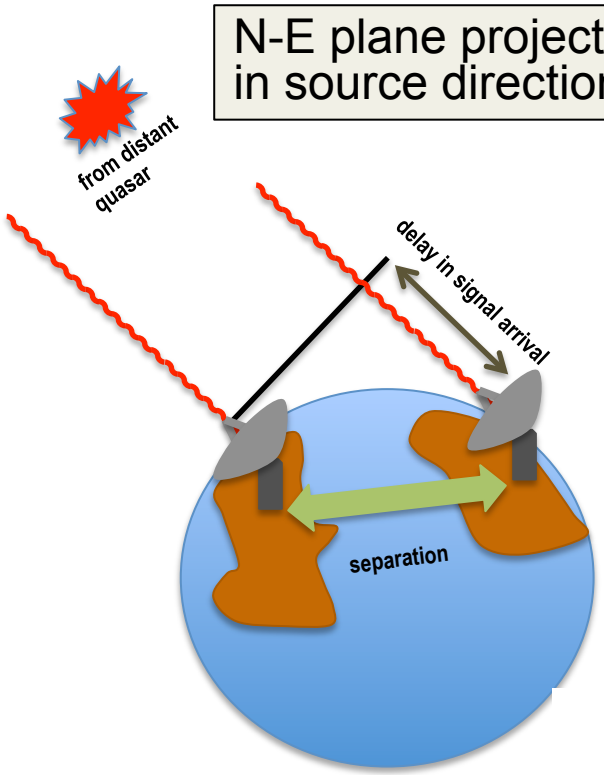
✧ interferometers measure correlated **amplitude** and **phase**



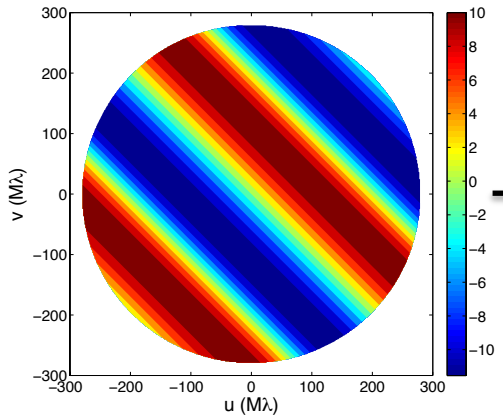
Visibility phase

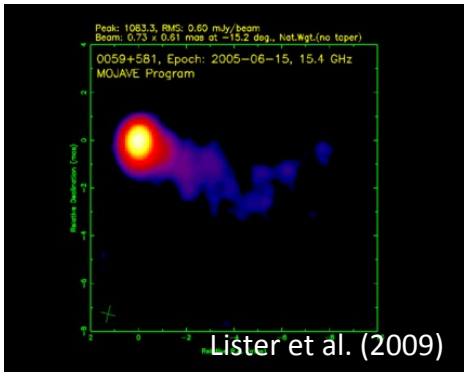
distances measured in units of wavelength $\lambda = c/\nu$

uv plane



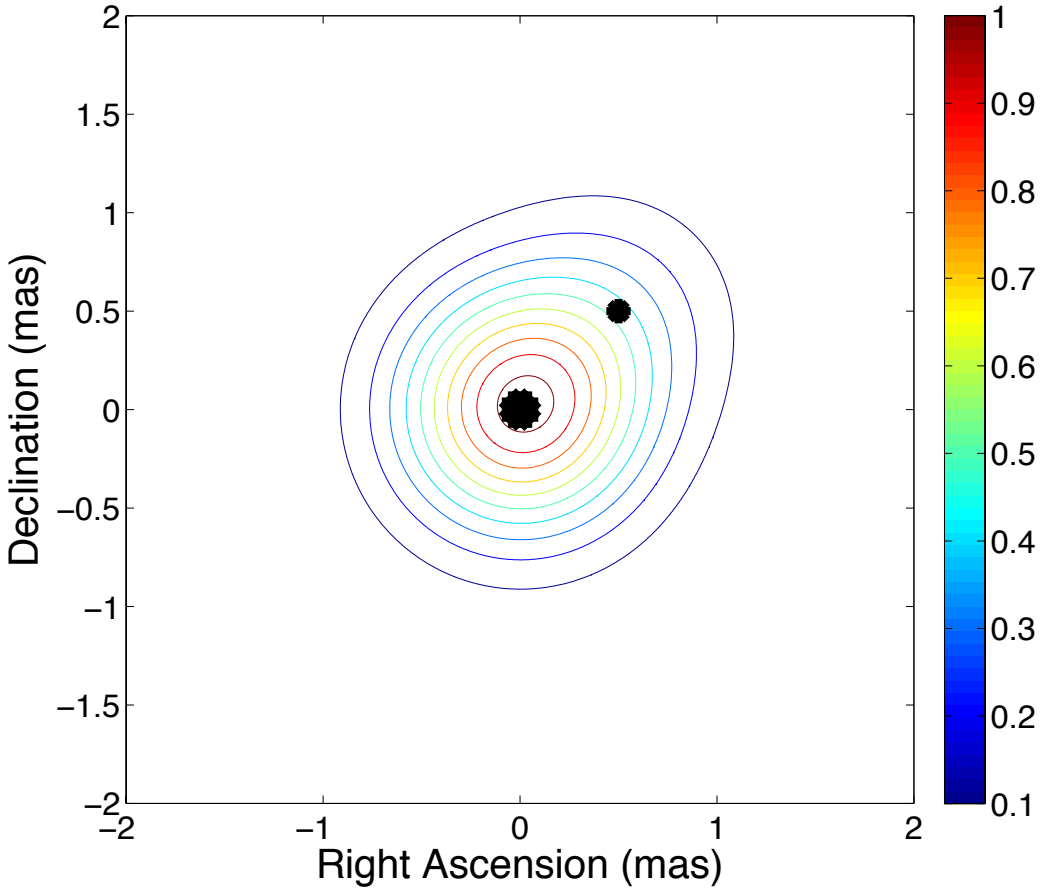
- ✧ interferometers measure correlated **amplitude** and **phase**
- ✧ image
  ←FourierTransform→
  amplitudes/phases in *uv* plane





Lister et al. (2009)

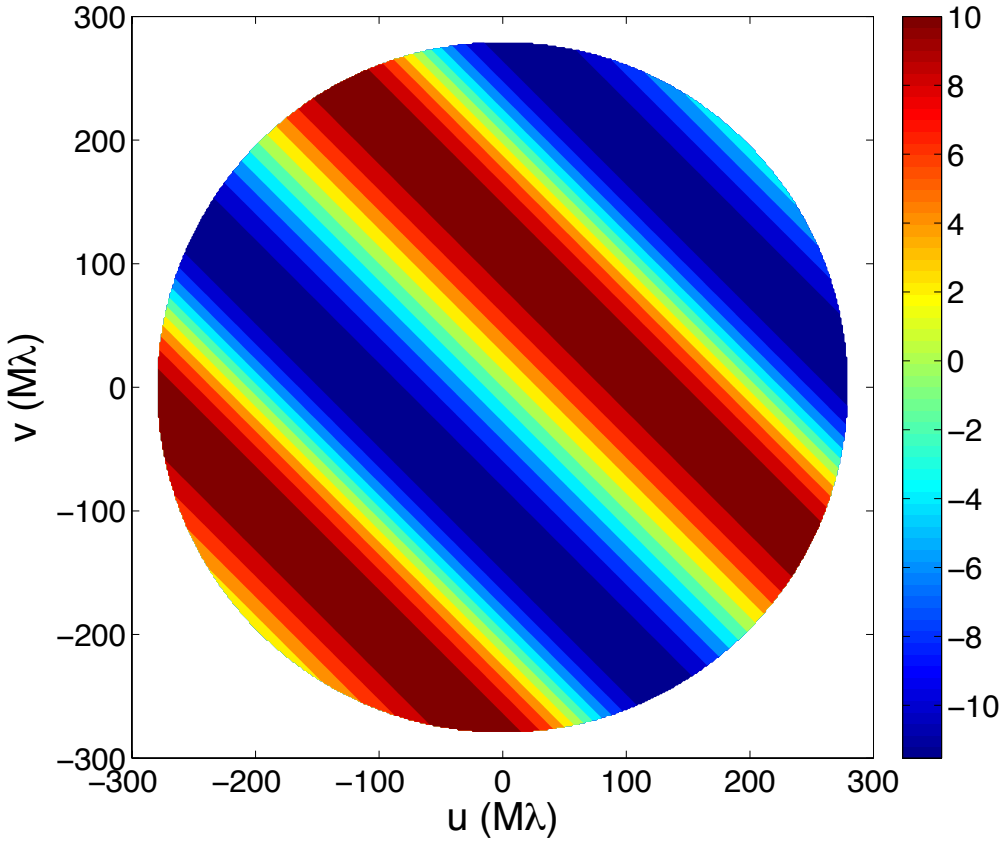
Simulated source



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 $\lambda = c/\nu$

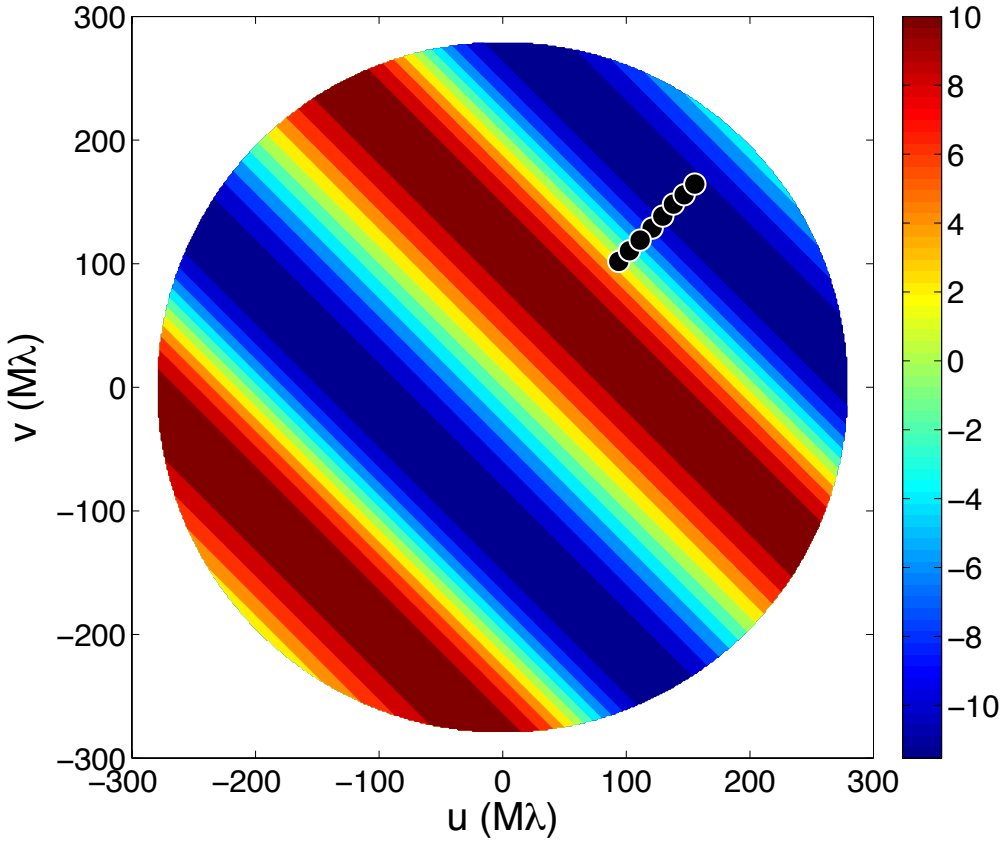
Source structure in geodetic VLBI

- 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

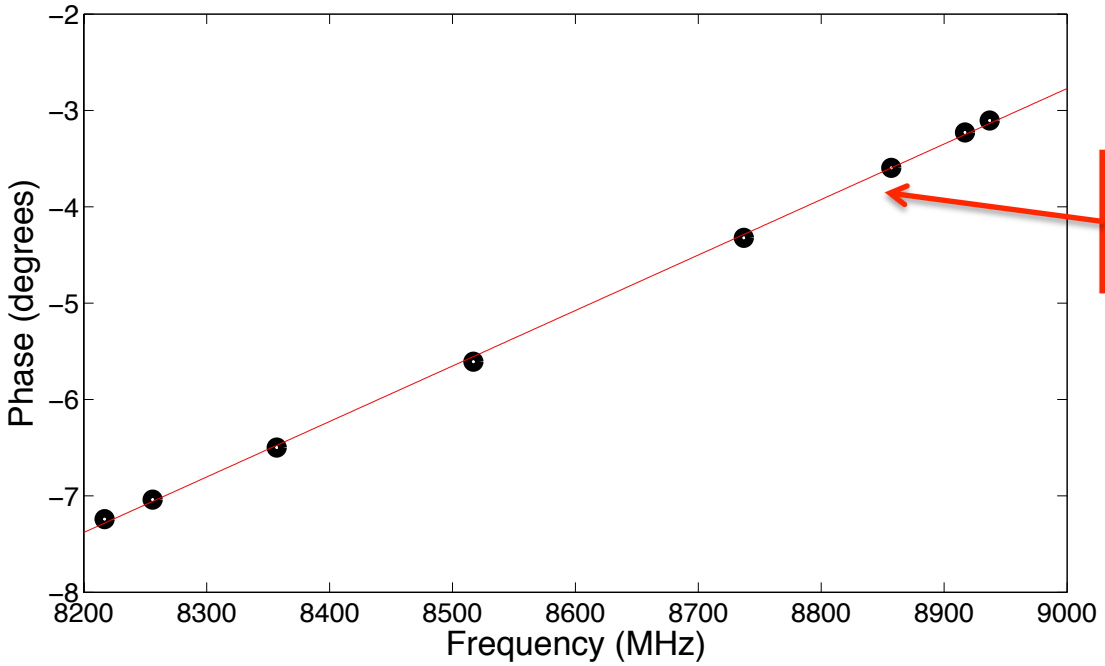
N-E plane projected in source direction

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

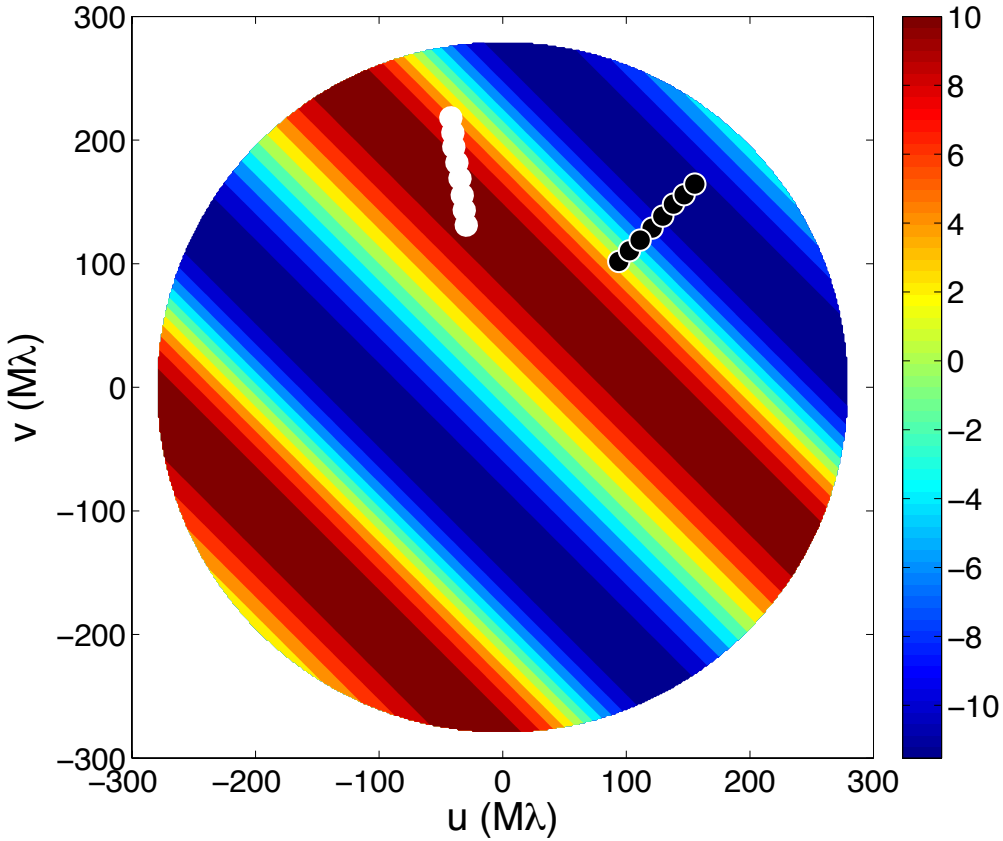


slope = structure delay

Visibility phase

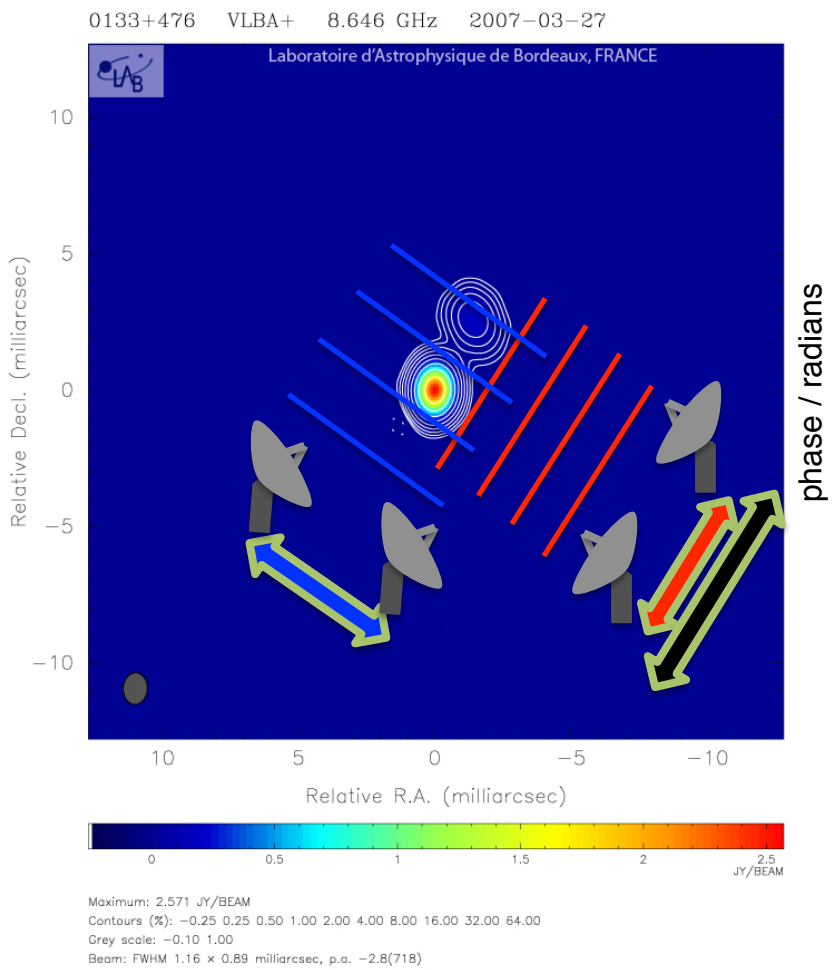
N-E plane projected in source direction

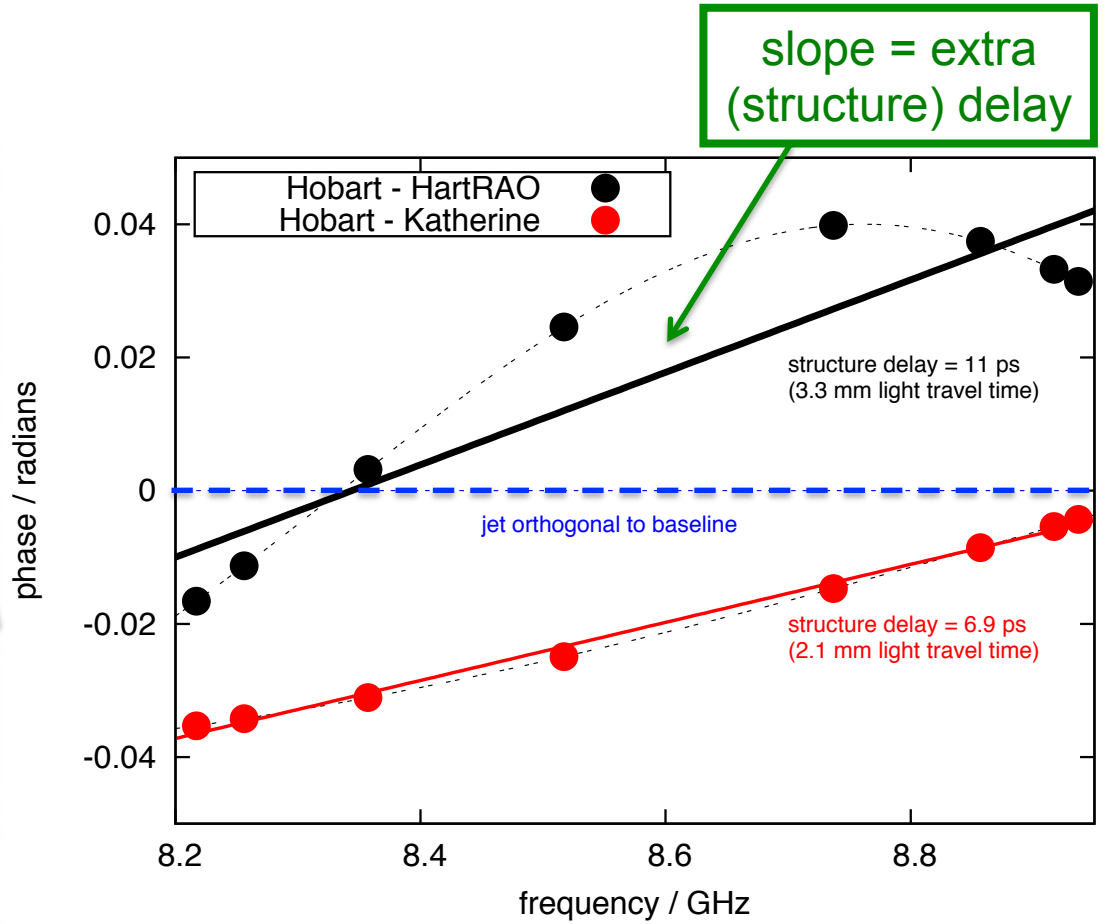
different location in *uv* plane depending on **frequency**, **baseline** and **time**



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

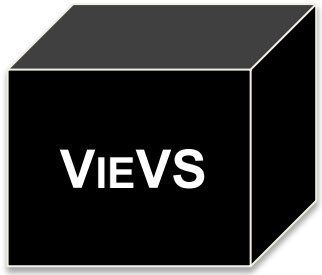
slope changes with projected structure

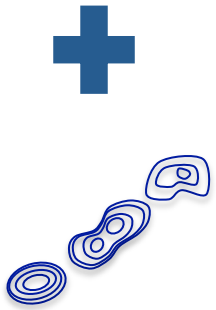
VieVS source structure simulator

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

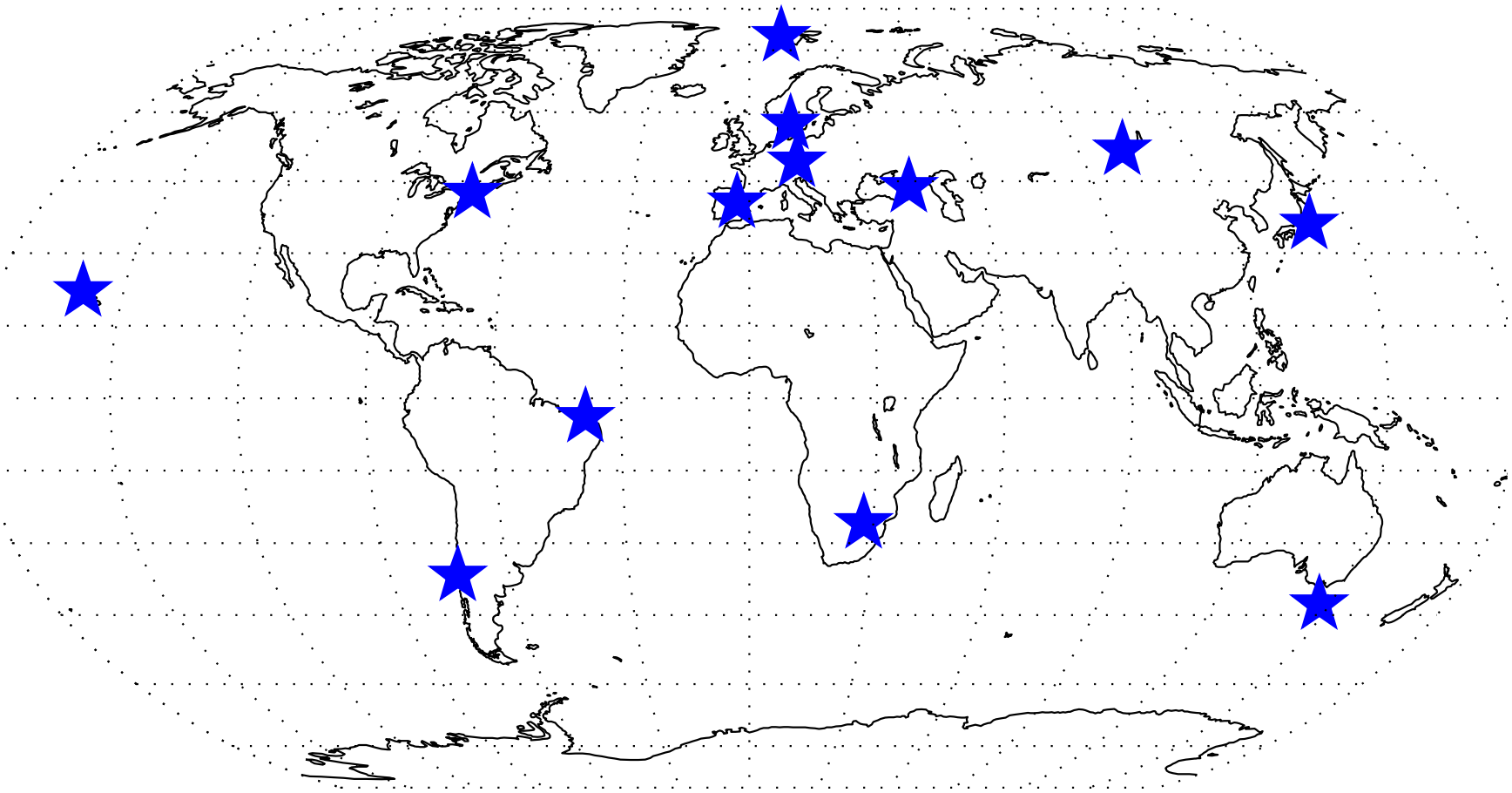
  $SI = 1 + 2 \log (\tau / ps)$

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

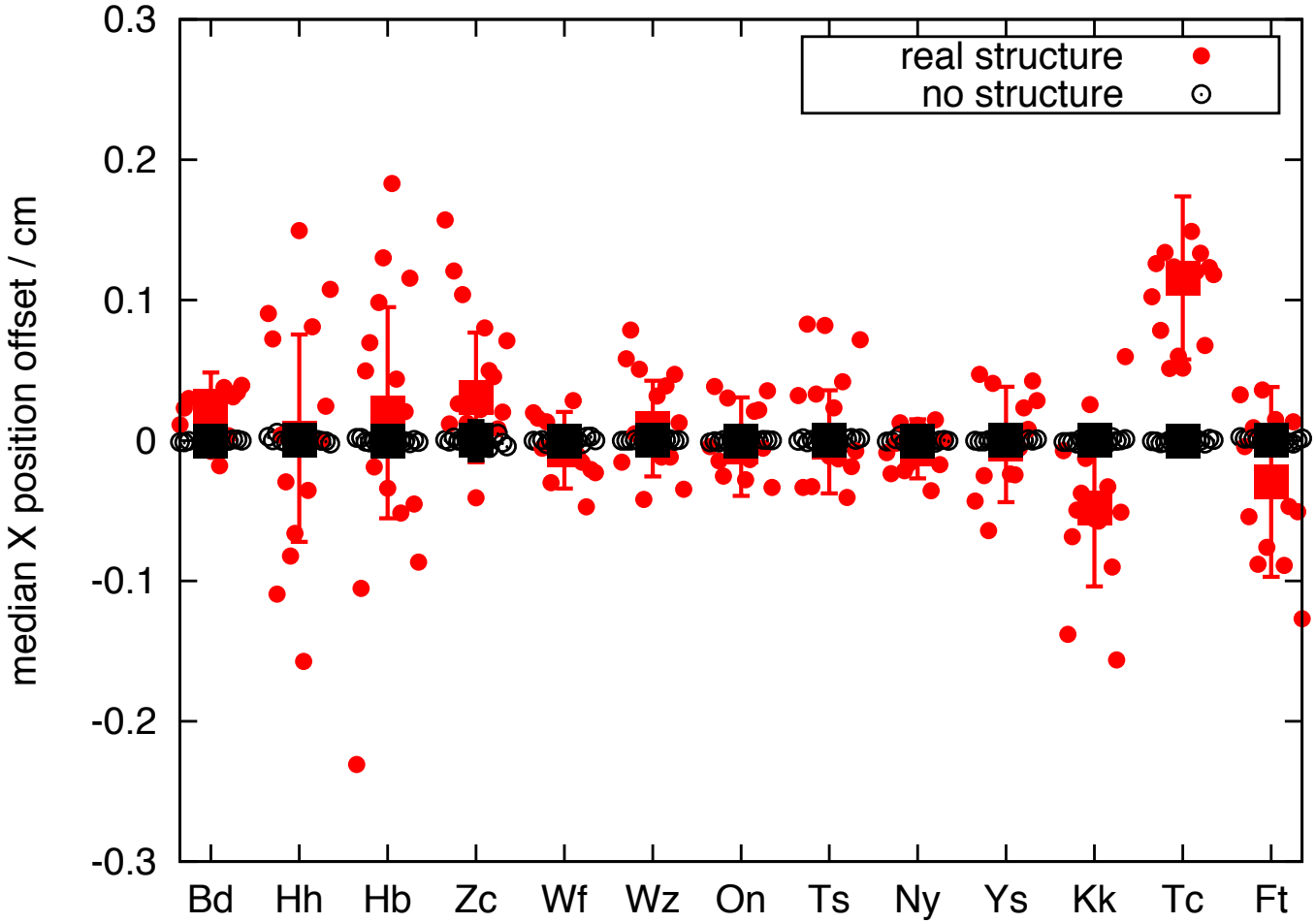
SI 3 = 10 ps

- 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

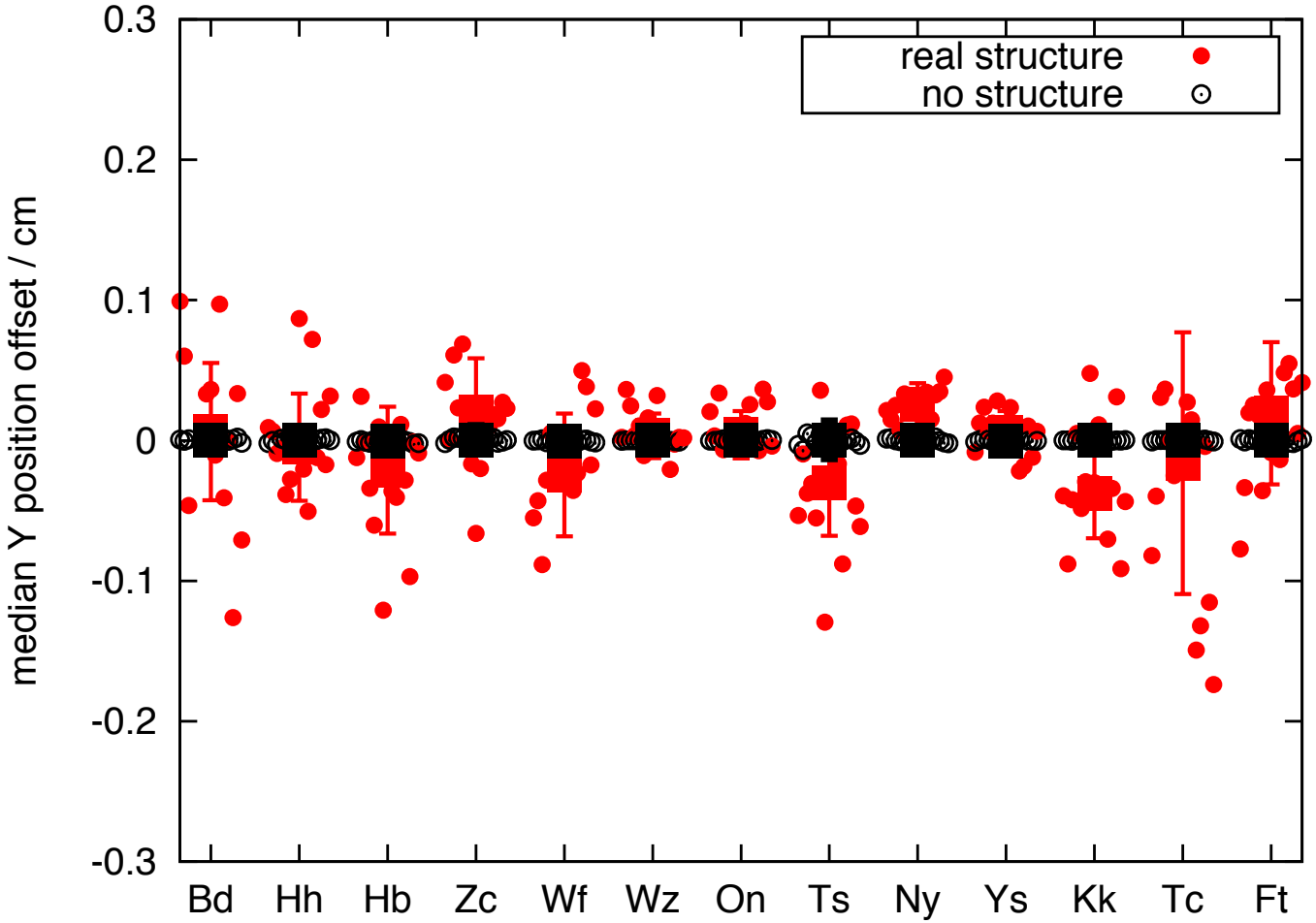


Real sources – X coord



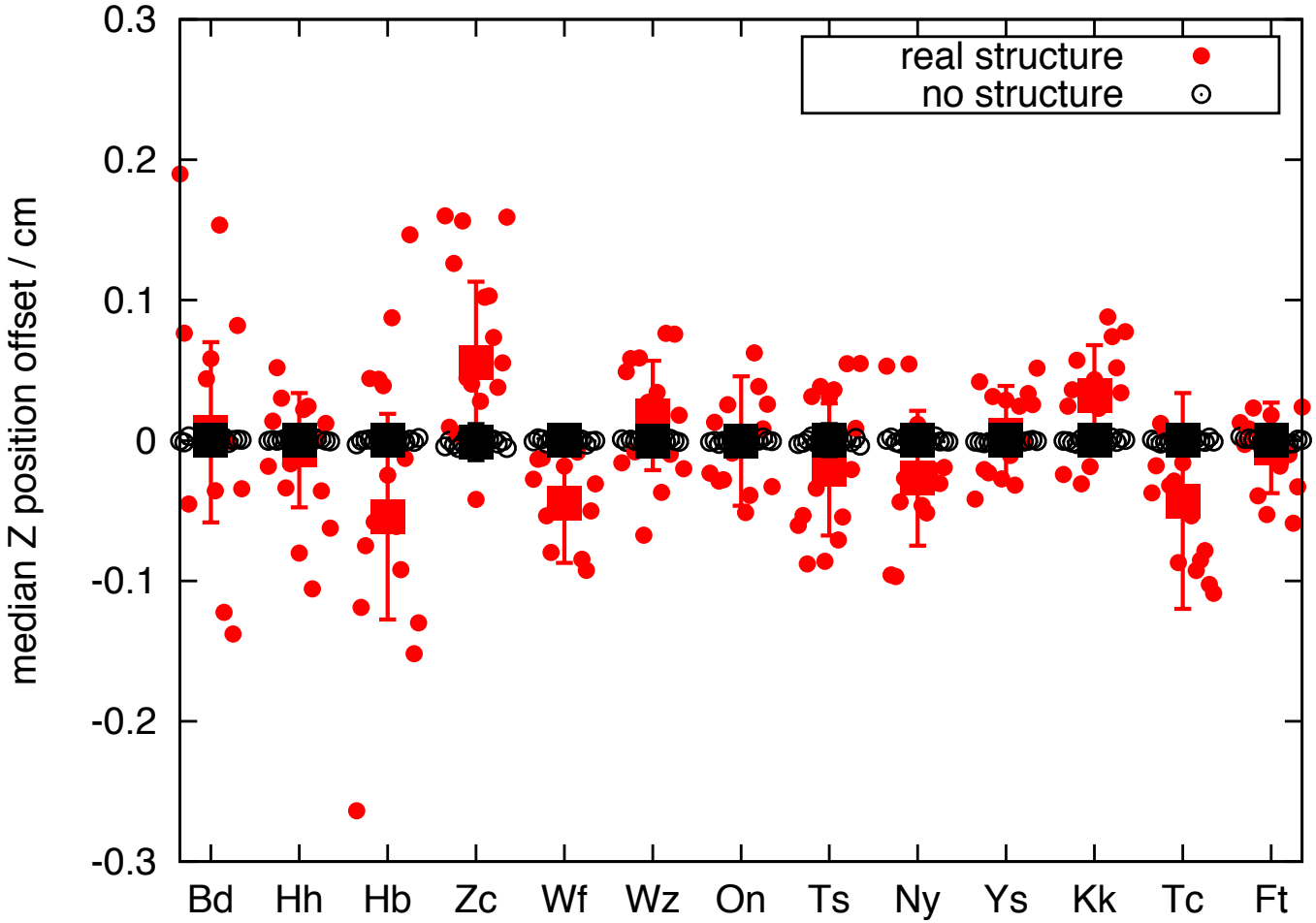
Shabala+14, J. Geod. submitted

Real sources – Y coord



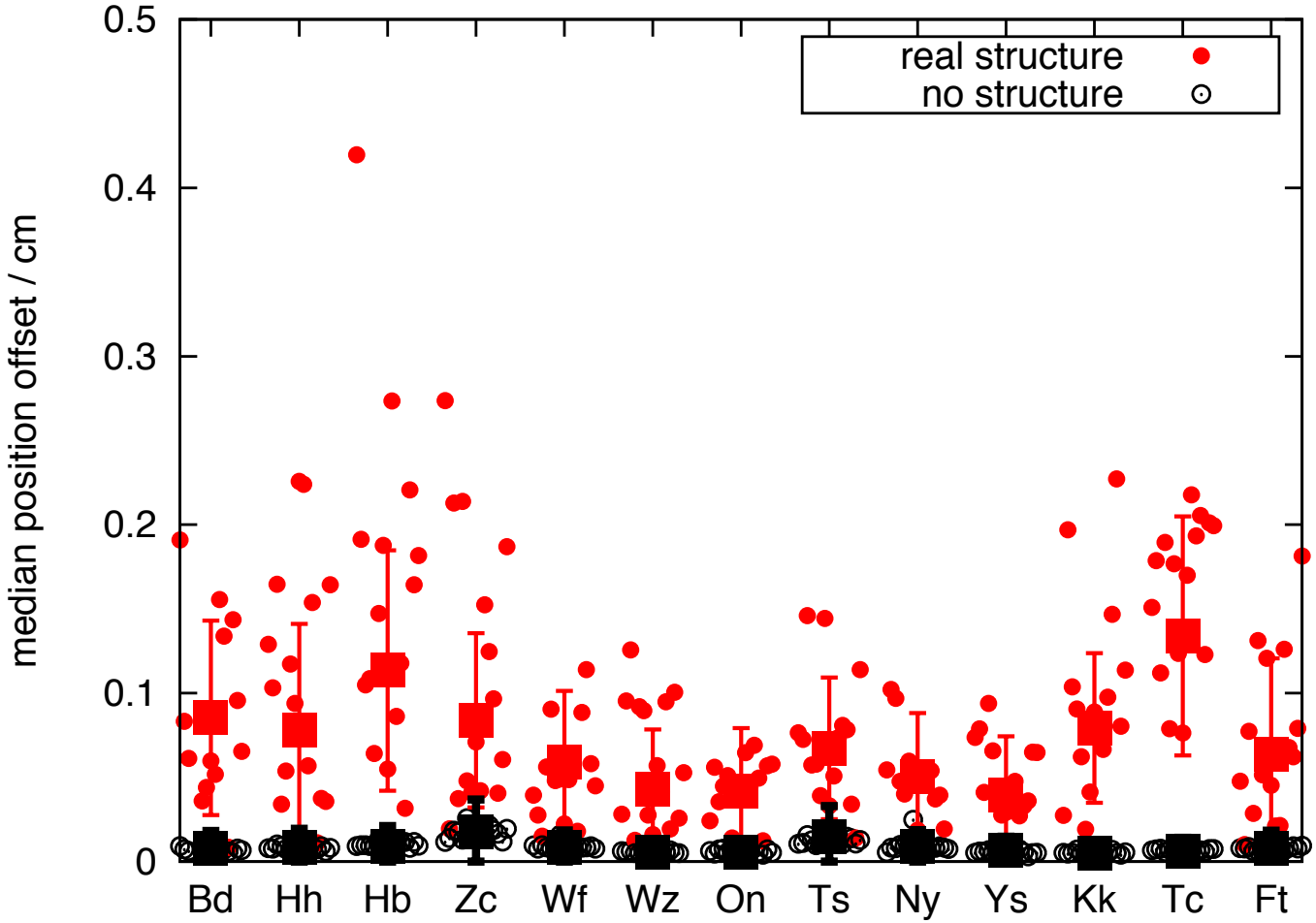
Shabala+14, J. Geod. submitted

Real sources – Z coord



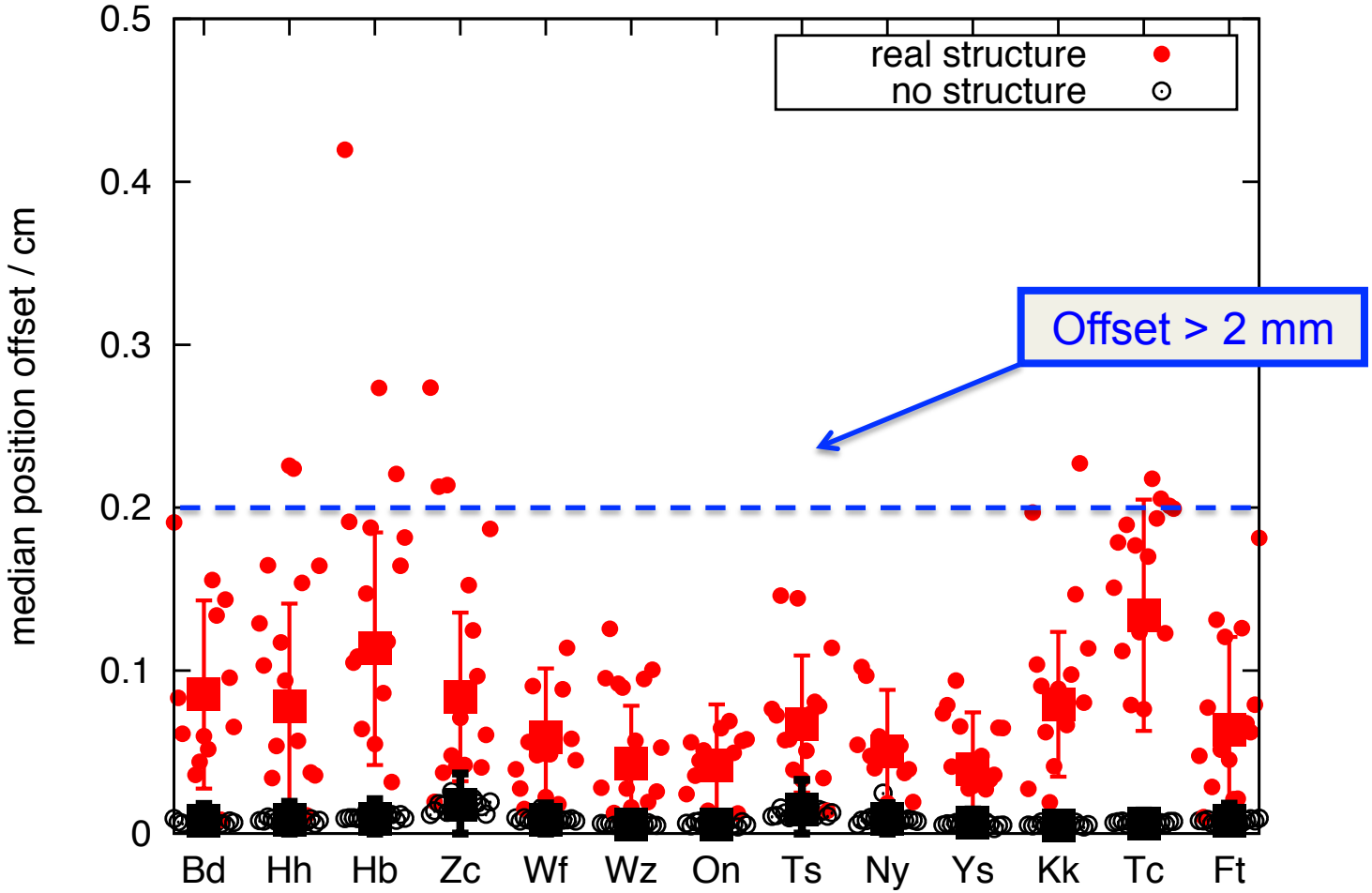
Shabala+14, J. Geod. submitted

Real sources – 3D coord offset



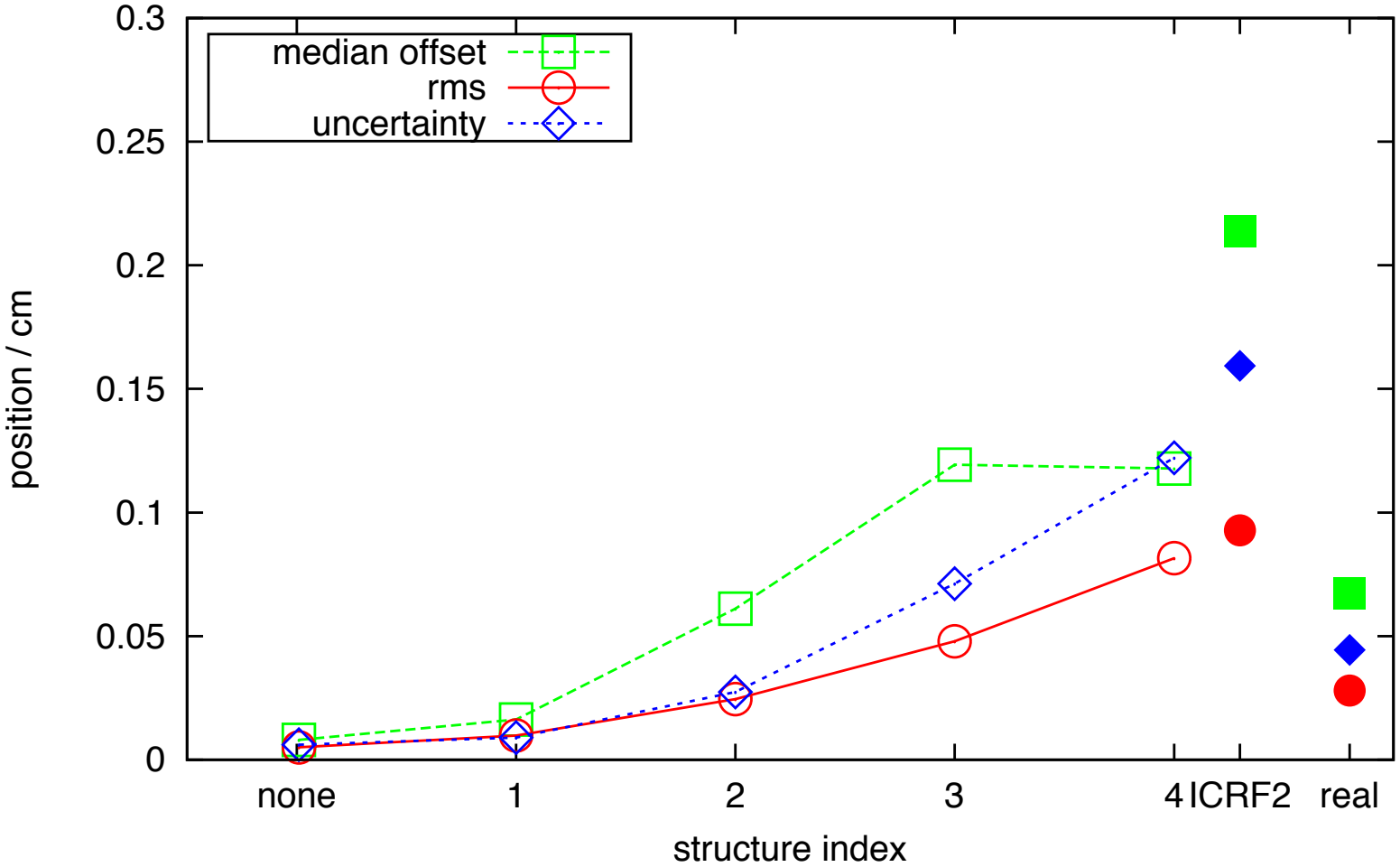
Shabala+14, J. Geod. submitted

Real sources – 3D coord offset



Shabala+14, J. Geod. submitted

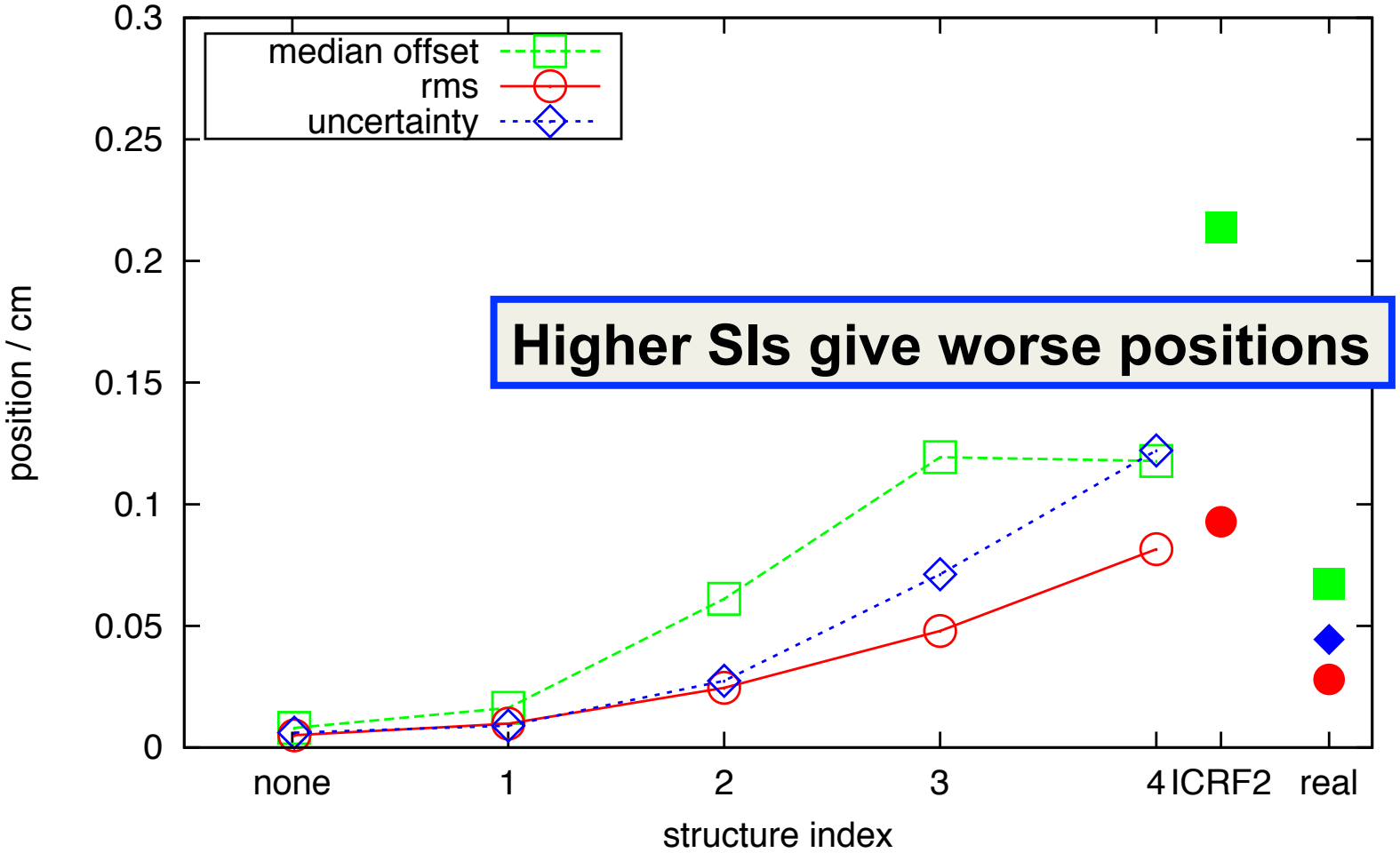
How important is quasar structure ?



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

Shabala+14, J. Geod. submitted

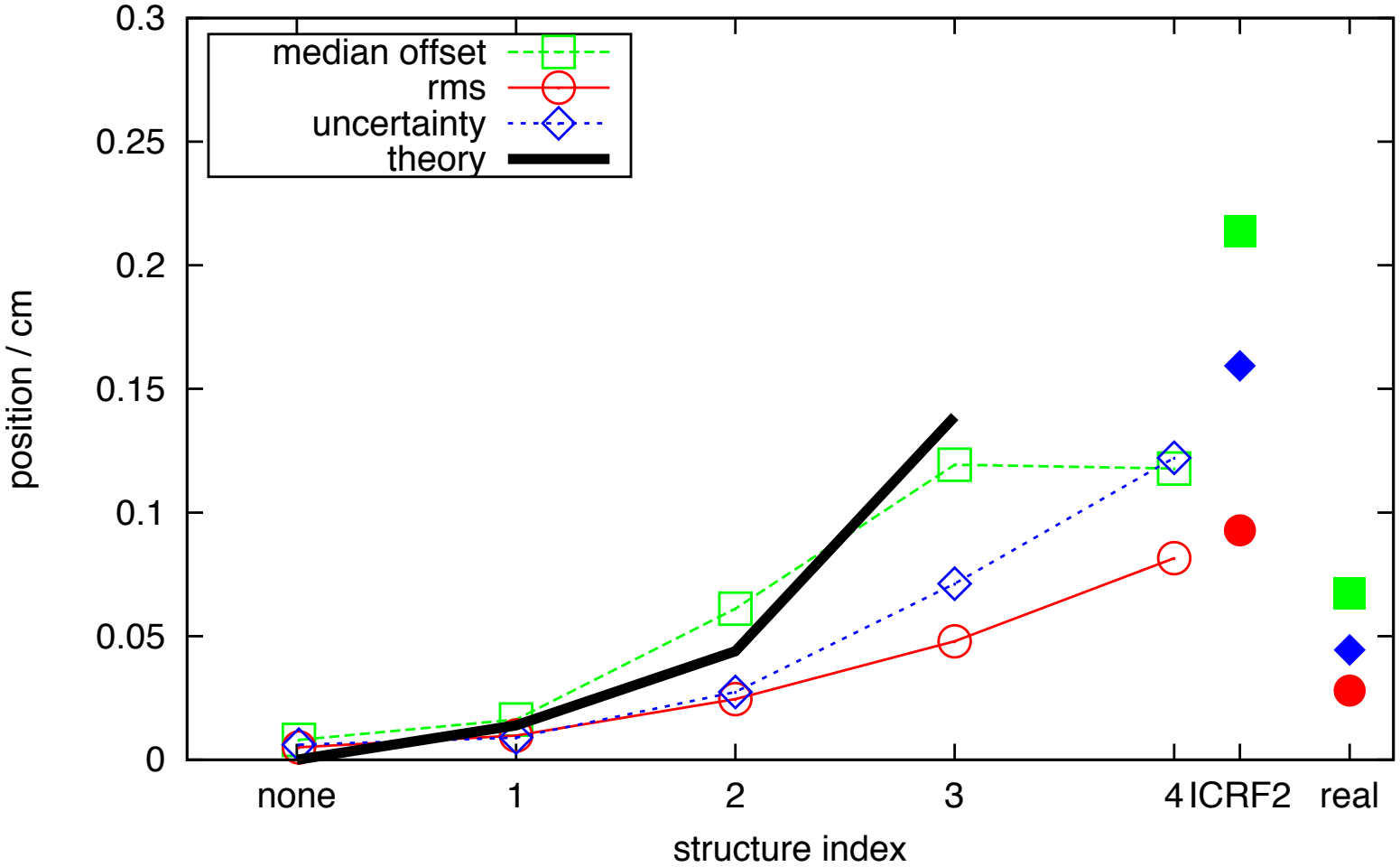
How important is quasar structure ?



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

Shabala+14, J. Geod. submitted

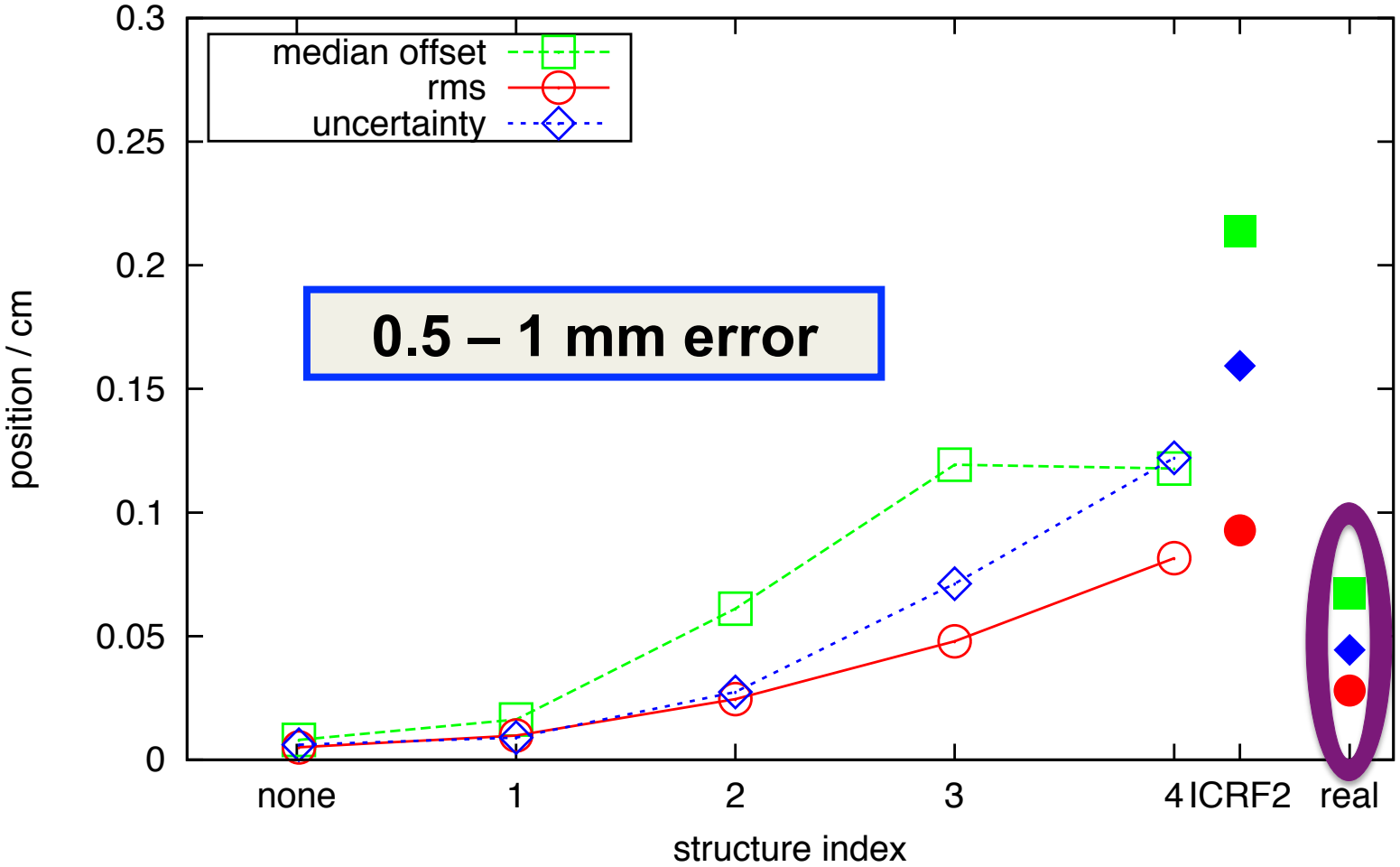
How important is quasar structure ?



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

Shabala+14, J. Geod. submitted

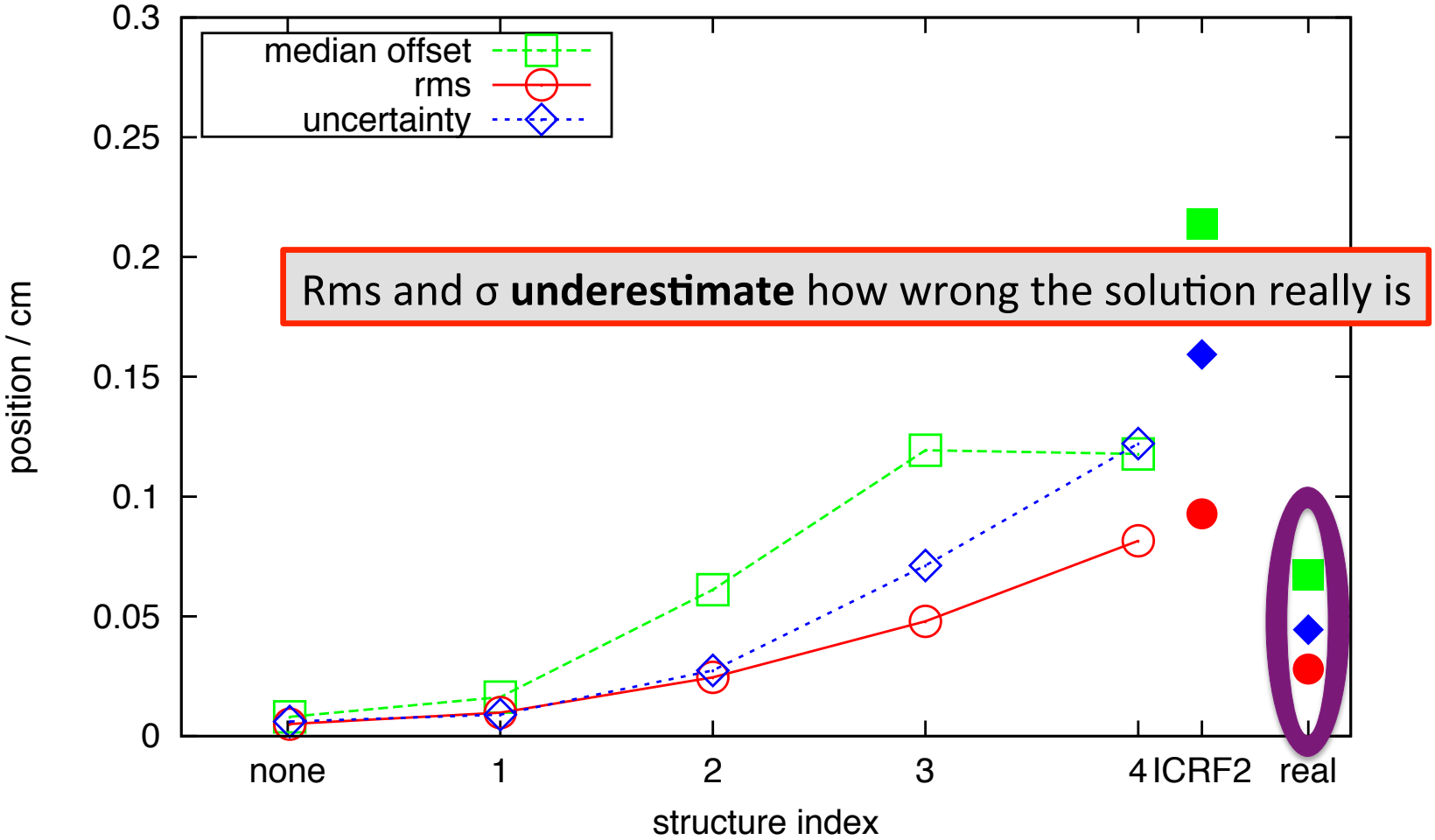
How important is quasar structure ?



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

Shabala+14, J. Geod. submitted

How important is quasar structure ?

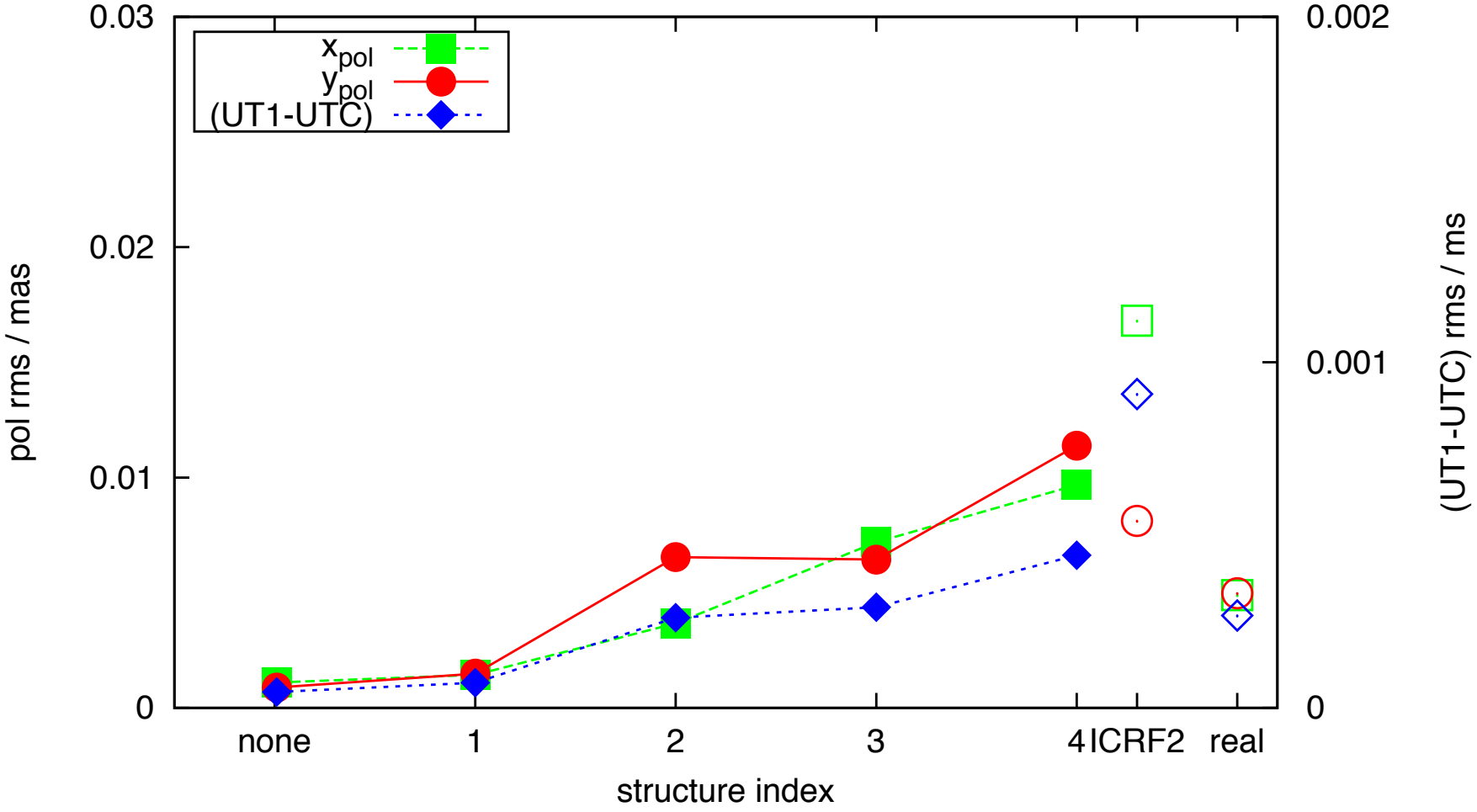


Rms and σ **underestimate** how wrong the solution really is

SI = 1 + 2 log (τ / ps)

Shabala+14, J. Geod. submitted

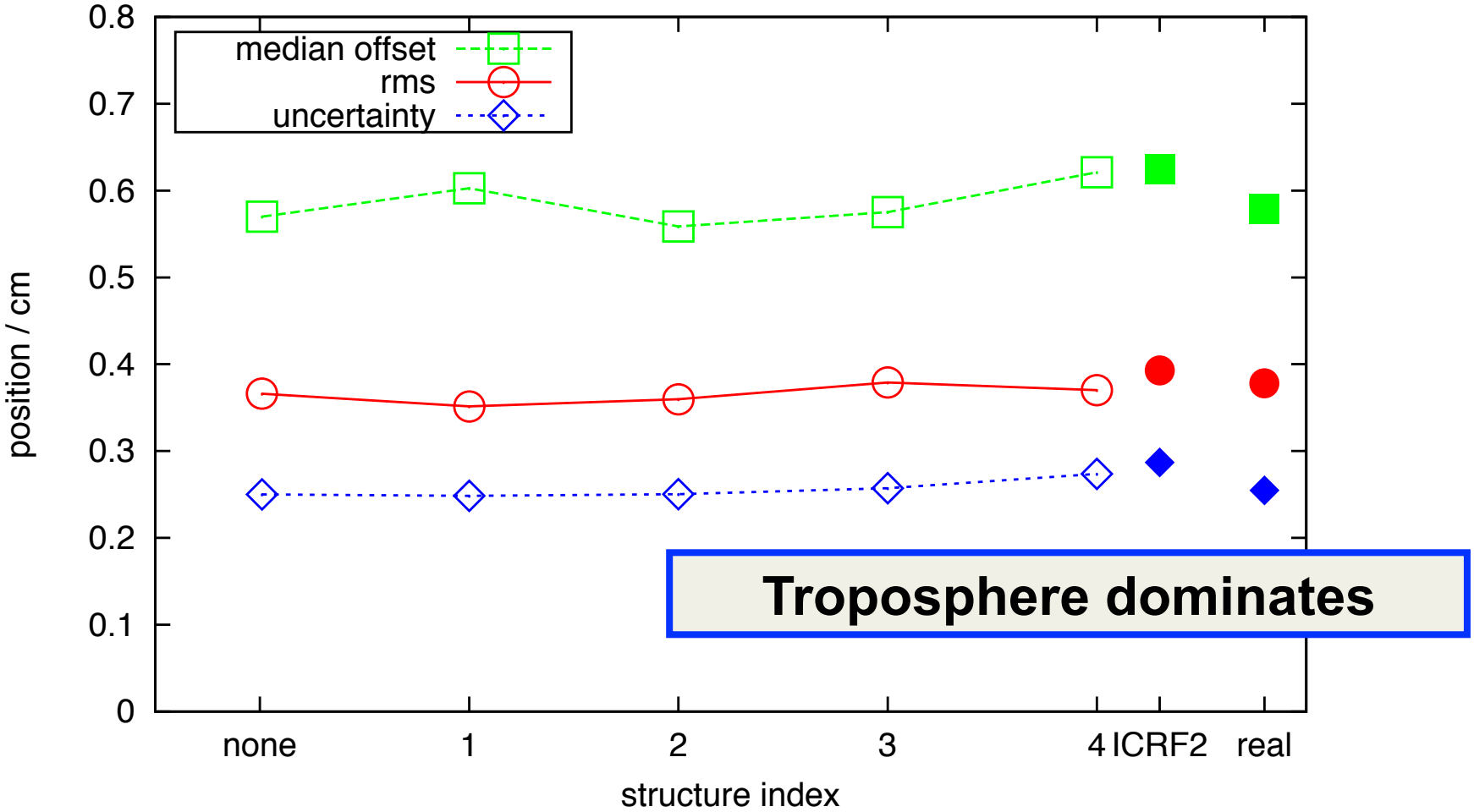
EOP rms



Shabala+14, J. Geod. submitted

What happens if we include troposphere ?

Station positions (with trop.)

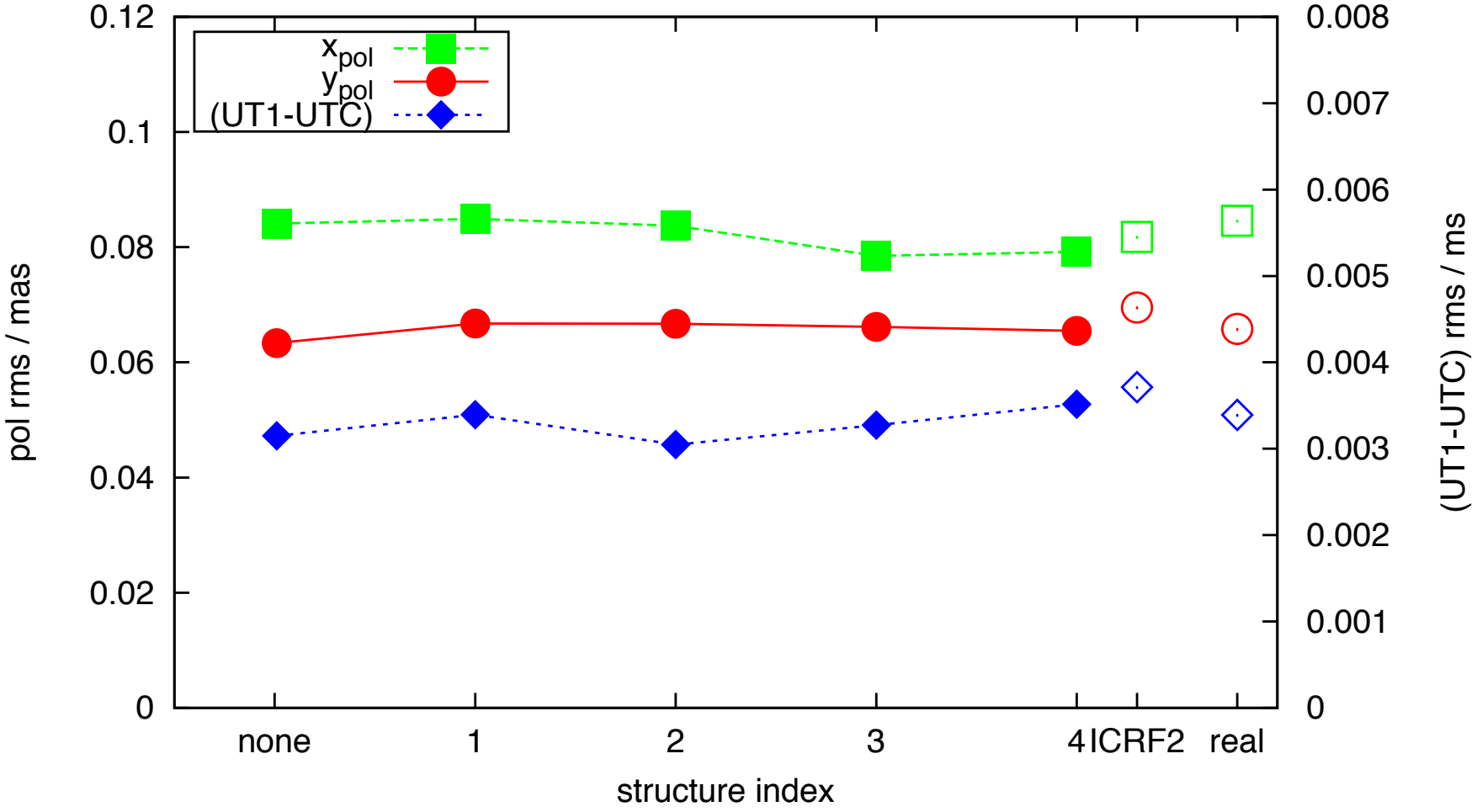


Troposphere dominates

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

Shabala+14, J. Geod. submitted

EOP rms (with troposphere)

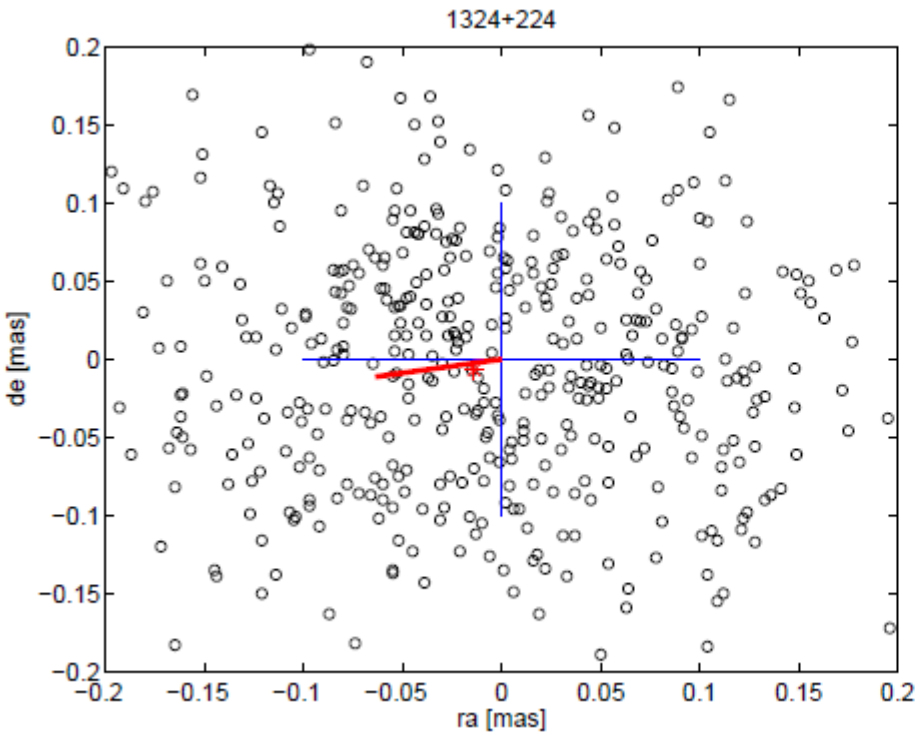


Shabala+14, J. Geod. submitted

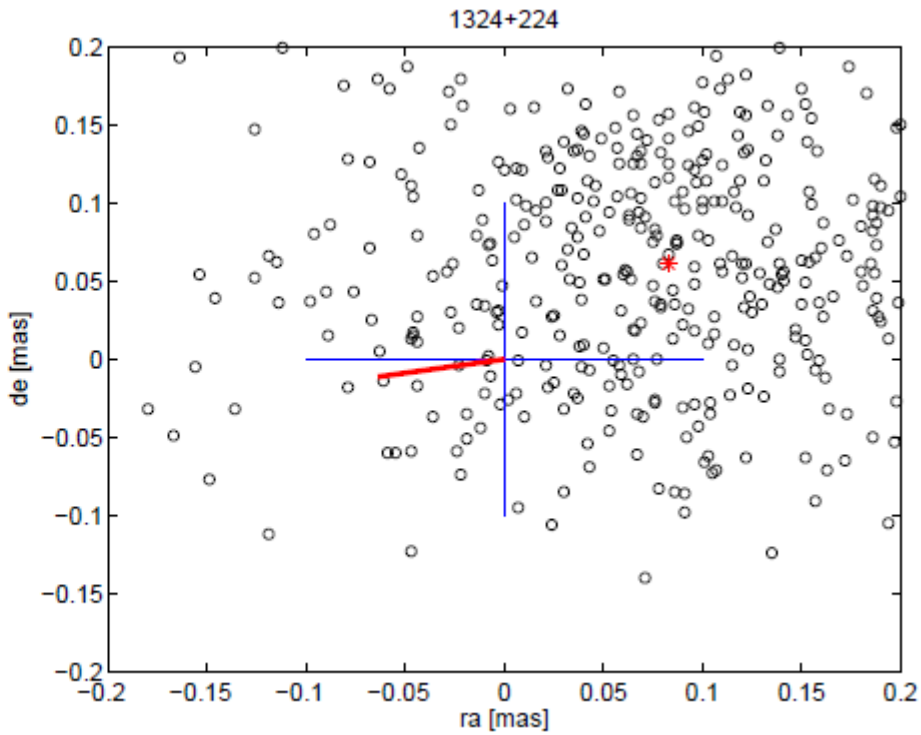
Source structure : effects on CRF

Simulation (Cont11), with troposphere & measurement noise

NO STRUCTURE



STRUCTURE, SI=3

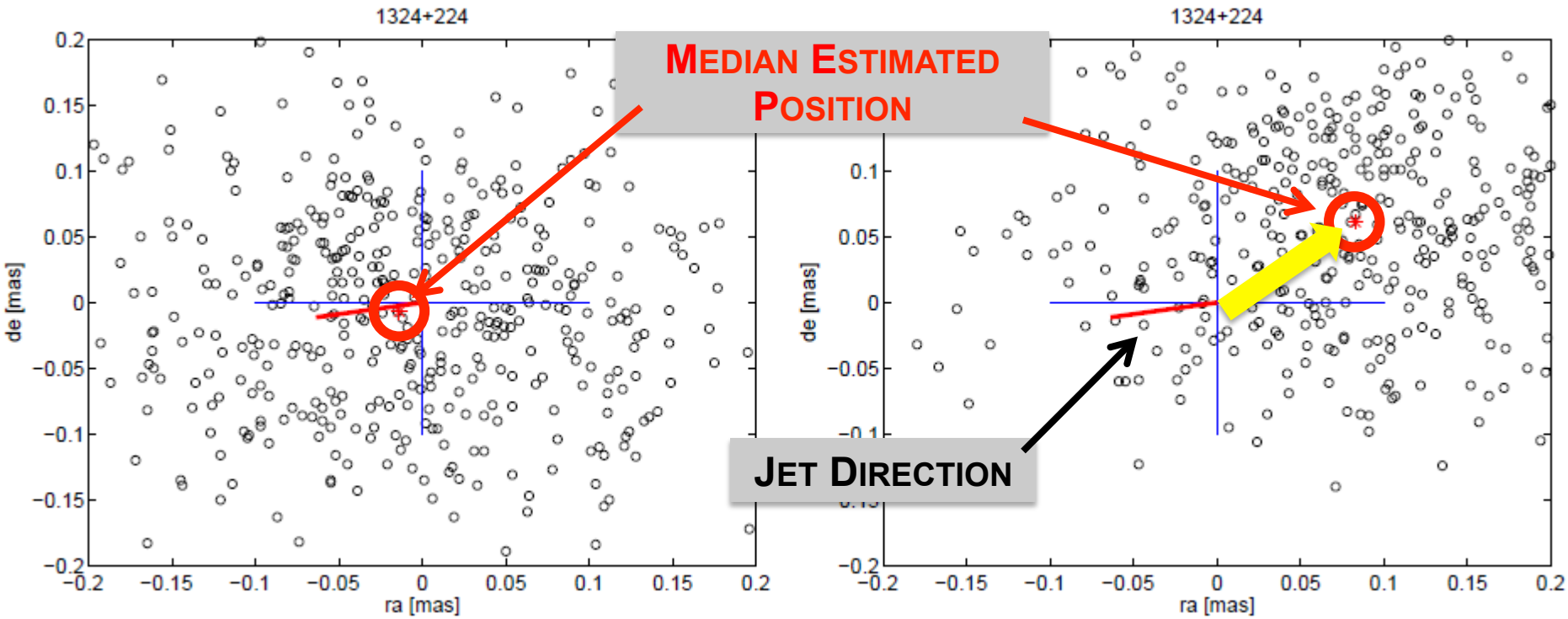


SIMULATED

Source structure : effects on CRF

Simulation (Cont11), with troposphere & measurement noise

No Structure | **Structure, SI=3**

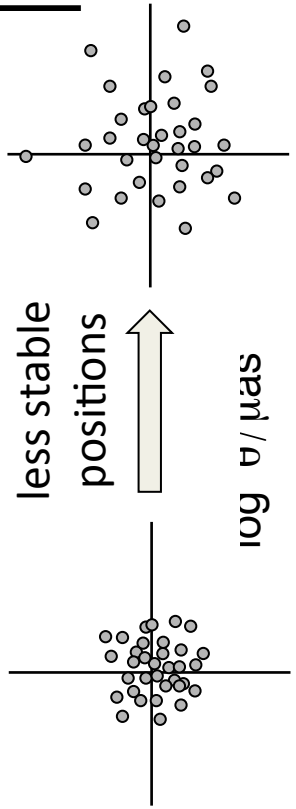


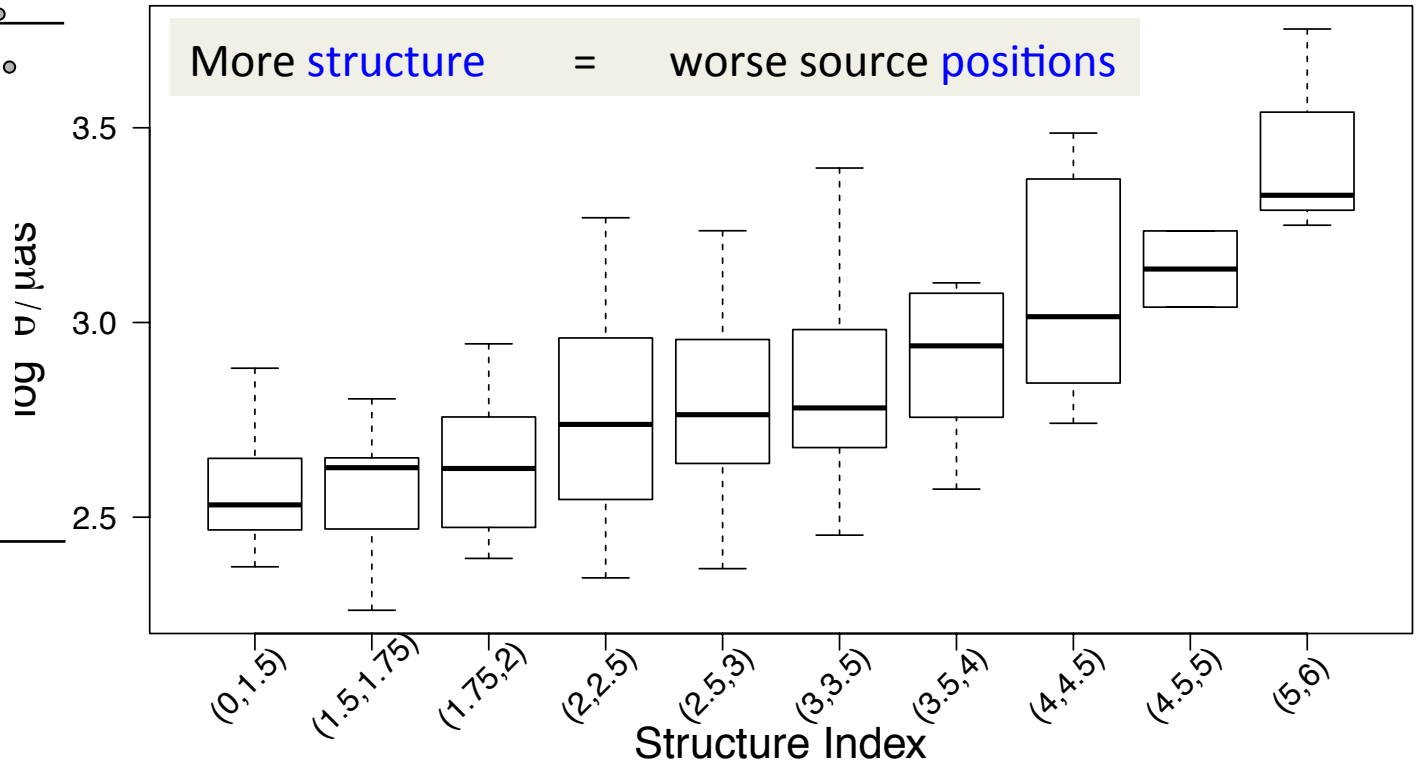
Simulated

Systematic displacement ~ 100 µas

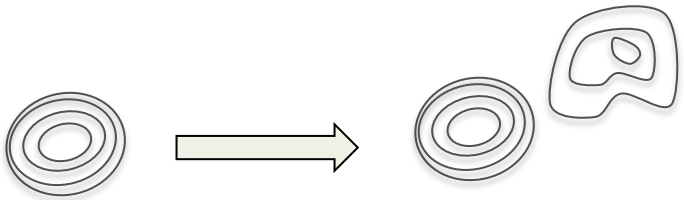
Source structure : effects on CRF

Schaap et al. 2013, MNRAS, 434, 585





OBSERVED



more structure

Problem summary

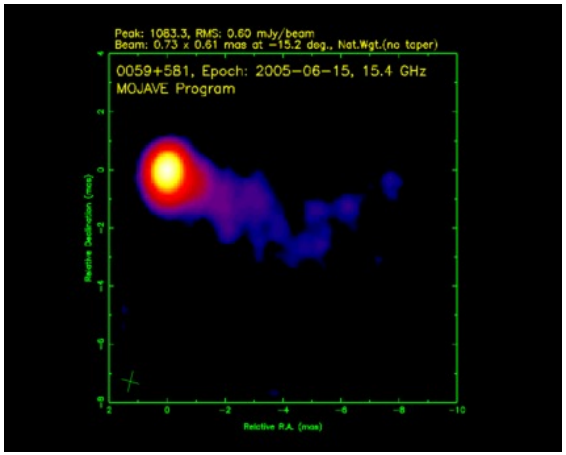
- ✧ Quasar structure simulations with *VieVS*
  - ✧ mock + real quasar catalogues
- ✧ Station positions
  - ◆ offset from true values
  - ◆ larger formal uncertainties
  - ◆ increased rms
  - ◆ important at **mm** level
- ✧ EOPs and source positions also get worse with increasing structure

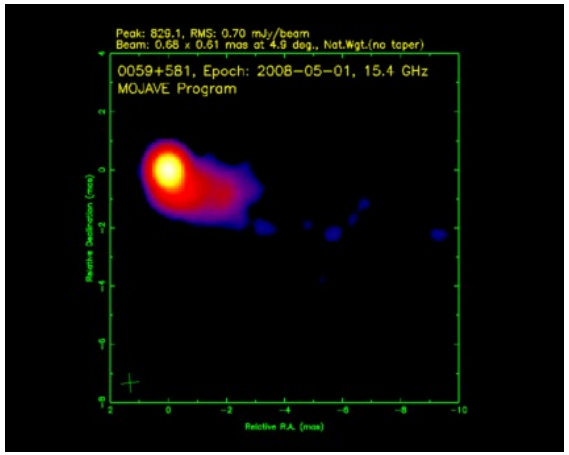
How do we improve the Reference Frames ?

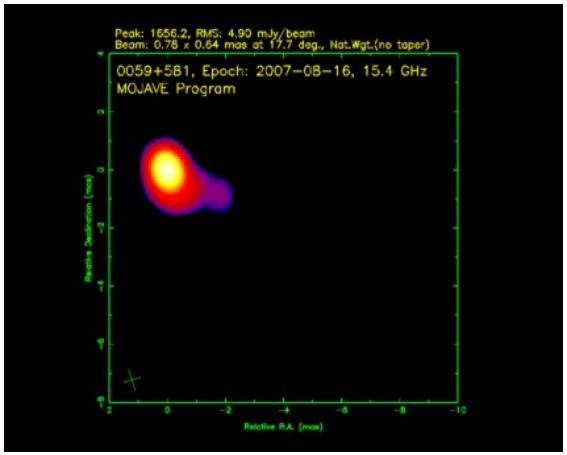
(with quasar physics)

Good news

① We can image quasar structure
(and make corrections)







Lister et al. (2009)

How do we improve the Reference Frames ?

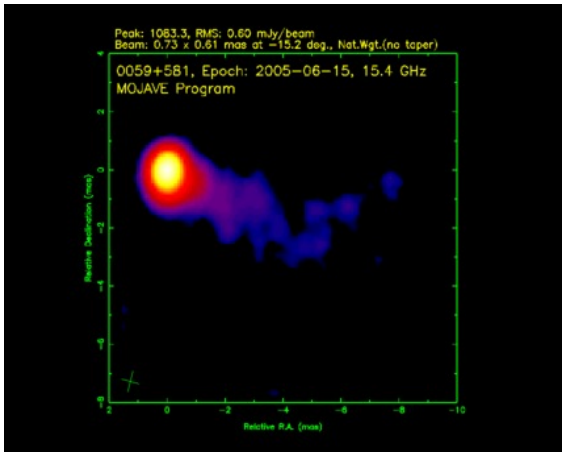
(with quasar physics)

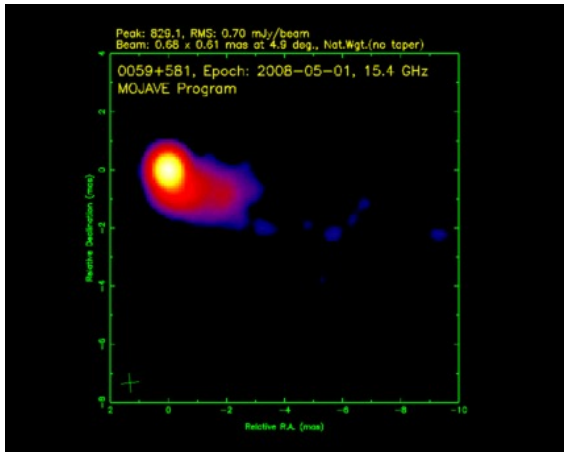
Good news

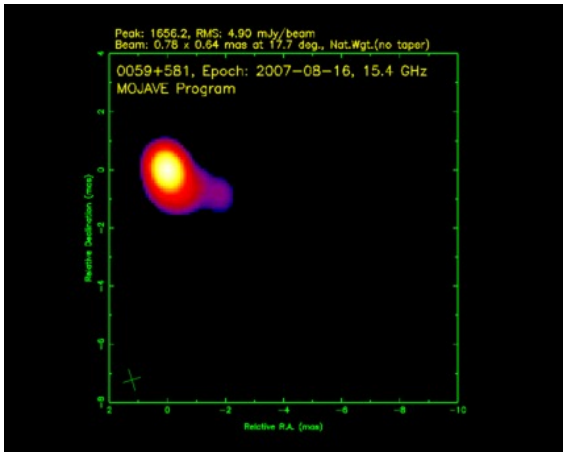
① We can image quasar structure
(and make corrections)

Bad news

Quasars evolve
(need to to this often)







Lister et al. (2009)

How do we improve the Reference Frames ?

(with quasar physics)

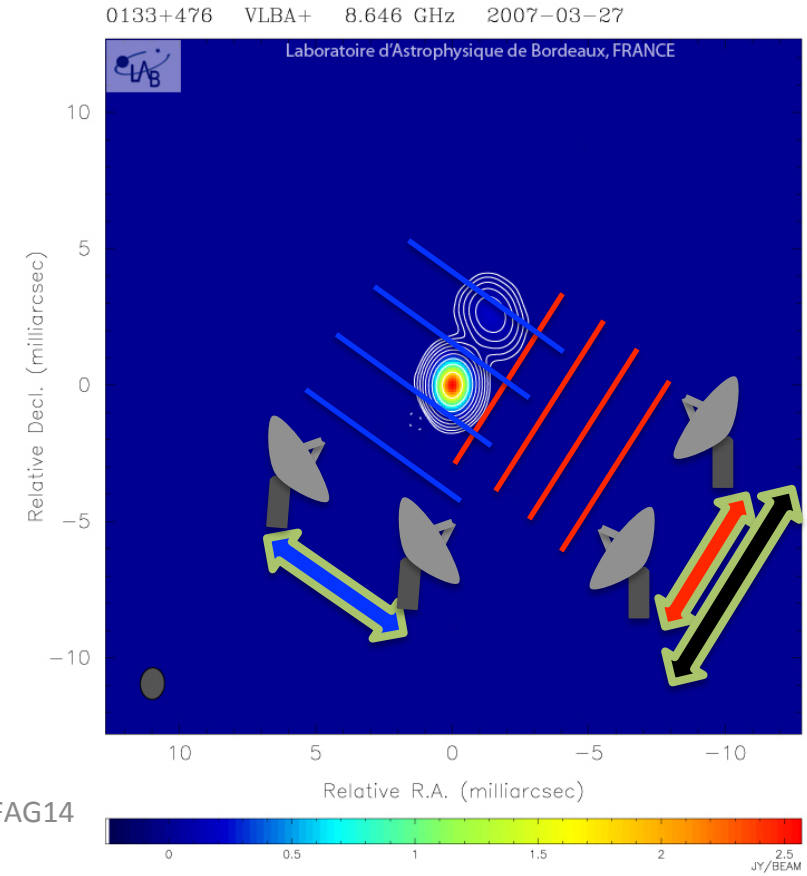
Good news

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

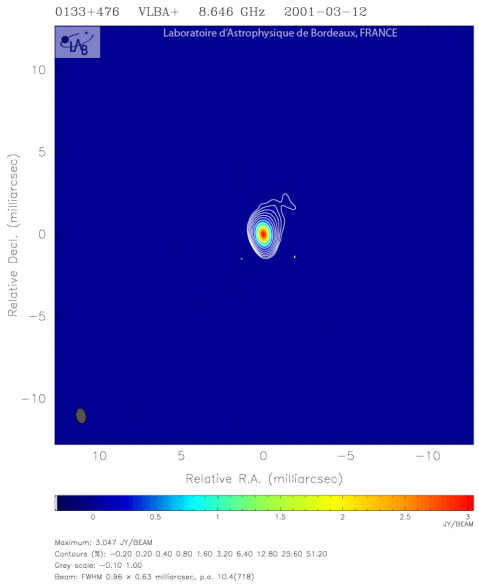
① We can image quasar structure

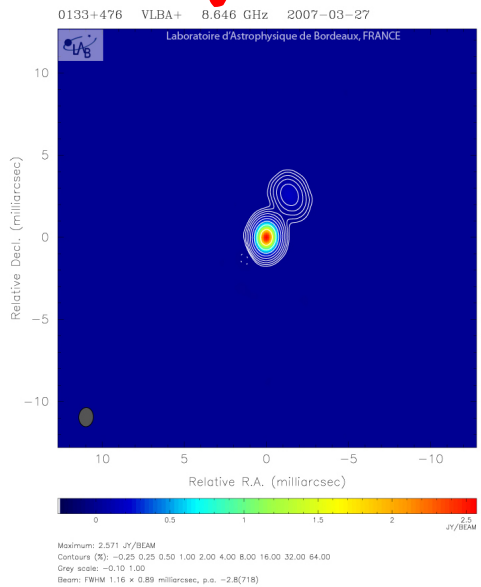
② Jet direction remains constant

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

Bad news

Quasars evolve





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 !

Bad news

Quasars evolve

Strategies

① Use real sources to correct observations

② Minimize projected structure through clever scheduling

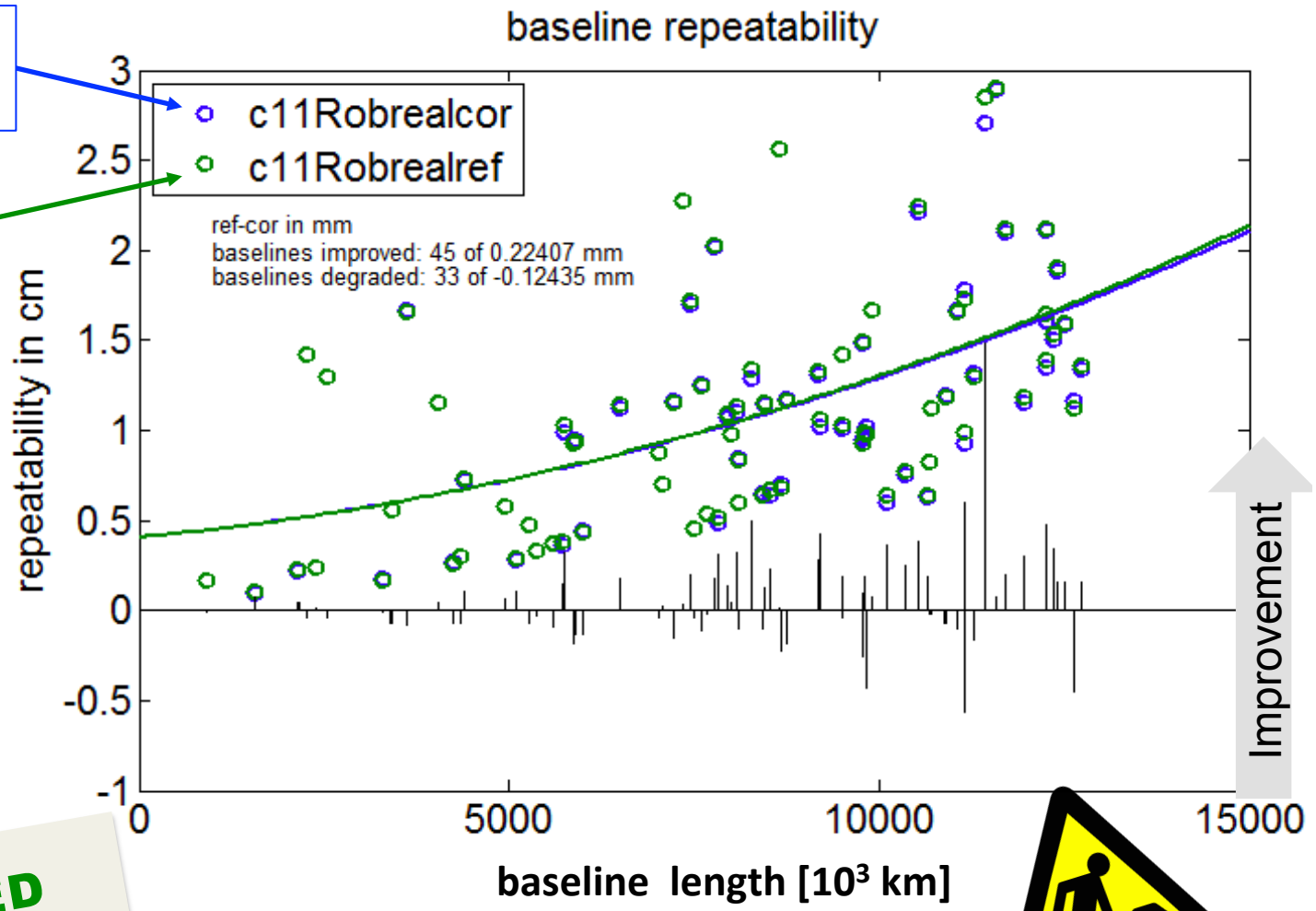
③ Include / exclude sources at appropriate times

1. Quasar structure corrections

Corrected using available images

Raw observations rms

CONT11
OBSERVATIONS



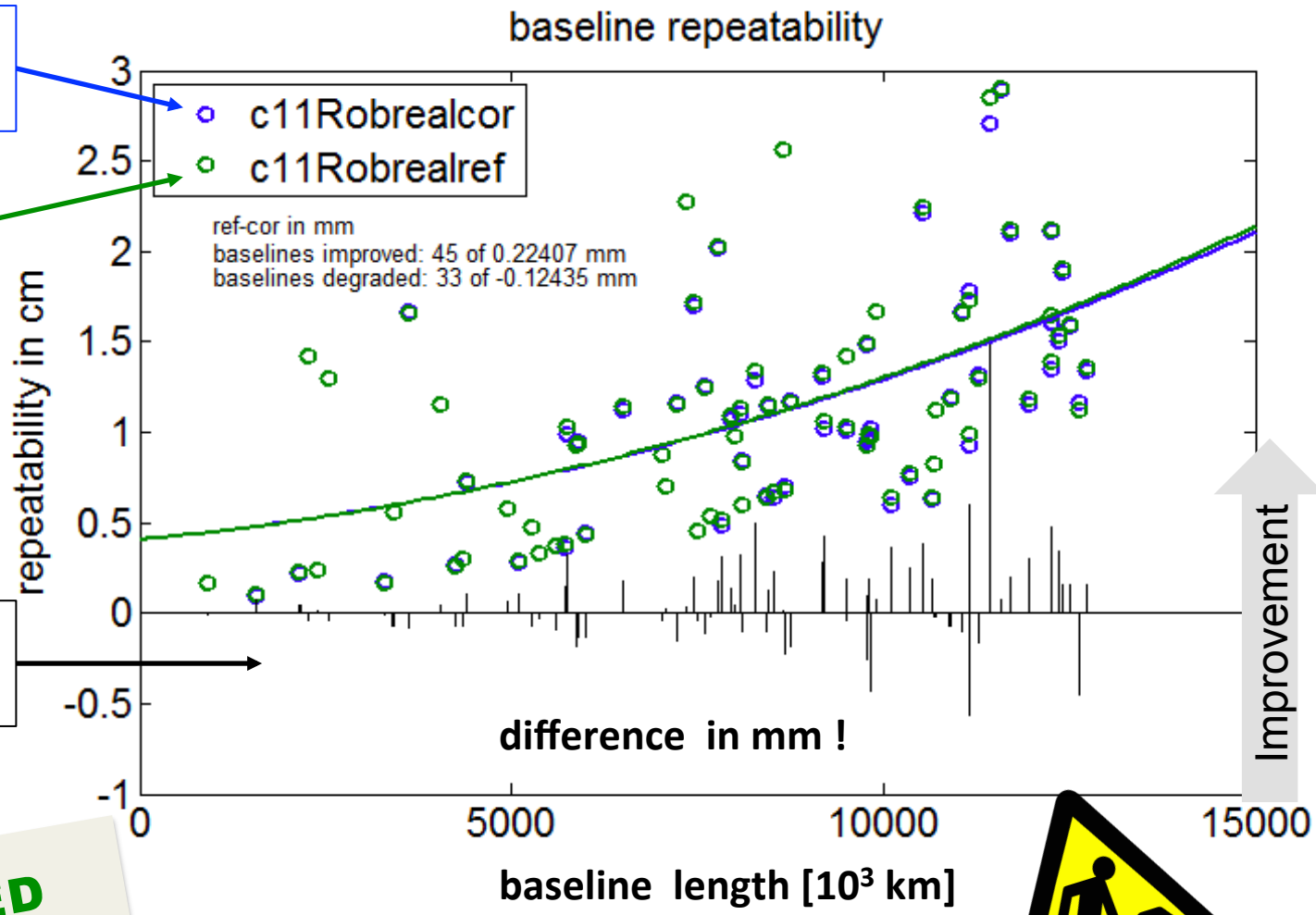
OBSERVED

1. Quasar structure corrections

Corrected using available images

Raw observations rms

Improvement = raw - corrected



OBSERVED

1. Quasar structure corrections

Small improvement

- 45 bl better: +0.22 mm
  33 bl worse: -0.12 mm

< 1 mm

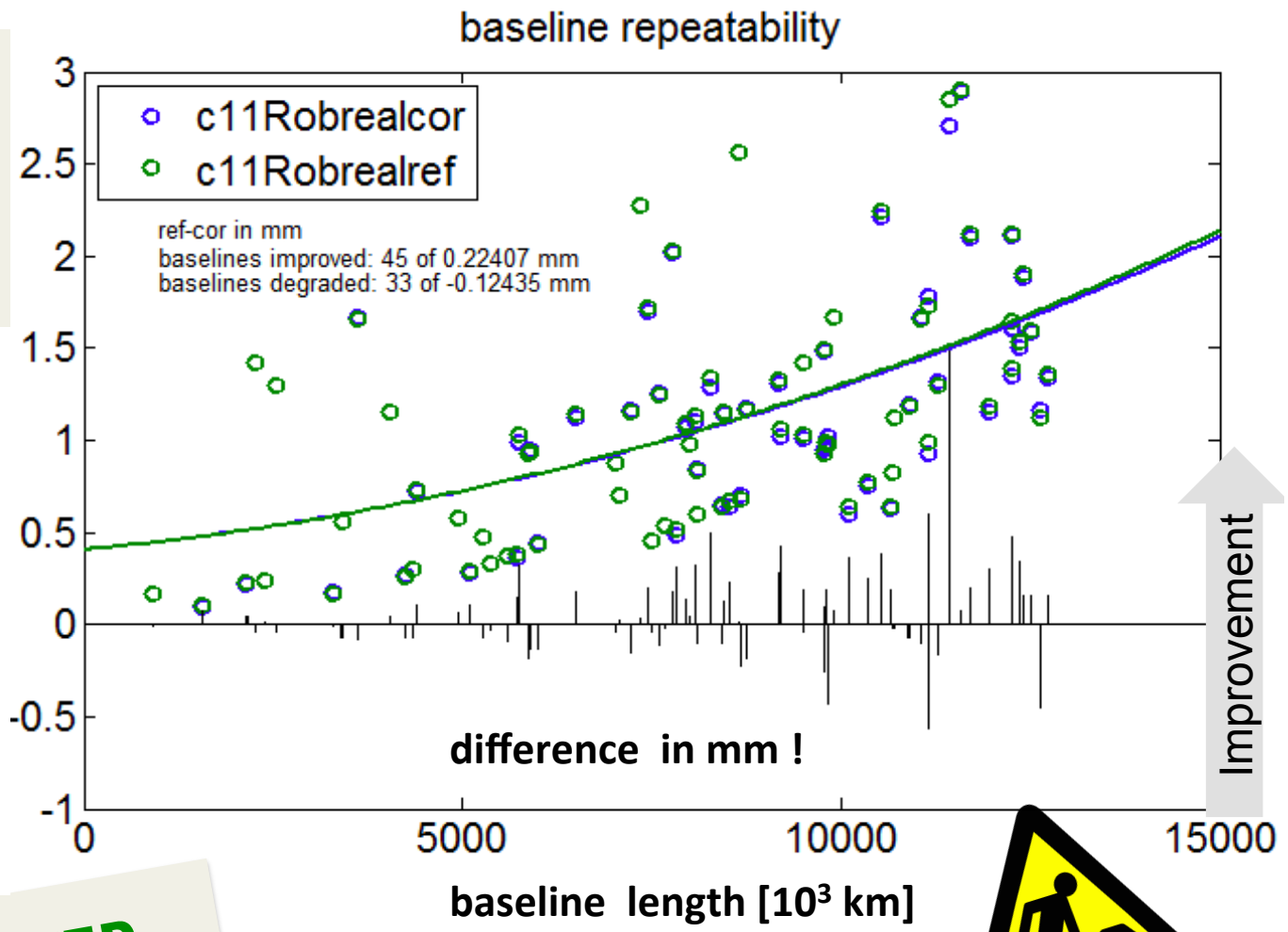
... but promising...

Problems

- Dominated by troposphere
- Many quasars don't have images
- Quasars evolve

Future

- Imaging from geodetic VLBI data



OBSERVED

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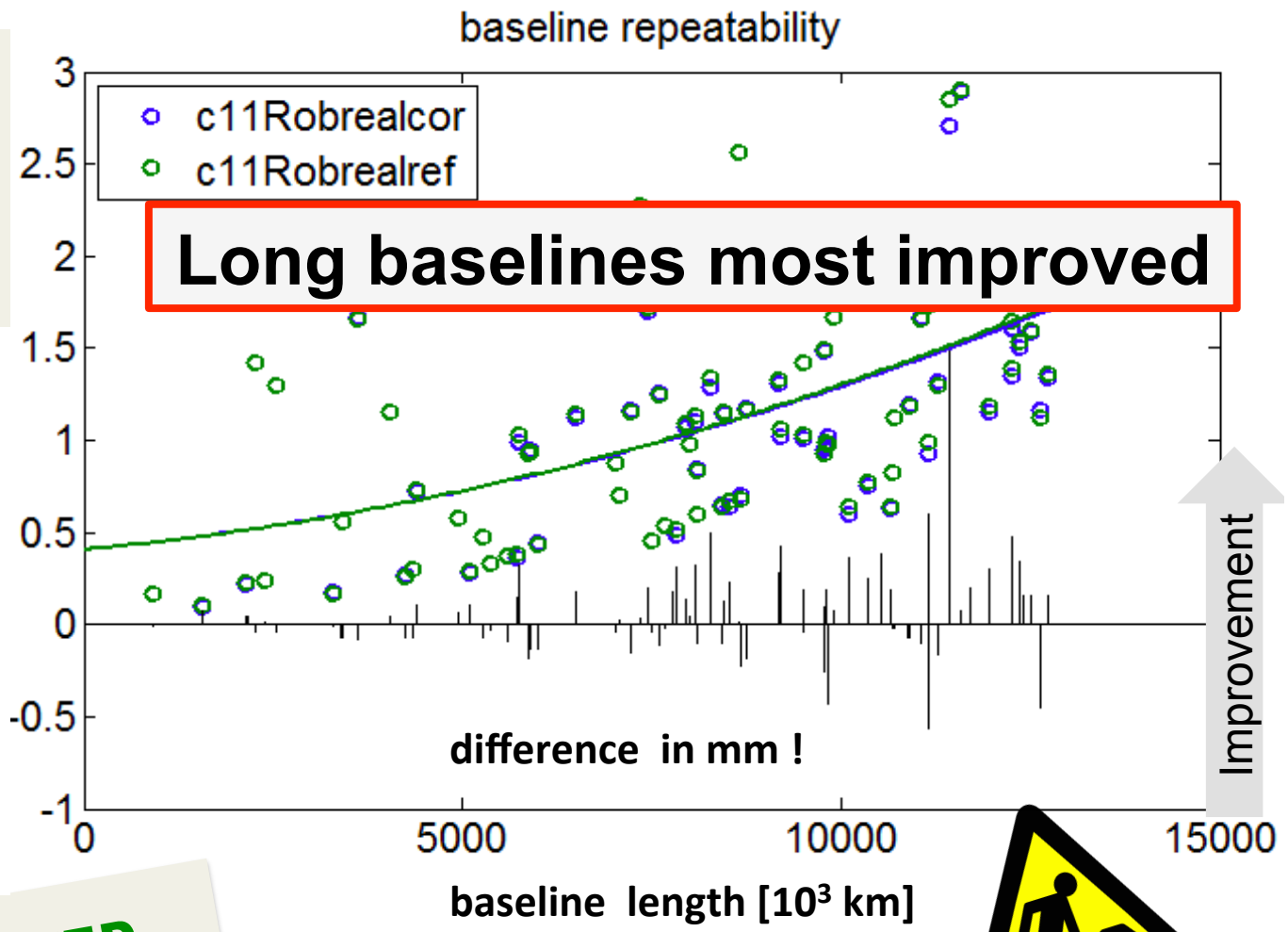
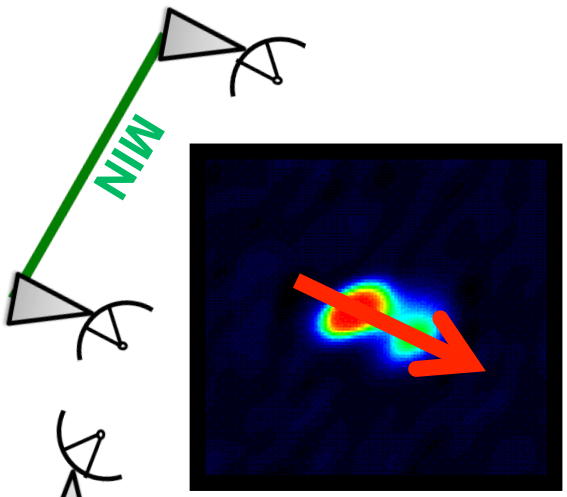


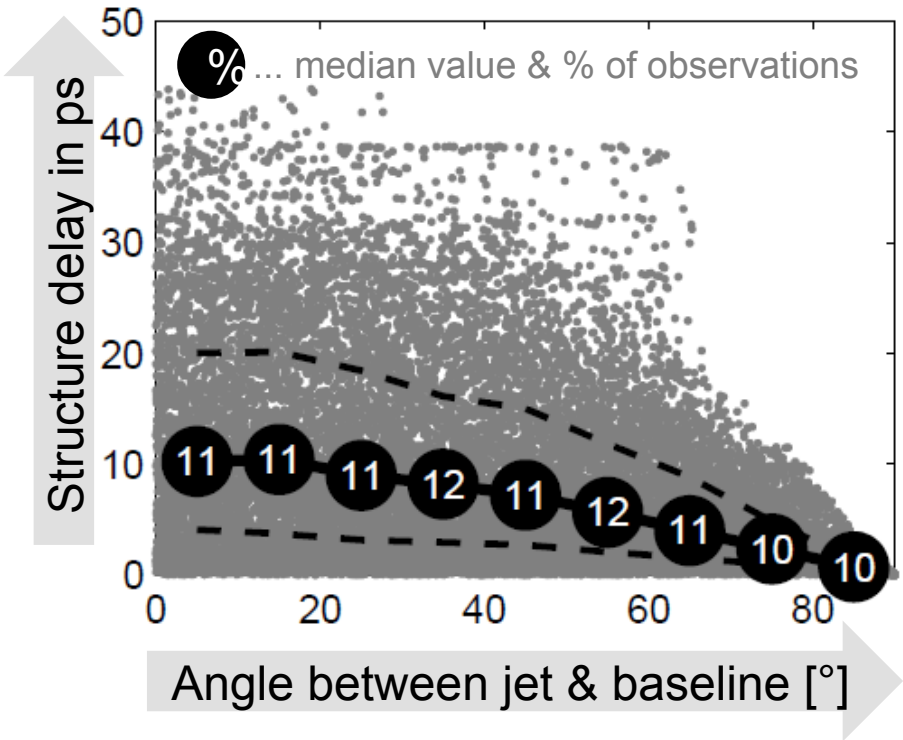
OBSERVED

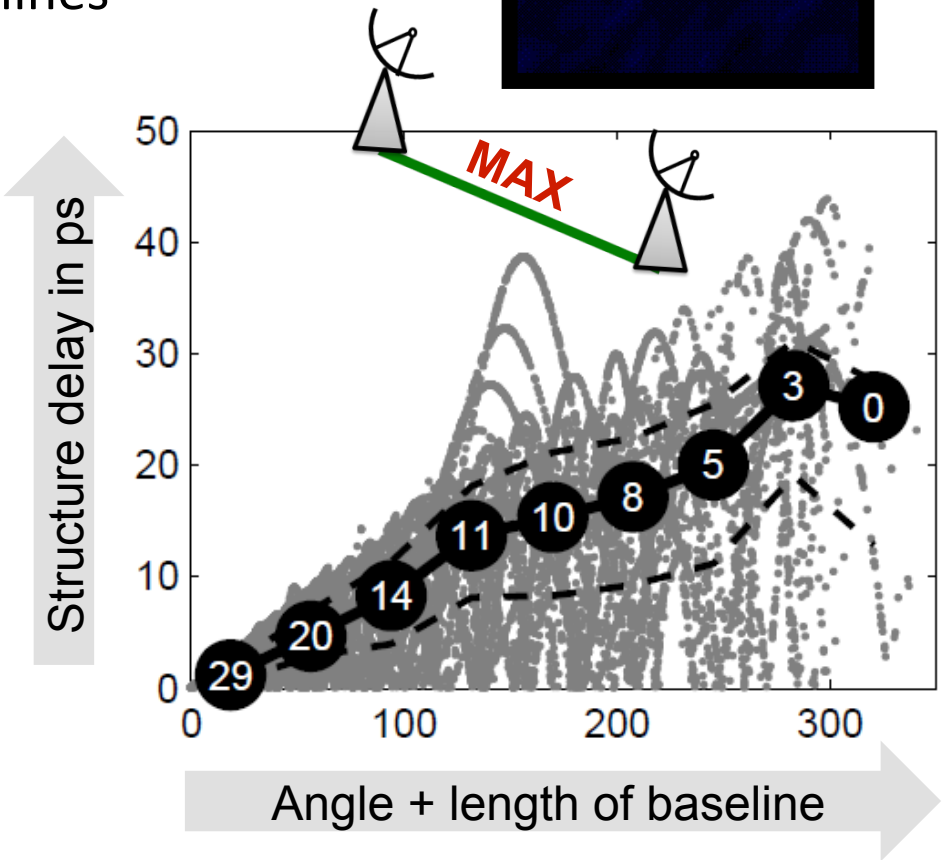
2. Re-analysis using source structure

- Jet direction is constant
- Worst case: parallel, long baselines



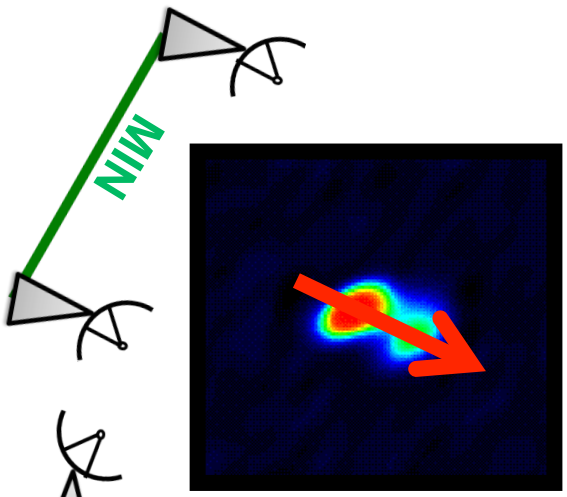
R1/R4 of Oct 2013, SI=3



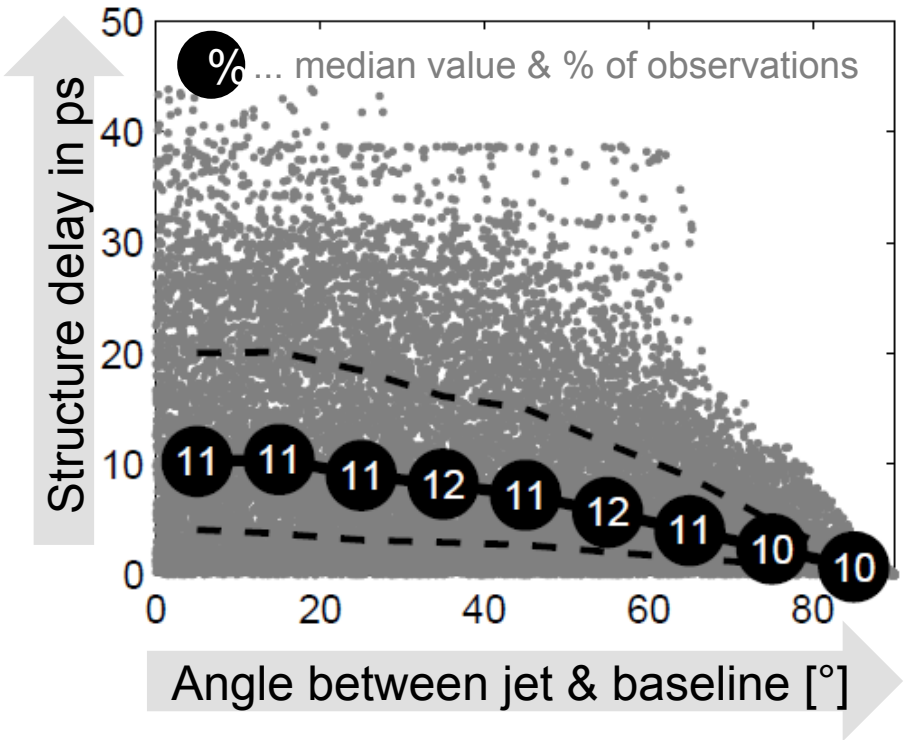


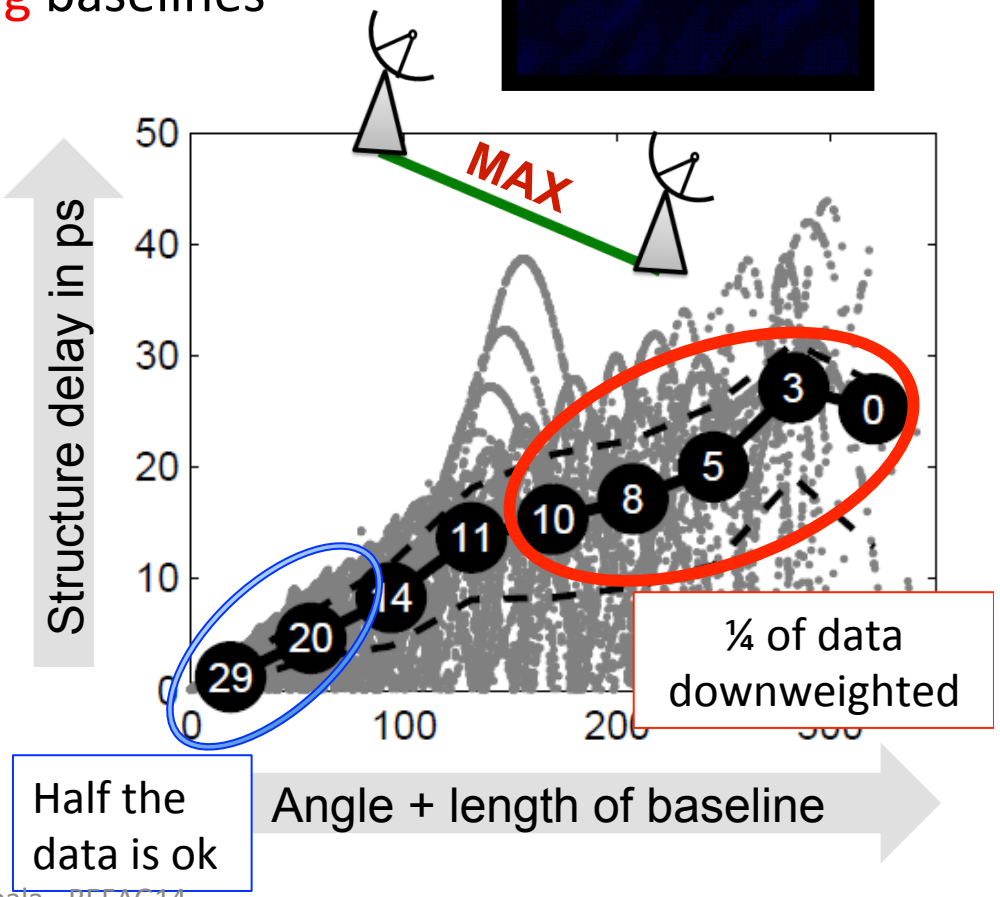
2. Re-analysis using source structure

- Jet direction is constant
- Worst case: perpendicular, long baselines



R1/R4 of Oct 2013, SI=3





2. Re-analysis using source structure

Simulation test

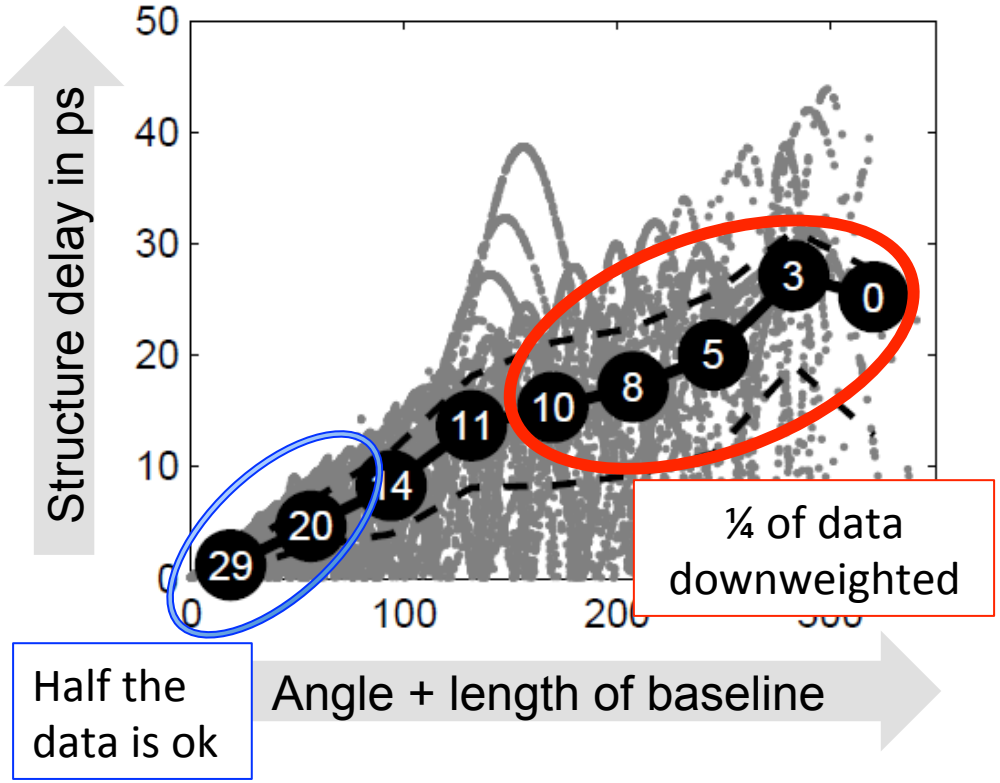
- Downweight 23% of observations
- Structure only simulations

Improvement

- Station positions by 22%
- Formal uncertainties by 30%

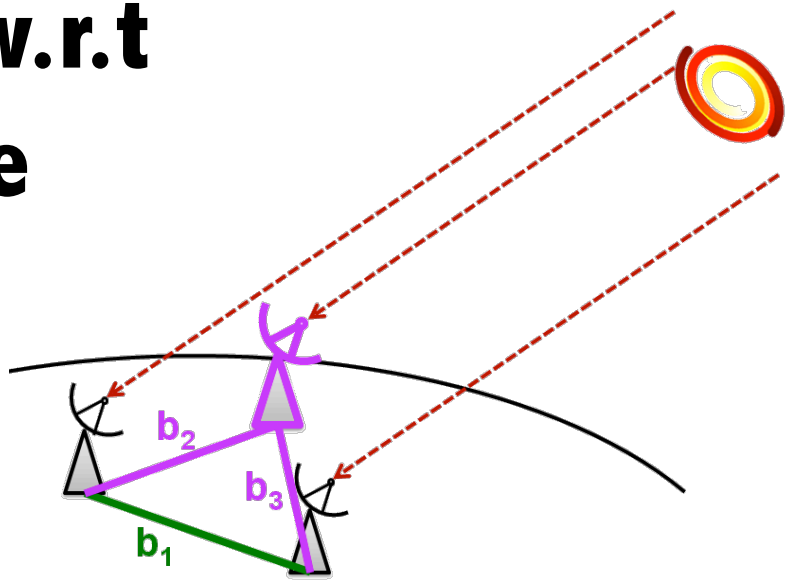
Problem

Need these observations to resolve troposphere !



SIMULATED

2. Re-scheduling w.r.t source structure



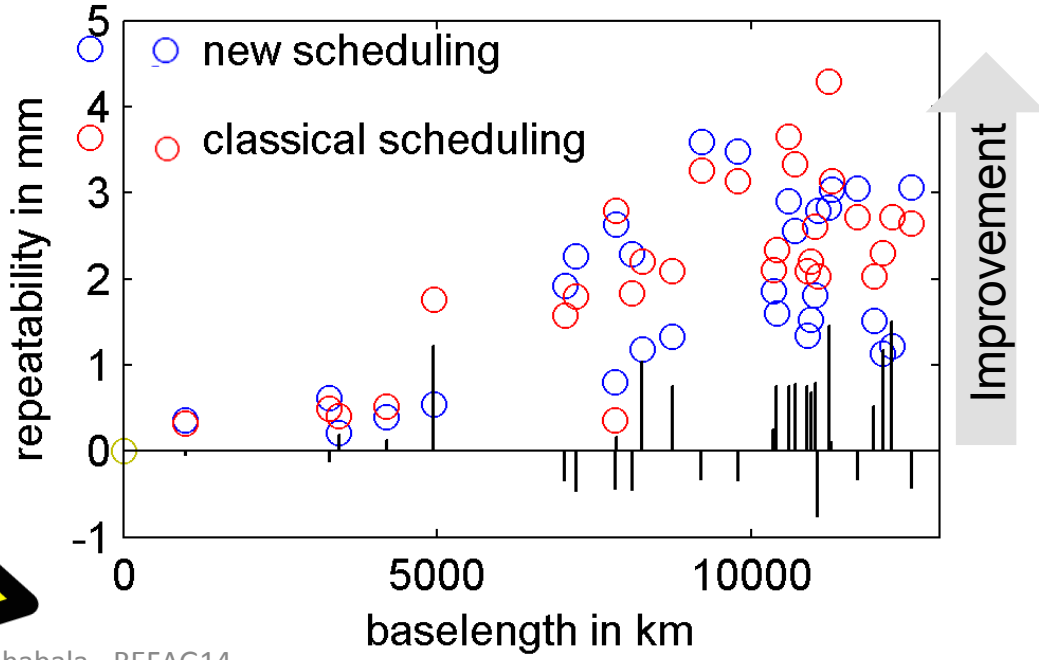
Scheduling

- Complex task
- Optimizing for max. number of scans, sky coverage, etc.

Strategy

- Schedule w.r.t. relative orientation and baseline length
- Simulate

R1/R4 (re-scheduled) of Oct 2013



First results appear promising

SIMULATED

3. Quasar evolution

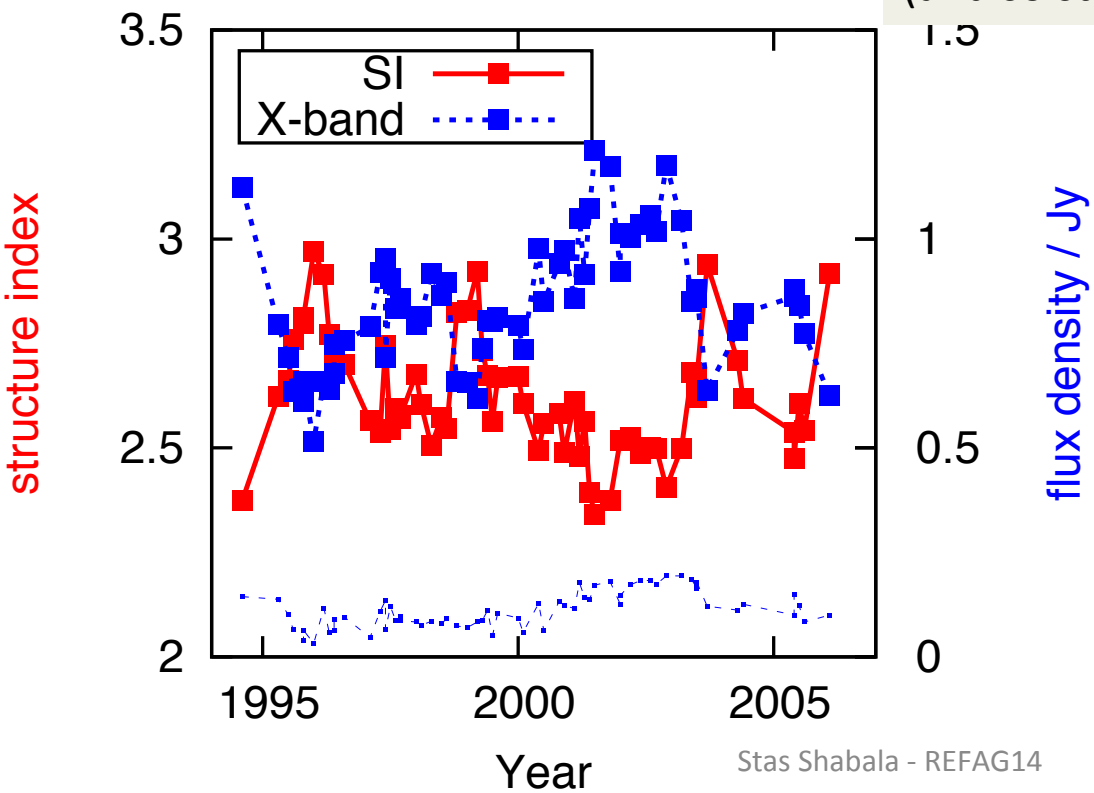
OBSERVED

! NEW !

- Structure anti-correlates with flux density

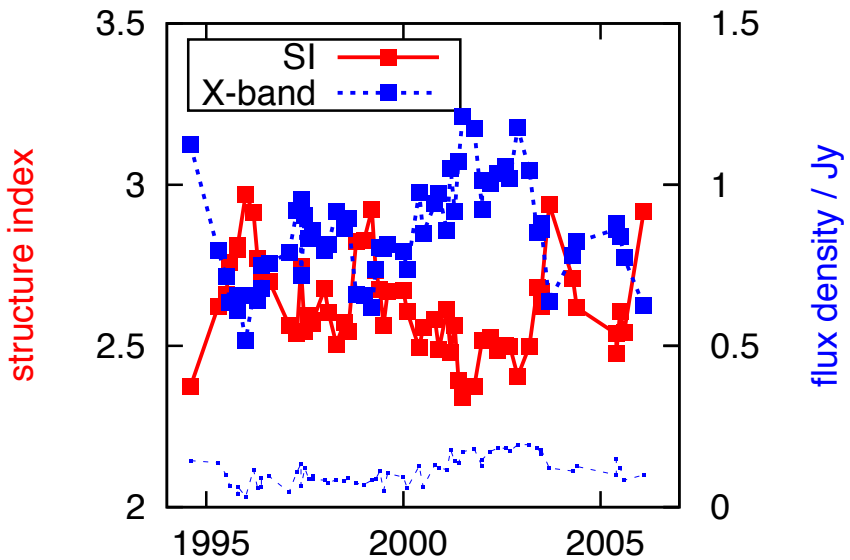
➔ Observe sources when flux density is high (and so structure is small)

Source 1357+769



3. Quasar evolution

OBSERVED



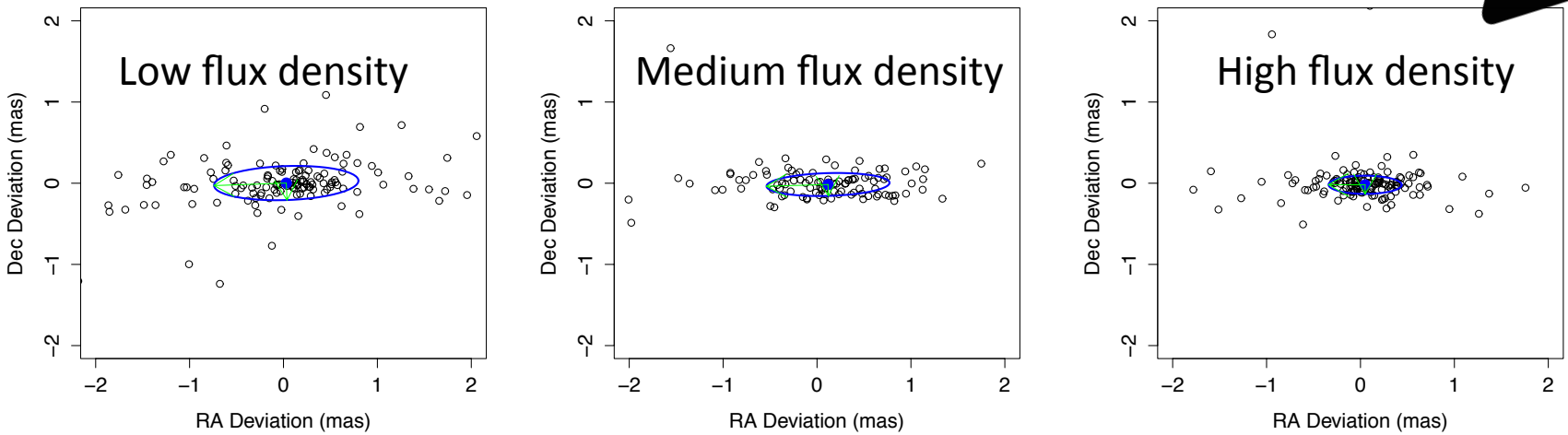
! NEW !

- 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



Summary

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

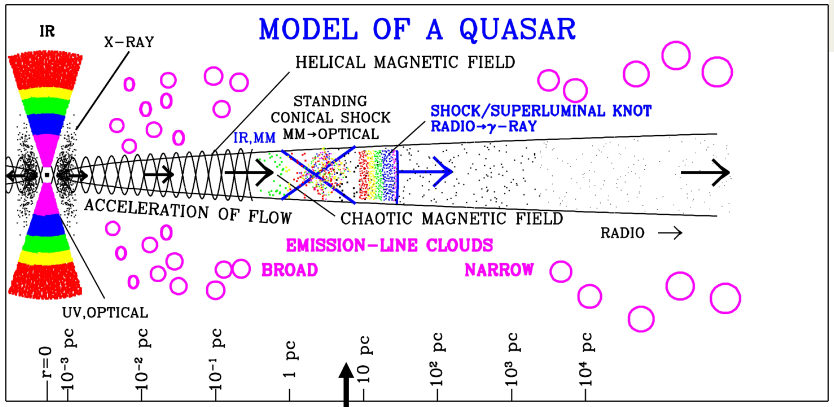
- **Quasar structure simulations** with *VieVS 2.2*
  - new source structure simulator module
  - mock + real quasar catalogues
  - station positions affected at mm level
  - troposphere dominates (for now)

- **Mitigation strategies**
  - corrections using source images in analysis
  - 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

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

Image: BU / A. Marscher



1 mas @ z=1

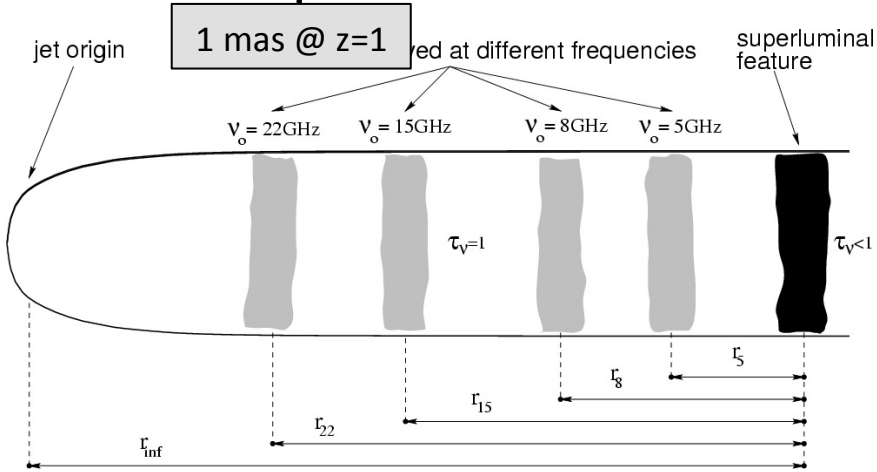
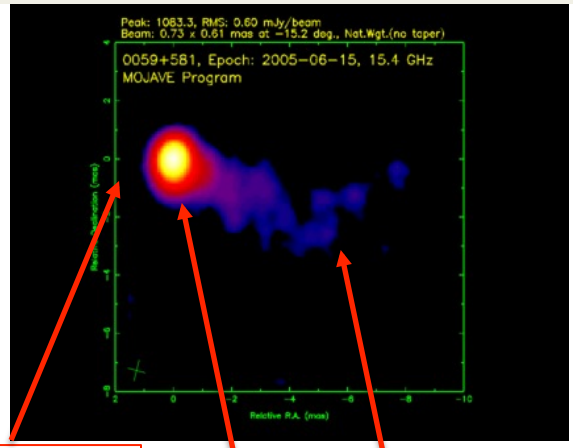


Image: Kovalev et al. (2008)



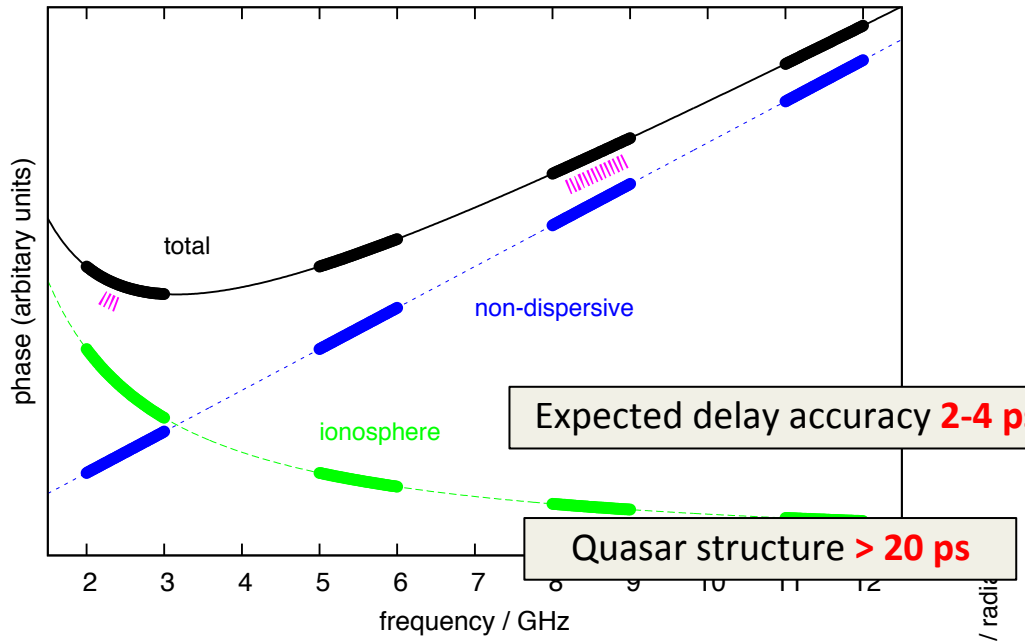
jet origin

core

jet

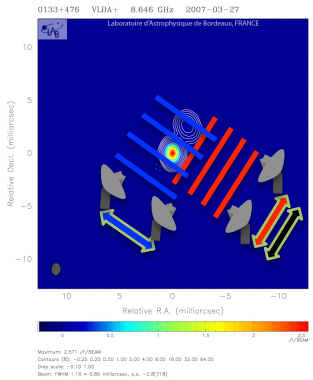
Synchrotron self-absorption
➔ core location depends on frequency
➔ **"Core Shift"**

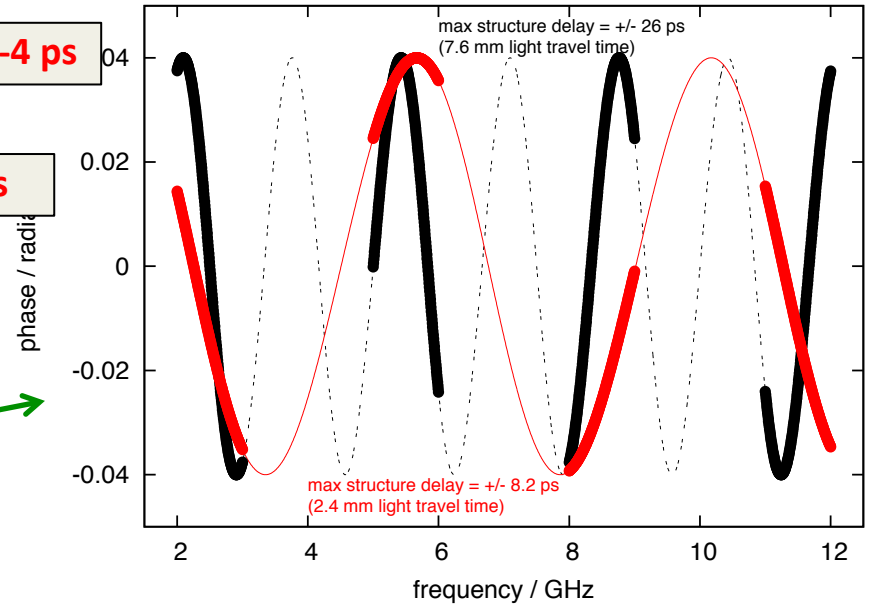
Quasar structure in VGOS



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

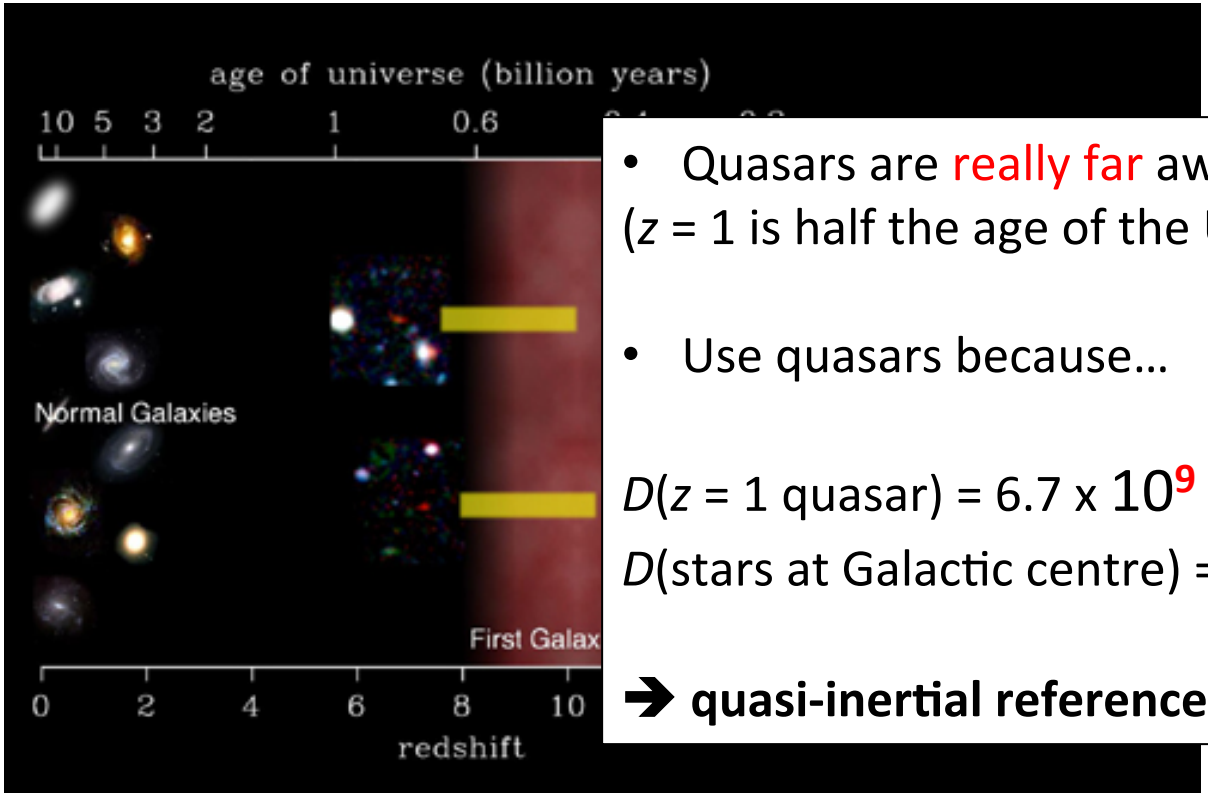
✧ Bright point sources

✧ 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)

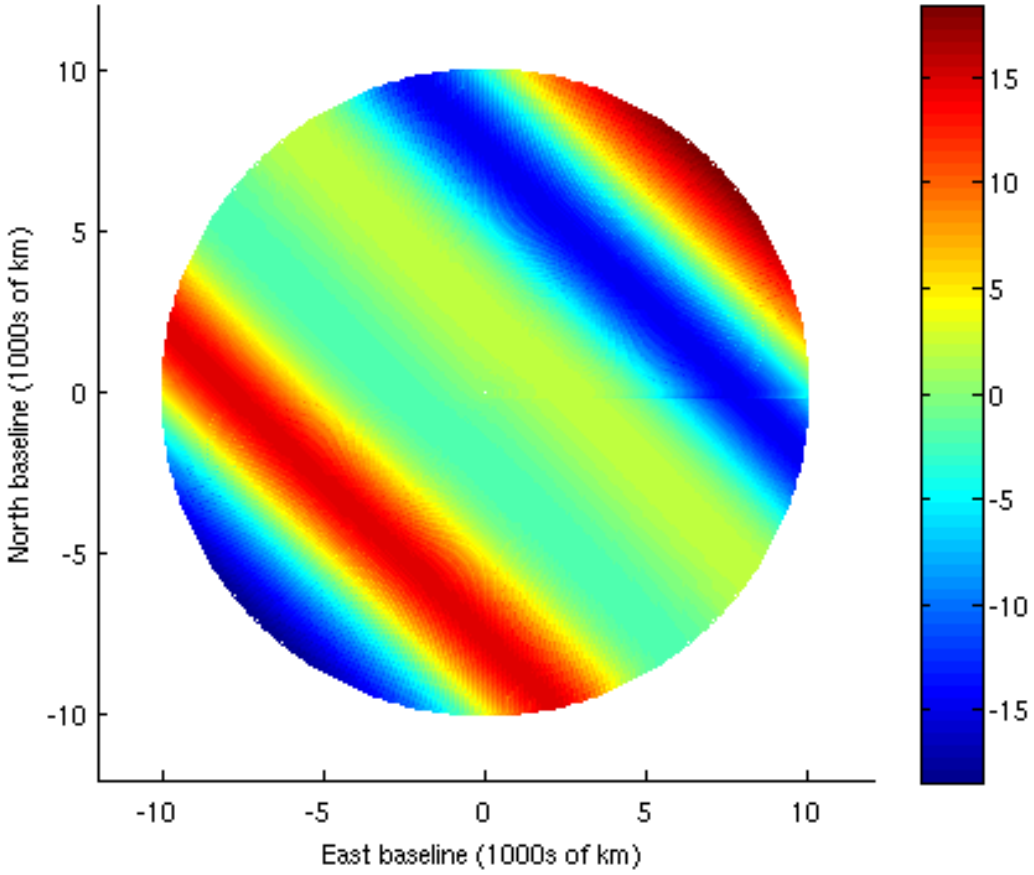
- Use quasars because…

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

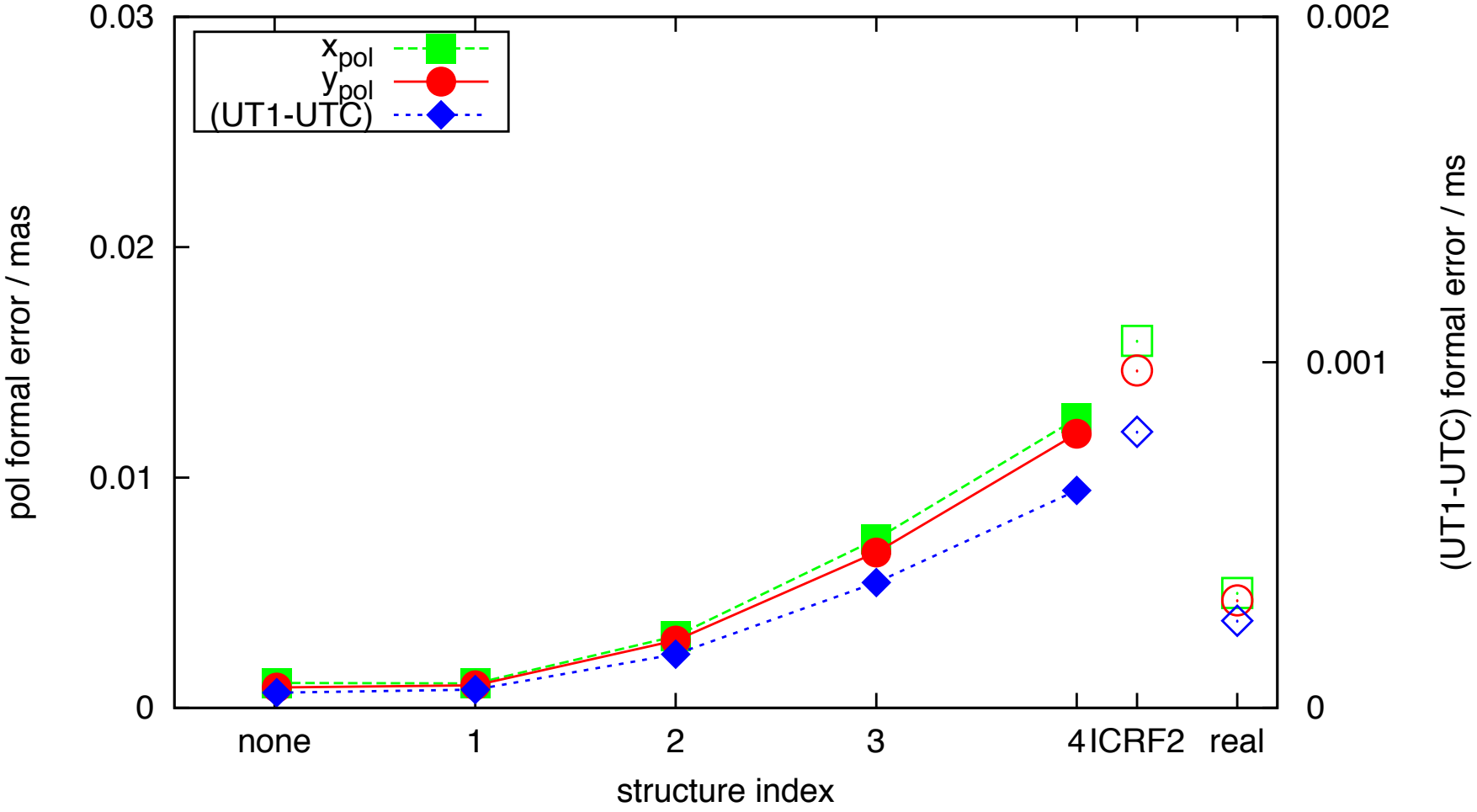
$D(\text{stars at Galactic centre}) = 8 \times 10^3$ pc

➔ **quasi-inertial reference frame**

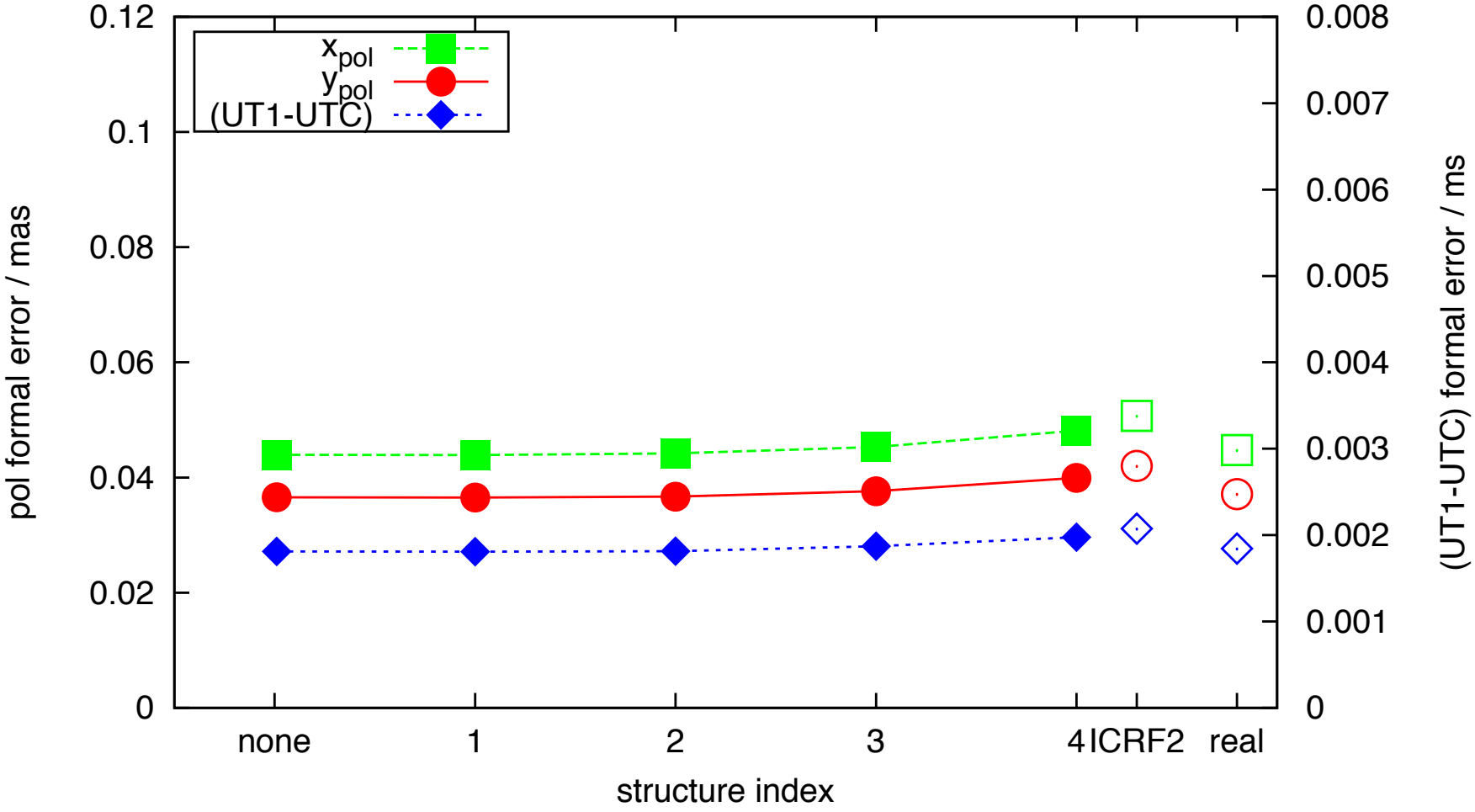
Structure delay (ps)



EOP formal error (structure only)

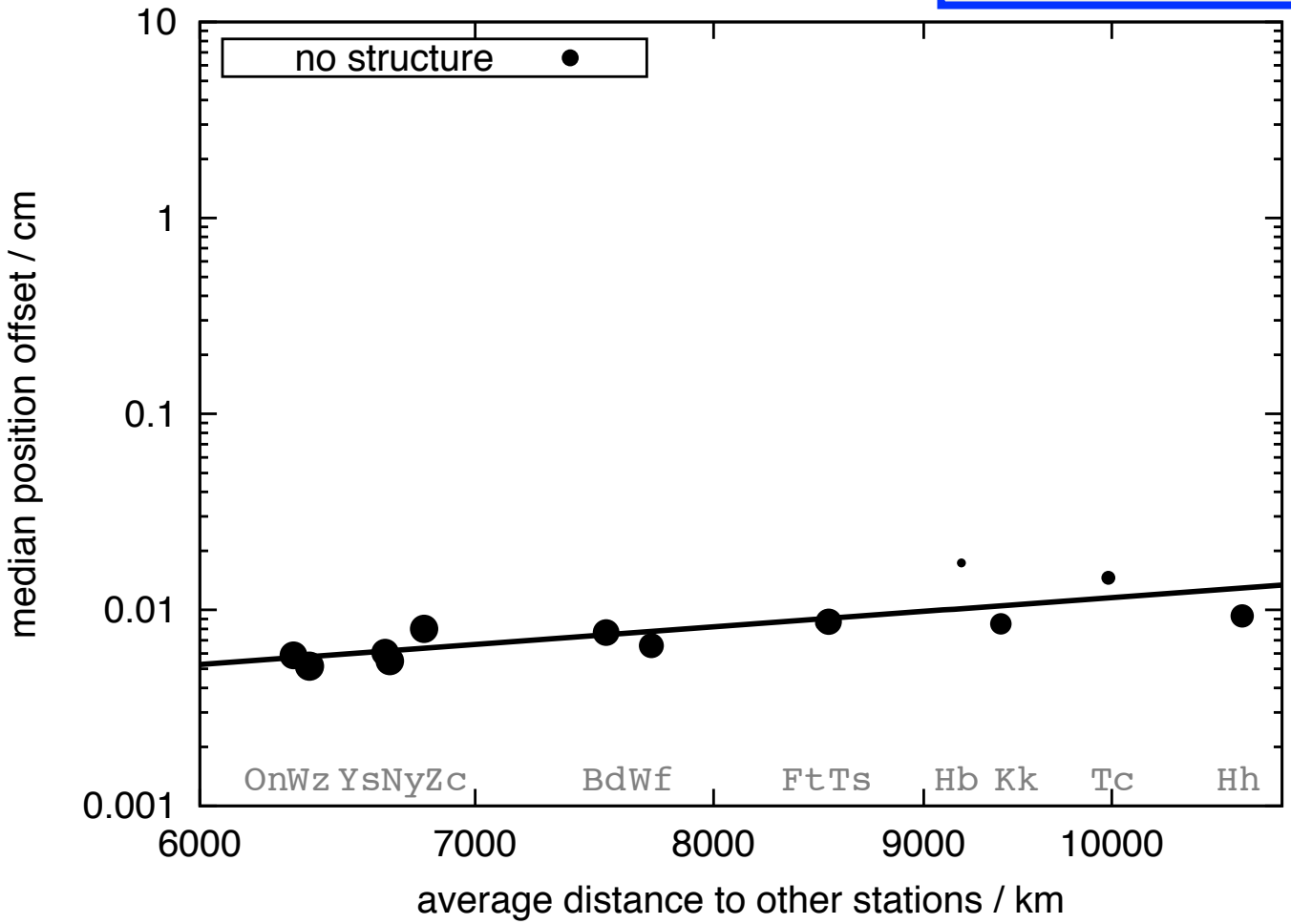


EOP formal error (with trop.)



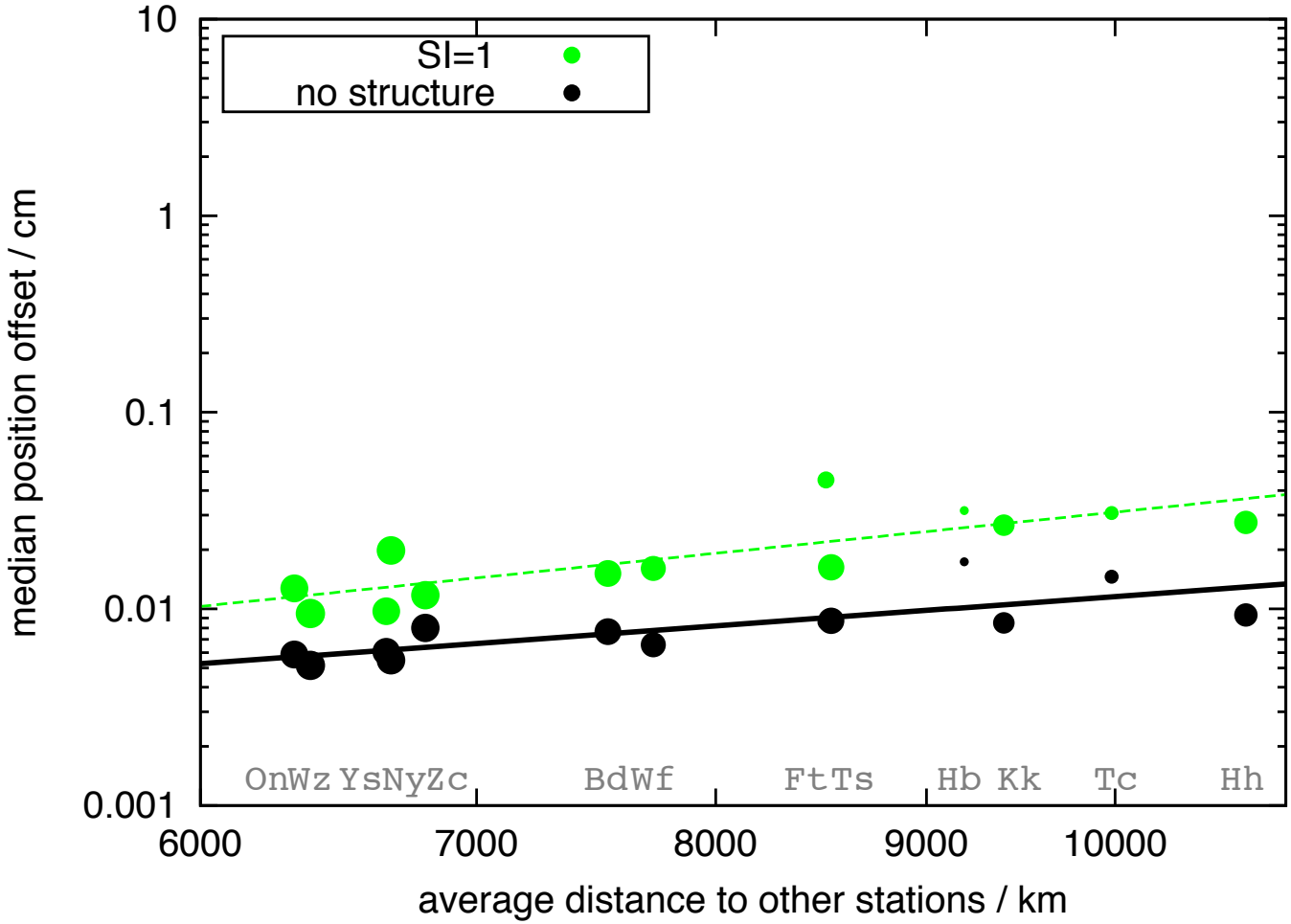
Median position offset

median of 15 x 30 realizations



Shabala+14, J. Geod. submitted

Median position offset



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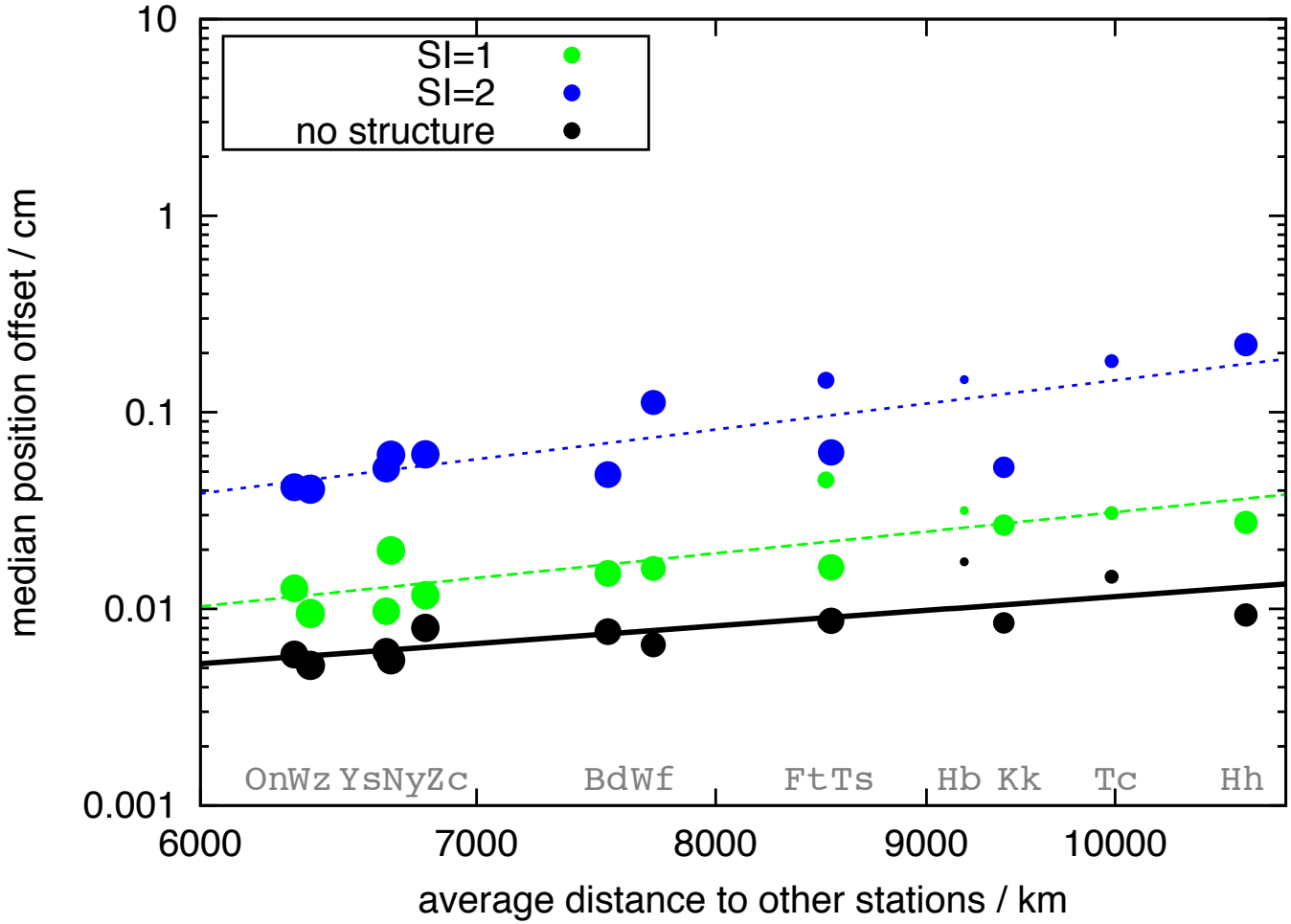

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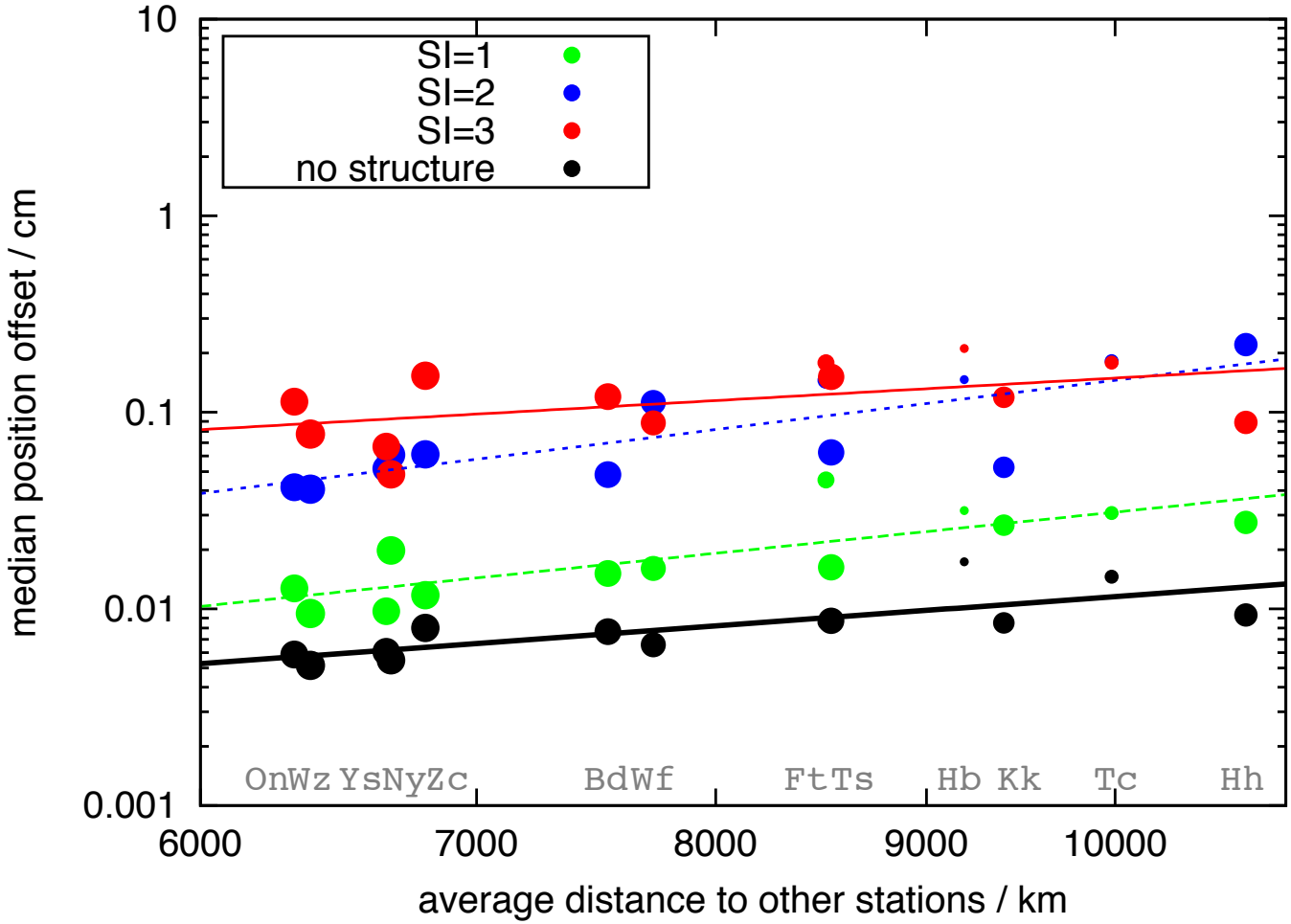

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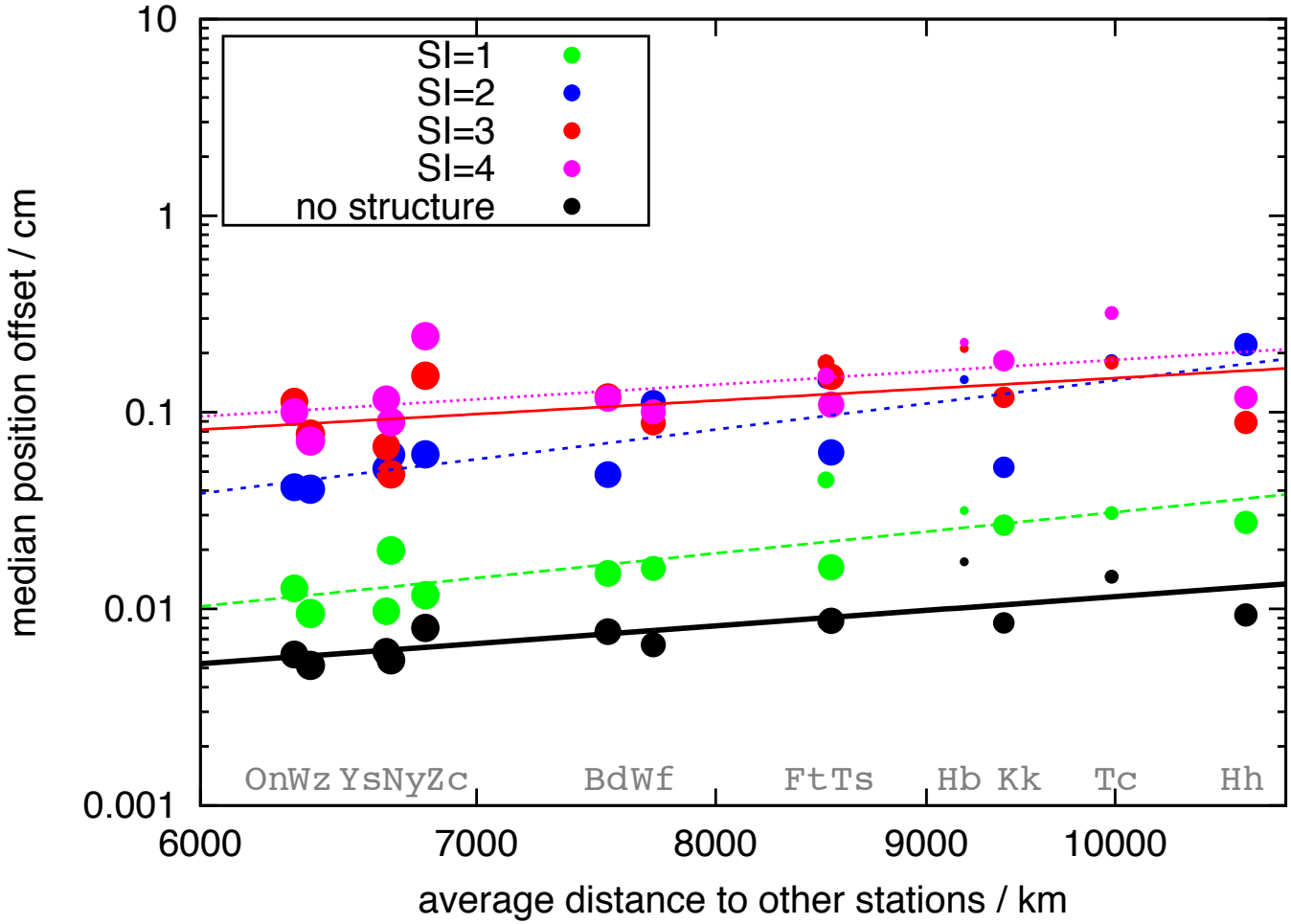

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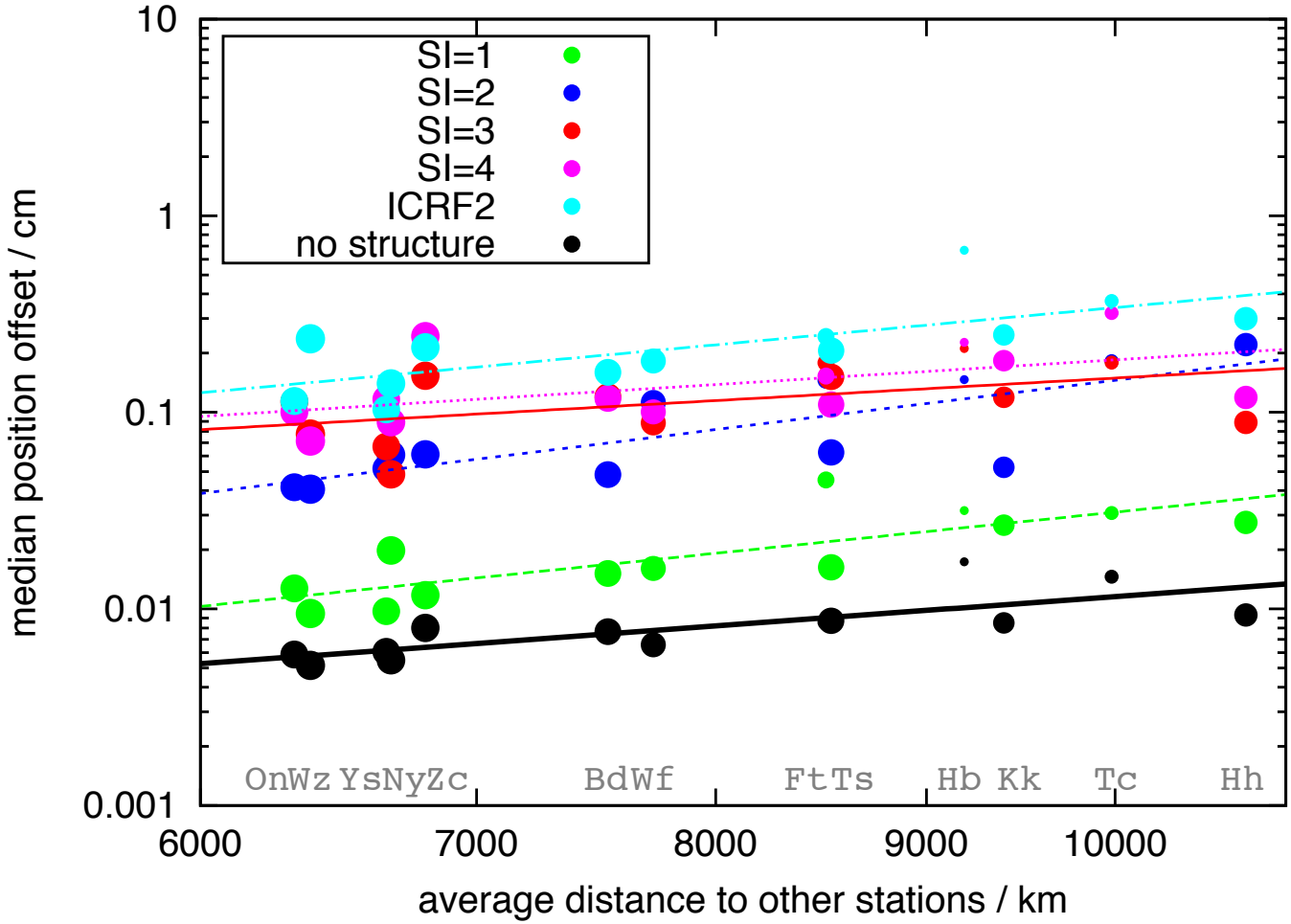

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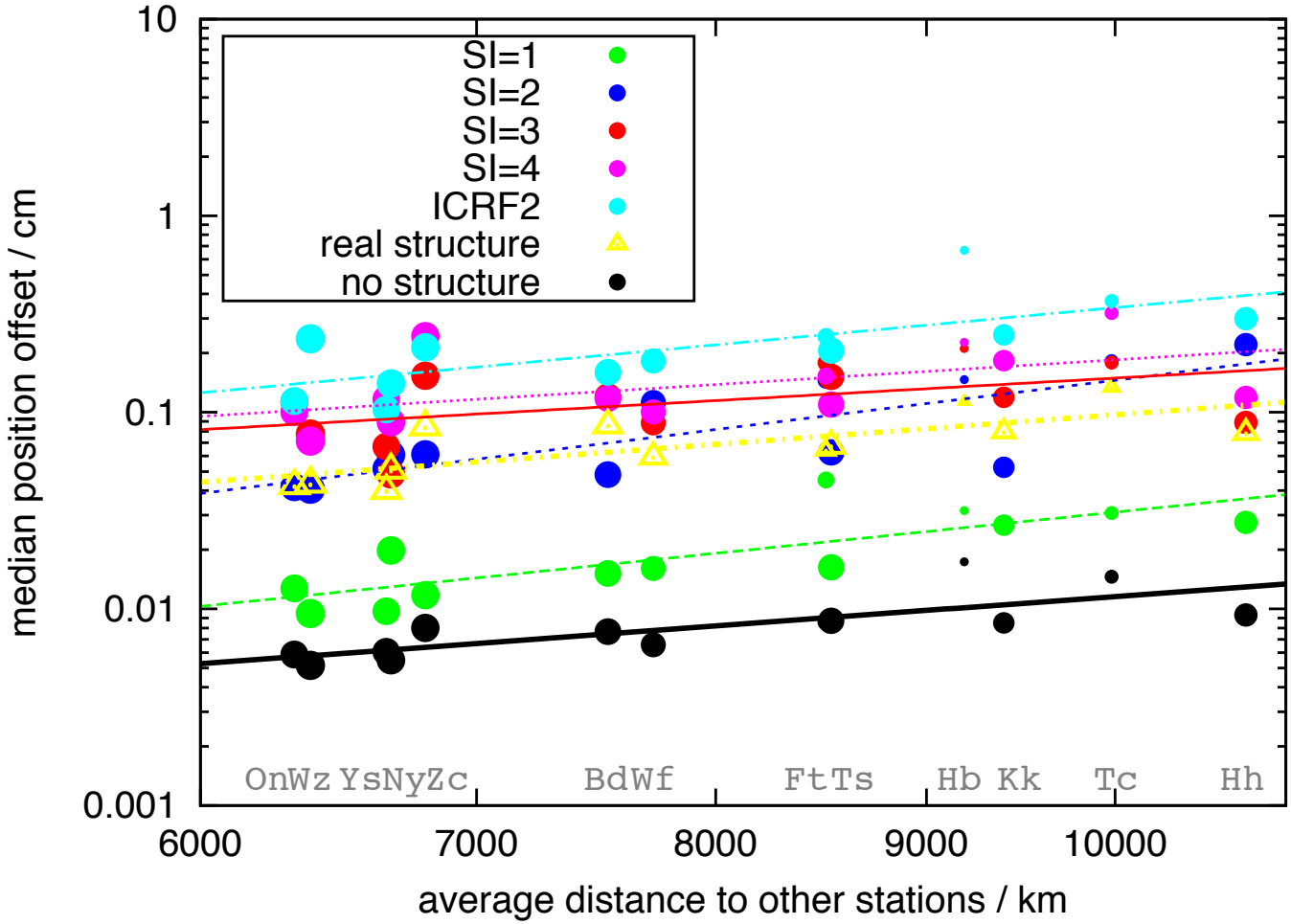

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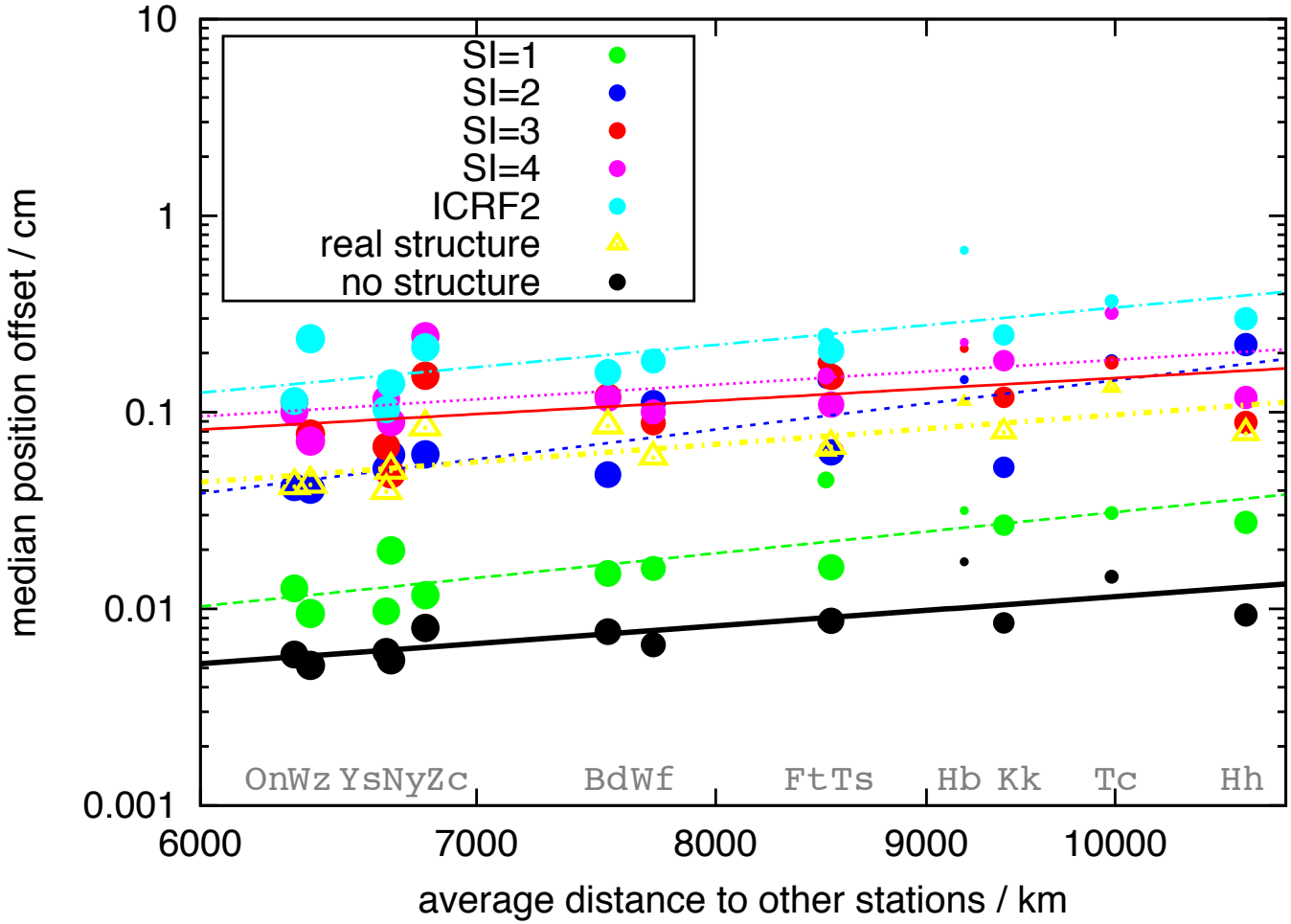

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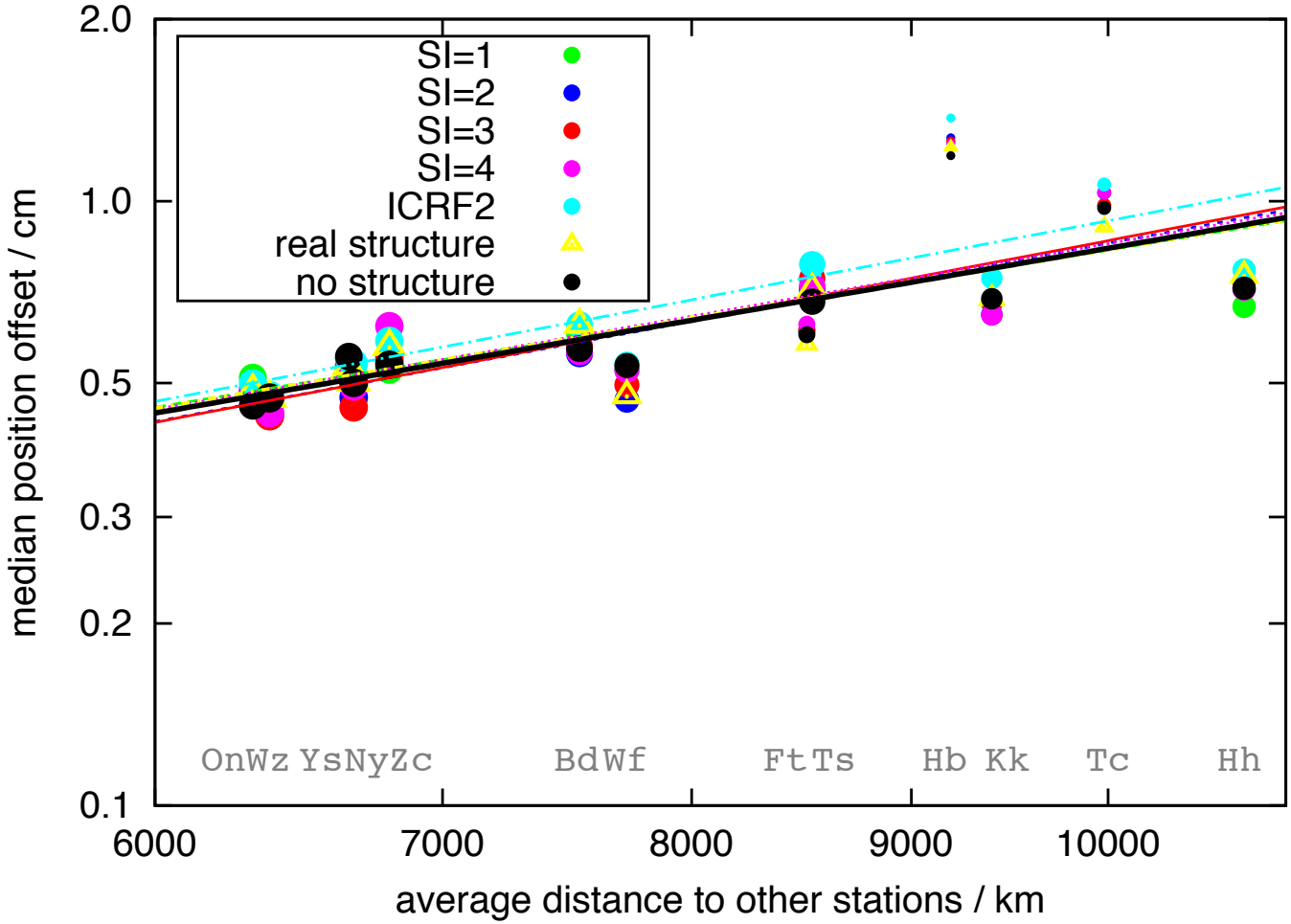

Shabala+14, J. Geod. submitted