Influence and detection of gravitational waves in Gaia-like astrometry

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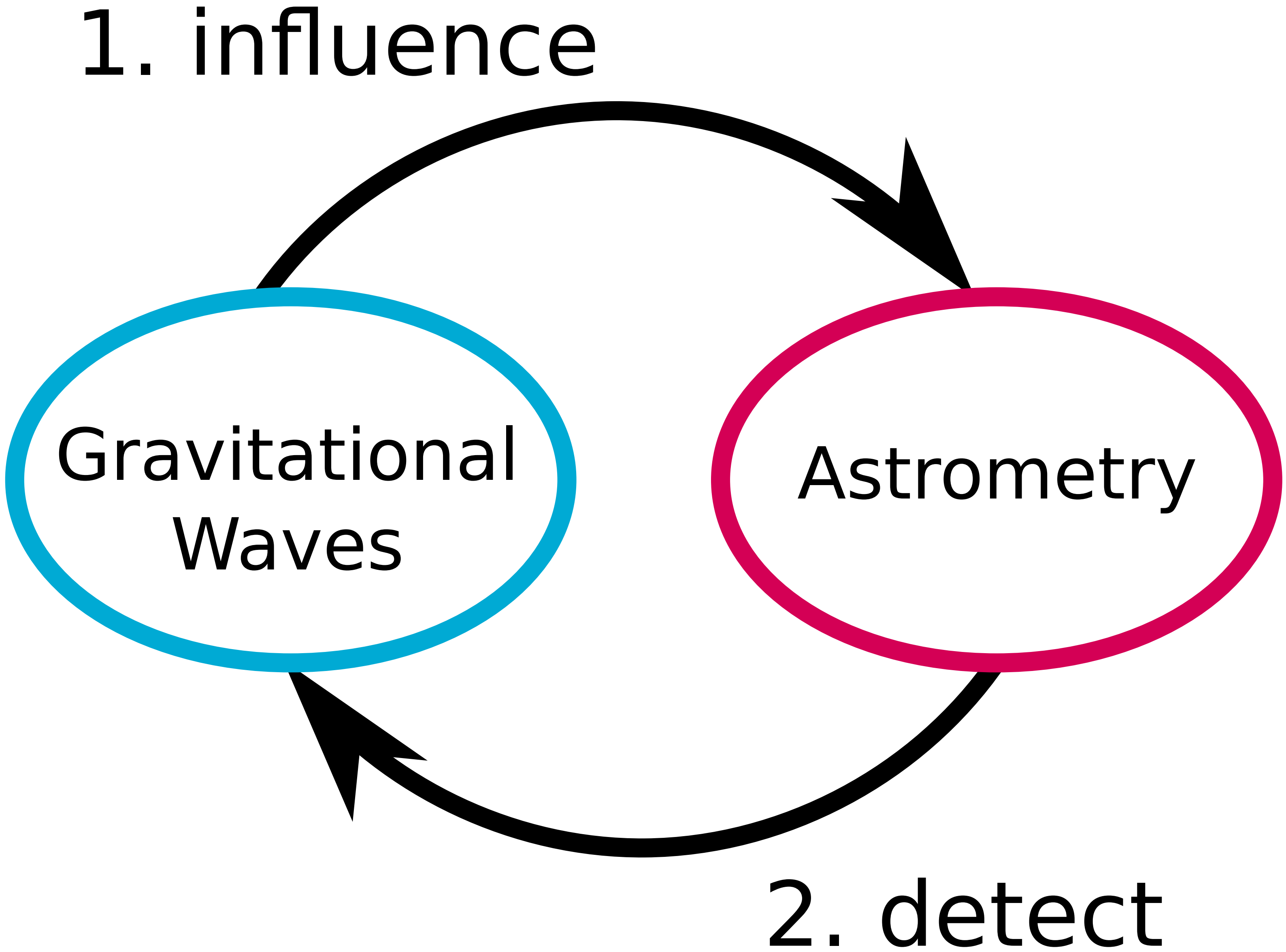
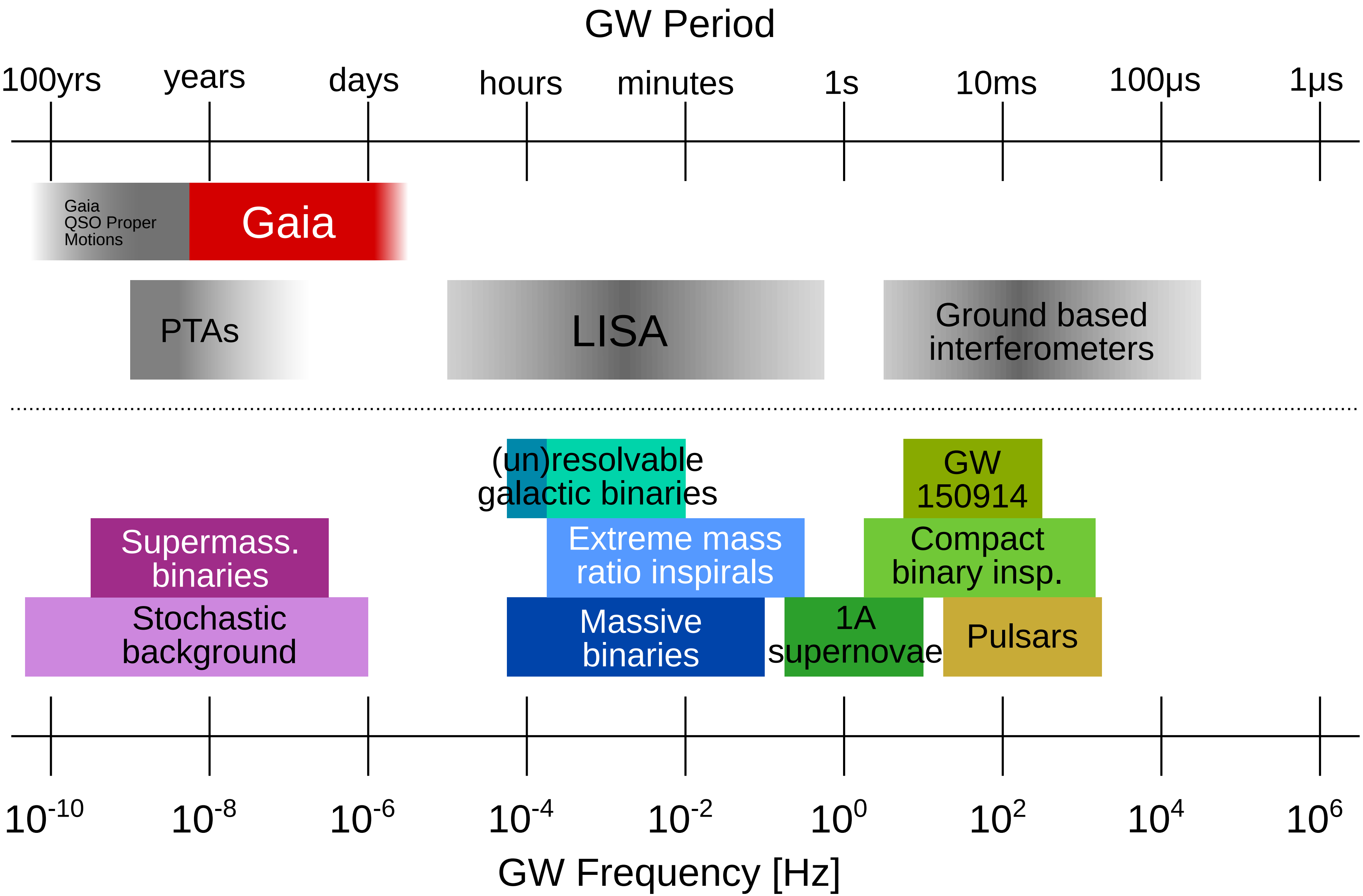

1. influence
Gravitational Waves
Astrometry
2. detect


GW Period
100yrs
years
days
hours
minutes
1s
10ms
100μs
1μs
Gaia
QSO Proper
Motions
Gaia
PTAs
LISA
Ground based
interferometers
(un)resolvable
galactic binaries
GW
150914
Supermass.
binaries
Extreme mass
ratio inspirals
Compact
binary insp.
Stochastic
background
Massive
binaries
1A
supernovae
Pulsars
10-10
10-8
10-6
10-4
10-2
100
102
104
106
GW Frequency [Hz]

1. how GWs influence Gaia-like astrometry

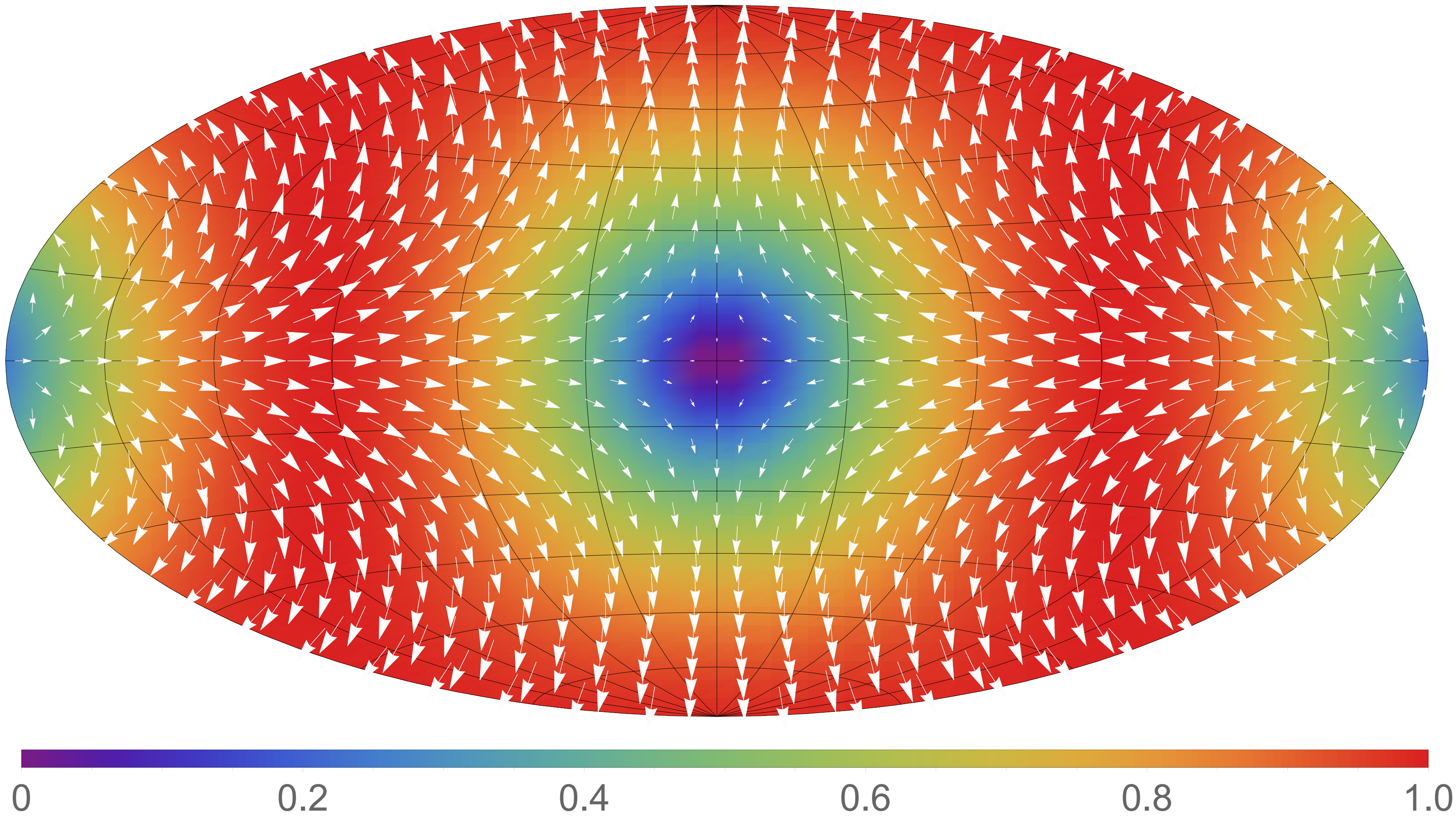
Intro I

Effect is long known, and has been described before: Pyne et al., 1996, Gwinn et al., 1997, Book et al., 2011 and Klioner, 2018.

GW passing through astrometric observer causes:

- a time-dependent,
- apparent shift in star positions,
- with magnitude and orientation of effect depending on
  - GW amplitude, frequency and polarization,
  - sky position of GW source and observed star,
  - and time (of observation).

Intro II



Effect on apparent star positions of +-polarized GW propagating towards center of sky-plot. Color code is magnitude of effect, normalized to maximum strength. The effect is time dependent, star position would "move along the vectors".

Astrometric GW Model I

One can write the GW model from Klioner, 2018 as:

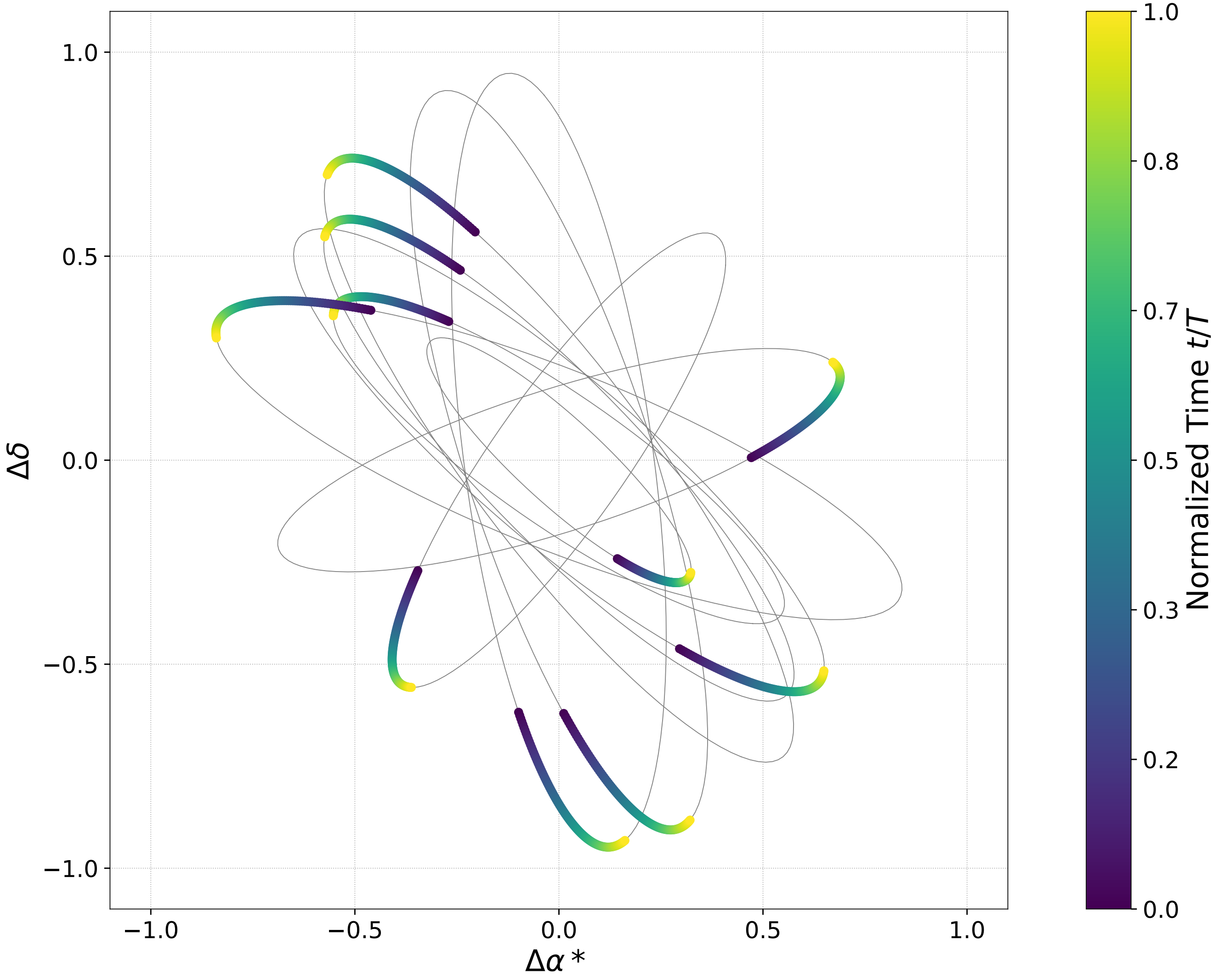
$$\begin{pmatrix} \Delta\alpha^* \\ \Delta\,\delta \end{pmatrix} = \begin{pmatrix} \delta\mathbf{u}\cdot\mathbf{e}_\alpha \\ \delta\mathbf{u}\cdot\mathbf{e}_\delta \end{pmatrix} = \mathbf{D}\,\begin{pmatrix} h_+^{\mathrm{s}}\sin\Phi + h_+^{\mathrm{c}}\cos\Phi \\ h_\times^{\mathrm{s}}\sin\Phi + h_\times^{\mathrm{c}}\cos\Phi \end{pmatrix}\,.$$

Where $\mathbf{D}$ is a rotation and scaling matrix, depending on observed sky position and GW direction $(\alpha_{\mathrm{GW}}, \delta_{\mathrm{GW}})$. Parameters $h_{+,\times}^{s,c}$ are 4 amplitudes, encoding also phase-shift, and $\Phi = 2\pi\nu_{\mathrm{GW}}t$.

$\Rightarrow$ **GW effect is an elliptical motion, with constant eccentricity, rotated and scaled depending on position on sky.**

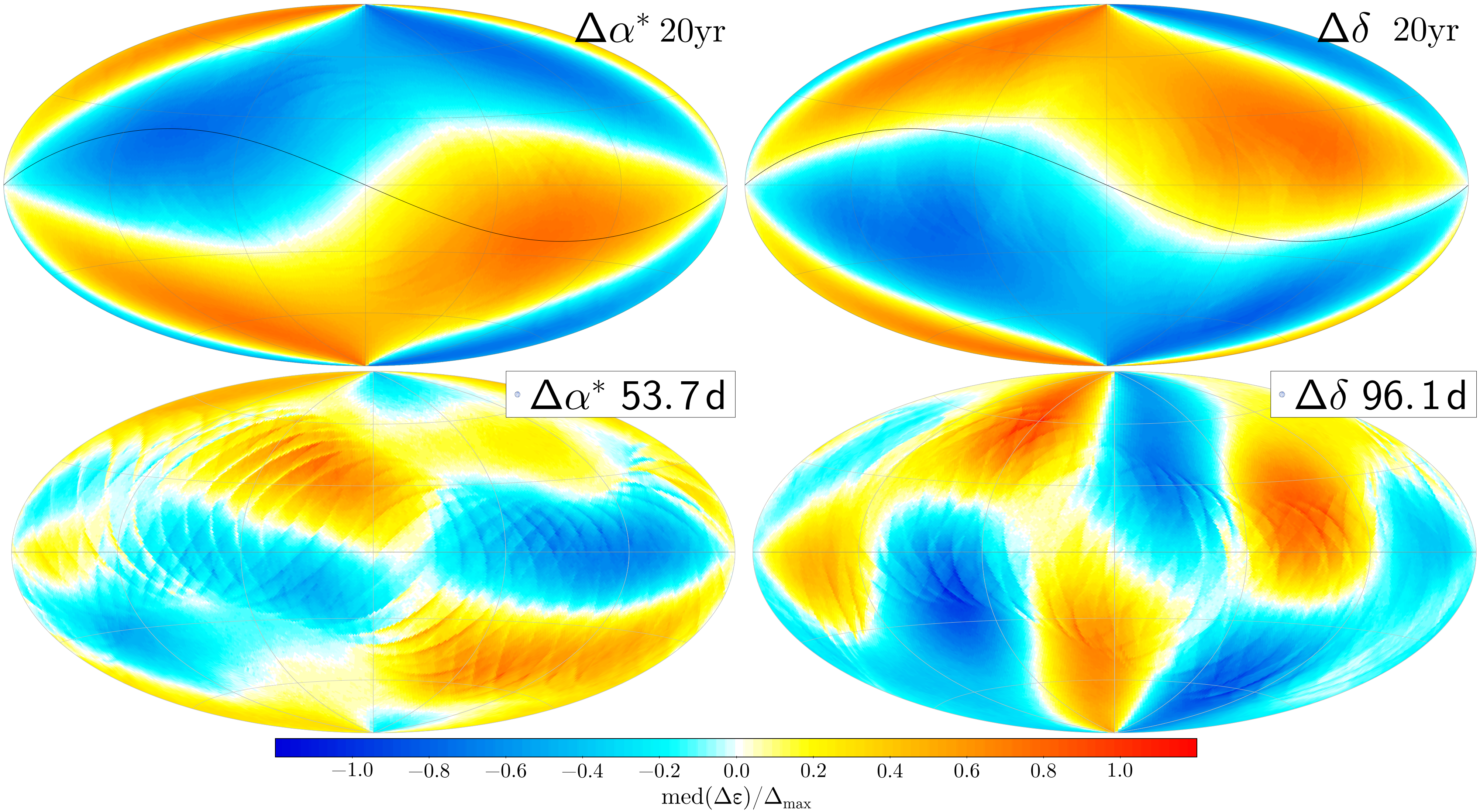
$\rightarrow$ Upcoming publication “Geyer, Klioner, et al. 2023”.

Astrometric GW Model II



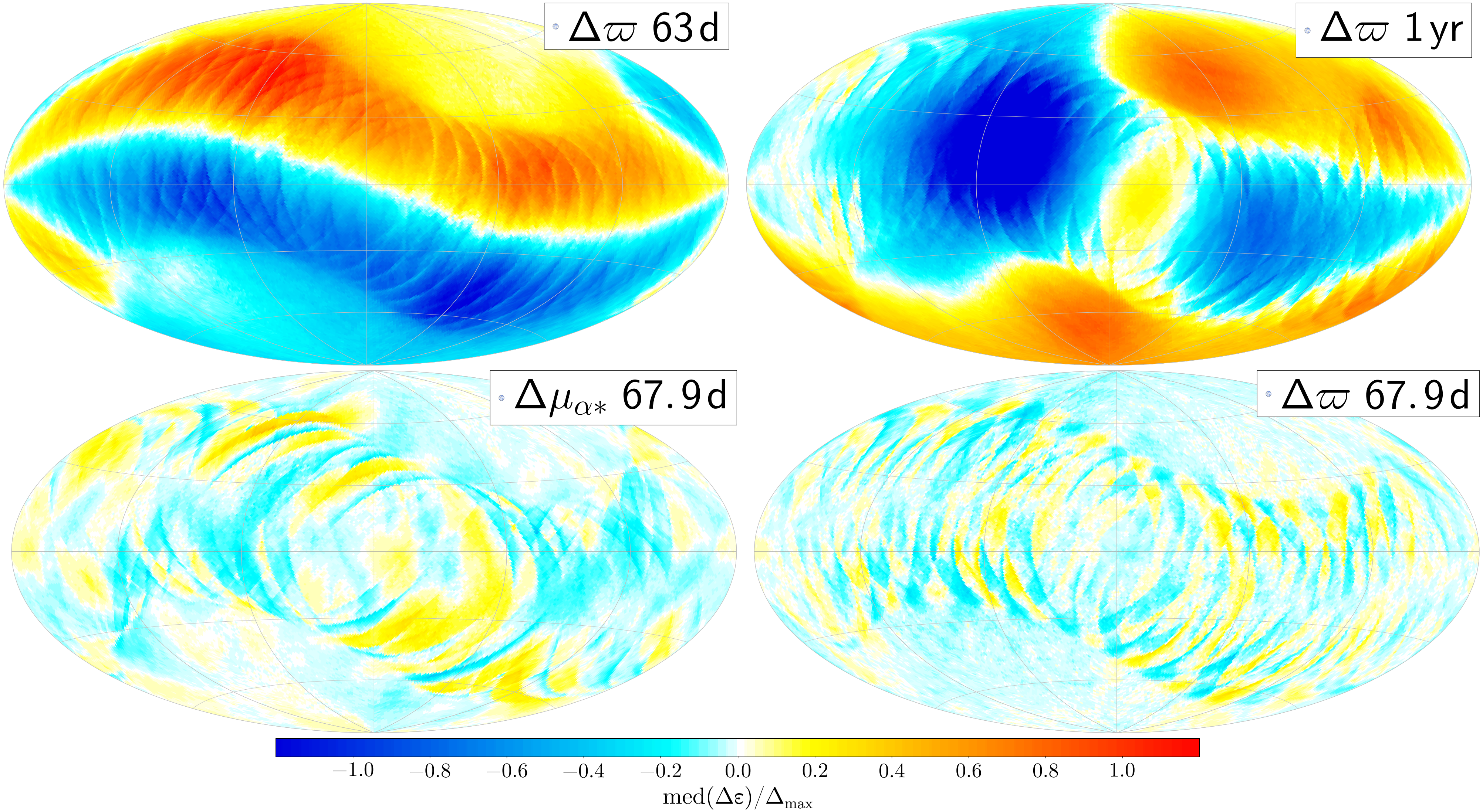
Examples of the positional changes due to a GW for 10 randomly selected astrometric sources are shown in their corresponding local tangential planes. GW period is 6T, gray lines show full motion.

Astrometric Effects I



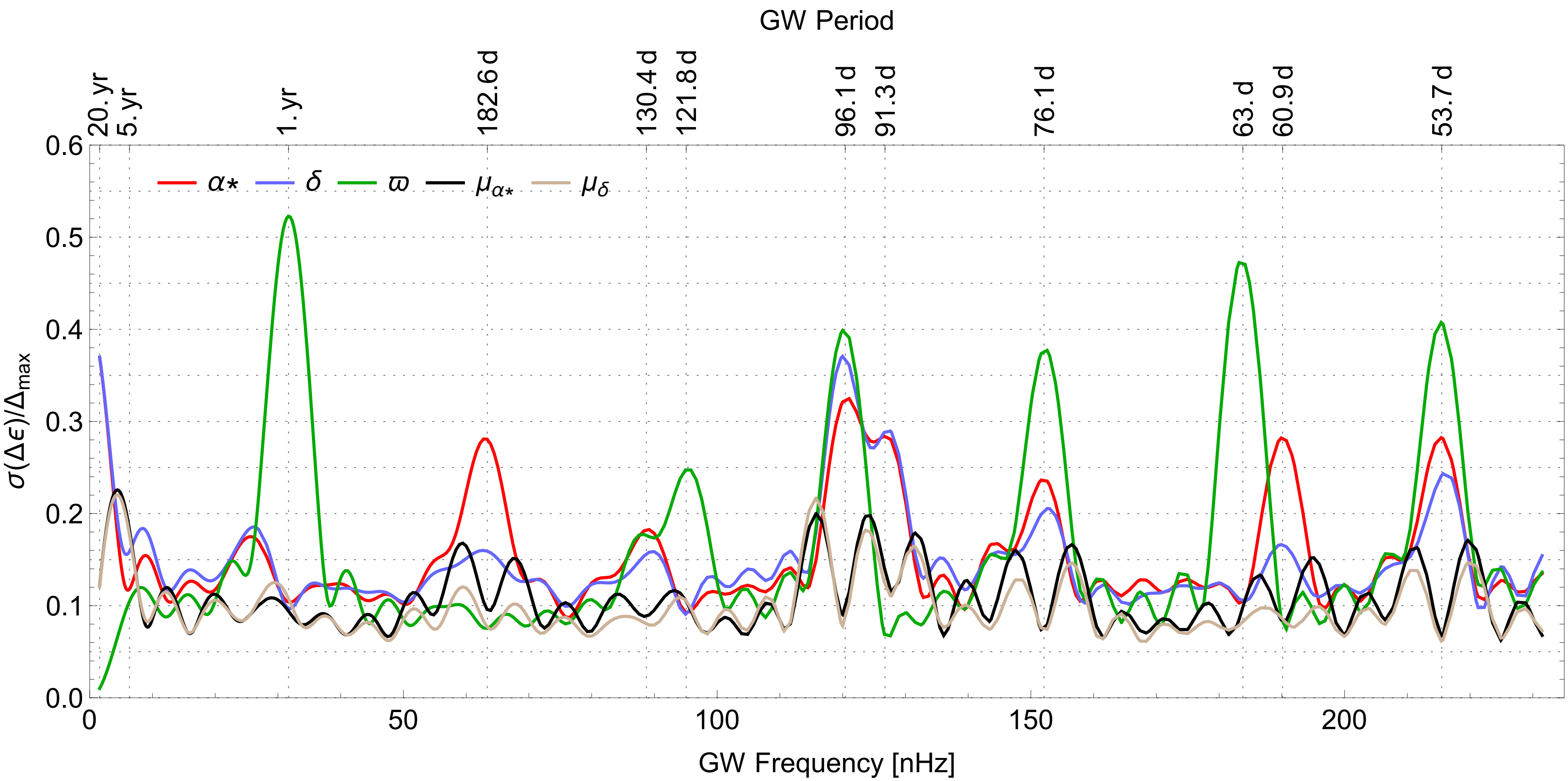
Simulated astrometric errors for Gaia mission, GW with all 4 amplitudes equal, GW direction to center.

Astrometric Effects II



Simulated astrometric errors for Gaia mission, GW with all 4 amplitudes equal, GW direction to center.

Astrometric Effects III



Typical magnitude of astrometric errors, normalized to GW amplitude, if GW is injected in a Gaia simulation.

Astrometric Effects IV

High astrometric errors are centered around

$$\nu_{k,l} = \frac{k}{1\,\mathrm{yr}} + \frac{l}{62.97\,\mathrm{d}}\ , \tag{1}$$

where k and l are integer numbers, and $62.97\,$d is the precession period of the scanning-law.

⇒ The fundamental frequencies of the scanning law, the visibilities, and scan direction of play a major role!

⇒ compare also with Gaia-like observations of binary stars (e.g. Holl et al., 2023 "*Gaia scan-angle-dependent signals and spurious periods*")

2. detection of GWs using Gaia-like astrometry

GW detection I

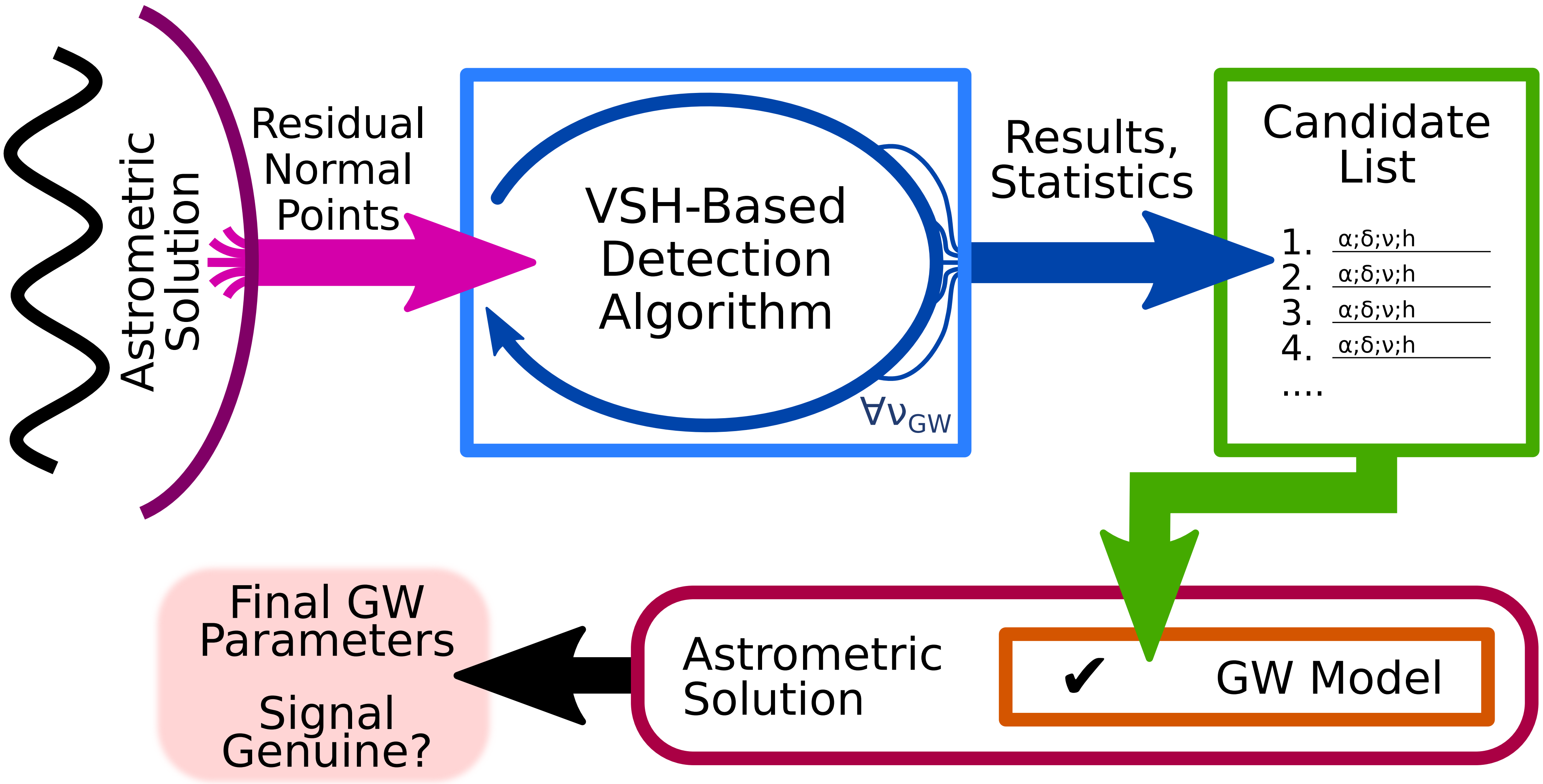
- GWs are not modeled in the astrometric solution:
  - non-linear problem, unknown start parameters
  - computationally very expensive
  - effect too small for individual observations
- If existent, **traces of GWs should be in astrometric residuals**.
- Considering reasonable astrophysical GW amplitudes, we search for:
  - individual, continuous GWs,
  - without frequency evolution (no inspiral),
  - in along-scan (AL) residuals (across-scan is absorbed by attitude determination),
  - using all AL residuals from complete mission time.

GW detection II

Challenges:

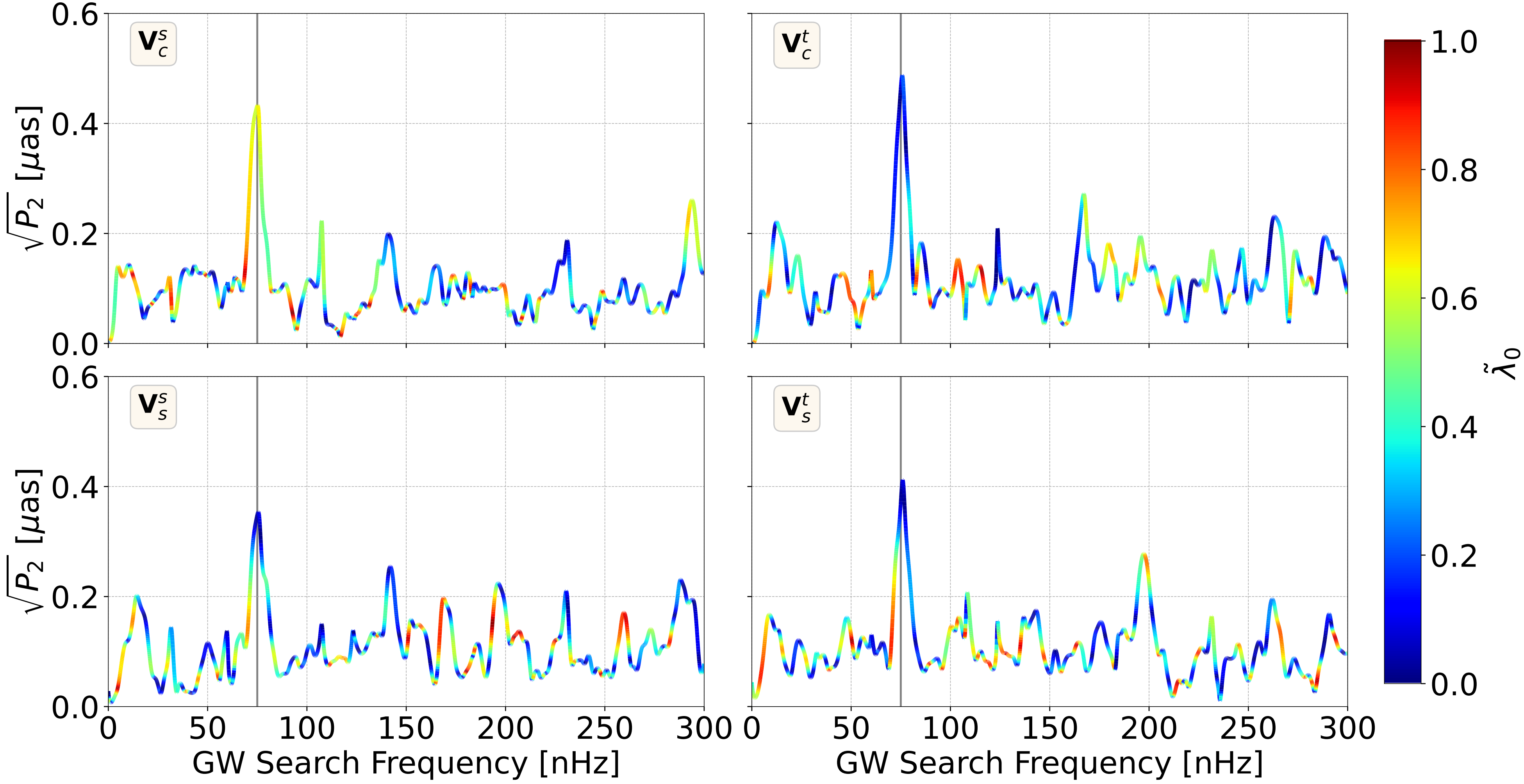
- observation direction and AL scan angle changes constantly
- only a fraction of GW signal can be measured, absorption by source parameter- and attitude determination
- enormous amount of data to process
- model w.r.t. ν_{GW}, α_{GW} and δ_{GW} is non-linear and values are unknown
  - no feasible way to determine such parameters in the astrometric core solution
  - full sampling of ν_{GW}, α_{GW} and δ_{GW} parameter space is too expensive

GW detection III



VSH = Vector Spherical Harmonics

GW detection IV



Simulated GW search results for all 4 components of our VSH model, at $\ell = 2$ (quadrupole). Signal at 75 nHz, at 5σ detection limit compared to noise. GW signal should have normalized minimal eigenvalue of quadrupole-matrix $\tilde{\lambda}_0 = 0$.

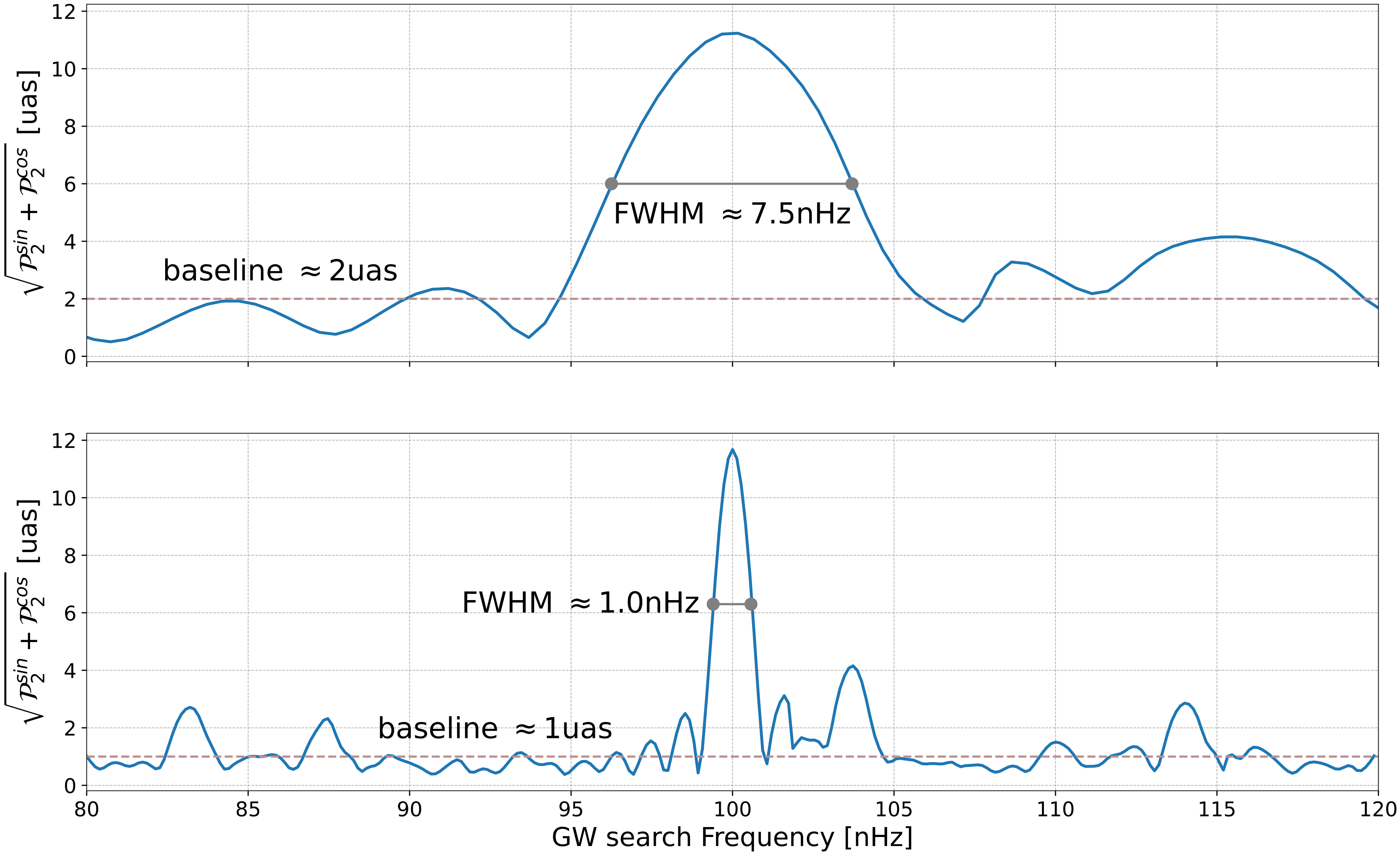
GW detection V

Results from simulations:

- successful recovery of GW parameters with good accuracy
- slight (30%) dependence of sensitivity on GW source direction
- at some GW frequencies, related to fundamental frequencies of the scanning-law: lower sensitivity, higher astrometric errors
- estimate for strain sensitivity using Gaia data (e.g. DR3): not better than 9-20 nas $\approx 10^{-14}$ rad

3. GWs and GaiaNIR

GaiaNIR I



Example: Simulated GW detection for signal at $\nu_{\mathrm{GW}} = 100\,$nHz injected in both Gaia (top) and Gaia + GaiaNIR (bottom) data. 5 yrs mission each, 30 yrs dead-time in between.

GaiaNIR II

- accuracy of GW detection will improve much more than just doubling observation time
- temporal "baseline" of tens of years offers strict constrains on phase- and frequency stability
- BUT: will most probably require modeling of frequency evolution due to inspiral

It's straightforward, right?

Things I did not talk about

- calibrating systematic instrument effects
- filtering effects caused by "resonances" with scanning-law
- testing for GWs from specific fixed sources, template-matching
- candidate selection and modeling in full astrometric solution
- Bayesian formulation of the problem
- search in basic-angle signals, not residuals

Conclusion

- GWs introduce systematic errors in astrometric solution
- given recent findings from PTAs (Antoniadis et al., 2023): GW effects possibly non-negligible if precision is increased $10\times$ – $100\times$
- Gaia-like astrometry can be used to detect GWs, provided GW amplitudes are large enough
- Gaia-like missions can give an upper limit estimate for GWs with periods from years to tens of days in any case