Limits:

Surface Structure, Microlensing, Binarity

U. Bastian, H. Hefele

updated version of Nov. 4, 2004 (a few errors removed)

Instead of an Introduction:

Motto of this talk:
One person‘s signal is another person‘s noise !

- Gaia‘s central astrometric goal:
  Measuring parallaxes and space velocities.

- Gaia‘s major limitation:
  The technical measurement noise.

- But there are also astronomical noise sources,
  i.e. genuine fluctuations in star positions.

Remarks on the previous page :

Goals:

- Measuring parallaxes for the size and luminosity calibration of stars and for the cosmic distance scale.
- Measuring space velocities for the structure and evolution of the Galaxy.

Measurement noise:

Determined by the size of the optics, the mission duration, the brightness of the optics, efficiency of detectors, data reduction procedures etc.

Genuine position fluctuations:

Detecting and measuring these fluctuations constitutes an important part of Gaia‘s scientific motivation and outputs.

But viewed from the basic goal of measuring star parallaxes and space velocities in our Galaxy, these disturbances are just noise, which may limit the ultimately reachable precision of the target quantities. And indeed, in some circumstances they may become really disturbing, as we will see.

Let us note that the astrometric fluctuations will frequently be accompanied by photometric ones, which will give clues to the cause of the noise.

Different nature of the disturbing effects:

Parallax:

Anything that can be interpreted as a Fourier component at 1 year period (and at the correct phase and position angle aspect ratio). It is not needed that the true motion has a component at that frequency, due to the convolution of the true motion's Fourier spectrum with the strange window function caused by Gaia's scanning law.
Of course, the truly 1-year-periodic motions are the most dangerous.

Space velocity:

Anything that mimics a mean motion over the mission duration. In other words, anything that gives a zero-frequency component after convolution with the window function.
Again, the truly constant motions give the biggest effect.

Three major categories of effects:

1. Surface structure of observed objects
   a) Convection (granulation)
   b) Star spots etc.
   c) asymmetric shape and albedo of asteroids

2. Gravitational lensing

3. Stellar multiplicity (including planetary systems)

4. Others?

Let us try to get a feeling for the significance of these effects for Gaia !

Remarks on the previous page:

All three categories of effects produce photometric as well as astrometric disturbances. This talk will concentrate on the astrometric ones.

I said “a feeling” rather than “a quantitative assessment” because simply giving median or an rms value would be misleading. The size distribution of the angular disturbances does not fall off steeply at large values.

At 5 sigma a Gaussian integral has about 10^{-7} remaining cases (i.e. ~100 stars for Gaia), but our \mu^-4 distribution has 0.15 percent (i.e. ~1.5 million stars for Gaia) in its tail beyond 5 rms.

Sizes of effects:

at 1 kpc:	1 au	=	1000 μas	=	100 percent of parallax
	10 mau	=	10 μas	=	1 percent of parallax
	1 au/5 yr	=	200 μas/yr	=	1 km/s
	10 mau/5 yr	=	2 μas/yr	=	10 m/s
at 10 kpc:	1 au	=	100 μas	=	100 percent of parallax
	10 mau	=	1 μas	=	1 percent of parallax
	1 au/5 yr	=	20 μas/yr	=	1 km/s
	10 mau/5 yr	=	0.2 μas/yr	=	10 m/s

Remarks on the previous page:

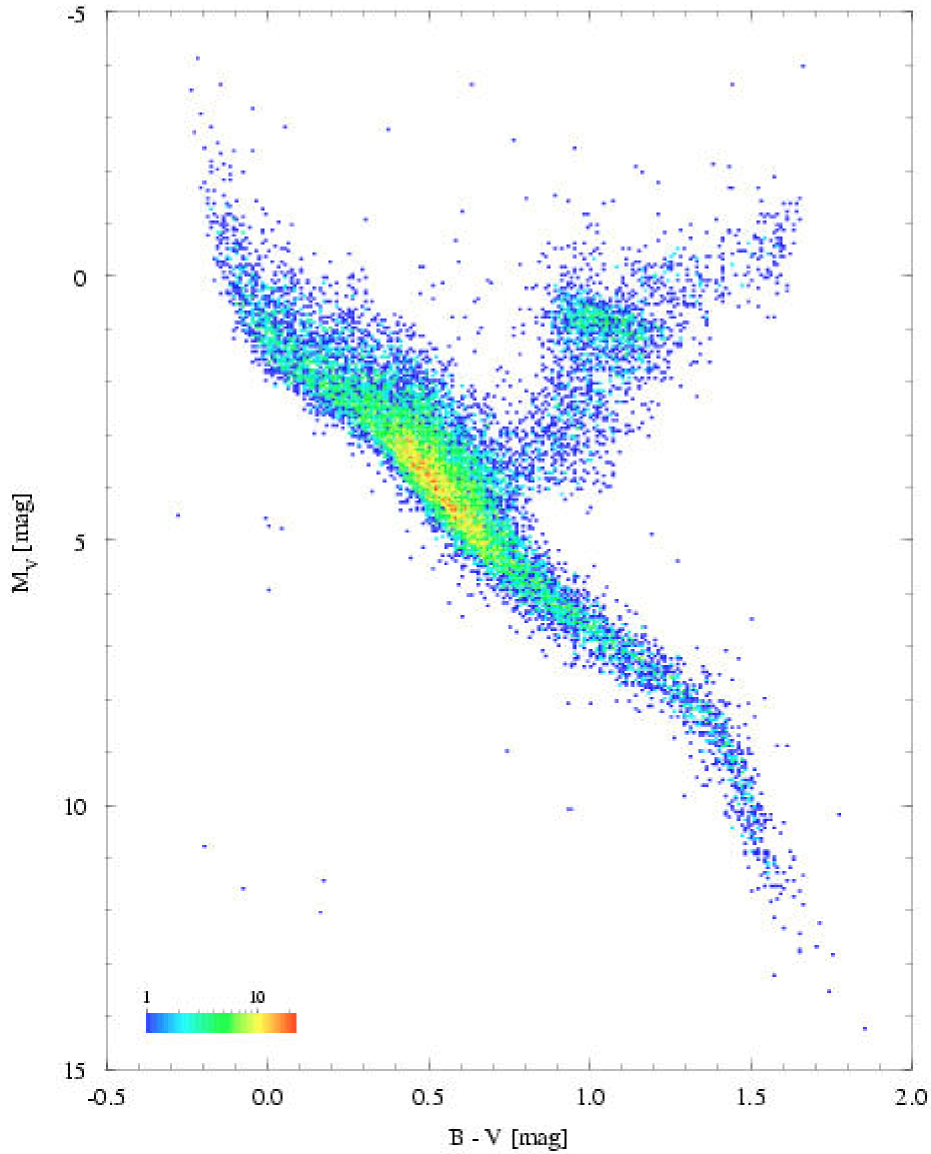
Most analyses presented in the following are based on the “Gaia1” design, 1998-2002, with 3-hour rotation period and two separate Astro telescopes and focal planes.
The new design “Gaia2”, 2002ff, with 6-hour rotation period and only one Astro focal plane, differs in its performance numbers, but not to a degree that would significantly change the conclusions of this talk.
The two designs are roughly compared in the following table (star-type- and sky-averaged data from Belokurov & Evans 2002 and from de Bruijne 2003):

	G (mag)	12	14	15	16	18	20
Gaia 1	σ(μas) one FoV transit	30	60	90	150	390	1400
	σ(μas) mission parallax	3	6	9	15	39	140
Gaia 2	σ(μas) one FoV transit	20	50	80	120	330	1100
	σ(μas) mission parallax	5	10	15	26	70	200

Addition to the previous page:

	G (mag)	12	14	15	16	18	20
Gaia 2	σ(μas) one FoV transit	20	50	80	120	330	1100
	σ(μas) mission parallax	5	10	15	26	70	200
	σ(μas) across scan one ASM transit		500	800	1200	3300	

Stars reached by Gaia:



V=20 „see“	V=15 „measure“
	(10 kpc)
100 kpc	10 kpc
(10 kpc)	
10 kpc	1 kpc
1 kpc	100 pc
100 pc	

in orange: including 3-4 mag of extinction

Surface structure:

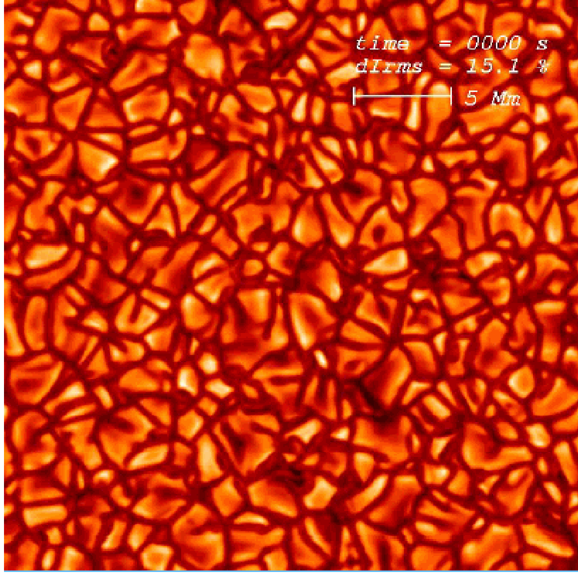
- time-independent structures do not matter.

- symmetric structures (rings, disks, zones) do not matter.

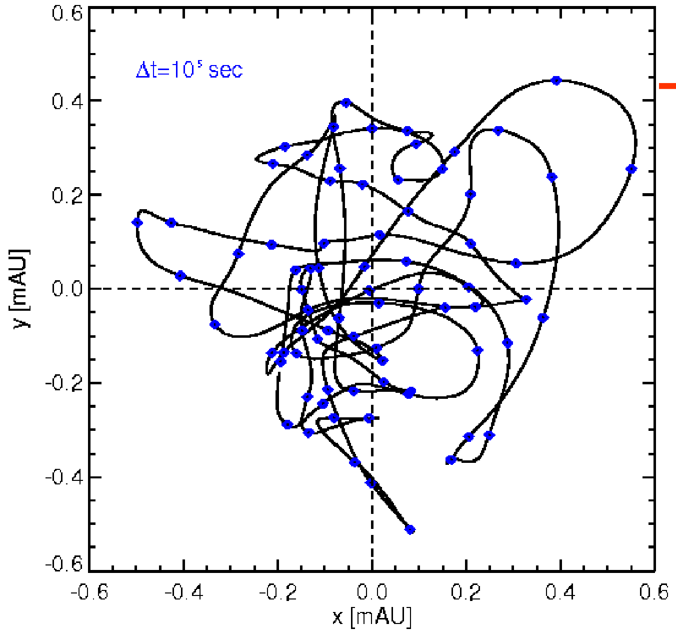
- so we are left with convection and magnetic activity, i.e. star spots and - to a lesser extent – chromospheric plagues.

Convection (granulation):

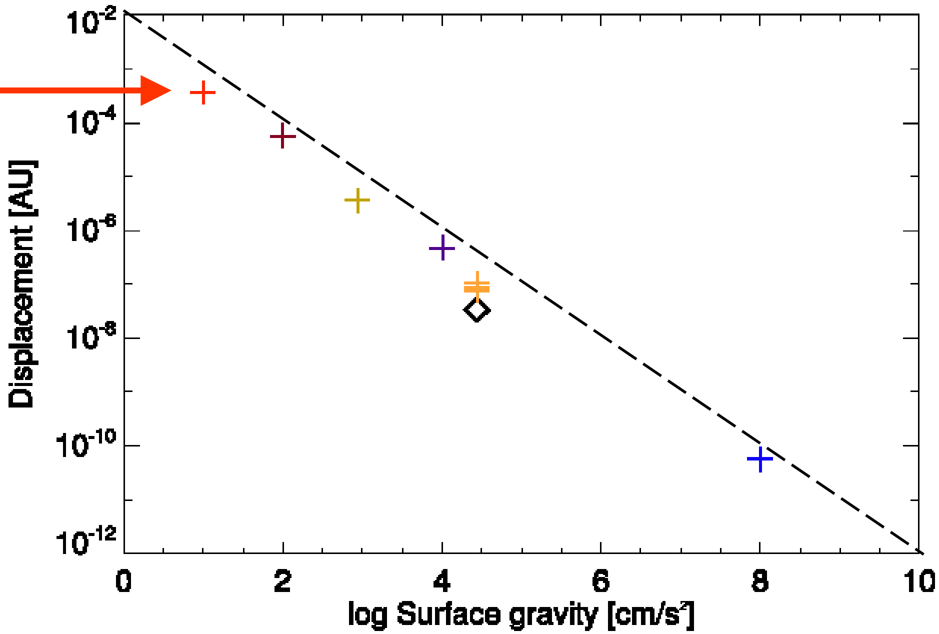
- completely absent in many types of stars
- easy to quantify
- rms displacement depending on cell size only (log g!)
- negligible for main-sequence stars
- measurable but irrelevant for nearby red giants
- problematic for Mira parallaxes and cool supergiants



example from giant star model:



rms displacement for different stars:



Remarks on the previous page:

The two graphs are Figs. 2 and 7 of F. Svensson, H.-G. Ludwig, Hydrodynamical simulations of convection-related stellar micro-variability, in: Proceedings of the Fifth Cool Stars Workshop, Hamburg, 5-9 July 2004, eds: F. Favata et al.

The diamond represents a metal-poor model star. Red giants have log g = 1, Cepheids have log g =2, the sun has log g = 4.4, and Miras have log g around zero.

Author of the movie: H.-G. Ludwig, Lund Observatory
The movie (11MB) can be found at
http://www.astro.lu.se/~hgl/public_files/supergran/d3gt57g44sg2_intens_400.mpg
and a much smaller version at
http://www.astro.lu.se/~hgl/public_files/gt57g44n65p-q_I.mpg

Side remark: The dependence on log g only:

The surface of a convective star is fully covered with convection cells. Each cell has an rms photocenter offset from the center of the star of \sqrt(1/6) times the radius of the star. So, for the average over N_{cell} cells we have approximately:

$$\sigma_{astrom} \sim \frac{1}{\sqrt{6}}\ R_{star}\ N_{cell}^{-1/2}\ \cdot \mathrm{contrast}$$

$$\sim \frac{1}{\sqrt{6}}\ R_{star}(r_{cell}^{-2}\ R_{star}^{2})^{-1/2}\ \cdot \mathrm{contrast}$$

$$\sim \frac{1}{\sqrt{6}}\ r_{cell}\ \cdot \mathrm{contrast}$$

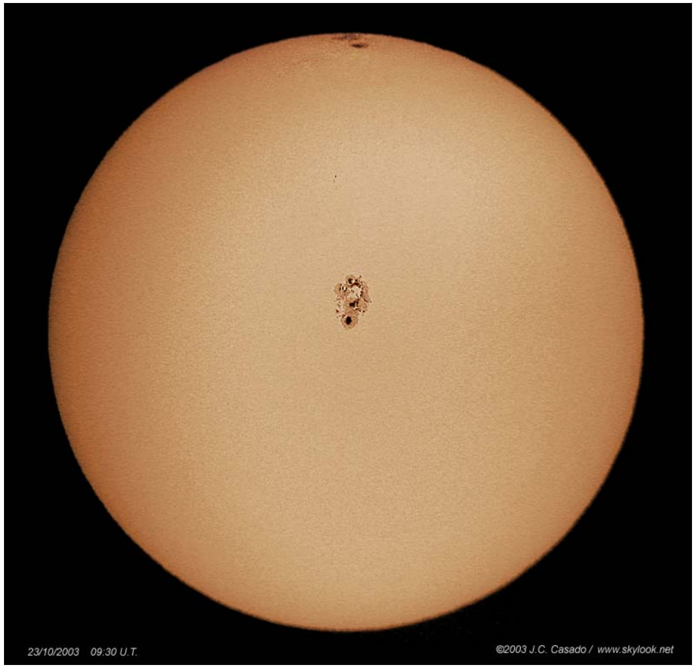
So, the radius of the star cancels out. The cell size is proportional to the surface pressure scale height, which in turn is inversely proportional to the surface gravity, with a comparatively small dependence on the mean molecular weight. Thus we have the rms displacement inversely proportional to log g.

Star spots (and other magnetic features):

Hard to quantify statistically !

Sun: max effect 0.5 r * 0.01 = 2.5 10^{-5} au
-> negligible

Solar-type stars: max effect 0.5 r = 2.5 10^{-3} au
-> negligible, although well measurable in some cases; danger of confusion with low-mass companions.
at 25 pc: 2.5 10^{-3} au = 100 μas



K giants: 10 times as big, rotating more slowly
-> still largely negligible; danger of confusion

Supergiants and M giants: 100 times as big, max effect 0.25 au
-> dangerous to parallax !
at 1 kpc: 0.25 au/5 yr = 50 μas/yr = 250 m/s

BY Dra stars, RS CVn stars: small and quickly rotating

Big spots are connected with brightness changes

Remarks on the previous page:

The most specific statement on the statistics of numbers, sizes etc.
of star spots vs. star type that I could find in the literature are :

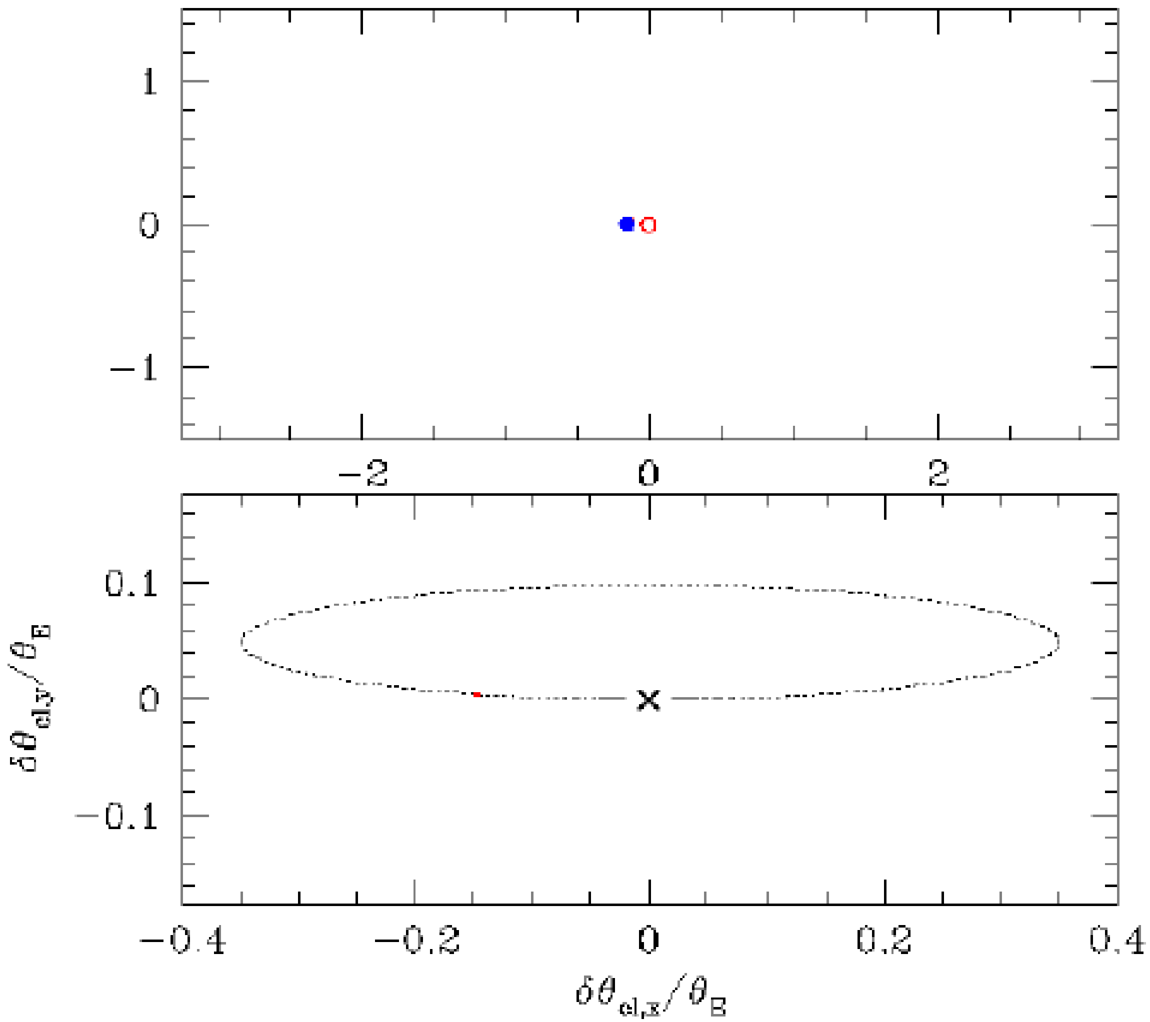
a) “spots are common among cool stars with outer convection zones”
b) complaints about the strong selection biases towards very active stars
c) discussions about supergiants: do we see dark spots or bright cells?

Plagues: larger in area, but much smaller contrast.

Gravitational lensing:

Movie by Scott Gaudi
CfA, Harvard, showing
microlensing event

(Source-centered view)



red circle:
unlensed source
(stellar disk)

blue dots:
lensed optical images

red dot:
lensed center of light
(astrometric position)

yellow:
lens

green:
Einstein radius

Remarks on the previous page:

The movie can be found at

http://cfa-www.harvard.edu/~sgaudi/Movies/centroid_s0.gif
http://cfa-www.harvard.edu/~sgaudi/Movies/centroid_s0.avi

Movie showing microlensing event:

Lens-centered view

red circle:
unlensed source
(stellar disk)

blue dots:
optical images

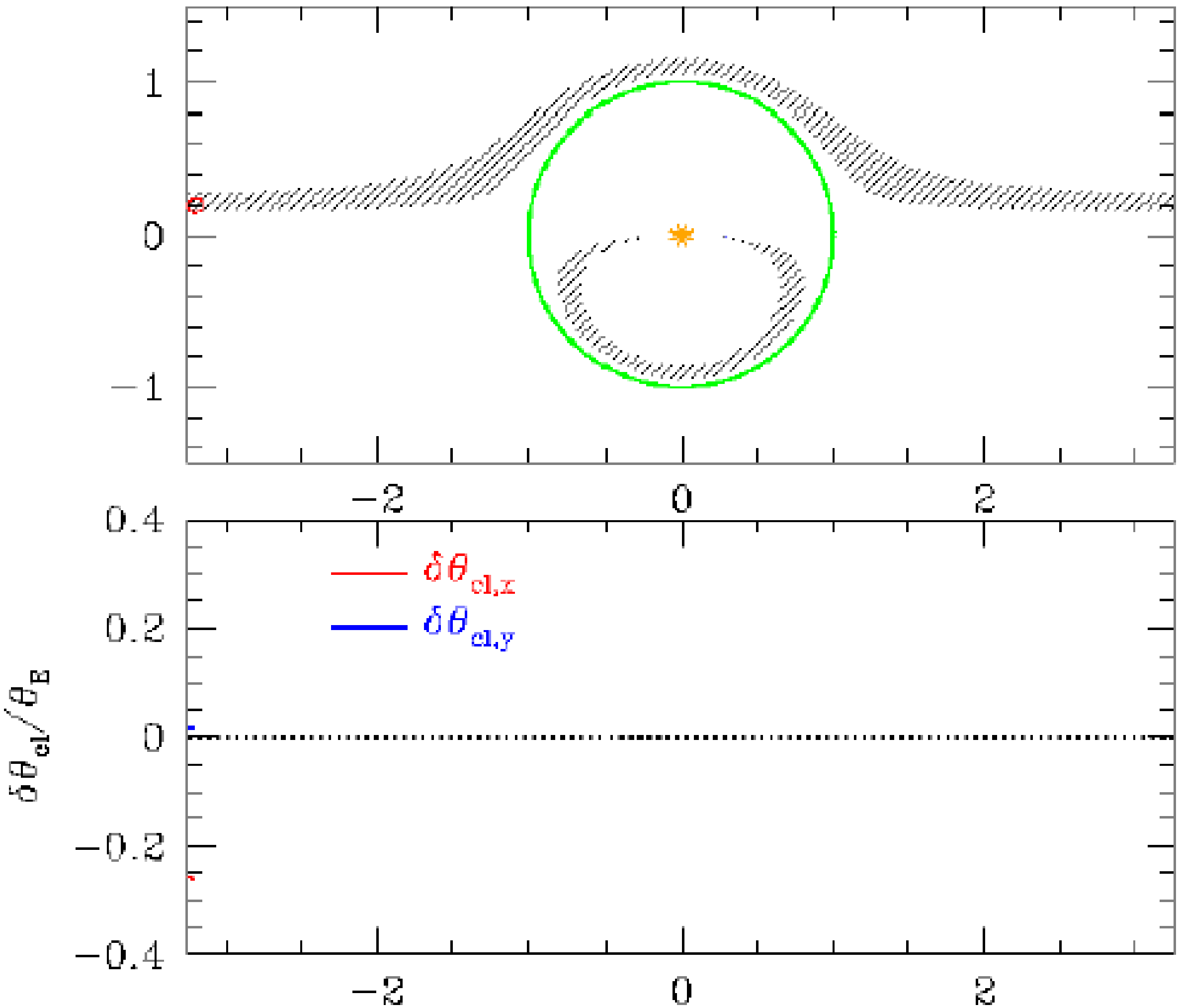
red dot:
lensed center of light
(astrometric position)

yellow:
lens

green:
Einstein radius

lower panel:
astrometric coordinates

Author of simulation:
Scott Gaudi
CfA, Harvard



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Gravitational lensing:

Macrolensing: arcsec, only for quasars

Strong microlensing: big, but rare

Maximum positional shift: 0.35 Einstein radii (r_E) when source at 1.41 r_E

Lens of 0.12 solar masses at 100 pc -> 0.35 r_E = 1.1 mas

Lens of 0.12 solar masses at 1 kpc -> 0.35 r_E = 0.35 mas

Proportional to the square roots of the lens mass and lens parallax.

Typical timescale: A few months, for the major astrometric “swing”

Weak microlensing: small, but ubiquitous

Typical size of the order of 1 μas, and of 0.01-0.1 μas/yr

timescale: decades to centuries.

Parallax bias ! (Sazhin, Zharov, Kalinina, MNRAS 2001)

Gravitational microlensing:

Stars:

(careful study by Belokurov and Evans, MNRAS 2002)

- Optical depth (at 7σ for 1 FoV transit) is about 2.5 10^{-5}, i.e. 25000 significant events for Gaia (yielding 2500 lens masses).

- The most important lenses are low-mass stars within a few hundred pc.

- The positional measurement of one source in every 20 000 is affected (at the 1σ level of the full-mission astrometric precision) for any instant of time.

- Still, microlensing is of negligible effect for the overall error budget of Gaia.

- For the few sources where its size is significant, it will rarely be mixed up with a proper motion or parallax effect.

Gravitational microlensing:

Note: 100 μas / sqrt (500 000) = 0.14 μas

Quasars:

Once thought to be the perfect inertial reference points, they are not:

A proper motion scatter in the range 10-100 μas/yr must be expected

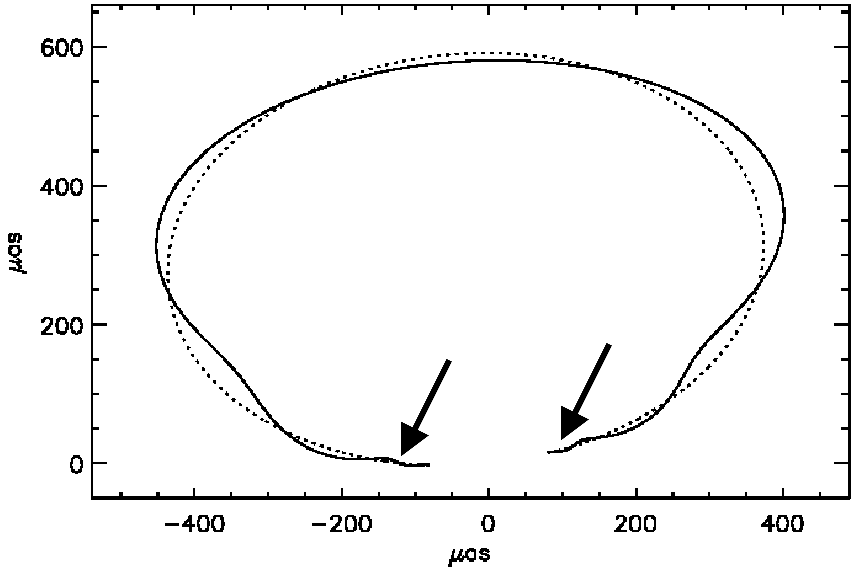
- random proper motions by jets, up to 500 μas/yr, but mostly small (extra noise)
- systematic proper motions due to galactocentric motion of the sun (no problem)
- centroiding problems due to underlying galaxy (extra noise)
- centroiding problems due to macrolensing by intervening galaxies (extra noise)
- centroiding problems due to non-stellar spectra (chromaticity, extra noise)

- weak microlensing by stars in our galaxy:
  - typical random proper motions 0.01-0.1 μas/yr (negligible)
  - negative parallax bias of the order of a few times 0.001 μas (negligible)

Remarks on the previous page:

There are a lot of relevant studies on quasars. They are summarized on pages 109-119 of the Gaia Concept and Technology Study, ESA-SCI(2000)4.

Two additional effects for macrolensed quasars (only 1 percent, but still several thousand) were not mentioned on the previous page: time variability of the macrolensing (due to relative motion of quasar and lens) and strong microlensing by stars in intervening galaxies (changes of relative brightness of images). Both will often cause one or a few μas/yr, up to dozens of μas/yr (small extra noise).



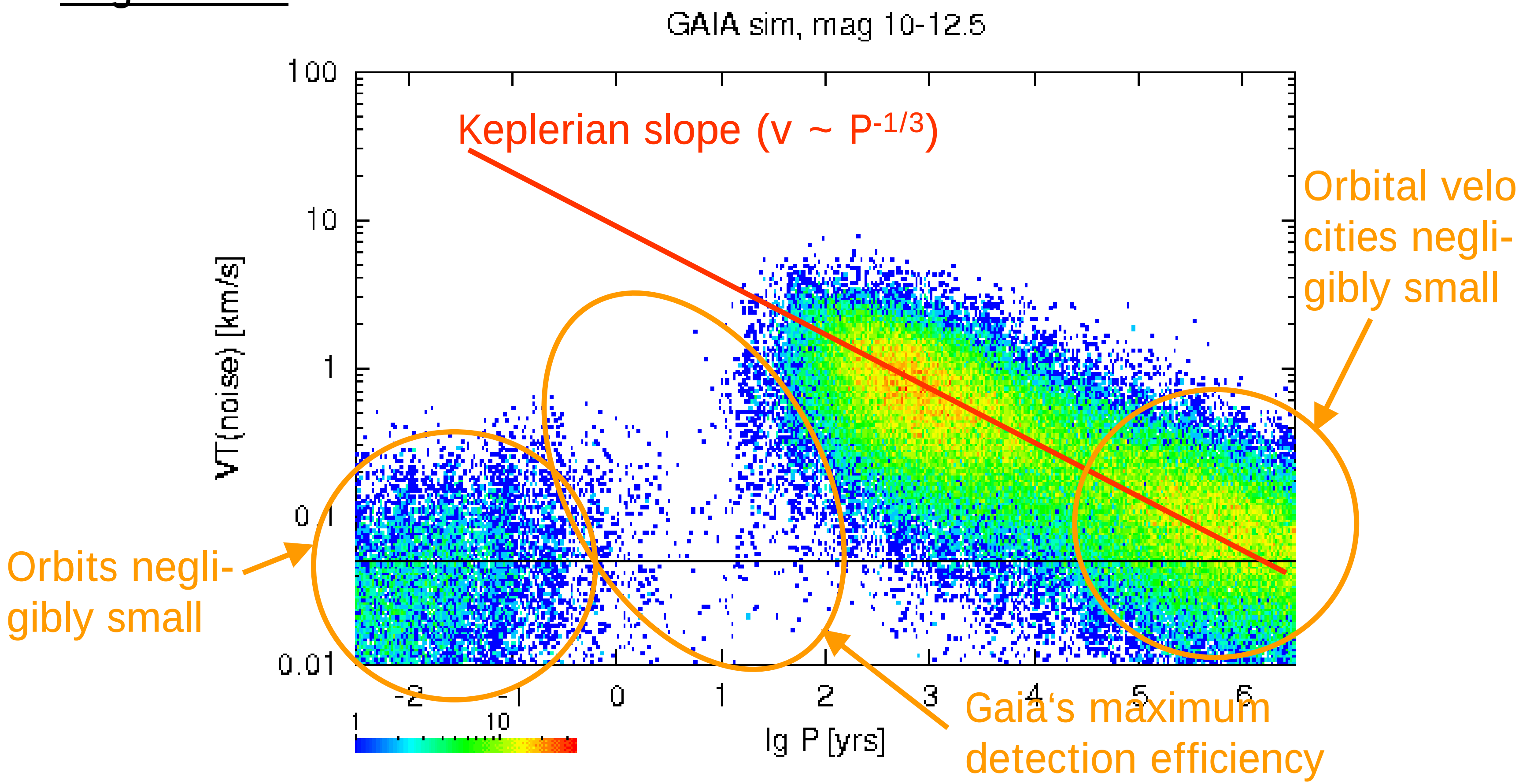
The mentioned parallax bias is caused by the small annual wiggles on the big microlensing loop, as illustrated by the adjacent graph from Belokurov and Evans, especially at times far from the instant of nearest approach.

Stellar multiplicity:

Space velocity effect of undetected binaries

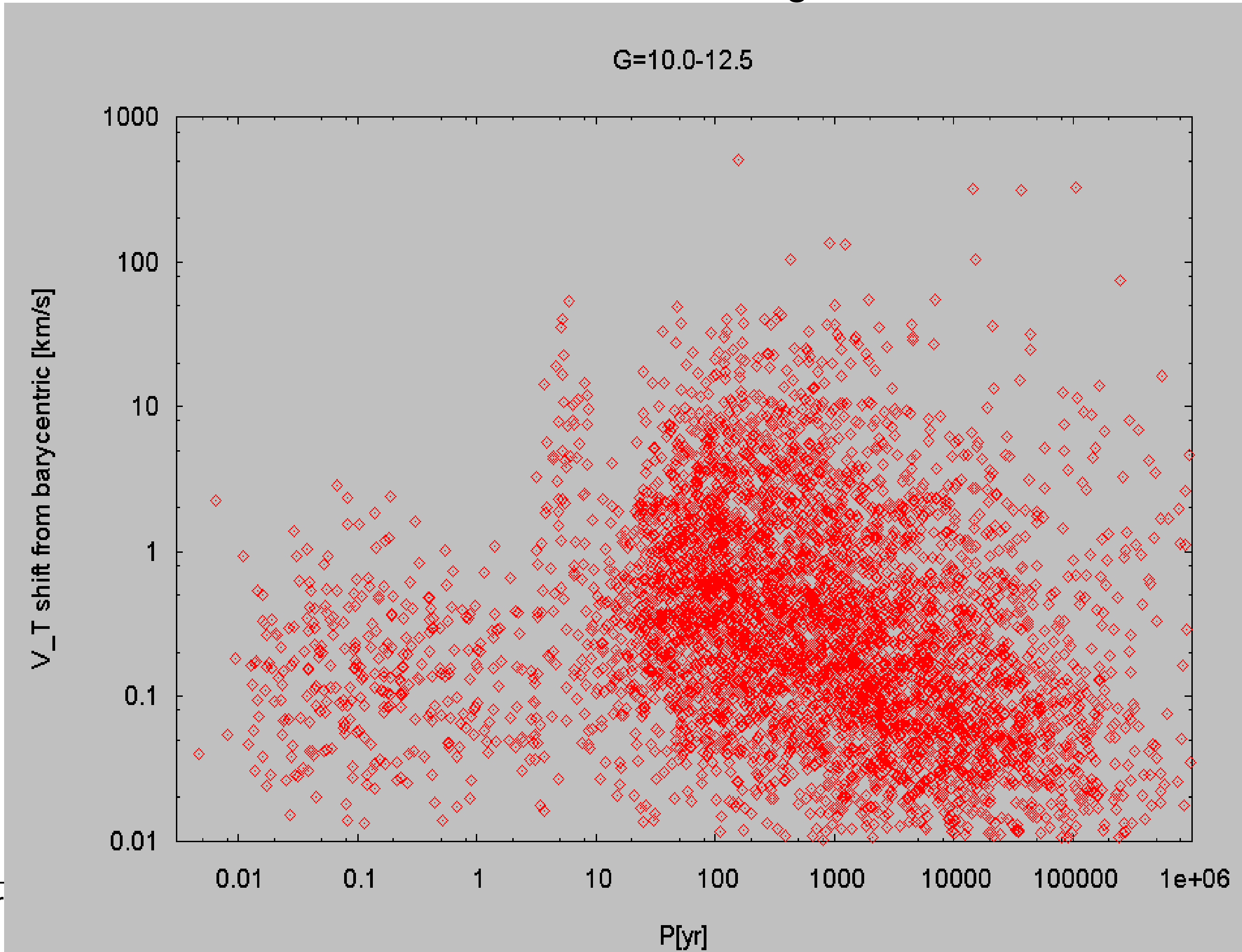
Bright stars:

(simulations by S. Soederhjelm)



Updated (Sep 2004) version of previous picture, using more detailed modelling:

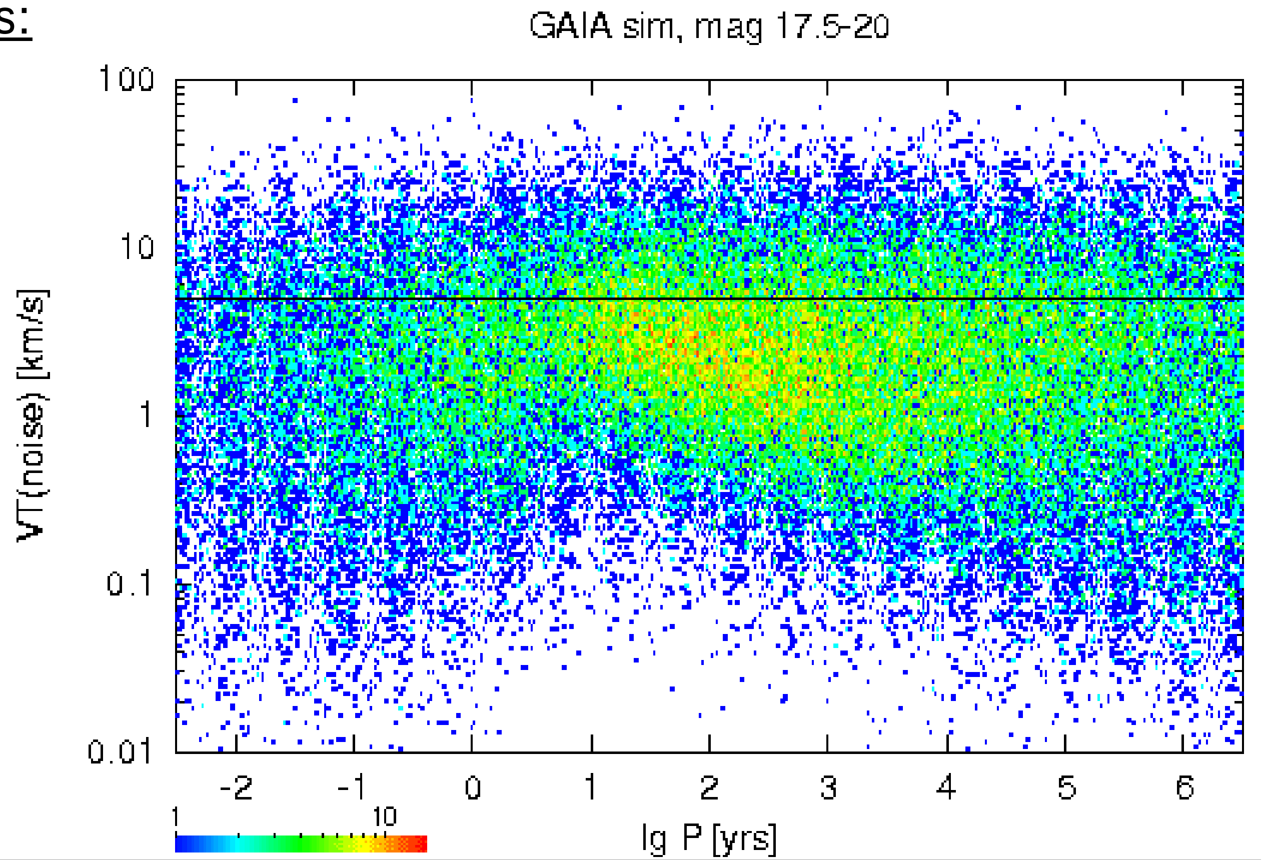
The left-hand blob is fainter due to inclusion of RV measurements; the central gap is less pronounced because the 5- to 10-year pairs are less efficiently found than in the simpler models; the right-hand blob is wider due to usage of “bad” parallaxes for p.m. to velocity transformation. But else there is little change in the essential results.



Stellar multiplicity:

Space velocity effect of undetected binaries

Faint stars:



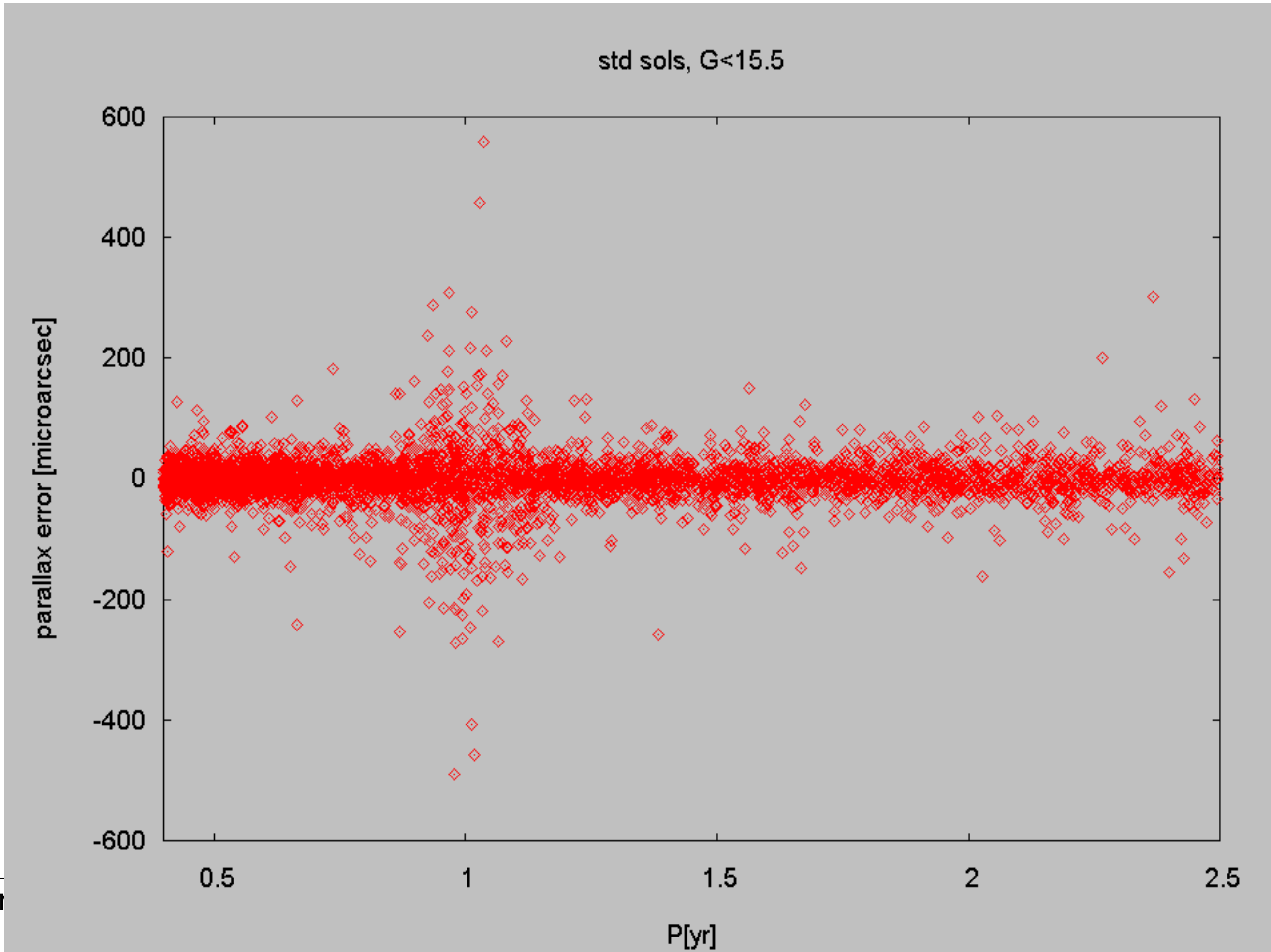
Same effects as before, but almost negligible compared to measurement errors

Remarks on the previous page:

The median measurement error is about two powers of ten higher than in the picture for the bright stars. Firstly, the (angular) measurements of the faint stars are about an order of magnitude less precise. Secondly, the faint stars are typically about an order of magnitude farther from the sun.

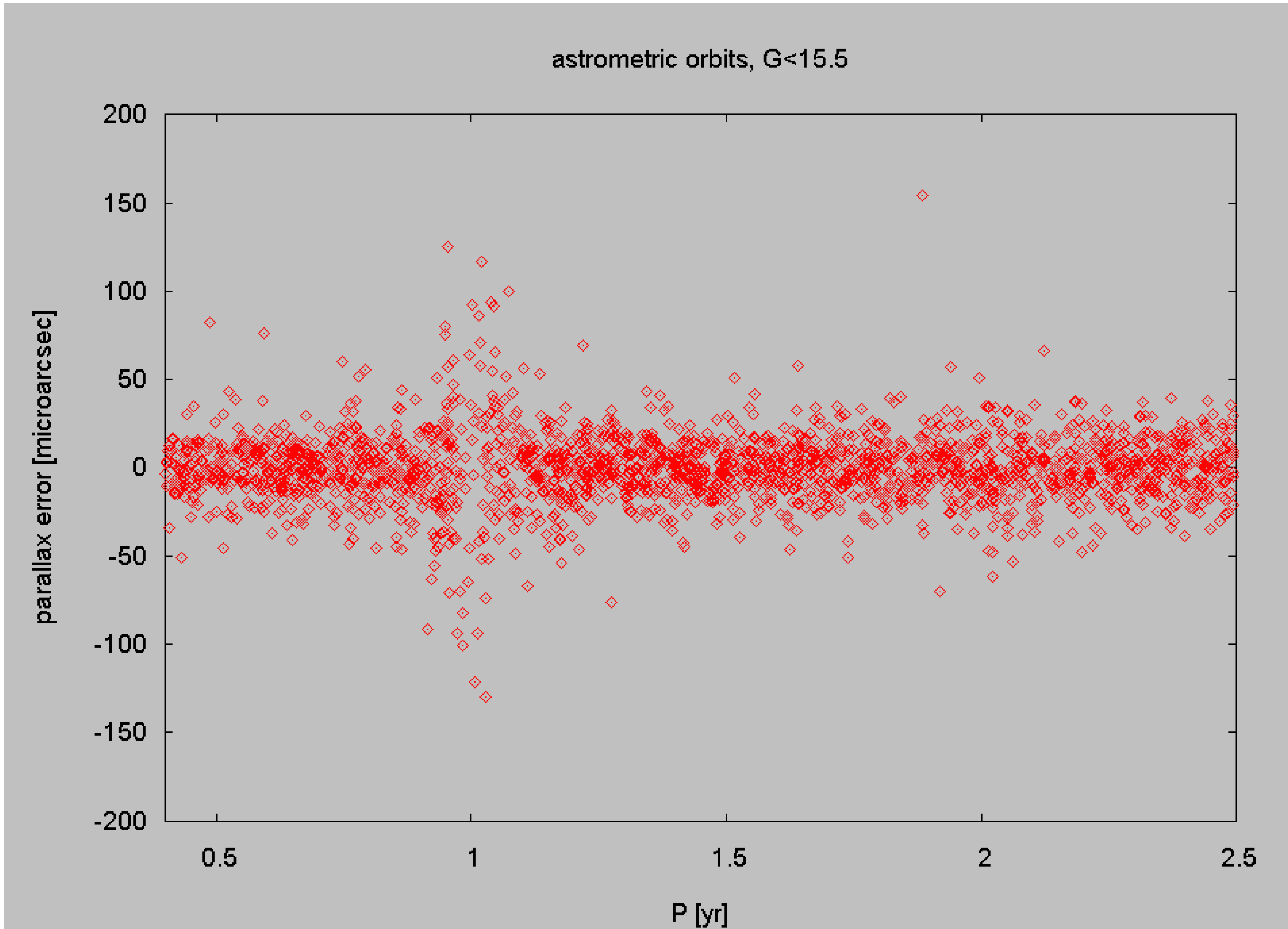
Parallax effect of undetected binaries:

Undetected binaries cause a flare-up of the scatter around one year period. But parallaxes are disturbed at other periods as well (there is as yet no investigation that nicely isolates the binarity effect from the ordinary measurement errors). Note the linear period scale in this plot. Next page: the complement to this plot, showing the astro-metric orbit solutions.



<u>Parallax disturbance even for detected binaries:</u>

Astrometric orbit solutions. Orbital parameters around 1 year are strongly correlated with parallax. This causes the paucity of orbit solutions and the larger scatter around one year period. Note the linear period scale in this plot.



Other effects?

- Asymmetric outbursts, gas jets etc. (rare, except for nearby quasars)
- interstellar and interplanetary scintillation (negligible in the optical)
- primordial gravitional radiation (very unlikely to be strong enough)
- local gravitational radiation (very improbable celestial configuration needed)
- unexpected discoveries ?

Other effects?

- Asymmetric outbursts, gas jets etc. (rare, except for nearby quasars, where motions of a few hundred μas in a few months will occur)
- interstellar and interplanetary scintillation (important in radio astronomy, negligible in the optical)
- primordial gravity waves (very unlikely to be strong enough, would be a major cosmological surprise)
- local gravity waves (won’t actually happen; very improbable celestial configuration needed)
- unexpected discoveries ?

Remarks on the previous page:

The discovery of pulsars came as unexpected as that of quasars, of the cosmic microwave background, of gamma-ray bursts etc.

I would be really happy to see someone make such a discovery from Gaia's final astrometric data. - That would be after my retirement, by the way.

One unexpected discovery have already been made, by myself, in 1997: Everybody had thought that quasars are so far away that they will have no measurable proper motion (except the random ones due to jets and lensing which were discussed above), as even the full speed of light corresponds to only 50 μas per year at $z=0.3$. Nevertheless all quasars will be seen by Gaia to systematically move towards the galactic centre, with an average proper motion of more than 3 μas per year (equivalent to 20 000 km/s at $z=0.3$).

How can that be? It is the gradual change of aberration due to the galacto-centric acceleration of the sun !

Conclusion:

Granulation: No problem except for a small number of cool supergiants.
Serious problem for Mira star parallaxes.

Star spots: Problematic for supergiants and cool giants; hard to quantify.

Binaries: Major problem for bright stars, especially for stellar aggregates of small velocity dispersion (small star clusters, associations, SFRs).
May also produce a small number of grossly wrong parallaxes.

Microlensing: Rare, and also harmless in nature for stars.

Others: Well ...

Remarks on the previous page:

Binaries: The small number of grossly wrong parallaxes will occur for binaries with orbital periods of about 1 year, especially for massive dark objects (WD, NS, BH) as companions

Others: Well … As I said, it would be nice if some unexpected effects would be discovered.