Gaia astrometric data reduction one year into science operations

Uwe Lammers, Lennart Lindegren,
Jose Hernandez, David Hobbs, Ulrich Bastian,
Daniel Michalik, Sergei Klioner

and the

AGIS Development Team

Outline

- Overview **A**strometric **G**lobal **I**terative **S**olution (AGIS)
- **T**ycho-**G**aia **A**strometric **S**olution (TGAS)
- Early results using flight data
- Basic Angle Variation and absolute parallaxes
- Concluding remarks

AGIS: Basic ideas

- Want to determine 5 x 1000 Million unknown source parameters (S) from all (>10^{12}) measurements in a globally, self-consistent manner
- Three different models are needed:
  - ***S***ource (star) model → wanted parameters
  - ***A***ttitude (pointing) model
  - ***C***alibration (focal plane geometry + optics) model

  } → nuisance parameters

  The nuisance parameters couple the wanted parameters in a complicated way.
- Problem is very well conditioned because
  - Clever design of instrument and observing strategy
  - Have 10^{12} observations to determine 5×10^9 S + ~10^7 A + ~10^5 C parameters
- **A**strometric **G**lobal **I**terative **S**olution (AGIS) consists of
  1. Needed S, A, C models ("observation model")
  2. Mathematical formulation of the problem whose solution gives the optimal fit between models and observations
  3. A *practical* method to solve the problem – a direct approach is computationally intractable by many orders of magnitude

AGIS: Weighted Least-Squares Minimisation task solved through linearized Normal equations

Unknowns: **S**ource+**A**ttitude +**C**alibration+**G**lobal

Residual (O-C) of observation *l*

Downweighting function (outlier rejection)

$$\min_x Q = \sum_l \frac{R_l(x)^2}{\sigma_l^2 + \varepsilon_l^2} w\left(\frac{R_l(x)}{\sqrt{\sigma_l^2 + \varepsilon_l^2}}\right)$$

Merit function

Sum over all observations

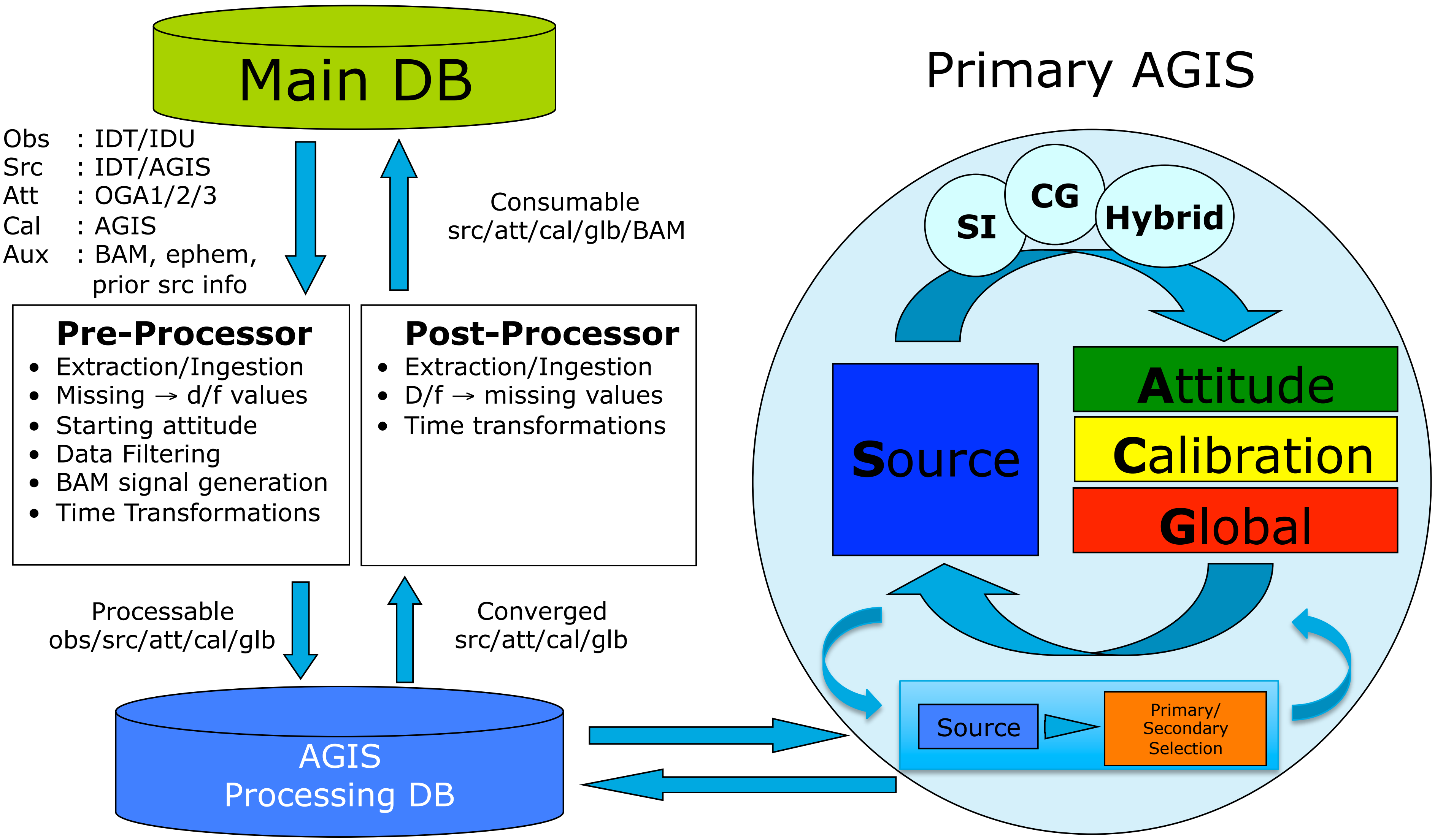
Observation noise

Excess noise

Then form linearized Normal equations which are solved through iterations

$$N \Delta x = b$$

AGIS: Overall processing concept



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Astronomy & Astrophysics

The astrometric core solution for the *Gaia* mission

Overview of models, algorithms, and software implementation

L. Lindegren[1], U. Lammers[2], D. Hobbs[1], W. O'Mullane[2], U. Bastian[3], and J. Hernández[2]

[1] Lund Observatory, Lund University, Box 43, 22100 Lund, Sweden
e-mail: [Lennart.Lindegren;David.Hobbs]@astro.lu.se
[2] European Space Agency (ESA), European Space Astronomy Centre (ESAC), PO Box (Apdo. de Correos) 78, 28691 Villanueva de la Cañada, Madrid, Spain
e-mail: [Uwe.Lammers;William.OMullane;Jose.Hernandez]@sciops.esa.int
[3] Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, Mönchhofstr. 12–14, 69120 Heidelberg, Germany
e-mail: bastian@ari.uni-heidelberg.de

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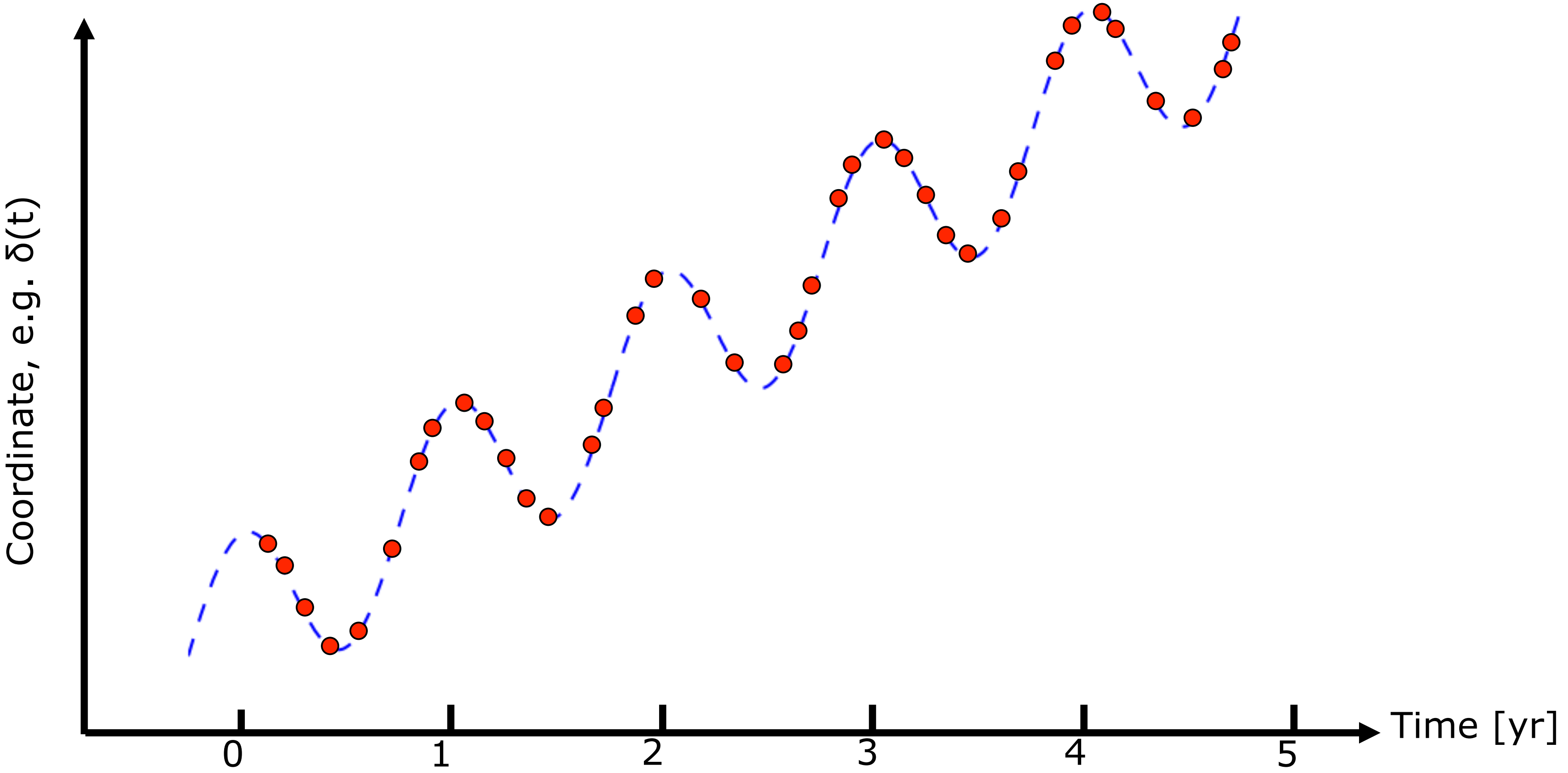
ABSTRACT

Context. The *Gaia* satellite will observe about one billion stars and other point-like sources. The astrometric core solution will determine the astrometric parameters (position, parallax, and proper motion) for a subset of these sources, using a global solution approach which must also include a large number of parameters for the satellite attitude and optical instrument. The accurate and efficient implementation of this solution is an extremely demanding task, but crucial for the outcome of the mission.

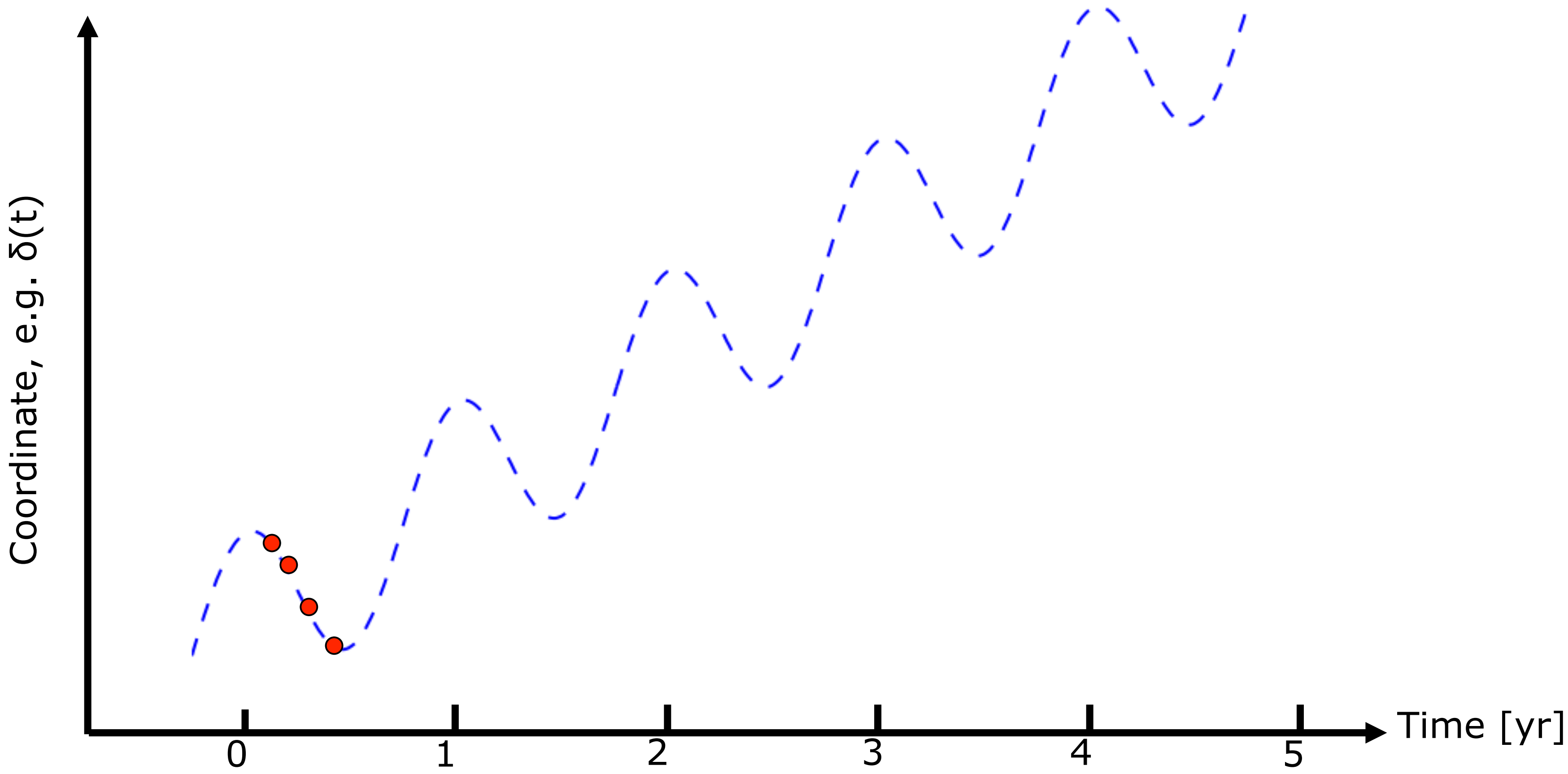
The Tycho-Gaia Astrometric Solution (TGAS)

- Trial runs with real data had started soon after the start of the nominal mission to “expose” AGIS to flight data for technical interface checks, etc.
- No scientific value in these early runs
  - no good attitude solution
  - can only solve for source positions
- Disentangling parallax and proper motion needs more than 1 yr of data
- But wanted to experiment with full 5-parameter solutions as soon as possible
- TGAS idea
  - Identify HIP+Tycho-2 stars among the Gaia stars and add their positions at 1991 (from the HIP+Tycho-2 catalogues) as additional observations
  - Solution then possible with less than 1 yr of Gaia data
  - Proper motions and parallaxes for all 2.5 million stars

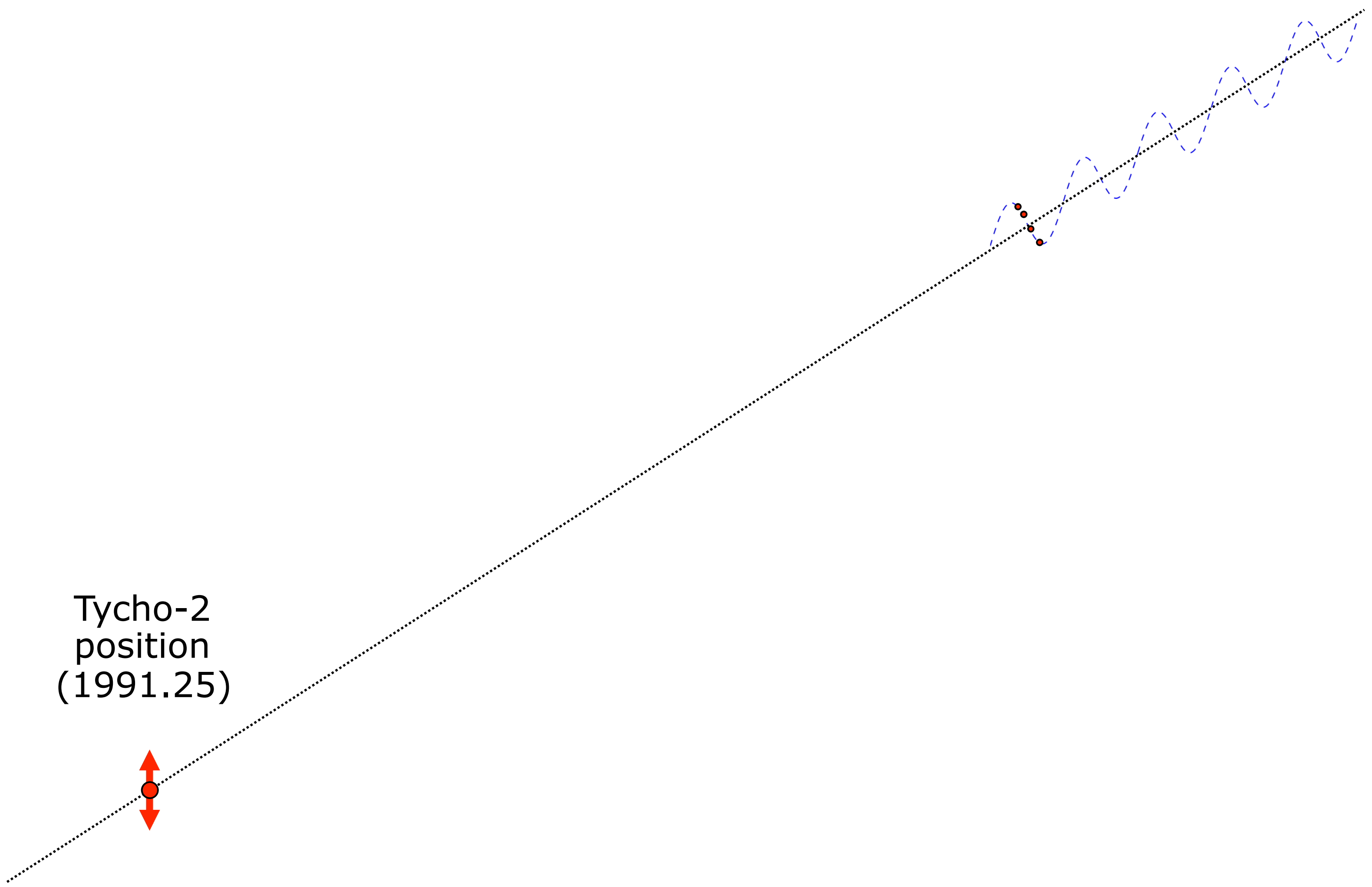
Gaia observations over 5 yr ⇒ pos, par, p.m.



μ–ϖ degeneracy for < 1 yr of observations



Lifting the degeneracy



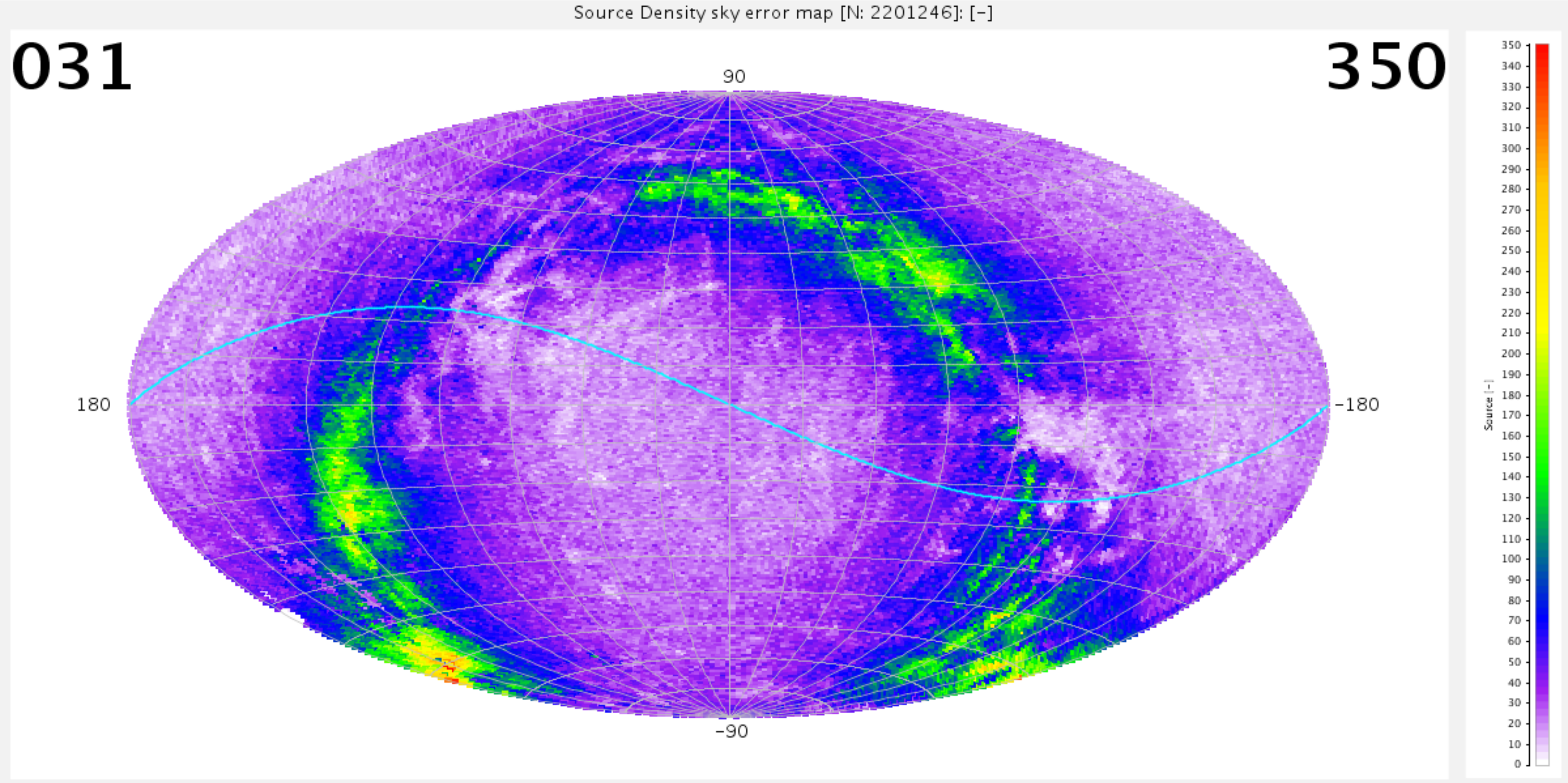
Input: Data used + configuration for current (June 2015) TGAS solutions

- Time period covered: 2014 July 25 - 2015 June 2 = data segment 0 with some additional filters applied (275 days over 10 months)
- Number of sources: 2,201,246 sources
  - Hipparcos: 99,070
  - Tycho-2 only: 2,102,176
- Number of CCD observations: 227,219,102 (most are both AL and AC)
- Source block: 5 parameters per source (reference epoch 2015.0)
  - Priors included (with appropriate covariances):
  - For Hipparcos stars: HIP positions @ 1991.25 + HIP proper motions (*) (**no HIP parallax used**)
  - For non-Hipparcos stars: Tycho-2 position @ 1991.25

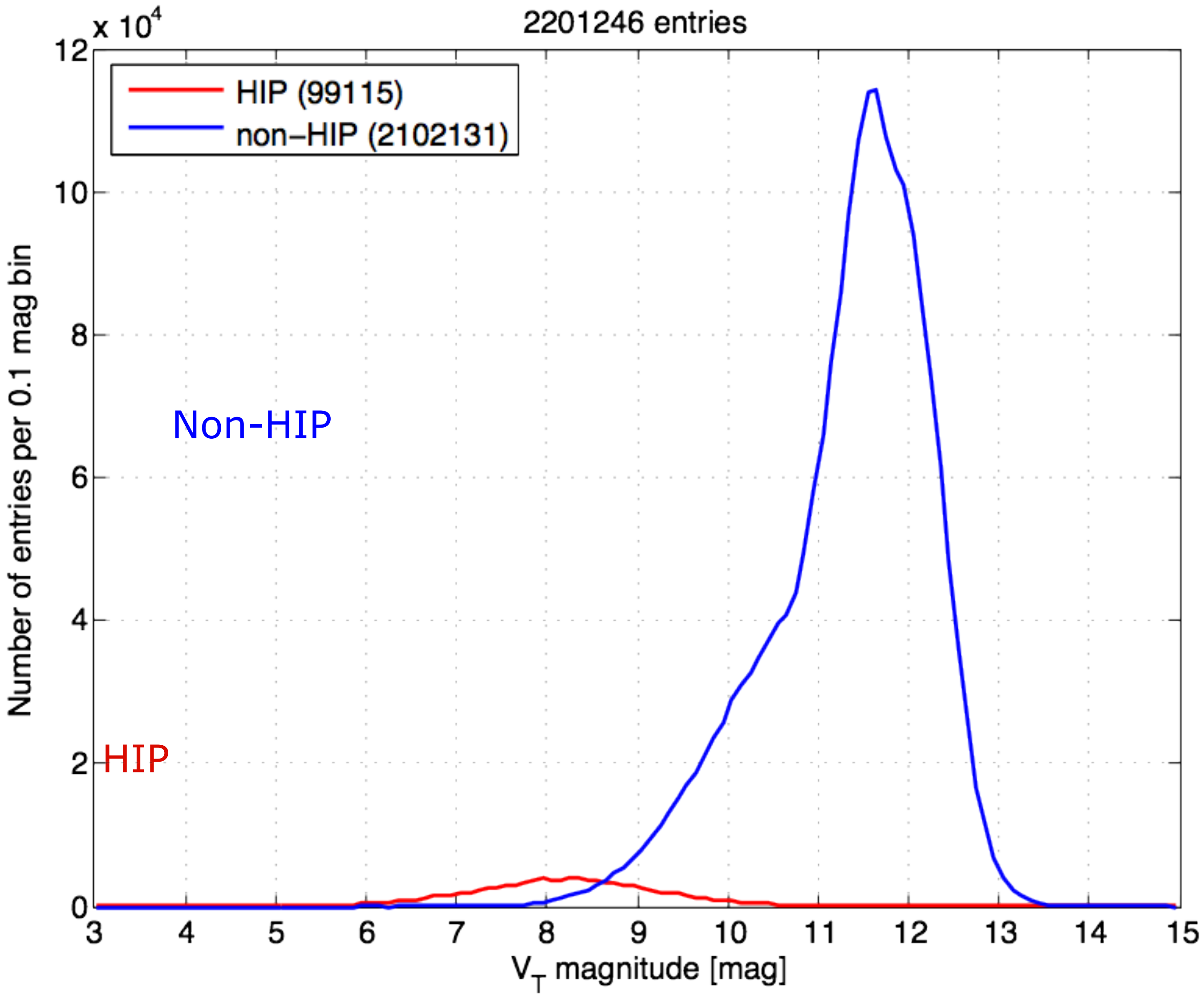
    (no Tycho-2 proper motion used)
- Empirical correction for Basic Angle Variation using BAM data

(*) van Leeuwen, 2007

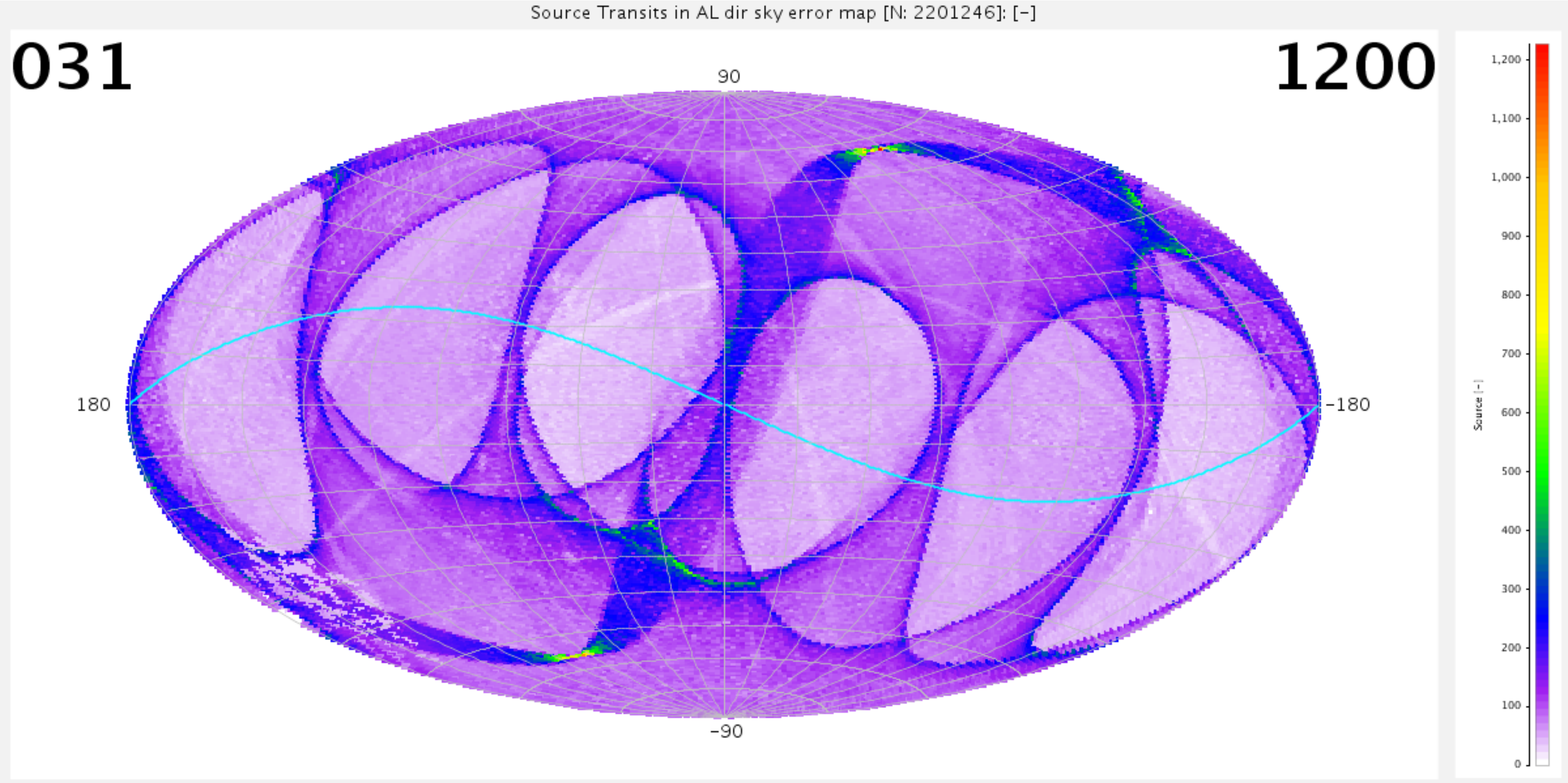
Input: Source distribution in position



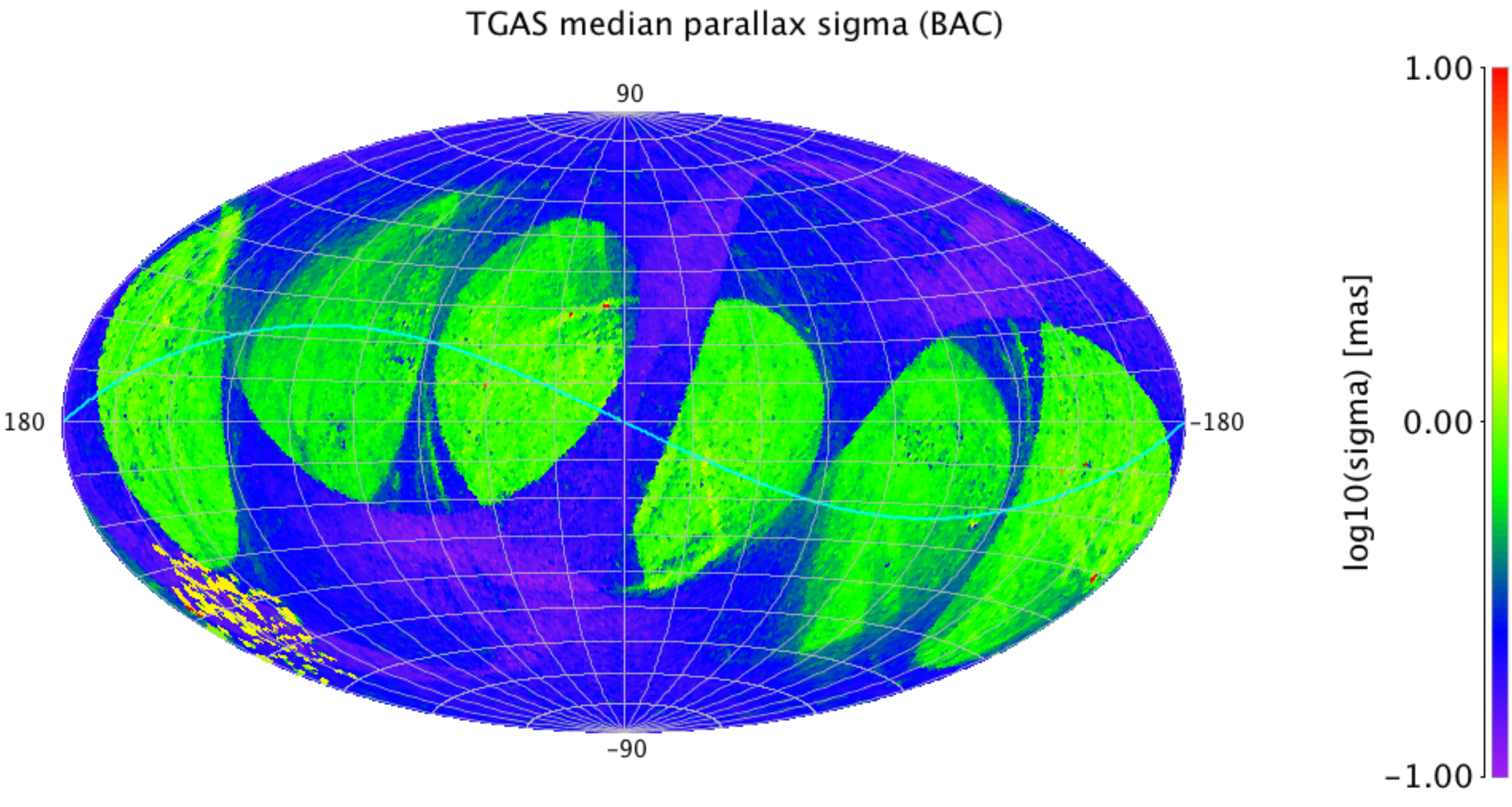
Input: Source distribution in magnitude



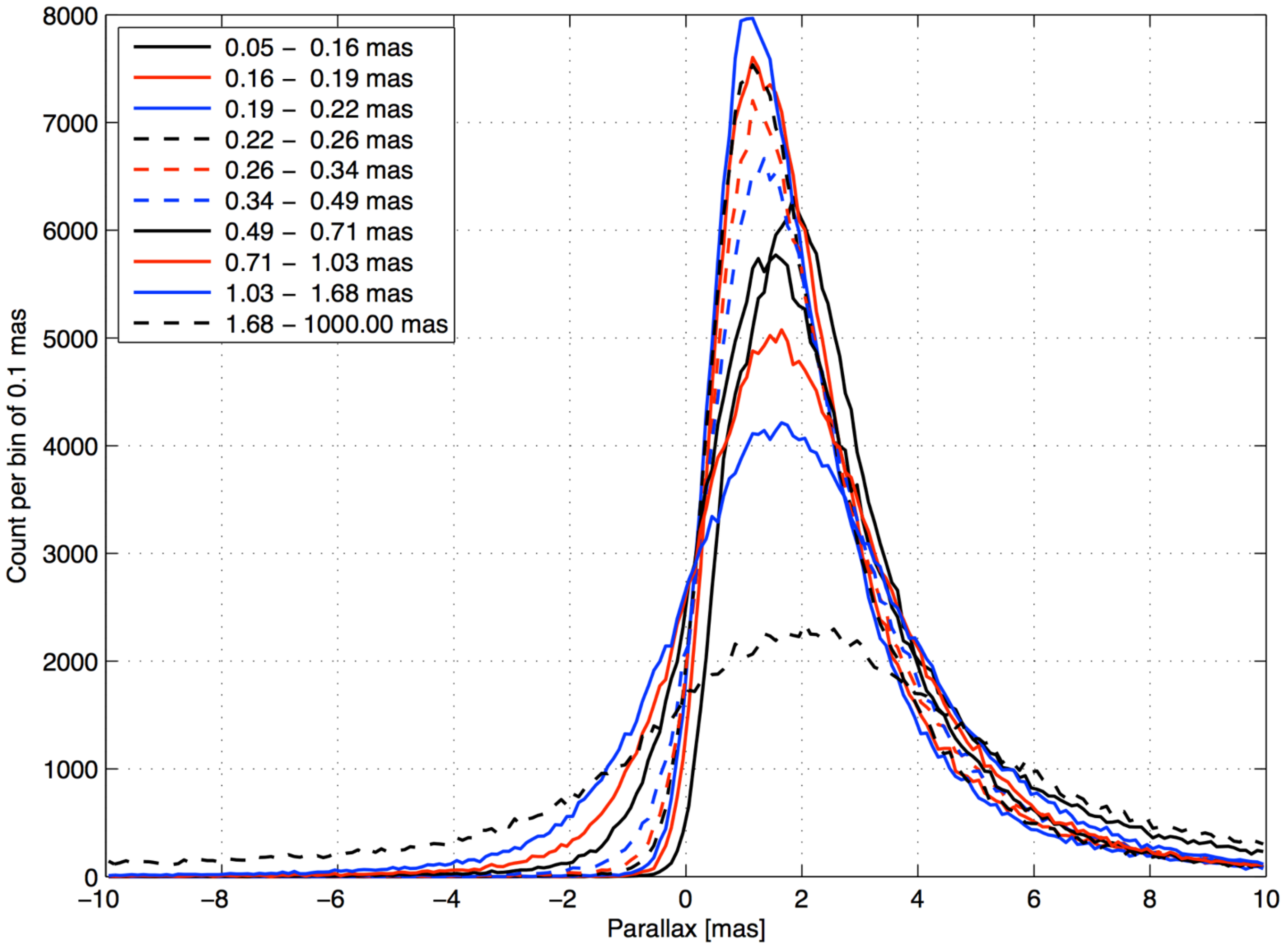
Input: Observation distribution (AL)



Results: Parallax formal standard uncertainties



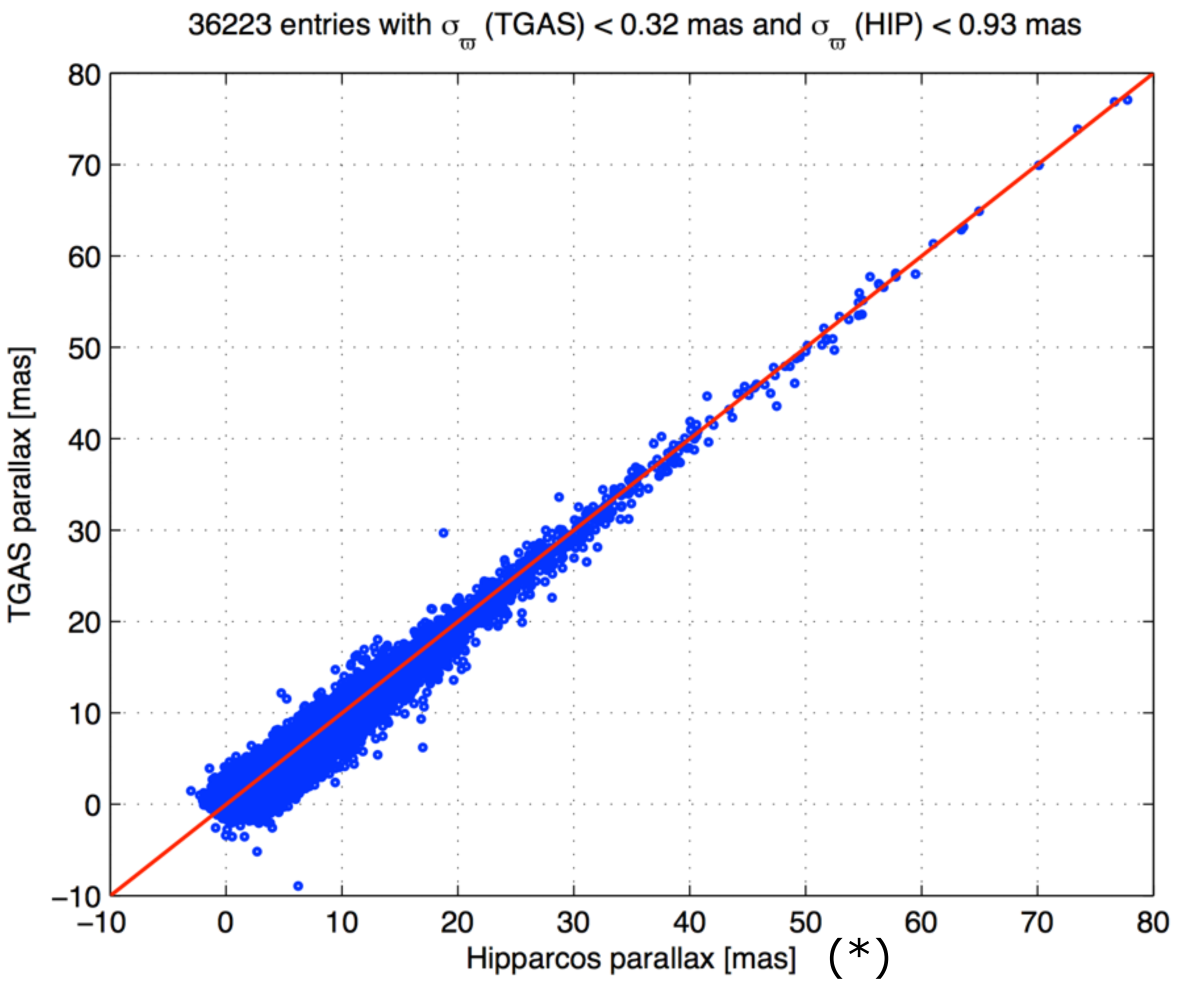
Results: Formal uncertainties (σ_ϖ) are meaningful



Subsequent analysis is mainly based on the "better half" subset (σ_ϖ < 0.34 mas)

no further filtering applied

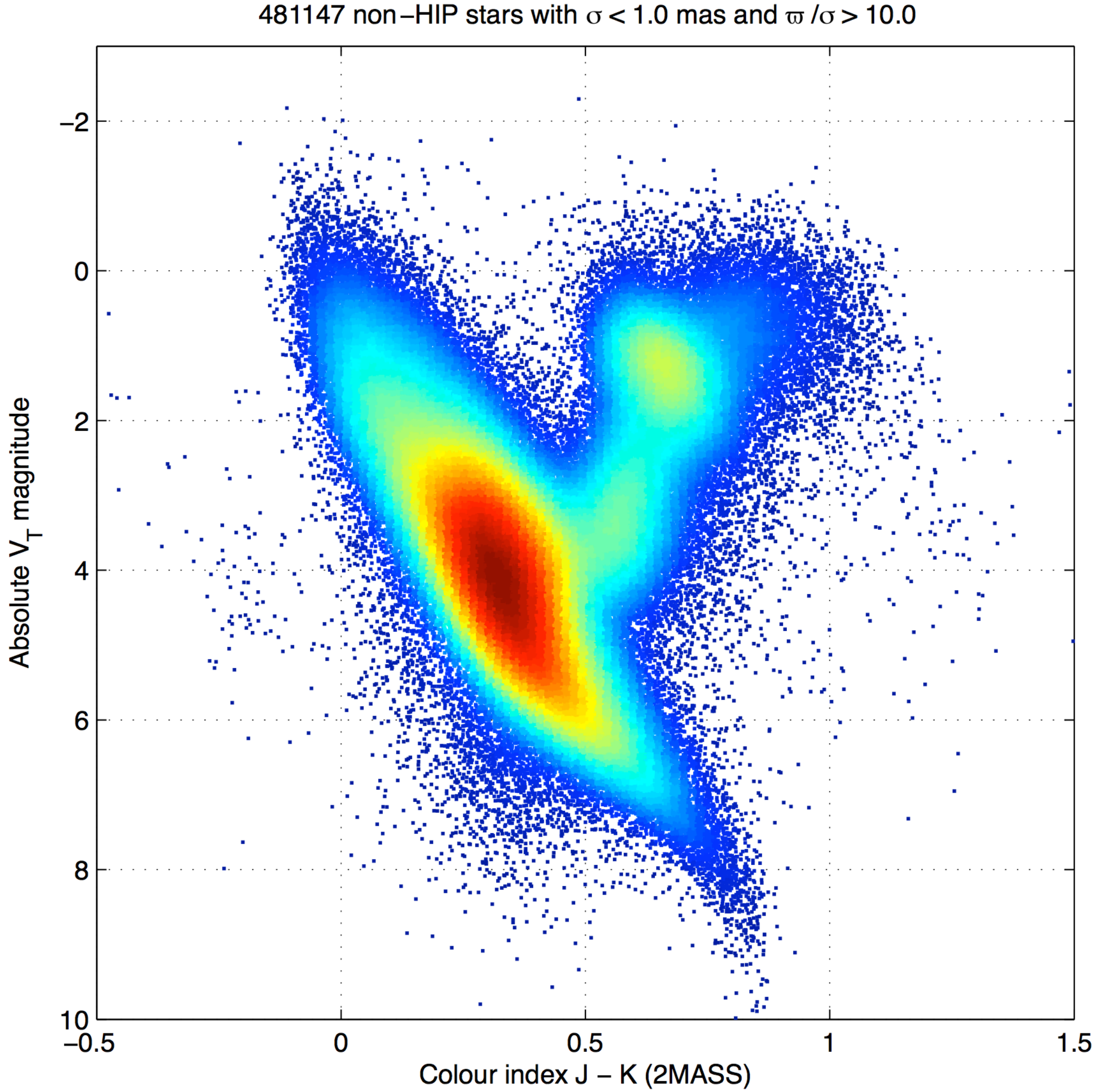
Results: ϖ_{TGAS} versus ϖ_{HIP}



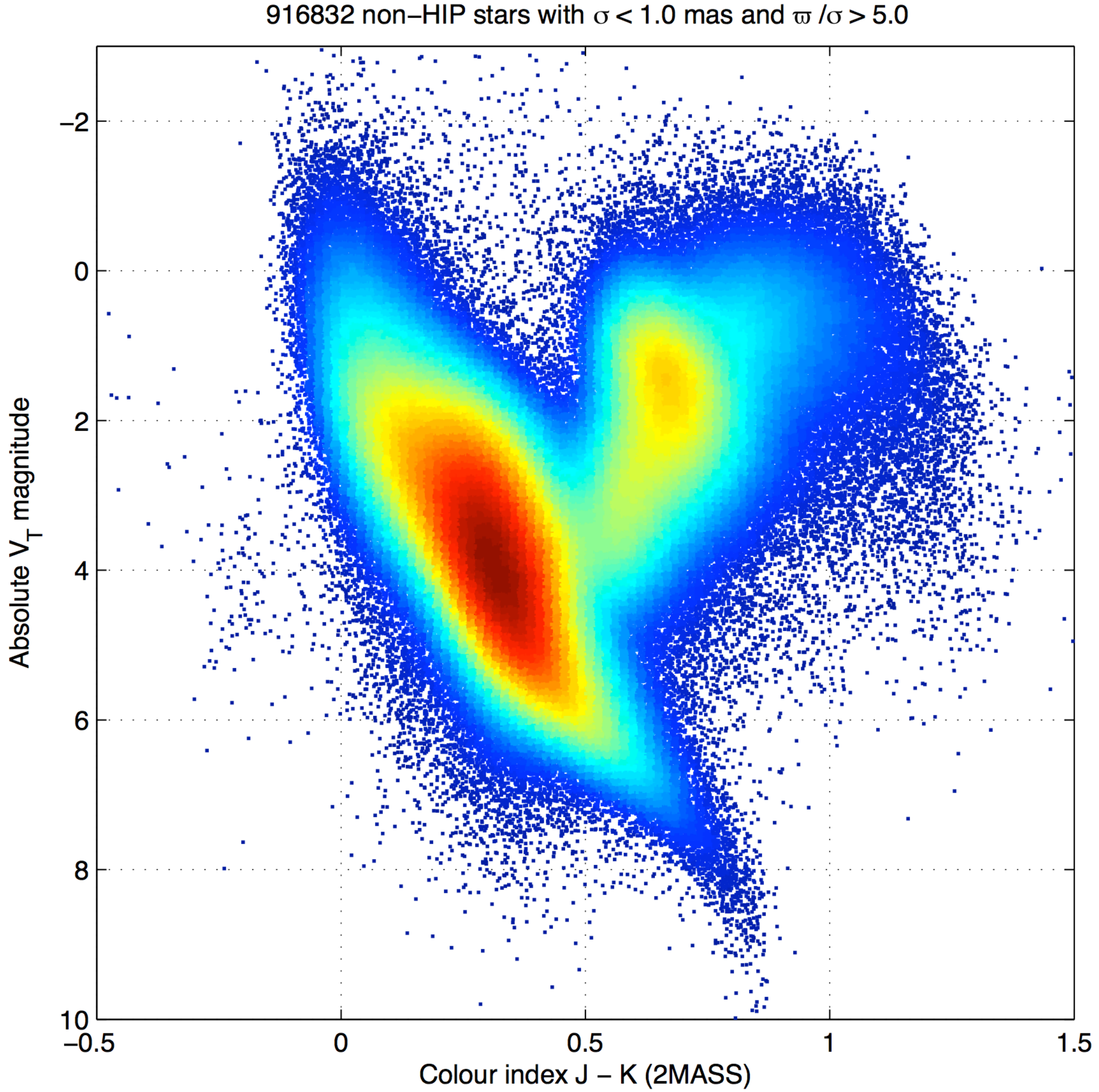
Note: TGAS parallaxes are independent of HIP parallaxes!

(*) van Leeuwen, 2007

Results: HR diagram for non-HIP subset (with BAC) (~481,147 stars with 2MASS col., $\varpi > 0$, $\sigma < 1$ mas, $\varpi/\sigma > 10$)

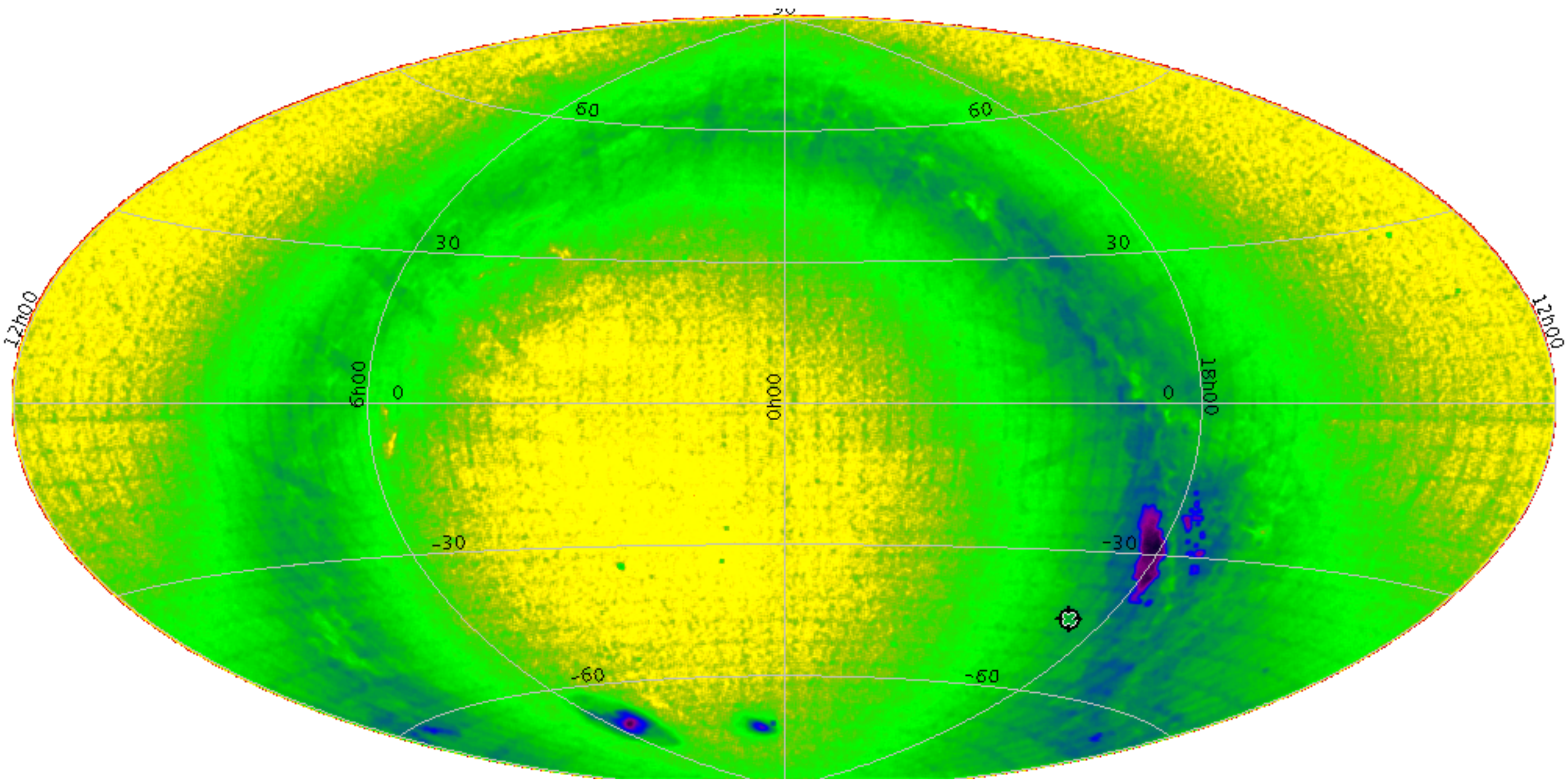


Results: HR diagram for non-HIP subset (with BAC)
(916,832 stars with 2MASS col., ϖ > 0, σ < 1mas, ϖ/σ > 5)

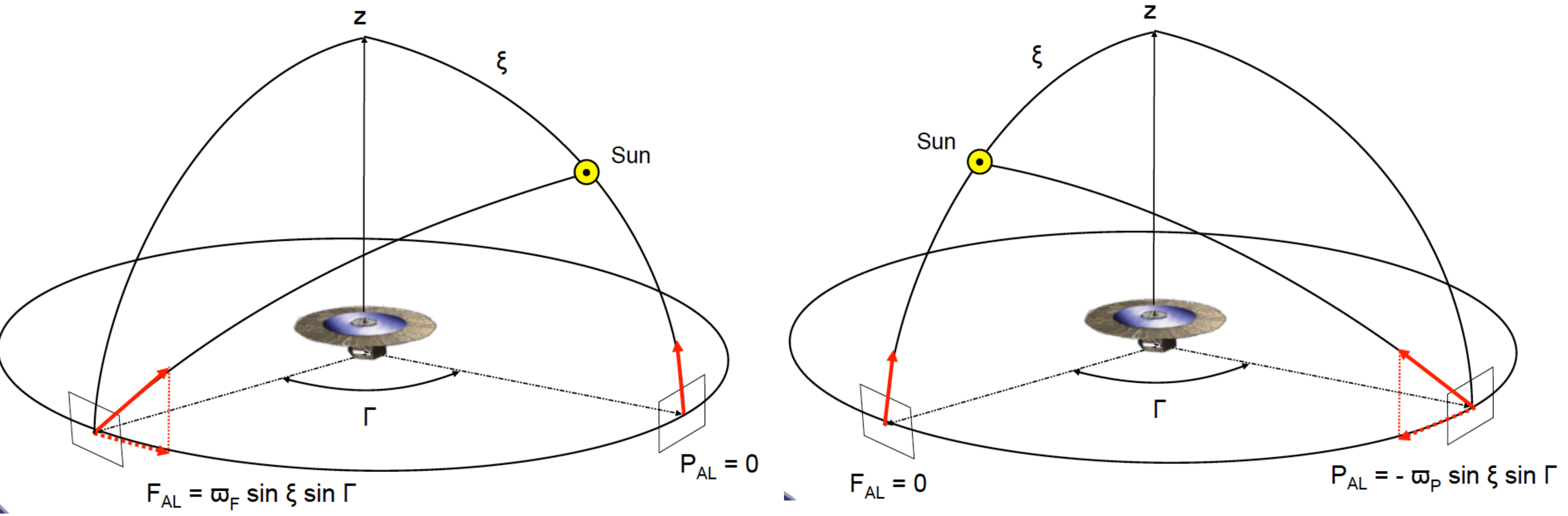


Results: Distribution of sources matched to IGSL in AGIS-00 solution (~1500 Million)

Using attitude + calibrations from the TGAS solution to derive provisional position for all objects seen by Gaia so far (>1.5 Billion)



Absolute parallax measurements and basic angle variations



- The determination of absolute parallaxes is based on differential along-scan measurements between the two FoVs
- This needs a stable Basic Angle Γ
- A signal of the form

Sun azimuth in SRS

$$\Gamma(t) = \Gamma_0 + C_1 \cos(\Omega)$$

has the same effect as a global parallax bias of

$$0.874 C_1$$

Basic Angle Correction (BAC)

- Harmonic model fitted to BAM data

$$\Delta\Gamma(t) = \left(\frac{R(t)}{1\ \mathrm{au}}\right)^{\alpha} \times \sum_{k=1}^{6} \left[C_k \cos(k\Omega) + S_k \sin(k\Omega)\right]$$

with $\alpha = -2.7$ and

C = (853.32, -113.18, -68.44, 19.65, 3.34, 2.91) µas,
S = (657.45 , -81.99, -66.39, 17.94, -0.4, 1.2) µas

- All shown results have been derived with this empirical correction
- The good TGAS results show BAC derived from BAM is essentially correct
- However we have indications that
  - The different harmonics need to be scaled with different factors (all of order 1)
  - There are variations of the BA across the focal plane
- **But: AGIS can solve self-consistently for the harmonics (except for C_1) and (very likely) also for the variations across the focal plane**
  ⇒ work in progress

Concluding remarks

- AGIS is a mathematically sound scheme: Fitness for astrometric catalogue generation demonstrated in numerous pre-launch simulation campaigns
- TGAS conceptually allow to do 5-parameter solutions with less than 1yr of Gaia data
- Preliminary results using data from first 10m of nominal mission look very exciting and promising
  - ~2.2 million parallaxes and proper motions of „Hipparcos-like“ quality
  - ~1 million of very high quality, individually better than „Hipparcos-like“ (σ_ϖ < 0.32 mas)
  - Parallaxes independent of Hipparcos parallaxes
  - Parallaxes and their uncertainties scientifically meaningful
  - Parallax zeropoint uncertain due to basic-angle variations
- Still a lot of detailed work ahead for getting a satisfactory solution, e.g.
  - Micro-meteoroid hits and (perhaps) big micro-clanks
  - No empirical BAV but solving harmonics self-consistently (except C1)
  - Add more data, filling of data gaps, re-generation of raw data affected by bugs in daily pipeline software, …
  - Alignment of calibration unit boundaries to real events
- Biggest worry is the BAV but AGIS still has a lot of „unexplored potential“ to largely mitigate, or ideally, totally solve this problem