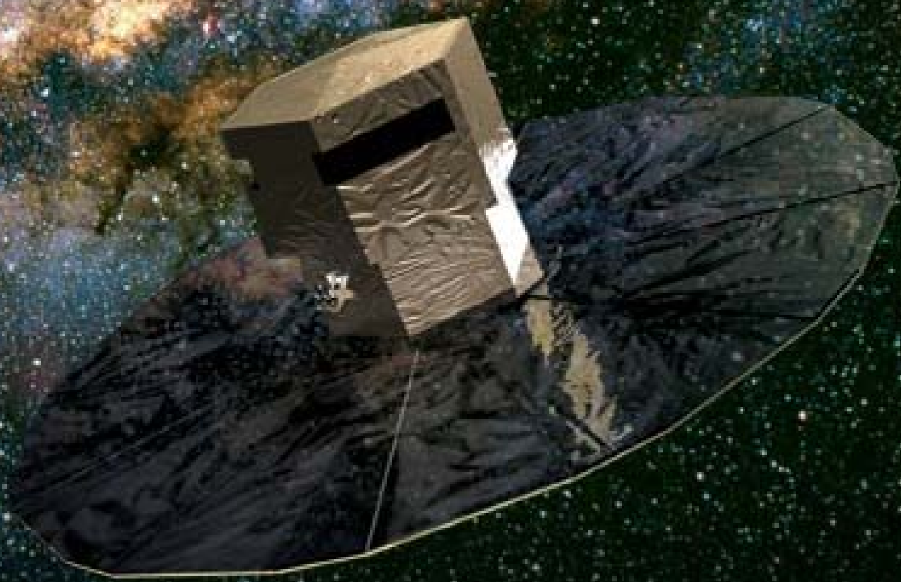
The Gaia mission. Part II

The Science promise



F. Figueras

on behalf of the Gaia team at the Barcelona University

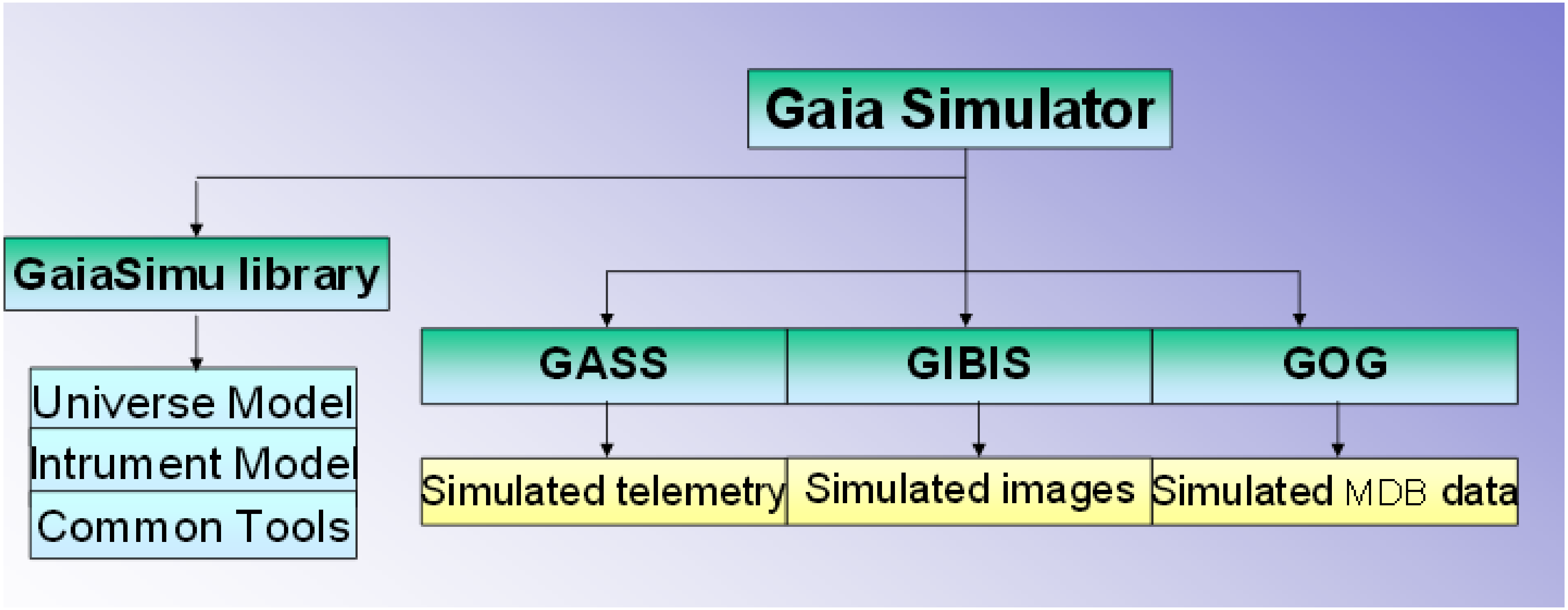
Outline

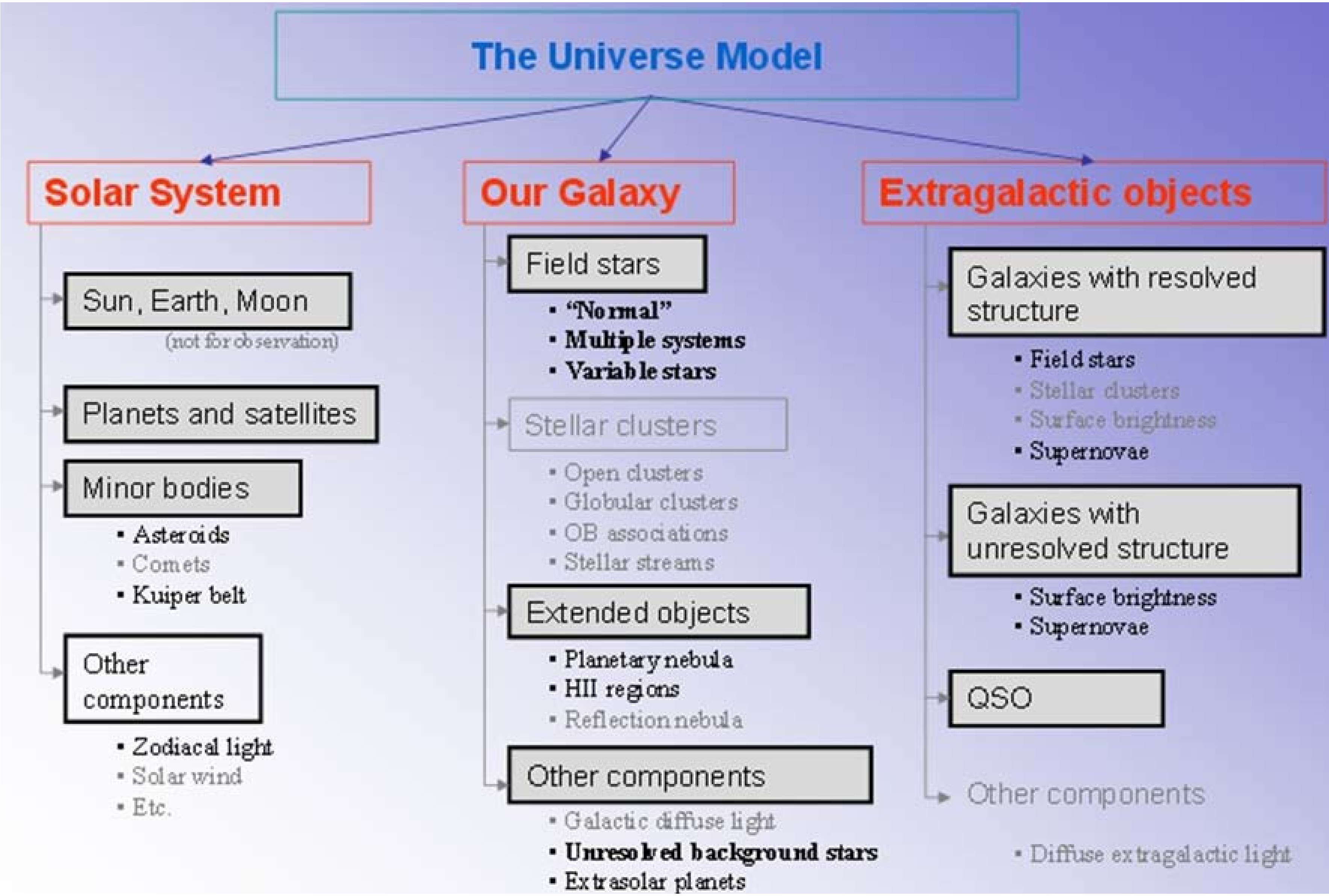
1. **What Gaia will observe**
2. The Data Releases
3. The archive
4. **Gaia Science Performances**
5. The Scientific promise
   Galactic structure and dynamics
6. Towards a chemo-dynamical model of the MW
7. Networks and schools

What Gaia will observe?

The Gaia Simulator(s)

As part of the Gaia Data Processing and Analyzing Consortium (DPAC)

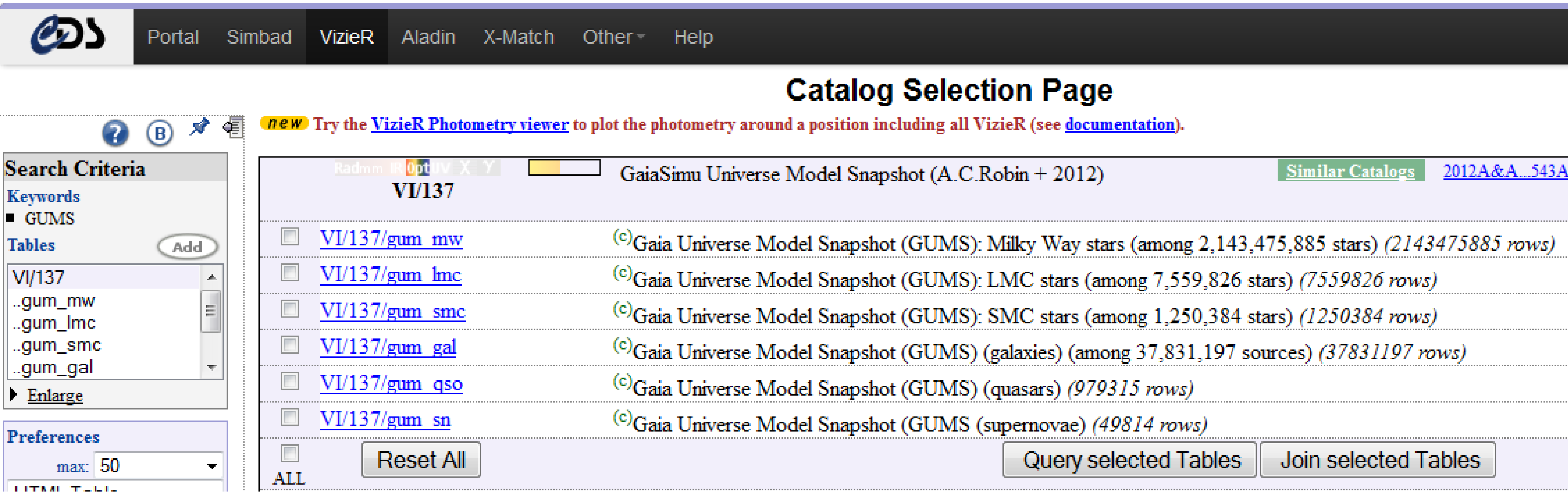




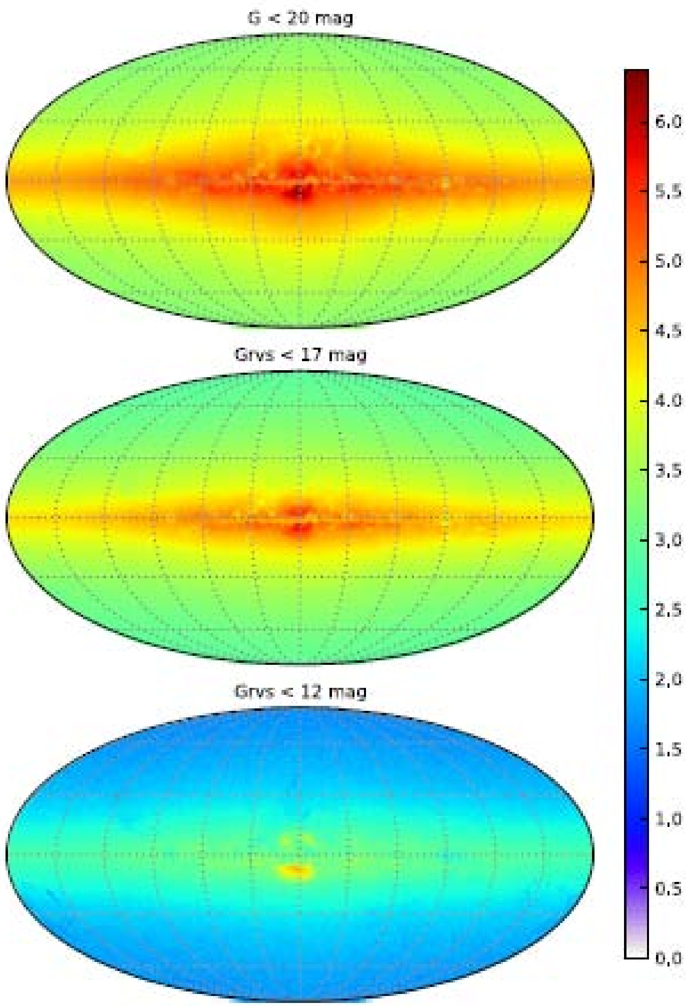
10 years effort!

Gaia Universe Model Simulator (GUMS)

Published: Robin et al. 2012 A&A
Available at CDS



The Gaia Simulator: MW stars



Stars per square-deg (log10)

Besançon Galaxy Model
Drimmel et al. (2003) 3D extinction

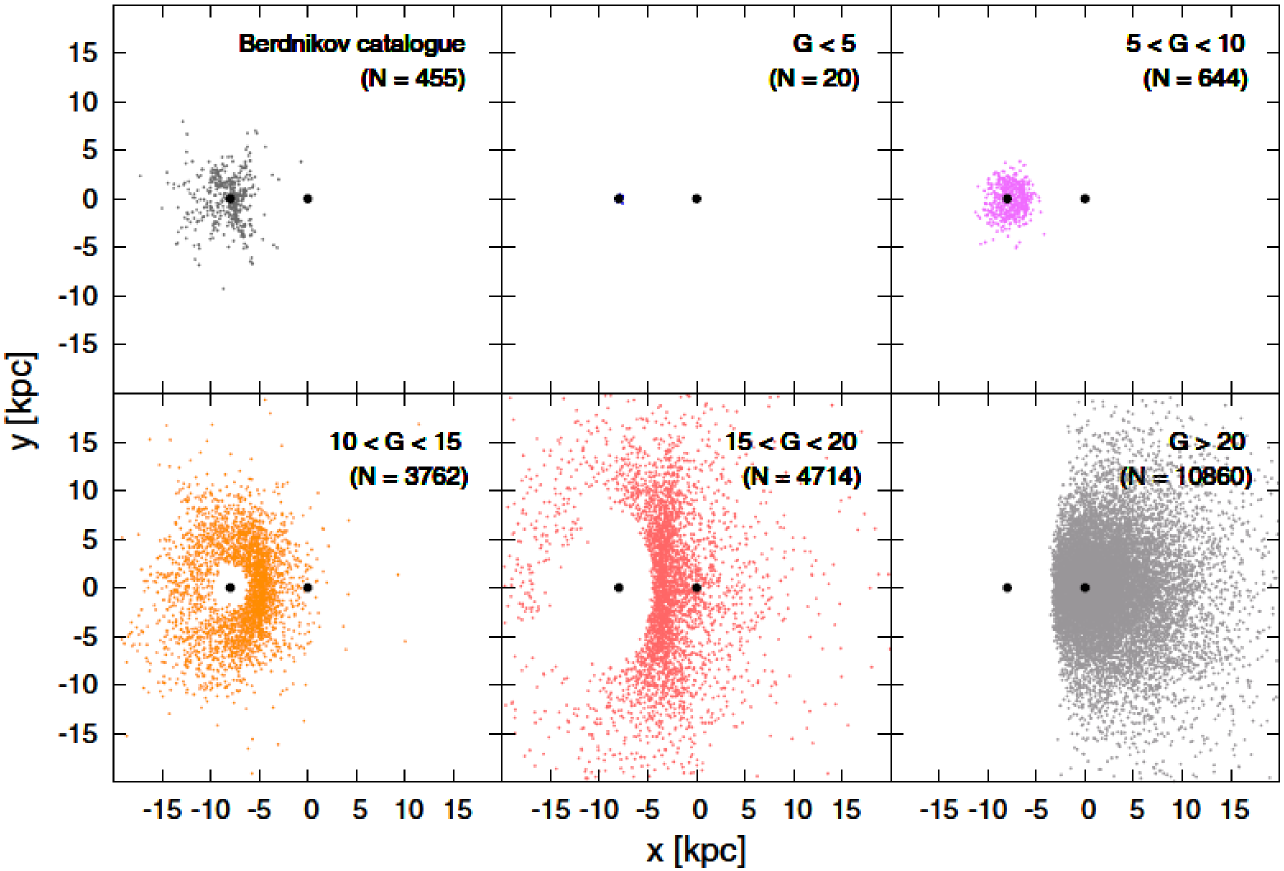
Stars	$G < 20$ mag	$G_{rvs} < 17$ mag	$G_{rvs} < 12$ mag
Single stars	31.59%	25.82%	12.91%
Stars in multiple systems	68.41%	74.18%	87.09%
⇒ *In binary systems*	*52.25%*	51.55%	*40.24%*
⇒ *Others (ternary, etc.)*	*16.16%*	*22.63%*	*46.85%*
Total stars	1 600 000 000	600 000 000	28 000 000
Individually observable	1 100 000 000	390 000 000	13 000 000
⇒ *Variable*	1.78%	3.06%	8.37%
⇒ *With planets*	1.75%	1.44%	0.66%

Variable stars:

Stars	$G < 20$ mag	$G_{rvs} < 17$ mag	$G_{rvs} < 12$ mag
Single variable stars	24.52%	25.79%	28.39%
Variable stars in multiple systems	75.48%	74.21%	71.61%
⇒ *In binary systems*	55.74%	52.65%	38.49%
⇒ *Others (ternary, etc.)*	19.73%	21.55%	33.12%
Total variable stars	28 000 000	19 000 000	2 700 000
Individually observable	21 500 000	16 000 000	2 000 000
With planets	2.09%	2.64%	2.09%

The Cepheids

Gaia will observe ~6000-9000 Galactic Cepheids (60-70% multiple systems)



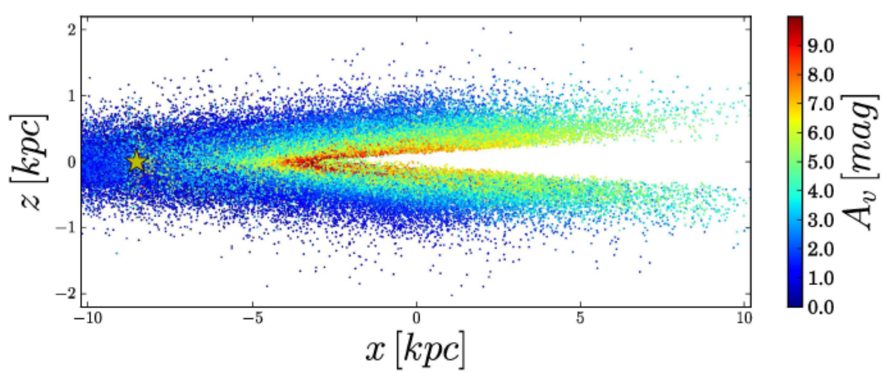
H. Leavitt, 1912

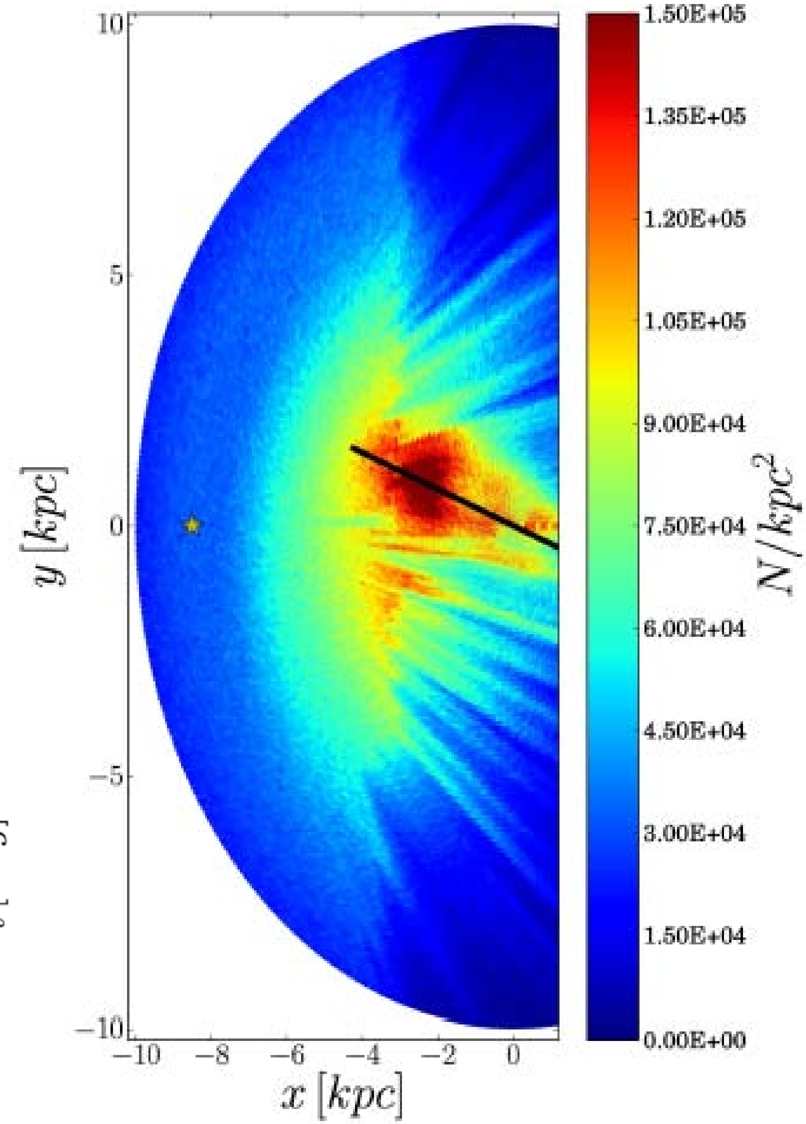
Windmark et al., 2011

Disk Red Clump Stars

	Number of stars
RC-all	57×10^6
RC-G20	26×10^6
RC-RVS	8.5×10^6

3D test particle simulations
3D extinction model
Gaia observational constraints





The Gaia Simulator: extragalactic objects

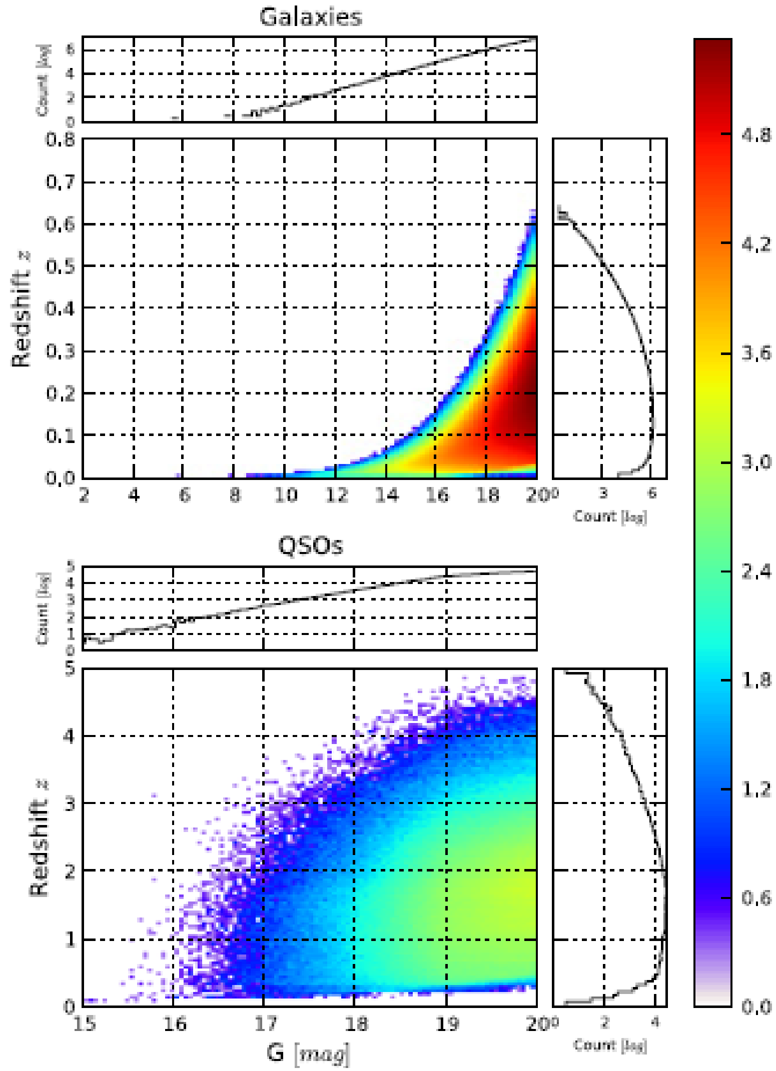


Fig. 21. Redshift and G relation for galaxies and QSOs. Colour scale indicates the $\log_{10}$ of the number of objects per 0.05 mag and 0.05 redshift difference.

Unsolved Galaxies

$\sim 3.8 \cdot 10^6$

$Z < 0.8$

Quasars

$\sim 5 \cdot 10^5$

$Z < 4$

Data Releases and Archive

Gaia Data Release Scenario

<u>From now on</u>:

Photometric science alerts

Near-Earth-asteroid information

<u>Summer 2016</u>

Positions + G magnitude (~all sky, single stars)

Calibrated Ecliptic pole data

The Hundred Thousand Proper Motion (HTPM) – Hipparcos

<u>Early 2017</u>

Five parameters astrometric solution (single stars)

Radial velocities for non-variable RV stars

Two-band photometry (+ Astrophysical parameters)

Gaia Data Release Scenario

2017/2018:

Orbital solutions for binaries

BP/RP and RVS spectra, object classification & AP

Mean Radial Velocities

2018/2019

Variable stars classifications + epoch photometry

Solar System results (orbital solution & epoch data)

Non single stars

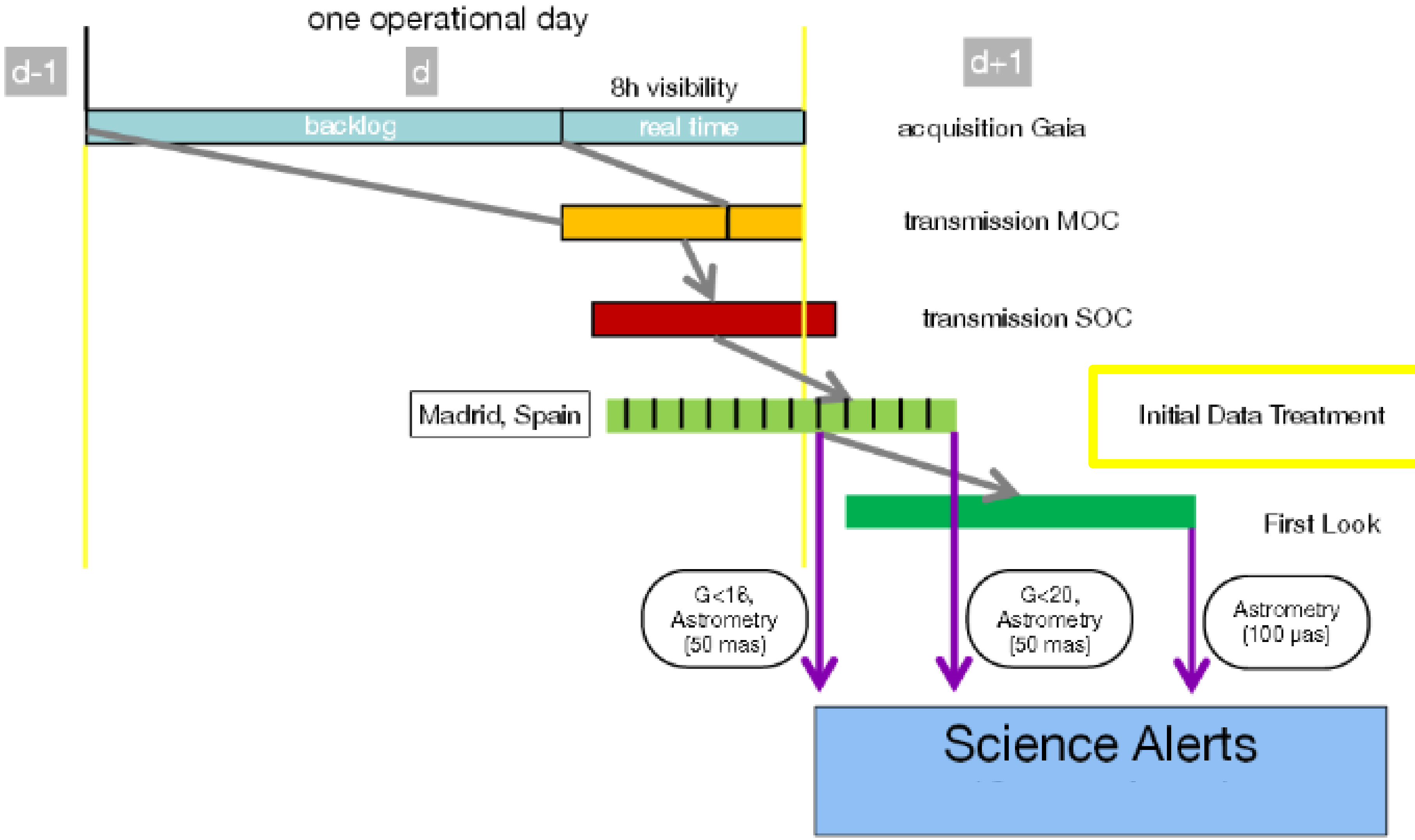
2020-2022: Final Release

All data archive (epoch + end-of-mission data)

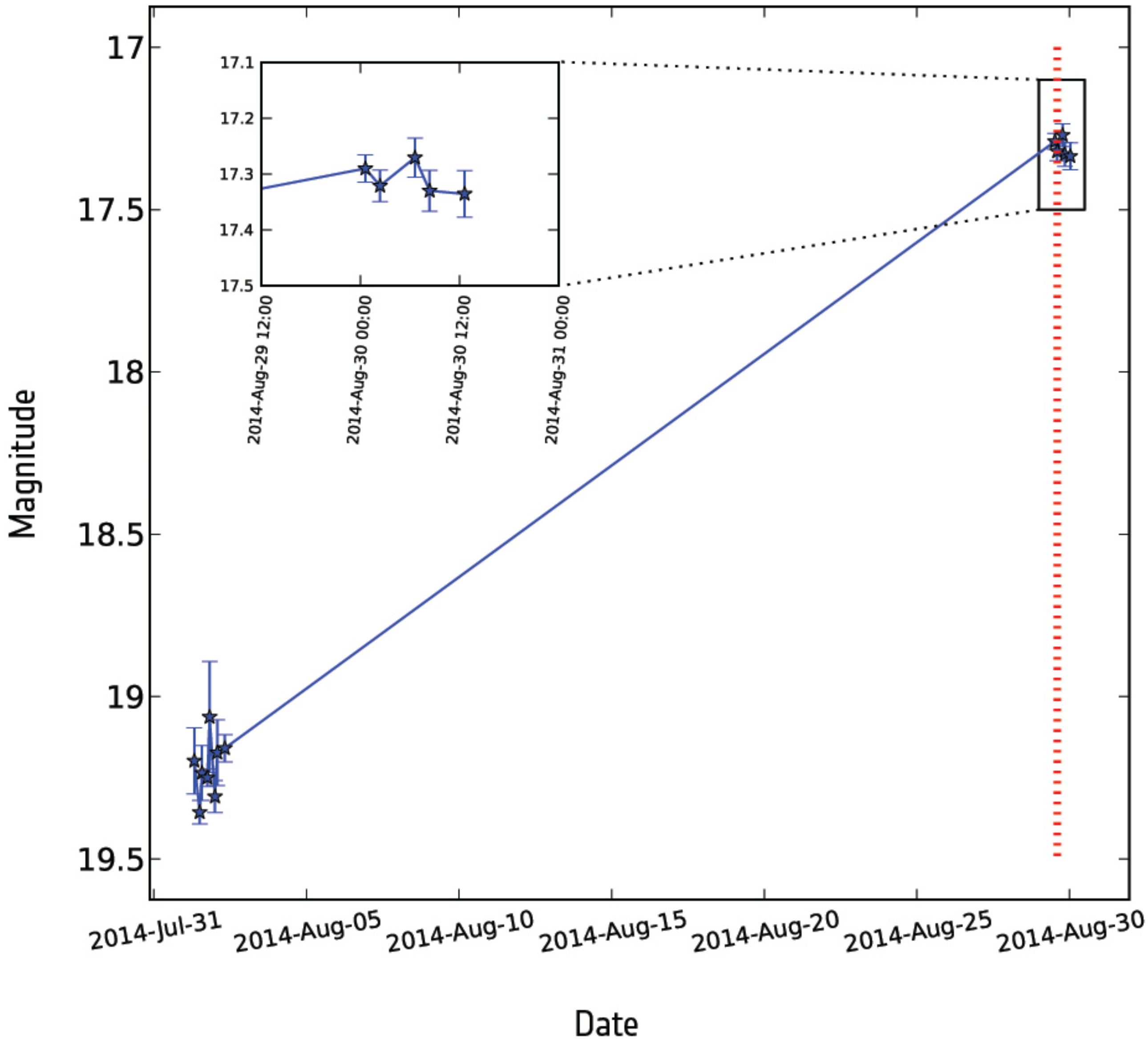
The first SNIa detected by Gaia

August, 2014

Timeline for Data Flow

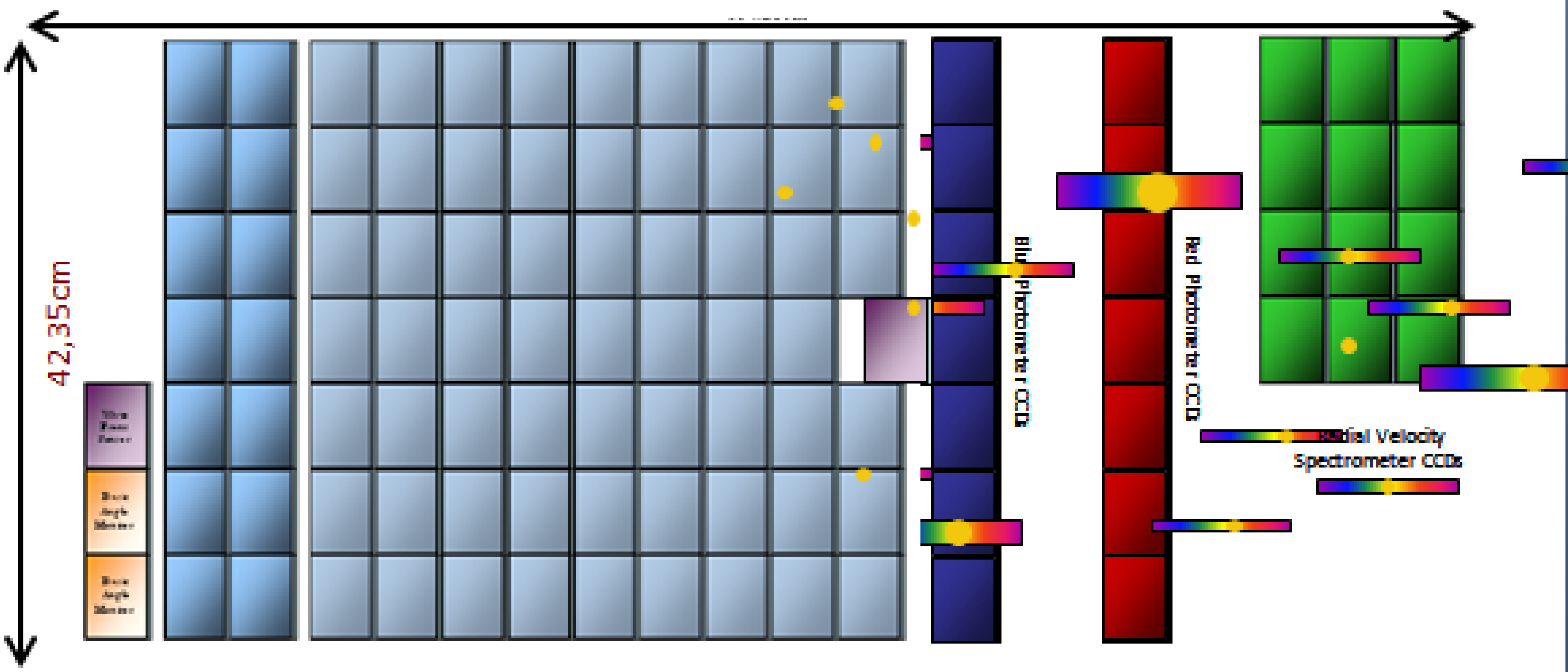


Gaia light curve of galaxy SDSS J132102.26+453223.8

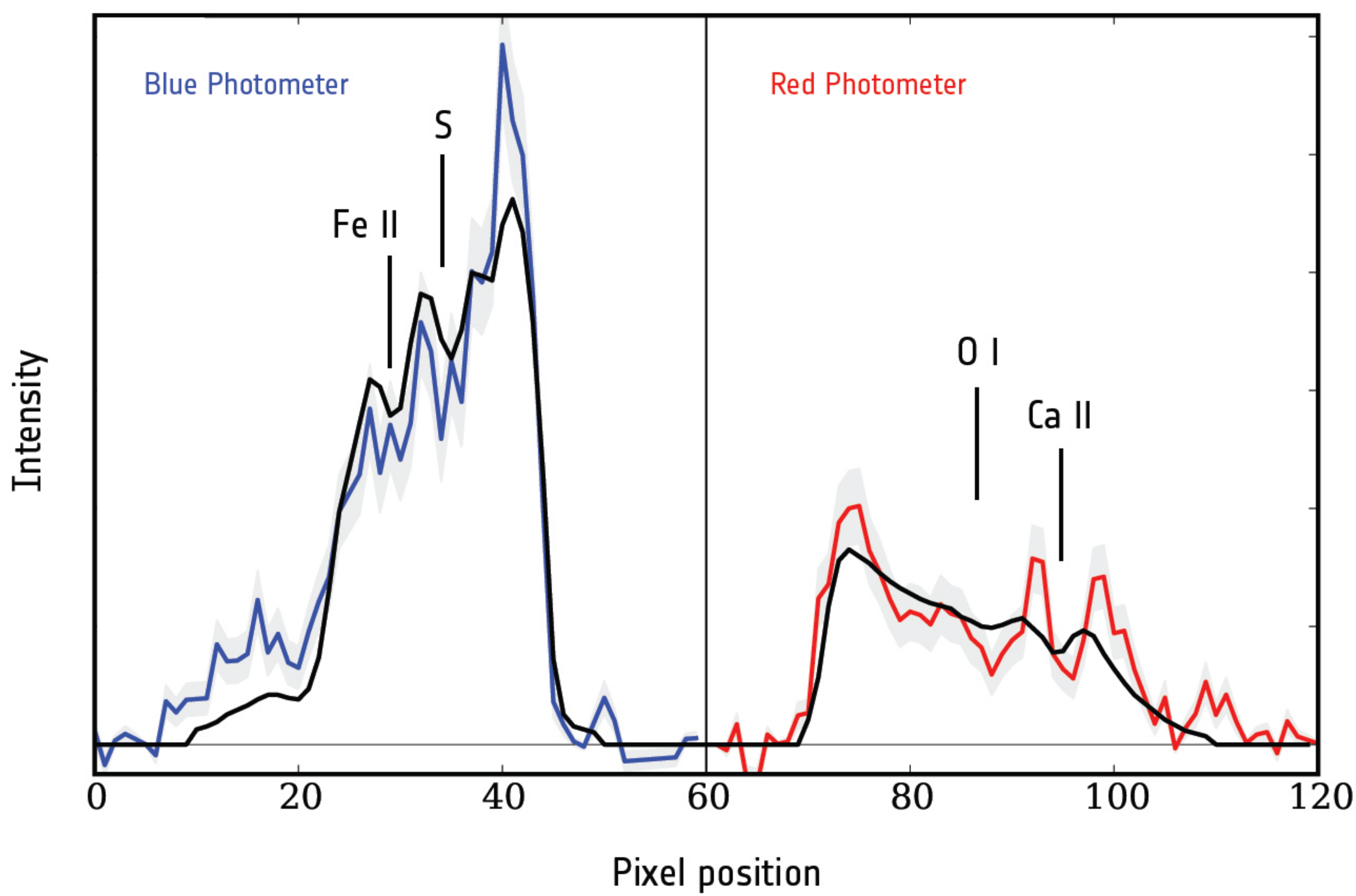


Scanning Space Astrometry:

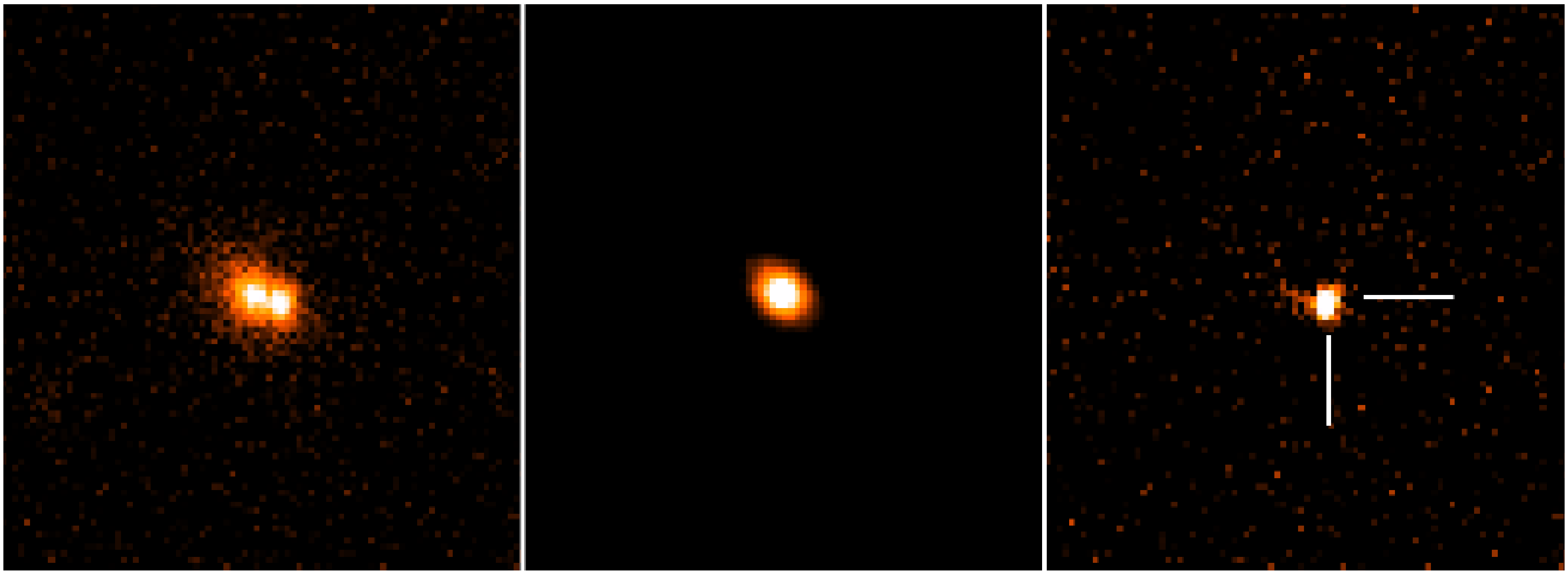
to transform positional information into timing data



Gaia low-resolution spectrum of Gaia2014aaa



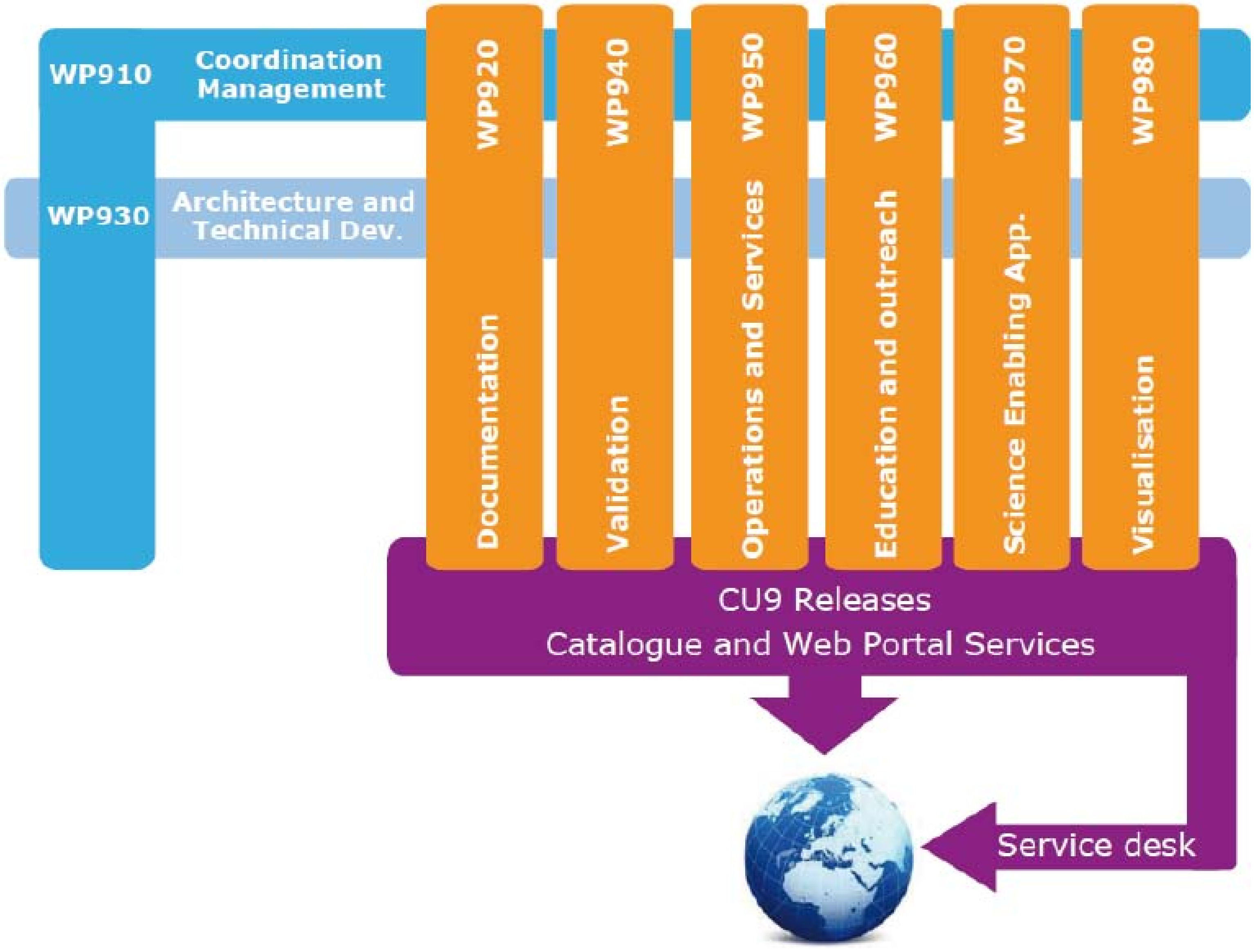
Supernova Gaia14aaa and its host galaxy



Caption: This image shows the supernova named Gaia14aaa as seen on 10 September 2014 with the robotic Liverpool Telescope on La Palma, in the Canary Islands, Spain. This is a Type Ia supernova – the explosion of a white dwarf locked in a binary system with a companion star

The Gaia Archive

A huge collective effort
2012-2022



WP910
Coordination Management
WP930
Architecture and Technical Dev.
WP920
Documentation
WP940
Validation
WP950
Operations and Services
WP960
Education and outreach
WP970
Science Enabling App.
WP980
Visualisation
CU9 Releases
Catalogue and Web Portal Services
Service desk

Gaia Science Performances

Nominal mission

(BL: Before launch)

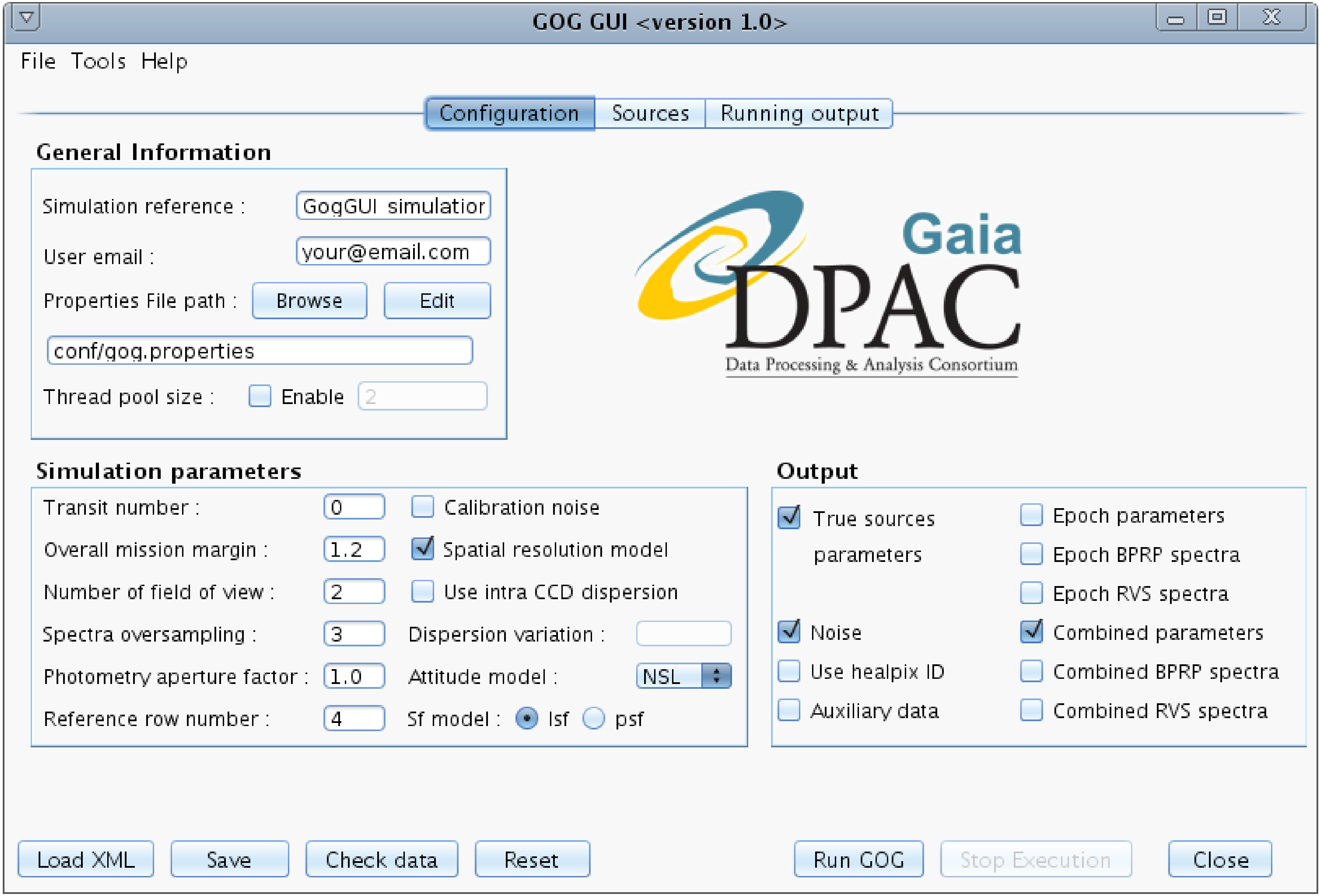
After commissioning (AC)

http://www.cosmos.esa.int/web/gaia/science-performance

GOG: Gaia Object Generator

An attempt to simulate Gaia products
GUMS + a model for Gaia errors

Goals:
To fill the Gaia Archive
For Science Exploitation


GOG GUI <version 1.0>
File Tools Help
Configuration
Sources
Running output
General Information
Simulation reference :
GogGUI simulatior
User email :
your@email.com
Properties File path :
Browse
Edit
conf/gog.properties
Thread pool size :
Enable
2
Gaia
DPAC
Data Processing & Analysis Consortium
Simulation parameters
Transit number :
0
Calibration noise
Overall mission margin :
1.2
Spatial resolution model
Number of field of view :
2
Use intra CCD dispersion
Spectra oversampling :
3
Dispersion variation :
Photometry aperture factor :
1.0
Attitude model :
NSL
Reference row number :
4
Sf model :
lsf
psf
Output
True sources parameters
Epoch parameters
Epoch BPRP spectra
Epoch RVS spectra
Noise
Combined parameters
Use healpix ID
Combined BPRP spectra
Auxiliary data
Combined RVS spectra
Load XML
Save
Check data
Reset
Run GOG
Stop Execution
Close

Astrometric standard errors

The mean end-of-mission standard error for parallax includes:

- all known instrumental effects
- an appropriate calibration error
- 20 % margin (results from the on-ground data processing are not included)

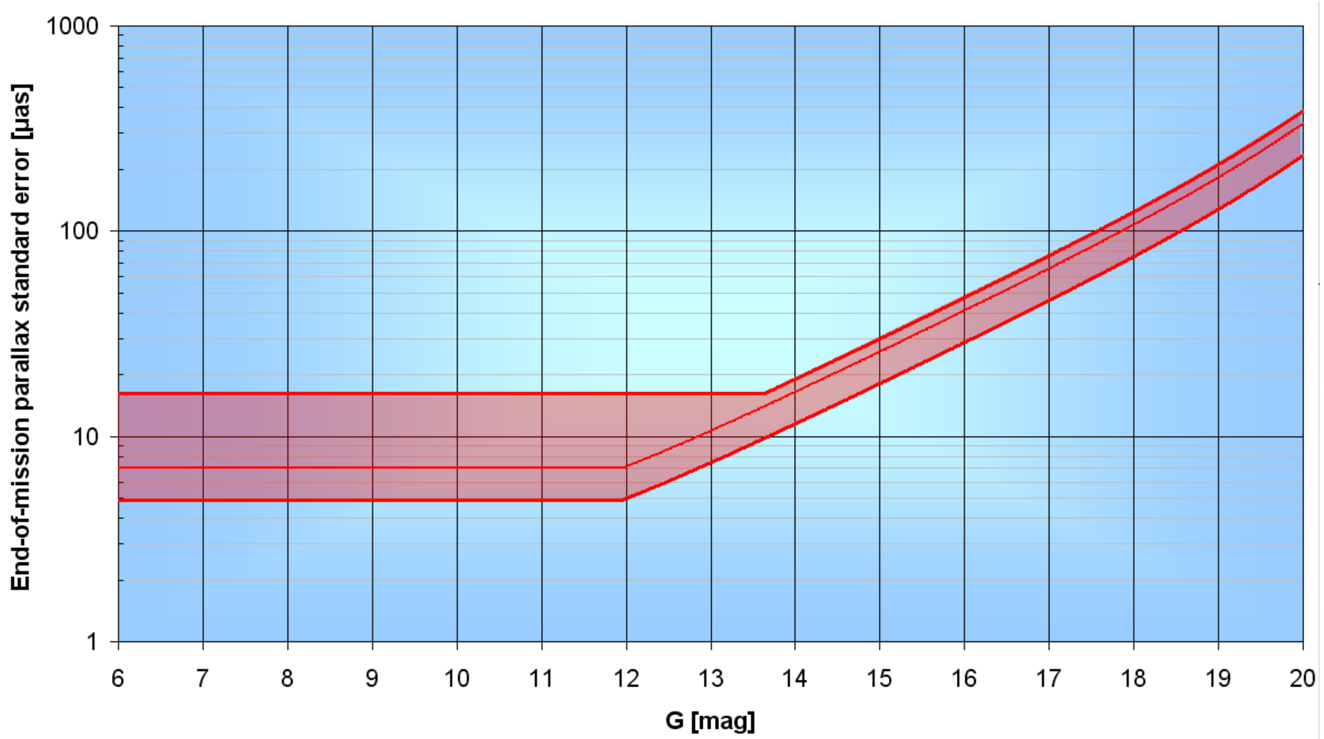
$$\sigma_\pi \,[\mu as] = (9.3 + 658.1 \cdot z + 4.568 \cdot z^2)^{1/2} \cdot [0.986 + (1 - 0.986) \cdot (V\text{-}I_C)],$$

where

$$z = \mathrm{MAX}[10^{0.4 \cdot (12 - 15)}, 10^{0.4 \cdot (G - 15)}], \qquad \text{(BL)}$$

It depends sensitively on the adopted TDI-gate scheme (G < 12 mag)
(The decrease of the CCD exposure time to avoid saturation of the pixels)

End-of-mission parallax standard error (BL)



For bright stars (G<12 mag) the standard error is dominated by calibration errors, not by the photon noise

Astrometric performance (AC)

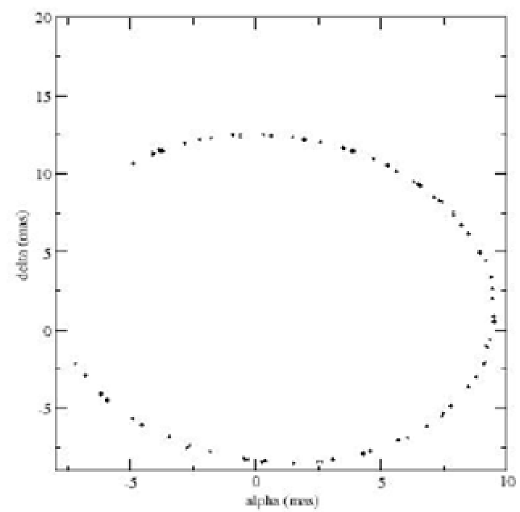
End-of-mission (5 years)

	B1V	G2V	M6V
$V\text{-}I_C$ [mag]	-0.22	0.75	3.85
Bright stars	5-14 µas (3 mag < V < 12 mag)	5-14 µas (3 mag < V < 12 mag)	5-14 µas (5 mag < V < 14 mag)
V = 15 mag	26 µas	24 µas	9 µas
V = 20 mag	600 µas	540 µas	130 µas

Single focal plane crossing

4.3 times worse than the end-of-mission

GOG epoch data for a binary system
(units: mass)



Astrometric end-of-mission errors

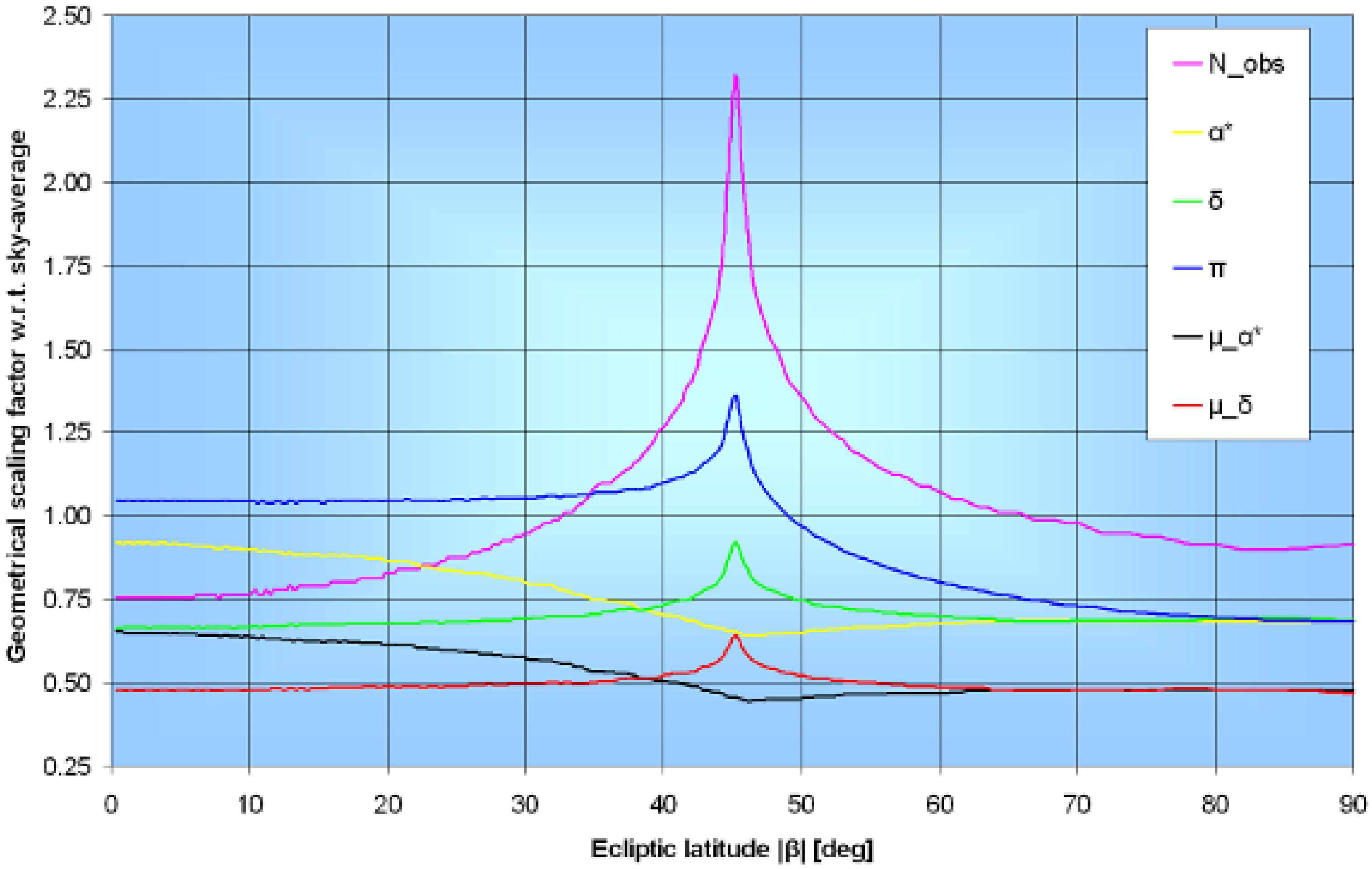
They depend on the scanning law:

1) Take into account the individual number of transits
2) Multiply the mean value by a geometrical scaling factor (g)

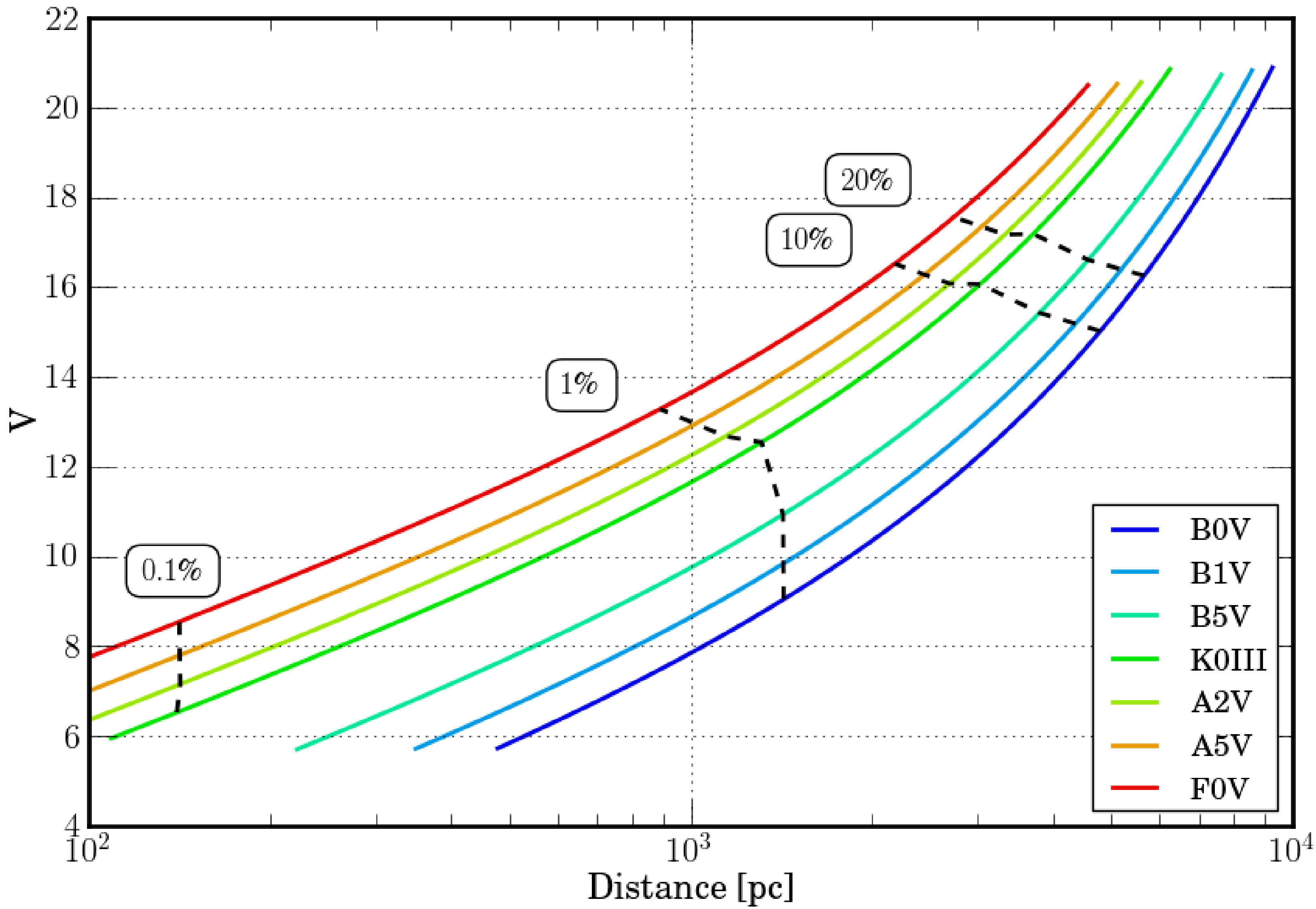
Geometrical scaling factor:

Each particular transit does not carry the same astrometric weight. The weight depends on the angle between the along-scan direction (where we make the measurement) and the circle from the star to the Sun (the parallax shift is directed along this circle).
Therefore, a large number of transits does not guarantee a small parallax error

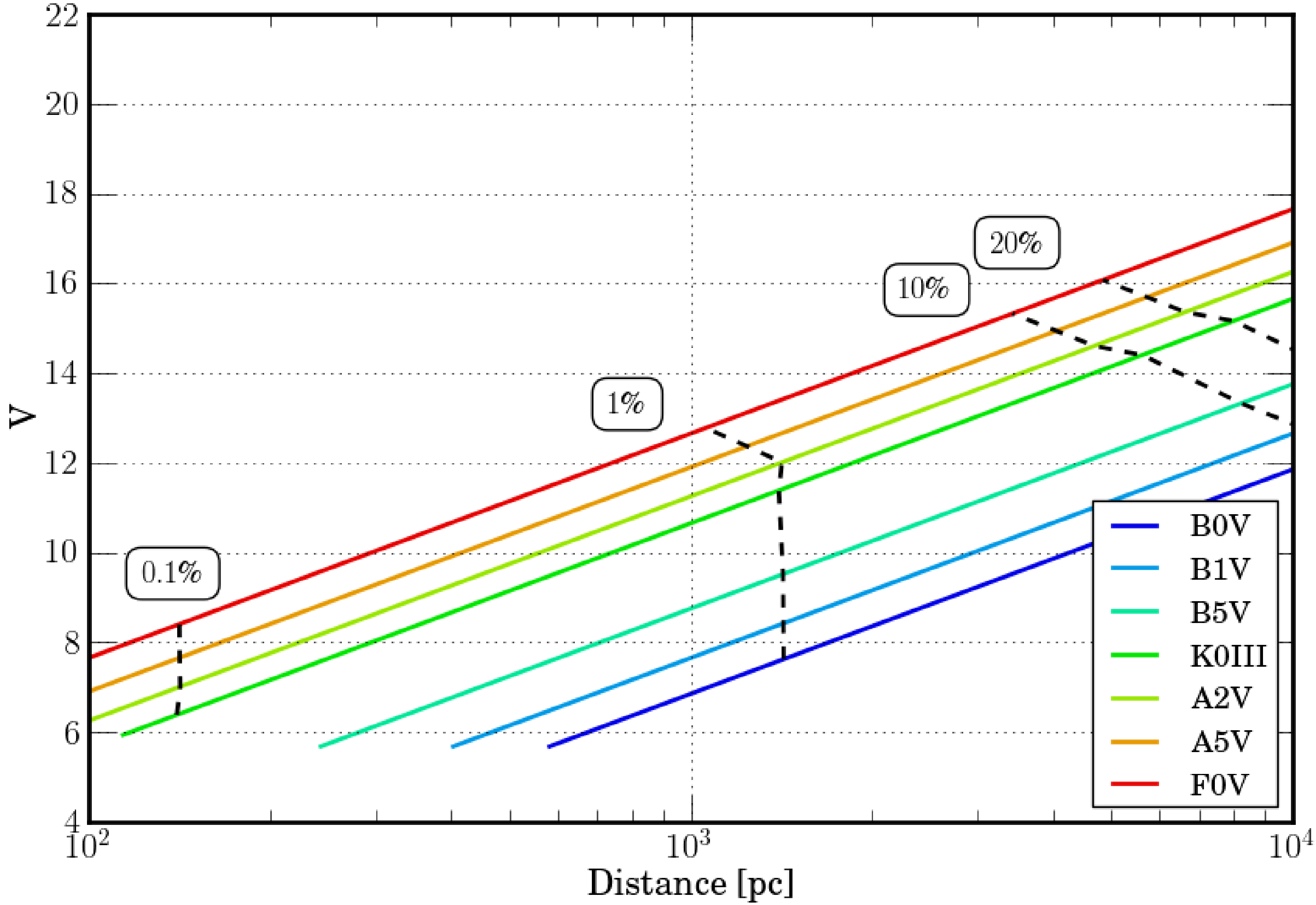
Geometric factor: a function of ecliptic latitude (β)



Gaia Parallax accuracy in the disk (Av =1mag/kpc, BL)



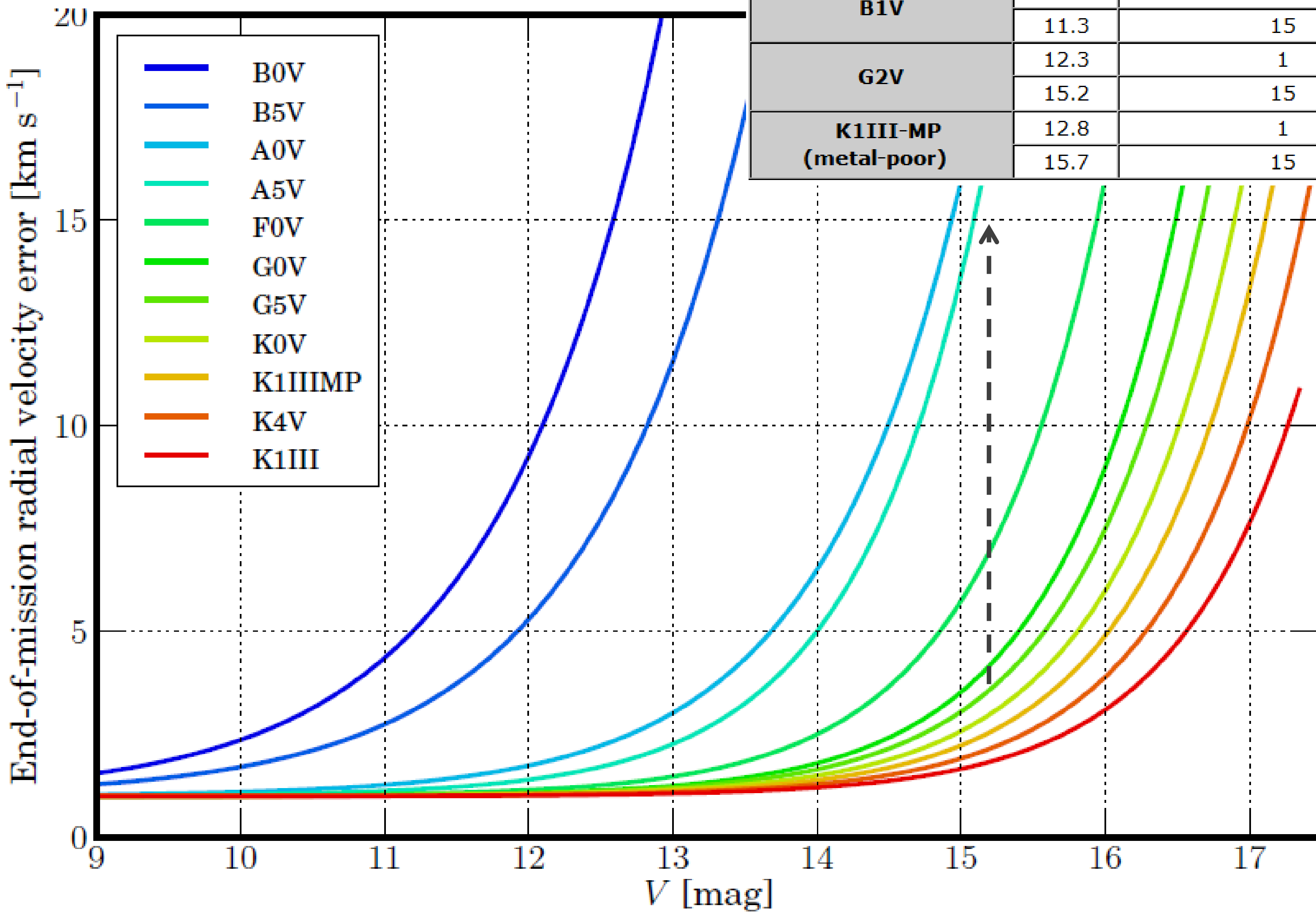
Gaia Parallax accuracy in the halo (Av =0, BL)



Gaia Radial Velocities – RVS

- Slitless spectroscopy in Ca triplet region

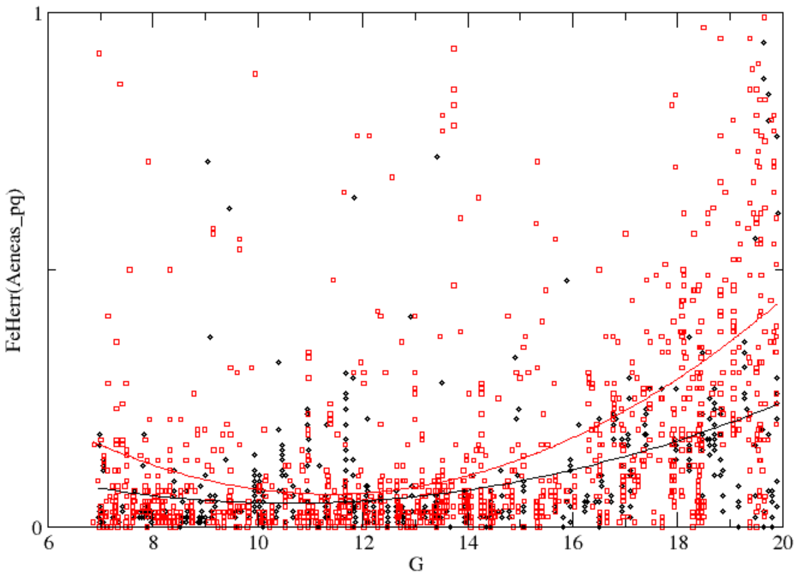
Before launch performances



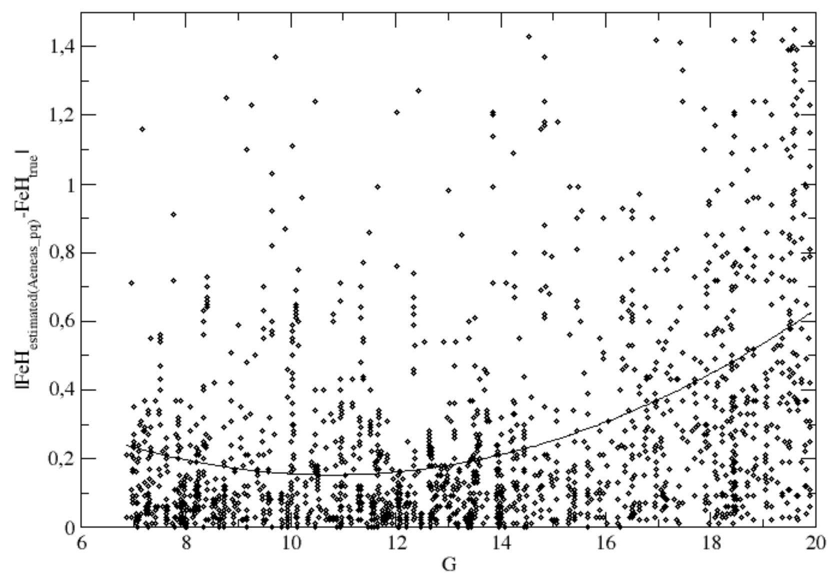
Spectral type	V [mag]	Radial-velocity error [km s^{-1}] (AC)
B1V	7.5	1
	11.3	15
G2V	12.3	1
	15.2	15
K1III-MP (metal-poor)	12.8	1
	15.7	15

[Fe/H] (from BP+RP+π)

Before launch performances



Aeneas-pq precision



|estimated values from Aeneaspq – true|

FGK star G=15: 0.1-0.2 dex accuracy

Liu et al. (2012), Antiche et al. (2013)

A critical degeneracy between Teff and Ao (extinction) is present

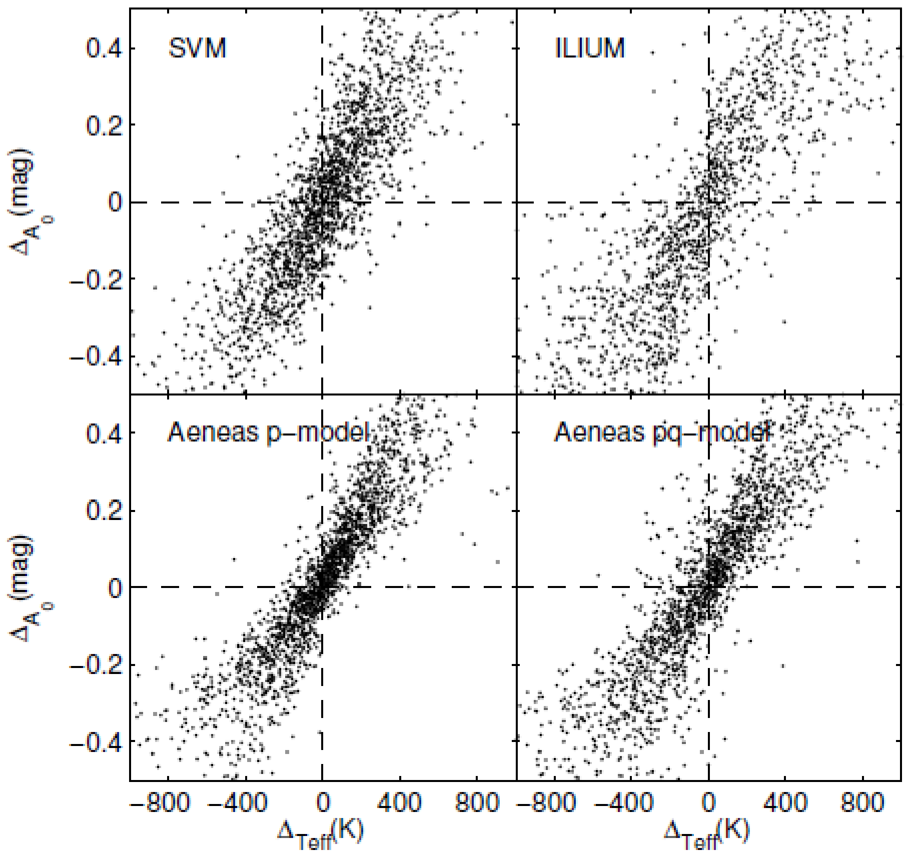


Figure 10. The correlation between the $T_{\rm eff}$ and A_0 residuals for stars with $G = 15$ mag (upper panels) and $G = 19$ mag (lower panels) for all four methods.

(Liu et al., 2012)

Scientific promise

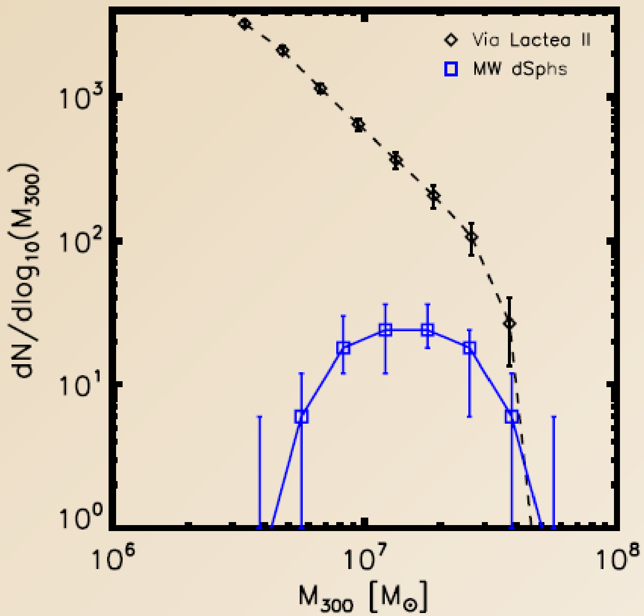
Searching for the ultra-faint dwarfs galaxies

An example of a collaborative effort
Research ang engineers from different disciplines

Aguilar, Luis (IA-UNAM/México)
Antiche, Erika (Univ. Barcelona/Spain
Antoja, Teresa (ESA/The Netherlands)
Aparicio, Antonio (IAC/Spain)
Brown, Anthony (Leiden/The Netherlands)
Figueras, Francesca (Univ. Barcelona/Spain)
Hidalgo, Sebastian (IAC/Spain)
Mateu, Cecilia (CIDA/Venezuela)
Valenzuela, Octavio (IA-UNAM/México)
Velázquez, Hector (IA-UNAM/México)

Missing satellite problem

Bullock 2010



Before by:
Kauffmann et al. (1993)
Klypin et al. (1999)
Moore et al. (1999)

observed
~25 satellites
with L> $10^3 L_\odot$

!?

expected
~400

~15 new satellites
in SDSS/SEGUE

Ultra Faint Dwarf Galaxies

Willman et al. (2005)
Zucker et al. (2006)
Grillmair (2006), (2009)
Majewski et al. (2007)
Belokurov et al. (2007, 2009)
Martin et al. (2009)

- $L \simeq 10^2 - 10^5 L_\odot$
- rh~20-800 pc
- distances 20-200 kpc
- high stellar velocity dispersion (~4-10 km/s)
- higher M/L ratios 10^2-10^3
- very metal poor

Method

Theoretical model

positions
kinematics
population

simulate "Gaia" observations

1) Observation limits

2) Model for errors

- G magnitude
- G-V colour
- sky position

→

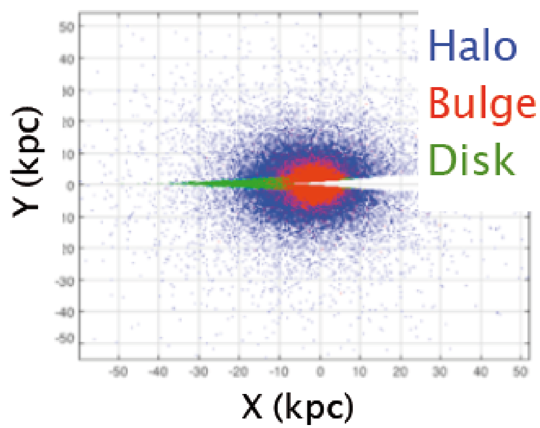
- $e\pi$
- $e\alpha,\delta$
- $e\mu$
- eRV

Gaia Mock Catalog

UF

Galaxy

GUMS
Gaia Universe
Model Snapshot

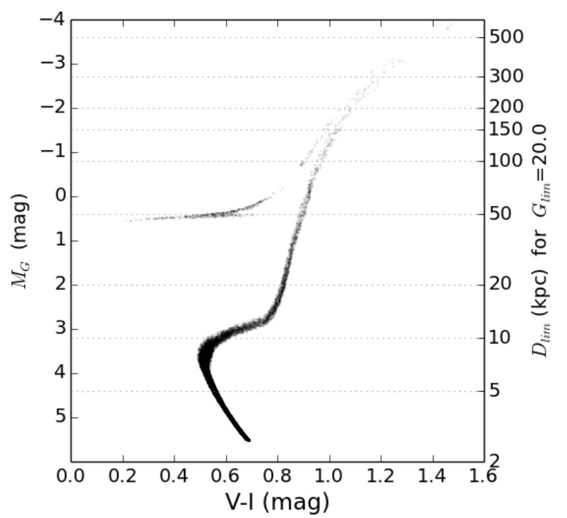


Generation of UF

- <u>Density & kinematics:</u>
  Isotropic Plummer sphere

$$\rho = \frac{3M}{4\pi b^3}\left(1+\frac{r^2}{b^2}\right)^{-5/2}$$

- <u>Population (light model):</u>
  - ✦ single age (10 Gyr)
  - ✦ metal poor [Fe/H]~−1.5
  - ✦ mixed in position



9 PARAMETERS

		ranges
intrinsic	rh (pc)	5−1000
	σV (km/s)	1−100
	Lv ($L_\odot$)	$10^2 - 10^5$
phase space coordinates	dist (kpc)	5−500
	l (deg)	0−360
	b (deg)	0− ±90
	Vgal (km/s)	100−500
	ϕ (deg)	0−360
	θ (deg)	0−360

→

M/L	$10^2 - 10^6$
M* ($M_\odot$)	$10 - 10^4$
Nobs	$10 - 10^5$

- e π ~100%
- no RV

→ search in l, b, μl, μb

ID	L_v ($L_\odot$)	rh_p (pc)	σ_V (km s^{-1})	D (kpc)	l (deg)	b (deg)	V_{gal} (km s^{-1})	ϕ (deg)	θ (deg)	M/L ($M_\odot/L_\odot$)	M_{st} ($M_\odot$)	$Nobs$
30009	$9 \cdot 10^2$	50	5	15	90	30	107.	0.	20.	55.	80.	99

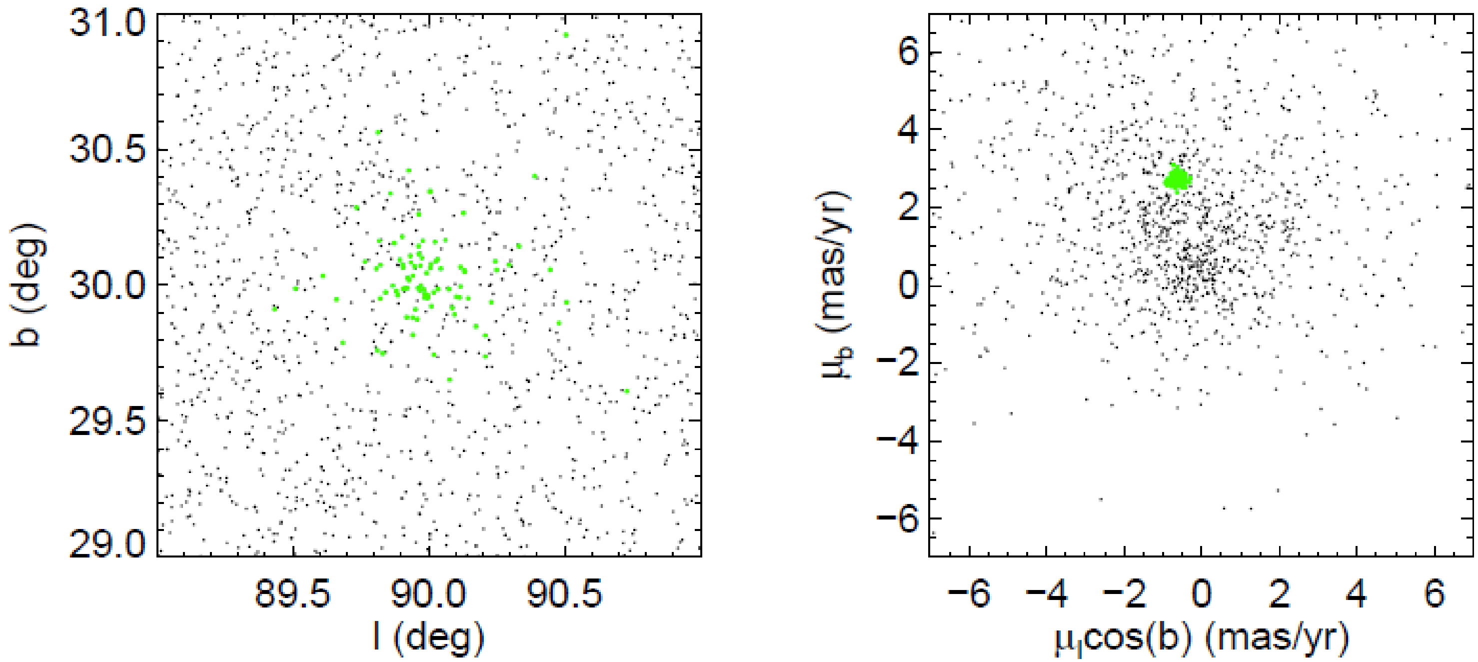


Figure 1. Sky (left) and proper motion plane (right) for the field of UFDG 3009. The stars belonging to the UFDG are shown as green dots while the foreground and background stars are in black.

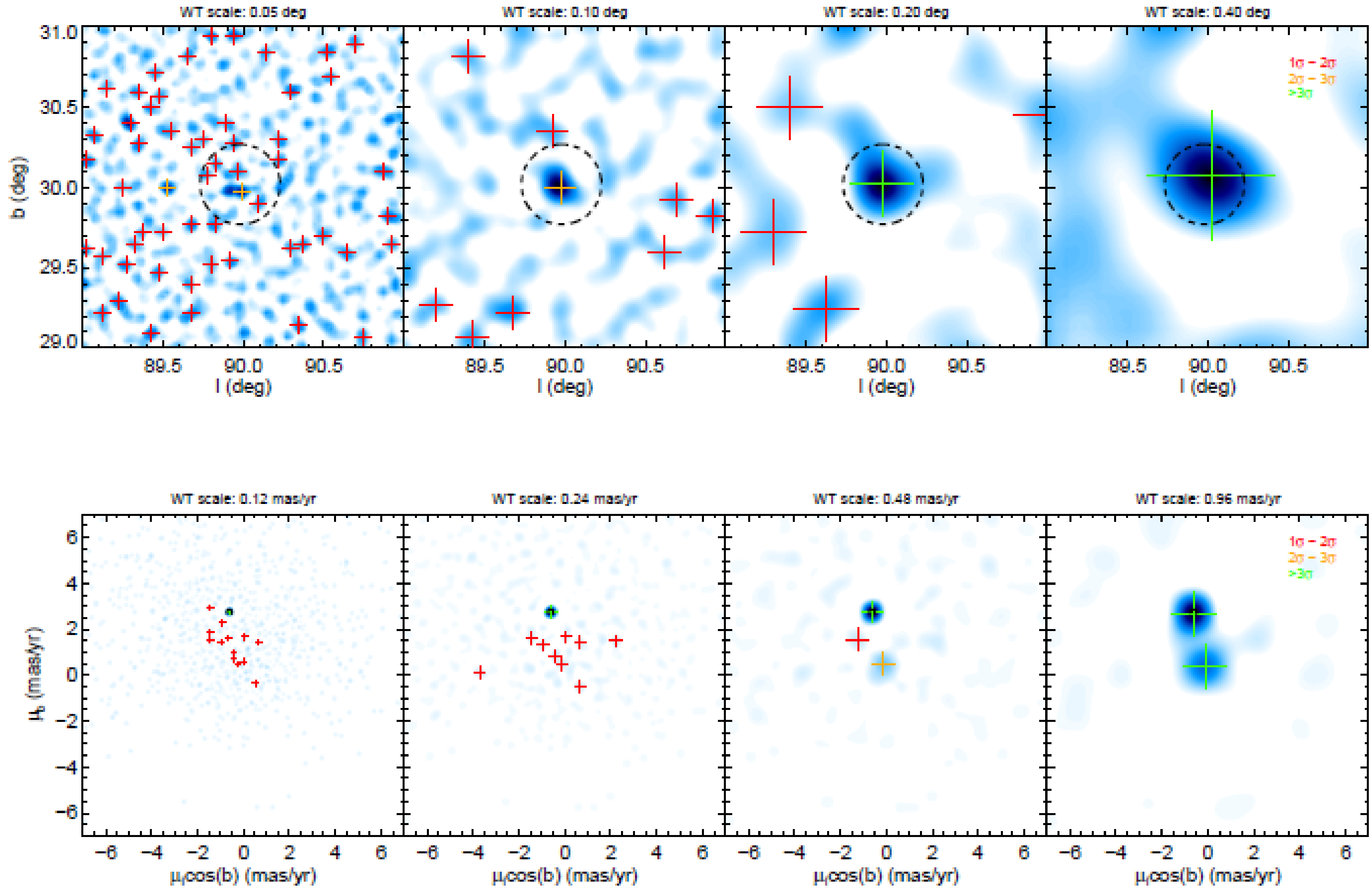
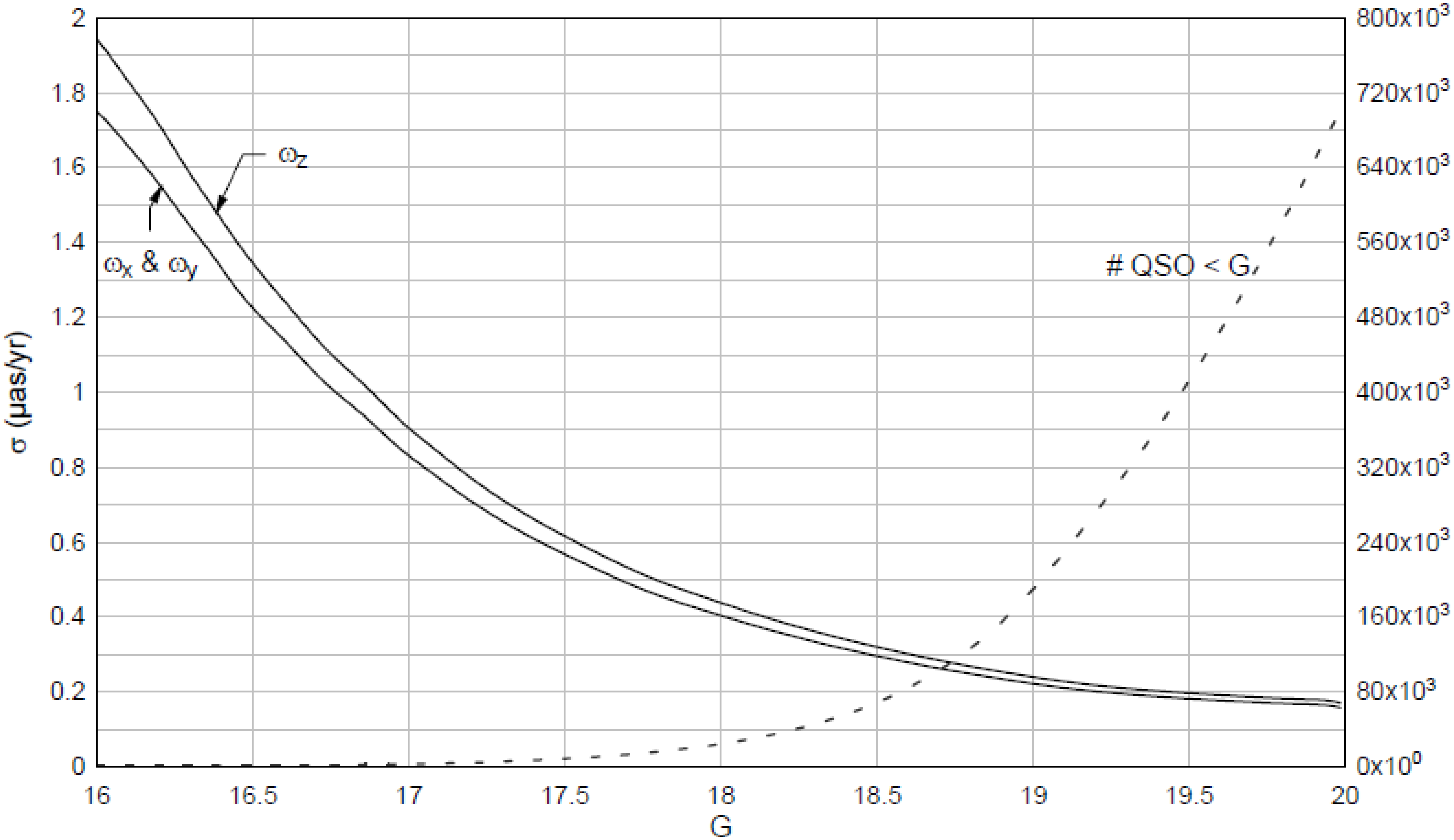


Figure 3. Wavelet Transform (WT) at different scales for UFDG 3009 for the sky (top) and proper motion plane (bottom). The black dashed circle shows the true position and size of the UF. The position is calculated as the median of the positions of the stars in the UF that are observed by Gaia and the size of the circle is simply the maximum between the standard deviation of the l and b coordinates. Red, orange and green crosses indicate peaks at between 1 and 2, between 2 and 3, and $> 3\ \sigma$ significance, respectively.

Inertiality of the Gaia Celestial Reference Frame



Accuracy of the residual rotation (units: μas/yr), Mignard (2011)

The distance to LMC and SMC

GUMS: Based on a real catalogue, $7.5 \cdot 10^6$ (LMC), $1.5\ 10^6$ (SMC)

Gaia data (BL):

Large error in individual distances

Maximum Likelihood techniques are mandatory (Luri et al., 1996)

Relative error in mean distance: 0.5% (LMC), 1.5% (SMC)

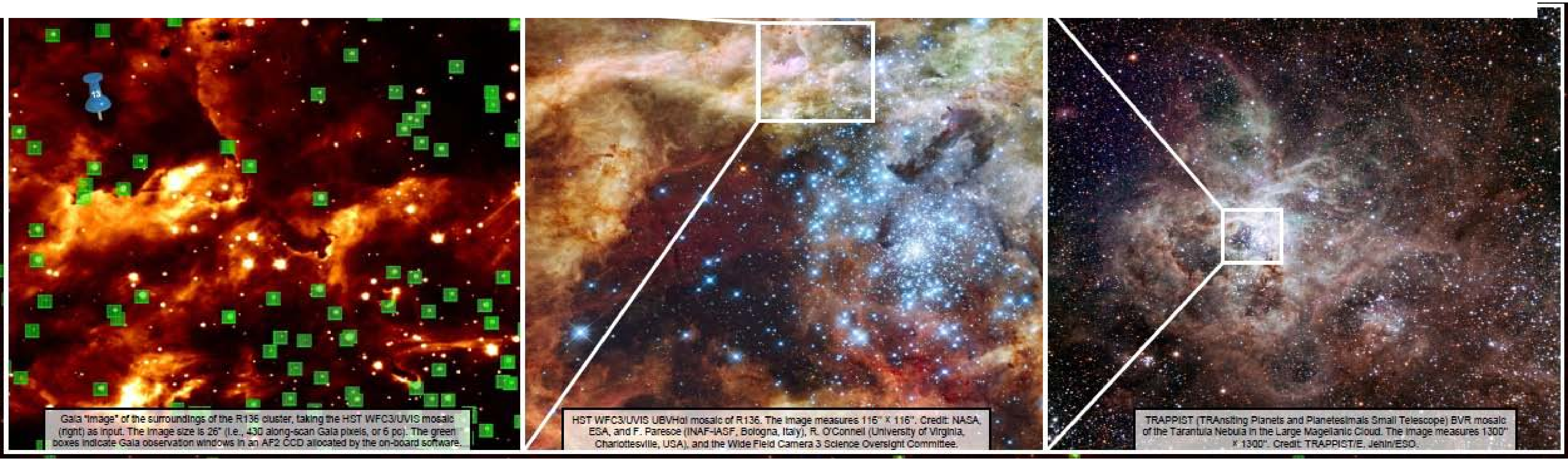
No 3D map

SMC with OGLE (Haschke et al., 2012):

Cepheids (2522 stars): 63.1 ± 3.0 kpc , 4.7 % accuracy

RR Lyrae (1494 stars): 61.5 ± 3.4 kpc , 5.5 % accuracy

R136, the star cluster in the Tarantula (30 Doradus)



Gaia (GIBIS) HST

GIBIS: Gaia Basic Image Simulator

Stellar density at G<20 ~1.4 10^6 stars /sqdeg

de Bruijne and de Marchi, 2011

Scientific promise

Galactic structure and dynamics

Some examples

The non-axisymmetric structures in the galactic disk

-One or two bars?

-The spiral arms: origin, nature, evolution

-The galactic warp

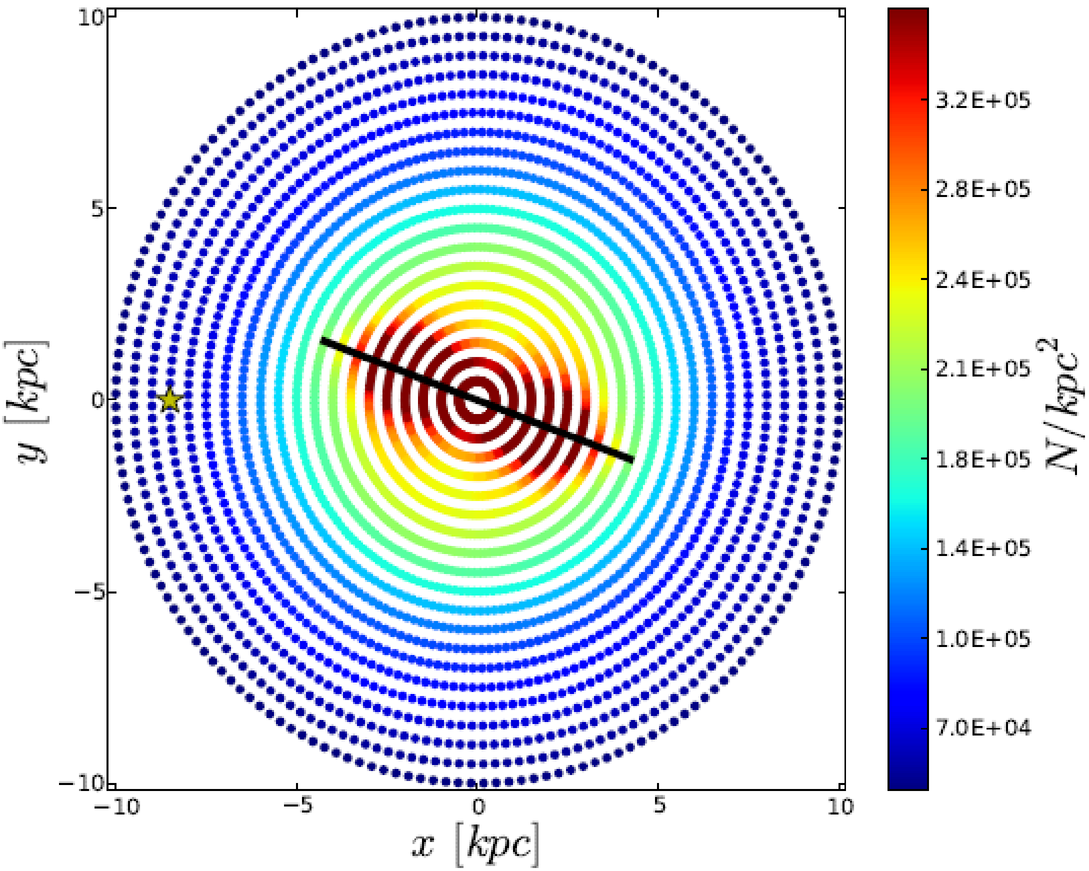
It is mandatory to change our mind

-Work in the space of the observables

- Selection of kinematic tracers

- new tools (MCMC,...) for model vs data (IMF, ..)

Red Clump stars: one or two bars?



Red clump surface density

	Number of stars	Surface density Long bar tangency
RC-all	57×10^6	201174
RC-G20	26×10^6	200841
RC-RVS	8.5×10^6	85827

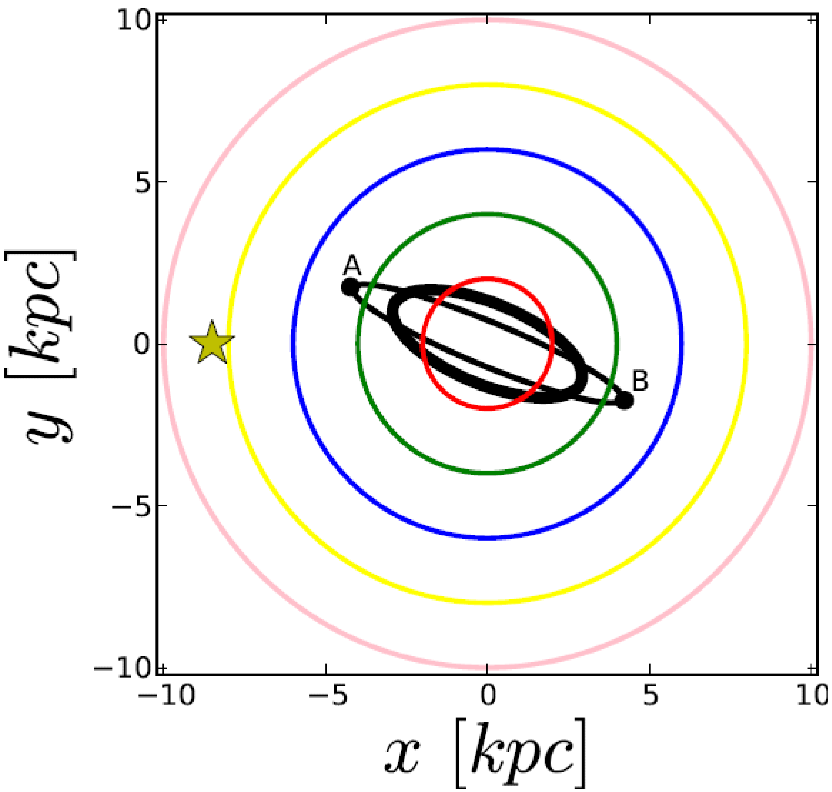
1/π is a biased estimates of the true distance!!

$$\frac{E\left[\left(\frac{1}{\pi}\right) - r\right]}{r} \neq 0$$

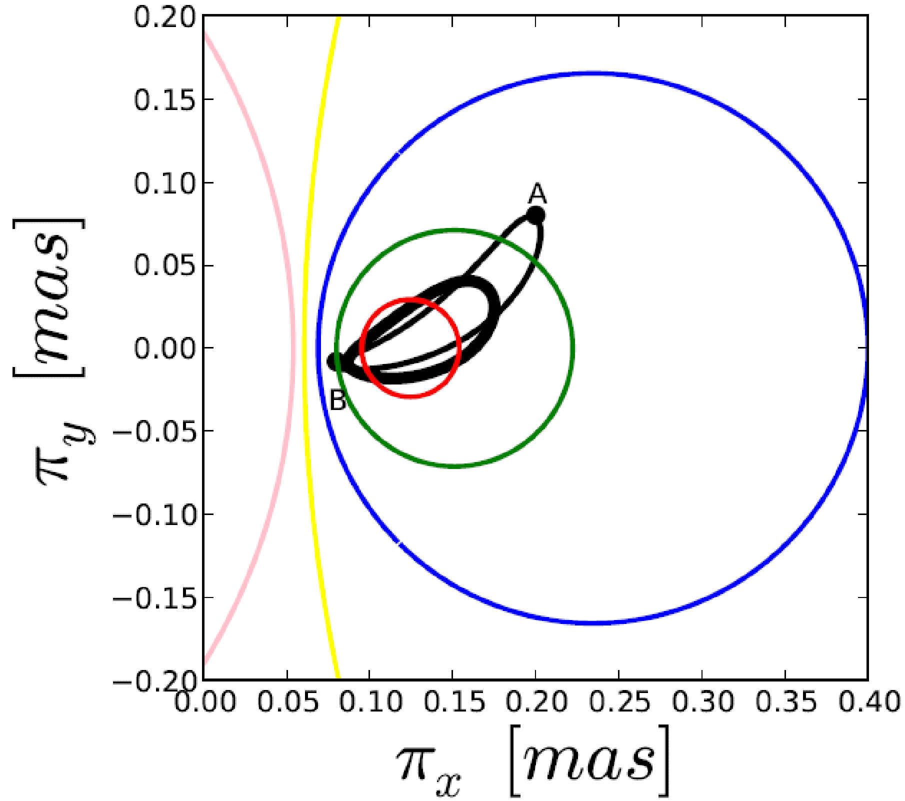
$$E\left[\frac{1}{\pi}\right] \neq \frac{1}{\pi}$$

Does our Galaxy have one/two bars?

work in the space of the observables!



distances

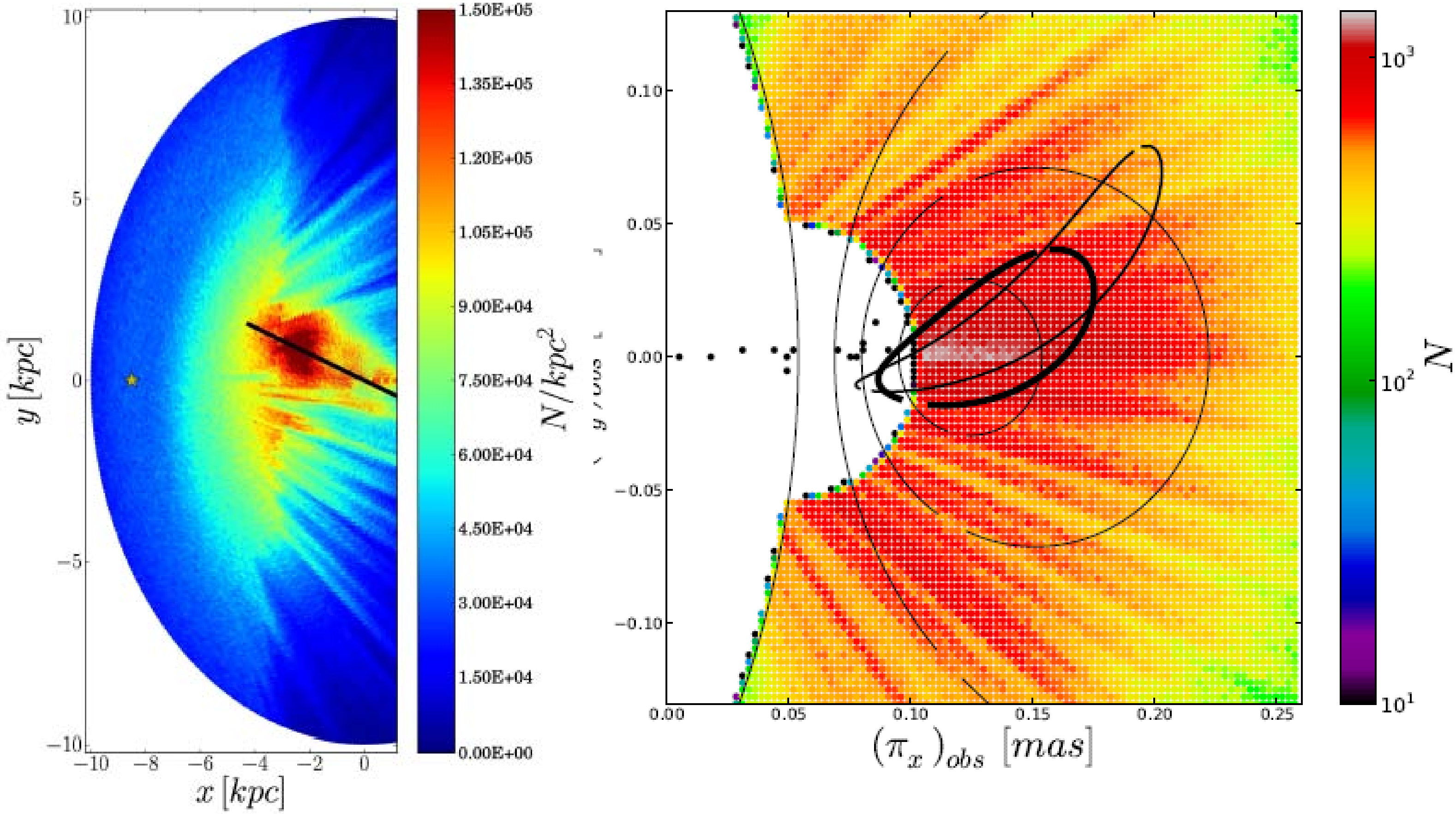


parallaxes

Romero-Gómez, Aguilar et al. 2014

Does our Galaxy have one/two bars?

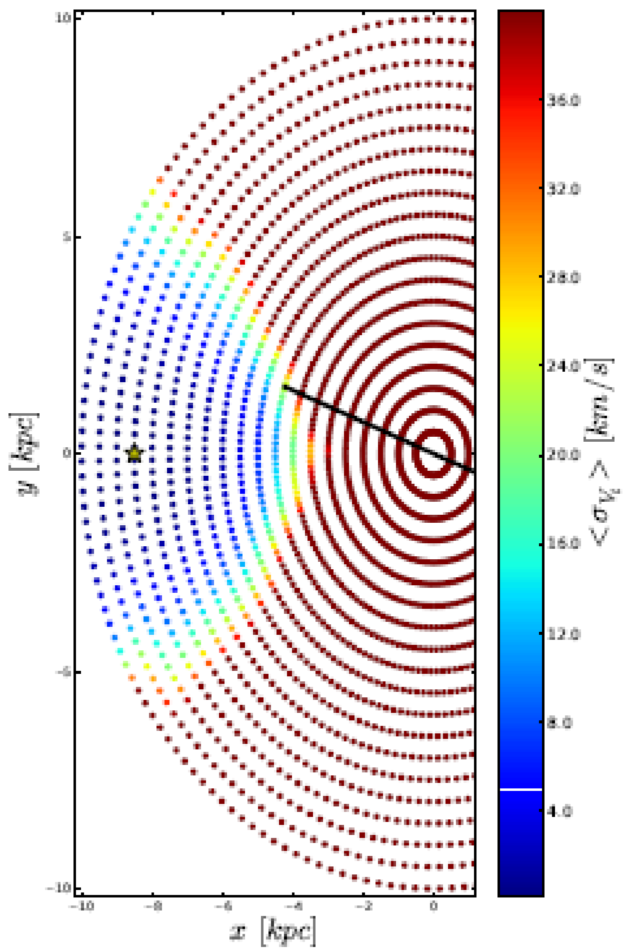
work in the space of the observables!



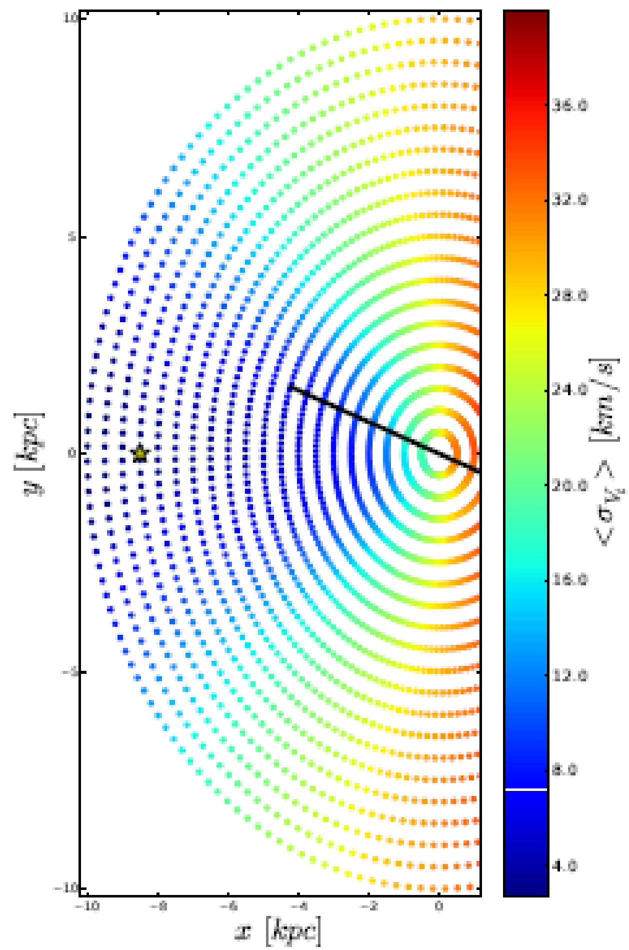
Extinction is critical: A new 3D map using Gaia and IR

Mandatory to combine Gaia and IR data

Red Clump: accuracy in tangential velocities



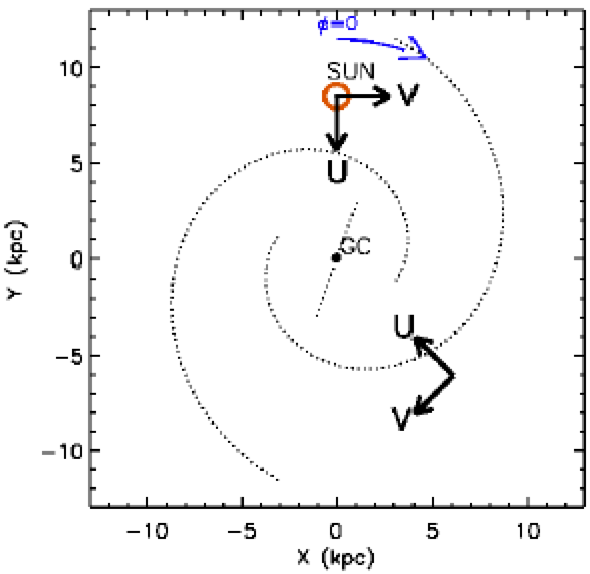
Gaia data

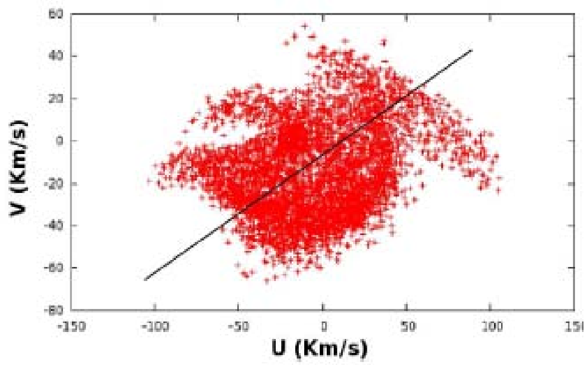


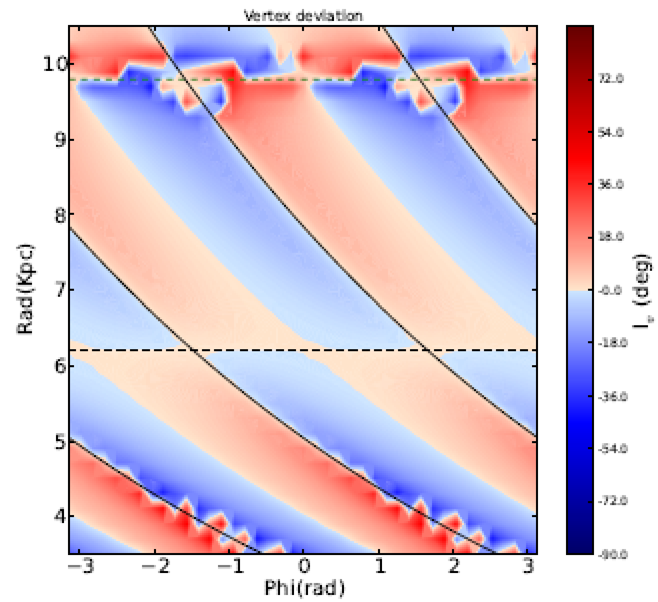
Gaia + IR distances (10%)

MW spiral arm pattern

A novel method to bracket the corotation radius in galaxy discs: vertex deviation maps



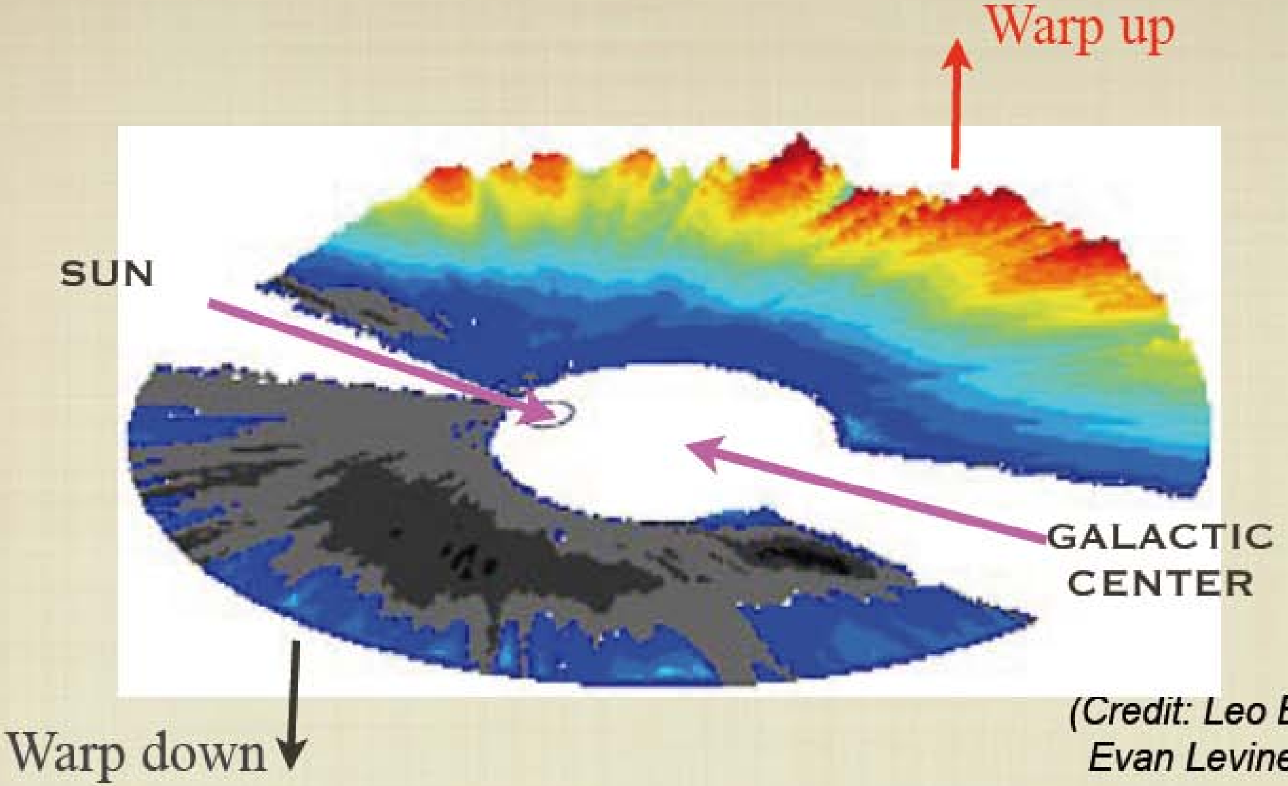




The study of phase space distribution function requires Radial Velocities
Radial velocity with accuracies of ~5km/s for a large set of data are required

S. Roca-Fàbrega et al., SEA-2014

The Galactic warp

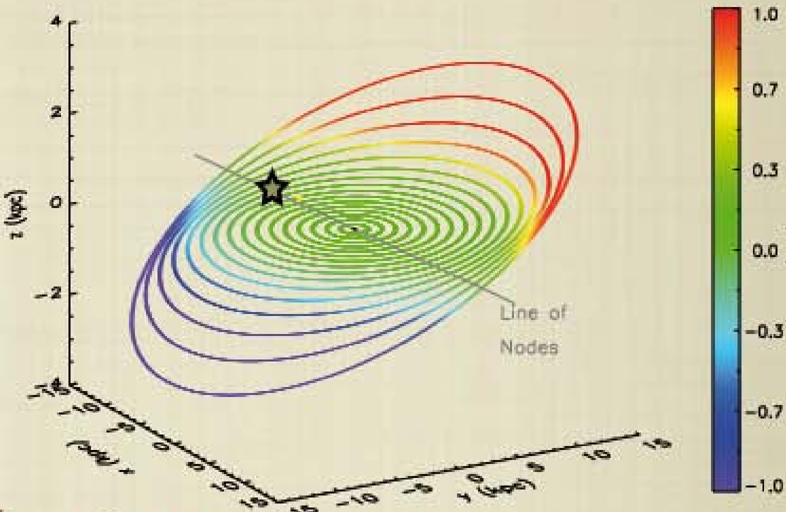


(Credit: Leo Blitz/Carl Heiles/ Evan Levine-UC Berkeley)

- The disk of our Galaxy is known to have a warp in the ISM (Kerr, 1957; Hartmann & Burton, 1997) that is also seen in the stellar component (e.g. Lopez-Corredoira et al. 2002) .
- The line of nodes roughly coincides with the Galactic Center-Sun line.

Recipe for making a warped population in statistical equilibrium

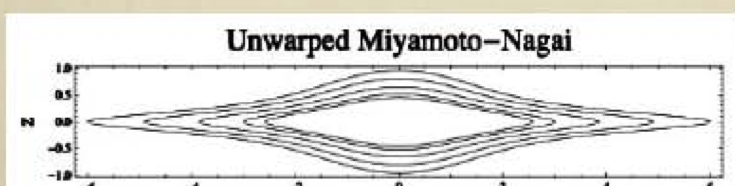
- Choose the stellar population
- 3D Galactic potential
- A geometric warp model

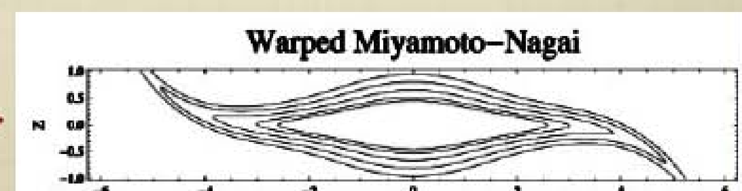


$$\Psi(r;r_1;r_2;\psi_{max},\alpha) = \psi_2((r-r_1)/(r_2-r_1))^{\alpha}, \;\; r > r_1$$

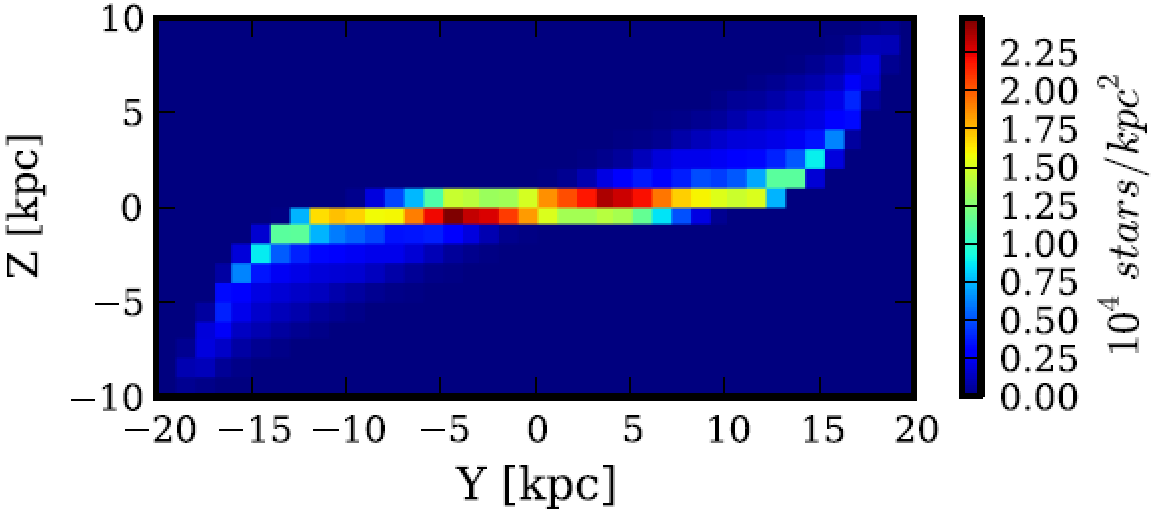
The tilt is applied beyond r_1. The resulting warp is such that the tilt angle increases as a power law whose exponent is α and such that at r_2 it has a value equal to Ψ_2.

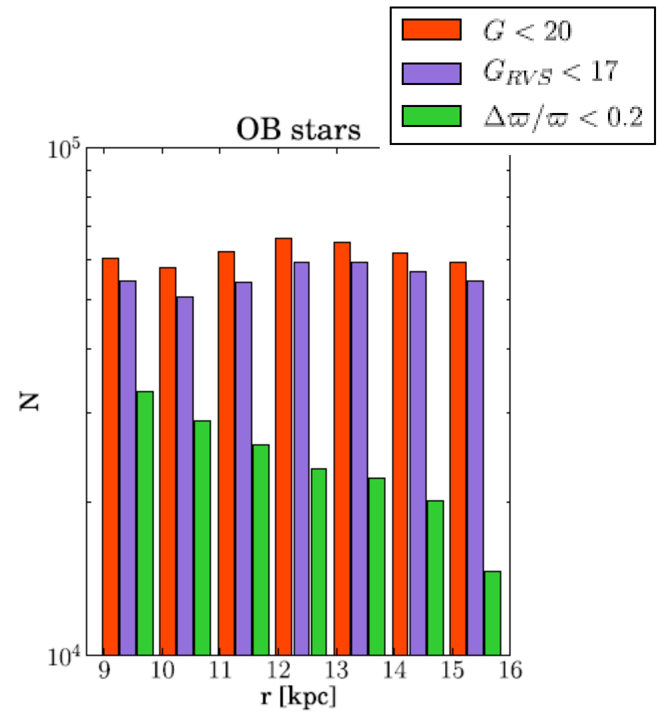
Abedi, Aguilar, Figueras et al., 2014





Gaia capabilities to characterize the dynamics of the galactic warp





OB type stars observed by Gaia (G<20)

Vertical velocities from proper motions of red clump giants

M. López-Corredoira[1, 2], H. Abedi[3], F. Garzón[1, 2], F. Figueras[3]

[1] Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain
[2] Departamento de Astrofísica, Universidad de La Laguna, E-38206 La Laguna, Tenerife, Spain
[3] Dept. d'Astronomia i Meteorologia, Institut de Ciències del Cosmos, Universitat de Barcelona, IEEC, Martí i Franqués 1, E08028 Barcelona, Spain

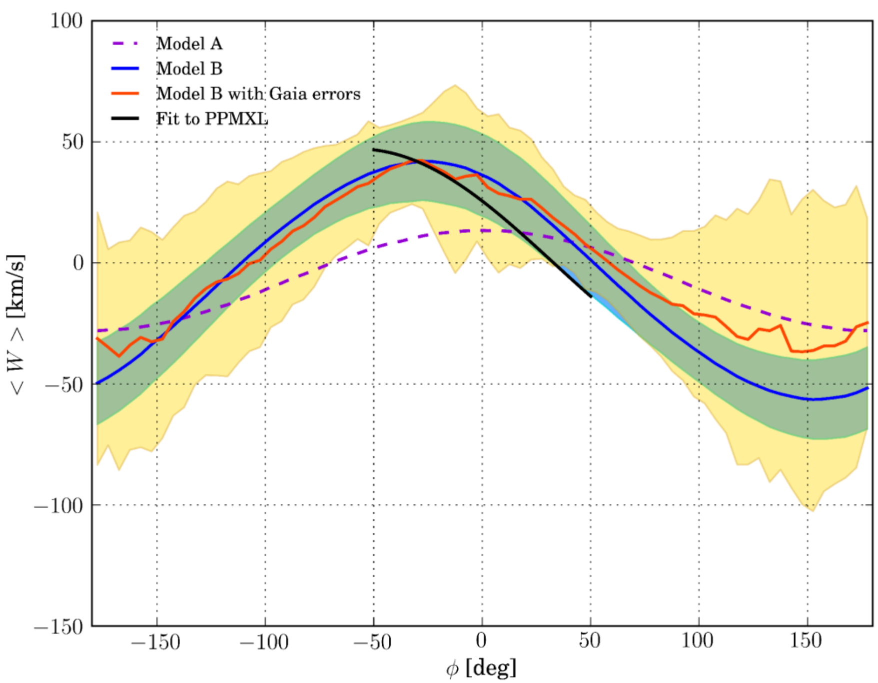
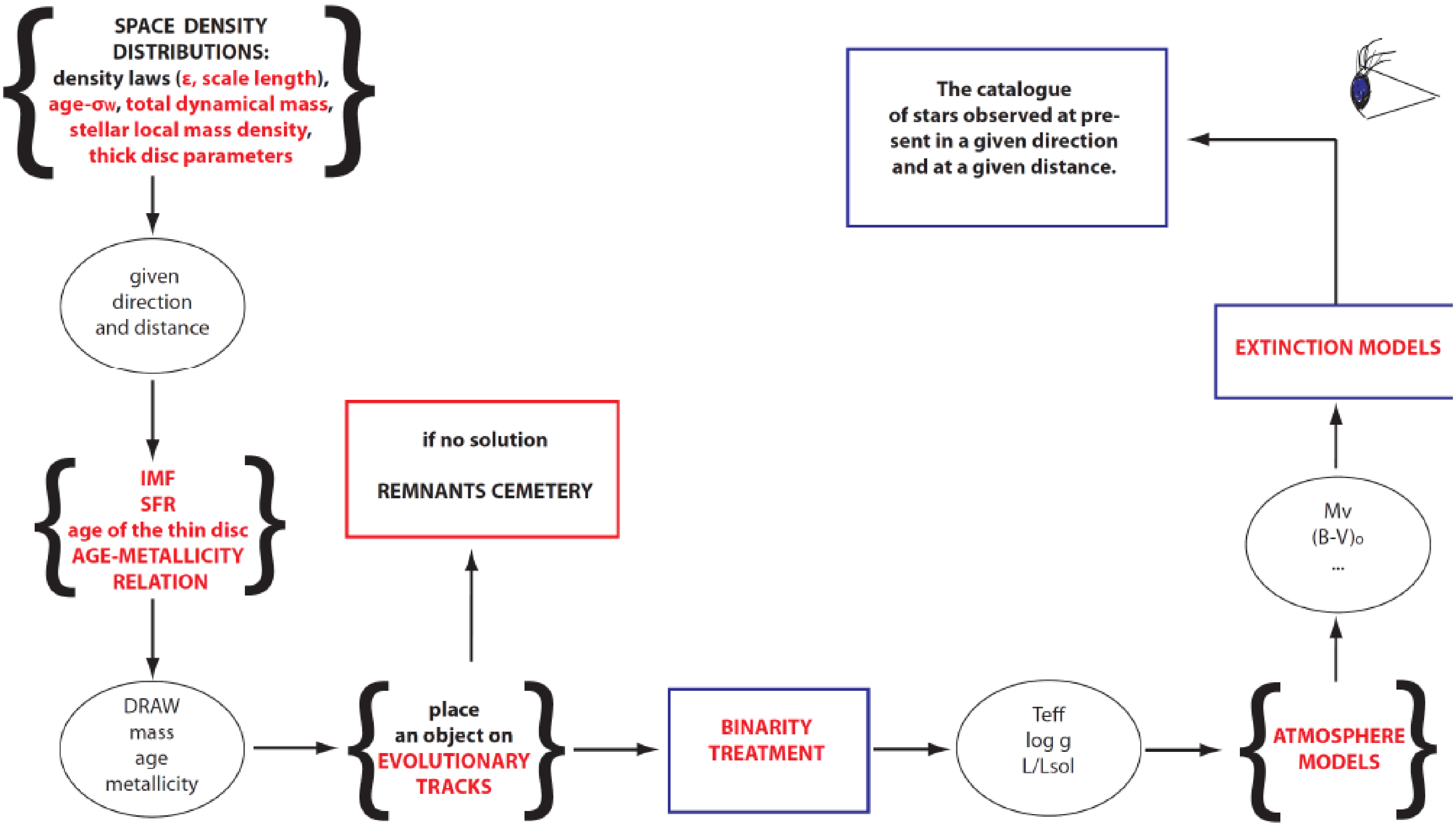


Fig. 9. The mean W velocity component as a function of galactocentric azimuth for RC stars at $13 < R(\mathrm{kpc}) < 14$. RCGs simulated using Model A and Model B are plotted respectively in dashed purple and solid blue lines. The fit to PPMXL data is in black, the same as the one seen in Fig. 5/bottom-left panel. The Gaia 'observed' values are plotted in orange. The shaded regions in blue and yellow represents the standard deviations of the W velocity for Model B respectively with and without Gaia errors. Note that the line of nodes is defined to coincide with the Sun-Galactic center line ($\phi_w = 0$).

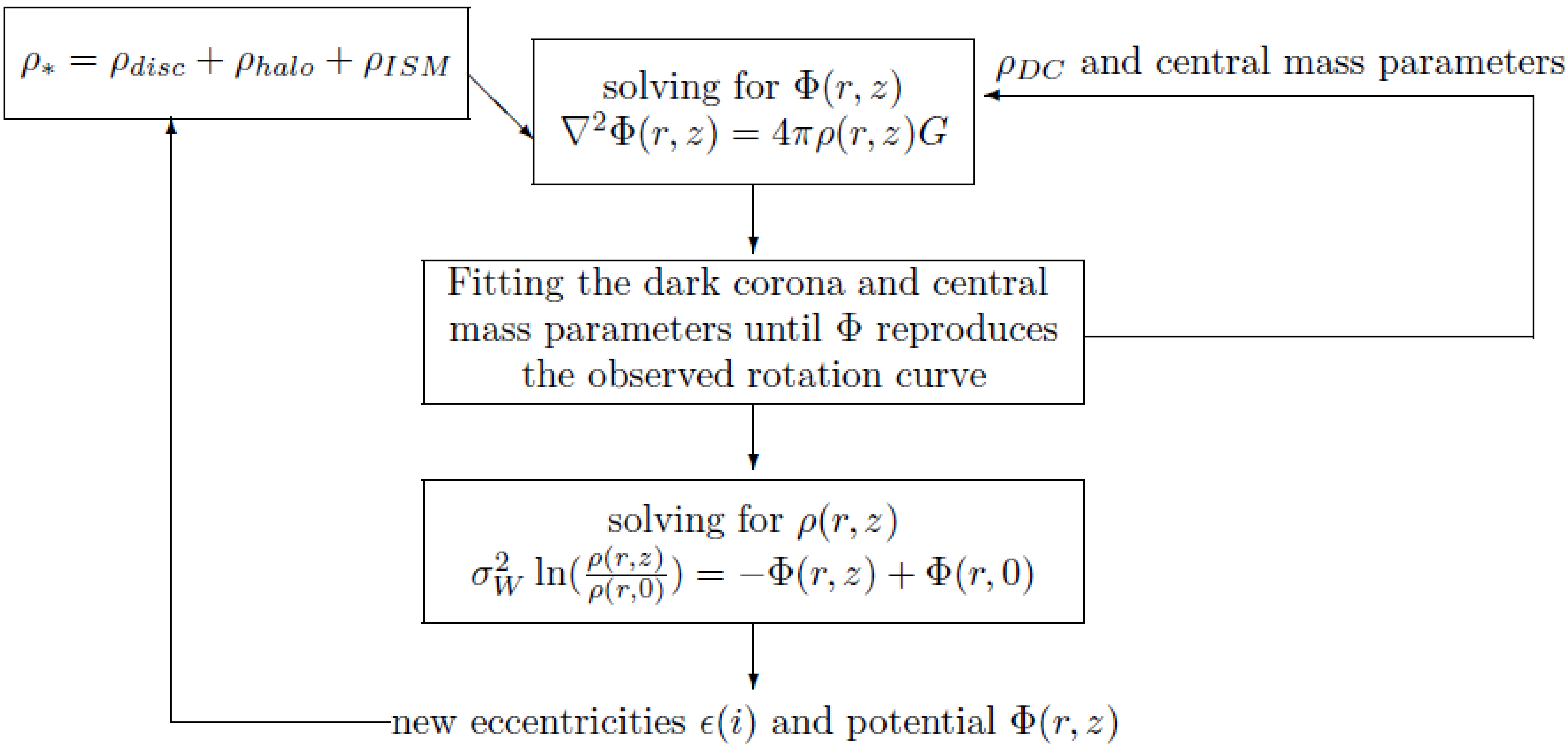
Improvement of the Population synthesis Galaxy models (BGM)

Working for Gaia Archive validation

Practical implementation: star generation



Looking for dynamical selfconsistency:



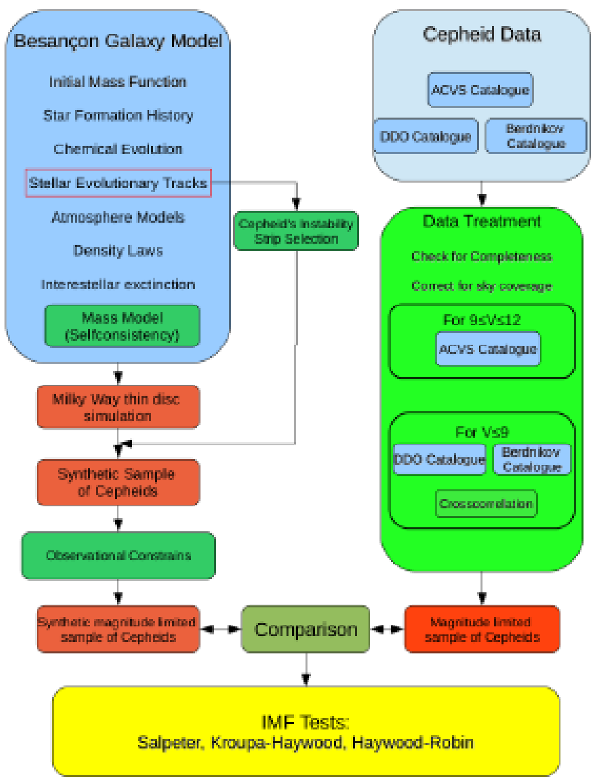
Constraining the intermediate-mass range of the Initial Mass Function using galactic Cepheids.

R. Mor[1] F. Figueras[1] A. Robin[2] B. Lemasle[3]

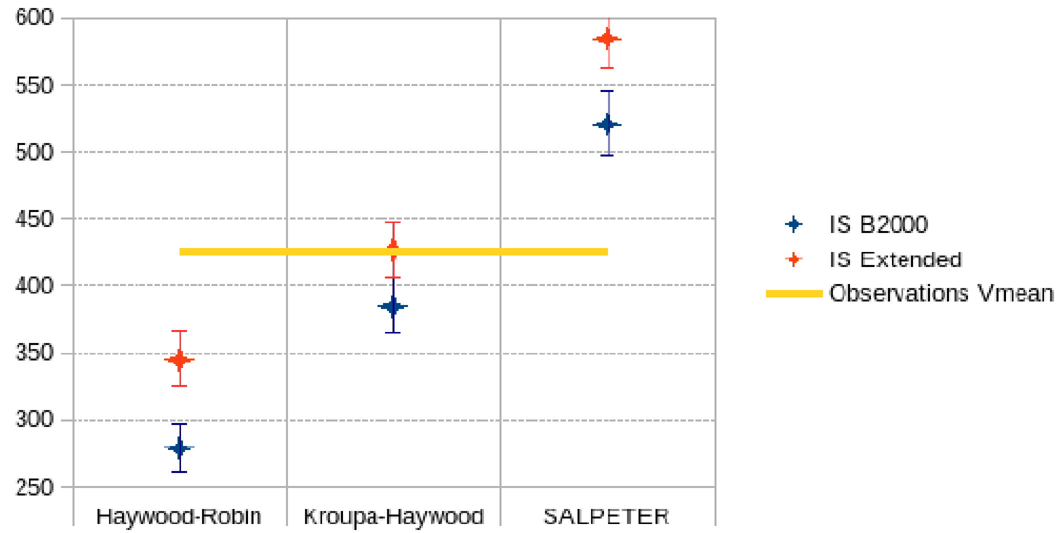
[1] Departament d'Astronomia i Meteorologia and IEEC-UB, Institut de Ciències del Cosmos de la Universitat de Barcelona, Martí i Franquès, 1, E-08028 Barcelona.
[2] Observatoire de Besançon (France)
[3] Anton Pannekoek Institute for Astronomy (Netherlands)

We tested three different IMFs comparing synthetic and observational samples of Galactic Cepheids

The IMF in range $\sim 4M_\odot$ to $\sim 10M_\odot$ points towards Kroupa-Haywood IMF. ($\alpha = 3.2$)



$$dN/dm = \xi(m) = km^{-\alpha} = km^{-(1+x)}$$



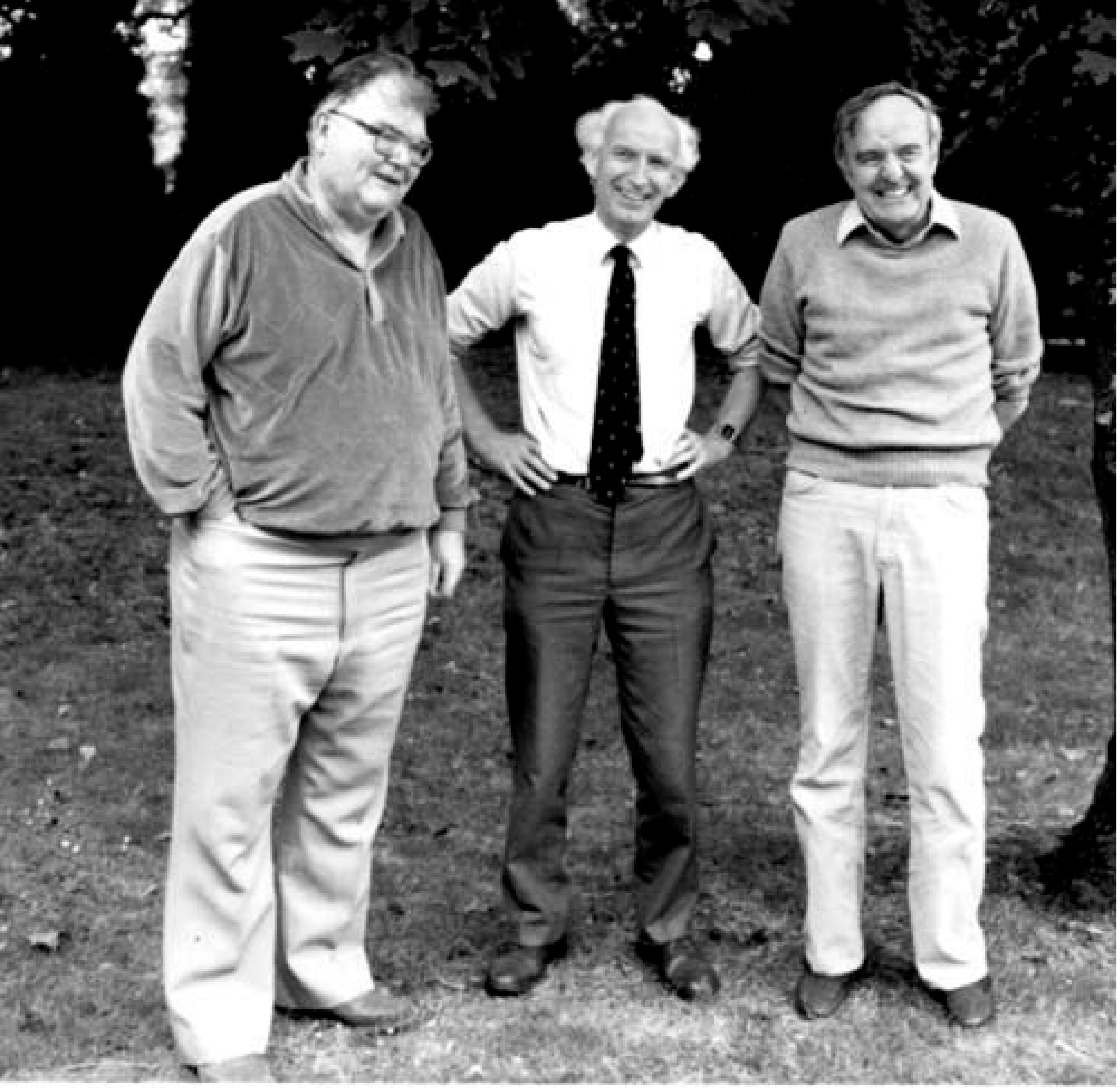
For more information see poster G22 or contact:
rmor@am.ub.es

Kroupa-Haywood Initial Mass Function gives better approach than Salpeter IMF in the Cepheids Mass Range

On-ground Spectroscopic Surveys complementary to Gaia

Towards a chemo-dynamical evolution of the MW

How did our galaxy and its components form?
XXI Century: the MW as a cosmological laboratory



Gaia + OSS
a dream in 1962!

Galaxy formation and evolution are encoded in the location, kinematics (6D) and chemistry of stars

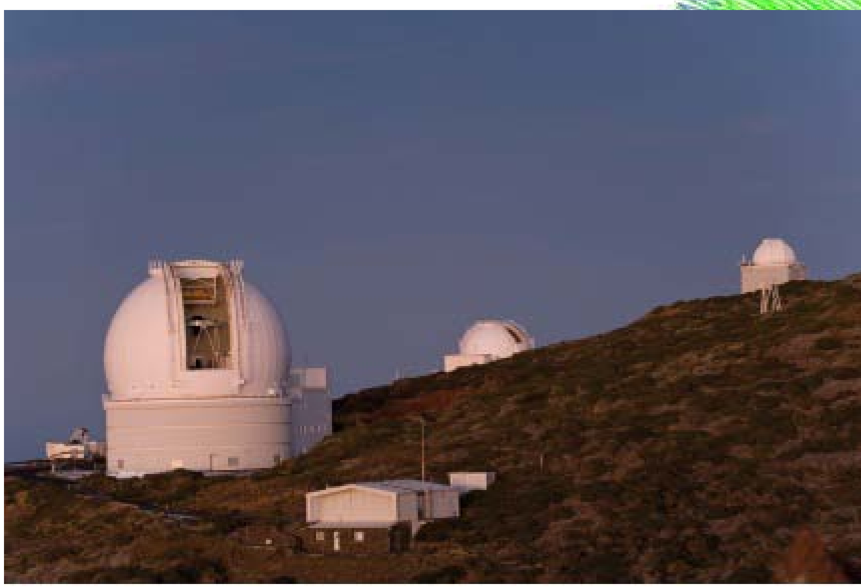
Gaia-ESO survey (GES)

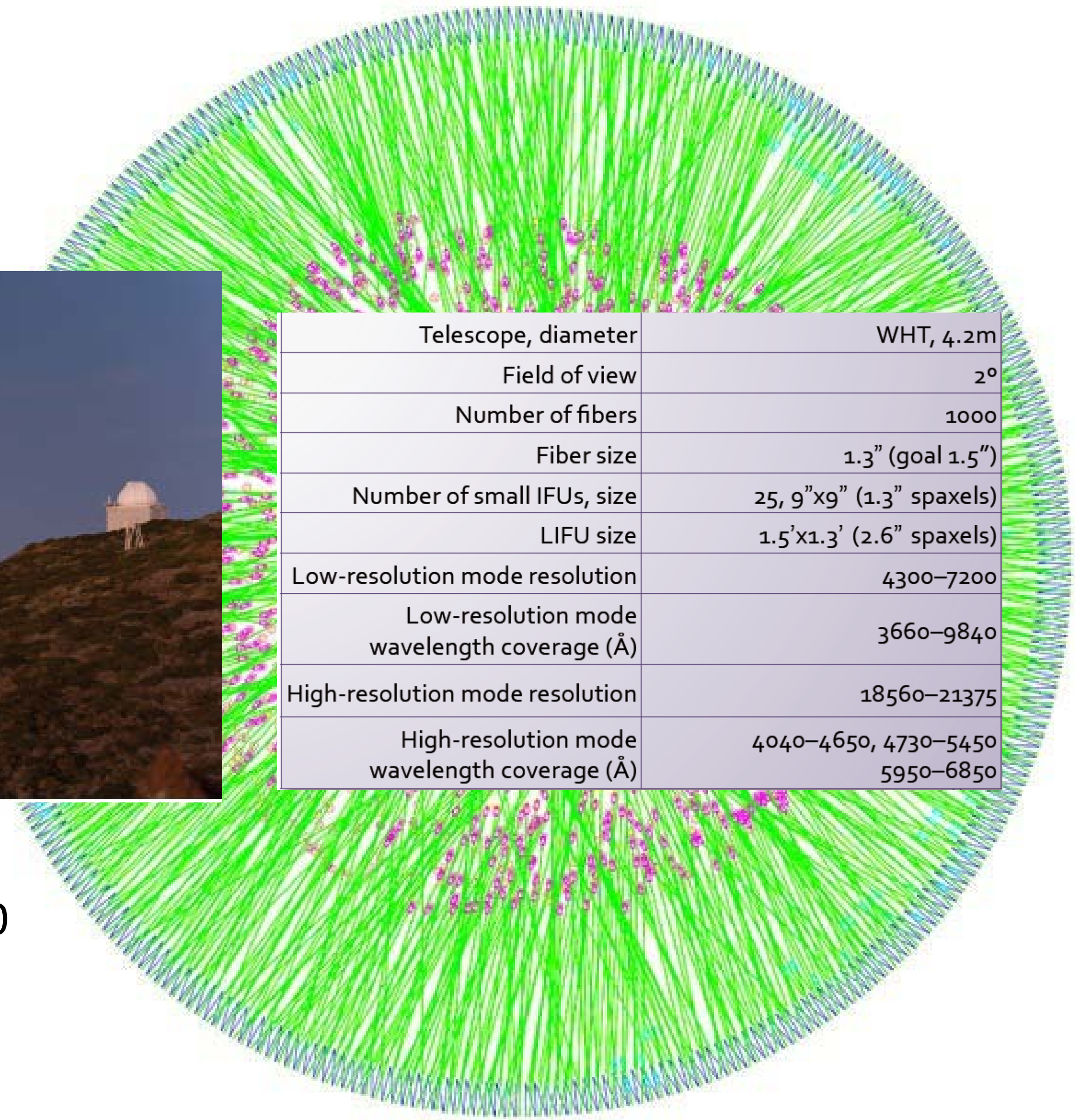
Public large spectroscopic survey with FLAMES@VLT
Started Feb/2012 + 5 years (300 nights)
Ips: Randich, Gimore + ~300 Co-Ips
All stellar populations: Halo, Bulge, Thick/Thin disk + open clusters

Products:

- 10^5 Giraffe spectra (R~16000-25000)
- 10^4 UVES spectra (R~47000)
- + ESO archive

An optical Multi-Object-Spectrograph (2017)
WEAVE@ WHT
Canary Island





Telescope, diameter	WHT, 4.2m
Field of view	2°
Number of fibers	1000
Fiber size	1.3" (goal 1.5")
Number of small IFUs, size	25, 9"x9" (1.3" spaxels)
LIFU size	1.5'x1.3' (2.6" spaxels)
Low-resolution mode resolution	4300–7200
Low-resolution mode wavelength coverage (Å)	3660–9840
High-resolution mode resolution	18560–21375
High-resolution mode wavelength coverage (Å)	4040–4650, 4730–5450 5950–6850

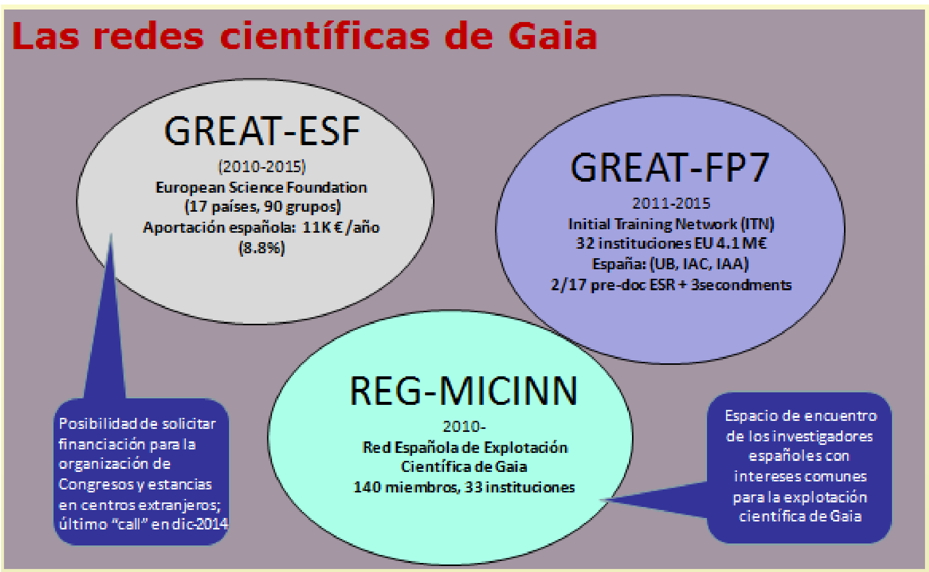
Radial velocities $\pm$2 km/s V=20

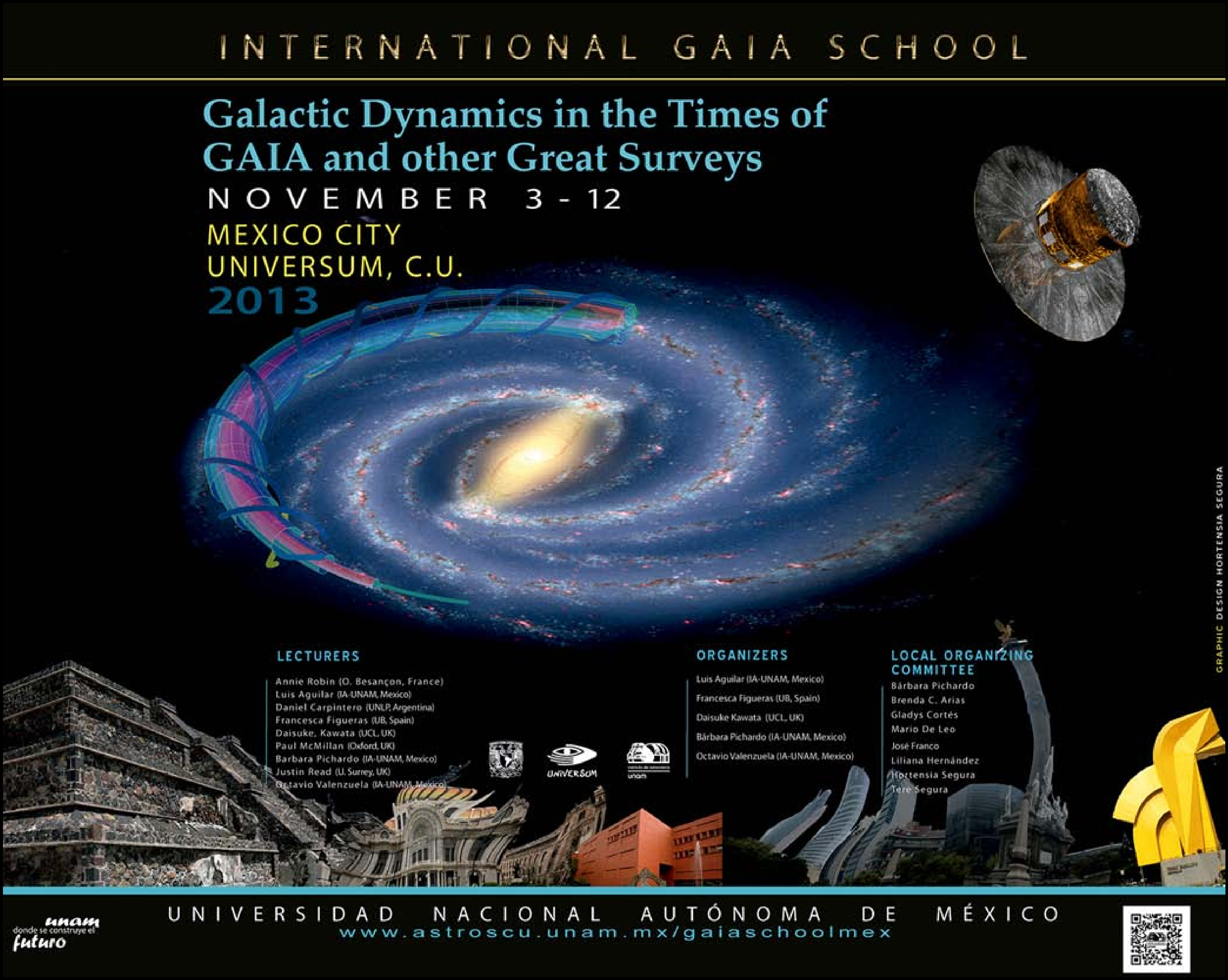
Abundances $V \leq 17$

Networks and schools

Las redes de explotación científica de *Gaia*

F. Figueras y C. Jordi en representación de los participantes españoles en REG y GREAT
Dept. Astronomia i Meteorologia, Universitat de Barcelona (ICCUB-IEEC)





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Justin Read (U. Surrey, UK)
Octavio Valenzuela (IA-UNAM, Mexico)
ORGANIZERS
Luis Aguilar (IA-UNAM, Mexico)
Francesca Figueras (UB, Spain)
Daisuke Kawata (UCL, UK)
Bárbara Pichardo (IA-UNAM, Mexico)
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