GAIA CONSTRAINTS ON GALACTIC STRUCTURE AND EXTINCTION

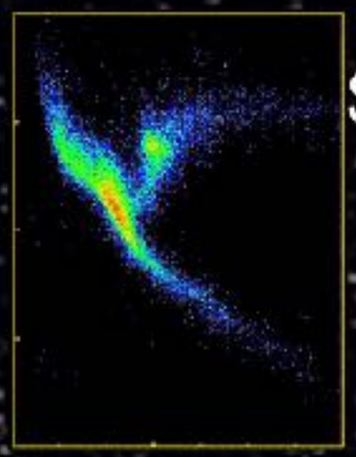
Camilla Danielski
and GEPI department.

Sagan Workshop 2017

Gaia collaboration, 2016a

gaia

Stellar Astrophysics



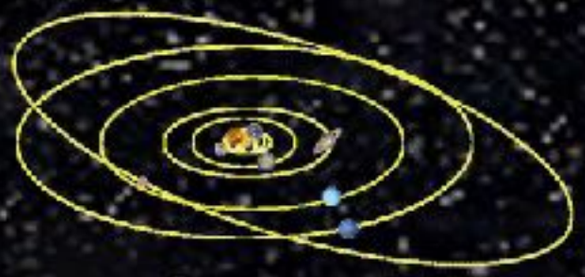
Star Formation History of the Milky Way

Galactic Structure

Fundamental Physics

Binaries and Brown Dwarfs

Extrasolar Planets

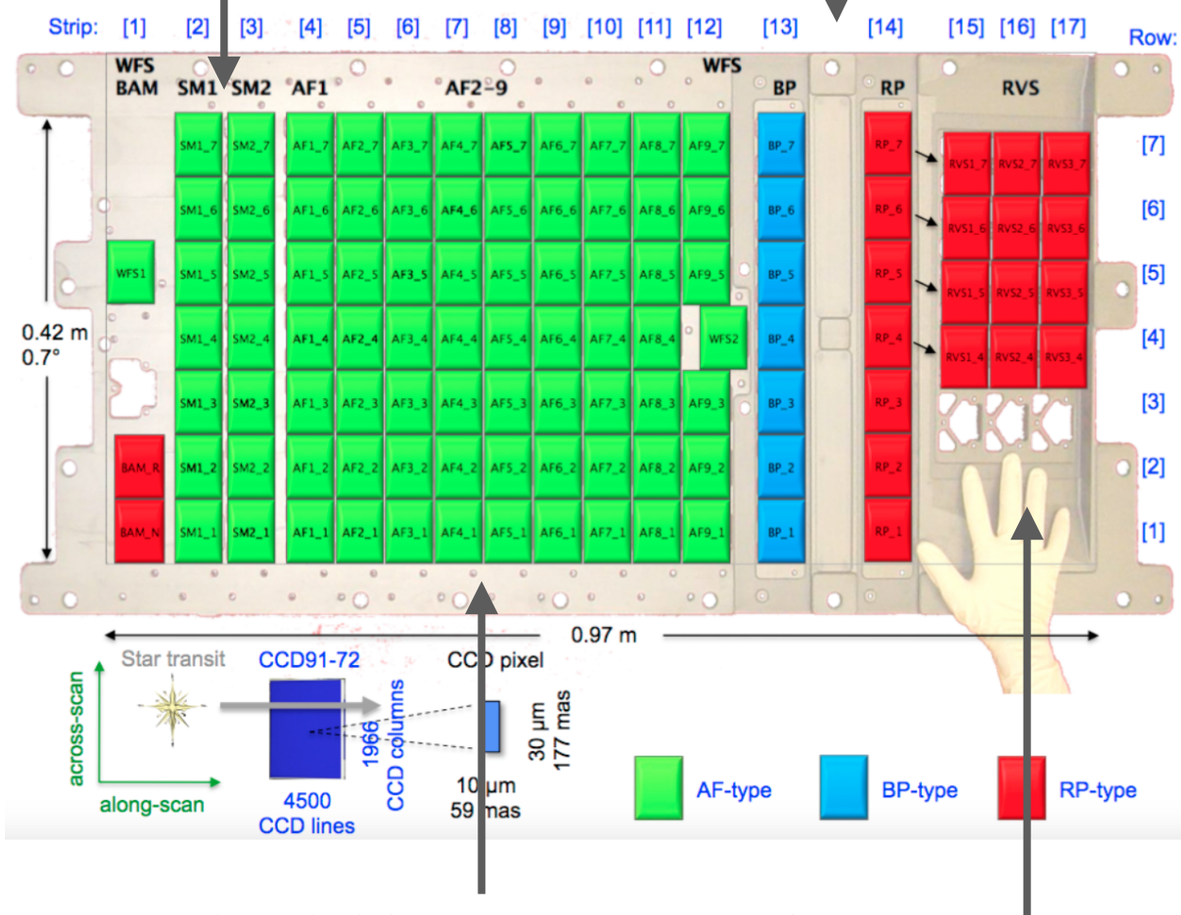


Solar System

Reference Frame

BP/RP: low resolution spectra (R = 20-100)

Sky mappers (1 &2): onboard detection of point-like sources

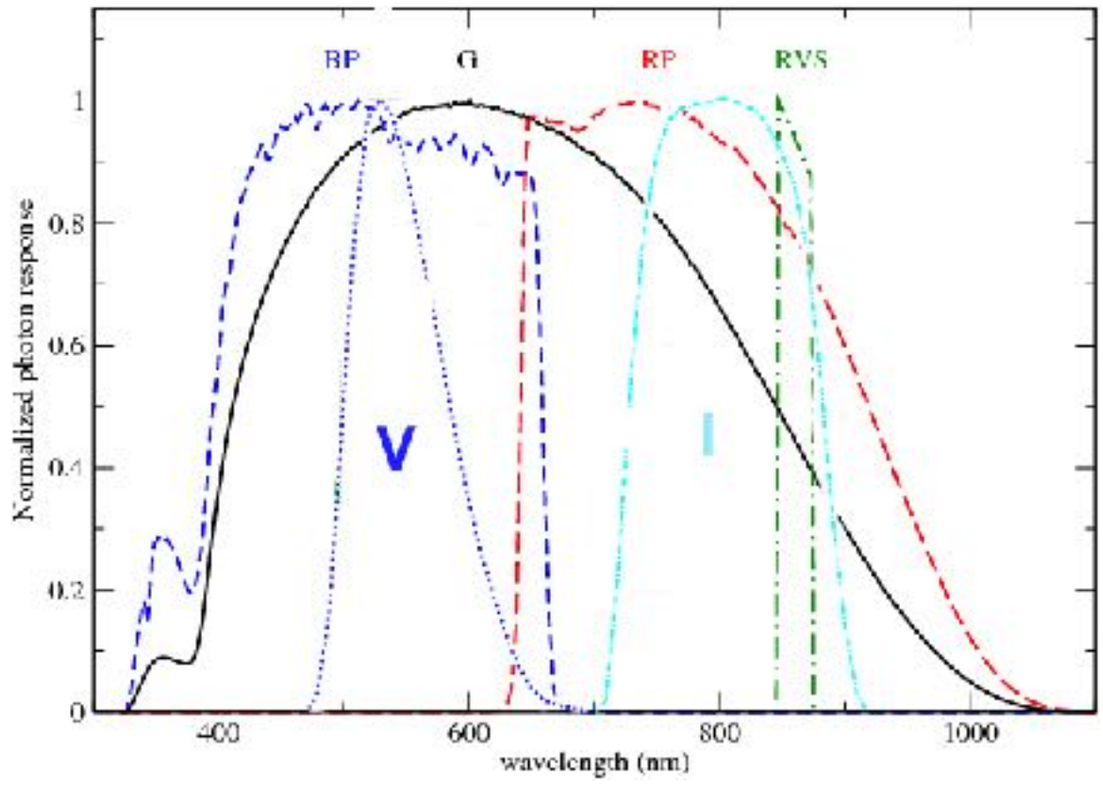


Astrometric Field: astrometry and photometry of point-like sources in the G band (white light passband)

— proper motions, parallaxes

In routine operations
- Since July 2014
- Nominal mission ends mid-2019

All sources 3 < G < 20.7 (V ~ 21 mag, and beyond)
- Bright stars covered with special observations
- Crowded regions observed with sky mappers



RVS: spectra R ~ 11700 in calcium triplet region (G <17 mag)

gaia

Gaia collaboration, 2016a

cnes CENTRE NATIONAL D'ETUDES SPATIALES

l'Observatoire de Paris — GEPI

Photometric

Astrophysical information for all objects (Bailer-Jones et al. 2013):

- Astrophysical classification (star, quasar, etc.)
- Astrophysical characterisation (interstellar reddenings, surface gravities, metallicities, and effective temperatures for stars, photometric redshifts for quasars, etc.).

Astrometric

Unbiased, flux-limited survey of the sky.

- Gaia measures the relative separations of the thousands of stars simultaneously present in the combined fields of view.
- Proper motions, parallaxes

Spectroscopic

- Radial velocities through Doppler-shift measurements → stars brighter than *G*RVS ≈ 16 mag → required for kinematical and dynamical studies of the Galactic populations and for deriving good astrometry of nearby, fast- moving sources
- Coarse stellar parametrisation for stars brighter than *G*RVS ≈ 14.5 mag
- Astrophysical information, such as interstellar reddening, atmospheric parameters, and rotational velocities, for stars brighter than *G*RVS ≈ 12.5 mag
- Individual element abundances for some elements (e.g. Fe, Ca, Mg, Ti, and Si) for stars brighter than *G*RVS ≈ 11 mag

End-of-mission performances

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

Photometric

	B1V			G2V			M6V		
G [mag]	G	BP	RP	G	BP	RP	G	BP	RP
3 - 13	0.2	1	1	0.2	1	1	0.2	1	1
14	0.2	1	1	0.2	1	1	0.2	2	1
15	0.2	1	2	0.2	1	1	0.2	5	1
16	0.4	2	3	0.4	2	2	0.4	10	1
17	0.6	3	6	0.6	4	4	0.6	25	2
18	0.9	6	15	0.9	9	8	0.9	63	4
19	1.8	15	37	1.8	23	20	1.8	157	8
20	3.7	37	91	3.7	56	48	3.7	395	20

Spectroscopic

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

Astrometric

	B1V	G2V	M6V
V-I_C [mag]	-0.22	0.75	3.85
Bright stars	5-16 μas (3 mag < V < 12 mag)	5-16 μas (3 mag < V < 12 mag)	5-16 μas (5 mag < V < 14 mag)
V = 15 mag	26 μas	24 μas	9 μas
V = 20 mag	600 μas	540 μas	130 μas

G	< 12	13	14	15	16	17	18	19	20	
σ_0	5.0	7.7	12.3	19.8	32.4	55.4	102	208	466	μas
σ_π	6.7	10.3	16.5	26.6	43.6	74.5	137	280	627	μas
σ_μ	3.5	5.4	8.7	14.0	22.9	39.2	72.3	147	330	μas yr^{-1}

Standard error in parallax (σπ), position at mid-epoch (σ0), proper motion (σμ), for an unreddened G2V star (V-IC = 0.75 mag, V-G = 0.16 mag).

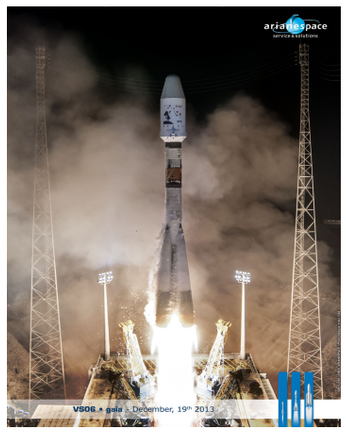
1990 2000 2010 2020

1993
1st concepts

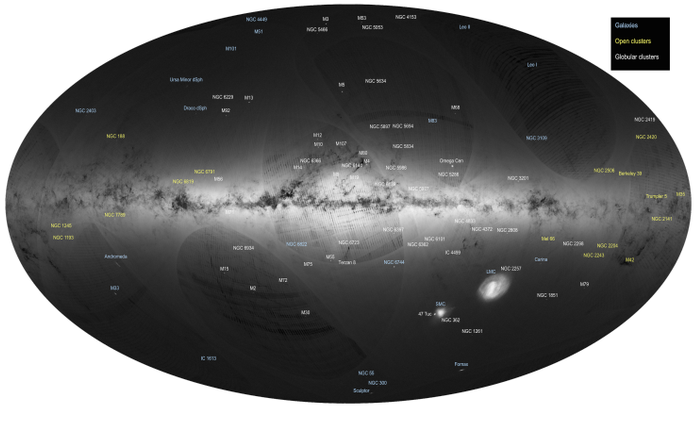
2000
Selected as
ESA cornerstone
mission

2006
DPAC

19 Dec 2013
Launch



14 Sep 2016
1st data release



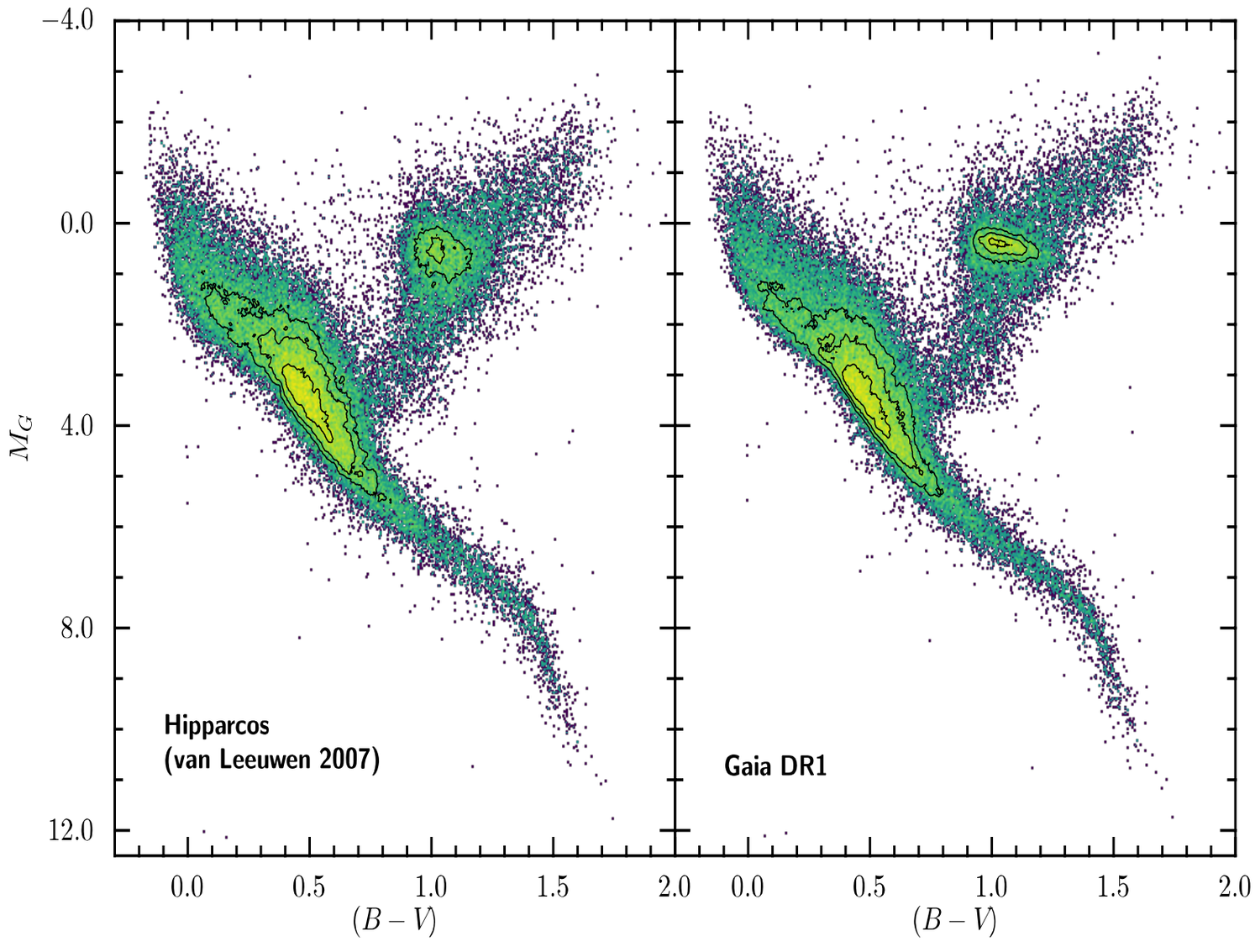
April 2018
2nd data release

Arenou et al. (2016),
Salgado et al. (2016).

	DR1	DR2
Astrometric	• Positions • Parallaxes • Proper-motions	• Positions • Parallaxes • Proper-motions • **Solar system objects**
Photometric	• G mag • Variable stars	• G mag • **Bp, Rp mag** • Variable stars • **Astrophysical parameters**
Spectroscopic		• **Radial velocities**

DR1 Improved precision: H-R diagram

Hipparcos *and* Gaia DR1 parallaxes precise to $\leq 20\%$
43 546 stars, 90% stars inside 280 pc



All stars from Hipparcos Catalogue

Parallaxes with precision better than 20% both in Hipparcos and TGAS & σ(G)<0.05 & σ(B-V)<0.05

		DR1	DR2
	Data processed	14 months	22 months
Astrometric	Positions	1.1 10^9	~1.5 10^9
	Parallaxes	2 10^6	~1.1 10^9
	Proper-motions	2 10^6	~1.1 10^9
	Solar system objects	- -	> 10 000
Photometric	G mag	1.1 10^9	~1.5 10^9
	Bp, Rp mag	- -	**~1.5 10^9**
	Variable stars	3 10^3	**Much more**
	Astrophysical parameters	- -	**G < 17**
Spectroscopic	Radial velocities	- -	**G_{RVS} < 12**

Data Release 3

- Targeted **mid/late 2020**

Examples of possible new products:

- Source classification
- Source APs from Bp/Rp/RVS spectra
- Bp/Rp/RVS spectra (sources with APs)

- Radial velocities: $G_{RVS} < 14$
- Non-single stars
- Extended variable stars catalogue
- Extended solar system objects catalogue

Data Release 4

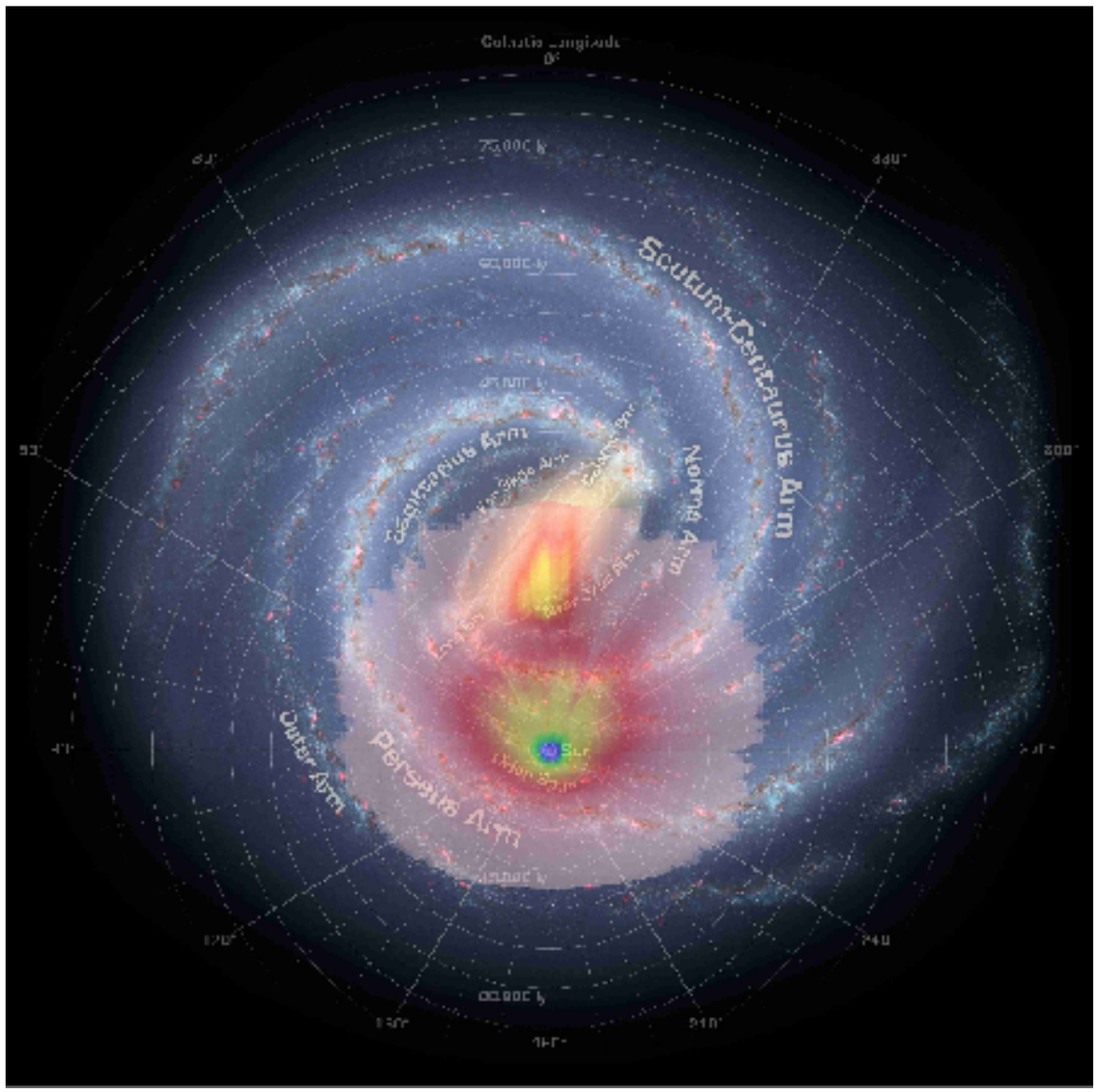
- Targeted **end 2022**

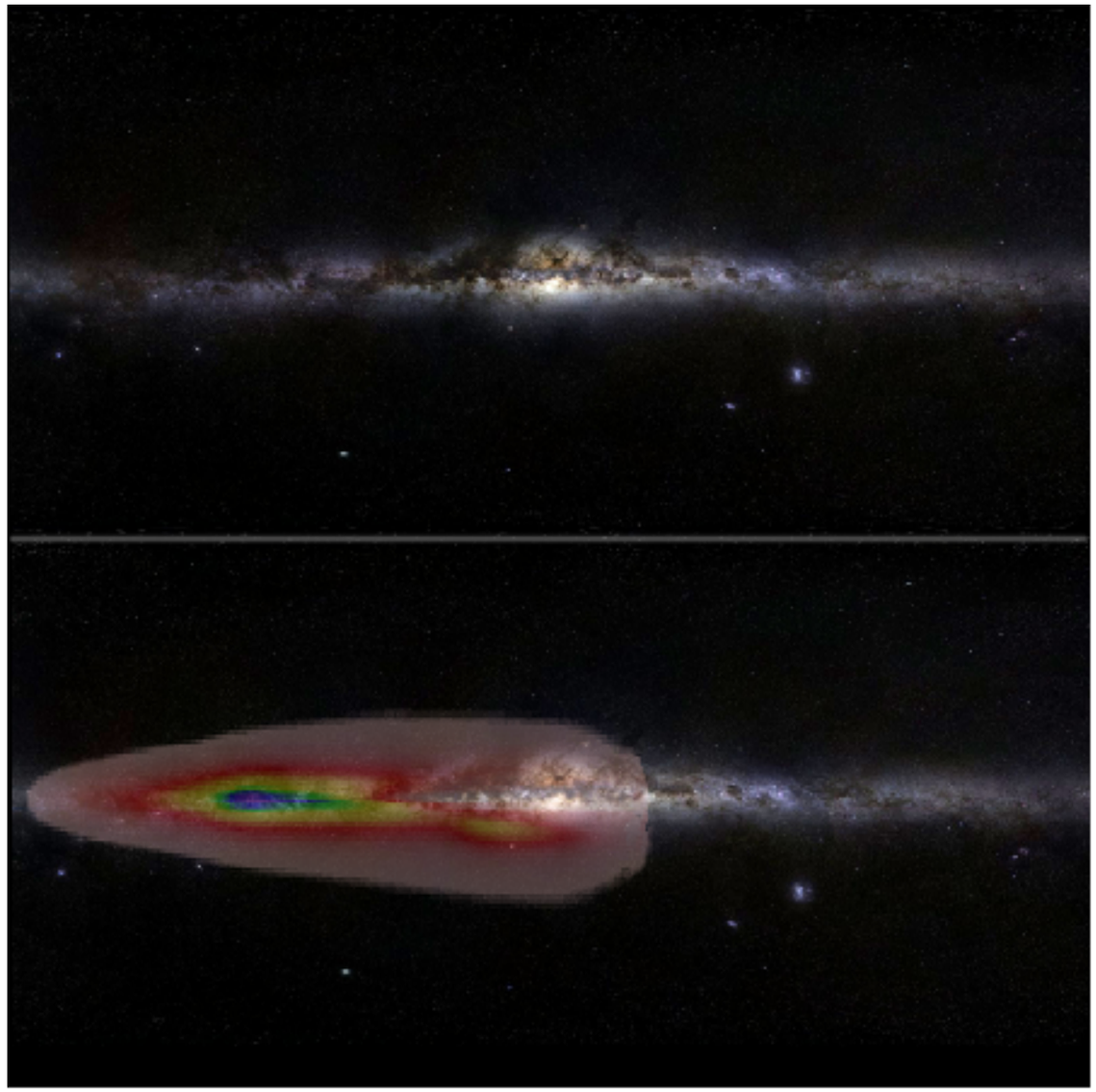
Final release for the nominal mission

Foreseen products

- **Full catalogues**: astrometry, photometry, radial velocities
- **All available variable and non-single stars** solutions
- **Classification/APs from X-instruments** information: AF, BP/RP/ RVS
- **Exo-planet** list
- **All epochs/transit** data

3D distribution in the milky way of the contents of the gaia catalogue

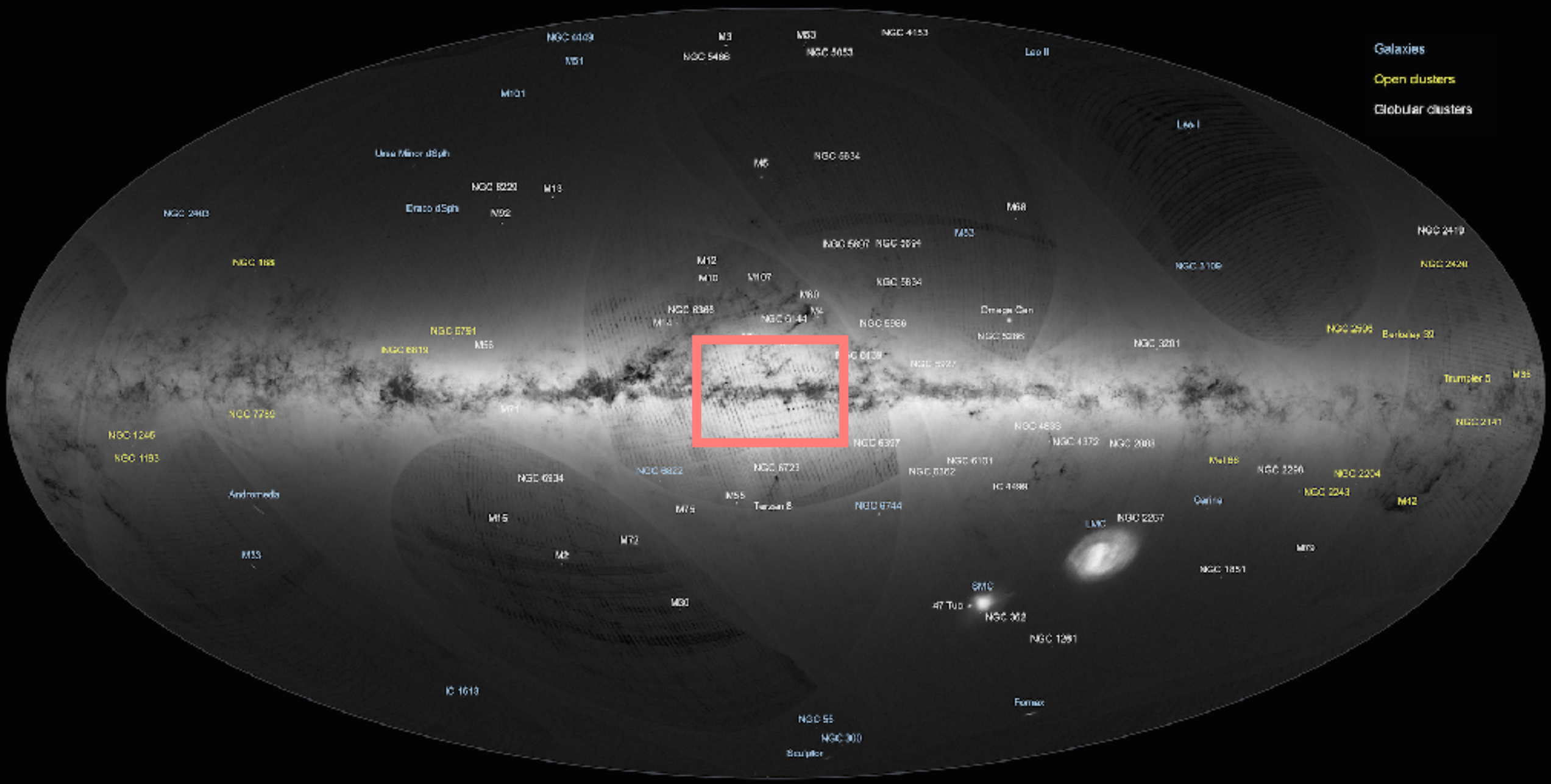




Credits: X. Luri & the DPAC-CU2. Simulations based on an adaptation for Gaia of the Besançon galaxy model (A. Robin et al.)

14 months of data

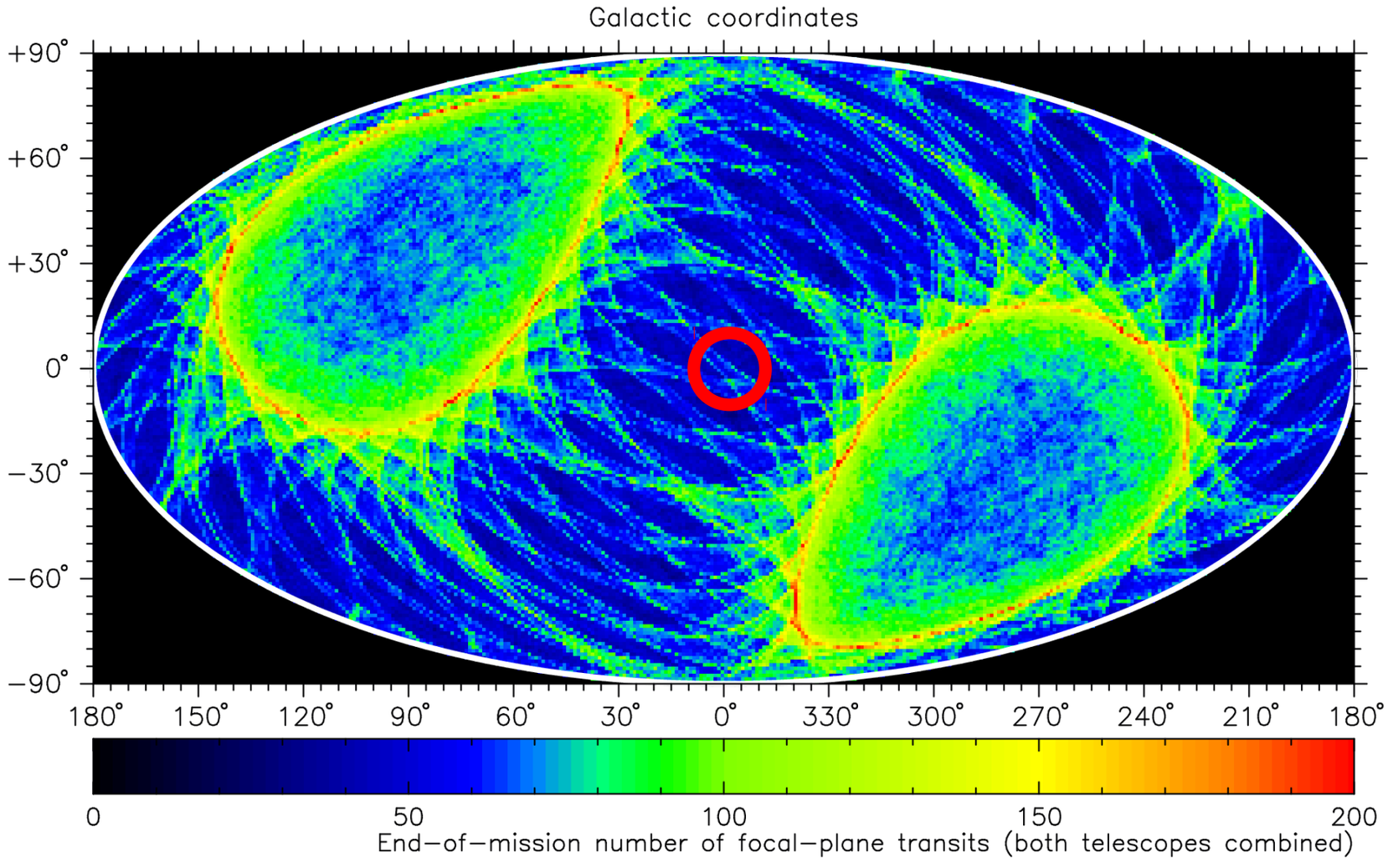
End of nominal mission: 40-250 transits



456 million new sources in Gaia DR1

The special case of the bulge...

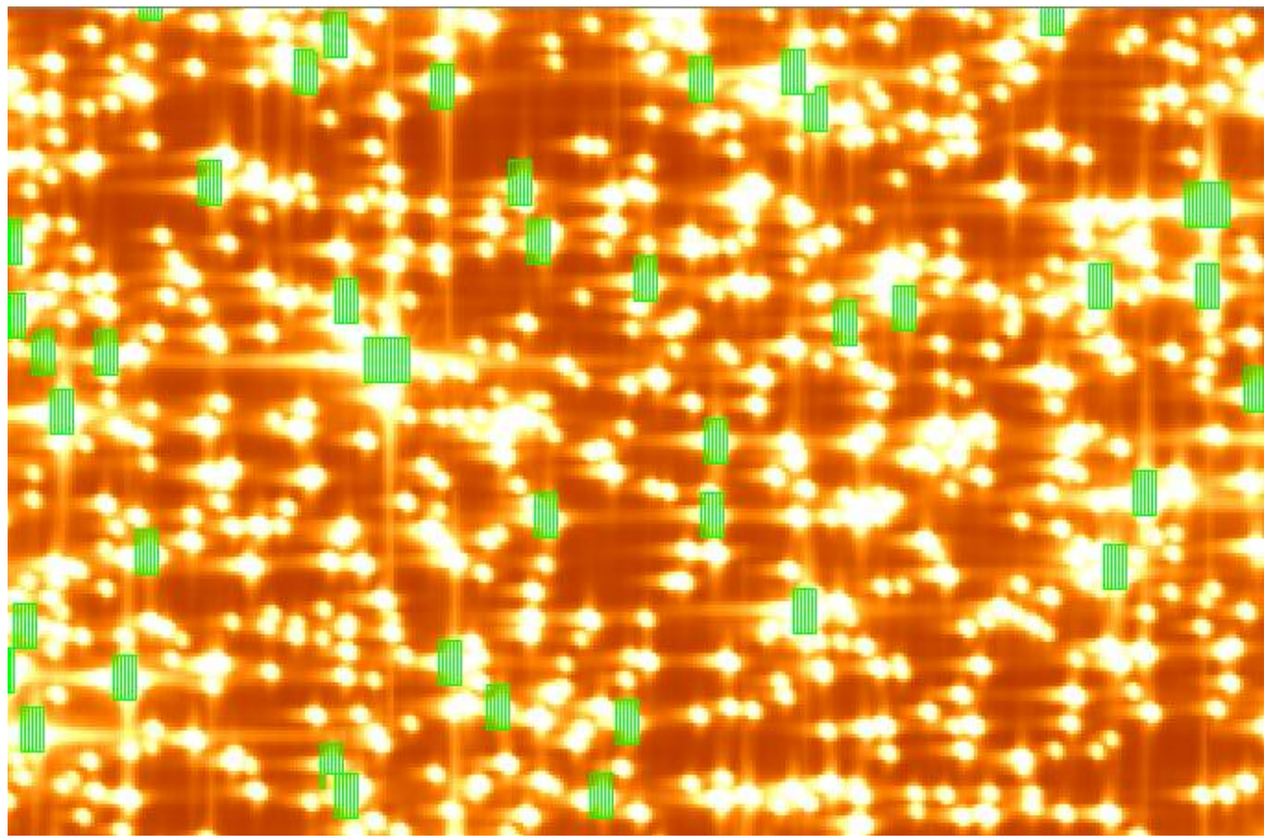
- Relatively low number of transits



The special case of the bulge...

- Crowding (flux contamination, as usual...)
- Highest densities : saturation of the on-board resources

Simulated Gaia astrometric observation of Baade's Window



GIBIS

(Gaia Instrument and Basic Image Simulator, Babusiaux et al., 2011)

20'' x 40''
pixel: 59 x 177 mas

Not taken into account in the nominal performances !

On-board resources limitations

- Design density : 600,000 stars/deg^2

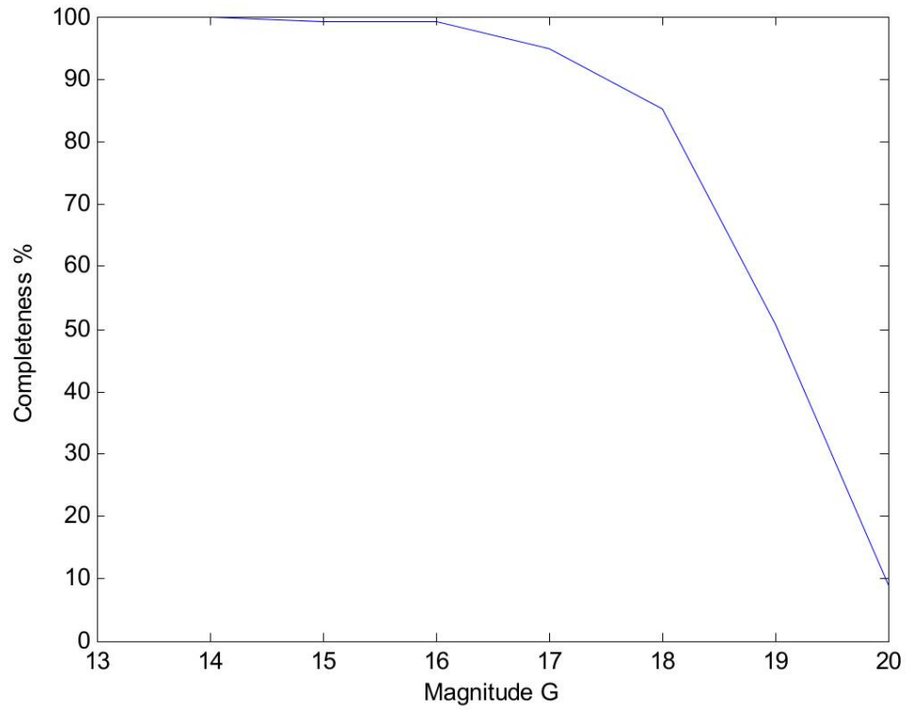
  → Gaia operates nominally

- Higher densities (up to 3 10^6 stars/deg^2)

  → Lower completeness, even close to the design density for first releases.

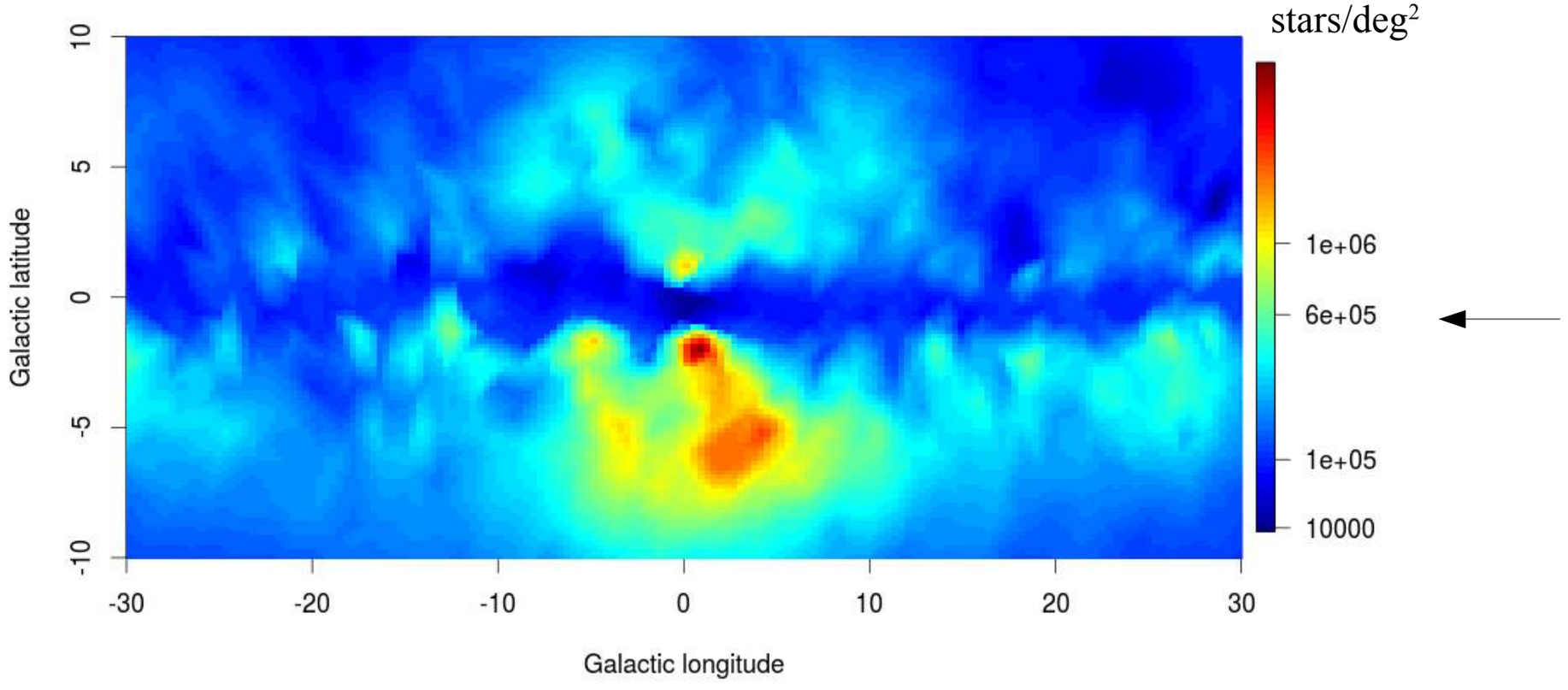
  → Degradation of performances for the faint stars

Simulation of a single observation completeness in Baade's Window (3 10^6 stars/deg^2)



Densities in the bulge

- Low extinction: high densities, resource issue
- High extinction: no crowding but bulge stars too faint



Mitigation options

- High Density Mode (random priority instead of magnitude driven)

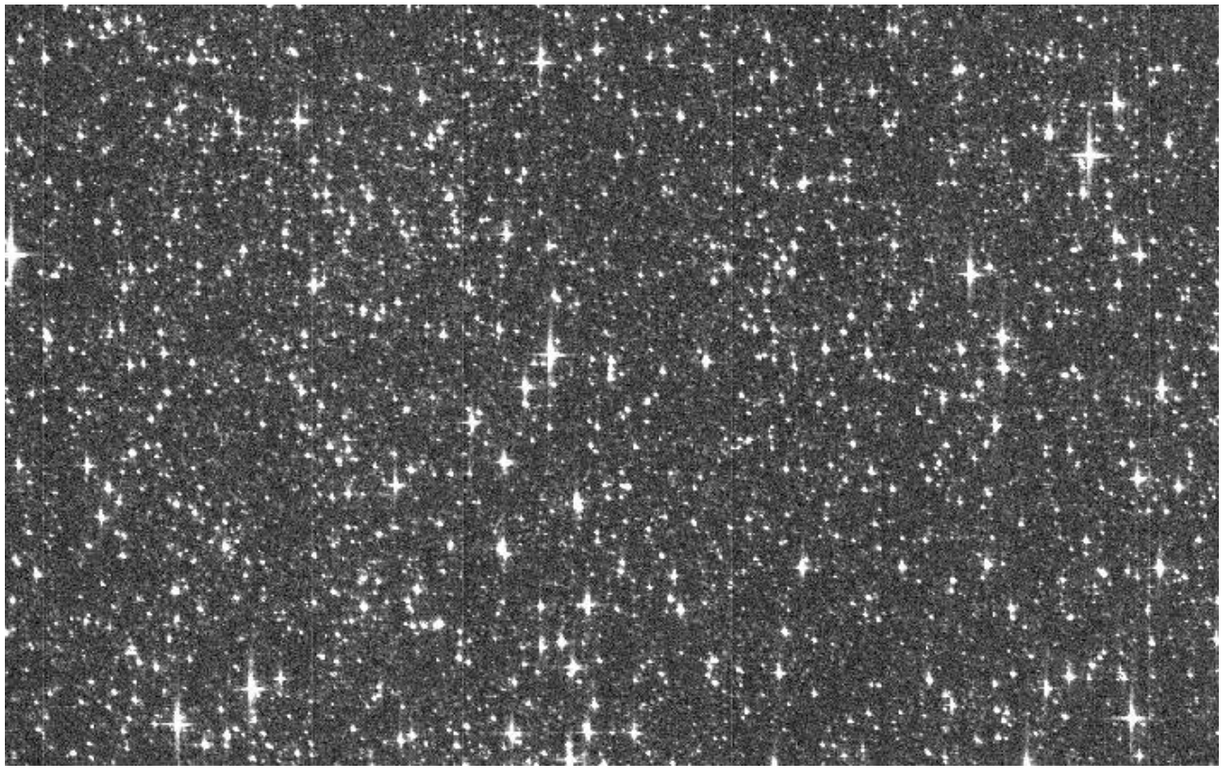
  + Modified Scanning Law (to cross several times the bulge area)

    not activated

- SIF images (Service Interface Function)

SIF images

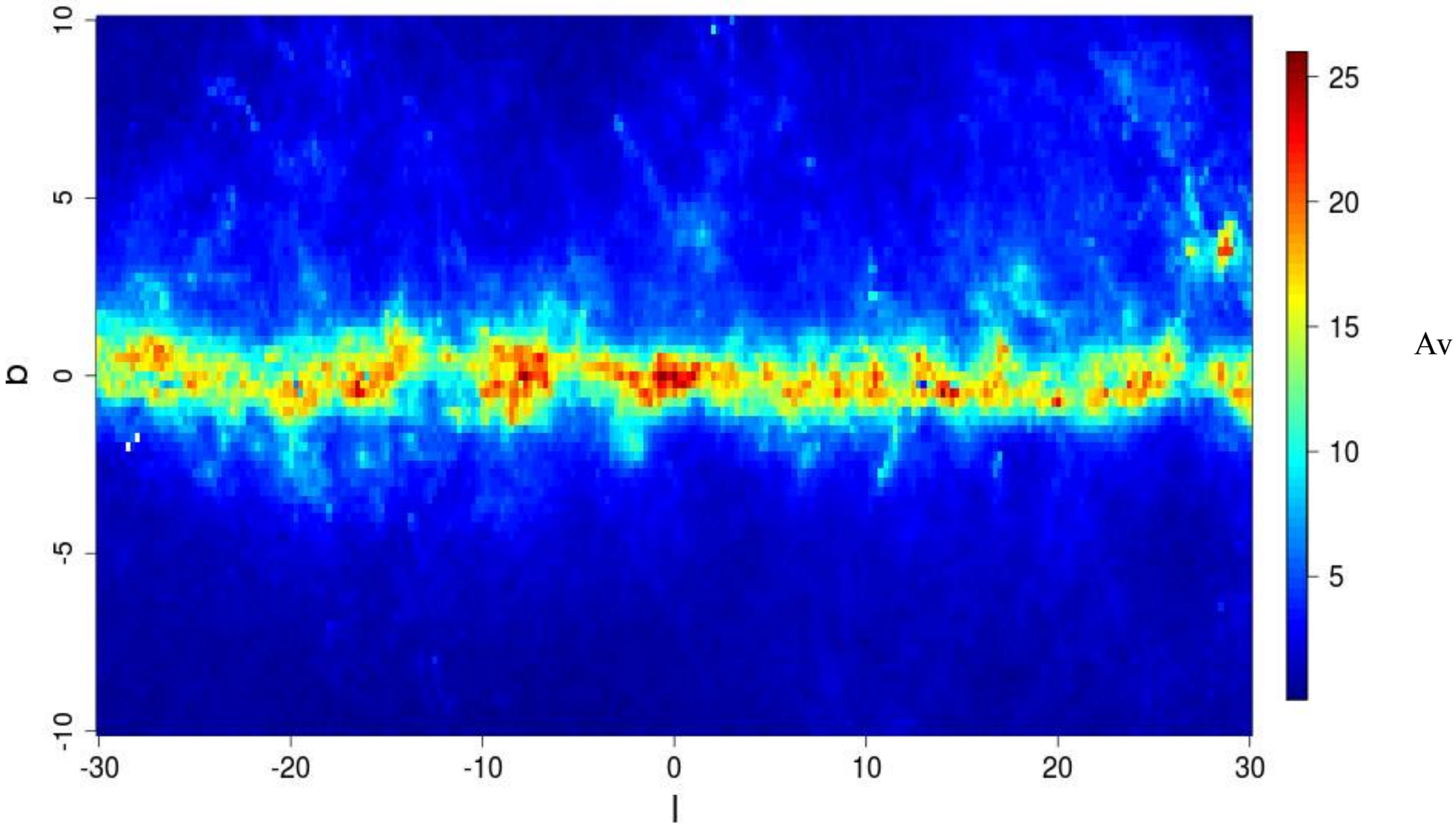
- Specific mode for test purposes.
- Several seconds of full-frame data of the Sky-Mapper CCDs are stored and downlinked.
- These images have fixed exposure time and lower spatial resolution than nominal Gaia observations (till G = 19)
- Downloaded each time Gaia sweeps across Baade's Window, but not during Galactic Plane Scans (telemetry issue)
- Good detection performances, final astrometric ones TBD



SIF image
Baade's Window
~ 5' x 10'
sample: 0.118" x 0.354"

The extinction factor

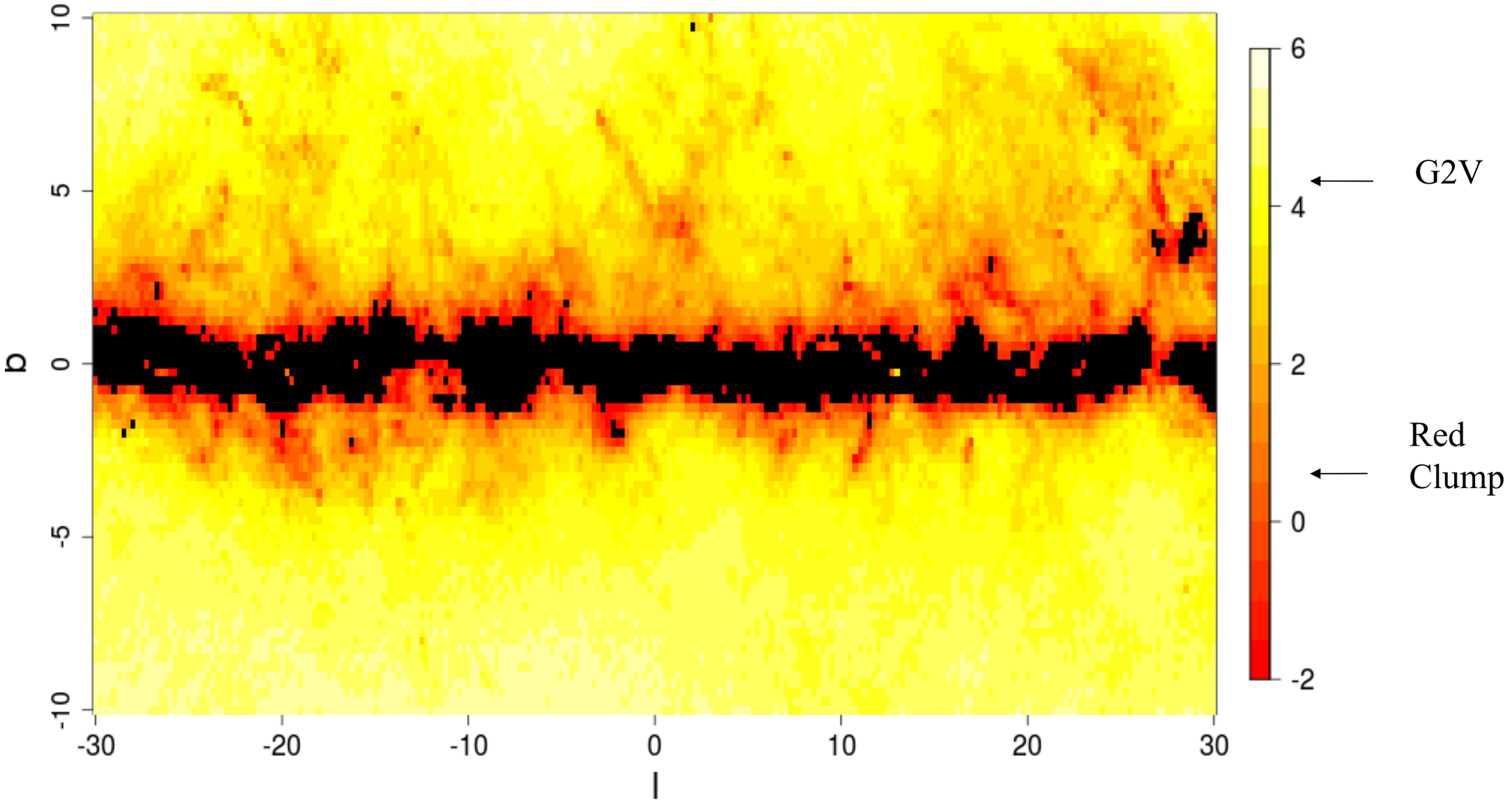
Extinction at 8 kpc



Extinction map from Marshall et al. 2006, A&A 453, 635

Which tracers for the bulge?

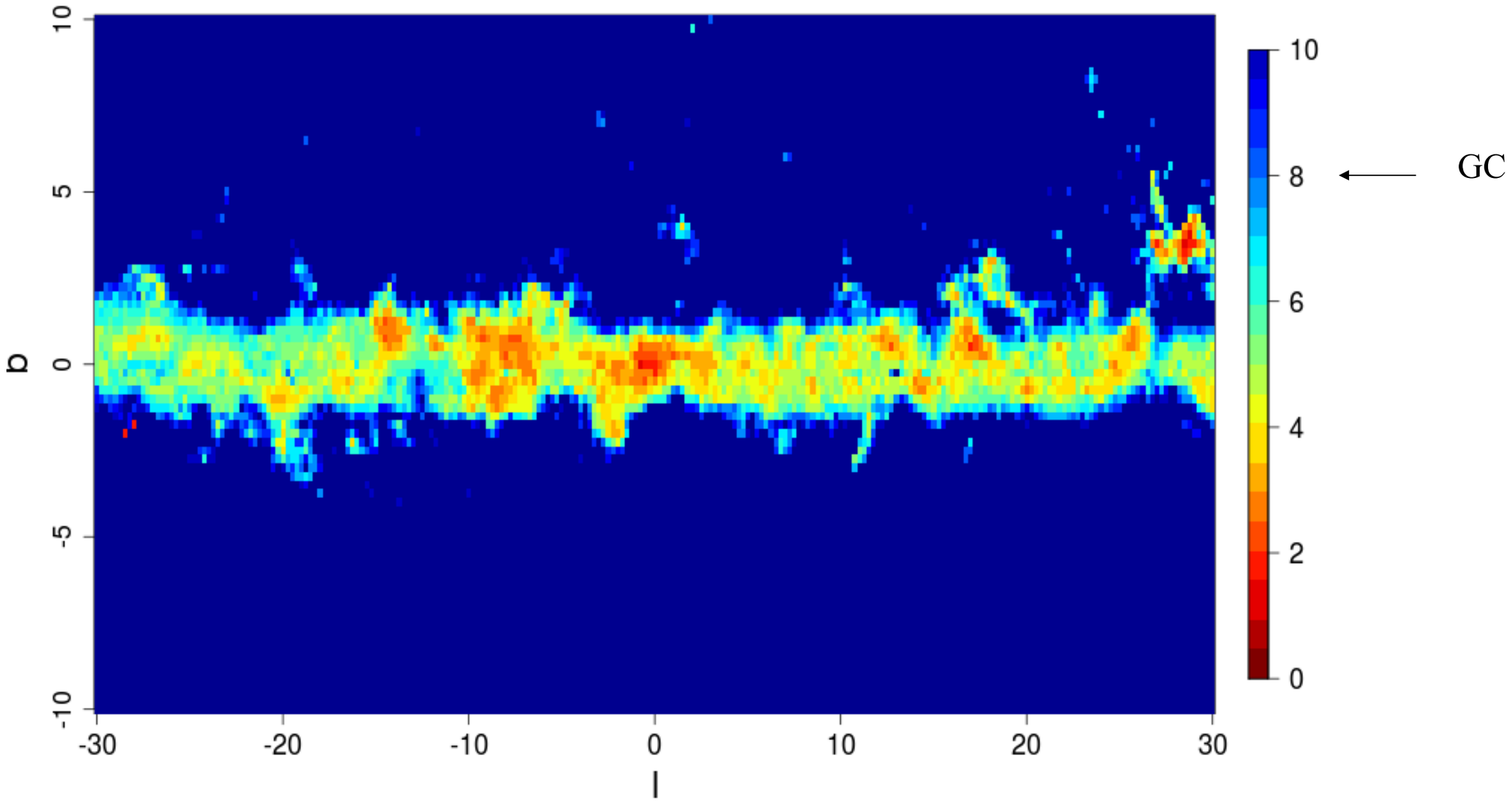
M_G corresponding to G=20 at 8 kpc



G=20 at 8kpc : σ_μ = 15 km/s

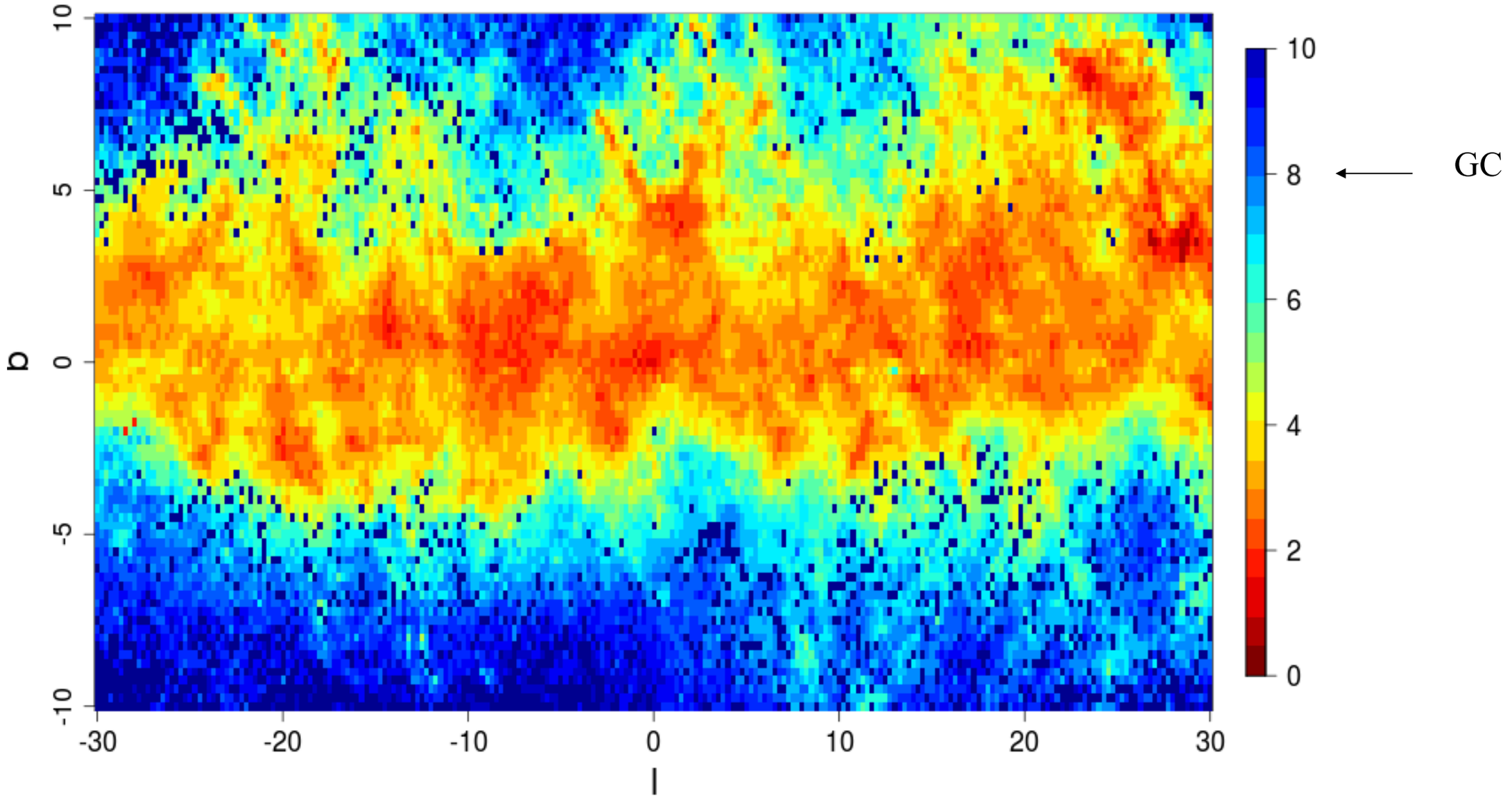
How far can we reach with Red Clump stars?

Distance reached by Red Clump stars at G=20



The brightest stars

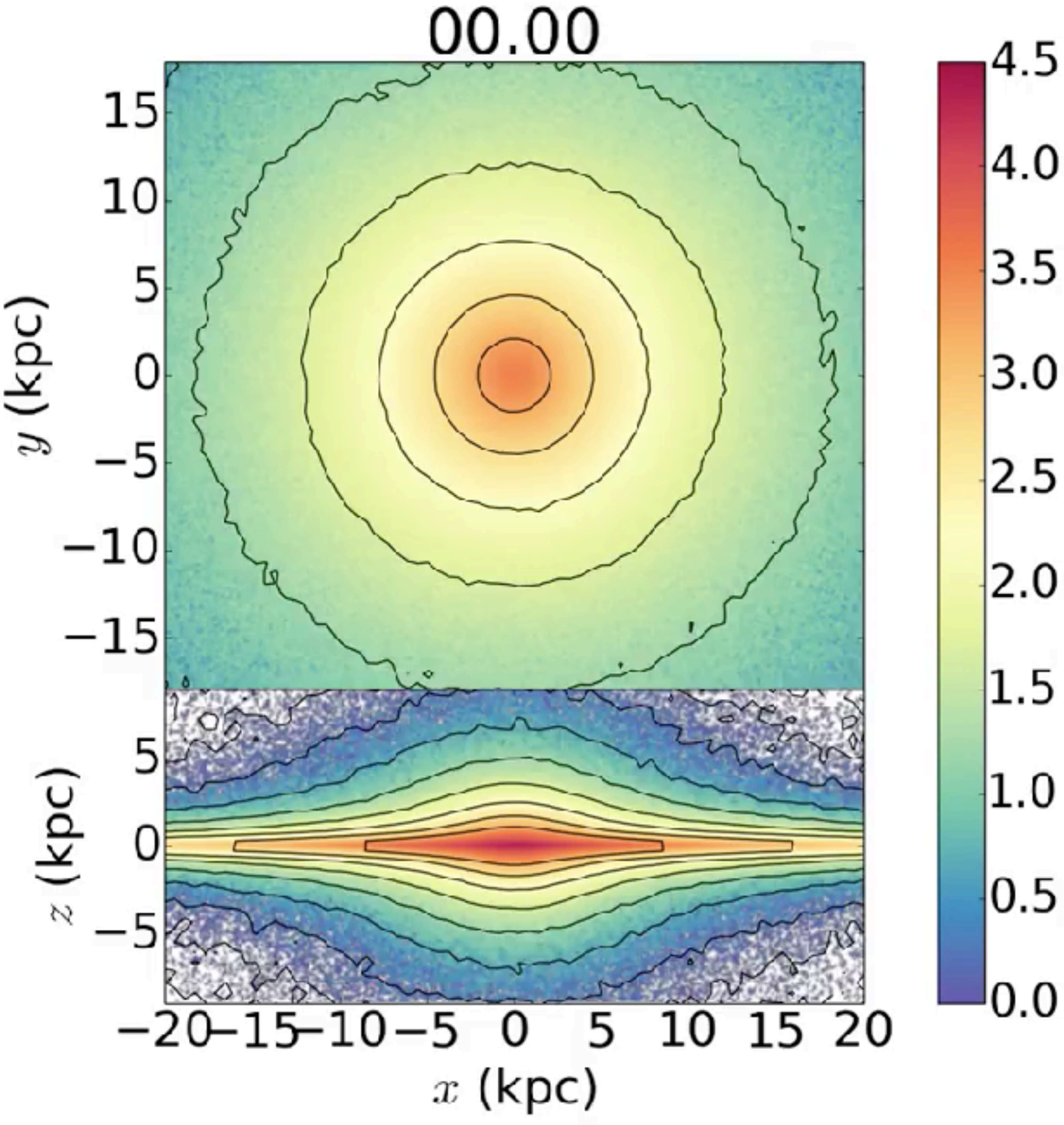
Distance reached by Red Clump stars at G=16



G=16 at 8kpc (RC with A_G=1) : σ_π/π = 40%, σ_μ = 1 km/s, σ_{Vr} = 15 km/s

Will less suffer from the resource allocation problem

Peanut bulge galaxy



This N-body simulation shows the spontaneous formation of a galactic bar in a self-gravitating stellar disc (where the disc is made up of a thin, kinematically cold, a thick kinematically hot and an intermediate disc). The galaxy is rotated so that the bar is always aligned along the x-axis.

The simulation has 20 million particles distributed in the disc and the dark matter halo. The time at the top is in Gyrs.

Credit: P. Di Matteo, F. Fragkoudi (GEPI)

Gaia performances in globular clusters

Pancino et al., 2017

- presently available Gaia deblending pipelines + their results on simulated data
- Additional crowding errors combined with post-launch science performances
- set of simulated GCs with different concentration, distance and field population

Cluster	c (dex)	distance (kpc)	background	n_{tot}	n_{GC}	$n_{classic}$	n_{blends}	n_{contam}	n_{clean}	Designation	Similar to
# 1	1.0	5	halo	73385	72510	4621	45101	52142	16093	*Easy case*	M13, M92
# 2	1.0	10	halo	30200	29325	3521	21550	23754	4275		M92
# 3	1.0	15	halo	14027	13152	2203	10312	11203	1495		NGC 5053
# 4	1.0	5	disk	54923	26816	1028	14115	17289	7379		M71
# 5	1.0	10	disk	33435	5328	326	3302	3812	1164	*Intermediate case*	M56, NGC 2298
# 6	1.0	15	disk	29737	1630	123	1048	1208	311		M79
# 7	1.0	5	bulge	1537592	71996	9833	69887	71600	218		M22, NGC 6553
# 8	1.0	10	bulge	1494601	29005	5620	28497	28919	36		M9, NGC 6638
# 9	1.0	15	bulge	1478538	12942	2998	12762	12911	15		Pal 11
# 10	2.5	5	halo	73385	72510	11902	47043	53029	15623		M5
# 11	2.5	10	halo	30200	29325	6914	21977	23944	4117		M3
# 12	2.5	15	halo	14027	13152	3663	10407	11176	1525		NGC 5466
# 13	2.5	5	disk	54923	26816	3236	15372	18085	6946		M92, Pal 10
# 14	2.5	10	disk	33435	5328	906	3491	3968	1055		M79, NGC 1851
# 15	2.5	15	disk	29737	1630	292	1097	1250	300		M15
# 16	2.5	5	bulge	1537592	71996	16564	70125	71648	190		NGC 6540, NGC 6558
# 17	2.5	10	bulge	1494601	29005	8726	28556	28924	40		NGC 6325, NGC 6342
# 18	2.5	15	bulge	1478538	12942	4378	12770	12914	13	*Difficult case*	M54, NGC 6517

➤ extinction assumption:
reddening = BG field's highest value

NB. Precession of Gaia: different scans correspond to different projected distances of two stars in the SM columns

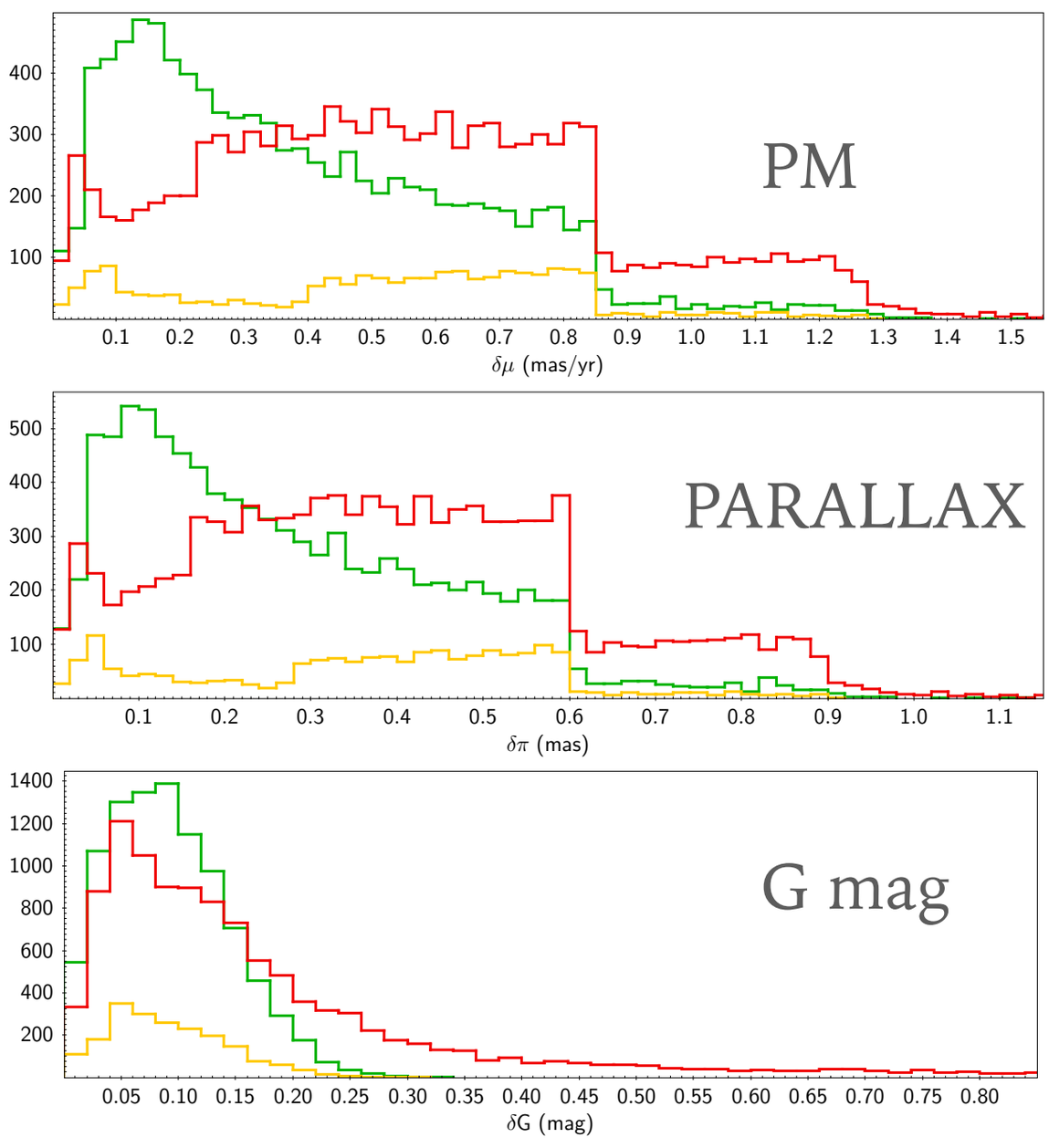
Gaia performances in globular clusters

Pancino et al., 2017 study based on the current status of deblending and decontamination pipelines — pessimistic.

Results:

- astrometry and G magnitude marginally affected by crowding even in the most contaminated GCs
- The proper motions of individual stars within GCs have sufficient quality to obtain mass estimates with 10% errors for GCs as far as 15 kpc at least
- difficult to simulate the exact completeness level of Gaia in GCs but the astrometric performances are still exceptional in the central arcminute of the simulated GCs: most of the stars have errors around a few 100 μas or μas yr−1
- BP/RP and RVS more affected by crowding

End-Of-Mission error distribution for all member stars down to G = 20.7



3D mapping of interstellar medium

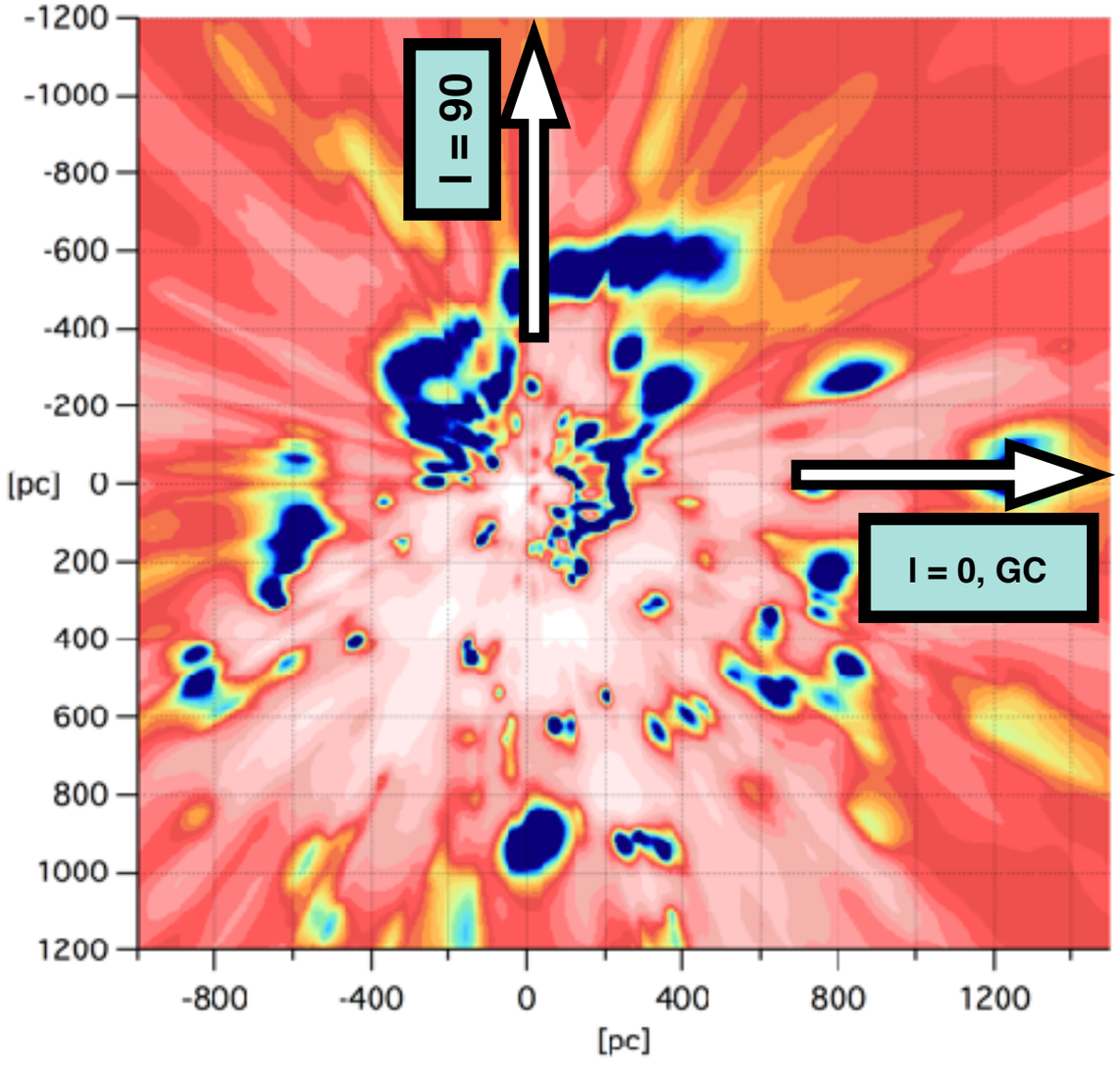
Capitanio et al., 2017

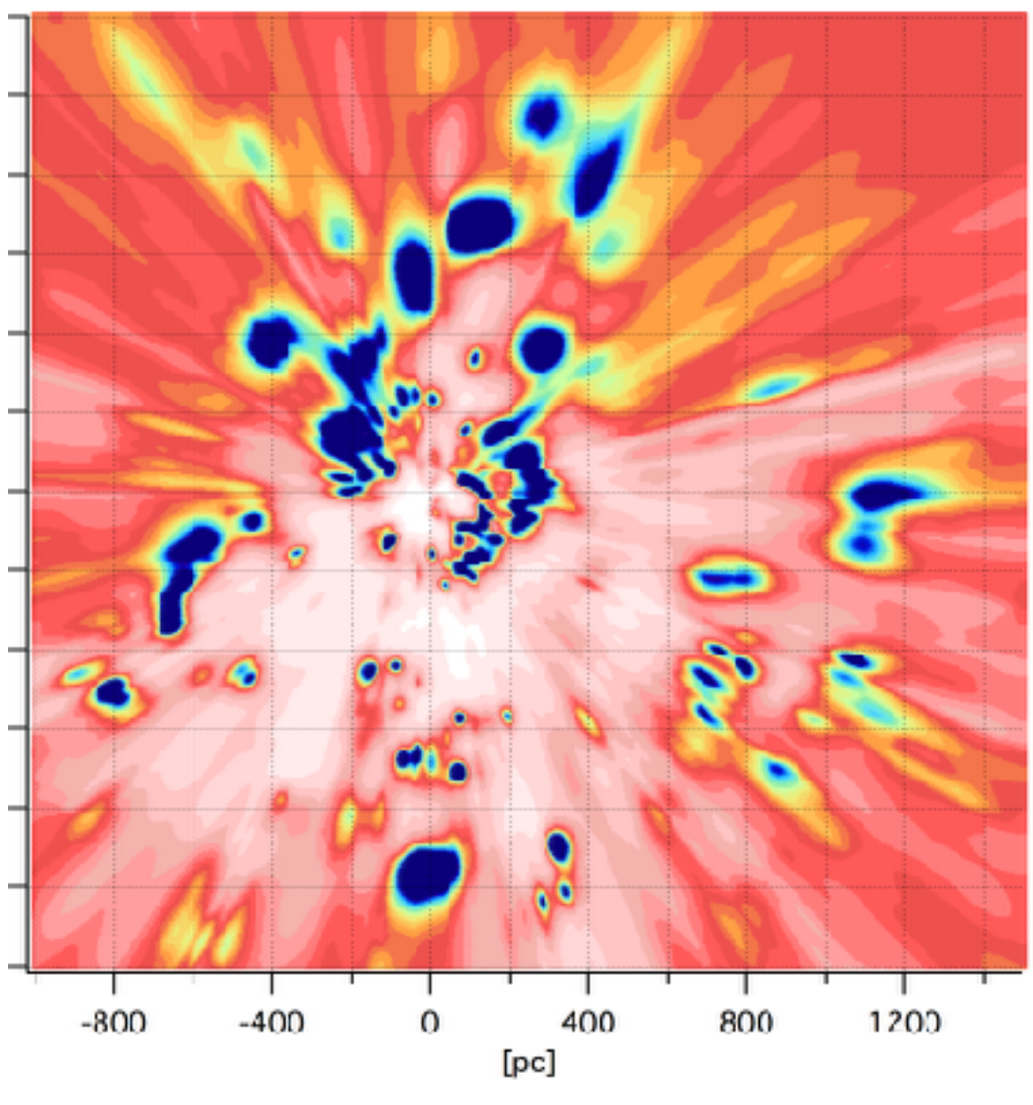
PRE-Gaia
(Lallement et al. 2014)

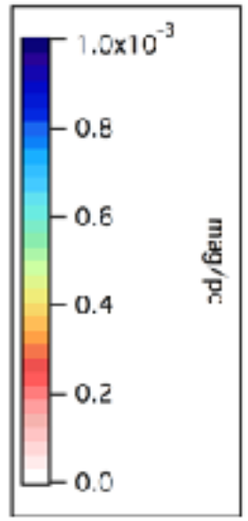
- color excess data alone
- Hipparcos or photometric distances

POST-Gaia

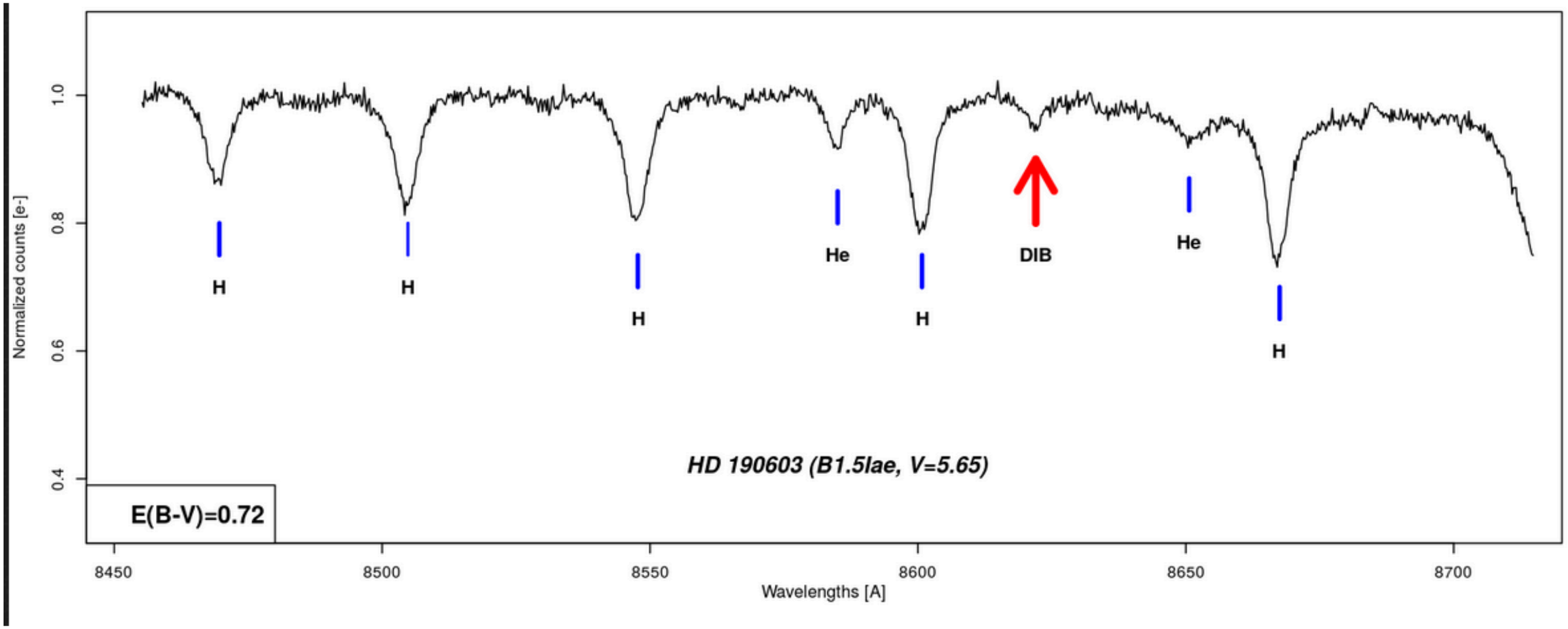
- replacement of 80% of the initial distances with Gaia-DR1 (TGAS) values





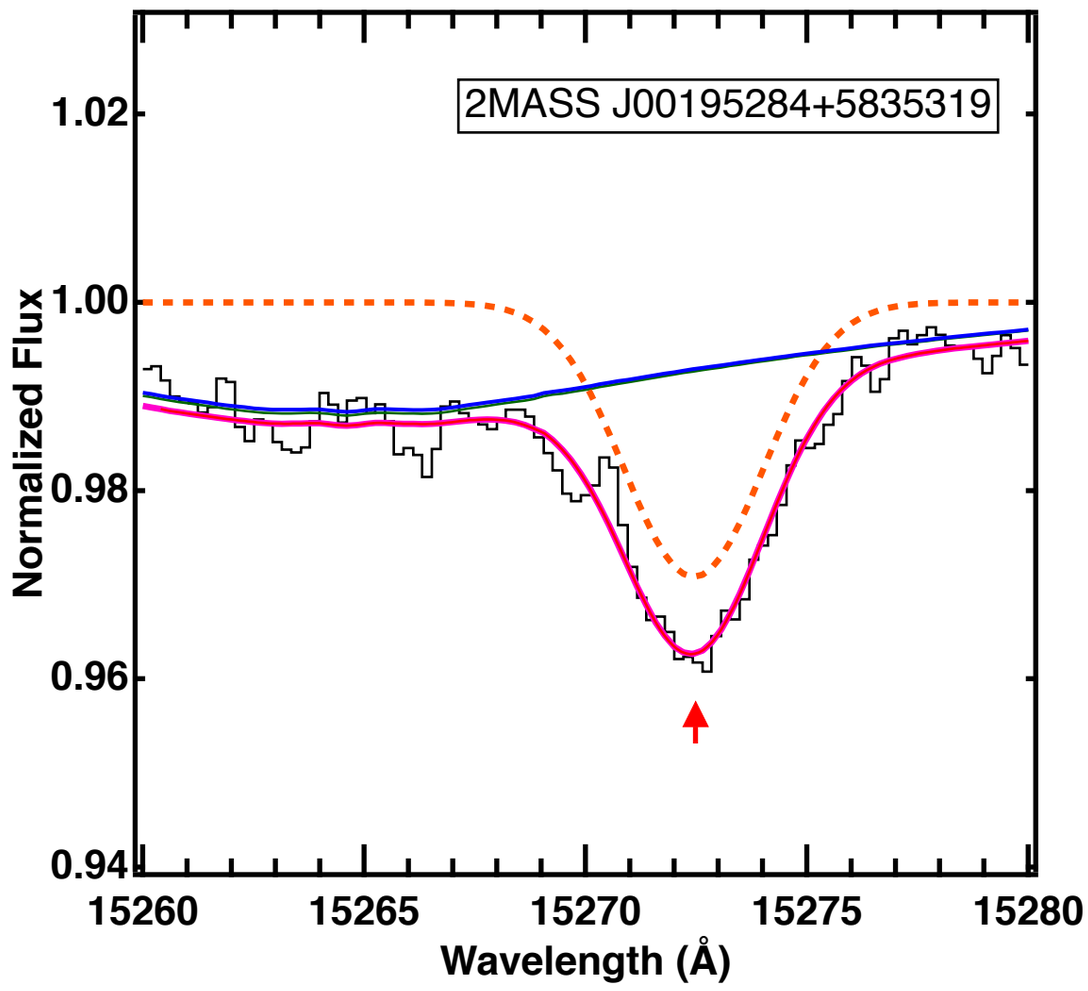


DIBs as matter tracers?



DIBs as matter tracers?

Elyajouri et al.,2017



E(B-V) mag ≈ EW(Ang) * 3.3
Zasowski et al, 2015

3D mapping of interstellar medium

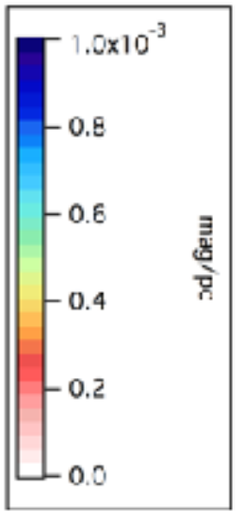
Capitanio et al., 2017

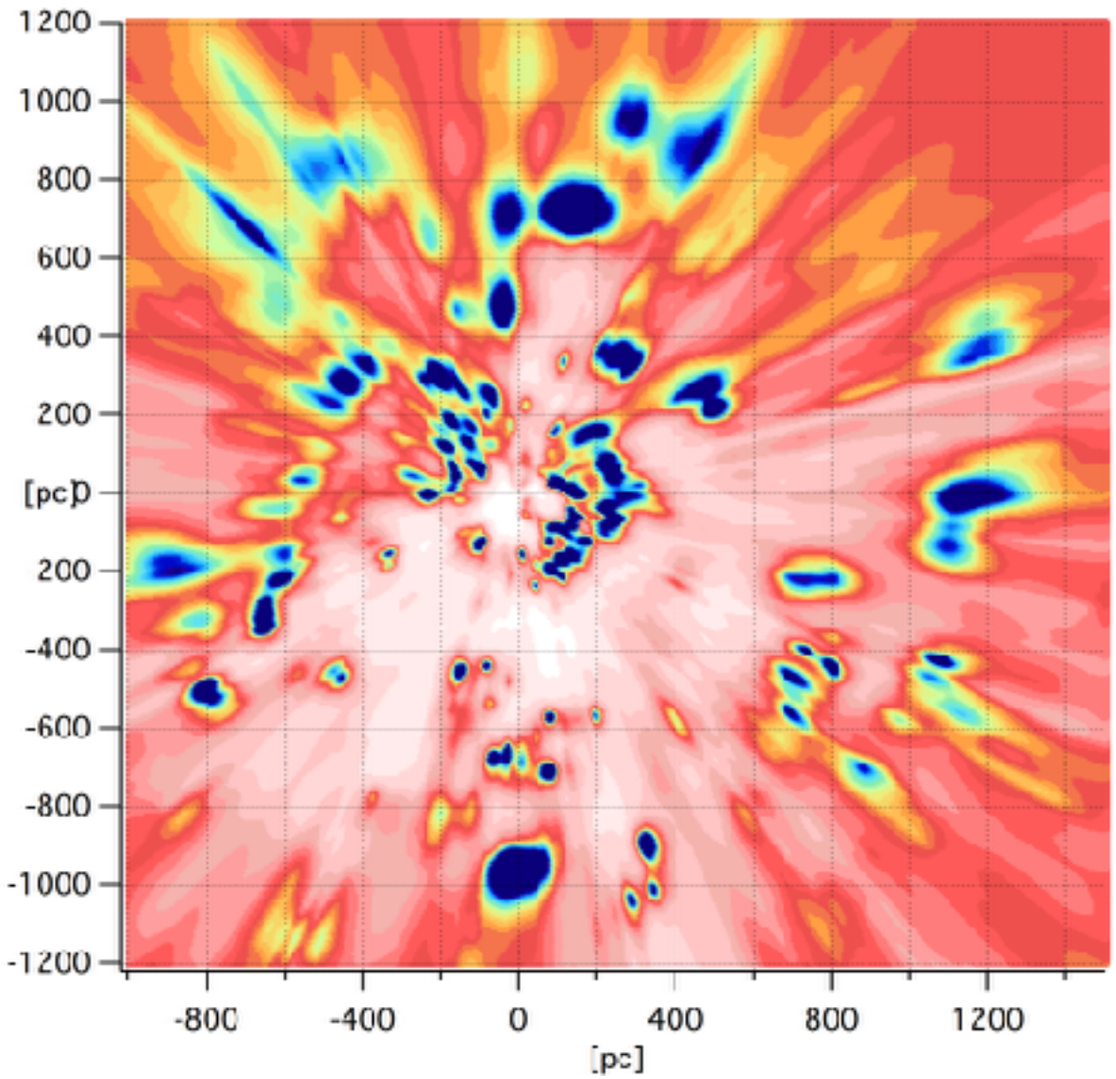
POST-Gaia

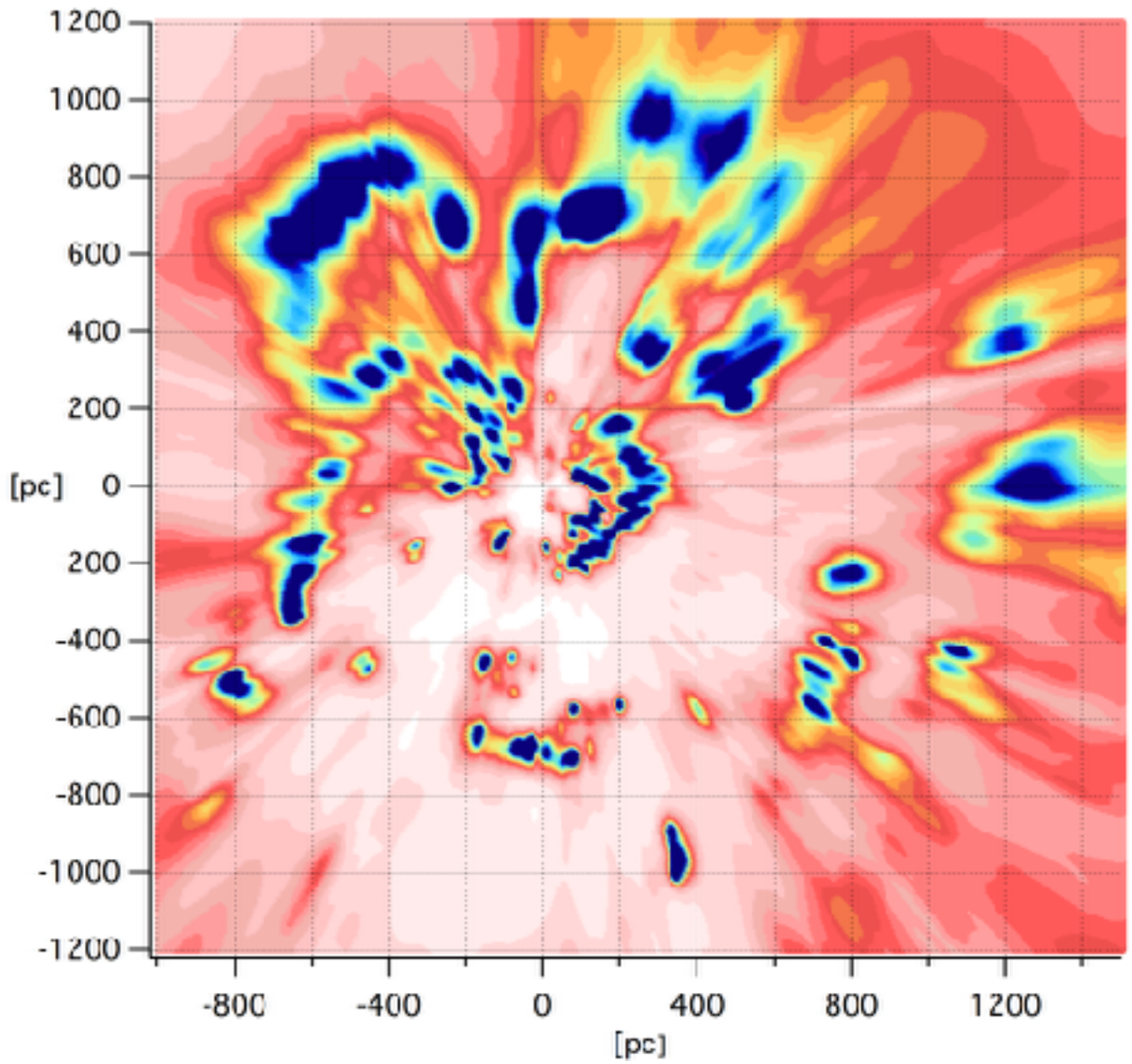
- of DIB-based color excess estimates for stars with a Gaia-DR1 parallax

POST-Gaia

- additionPan-STARRS based prior distribution instead of a homogeneous distribution



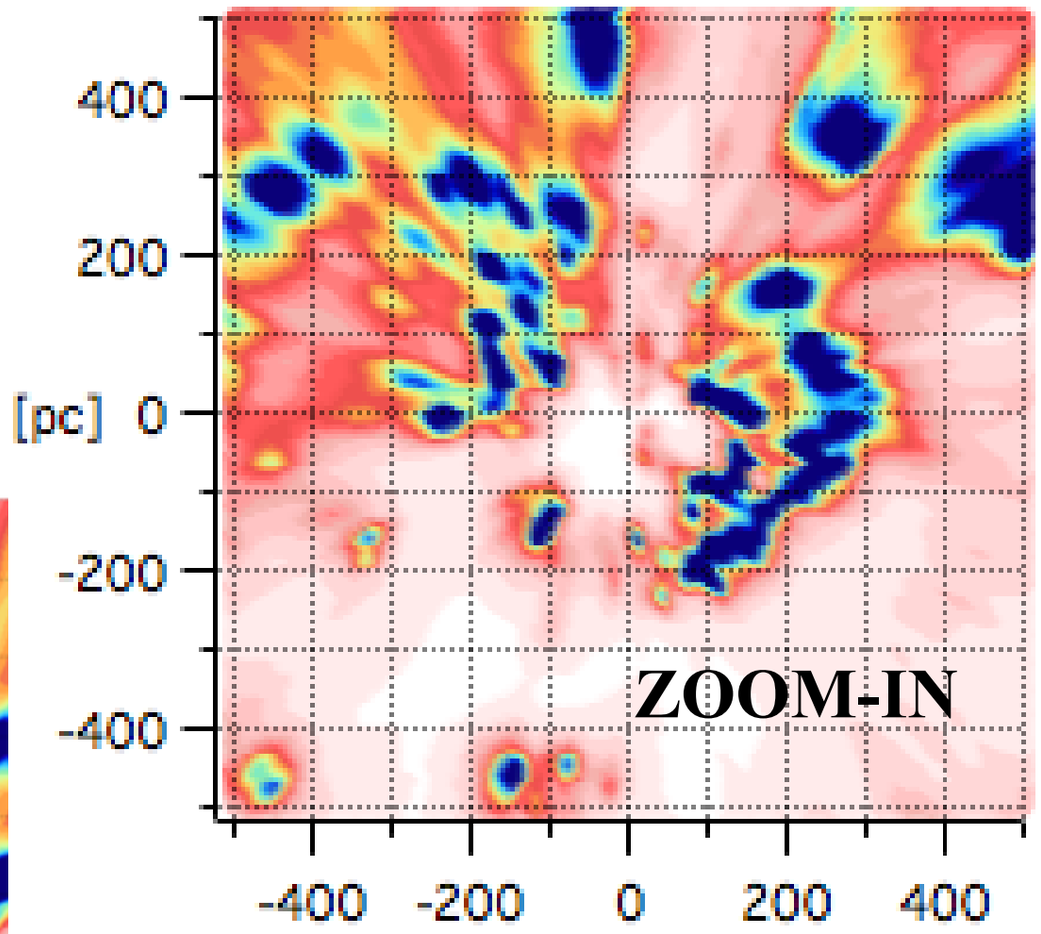


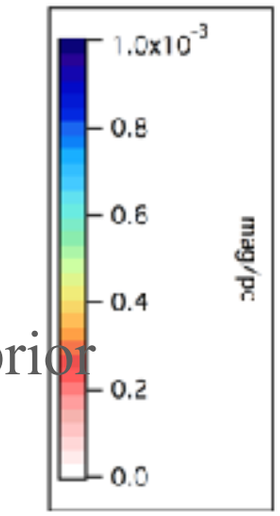


3D mapping of interstellar medium

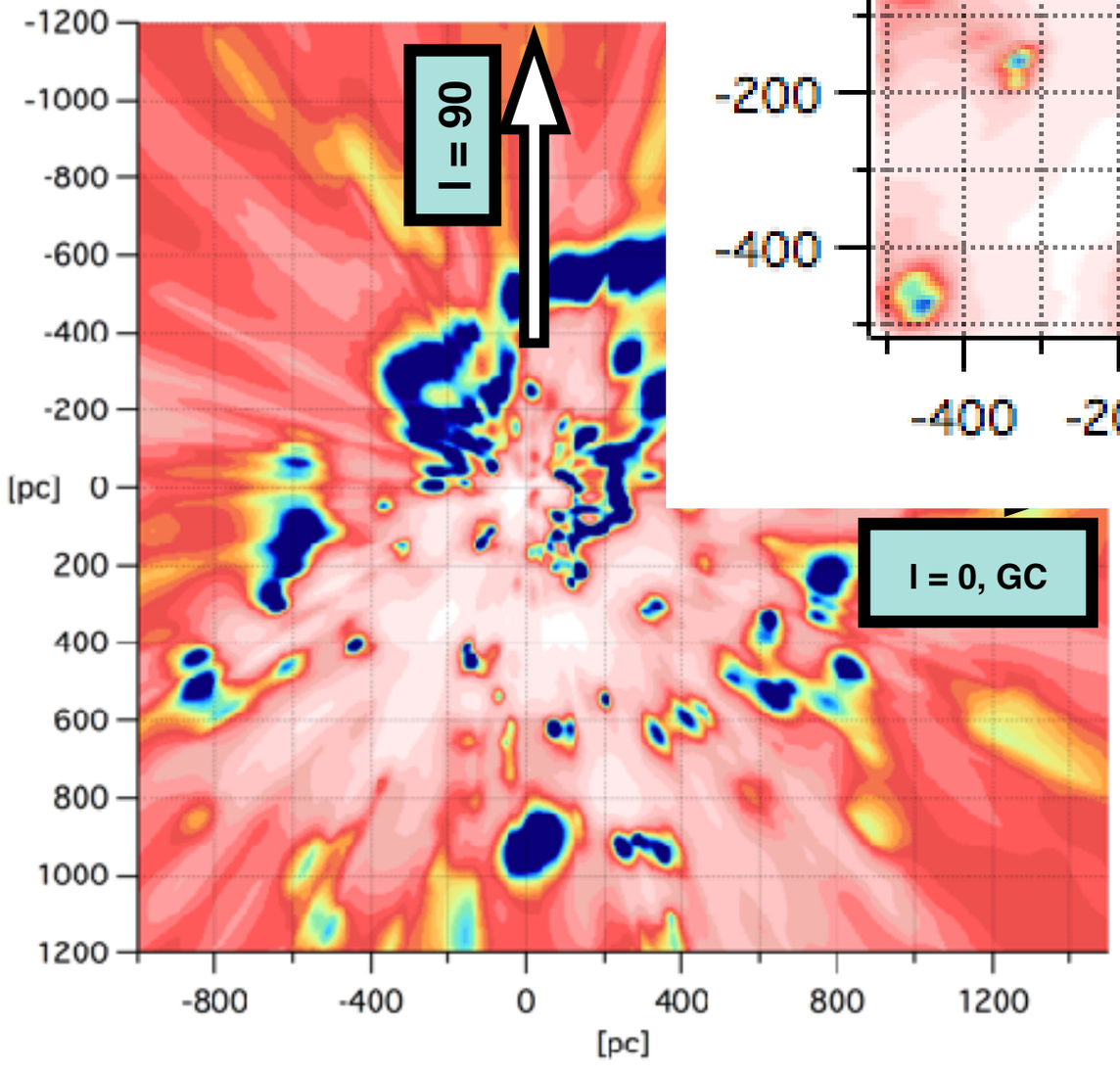
Capitanio et al., 2017

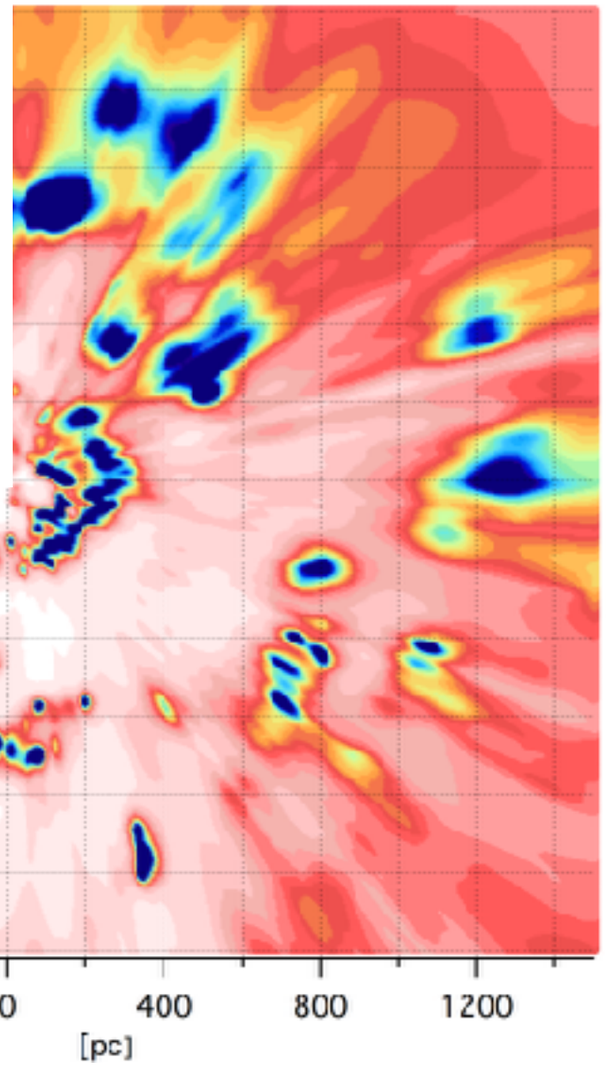
PRE-Gaia
(Lallement et al. 2014)





ARRS based prior
ead of a
istribution

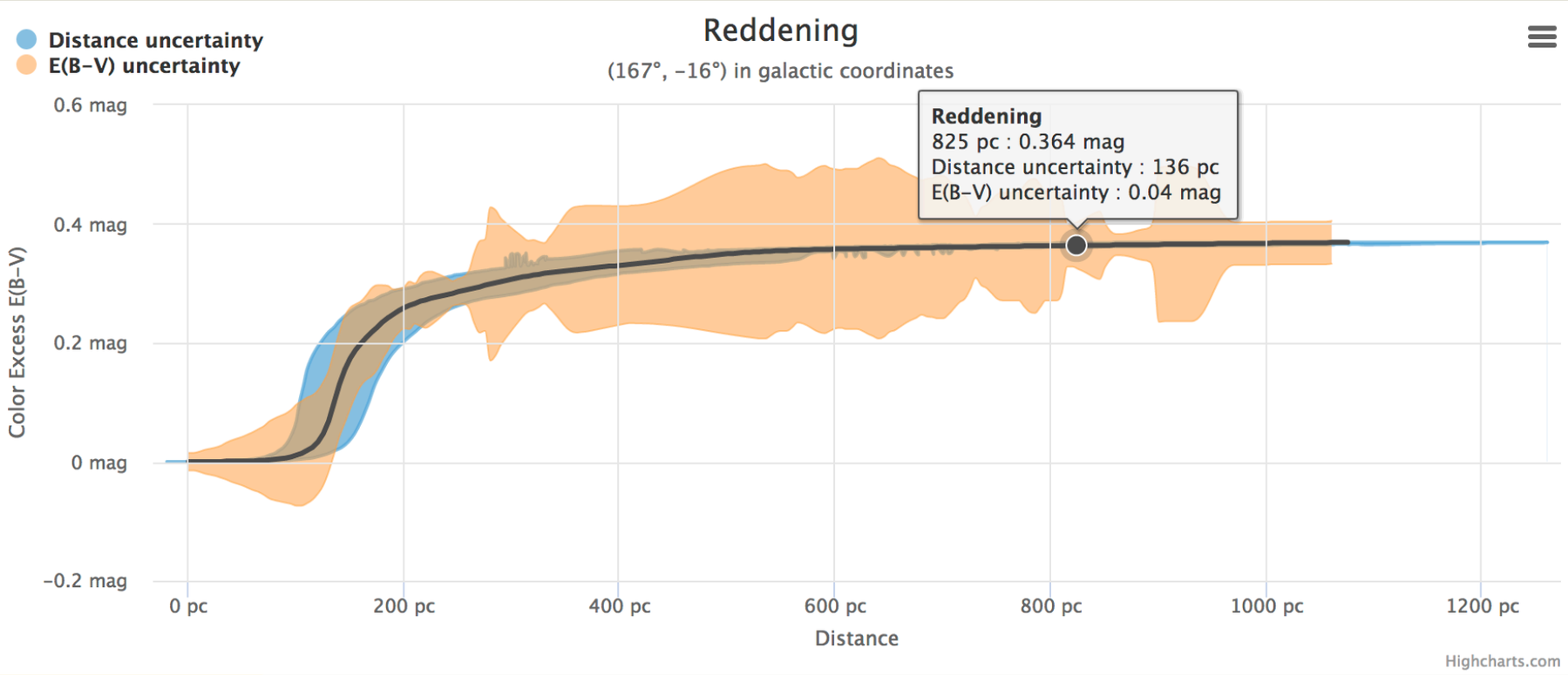




On-line TOOL: stilism.obspm.fr

ne / Reddening

You can zoom on a region with the mouse



Gaia G-band empirical extinction coefficient

No Gaia filter response till DR2 => need to estimate it empirically

Substantial degeneracy between extinction, effective temperature and spectral energy distribution (SED).

A star which has the greater fraction of its radiation in the blue-end of the spectrum (a bluer star), has a larger extinction coefficient than a redder star.

$$k_m = a_1 + a_2\hat{T} + a_3\hat{T}^2 + a_4\hat{T}^3 + a_5 A_0 + a_6 A_0^2 + a_7 \hat{T} A_0$$

but also as a function of colour $(G-K)_0$

INGREDIENTS:

- Spectrometry: LAMOST (MS) APOGEE(RG)
- Photometry: Gaia DR1 and 2MASS (J,K)
- E(B-V) Capitanio+, 2017 3D MAP
- Photometric calibration (RG + MS)
  (for RG: Ruiz-Dern et al., submitted)

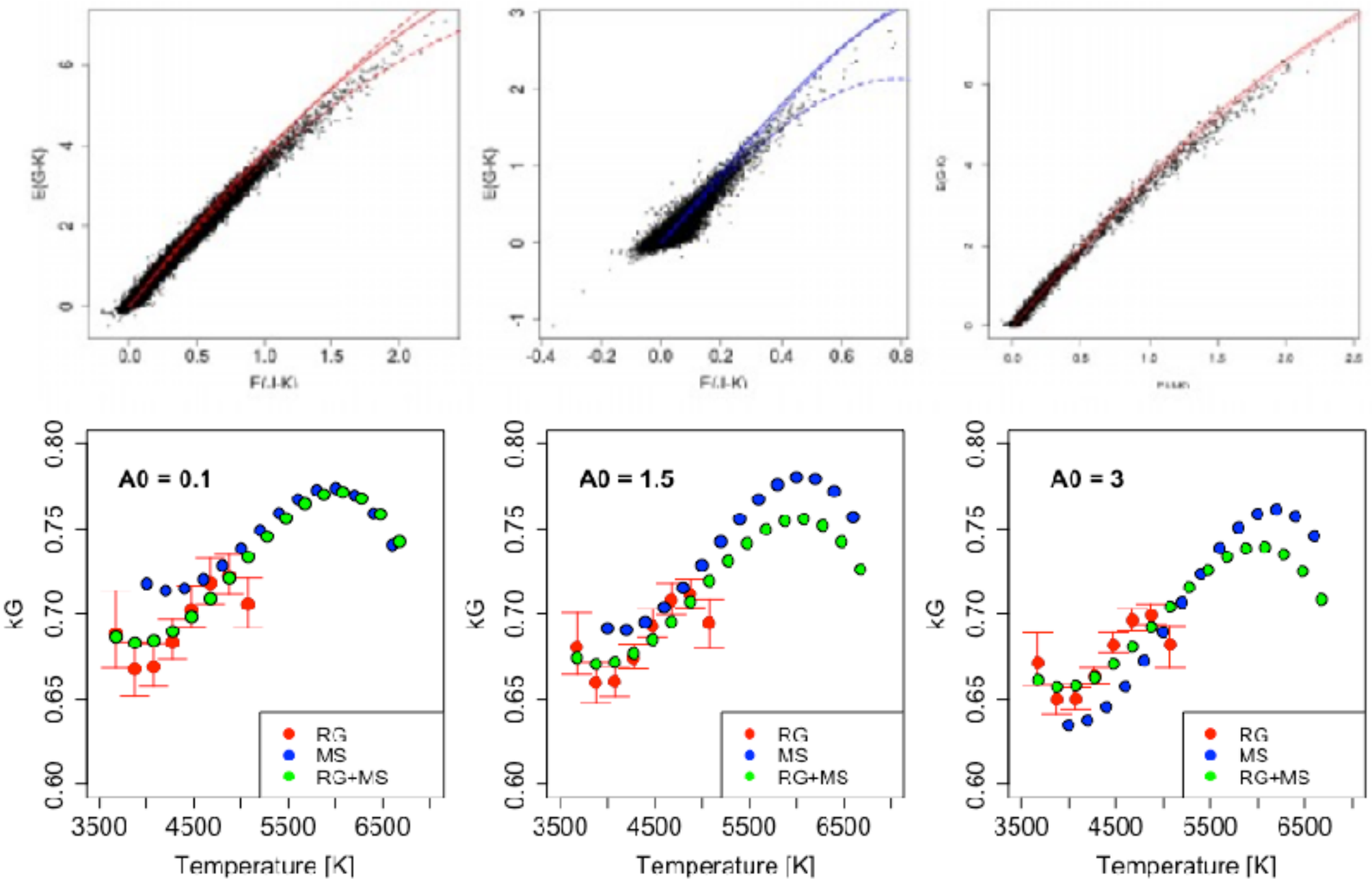
$$\begin{aligned}(G-K_S)_0 &= c_1 + c_2\,\hat{T} + c_3\,\hat{T}^2 + c_4\,[Fe/H] + \ldots \\ &\quad + c_5\,[Fe/H]^2 + c_6\,\hat{T}\,[Fe/H]^2 \\ (J-K_S)_0 &= c_7 + c_8\,(G-K_S)_0 + c_9\,(G-K_S)_0^2 + \ldots \\ &\quad + c_{10}\,[Fe/H] + c_{11}\,[Fe/H]^2 + c_{12}\,\hat{T}\,[Fe/H]\end{aligned}$$

Gaia G-band empirical extinction coefficient

Danielski et al., in prep.

$$k_m = a_1 + a_2\hat{T} + a_3\hat{T}^2 + a_4\hat{T}^3 + a_5 A_0 + a_6 A_0^2 + a_7 \hat{T} A_0$$

Work in progress…



Conclusions

- ✓ **Distances G < 16**
  - → 3D structures studies of the bulge/bar(s)/spiral arms/thin disc interface
  - → bulge / thick disc / halo interface
- ✓ **Proper motions G < 20**
  - → large clean bulge sample
  - → dynamical studies
- ✓ **Spectrophotometry G < 20**
  - → homogeneous photometry
  - → atmospheric parameters
- ✓ **Radial velocities G_{RVS} < 16**
  - → 6D dynamical studies for the brightest bulge stars (position and velocity vectors)
- ✓ **Classification, Variability, Binarity**

Conclusions

- Proper motions are determined with the AF, hence impact of crowding is less severe than BR/RP or RVS

- new 3D extinction map, larger and more precise
  Tool ONLINE for measuring E(B-V): stilism.obspm.fr

- Empirical Gaia G-band extinction coefficient (DR1)
  important to model it as a function of temperature and absorption in large passbands

Meanwhile, when using DR1 ...
Please acknowledge the work of DPAC and ESA in your papers
help us argue the case for continued funding of the data processing
strengthens the mission extension case

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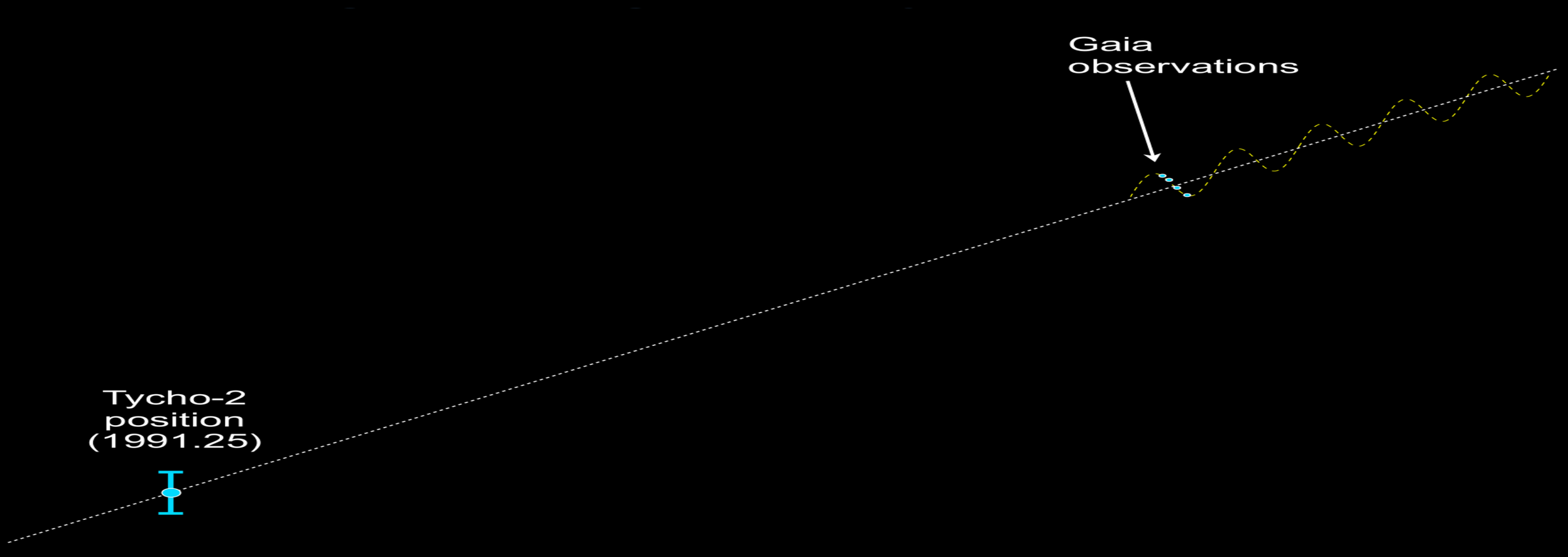
Rosine Lallement, Paola di Matteo and GEPI department.



14 months data only

How to decouple parallaxes from proper motions ?

Prior: Hipparcos & Tycho-2 positions

2 million sources up to G ~ 11.5