A scientific guide to Gaia Astrophysical Parameters

23 March 2023

organized by Coordination Unit 8

GSP-Spec module

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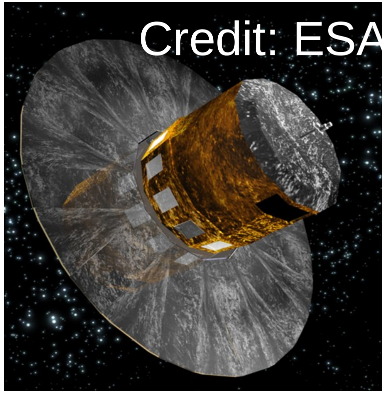
Topics

- **Gaia RVS overview**
- The GSP-Spec module
- The GSP-Spec output
- Some scientific applications
- Recommendations
- Conclusions

Gaia: the one billion survey

- Launched in 2013
- **Most advance astrometric** mission to date.
- **Micro-arc astrometry** for ~1.8 billion sources
- **Radial velocities** for a subset of bright sources (on-board spectrograph RVS).
- **Gaia DR3**: Stellar Param. & Chemistry determined by the GSP-Spec module (Recio-Blanco et al.+22)

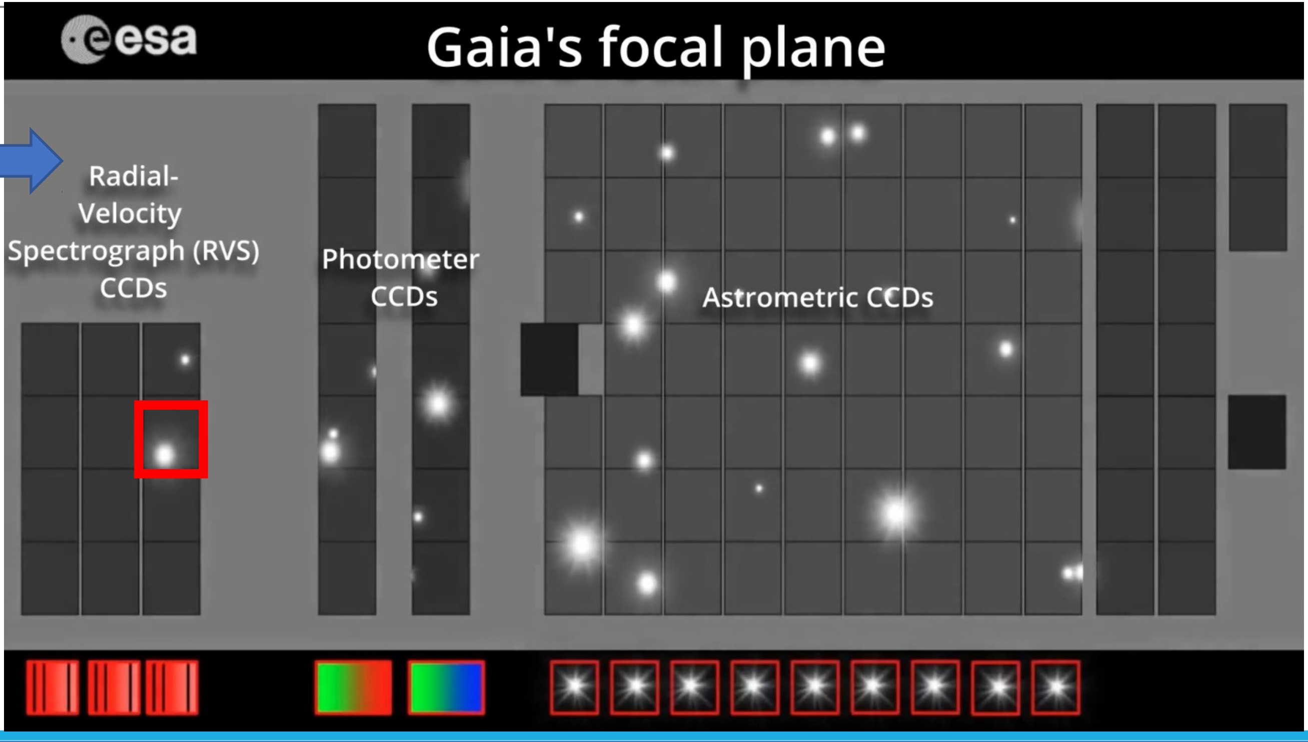


Gaia/RVS: a space spectroscopic survey

RVS

Resolving power: 11,500

Wavelength domain (nIR CaII triplet): 846 - 870 nm



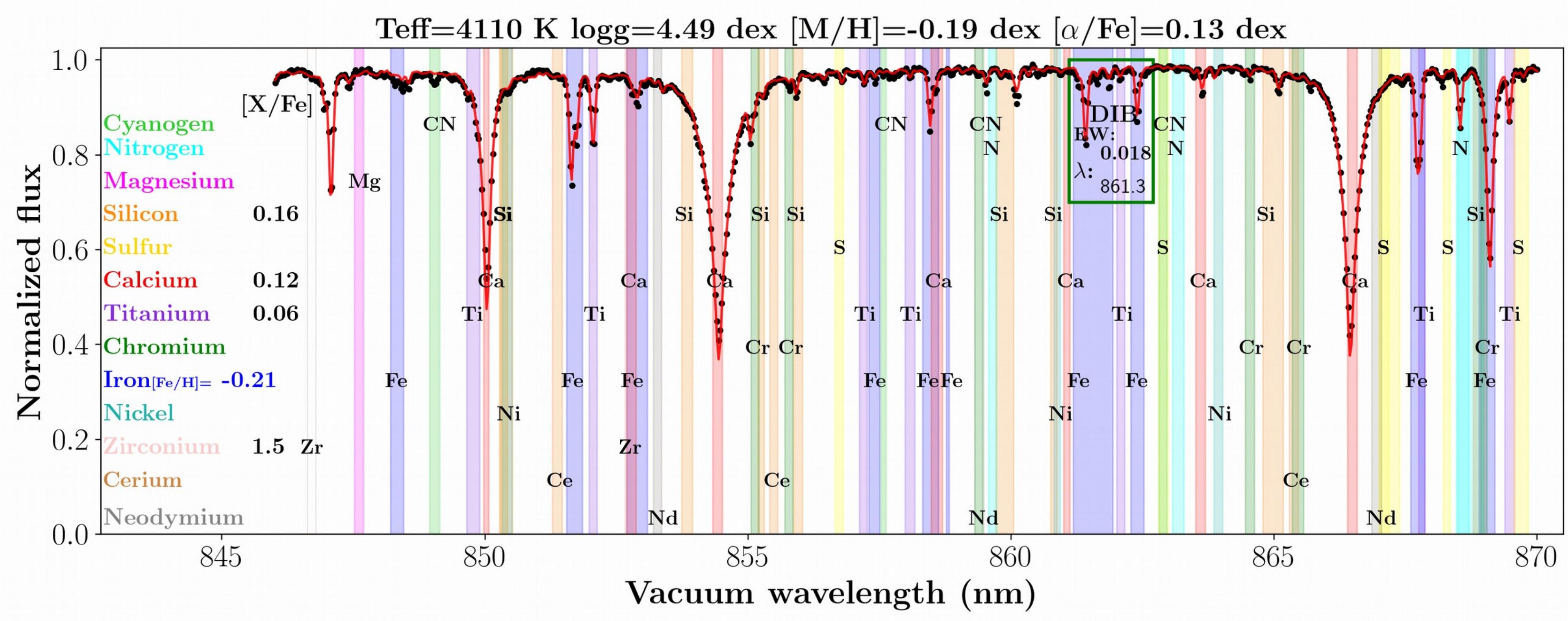
Gaia/RVS: a space spectroscopic survey

Gaia/RVS is **SPACE spectroscopy** ≠ ground based spectroscopy

- **Continuous observations** for years (34 months for DR3, ~25 000h of continuous observations)
- **Stable conditions** (no atmosphere)
- Very good control and modeling of **systematics**
- Extremely **homogeneous** treatment
- **High number statistics** providing hundreds of thousands of high SNR (>150) data
- Parametrization quality **comparable to ground-based surveys** of higher spectral resolution and wavelength coverage.

Gaia/RVS: a space spectroscopic survey

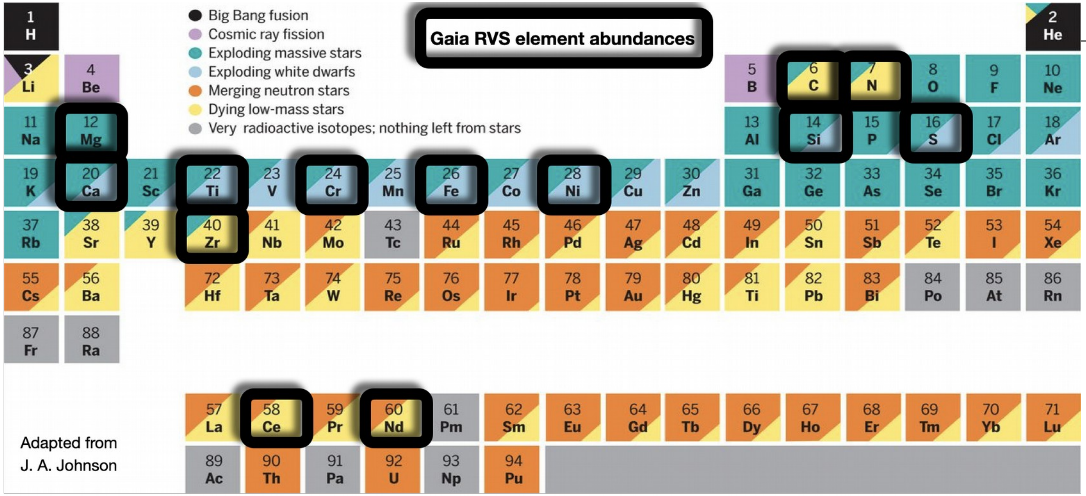
CU8/GSPspec: The chemical composition of **5.6 million** stars.

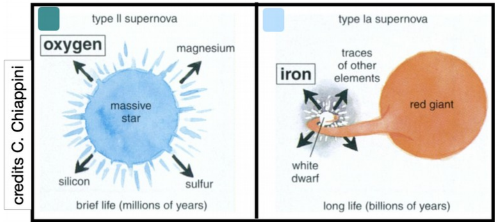


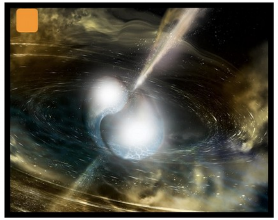
Gaia IoW. Credits:ESA/GAIA/DPAC-CU8-CU6 Recio-Blanco and the GSPspec team

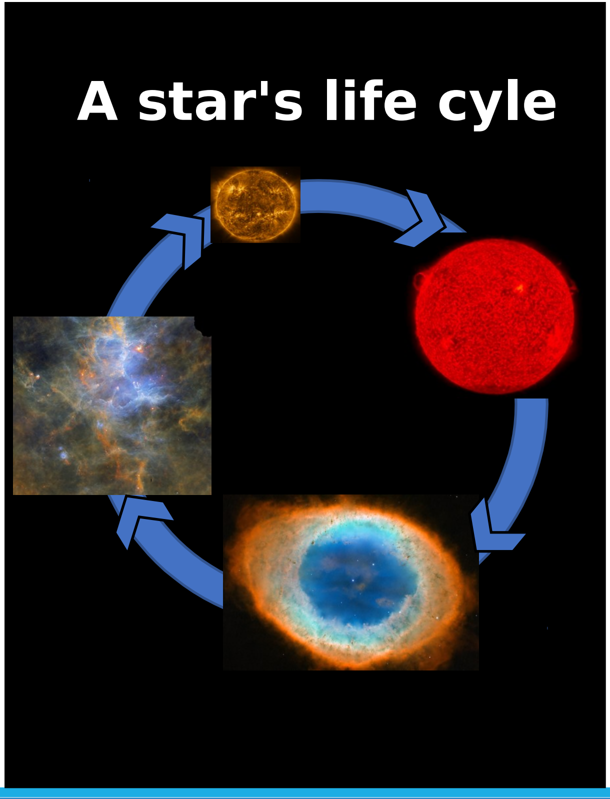
Gaia/RVS: a space spectroscopic survey

Different nucleosynthesis channels









Topics

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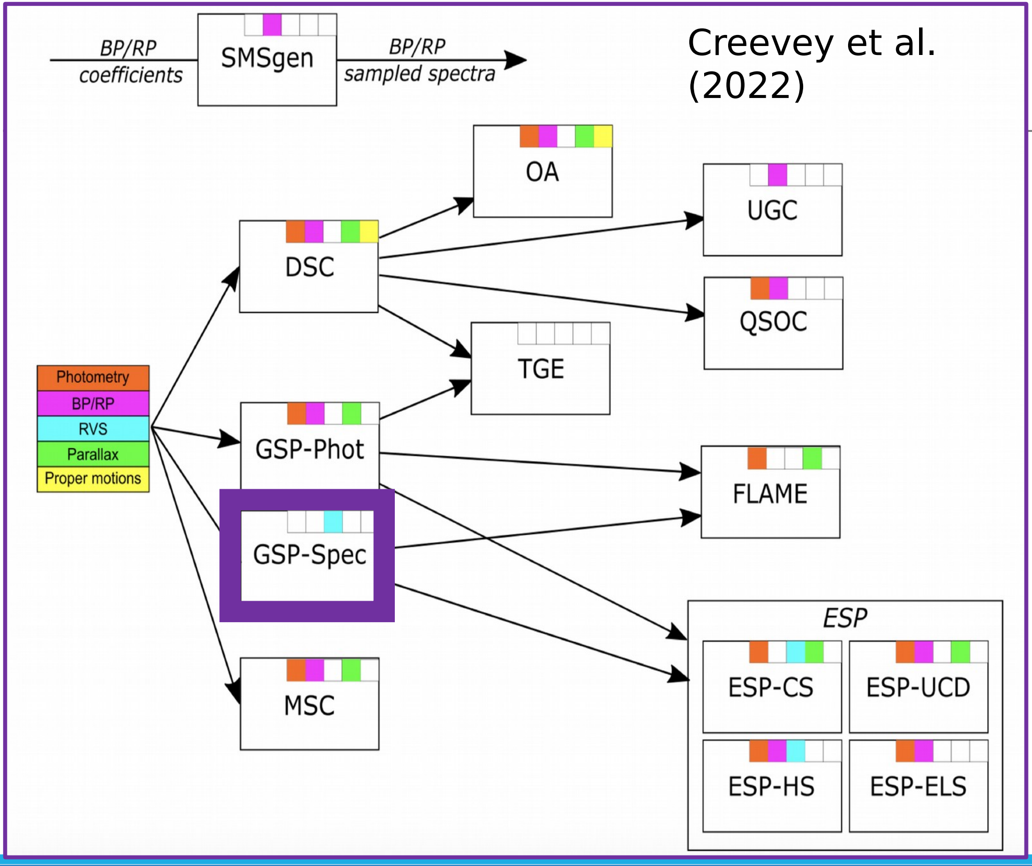
- **The GSP-Spec module**
- The GSP-Spec output
- Some scientific applications
- Recommendations

General Stellar Parametrizer – spectroscopy (GSPspec)

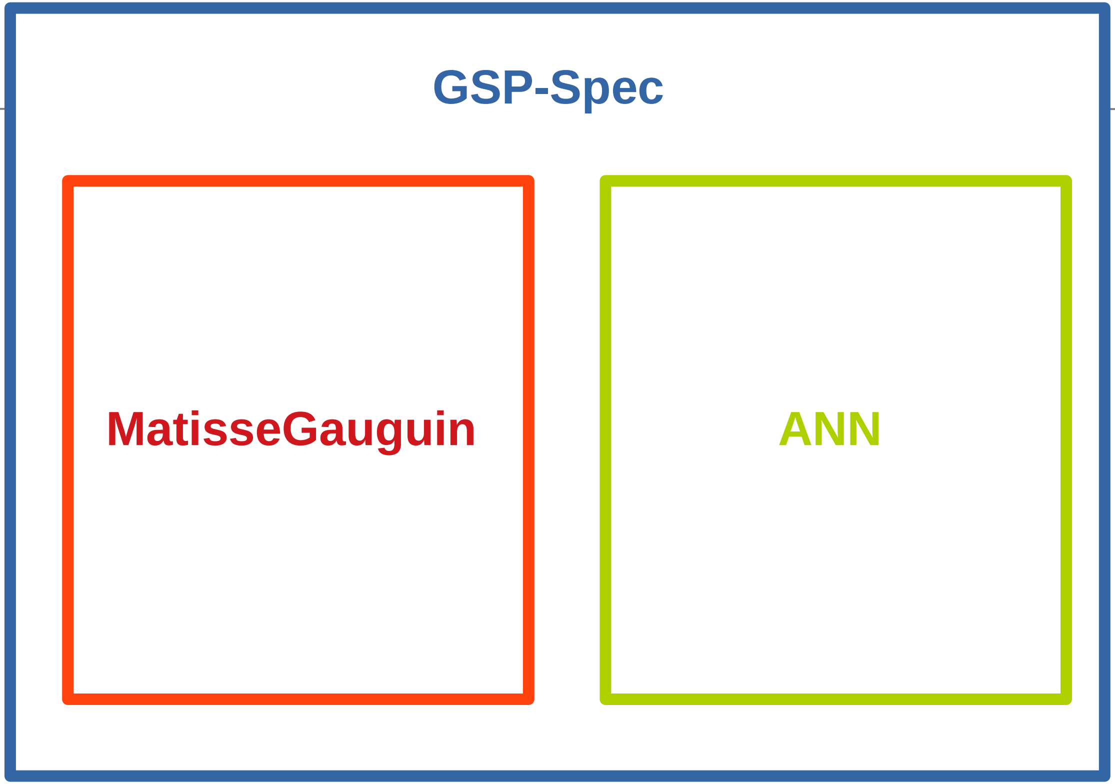


Apsis DPAC/CU8 pipeline

GSPspec (Recio-Blanco et al. 2022) is an up-stream module of the Astrophysical parameters inference system (Creevey et al. 2022)

Treats RVS stacked spectra produced by CU6 (Katz et al. 2022)

Inside the GSPSpec module



Inside the GSPSpec module

GSP-Spec

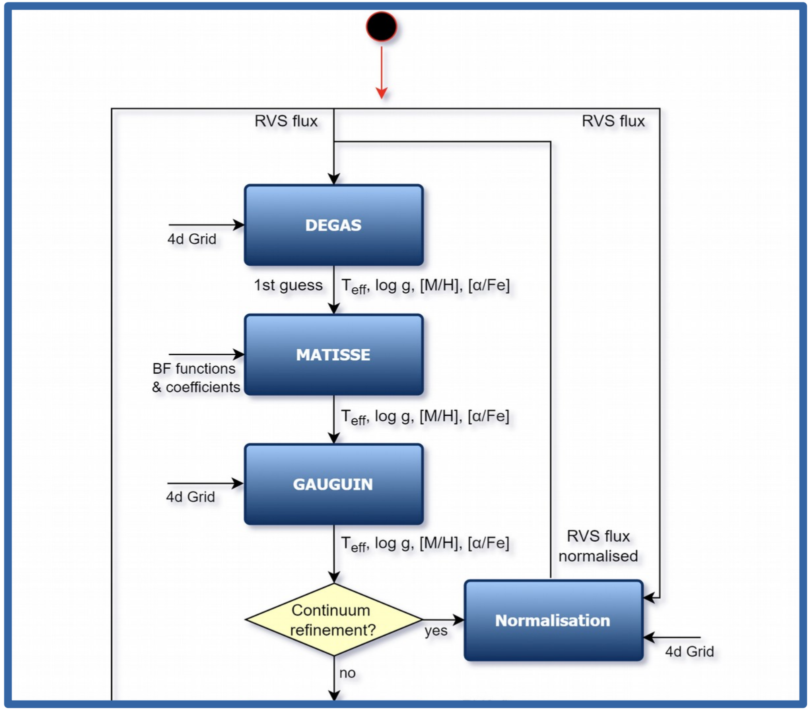
MatisseGauguin

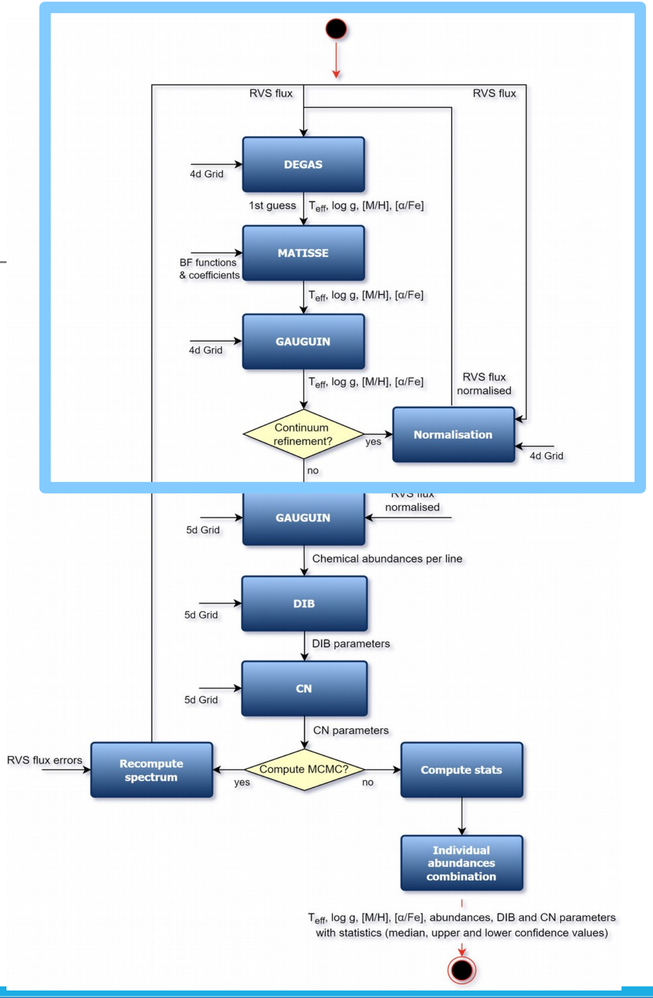
- Stellar Atmospheric Parameters: Teff, logg, [M/H], [α/Fe]
- Chem. Abundances
- DIB
- Differential CN Eq. Width
- **Flags** (!)

ANN

- Stellar Atmospheric Parameters
- **Flags** (!)

Inside the GSPSpec module: MatisseGauguin workflow (parameters)





Gaia/RVS: a model driven success

- **MATISSE** : Recio-Blanco et al. 2006

Projection method. Local multilinear regression

Synthetic grid spectra

Correlation matrix $c_{ij} = S_i\, S_j$

Stellar parameters Teff, logg, [M/H], [alpha/Fe]

Observed spectrum

$$B_{\theta_i}(\lambda) = \sum_j \alpha_{ij} S_j(\lambda)$$

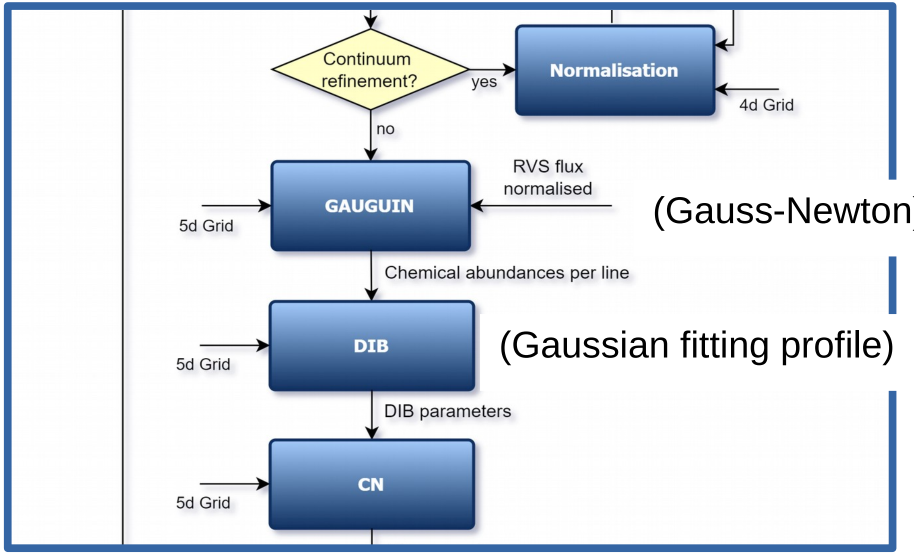
$$\Theta_i = C\alpha_i,$$

$$\hat{\theta}_i = \sum_\lambda B_{\theta_i}(\lambda) O(\lambda).$$

Training phase

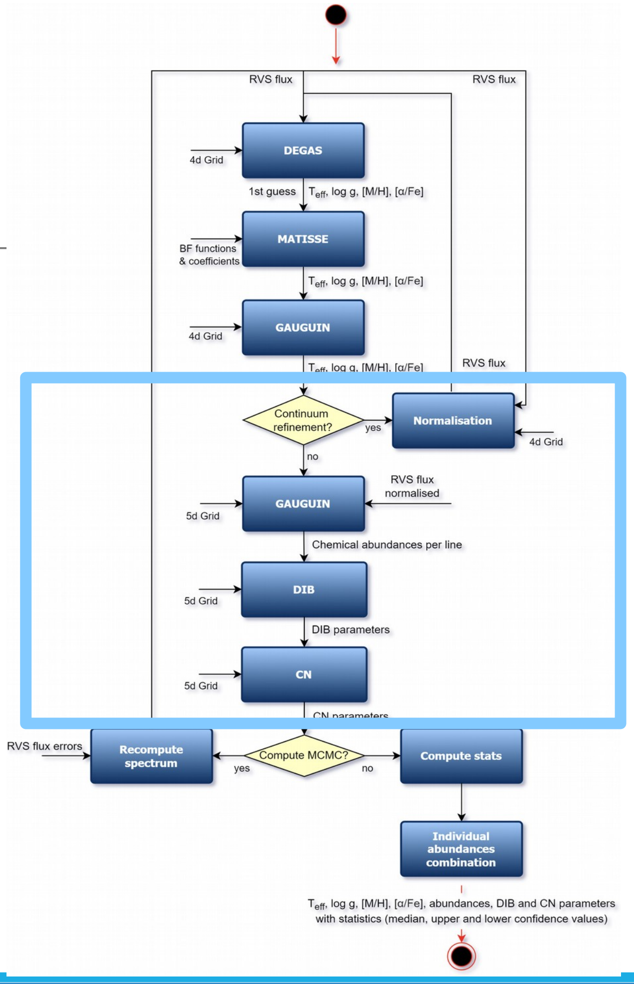
Application phase

Inside the GSPSpec module: MatisseGauguin workflow (abundances)



(Gauss-Newton)

(Gaussian fitting profile)



Gaia/RVS: a model driven success

- **GAUGUIN :** Bijaoui, Recio-Blanco et al. 2012

Optimization method. Gauss-Newton algorithm

Linearization around a parameter set Θ associated to a theoretical spectrum $\mathbf{S}_0$. Corrections obtained with:

Observed spectrum

Synthetic spectrum

$$\delta\Theta = (\mathbf{J}^T\mathbf{J})^{-1}\mathbf{J}^T(\mathbf{O} - \mathbf{S}_0)$$

Jacobian matrix $[\partial S(l, \Theta(0))/\partial\theta i]$

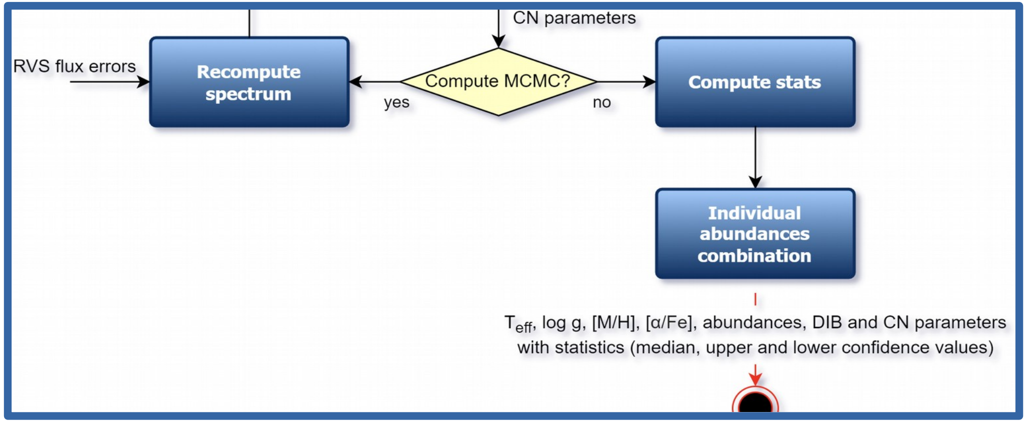
Used after MATISSE -> atmospheric parameters

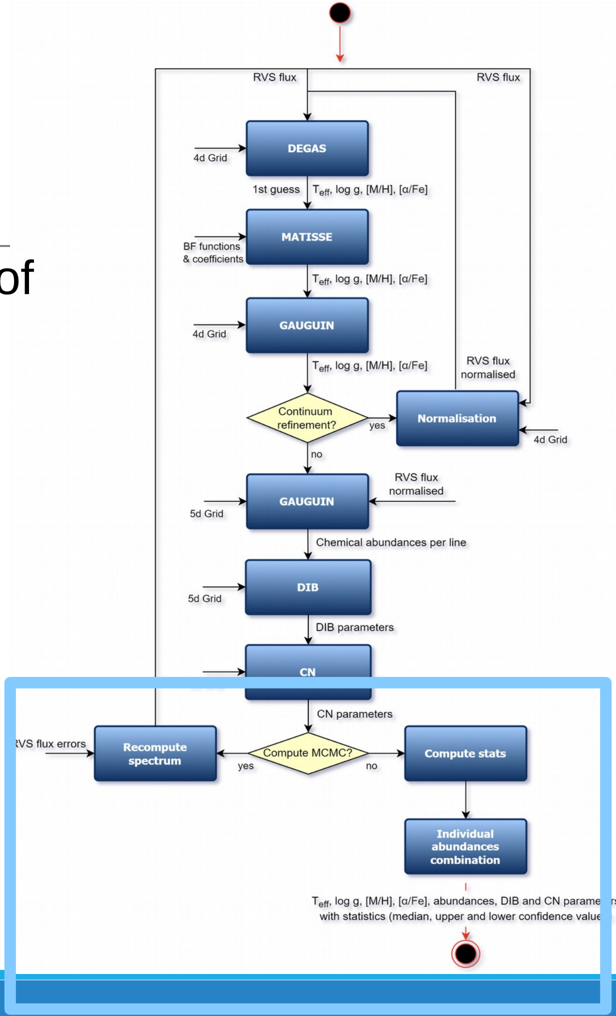
Used alone -> individual chemical abundances

GAUGUIN is used **both** for the **atmospheric parameters** and the **chemical abundances**

Inside the GSPSpec module: MatisseGauguin workflow (errors)

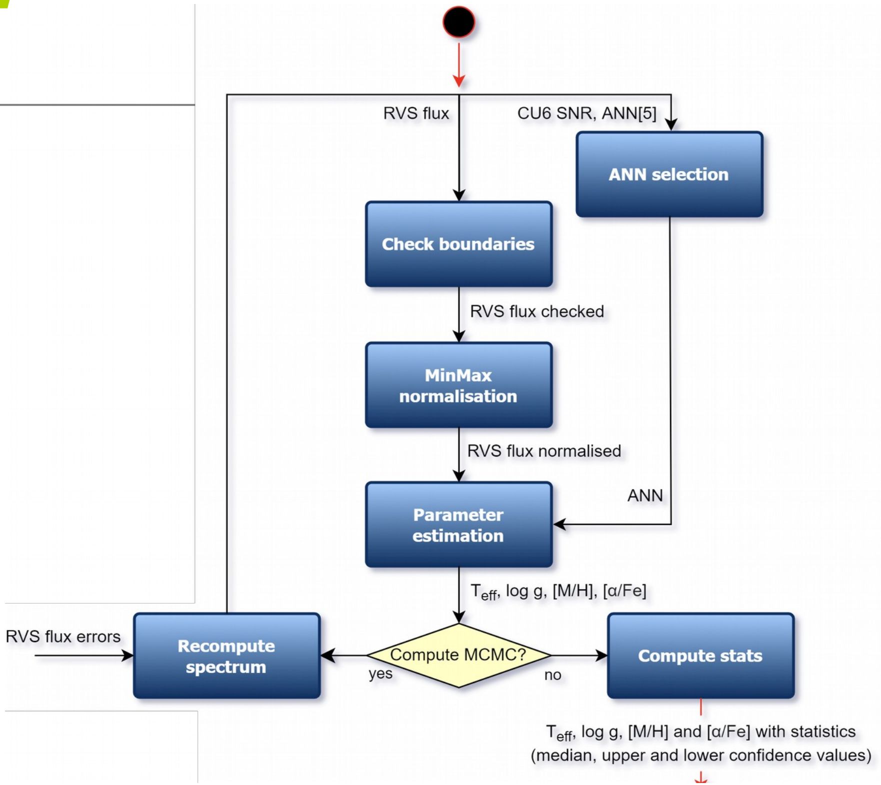
Error propagation through **50 random realisations** of the input spectra using its error → Loop over MatisseGauguin





When finished, perform statistics, line combination, flags...

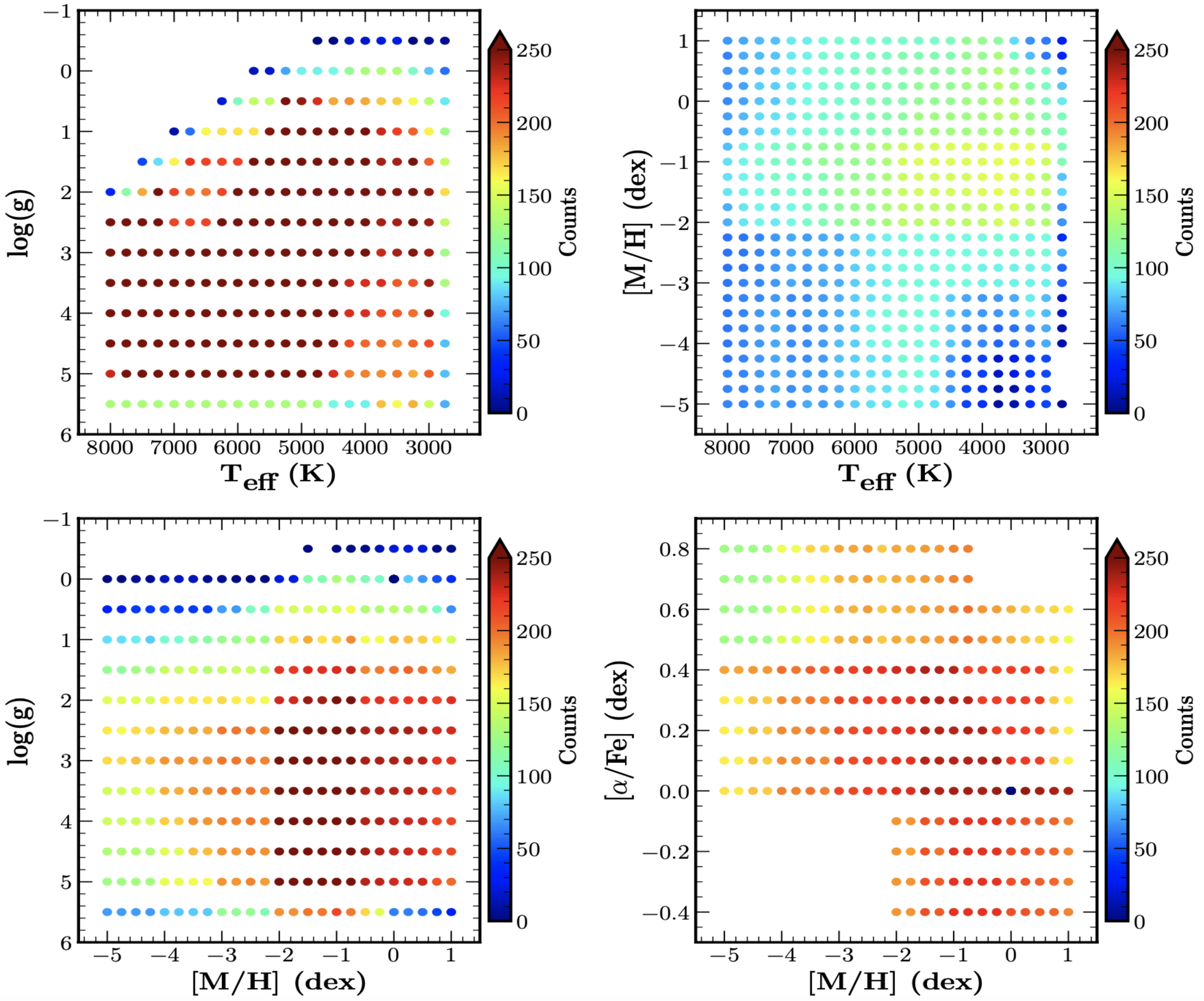
Inside the GSPSpec module:
ANN workflow



Synthetic spectra GRIDS:

MARCS atm. models + Turbospectrum

Added more nodes in the metal poor regime for Fe, Ca and Si



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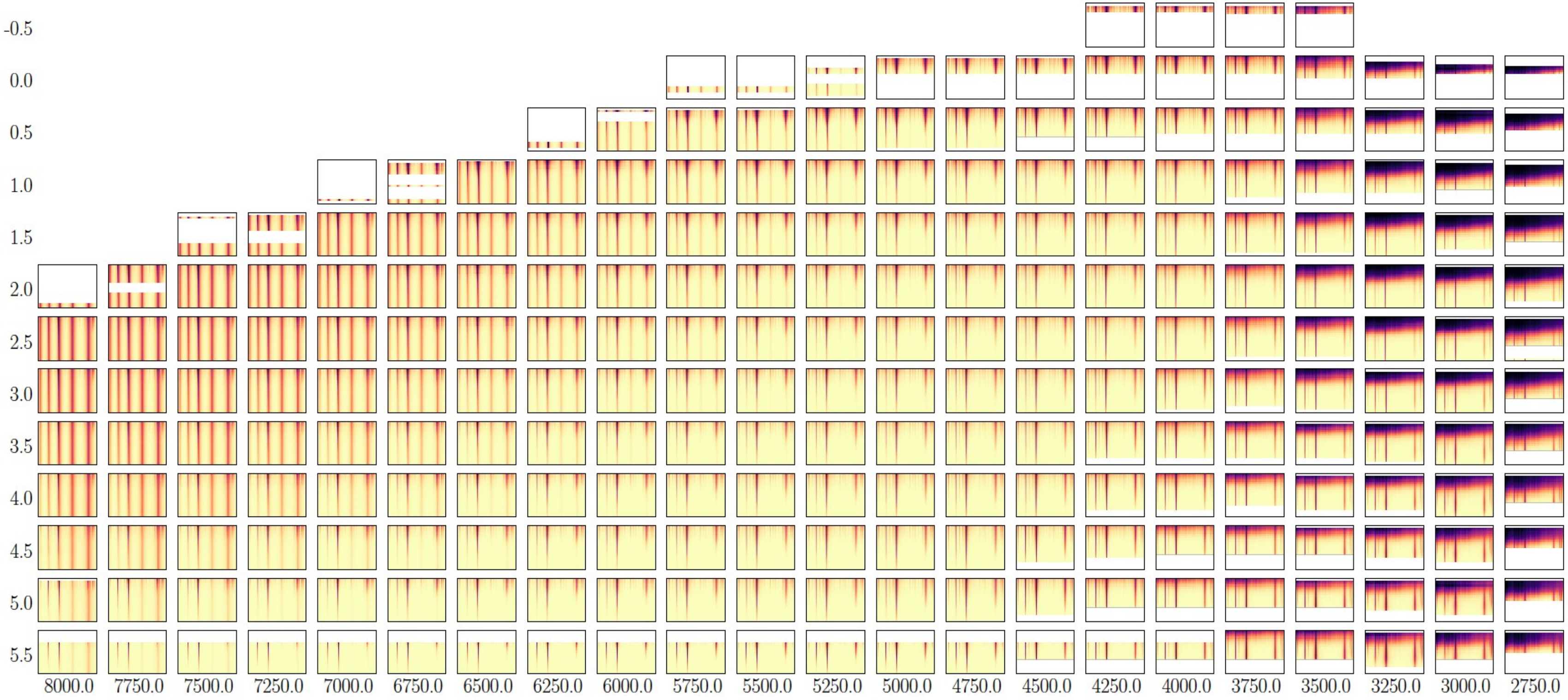

Atomic lines:

33 lines selected after several quality evaluation test and inspection
See Recio-Blanco et al. 2022 and Contursi et al. 2021

Elt	λ	λ^{-}_{ab}	λ^{+}_{ab}	λ^{-}_{norm}	λ^{+}_{norm}
N I	863.161	863.071	863.281	862.891	863.371
N I	868.579	868.489	868.699	868.309	868.939
Mg I	847.602	847.512	847.692	847.212	847.812
Si I	853.851	853.731	853.941	853.371	854.961
*Si I	855.916	855.856	856.036	855.376	856.156
Si I	868.872	868.782	868.992	868.602	869.232
*S I	867.258	866.988	867.378	866.898	867.998
*S I	869.701	869.551	869.821	869.281	869.971
Ca I	863.631	863.511	863.691	863.361	863.931
Ca II	849.856	849.706	849.976	849.586	850.276
Ca II	850.216	850.156	850.276	849.886	850.306
Ca II	854.264	854.114	854.384	853.544	854.864
Ca II	854.624	854.564	854.744	854.294	854.804
Ca II	866.272	866.152	866.332	866.002	866.572
Ca II	866.632	866.512	866.692	866.302	866.782
*Ti I	852.069	851.979	852.129	851.799	852.249
Ti I	857.209	857.119	857.269	856.999	857.359
Ti I	869.472	869.382	869.562	869.292	869.832
Cr I	855.118	855.058	855.208	854.878	855.478
Cr I	864.567	864.447	864.627	864.207	864.867
*Fe I	848.296	848.206	848.446	847.666	848.896
*Fe I	851.641	851.551	851.851	851.281	852.001
*Fe I	852.901	852.691	853.081	852.481	853.321
Fe I	857.416	857.296	857.506	856.876	858.166
Fe I	858.462	858.312	858.612	858.132	858.762
Fe I	862.397	862.277	862.517	862.127	862.697
Fe I	867.713	867.593	867.863	867.443	868.013
*Fe I	869.101	868.891	869.191	868.441	869.821
Fe II	858.794	858.764	858.824	858.254	859.274
Ni I	863.937	863.847	864.027	863.697	864.147
Zr II	852.748	852.658	852.838	852.388	853.018
*Ce II	851.375	851.285	851.465	851.015	851.555
Nd II	859.389	859.299	859.479	859.209	859.689

Atomic lines:

Each line has its own window for
an additional normalisation
(see Santos-Peral et al. 2020)

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*Ce II	851.375	851.285	851.465	851.015	851.555
Nd II	859.389	859.299	859.479	859.209	859.689

Atomic lines:

Also, each line has a different abundance determination window depending on the blends, presence of other lines…

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Nd II	859.389	859.299	859.479	859.209	859.689

Atomic lines:

Calcium triplet is special: abundance measurement looking at the “wings”

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Atomic lines:

Some doublets/triplets or consecutive lines of the same element are treated as a unique line.
(but the individual line cases have also been tested)

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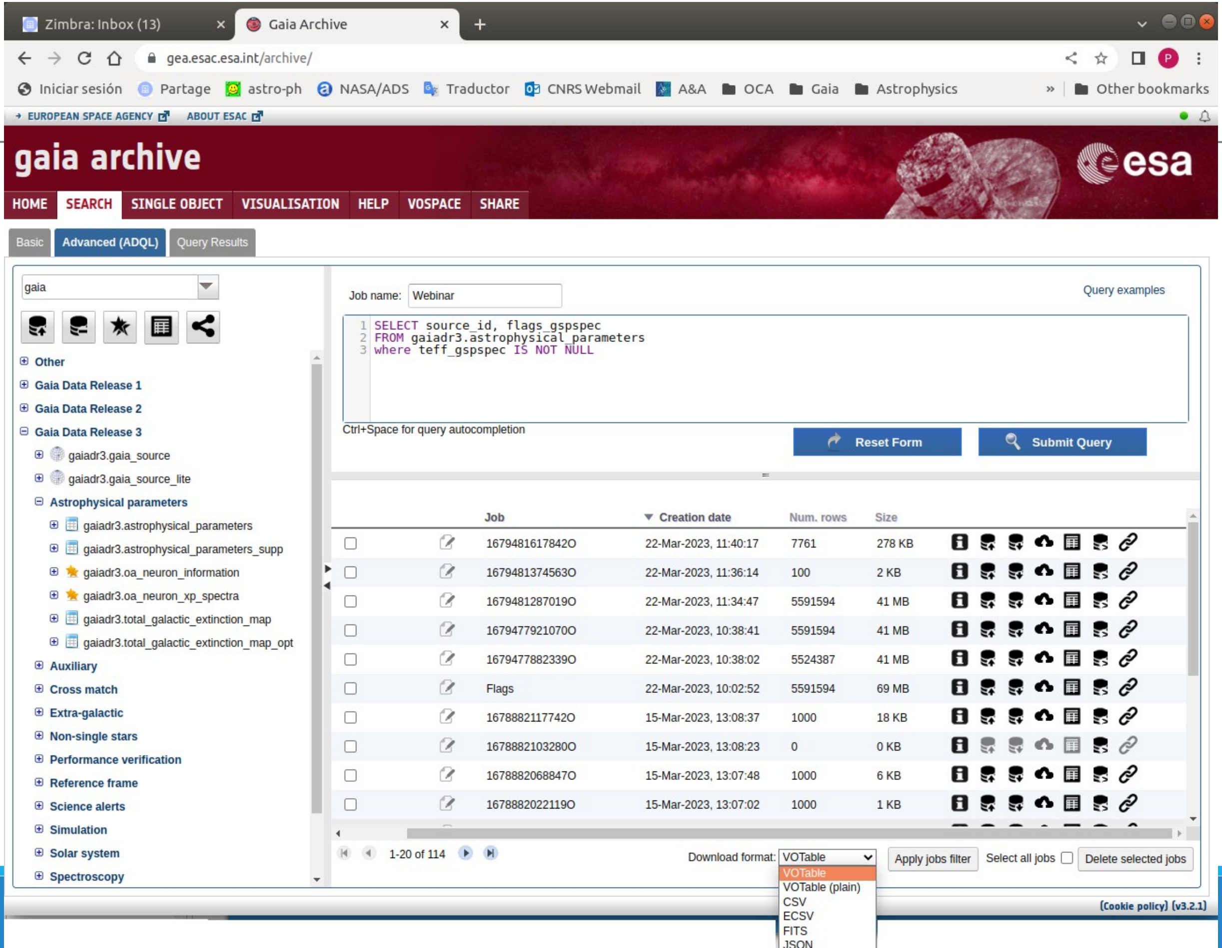
Statistics and implementation of GSPSpec module

- DR3 operations at DPCC (CNES-Toulouse)
- 6.9 million spectra treated
- 50 random realisations of each RVS spectrum → AP uncertainties
- 110,000h (eq. 12.6 years) spread on 2100 cores
- Execution time of 150h (~one second per spectrum realisation)

Topics

- Gaia RVS overview
- The GSP-Spec module
- **The GSP-Spec output**
  - Comparison with Literature
  - The importance of GSP-Spec flags
  - GSP-Spec results
- Some scientific applications
- Recommendations

GSPSpec in the Gaia Archive



GSPSpec in the Gaia Archive

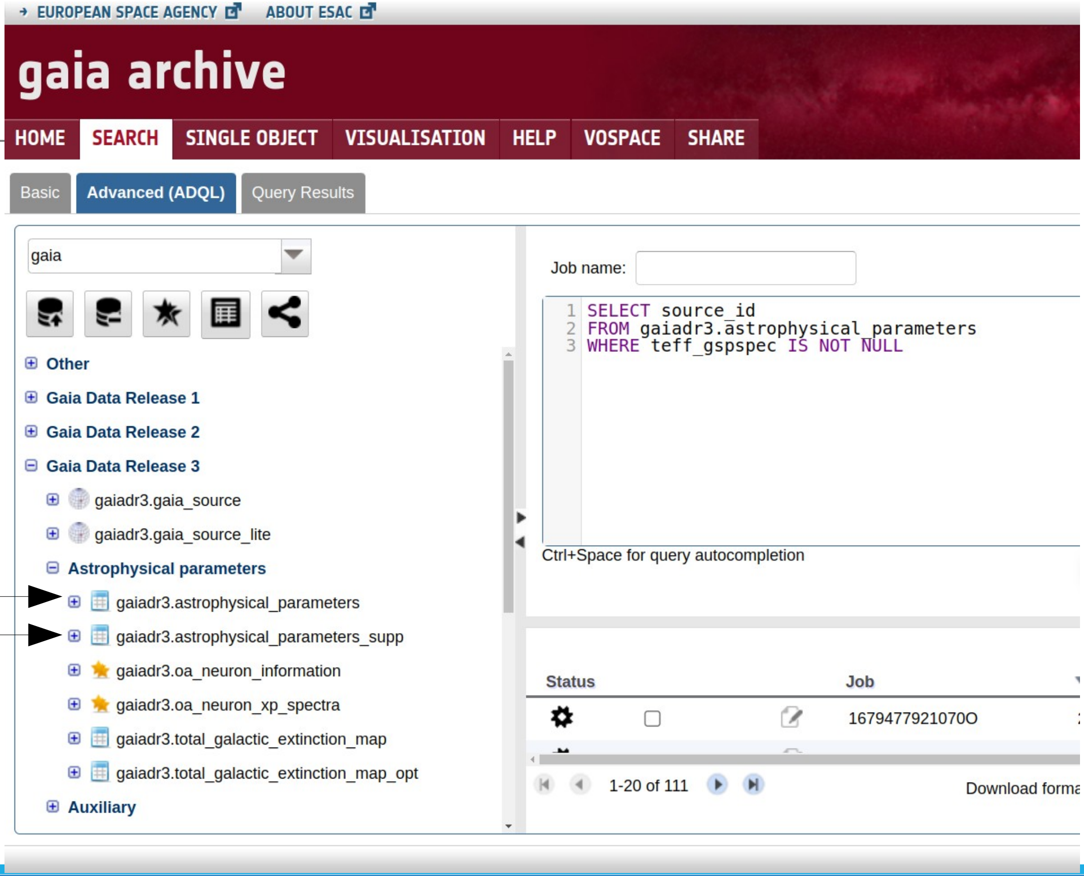
GSP-Spec output has already been ingested in the **Gaia Archive** (https://gea.esac.esa.int/archive/)

Approx. 5.6M sources with GSP-Spec data

MatisseGauguin output

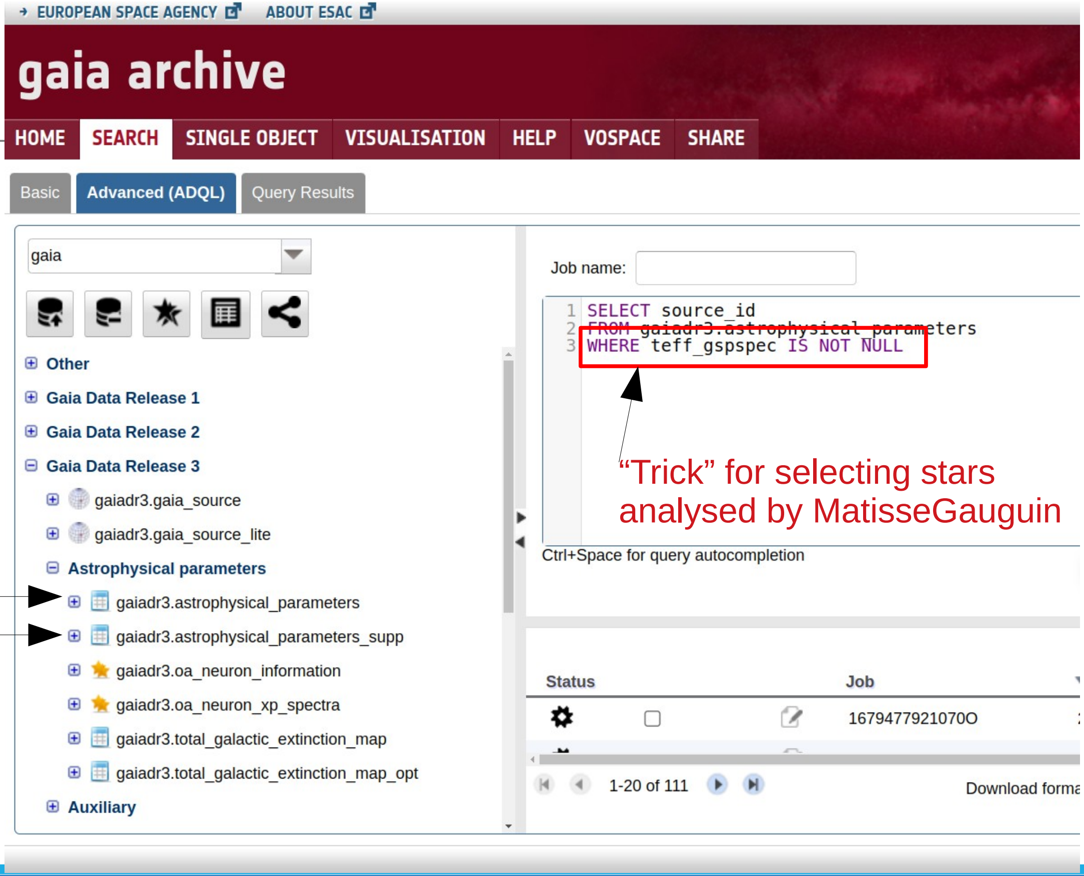
ANN output

The associated fields (columns) have "_gspspec"/ "_gspspec_ann" in their names.



GSPSpec in the Gaia Archive

GSP-Spec output has already been ingested in the **Gaia Archive** (https://gea.esac.esa.int/archive/)

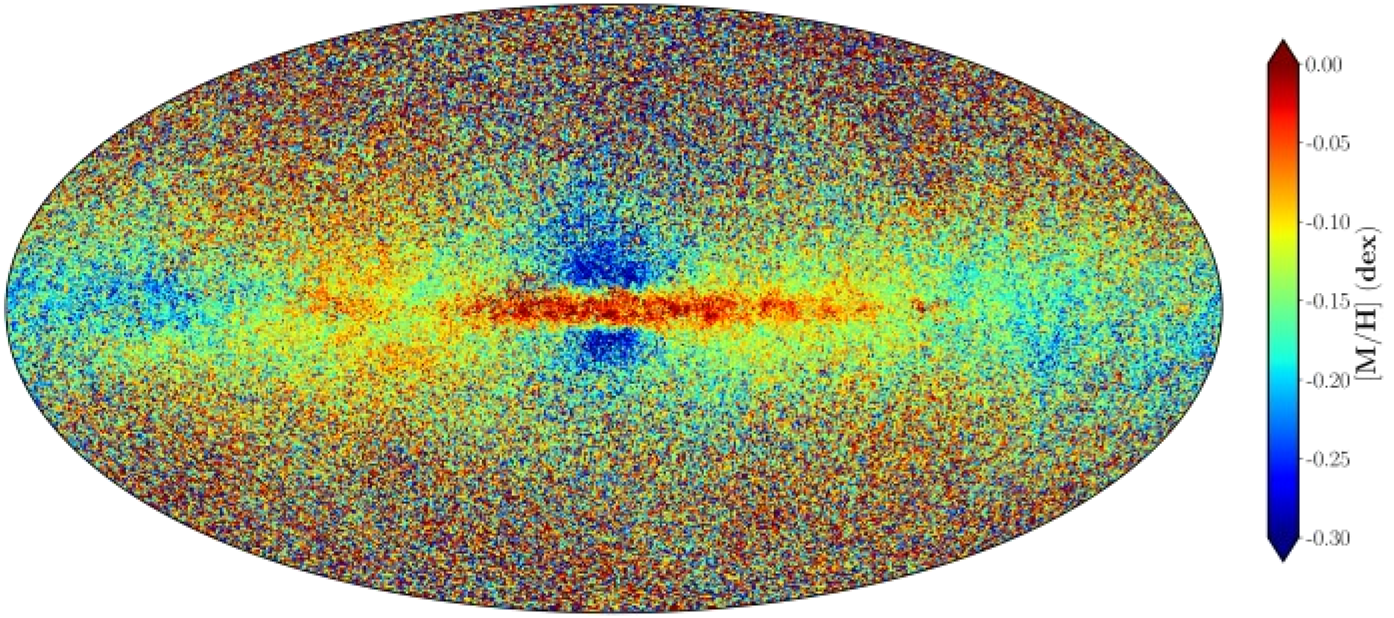


MatisseGauguin output

ANN output

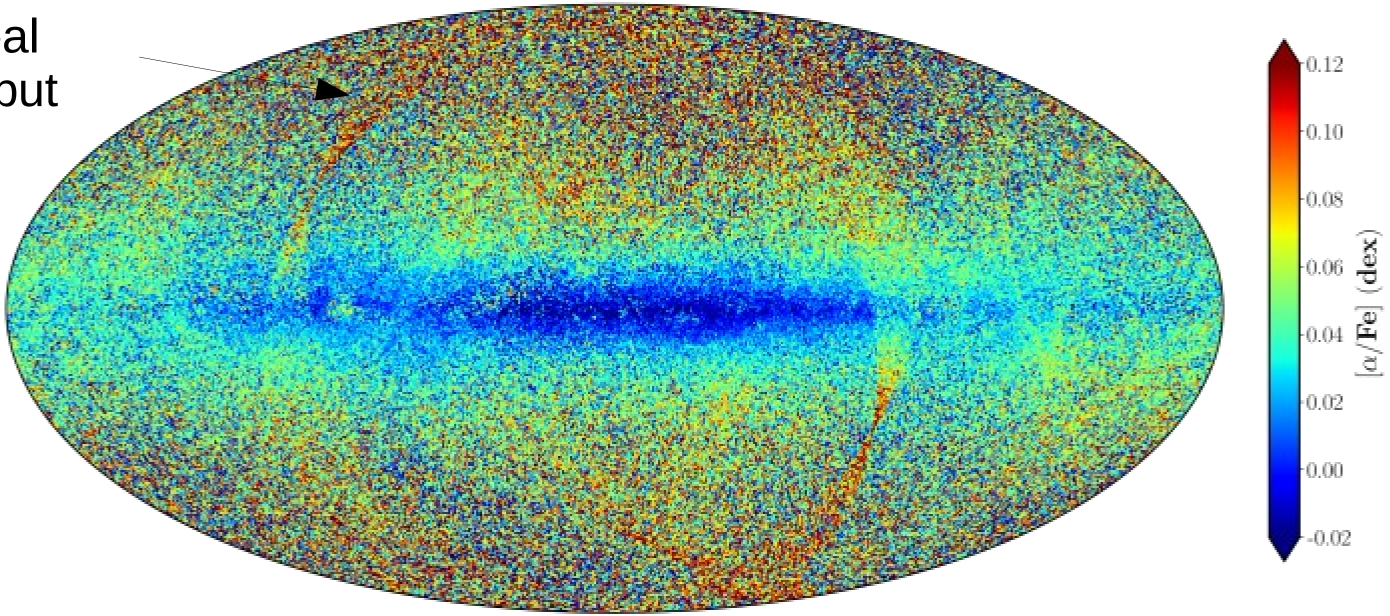
The associated fields (columns) have "_gspspec"/ "_gspspec_ann" in their names.

Behold the chemistry of the MW!

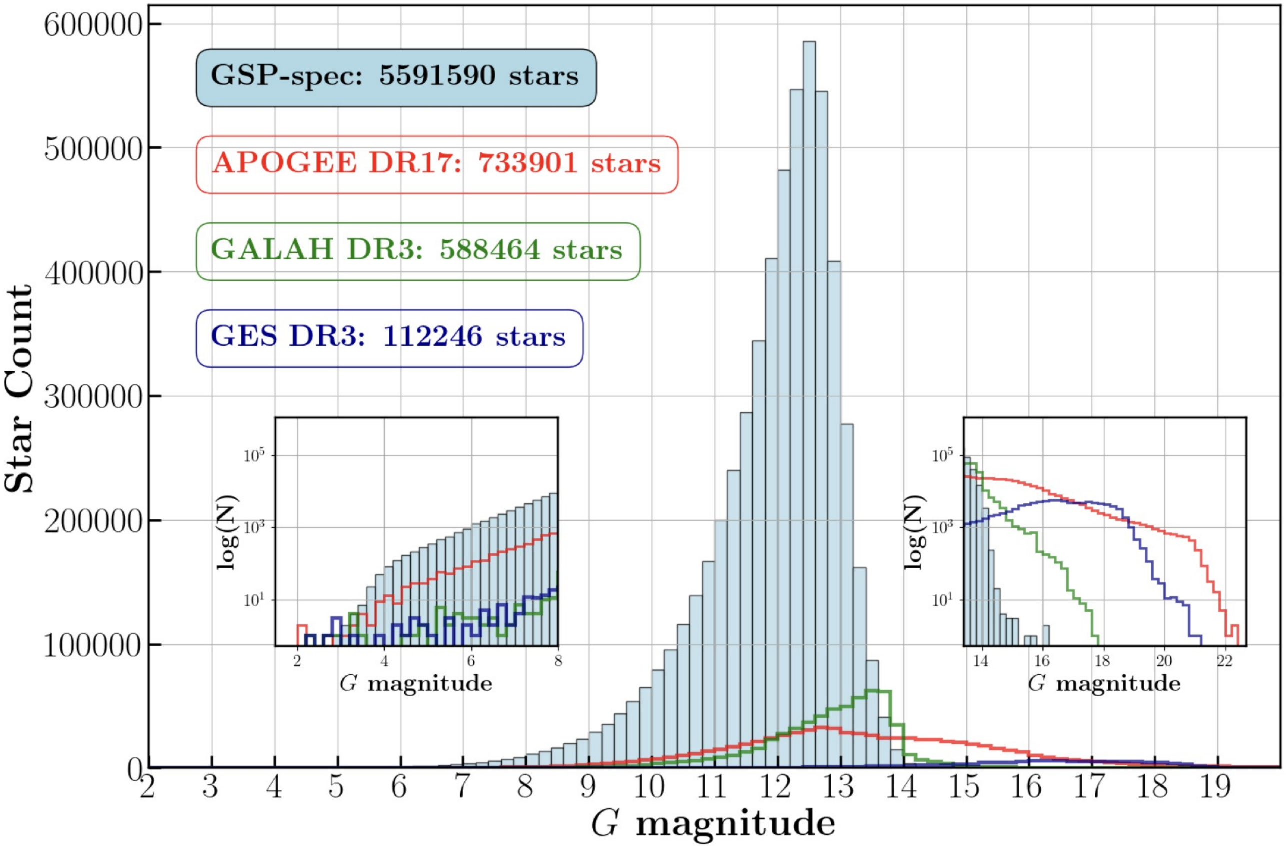


Behold the chemistry of the MW!

Not a real stream but Gaia Scan. Law



The chemical composition of 5.6 million stars



More stars than the combination of other large surveys.

The chemical composition of 5.6 million stars

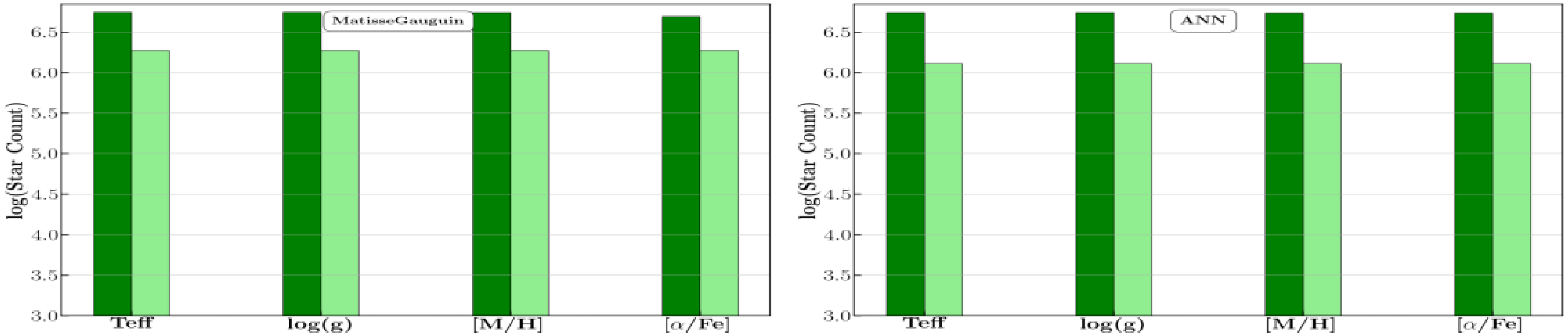
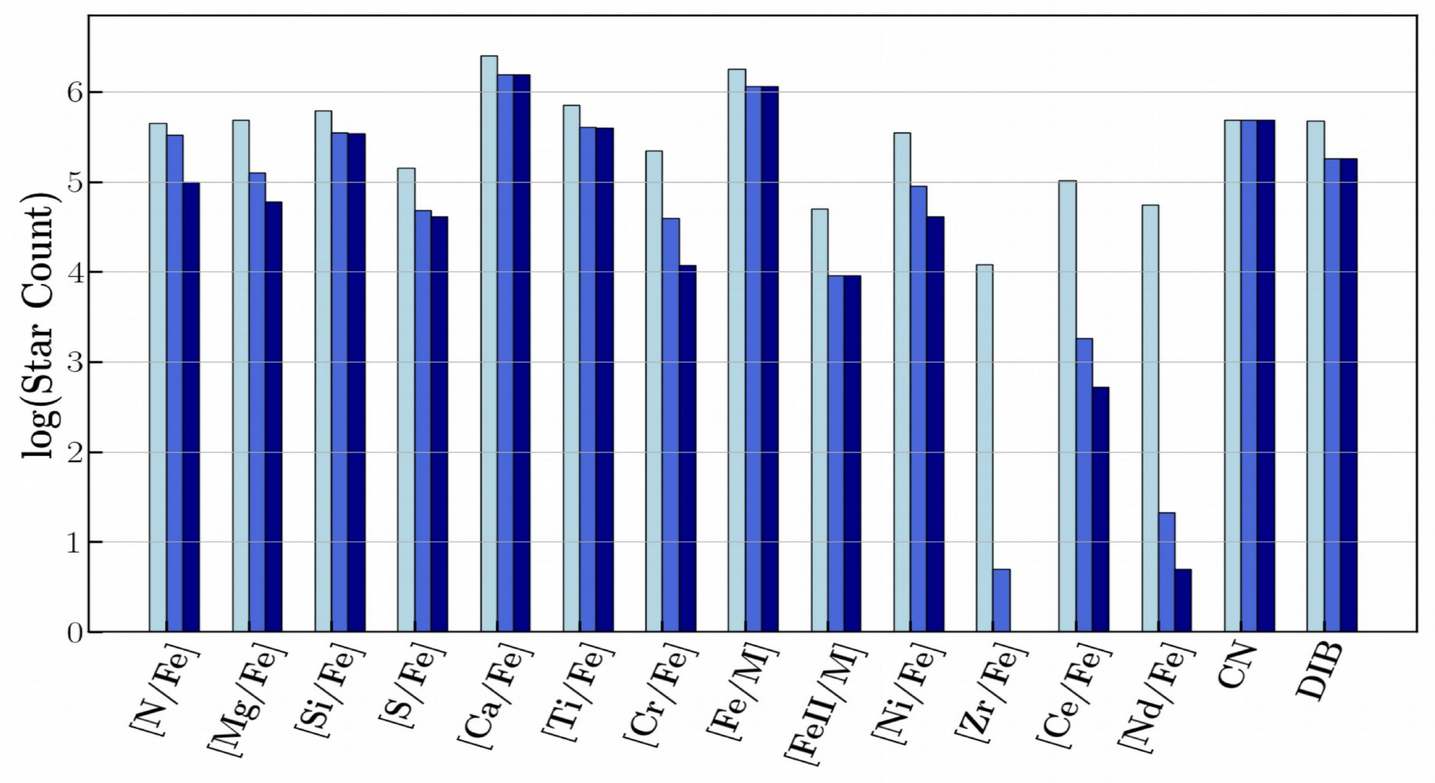


Fig. 17. Number of stars whose atmospheric parameters have been derived by MatisseGauguin and ANN (left and right panels, respectively). The dark green histograms refer to the whole sample whereas the light-green ones show only the very best parametrised stars with all their parameter quality flags equal to zero.

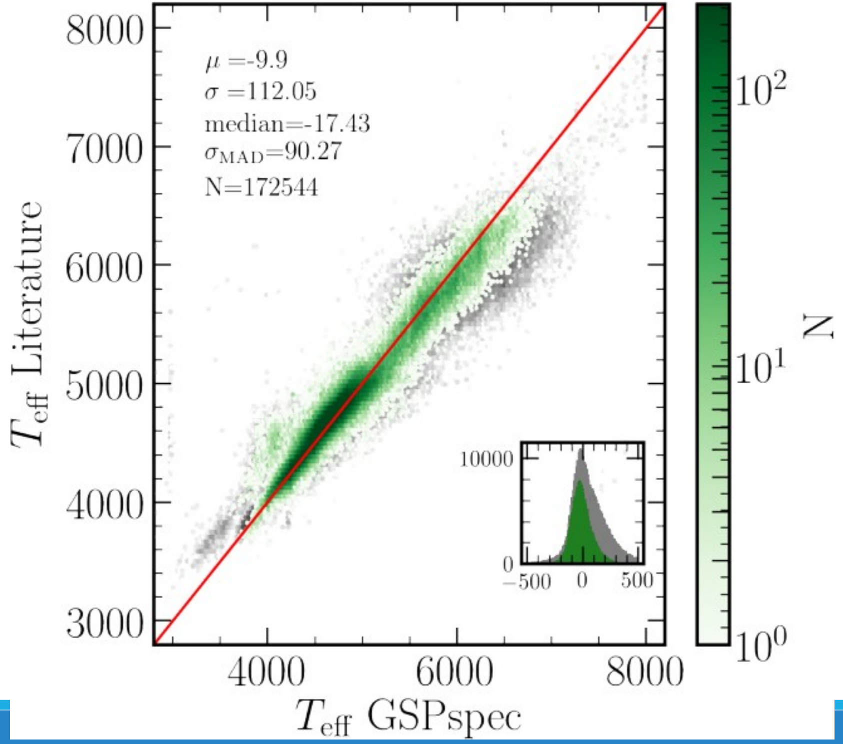
The chemical composition of 5.6 million stars



Comparison with Literature: Teff

Literature: APOGEE DR17, GALAH-DR3, RAVE-DR6

In grey: Medium quality sample
In Green: Best quality sample
(Will be explained later)

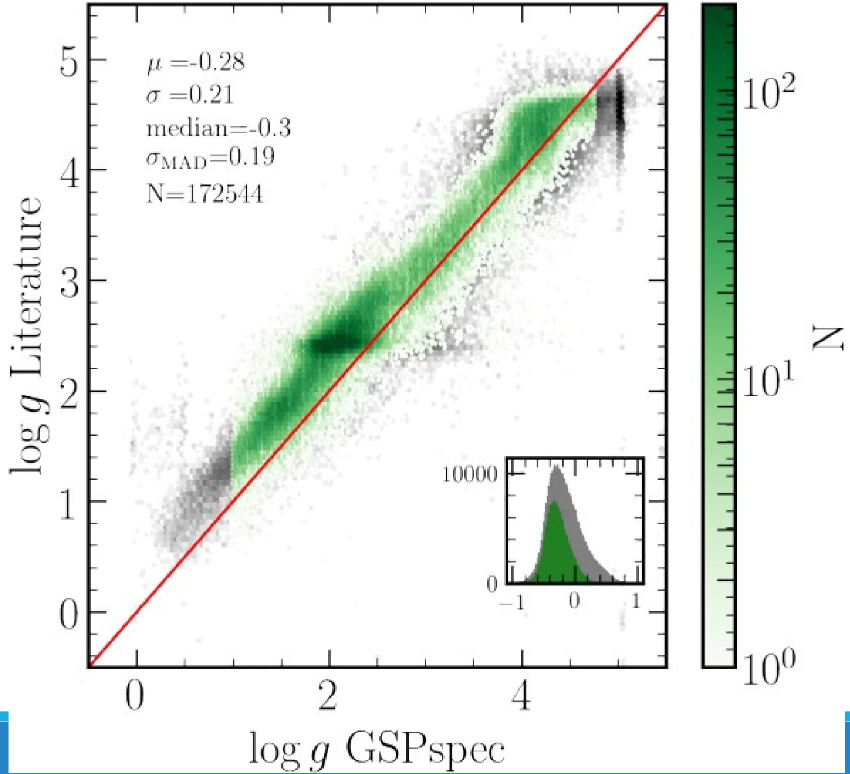


Comparison with Literature: logg !

Literature: APOGEE DR17, GALAH-DR3, RAVE-DR6

In grey: Medium quality sample
In Green: Best quality sample
(Will be explained later)

Bias detected. Solution: calibration

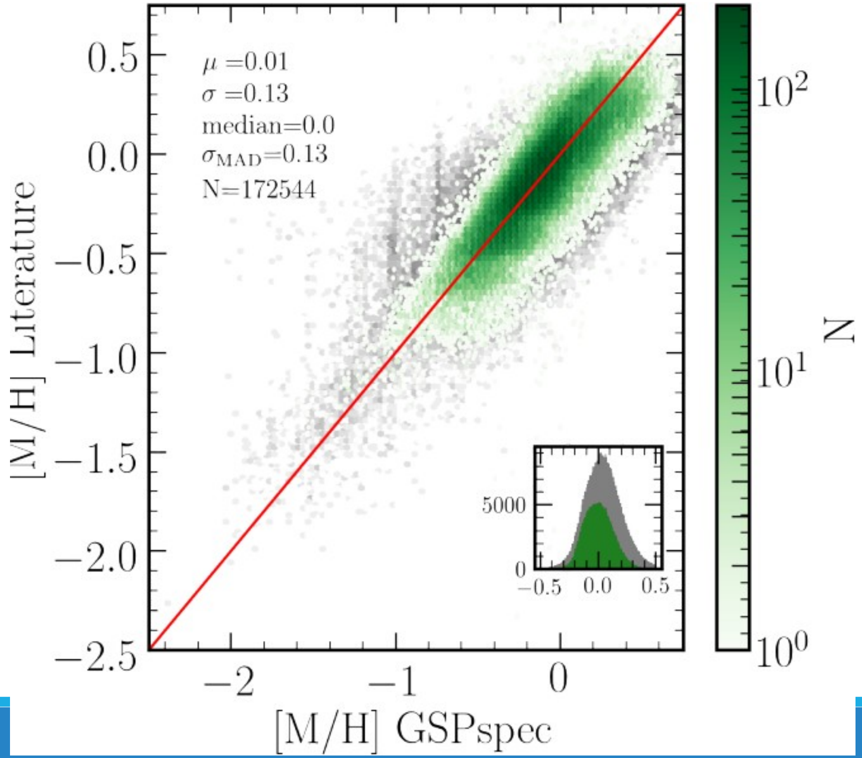


Comparison with Literature: [M/H]

Literature: APOGEE DR17, GALAH-DR3, RAVE-DR6

In grey: Medium quality sample
In Green: Best quality sample
(Will be explained later)

Apparently no bias on average, but **subestimated** (**overestimated**) metallicities are found for **giants** (**dwarfs**)



CU8/GSPspec: Offset corrections (parameters)

$$X_{Calibr.} = X_{Uncalibr.} + p_0 + p_1 \log(g) + p_2 \log(g)^2 + p_3 \log(g)^3 + p_4 \log(g)^4$$

Parameter	p_0	p_1	p_2	p_3	p_4
log(g)	0.4496	-0.0036	-0.0224		
[M/H]	0.274	-0.1373	-0.0050	0.0048	
$[M/H]_{OC}$	-0.7541	1.8108	-1.1779	0.2809	-0.0222

Full table in **Recio-Blanco et al. (2022)**

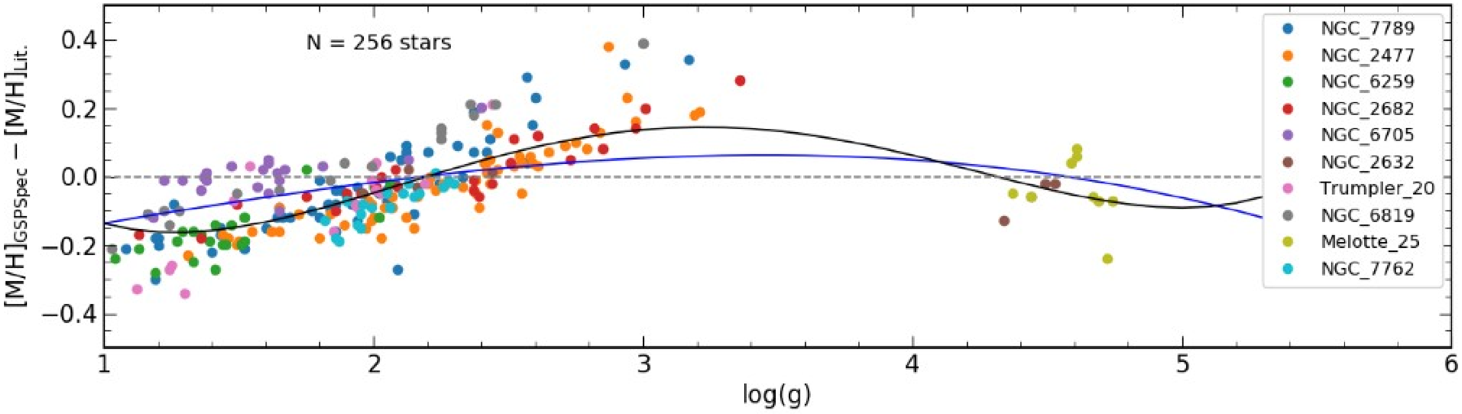
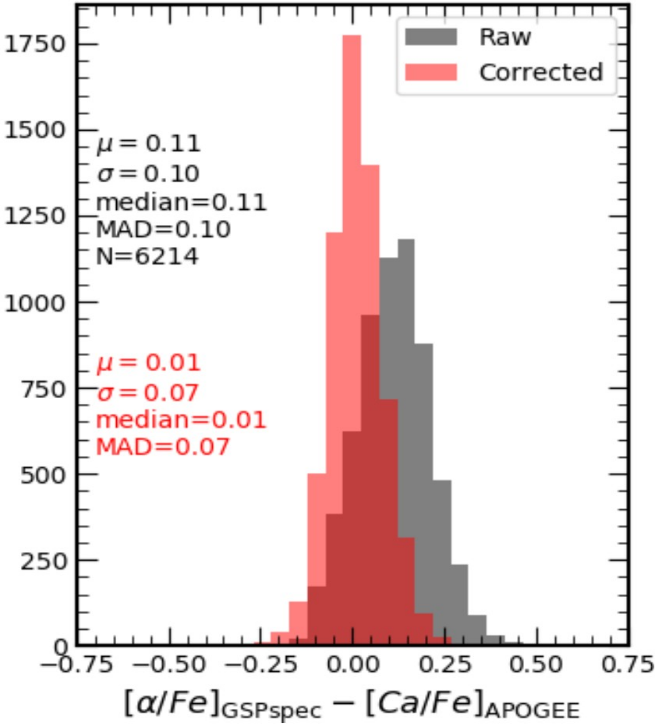


Fig. 13. Metallicity bias with respect to the literature as a function of log(g) for the open cluster stars, excluding dwarfs with S/N lower than 50. The colour code used for each cluster is indicated in the legend. Solid blue line corresponds to the general metallicity correction while the black line refers to that specifically obtained from the open clusters.

Comparison with Literature

The **global alpha-abundace is dominated** by Calcium

The calibration reduces the bias



CU8/GSPspec: Offset corrections (abundances)

$$X_{Calibr.} = X_{Uncalibr.} + p_0 + p_1 \log(g) + p_2 \log(g)^2 + p_3 \log(g)^3 + p_4 \log(g)^4$$

Full table in **Recio-Blanco et al. (2022)**

Element	p_0	p_1	p_2	p_3	p_4	Recommended interval		*extrapol* flag
	As a function of log(g)					Min log(g)	Max log(g)	
[α/Fe]	-0.5809	0.7018	-0.2402	0.0239	0.0000	1.01	4.85	0
[Ca/Fe]	-0.6250	0.7558	-0.2581	0.0256	0.0000	1.01	4.85	0
[Mg/Fe]	-0.7244	0.3779	-0.0421	-0.0038	0.0000	1.30	4.38	0
[S/Fe]	-17.6080	12.3239	-2.8595	0.2192	0.0000	3.38	4.81	0
[Si/Fe]	-0.3491	0.3757	-0.1051	0.0092	0.0000	1.28	4.85	0
[Ti/Fe]	-0.2656	0.4551	-0.1901	0.0209	0.0000	1.01	4.39	0
[Cr/Fe]	-0.0769	-0.1299	0.1009	-0.0200	0.0000	1.01	4.45	0
[Fe I/H]	0.3699	-0.0680	0.0028	-0.0004	0.0000	1.01	4.85	0
[Fe II/H]	35.5994	-27.9179	7.1822	-0.6086	0.0000	3.53	4.82	0
[Ni/Fe]	-0.2902	0.4066	-0.1313	0.0105	0.0000	1.41	4.81	0
[N/Fe]	0.0975	-0.0293	0.0238	-0.0071	0.0000	1.21	4.79	0
[α/Fe]	-0.2838	0.3713	-0.1236	0.0106	0.0002	0.84	4.44	≤ 1
[Ca/Fe]	-0.3128	0.3587	-0.0816	-0.0066	0.0020	0.84	4.98	≤ 1
	As a function of $t = T_{\rm eff}/5750$					Min $T_{\rm eff}$	Max $T_{\rm eff}$	
[α/Fe]	-6.6960	20.8770	-21.0976	6.8313	0.0000	4000	6830	≤ 1
[Ca/Fe]	-7.4577	23.2759	-23.6621	7.7657	0.0000	4000	6830	≤ 1
[S/Fe]	0.1930	-0.2234	0.0000	0.0000	0.0000	5700	6800	≤ 1

CU8/GSPspec: Offset corrections (abundances)

$$X_{Calibr.} = X_{Uncalibr.} + p_0 + p_1 \log(g) + p_2 \log(g)^2 + p_3 \log(g)^3 + p_4 \log(g)^4$$

Full table in **Recio-Blanco et al. (2022)**

Element	p_0	p_1	p_2	p_3	p_4	Recommended interval		*extrapol* flag
	As a function of log(g)					Min log(g)	Max log(g)	
[α/Fe]	-0.5809	0.7018	-0.2402	0.0239	0.0000	1.01	4.85	0
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[S/Fe]	-17.6080	12.3239	-2.8595	0.2192	0.0000	3.38	4.81	0
[Si/Fe]	-0.3491	0.3757	-0.1051	0.0092	0.0000	1.28	4.85	0
[Ti/Fe]	-0.2656	0.4551	-0.1901	0.0209	0.0000	1.01	4.39	0
[Cr/Fe]	-0.0769	-0.1299	0.1009	-0.0200	0.0000	1.01	4.45	0
[Fe I/H]	0.3699	-0.0680	0.0028	-0.0004	0.0000	1.01	4.85	0
[Fe II/H]	35.5994	-27.9179	7.1822	-0.6086	0.0000	3.53	4.82	0
[Ni/Fe]	-0.2902	0.4066	-0.1313	0.0105	0.0000	1.41	4.81	0
[N/Fe]	0.0975	-0.0293	0.0238	-0.0071	0.0000	1.21	4.79	0
[α/Fe]	-0.2838	0.3713	-0.1236	[illegible]	0.0002	0.84	4.44	≤ 1
[Ca/Fe]	-0.3128	0.3587	-0.0816	[illegible]	0.0020	0.84	4.98	≤ 1
	As a function of $t = T_{eff}/5750$					Min T_{eff}	Max T_{eff}	
[α/Fe]	-6.6960	20.8770	-21.0976	6.8313	0.0000	4000	6830	≤ 1
[Ca/Fe]	-7.4577	23.2759	-23.6621	7.7657	0.0000	4000	6830	≤ 1
[S/Fe]	0.1930	-0.2234	0.0000	0.0000	0.0000	5700	6800	≤ 1

Out of this range, keep the edge values (suggestion)

CU8/GSPspec: Offset corrections (abundances)

$$X_{Calibr.} = X_{Uncalibr.} + p_0 + p_1 \log(g) + p_2 \log(g)^2 + p_3 \log(g)^3 + p_4 \log(g)^4$$

Full table in **Recio-Blanco et al. (2022)**

Element	p_0	p_1	p_2	p_3	p_4	Recommended interval		*extrapol* flag
	As a function of log(g)					Min log(g)	Max log(g)	
[α/Fe]	-0.5809	0.7018	-0.2402	0.0239	0.0000	1.01	4.85	0
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[Mg/Fe]	-0.7244	0.3779	-0.0421	-0.0038	0.0000	1.30	4.38	0
[S/Fe]	-17.6080	12.3239	-2.8595	0.2192	0.0000	3.38	4.81	0
[Si/Fe]	-0.3491	0.3757	-0.1051	0.0092	0.0000	1.28	4.85	0
[Ti/Fe]	-0.2656	0.4551	-0.1901	0.0209	0.0000	1.01	4.39	0
[Cr/Fe]	-0.0769	-0.1299	0.1009	-0.0200	0.0000	1.01	4.45	0
[Fe I/H]	0.3699	-0.0680	0.0028	-0.0004	0.0000	1.01	4.85	0
[Fe II/H]	35.5994	-27.9179	7.1822	-0.6086	0.0000	3.53	4.82	0
[Ni/Fe]	-0.2902	0.4066	-0.1313	0.0105	0.0000	1.41	4.81	0
[N/Fe]	0.0975	0.0293	0.0238	0.0071	0.0000	1.21	4.79	0
[α/Fe]	-0.2838	0.3713	-0.1236	0.0106	0.0002	0.84	4.44	≤ 1
[Ca/Fe]	-0.3128	0.3587	-0.0816	-0.0066	0.0020	0.84	4.98	≤ 1
	As a function of $t = T_{\rm eff}/5750$					Min $T_{\rm eff}$	Max $T_{\rm eff}$	
[α/Fe]	-6.6960	20.8770	-21.0976	6.8313	0.0000	4000	6830	≤ 1
[Ca/Fe]	-7.4577	23.2759	-23.6621	7.7657	0.0000	4000	6830	≤ 1
[S/Fe]	0.1930	-0.2234	0.0000	0.0000	0.0000	5700	6800	≤ 1

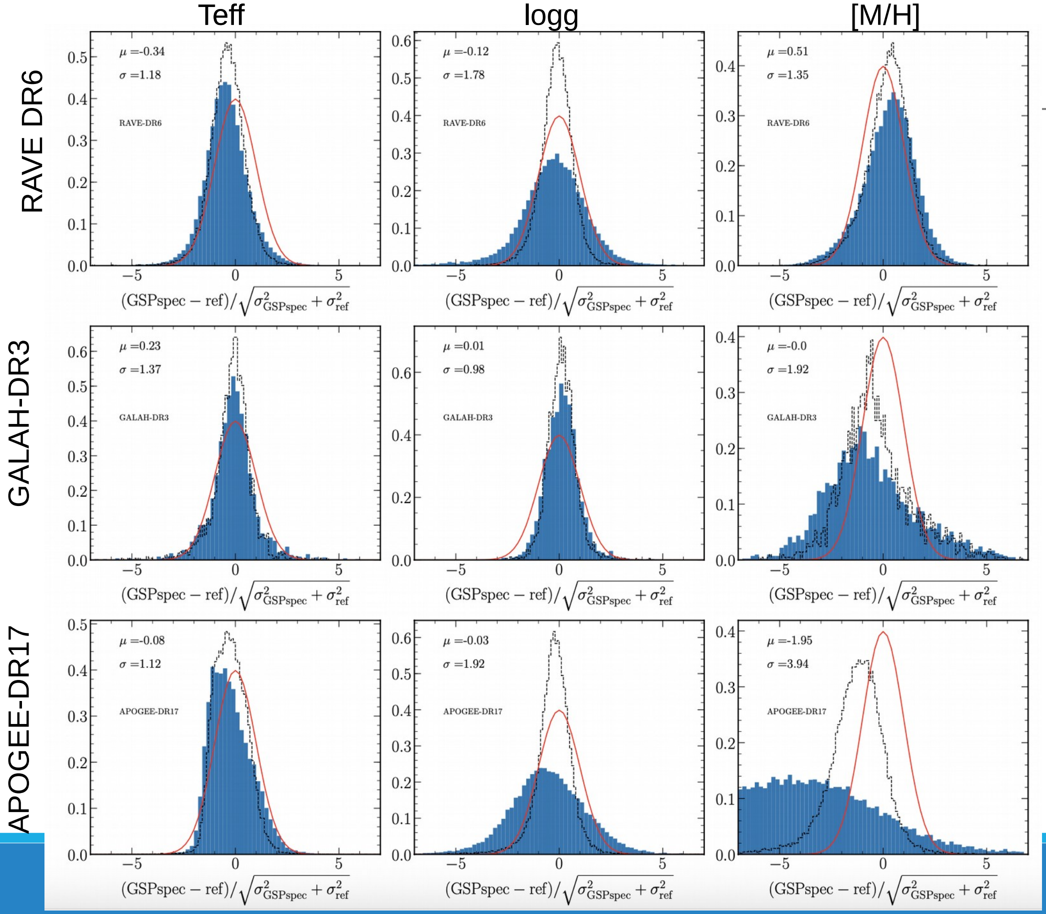
CU8/GSPspec: Offset corrections (abundances)

$$X_{Calibr.} = X_{Uncalibr.} + p_0 + p_1 \log(g) + p_2 \log(g)^2 + p_3 \log(g)^3 + p_4 \log(g)^4$$

Full table in **Recio-Blanco et al. (2022)**

Element	p_0	p_1	p_2	p_3	p_4	Recommended interval		*extrapol* flag
	As a function of log(g)					Min log(g)	Max log(g)	
[α/Fe]	-0.5809	0.7018	-0.2402	0.0239	0.0000	1.01	4.85	0
[Ca/Fe]	-0.6250	0.7558	-0.2581	0.0256	0.0000	1.01	4.85	0
[Mg/Fe]	-0.7244	0.3779	-0.0421	-0.0038	0.0000	1.30	4.38	0
[S/Fe]	-17.6080	12.3239	-2.8595	0.2192	0.0000	3.38	4.81	0
[Si/Fe]	-0.3491	0.3757	-0.1051	0.0092	0.0000	1.28	4.85	0
[Ti/Fe]	-0.2656	0.4551	-0.1901	0.0209	0.0000	1.01	4.39	0
[Cr/Fe]	-0.0769	-0.1299	0.1009	-0.0200	0.0000	1.01	4.45	0
[Fe I/H]	0.3699	-0.0680	0.0028	-0.0004	0.0000	1.01	4.85	0
[Fe II/H]	35.5994	-27.9179	7.1822	-0.6086	0.0000	3.53	4.82	0
[Ni/Fe]	-0.2902	0.4066	-0.1313	0.0105	0.0000	1.41	4.81	0
[N/Fe]	0.0975	-0.0293	0.0238	-0.0071	0.0000	1.21	4.79	0
[α/Fe]	-0.2838	0.3713	-0.1236	0.0106	0.0002	0.84	4.44	≤ 1
[Ca/Fe]	-0.3128	0.3587	-0.0816	-0.0066	0.0020	0.84	4.98	≤ 1
	As a function of $t = T_{\rm eff}/5750$					Min $T_{\rm eff}$	Max $T_{\rm eff}$	
[α/Fe]	-6.6960	20.8770	-21.0976	6.8313	0.0000	4000	6830	≤ 1
[Ca/Fe]	-7.4577	23.2759	-23.6621	7.7657	0.0000	4000	6830	≤ 1
[S/Fe]	0.1930	-0.2234	0.0000	0.0000	0.0000	5700	6800	≤ 1

	T_{eff}	$\log(g)$	[M/H]	$\log(g)_{\text{calibrated}}$	$[M/H]_{\text{calibrated}}$	RVS S/N
RAVE-DR6	(-12; 93)	(-0.28; 0.19)	(-0.05; 0.11)	(-0.003; 0.18)	(-0.05; 0.09)	(94; 64)
GALAH-DR3	(20;87)	(-0.26; 0.21)	(0.01; 0.10)	(0.003; 0.18)	(-0.001; 0.10)	(68; 53)
APOGEE-DR17	(-32; 86)	(-0.32; 0.17)	(0.04; 0.12)	(-0.005; 0.15)	(0.06; 0.12)	(65; 80)



- General very good agreement*
- The extreme homogeneity of Gaia RVS/GSPspec highlights literature inhomogeneity (in methods, models, reference data, uncertainty definitions, selection functions...)

*GSP-Spec values are calibrated.
Dotted line: inflated errors by a factor of 4

Topics

- Gaia RVS overview
- The GSP-Spec module
- The GSP-Spec output
    - Comparison with Literature
    - **The importance of GSP-Spec flags**
    - GSP-Spec results
- Some scientific applications
- Recommendations

Family of GSP-Spec Flags

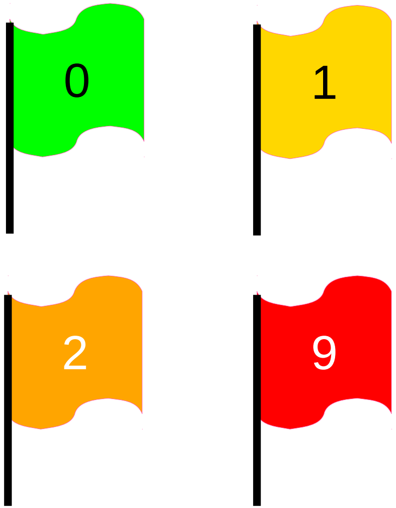
Parameters flags

Abundance flags

CN/DIB flags

Chain character number - name	Considered quality aspect	Possible adopted values	Related subsection and table
1 vbroadT	vbroad induced bias in $T_{\rm eff}$	0,1,2,9	8.1 & C.1
2 vbroadG	vbroad induced bias in $\log(g)$	0,1,2,9	8.1 & C.1
3 vbroadM	vbroad induced bias in [M/H]	0,1,2,9	8.1 & C.1
4 vradT	vrad induced bias in $T_{\rm eff}$	0,1,2,9	8.2 & C.2
5 vradG	vrad induced bias in $\log(g)$	0,1,2,9	8.2 & C.2
6 vradM	vrad induced bias in [M/H]	0,1,2,9	8.2 & C.2
7 fluxNoise	flux noise uncertainties	0,1,2,3,4,5,9	8.3 & C.3, C.4
8 extrapol	extrapolation	0,1,2,3,4,9	8.4 & C.5, C.6
9 negFlux	negative flux pixels	0,9	8.5 & C.7
10 nanFlux	NaN flux pixels	0,1,9	8.5 & C.7
11 emission	emission line	0,1,9	8.5 & C.7
12 nullFluxErr	null uncertainties	0,1,9	8.5 & C.7
13 KMgiantPar	KM-type giant stars	0,1,2,9	8.6 & C.8
14 NUpLim	Nitrogen abundance upper limit	0,1,2,9	8.7 & C.9
15 NUncer	Nitrogen abundance uncertainty quality	0,1,2,9	8.7 & C.10
16 MgUpLim	Magnesium abundance upper limit	0,1,2,9	8.7 & C.9
17 MgUncer	Magnesium abundance uncertainty quality	0,1,2,9	8.7 & C.10
18 SiUpLim	Silicon abundance upper limit	0,1,2,9	8.7 & C.9
19 SiUncer	Silicon abundance uncertainty quality	0,1,2,9	8.7 & C.10
20 SUpLim	Sulphur abundance upper limit	0,1,2,9	8.7 & C.9
21 SUncer	Sulphur abundance uncertainty quality	0,1,2,9	8.7 & C.10
22 CaUpLim	Calcium abundance upper limit	0,1,2,9	8.7 & C.9
23 CaUncer	Calcium abundance uncertainty quality	0,1,2,9	8.7 & C.10
24 TiUpLim	Titanium abundance upper limit	0,1,2,9	8.7 & C.9
25 TiUncer	Titanium abundance uncertainty quality	0,1,2,9	8.7 & C.10
26 CrUpLim	Chromium abundance upper limit	0,1,2,9	8.7 & C.9
27 CrUncer	Chromium abundance uncertainty quality	0,1,2,9	8.7 & C.10
28 FeUpLim	Neutral iron abundance upper limit	0,1,2,9	8.7 & C.9
29 FeUncer	Neutral iron abundance uncertainty quality	0,1,2,9	8.7 & C.10
30 FeIIUpLim	Ionised iron abundance upper limit	0,1,2,9	8.7 & C.9
31 FeIIUncer	Ionised iron abundance uncertainty quality	0,1,2,9	8.7 & C.10
32 NiUpLim	Nickel abundance upper limit	0,1,2,9	8.7 & C.9
33 NiUncer	Nickel abundance uncertainty quality	0,1,2,9	8.7 & C.10
34 ZrUpLim	Zirconium abundance upper limit	0,1,2,9	8.7 & C.9
35 ZrUncer	Zirconium abundance uncertainty quality	0,1,2,9	8.7 & C.10
36 CeUpLim	Cerium abundance upper limit	0,1,2,9	8.7 & C.9
37 CeUncer	Cerium abundance uncertainty quality	0,1,2,9	8.7 & C.10
38 NdUpLim	Neodymium abundance upper limit	0,1,2,9	8.7 & C.9
39 NdUncer	Neodymium abundance uncertainty quality	0,1,2,9	8.7 & C.10
40 DeltaCNq	Cyanogen differential equivalent width quality	0,1,2,9	8.9 & C.12
41 DIBq	DIB quality flag	0,1,2,3,4,5,9	8.8 & C.13

To be used and adapted to your scientific goal



Full table in **Recio-Blanco et al. (2022)**

Family of GSP-Spec Flags

KM flag

Problems with the molecular lines in the cool regime. Dependence of F_{min}

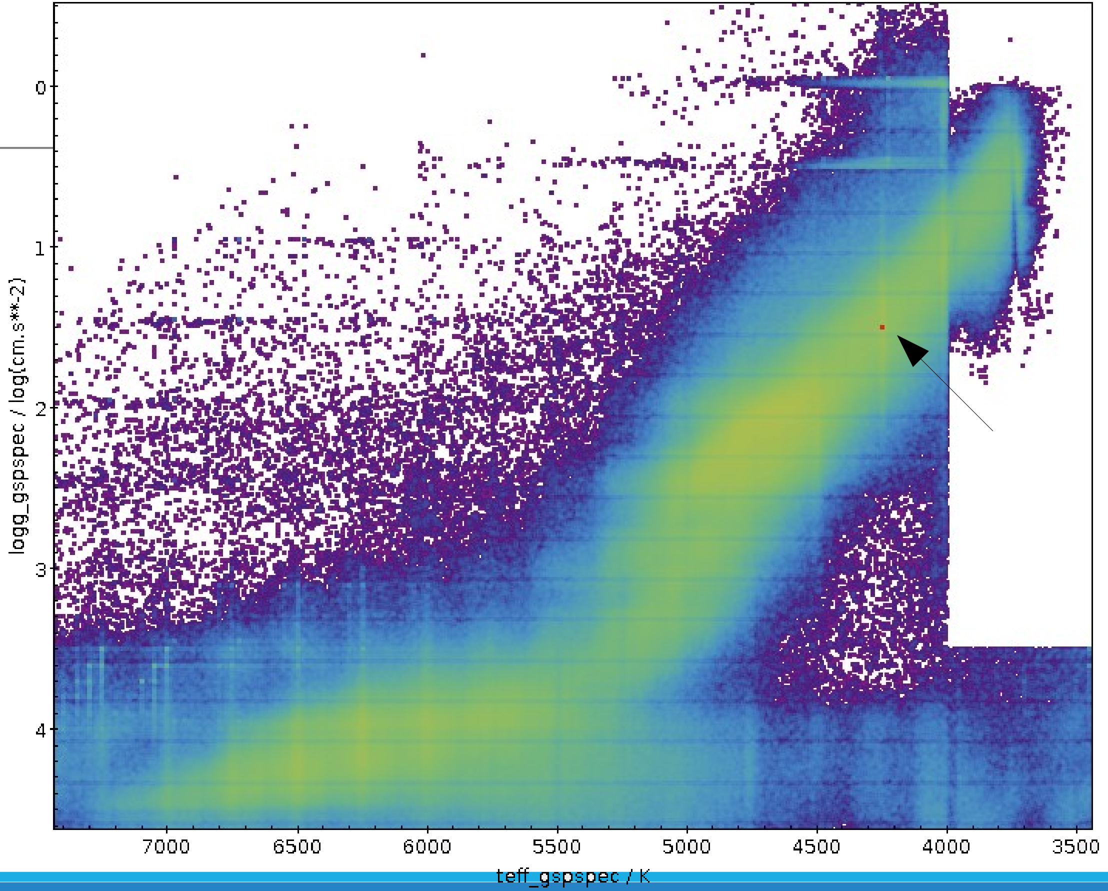


Image: Kiel diagram colorcoded with density

Family of GSP-Spec Flags

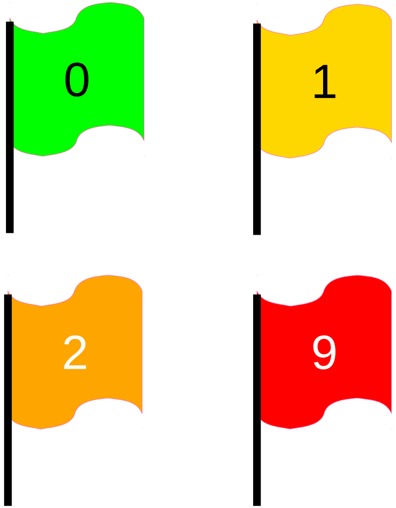
Parameters flags

Abundance flags

CN/DIB flags

Chain character number - name	Considered quality aspect	Possible adopted values	Related subsection and table
1 **vbroadT**	vbroad induced bias in $T_{\rm eff}$	0,1,2,9	8.1 & C.1
2 **vbroadG**	vbroad induced bias in $\log(g)$	0,1,2,9	8.1 & C.1
3 **vbroadM**	vbroad induced bias in [M/H]	0,1,2,9	8.1 & C.1
4 **vradT**	vrad induced bias in $T_{\rm eff}$	0,1,2,9	8.2 & C.2
5 **vradG**	vrad induced bias in $\log(g)$	0,1,2,9	8.2 & C.2
6 **vradM**	vrad induced bias in [M/H]	0,1,2,9	8.2 & C.2
7 **fluxNoise**	flux noise uncertainties	0,1,2,3,4,5,9	8.3 & C.3, C.4
8 **extrapol**	extrapolation	0,1,2,3,4,9	8.4 & C.5, C.6
9 **negFlux**	negative flux pixels	0,9	8.5 & C.7
10 **nanFlux**	NaN flux pixels	0,1,9	8.5 & C.7
11 **emission**	emission line	0,1,9	8.5 & C.7
12 **nullFluxErr**	null uncertainties	0,1,9	8.5 & C.7
13 **KMgiantPar**	KM-type giant stars	0,1,2,9	8.6 & C.8
14 **NUpLim**	Nitrogen abundance upper limit	0,1,2,9	8.7 & C.9
15 **NUncer**	Nitrogen abundance uncertainty quality	0,1,2,9	8.7 & C.10
16 **MgUpLim**	Magnesium abundance upper limit	0,1,2,9	8.7 & C.9
17 **MgUncer**	Magnesium abundance uncertainty quality	0,1,2,9	8.7 & C.10
18 **SiUpLim**	Silicon abundance upper limit	0,1,2,9	8.7 & C.9
19 **SiUncer**	Silicon abundance uncertainty quality	0,1,2,9	8.7 & C.10
20 **SUpLim**	Sulphur abundance upper limit	0,1,2,9	8.7 & C.9
21 **SUncer**	Sulphur abundance uncertainty quality	0,1,2,9	8.7 & C.10
22 **CaUpLim**	Calcium abundance upper limit	0,1,2,9	8.7 & C.9
23 **CaUncer**	Calcium abundance uncertainty quality	0,1,2,9	8.7 & C.10
24 **TiUpLim**	Titanium abundance upper limit	0,1,2,9	8.7 & C.9
25 **TiUncer**	Titanium abundance uncertainty quality	0,1,2,9	8.7 & C.10
26 **CrUpLim**	Chromium abundance upper limit	0,1,2,9	8.7 & C.9
27 **CrUncer**	Chromium abundance uncertainty quality	0,1,2,9	8.7 & C.10
28 **FeUpLim**	Neutral iron abundance upper limit	0,1,2,9	8.7 & C.9
29 **FeUncer**	Neutral iron abundance uncertainty quality	0,1,2,9	8.7 & C.10
30 **FeIIUpLim**	Ionised iron abundance upper limit	0,1,2,9	8.7 & C.9
31 **FeIIUncer**	Ionised iron abundance uncertainty quality	0,1,2,9	8.7 & C.10
32 **NiUpLim**	Nickel abundance upper limit	0,1,2,9	8.7 & C.9
33 **NiUncer**	Nickel abundance uncertainty quality	0,1,2,9	8.7 & C.10
34 **ZrUpLim**	Zirconium abundance upper limit	0,1,2,9	8.7 & C.9
35 **ZrUncer**	Zirconium abundance uncertainty quality	0,1,2,9	8.7 & C.10
36 **CeUpLim**	Cerium abundance upper limit	0,1,2,9	8.7 & C.9
37 **CeUncer**	Cerium abundance uncertainty quality	0,1,2,9	8.7 & C.10
38 **NdUpLim**	Neodymium abundance upper limit	0,1,2,9	8.7 & C.9
39 **NdUncer**	Neodymium abundance uncertainty quality	0,1,2,9	8.7 & C.10
40 **DeltaCNq**	Cyanogen differential equivalent width quality	0,1,2,9	8.9 & C.12
41 **DIBq**	DIB quality flag	0,1,2,3,4,5,9	8.8 & C.13

To be used and adapted to your scientific goal



Full table in **Recio-Blanco et al. (2022)**

Working with flags in the Gaia Archive

GSP-Spec flags are distributed as **strings** in the **Gaia Archive**

- Not easy to handle with them, but possible.
- The key is the **LIKE** keyword.
- *string1* **LIKE** *string2* performs an element-wise comparison of the characters in *string1* and *string2*
- (*string1* **LIKE** *string2)* is **true** string1 has the same form as string2. Otherwise it is **false**.

```
SELECT source_id
FROM user_dr3int6.astrophysical_parameters
WHERE (teff_gspspec>3500) AND (logg_gspspec>0) AND
    (logg_gspspec<5) AND
    ((teff_gspspec_upper-teff_gspspec_lower)<750)
    AND ((logg_gspspec_upper-logg_gspspec_lower)<1.)
    AND ((mh_gspspec_upper-mh_gspspec_lower)<.5) AND
    (teff_gspspec>=3800 OR logg_gspspec<=3.5) AND
    (teff_gspspec>=4150 OR logg_gspspec<=2.4 OR
    logg_gspspec>=3.6 ) AND ((flags_gspspec LIKE
    "____________0%") OR (flags_gspspec LIKE
    "____________1%")) AND ((flags_gspspec LIKE
    "0%") OR (flags_gspspec LIKE "1%")) AND
    ((flags_gspspec LIKE "_0%") OR (flags_gspspec
    LIKE "_1%")) AND ((flags_gspspec LIKE "__0%") OR
    (flags_gspspec LIKE "__1%")) AND ((flags_gspspec
    LIKE "___0%") OR (flags_gspspec LIKE "___1%"))
    AND ((flags_gspspec LIKE "____0%") OR
    (flags_gspspec LIKE "____1%")) AND
    ((flags_gspspec LIKE "_____0%") OR
    (flags_gspspec LIKE "_____1%")) AND
    ((flags_gspspec LIKE "______0%") OR
    (flags_gspspec LIKE "______1%") OR
    (flags_gspspec LIKE "______2%") OR
    (flags_gspspec LIKE "______3%")) AND
    ((flags_gspspec LIKE "_______0%") OR
    (flags_gspspec LIKE "_______1%") OR
    (flags_gspspec LIKE "_______2%"))
```

Listing 2. ADQL query example including conditions on the parameter flags (c.f. Table 2)

Working with flags in the Gaia Archive

GSP-Spec flags are distributed as **strings** in the **Gaia Archive**

- The underscore (_) refers to "any **single** character".
- The percentage symbol (%) means "**multiple** characters".

flags_gspspec LIKE "_____0%"

Don't change this   5 underscores

True if the 6^{th} flag (vradM) is zero

```
SELECT source_id
FROM user_dr3int6.astrophysical_parameters
WHERE (teff_gspspec>3500) AND (logg_gspspec>0) AND
    (logg_gspspec<5) AND
    ((teff_gspspec_upper-teff_gspspec_lower)<750)
    AND ((logg_gspspec_upper-logg_gspspec_lower)<1.)
    AND ((mh_gspspec_upper-mh_gspspec_lower)<.5) AND
    (teff_gspspec>=3800 OR logg_gspspec<=3.5) AND
    (teff_gspspec>=4150 OR logg_gspspec<=2.4 OR
    logg_gspspec>=3.6 ) AND ((flags_gspspec LIKE
    "____________0%") OR (flags_gspspec LIKE
    "____________1%")) AND ((flags_gspspec LIKE
    "0%") OR (flags_gspspec LIKE "1%")) AND
    ((flags_gspspec LIKE "_0%") OR (flags_gspspec
    LIKE "_1%")) AND ((flags_gspspec LIKE "__0%") OR
    (flags_gspspec LIKE "__1%")) AND ((flags_gspspec
    LIKE "___0%") OR (flags_gspspec LIKE "___1%"))
    AND ((flags_gspspec LIKE "____0%") OR
    (flags_gspspec LIKE "____1%")) AND
    ((flags_gspspec LIKE "_____0%") OR
    (flags_gspspec LIKE "_____1%")) AND
    ((flags_gspspec LIKE "______0%") OR
    (flags_gspspec LIKE "______1%") OR
    (flags_gspspec LIKE "______2%") OR
    (flags_gspspec LIKE "______3%")) AND
    ((flags_gspspec LIKE "_______0%") OR
    (flags_gspspec LIKE "_______1%") OR
    (flags_gspspec LIKE "_______2%"))
```

Listing 2. ADQL query example including conditions on the parameter flags (c.f. Table 2)

Working with flags in the Gaia Archive

What if we want vradM≤1?

- Just use **OR**

(flags_gspspec LIKE “_____0%”)
OR
(flags_gspspec LIKE “_____1%”)

True if the 6th flag (vradM) is zero or one

```
SELECT source_id
FROM user_dr3int6.astrophysical_parameters
WHERE (teff_gspspec>3500) AND (logg_gspspec>0) AND
    (logg_gspspec<5) AND
    ((teff_gspspec_upper-teff_gspspec_lower)<750)
    AND ((logg_gspspec_upper-logg_gspspec_lower)<1.)
    AND ((mh_gspspec_upper-mh_gspspec_lower)<.5) AND
    (teff_gspspec>=3800 OR logg_gspspec<=3.5) AND
    (teff_gspspec>=4150 OR logg_gspspec<=2.4 OR
    logg_gspspec>=3.6 ) AND ((flags_gspspec LIKE
    "____________0%") OR (flags_gspspec LIKE
    "____________1%")) AND ((flags_gspspec LIKE
    "0%") OR (flags_gspspec LIKE "1%")) AND
    ((flags_gspspec LIKE "_0%") OR (flags_gspspec
    LIKE "_1%")) AND ((flags_gspspec LIKE "__0%") OR
    (flags_gspspec LIKE "__1%")) AND ((flags_gspspec
    LIKE "___0%") OR (flags_gspspec LIKE "___1%"))
    AND ((flags_gspspec LIKE "____0%") OR
    (flags_gspspec LIKE "____1%")) AND
    ((flags_gspspec LIKE "_____0%") OR
    (flags_gspspec LIKE "_____1%")) AND
    ((flags_gspspec LIKE "______0%") OR
    (flags_gspspec LIKE "______1%") OR
    (flags_gspspec LIKE "______2%") OR
    (flags_gspspec LIKE "______3%")) AND
    ((flags_gspspec LIKE "_______0%") OR
    (flags_gspspec LIKE "_______1%") OR
    (flags_gspspec LIKE "_______2%"))
```

Listing 2. ADQL query example including conditions on the parameter flags (c.f. Table 2)

Working with flags in the Gaia Archive

Recommendation for complex ADQL queries: use parenthesis

GOOD

((flags_gspspec LIKE "_____0%") **OR** (flags_gspspec LIKE "_____1%")**)**

AND

((flags_gspspec LIKE "____0%") **OR** (flags_gspspec LIKE "____1%"))

True if both 6th and 5th flags (vradM, vradG) are zero or one. It is different from

BAD

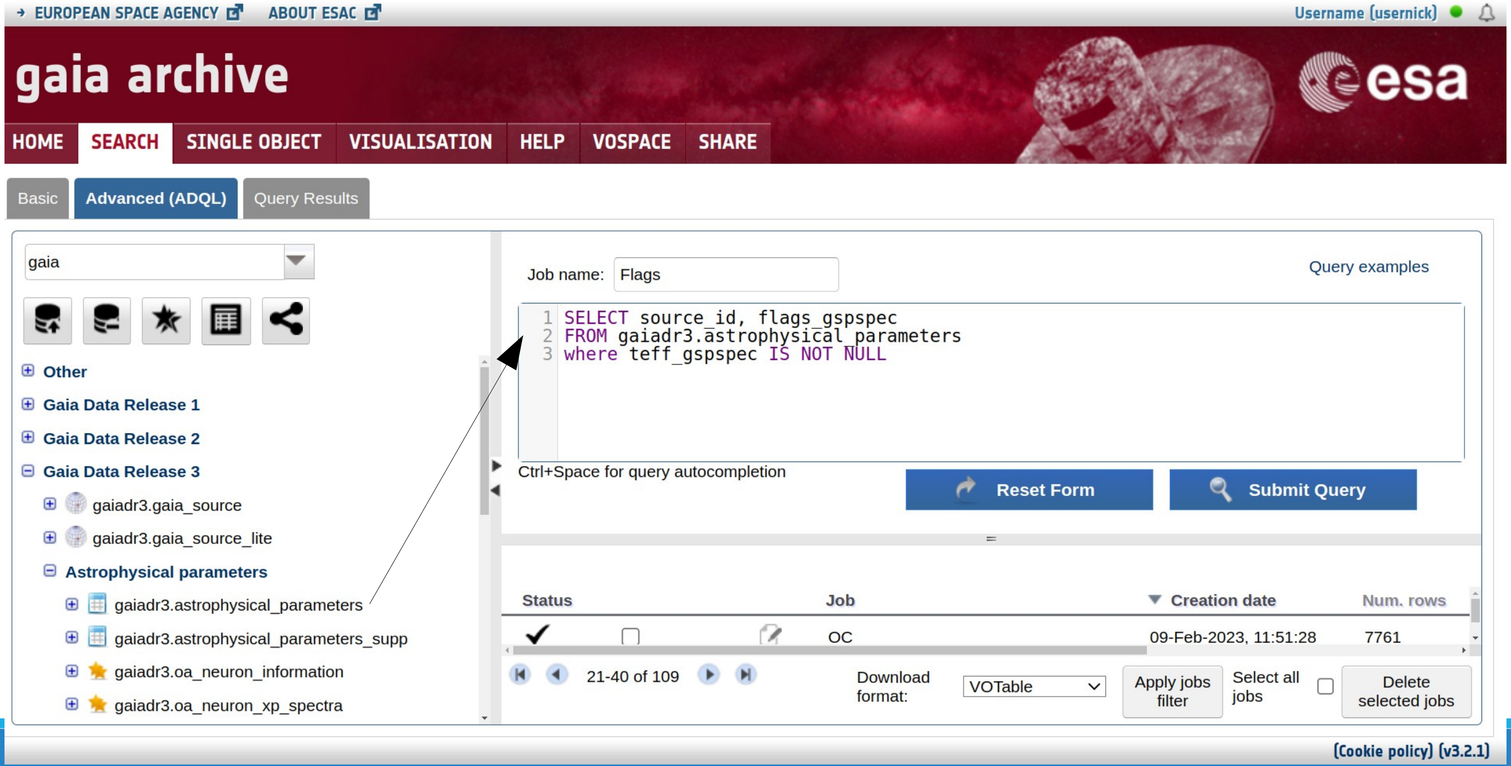
(flags_gspspec LIKE "_____0%") **OR** (flags_gspspec LIKE "_____1%")

AND

(flags_gspspec LIKE "____0%") **OR** (flags_gspspec LIKE "____1%")

Working with flags in ~~the Gaia Archive~~ Python

Alternatively, you may prefer to download a wider sample an perform the flag filtering in Python. Here is an example query*:



*Not recommended: Gaia archive queries should be more specific!

Working with flags in ~~the Gaia Archive~~ Python

Alternatively, you may prefer to download a wider sample an perform the flag filtering in Python. Here is an example code*:

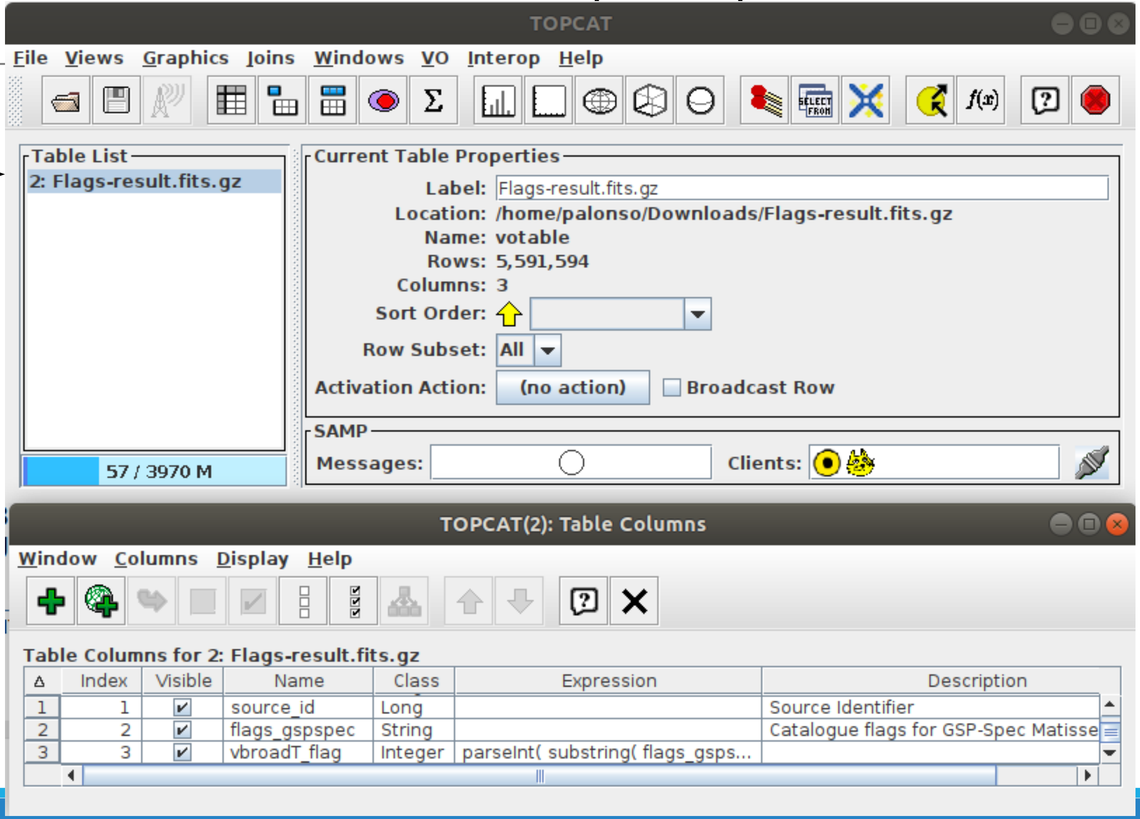
```
def getflagn(x,n):
        # Get the n-th column of the array of strings "x"
        # n>=0
        # Note n starts at zero, not at one!
        # The output is an array of integers
        z = map(lambda y: y[n], x)
        z = list(z)
        z = np.uint8(z)
        return(z)
```

*Depending on the Python version and the input file format, you may have to tune this code.

Working with flags in Topcat

Alternatively, you may prefer to download a wider sample an perform the flag filtering in Topcat.

Output of the previous query (~70 Mb)



We can extract the **numeric value** of the n-th flag by concatenating parseInt and substring functions:

parseInt(substring(flags_gspspec,0,1))

n-th

(n+1)-th

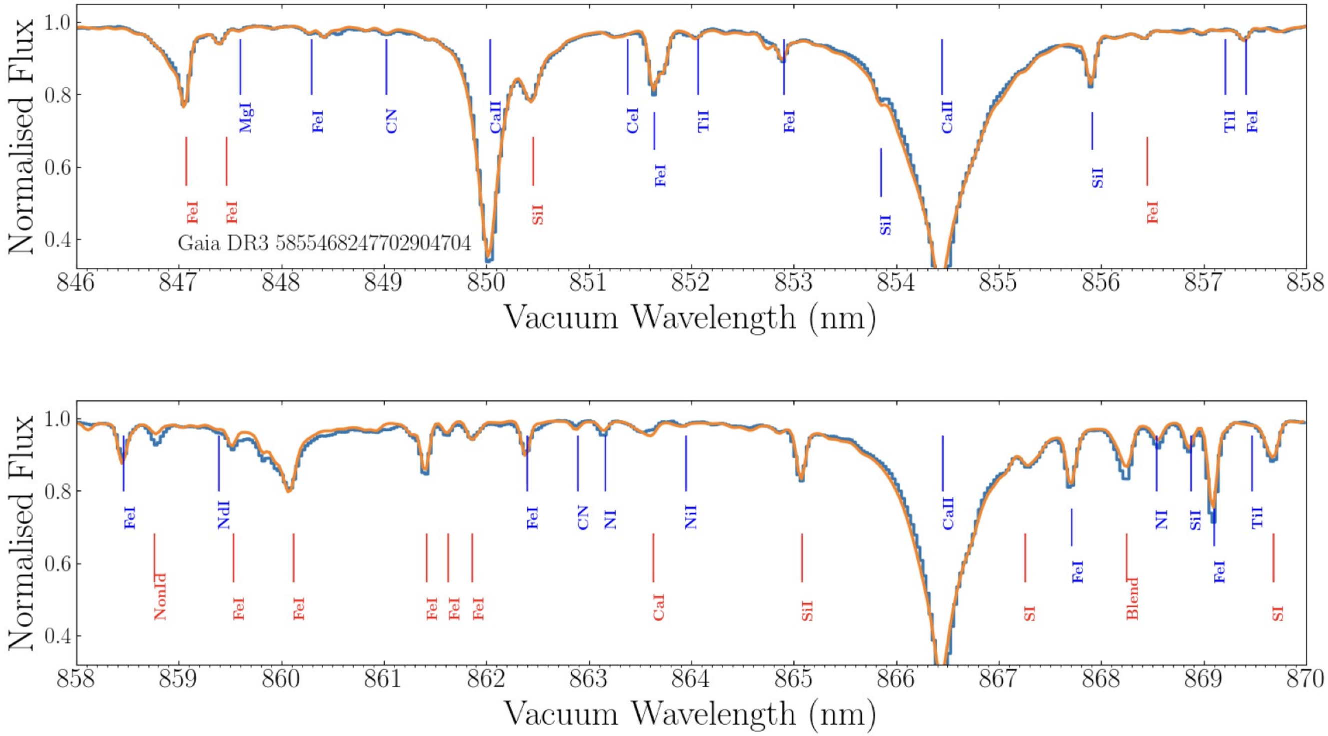
Topics

- Gaia RVS overview
- The GSP-Spec module
- The GSP-Spec output
    - Comparison with Literature
    - The importance of GSP-Spec flags
    - **GSP-Spec results**
- Some scientific applications
- Recommendations

High quality spectra and fitting

Continuous observations for 3 years, no atmosphere, control of systematics, … Gaia is not a ground-based survey!

Teff 5477K
Logg 1.44
Met. 0.07 dex
Alpha 0.11 dex



Ionized iron line

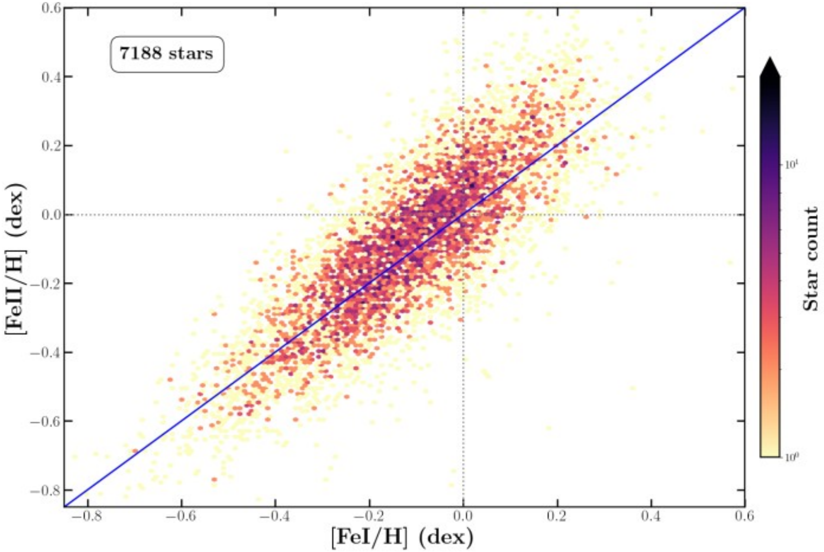
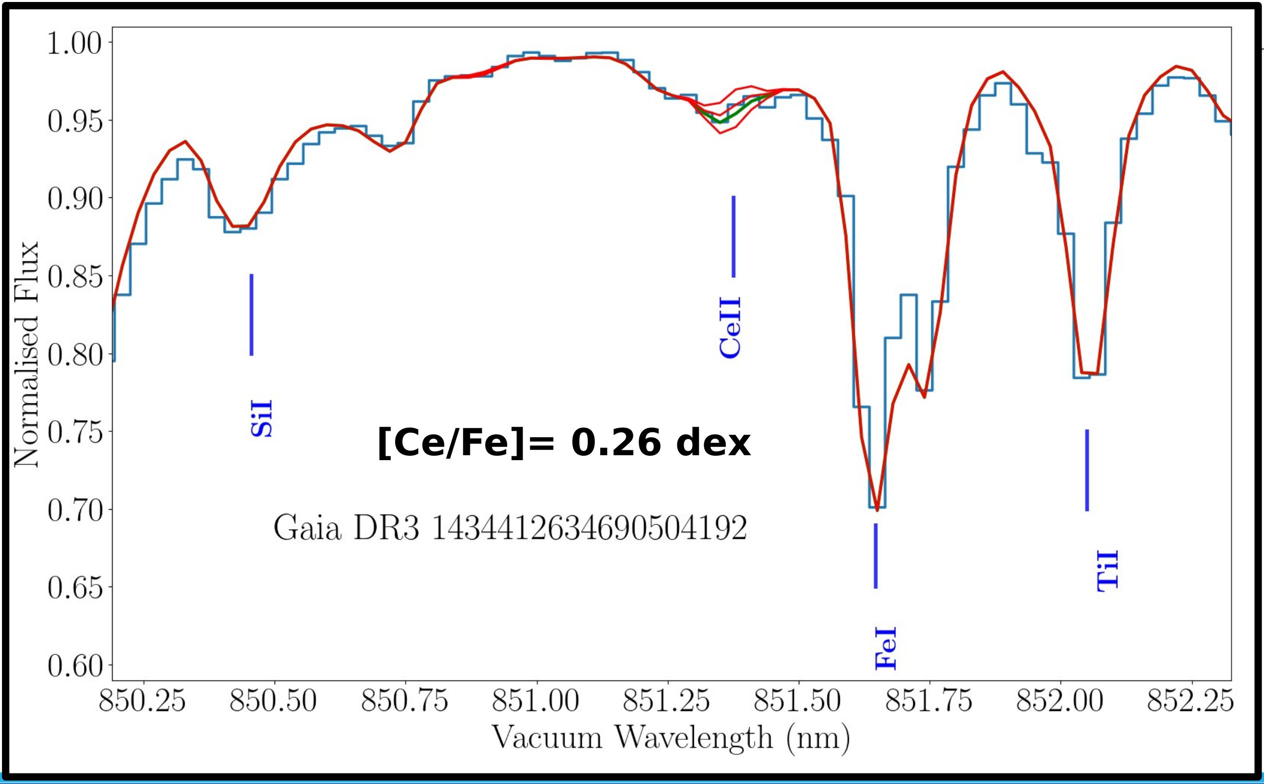


Fig. 10. Comparison between iron abundances measured from the proposed Fe II line at 858.79 nm and from all the other Fe I lines. The Spearman correlation coefficient is equal to 0.82. See text for more details.

Recio-Blanco et al. (2022)

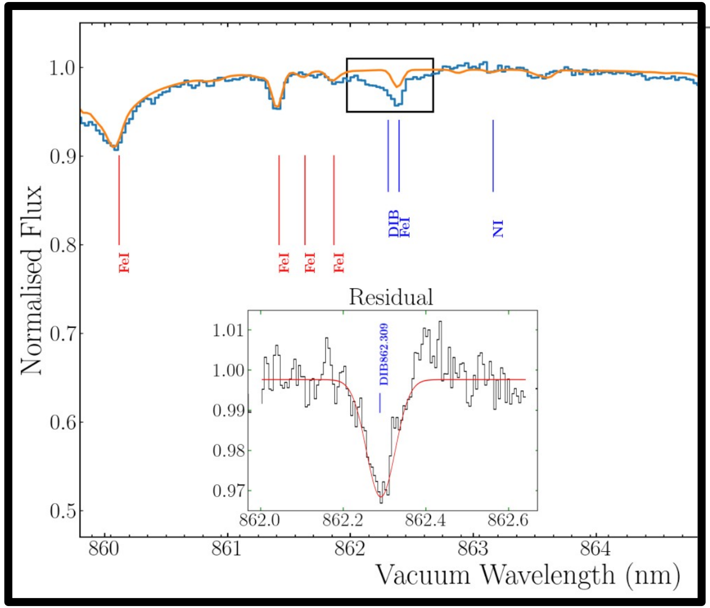
High quality spectra and fitting

Continuous observations for 3 years, no atmosphere, control of systematics, ... Gaia is not a ground-based survey!

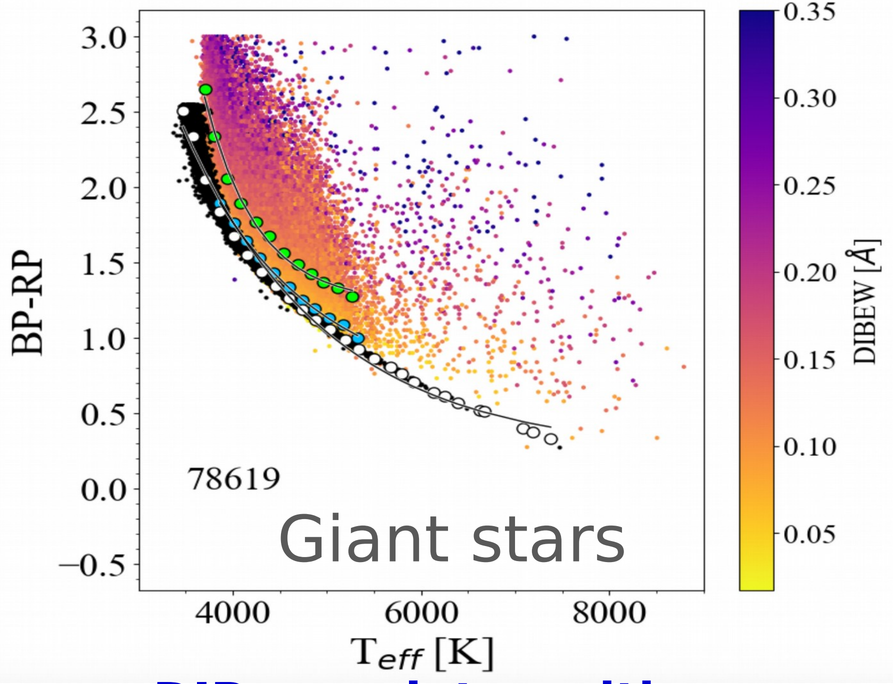


See **Contursi et al. 2022** for the scientific exploitation of Cerium

Absorption from interstellar dust molecules (DIB) on an individual spectrum basis



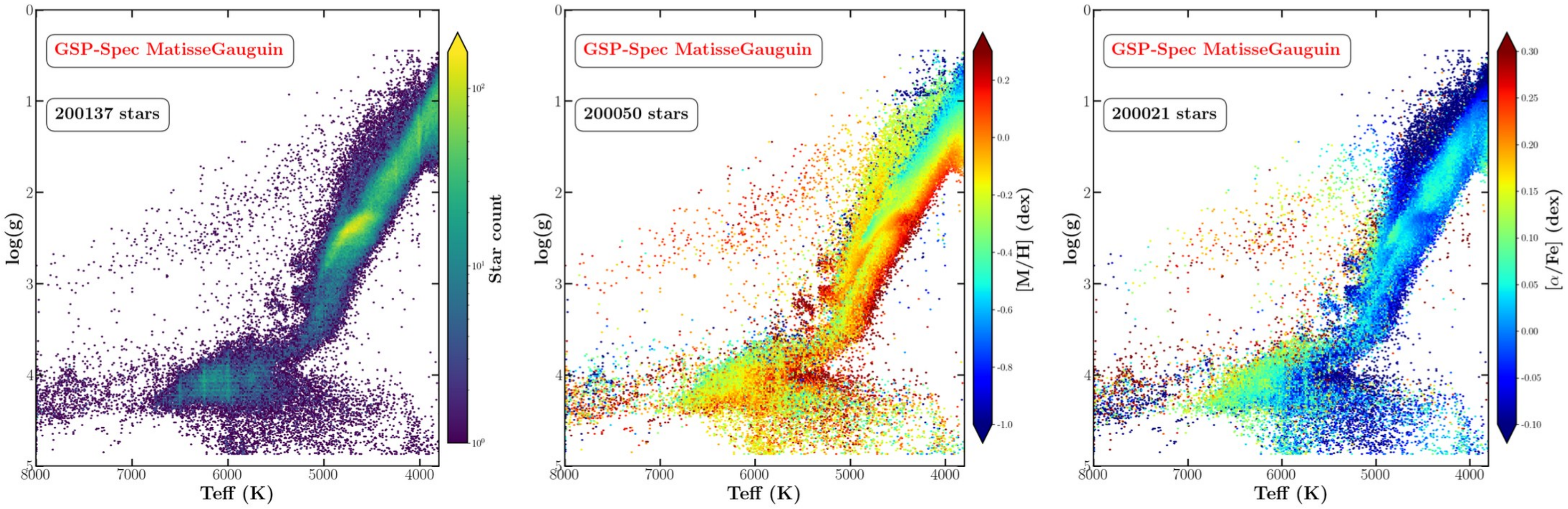
Recio-Blanco et al. (2022)

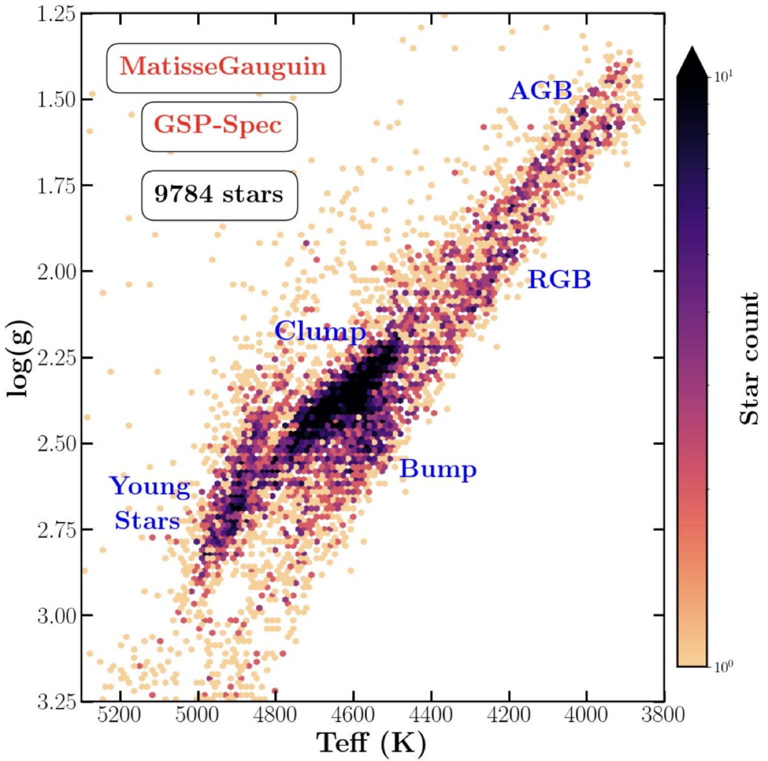


DIB correlates with Teff-color discrepancy

SNR>150

High quality parameter flags



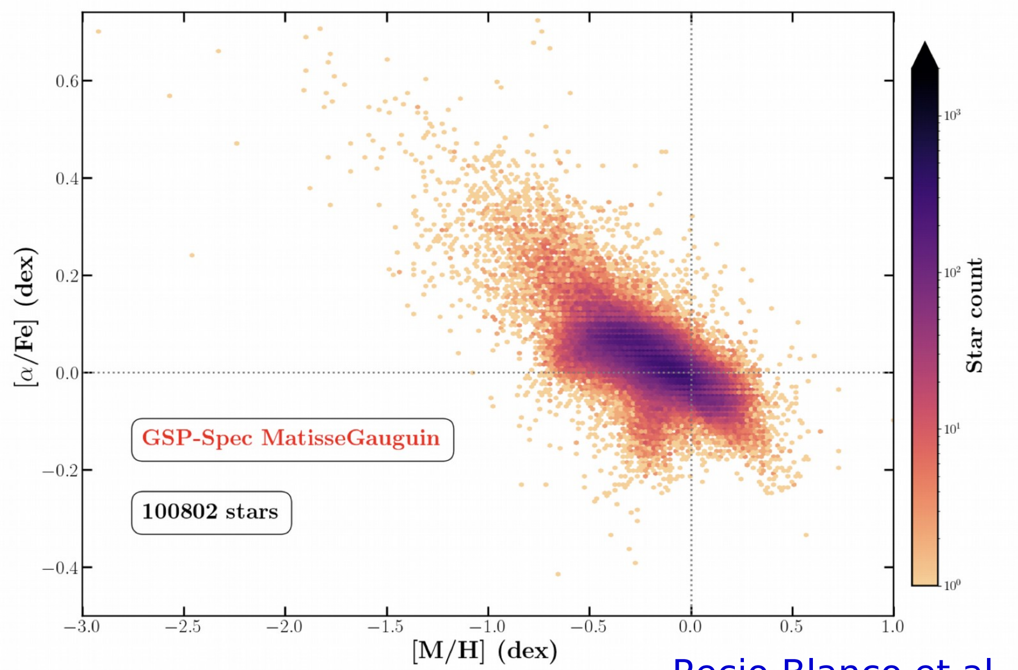


Recio-Blanco et al. (2022)

- Sample of stars with more than 68% of probability of solar metallicity (-0.05 dex < [M/H] < 0.05 dex)

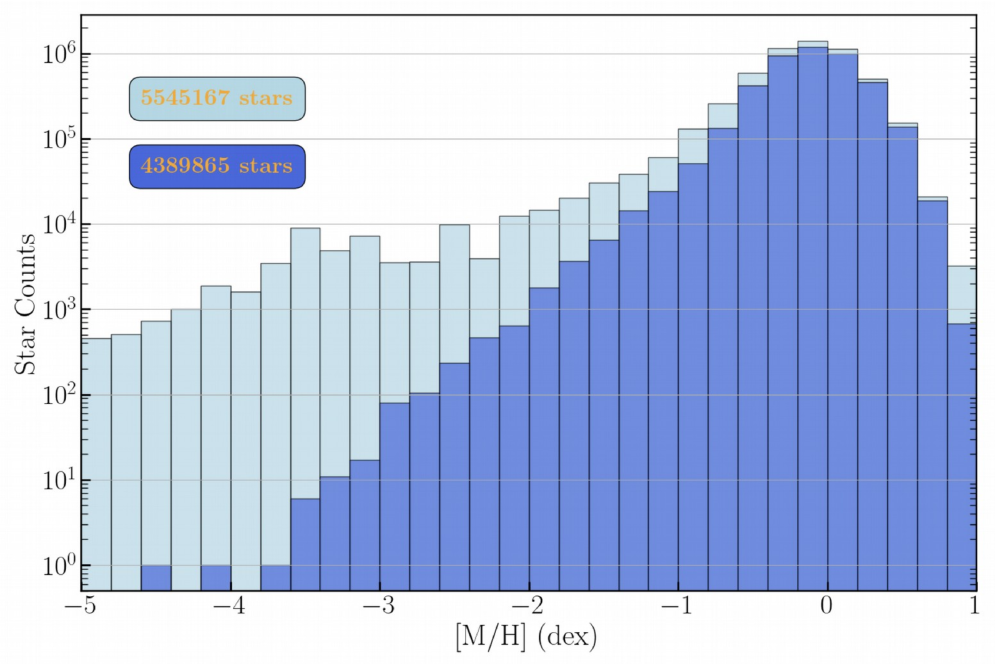
Thick-thin disc dichotomy

- RGB+Massive stars
- SNR>150



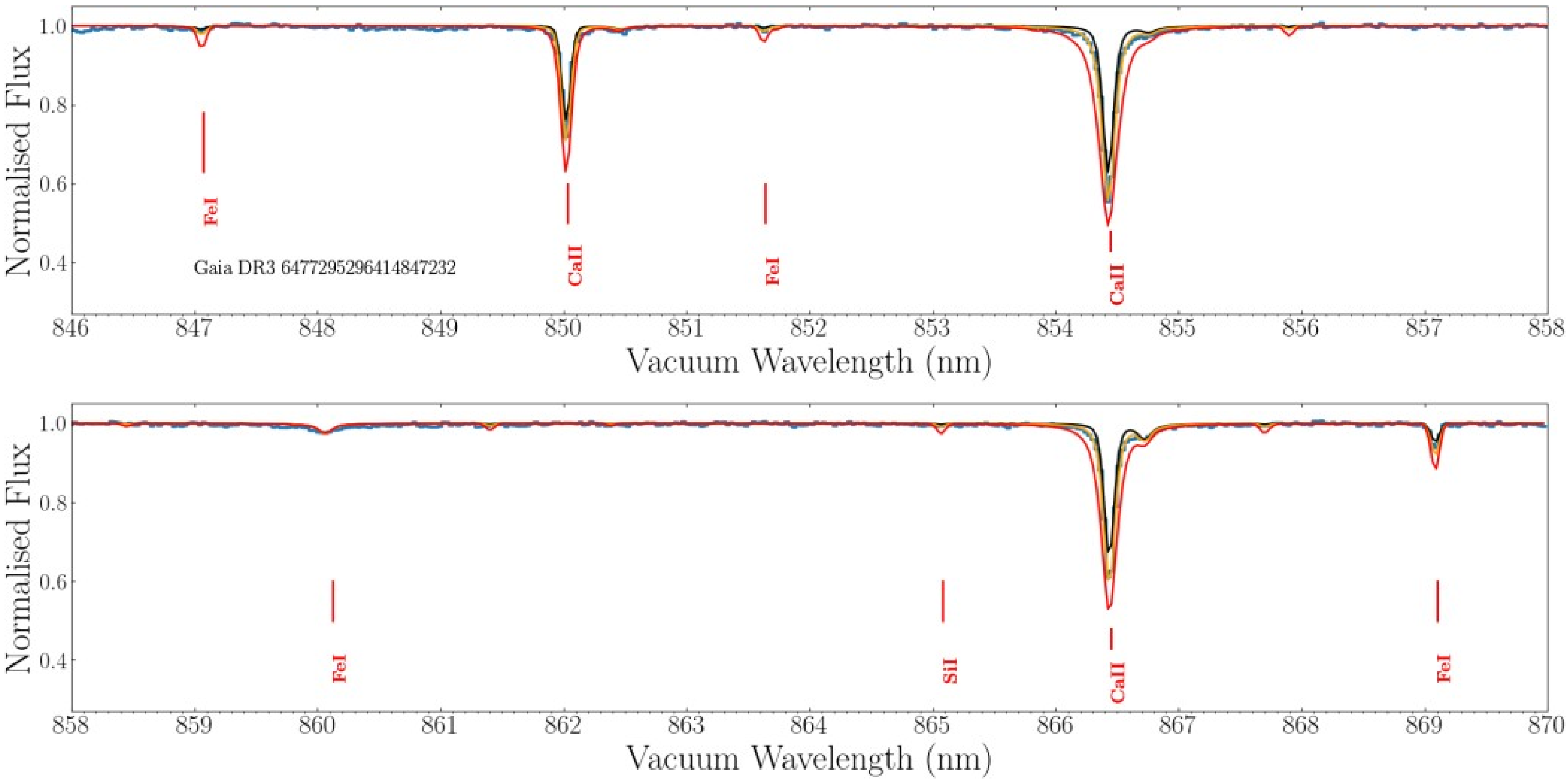
Recio-Blanco et al. (2022)

Observing metal poor stars



Extremely metal-poor stars can be selected in the Gaia DR3 GSPspec table (special ADQL query is required [Section 10.5 in Recio-Blanco et al. 2022])

Observing metal poor stars ([M/H]=-3.52 dex)

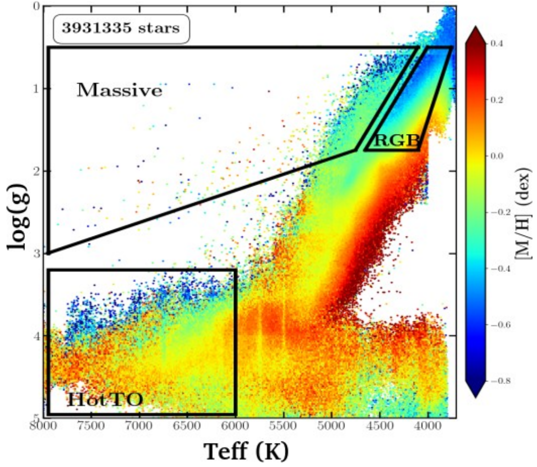


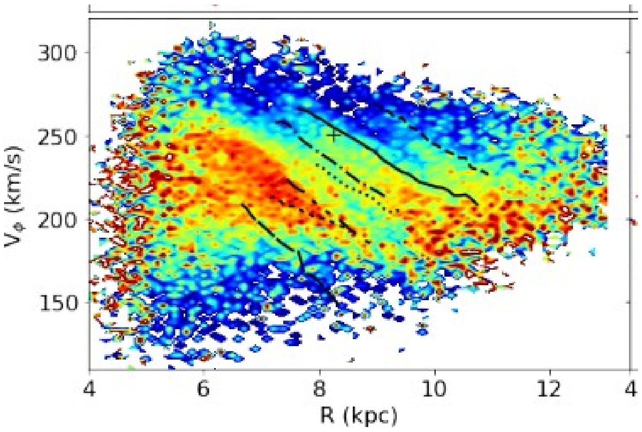
Topics

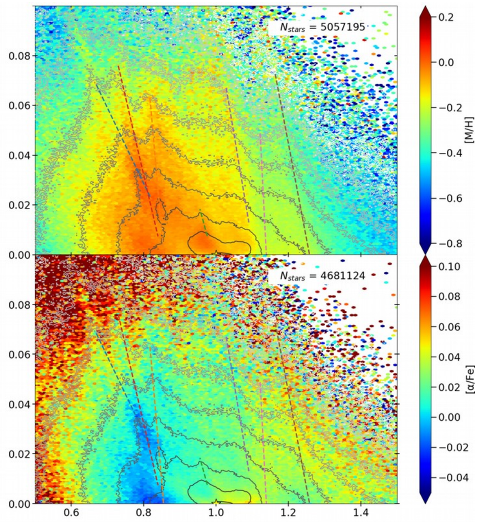
- Gaia RVS overview
- The GSP-Spec module
- The GSP-Spec output
- **Some scientific applications**
- Recommendations

Scientific exploitation examples of GSP-Spec data

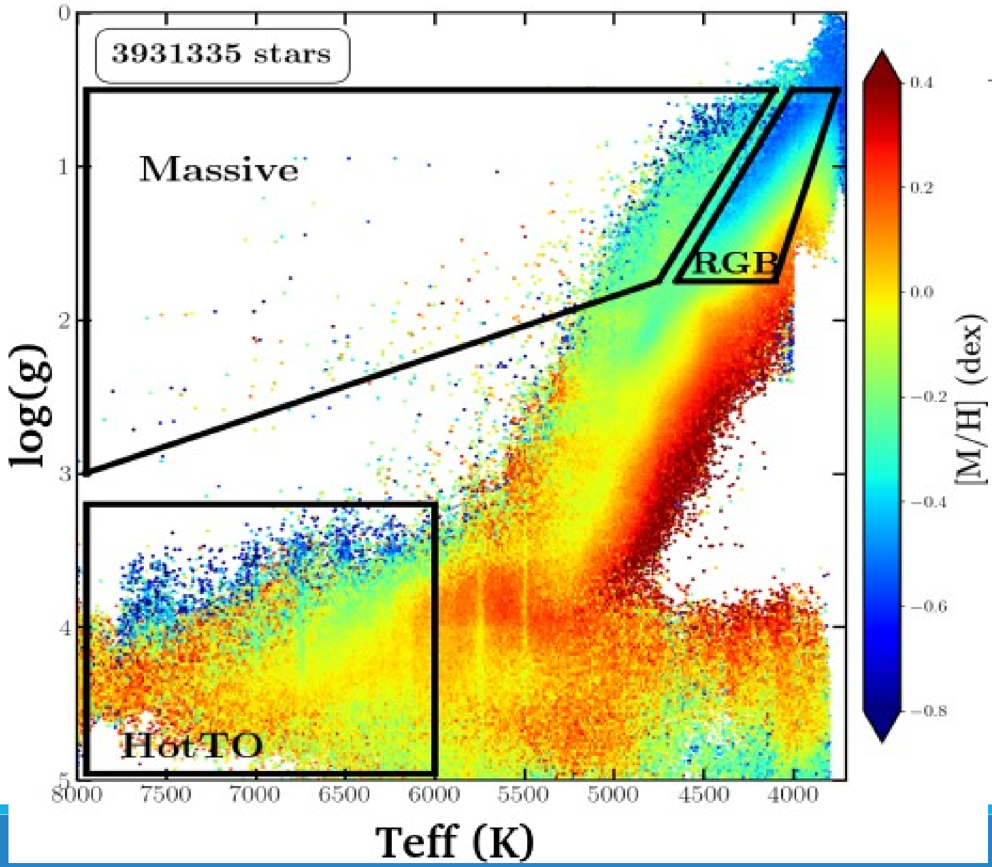
Many examples in the Performance Verification Paper *Chemical Cartography of the Milky Way* (Gaia Collaboration, Recio-Blanco et al. 2022)



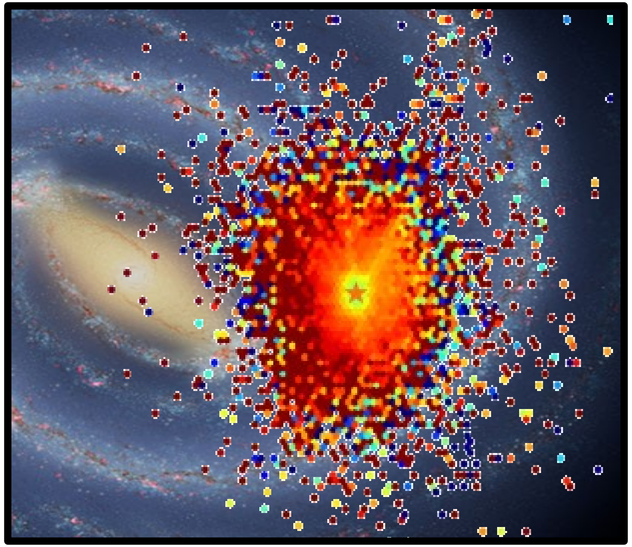




Hot Turn Off sample

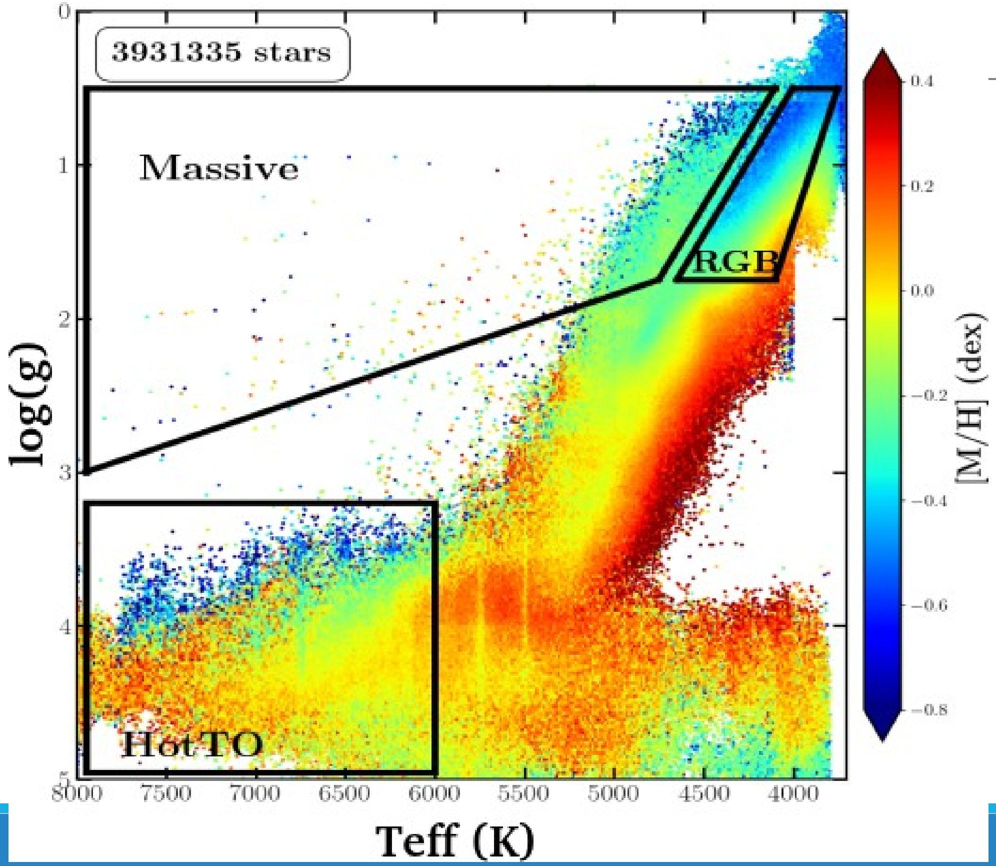


Hot TO sample

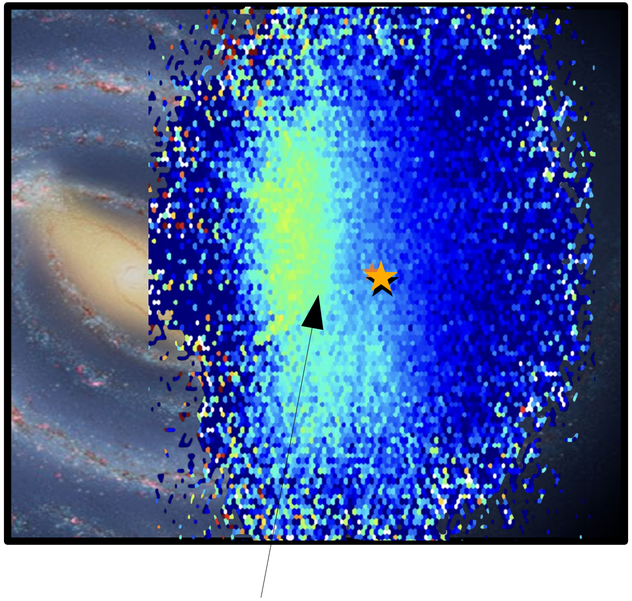


Most of them are within 1 kpc.

Bright RGB

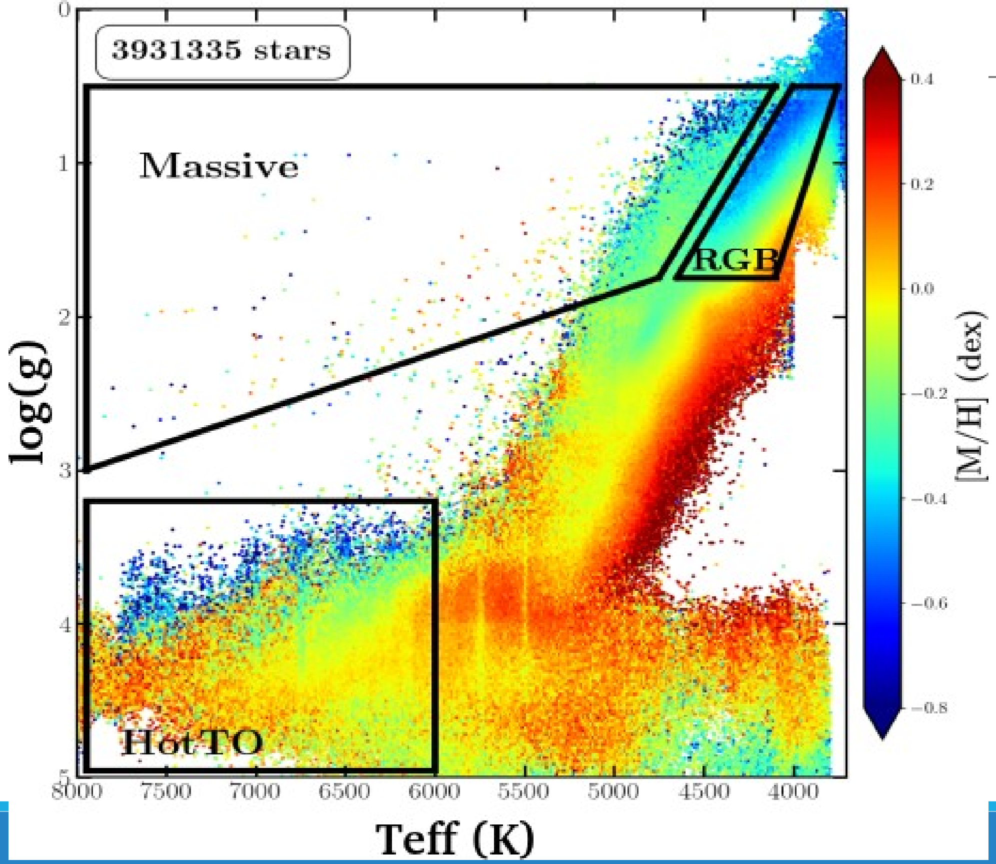


Bright RGB sample

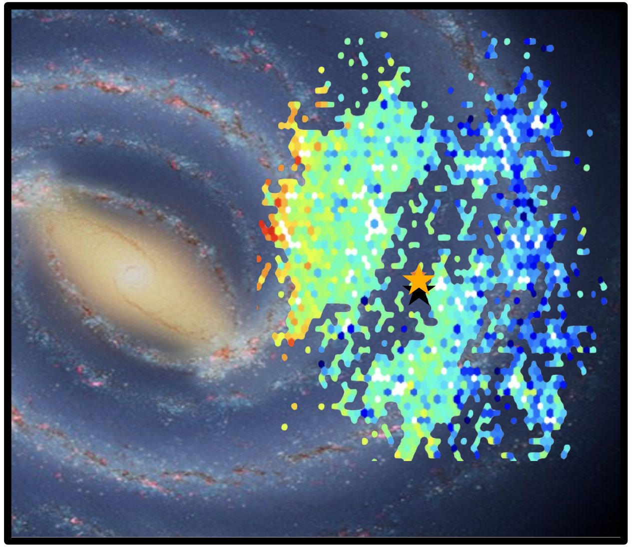


Innermost spiral arm and bar

Young population in the spiral arms

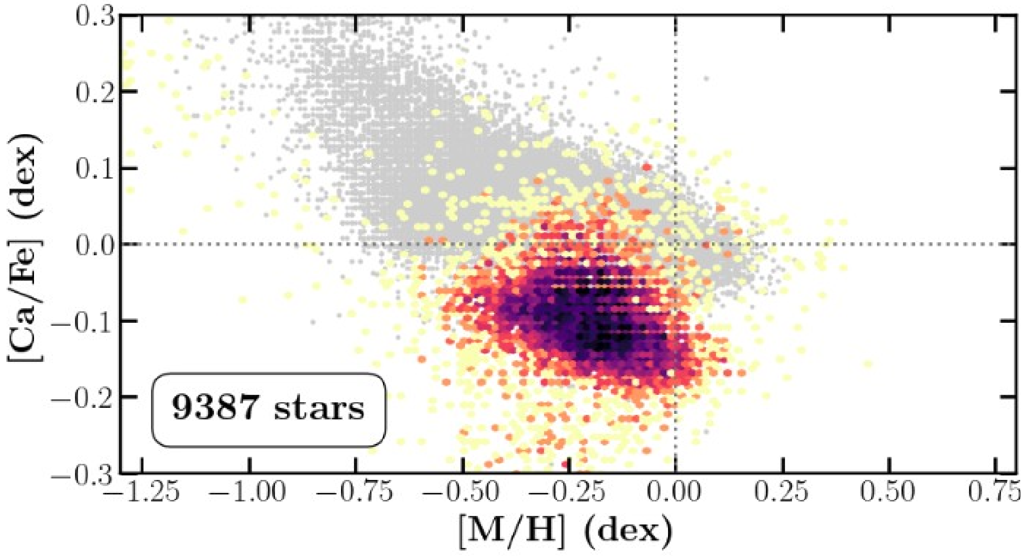


Massive sample



The **massive sample** traces the spiral arms.

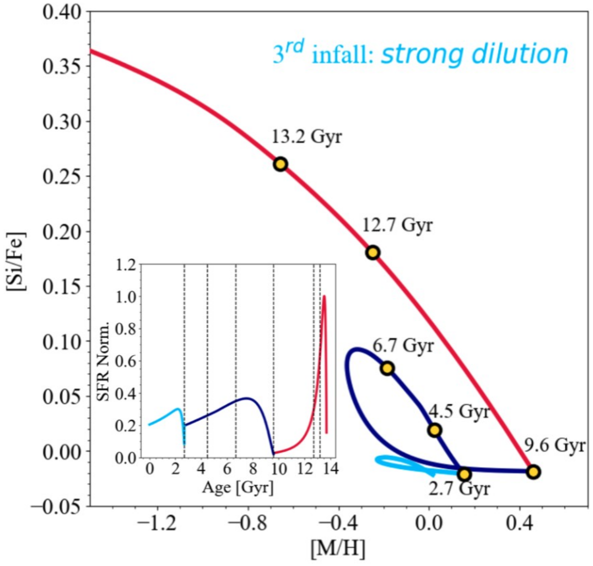
Chemical impoverishment ?



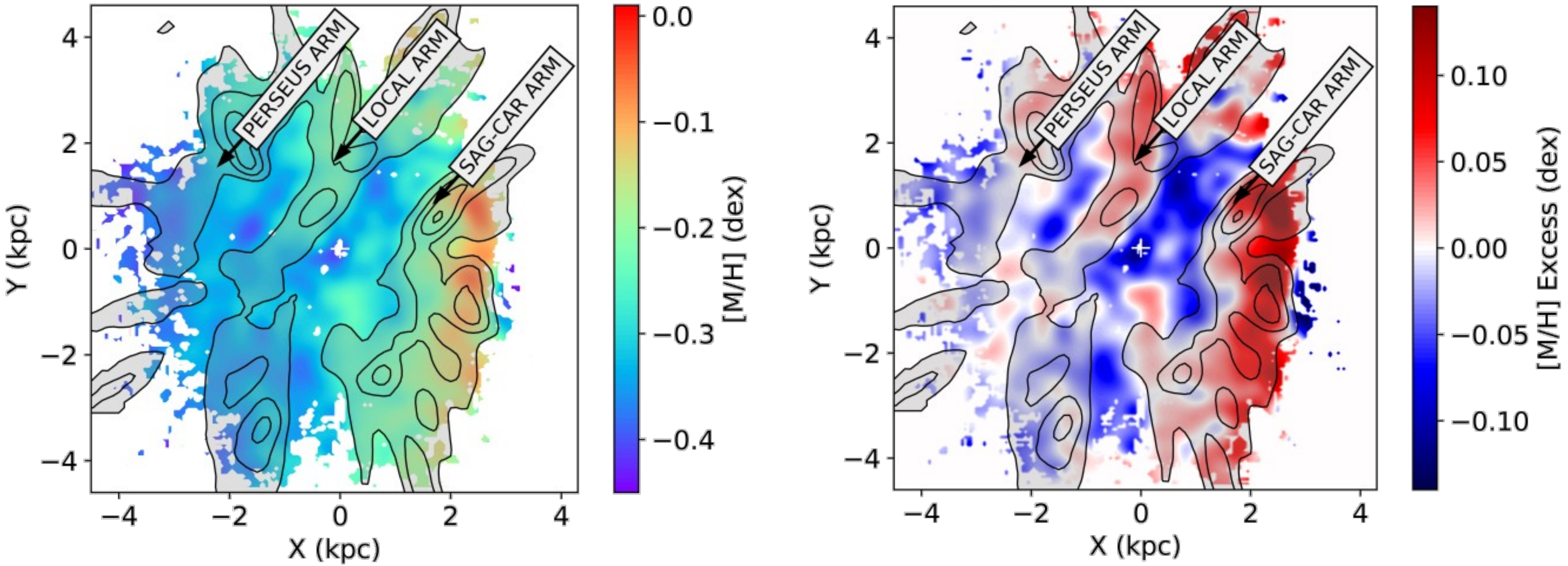
Gaia Collaboration, Recio-Blanco et al. (2022)

Depletion consistent with other HR surveys (APOGEE)

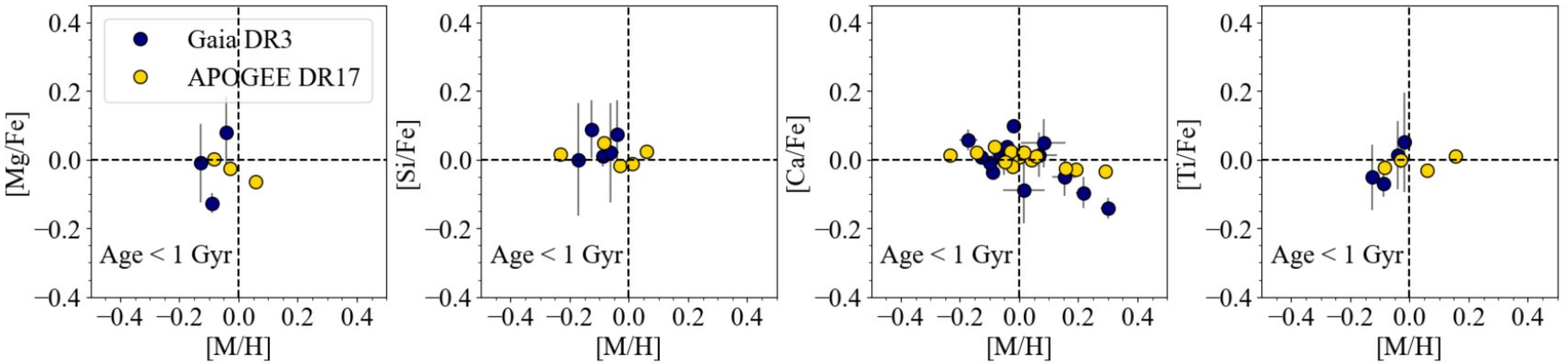
- Recent gas infall?
- Missing physics?



Signatures of the spiral arms in the metallicity distribution

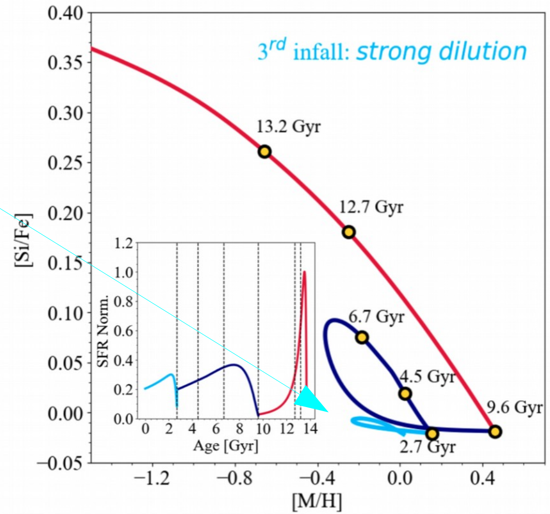


Poggio et al. 2022

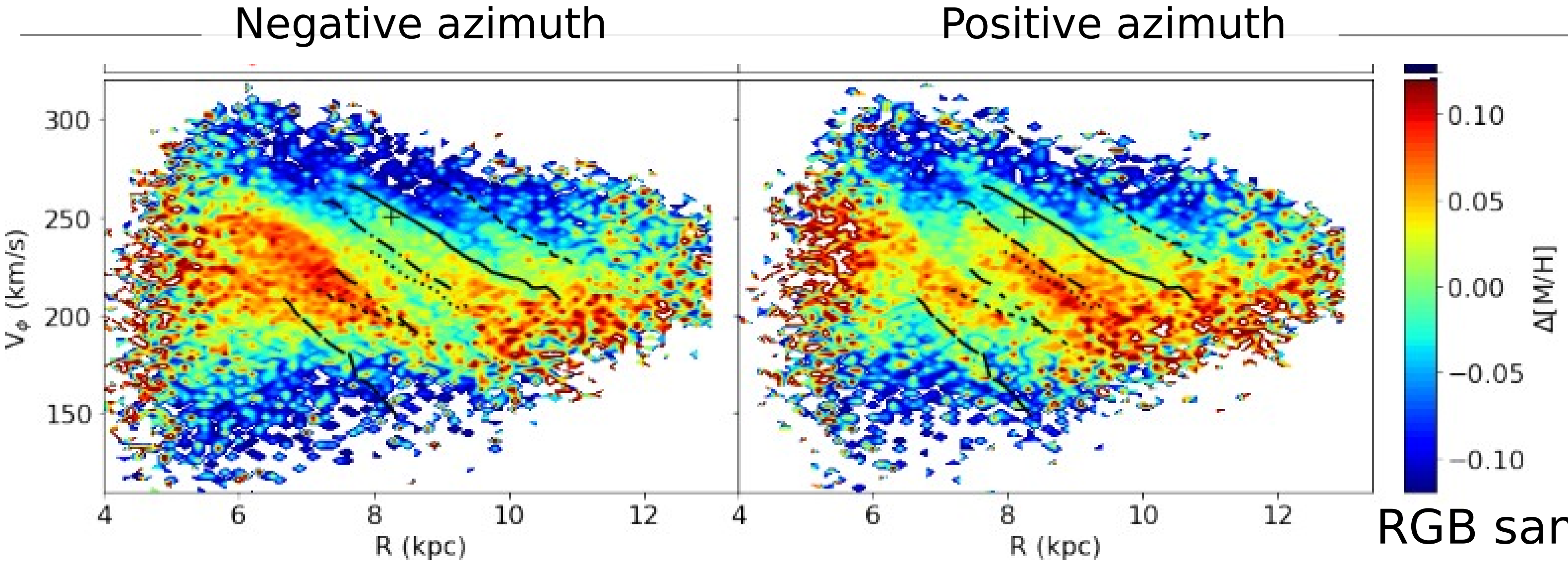


Spitoni et al. 2023

(We have more young metal poor stars than these shown above, but they are not in common with APOGEE DR17)



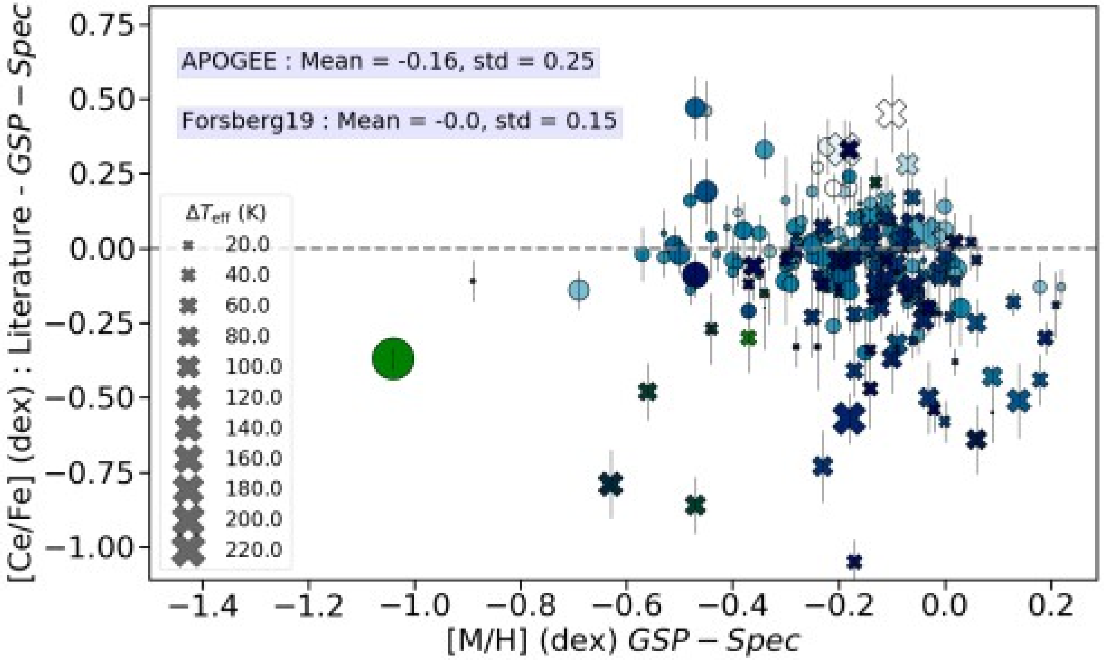
Ridges in the Chemodynamical space (vel. profile)



RGB sample.

Ridges in metallicity excess suggest a connetion with these in azimuthal velocity (moving groups?). Gaia Collab., Recio-Blanco et al. 2022

Cerium abundances

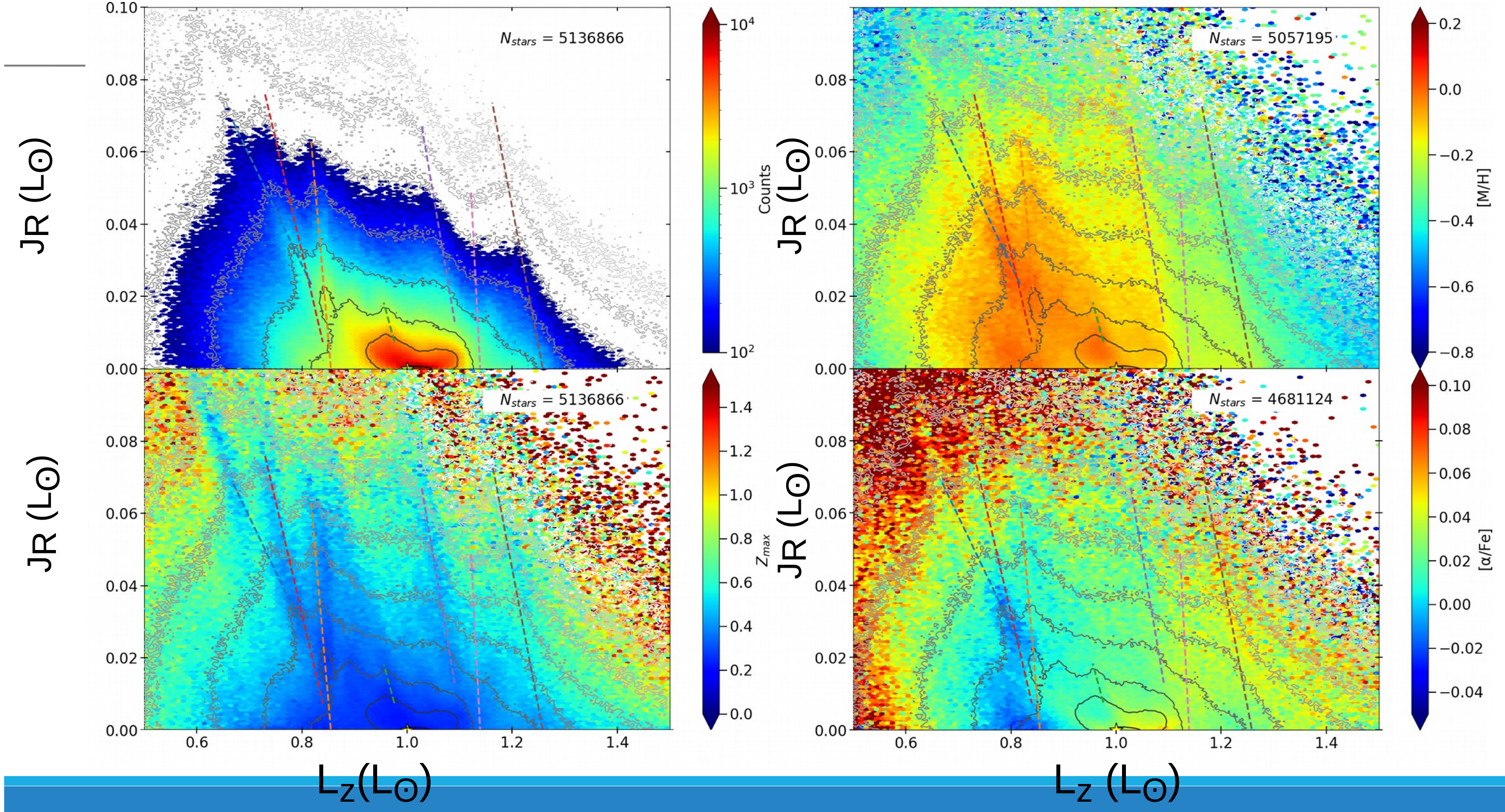


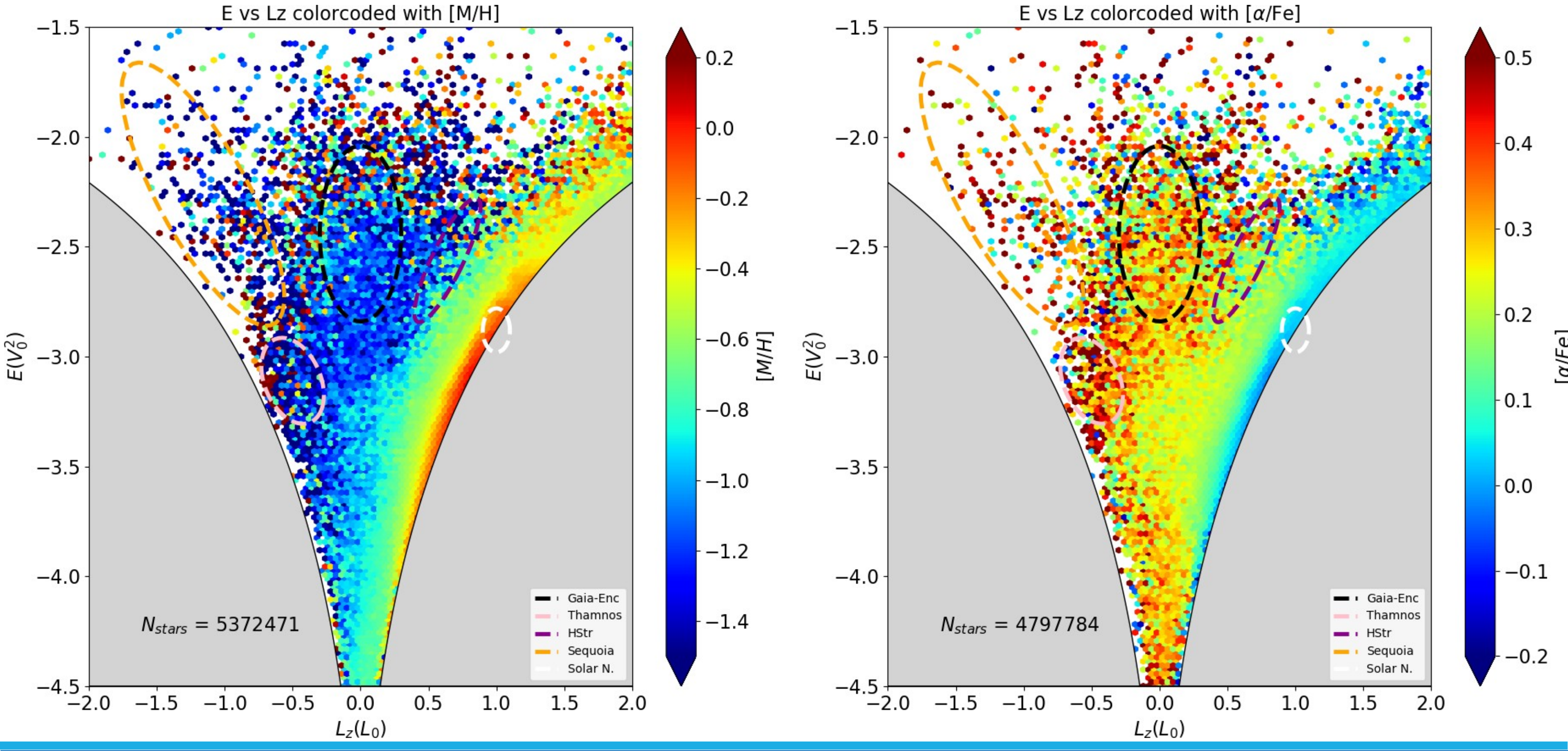
Contursi et al. 2023

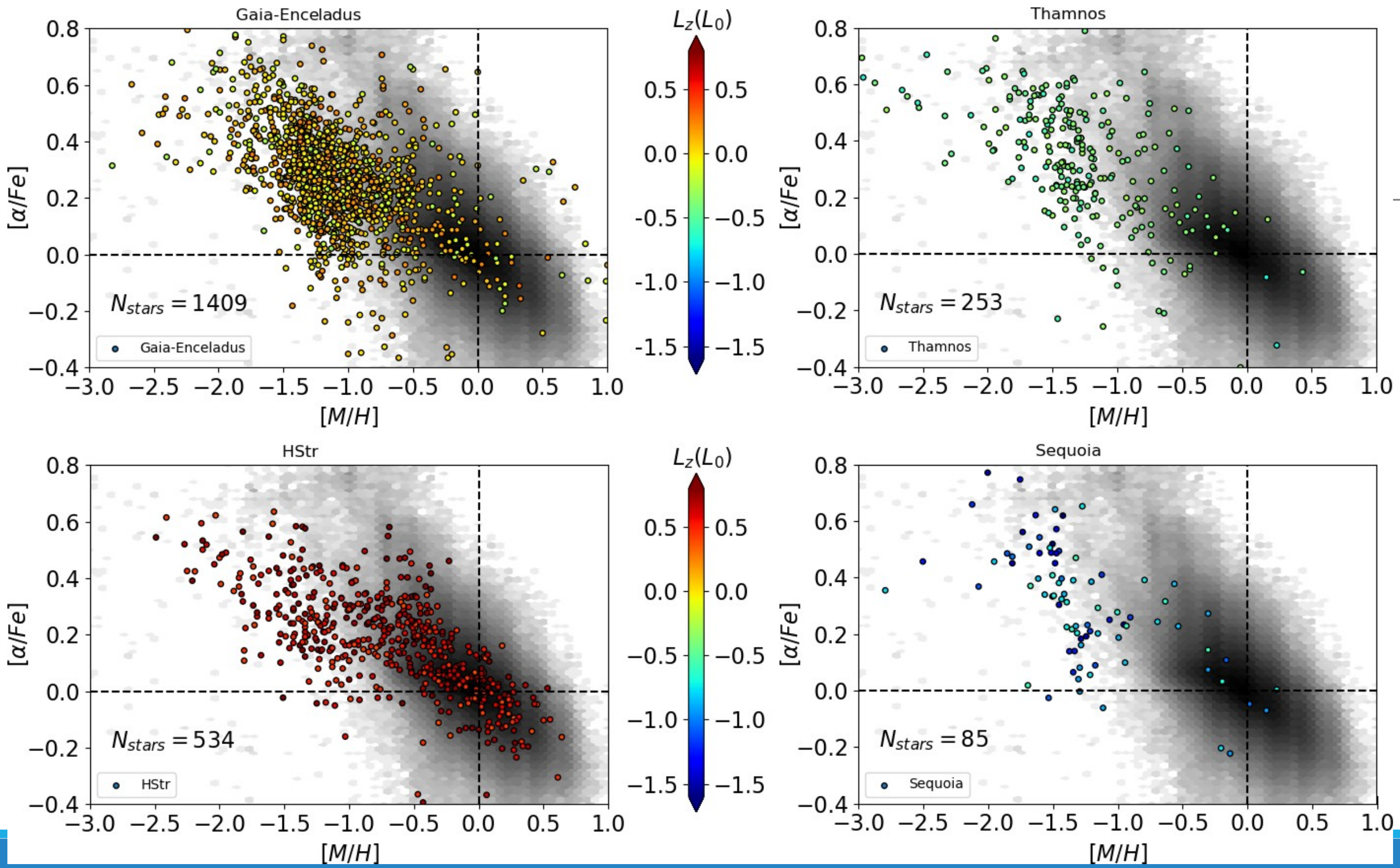
Ridges in the Chemodynamical space (actions)

J_R (radial action) is a momentum variable that tunes the motion in the radial direction.

L_Z (angular mom.) determines the "guiding radii" around the Galactic Center.




E vs Lz colorcoded with [M/H]
N_{stars} = 5372471
Gaia-Enc
Thamnos
HStr
Sequoia
Solar N.
$E(V_0^2)$
$L_z(L_0)$
[M/H]
E vs Lz colorcoded with [α/Fe]
N_{stars} = 4797784
[α/Fe]


Gaia-Enceladus
Thamnos
HStr
Sequoia
$N_{stars} = 1409$
$N_{stars} = 253$
$N_{stars} = 534$
$N_{stars} = 85$
$[\alpha/Fe]$
$[M/H]$
$L_z(L_0)$

Topics

- Gaia RVS overview
- The GSP-Spec module
- The GSP-Spec output
- Some scientific applications
- **Recommendations**
- Conclusions

Good practices

Calibration is mandatory: Always start with the calibrated values

---

Use the flags!

- A good initial flag filtering is to **keep the 13th first flags equal to zero**.
- Depending on the volume, quality and application, relax this condition.
- Specific filtering suggestions were provided in **Recio-Blanco et al.** (2022) for the Chem. Abundances

You can (reasonably) apply your own bias correction when comparing with other surveys.

Good practices

- **Best quality sample**: the 13th first flags equal to zero.
- **Medium quality sample**: Like the best quality sample but flags lower or equal to one, except KMflag (still 0), fluxnoise flag (<4)
- **More specific samples**: Appendix B of “Chemical Cartography of the Milky Way” (Gaia Collaboration, Recio-Blanco et al. 2022)

Conclusions

- **Gaia DR3 GSP-Spec** constitutes the l**argest all-sky chemical survey ever** (data for 5.6 million sources).
- It is the **first** based on satellite observations.
- It provides **very competitive** results compared to other large spectroscopic surveys, although **calibration** and **filtering** may be required.
- **Calibration is mandatory**. Flags must be used (Gaia archieve, python or topcat, but use them!)
- A wide variety of **scientific results** has already been discovered using the GSP-Spec catalog (Spiral structure, accreted systems, chemical evolution, chemodynamic relations...)