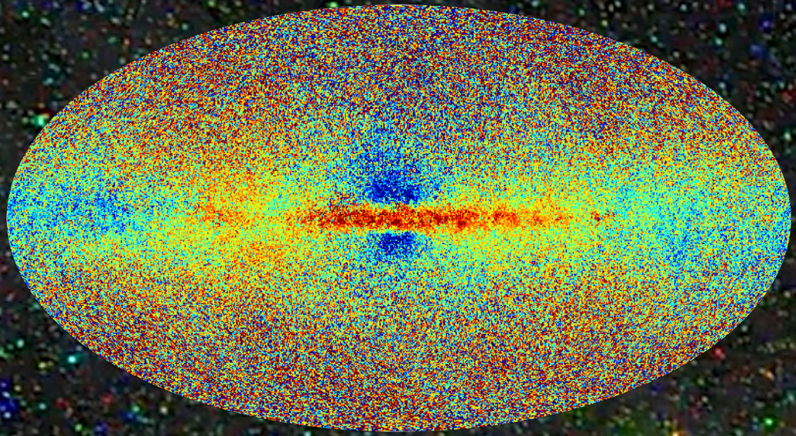
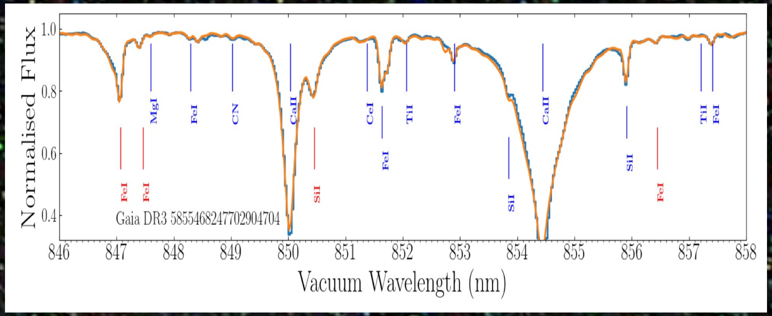
Gaia RVS spectroscopy: do you *really* know it?

Alejandra Recio-Blanco

Observatoire de la Côte d'Azur (Lab. Lagrange)





RVS = Radial Velocity Spectrograph

GSPspec = General Stellar Parametrizer - spectroscopy

esa gaia

OBSERVATOIRE DE LA CÔTE D'AZUR UNIVERSITÉ CÔTE D'AZUR

LAGRANGE

Gaia DPAC

cnes

Horizon 2020 research No 101004214

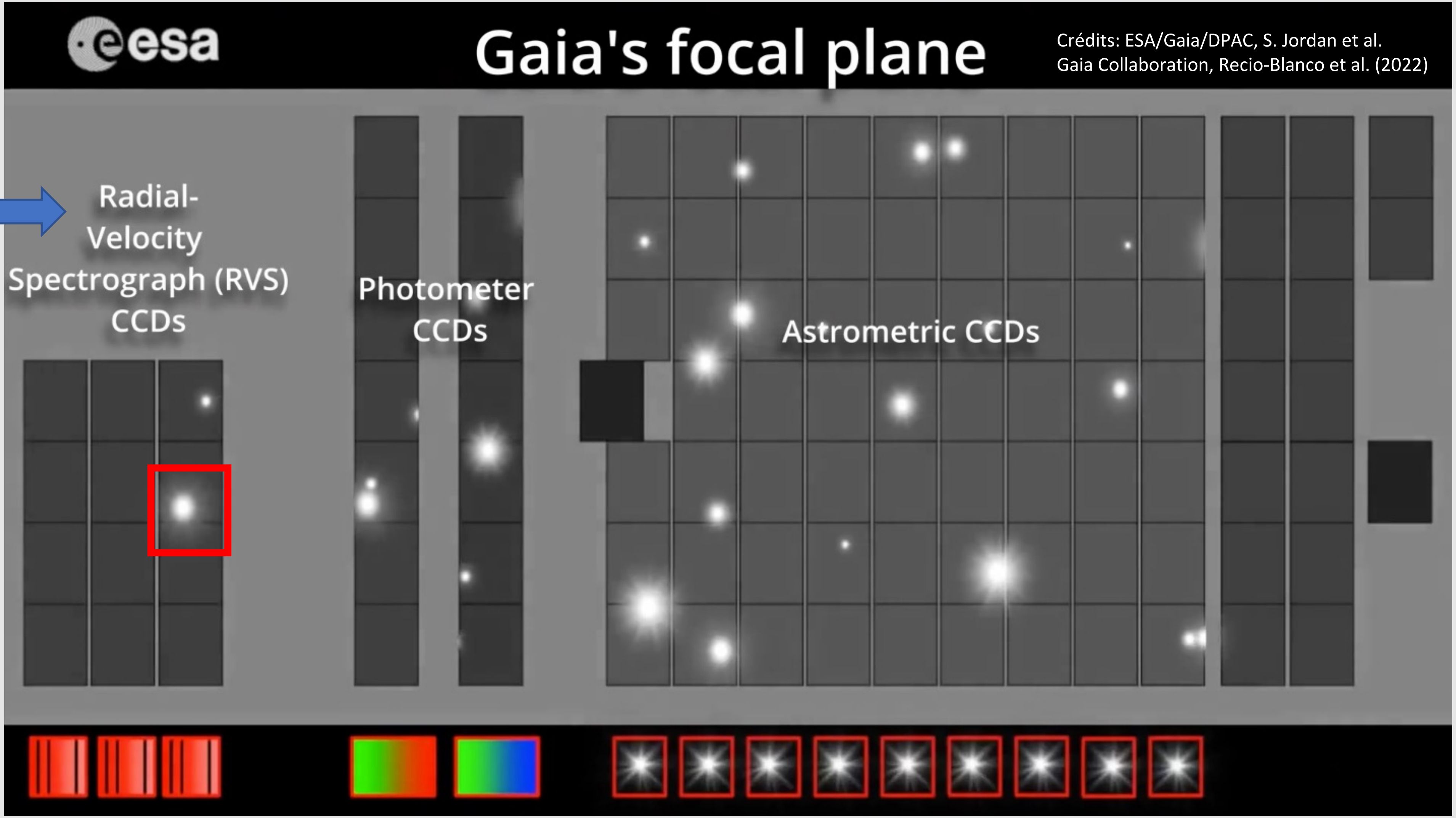
MARIE CURIE ACTIONS

Gaia/RVS: a space spectroscopic survey

RVS

Resolving power:
11 500

Wavelength domain:
846 - 870 nm



1. RVS parametrization in a nutshell

2. Why is it unique (and you maybe did not realize it) ?

1. RVS parametrization in a nutshell

2. Why is it unique ?

Physics:

RVS spectroscopy adds to Gaia's astrometric classical approach, a physical approach of modern astrophysics

Diversity:

Medium resolution spectroscopy coupled to high nb statistics increases dimensionality of parameter space to unprecedented levels

Precision (spectral fidelity + homogeneous treatment):

RVS allows a stellar parametrization of quality comparable to ground-based data of higher resolution/spectral coverage:
ex. high precision params., heavy elements, thin/thick disc chemical separation power, ...

1. RVS parametrization in a nutshell

2. Why is it unique ?

Physics:

RVS spectroscopy adds to Gaia's astrometric classical approach, a physical approach of modern astrophysics

Diversity:

Medium resolution spectroscopy coupled to high nb statistics increases dimensionality of parameter space to unprecedented levels

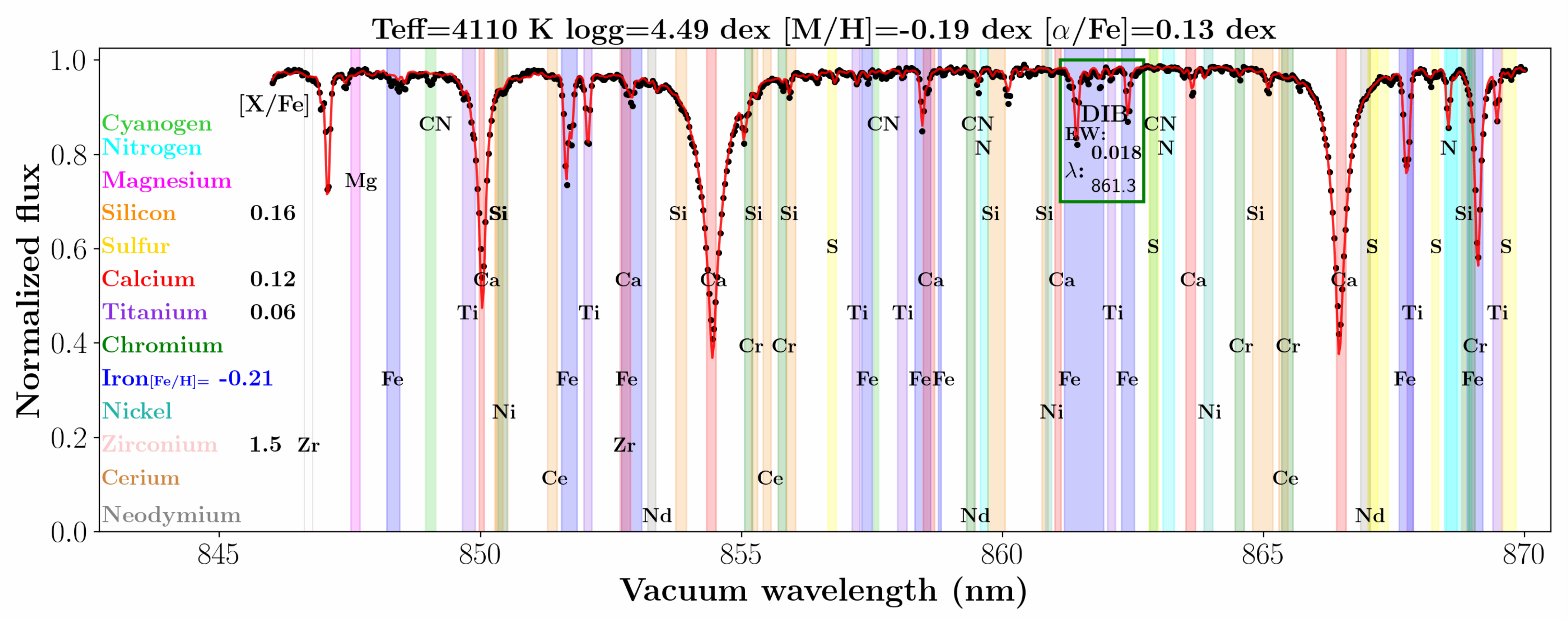
Precision (spectral fidelity + homogeneous treatment):

RVS allows a stellar parametrization of quality comparable to ground-based data of higher resolution/spectral coverage:

ex. high precision params., heavy elements, thin/thick disc chemical separation power, ...

Gaia/RVS: a space spectroscopic survey

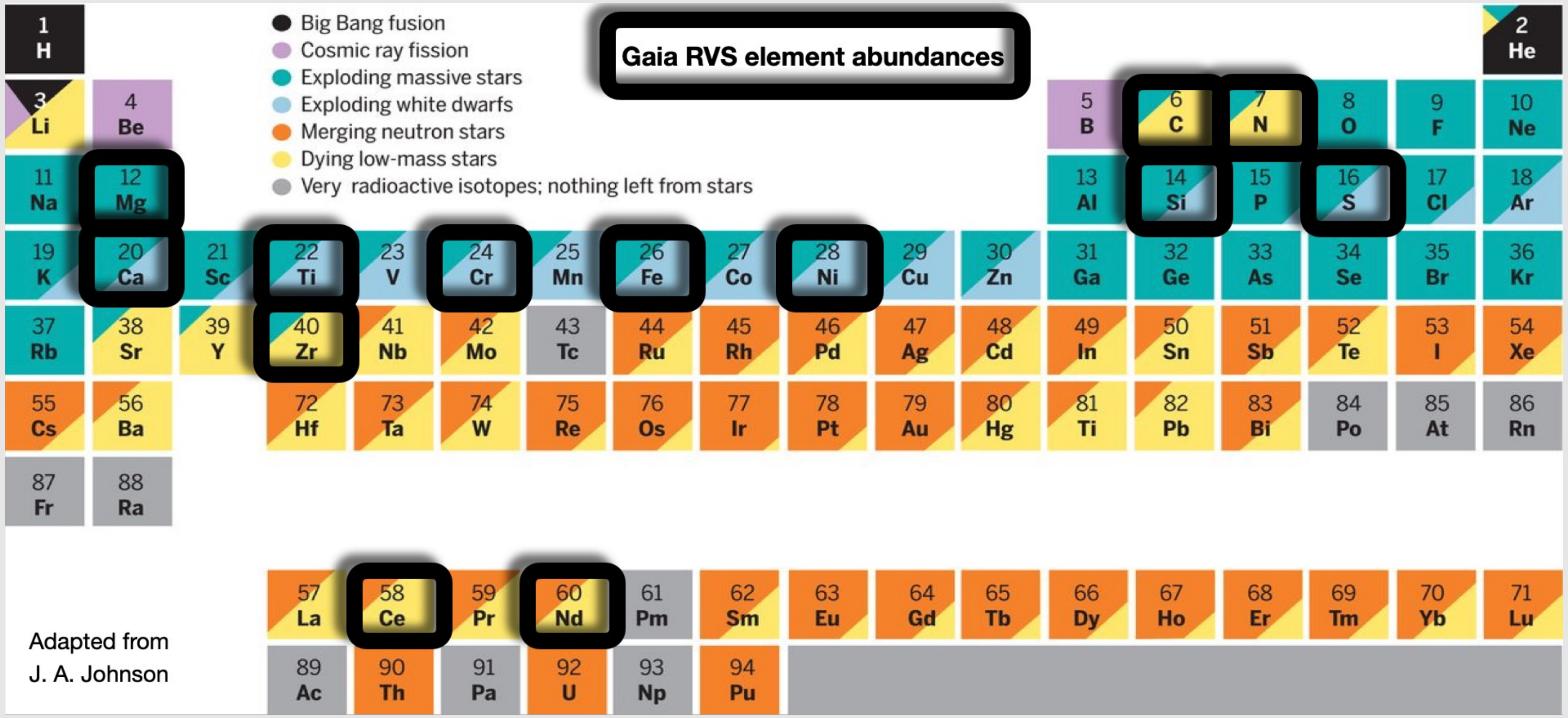
CU8/GSPspec: The chemical composition of 5.6 million stars



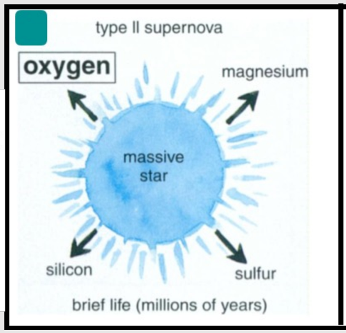
Credits:ESA/GAIA/DPAC-CU8-CU6 Recio-Blanco and the GSPspec team

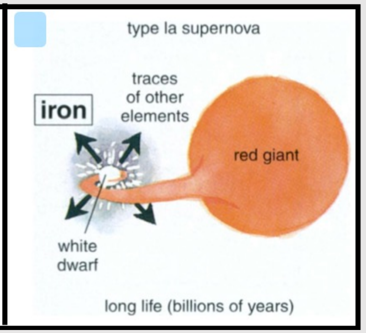
Galactic alchemists

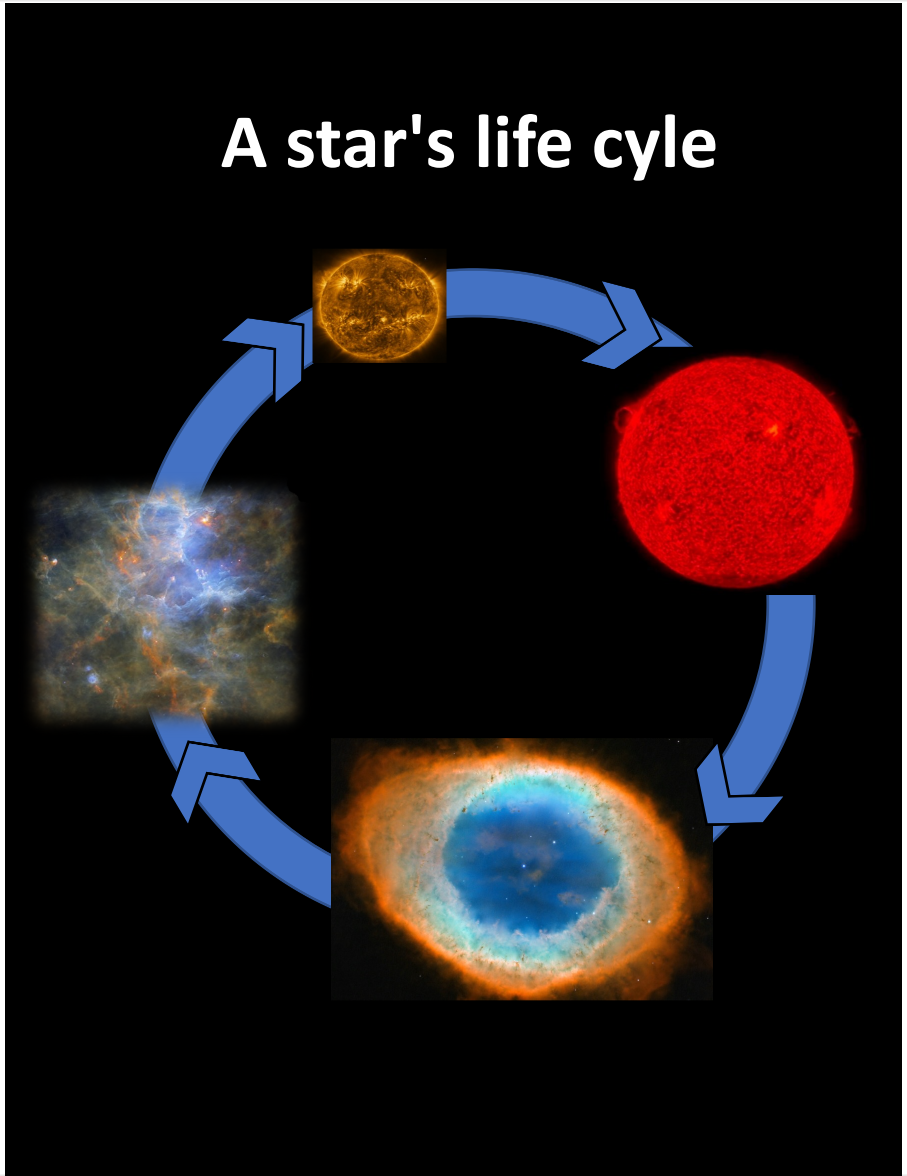
Different nucleosynthetic channels



credits C. Chiappini

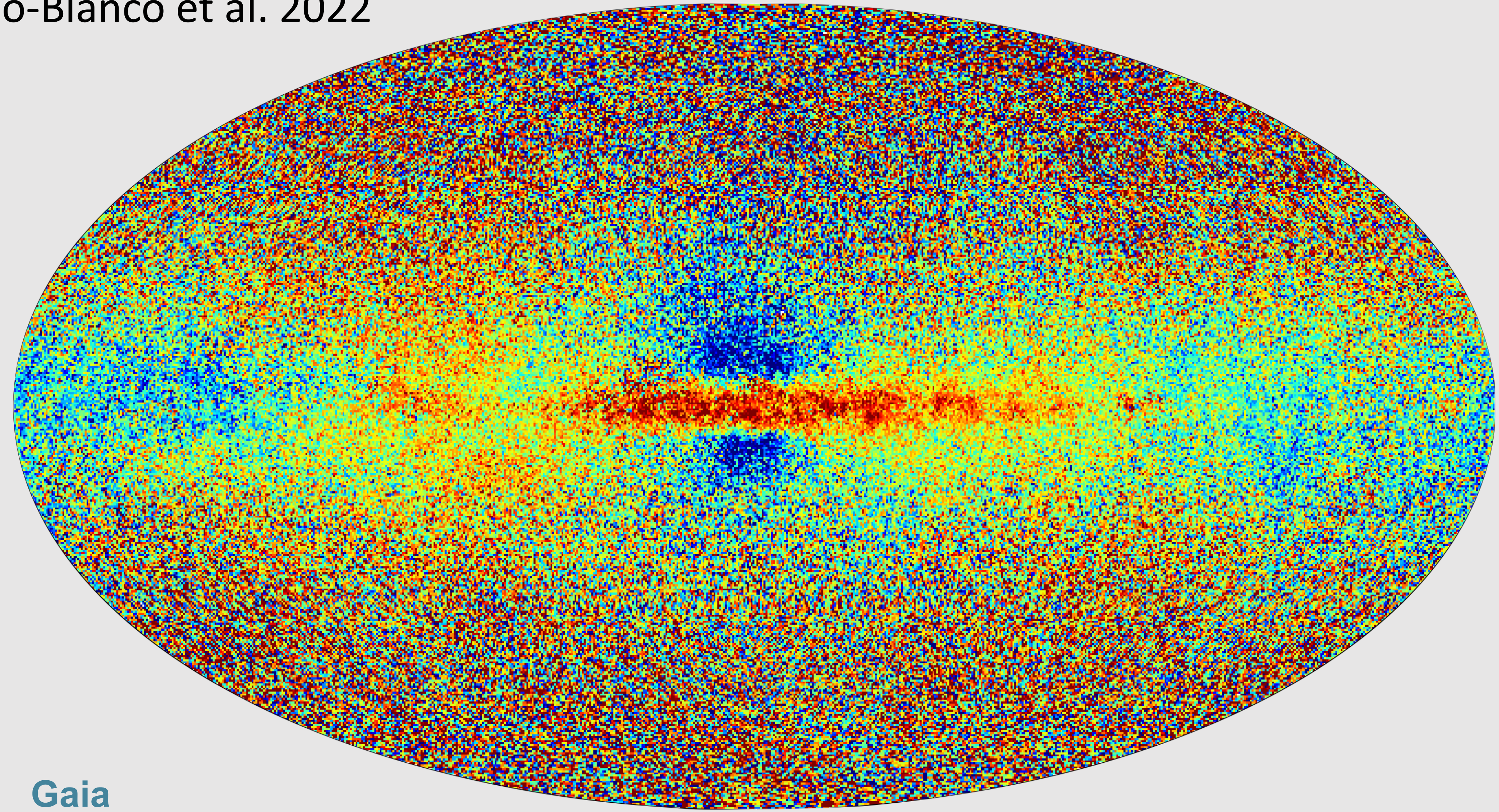






Gaia DR3: 5.6 milion stars with chemo-physical parameters

Recio-Blanco et al. 2022



Gaia Collaboration, Recio-Blanco et al. 2022

Related Gaia DR3 Papers

Gaia DPAC

Astronomy & Astrophysics
Special issue

- Recio-Blanco et al. 2023

Gaia Data Release 3

Analysis of RVS spectra using the General Stellar Parametriser from spectroscopy

- Gaia Collaboration, Recio-Blanco et al. 2023

Gaia Data Release 3

Chemical cartography of the Milky Way

- Vallenari et al. 2023; Creevey et al. 2023; Fouesneau et al 2023
- Katz et al. 2023; Seabroke et al. 2023

Related Gaia DR3 Papers

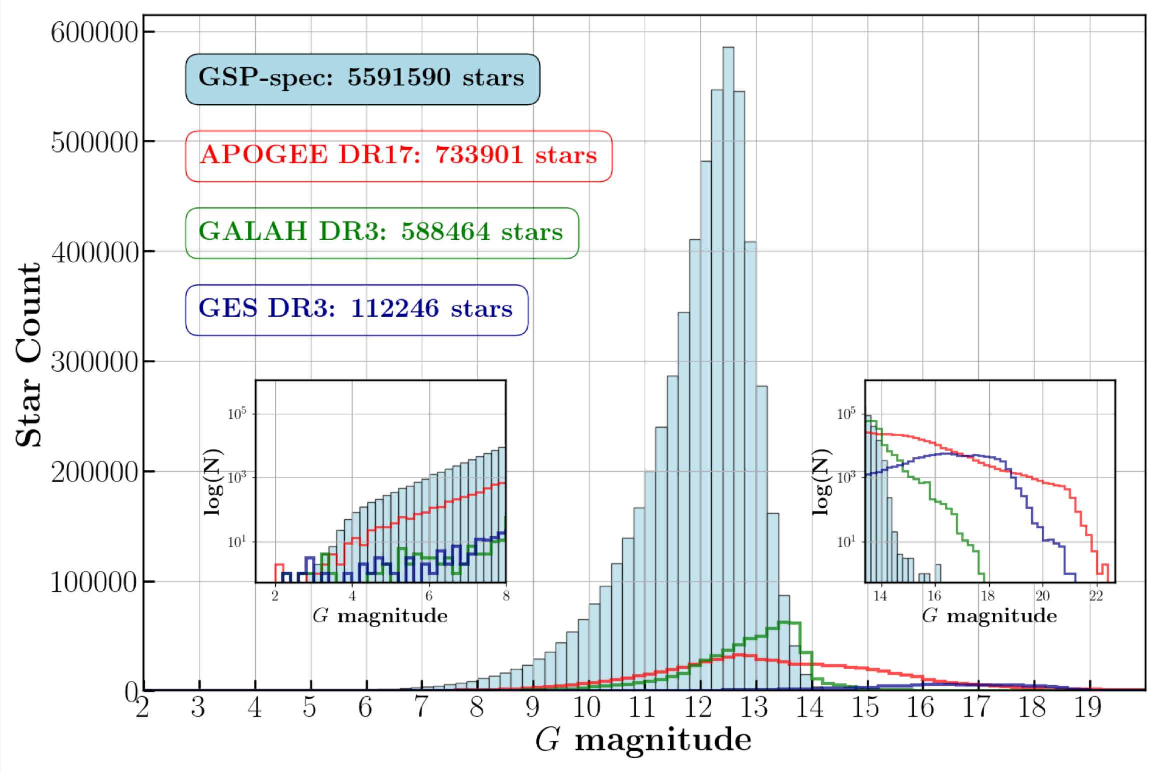
Gaia DPAC

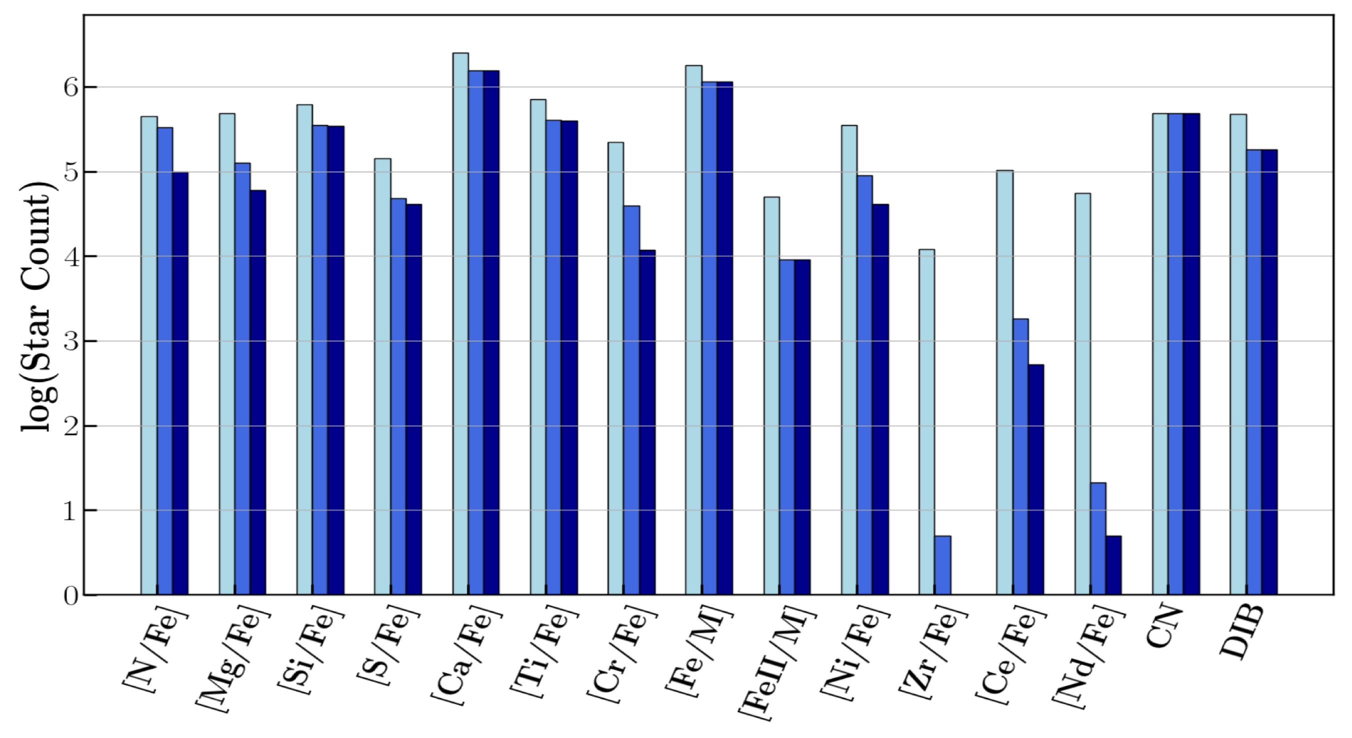
Astronomy & Astrophysics
Special issue

- **Recio-Blanco et al. 2023**

Gaia Data Release 3

Analysis of RVS spectra using the General Stellar Parametriser from spectroscopy





• Recio-Blanco et al. 2023

Quality flags and offset corrections (c.f tables 2-4)

Chain character number - name	Considered quality aspect	Possible adopted values	Related subsection and table
1 vbroadT	vbroad induced bias in T_{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_{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

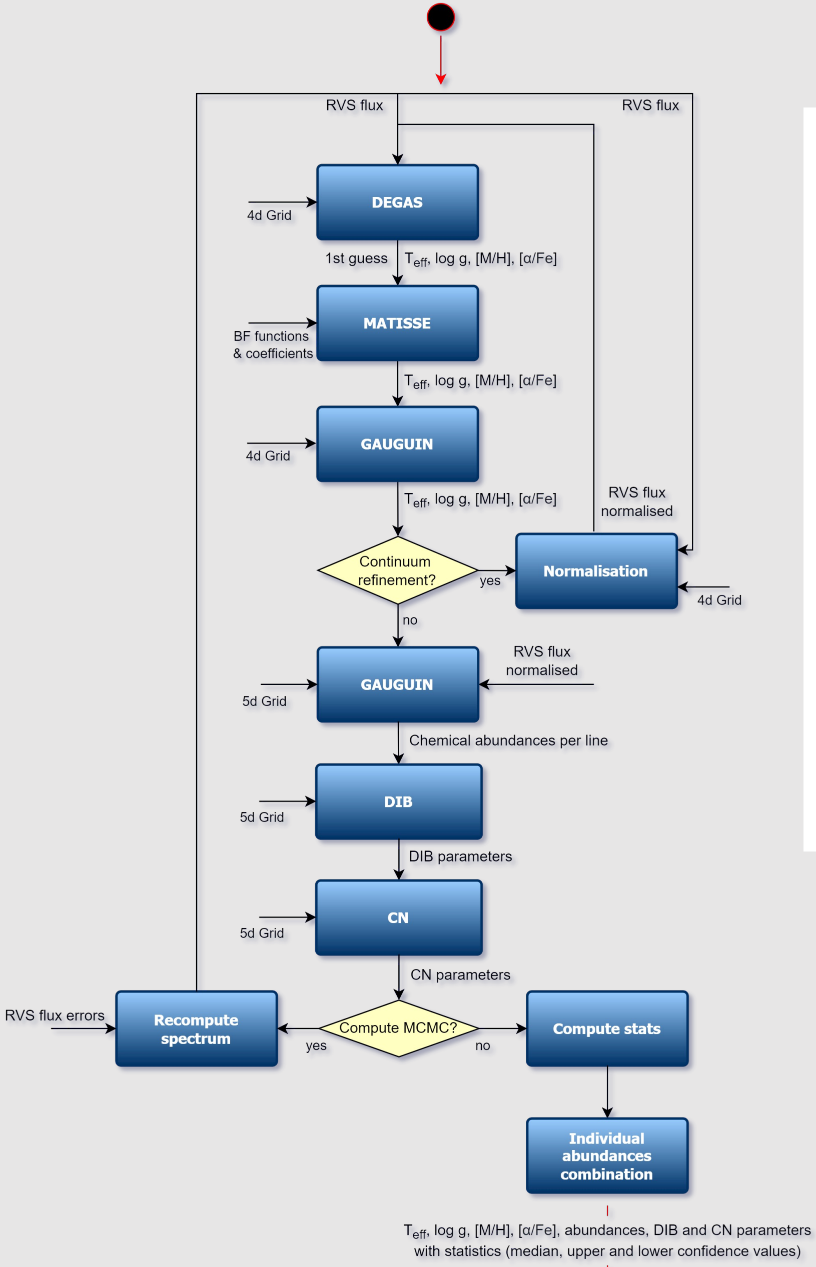
To be used and adapted to your scientific goal

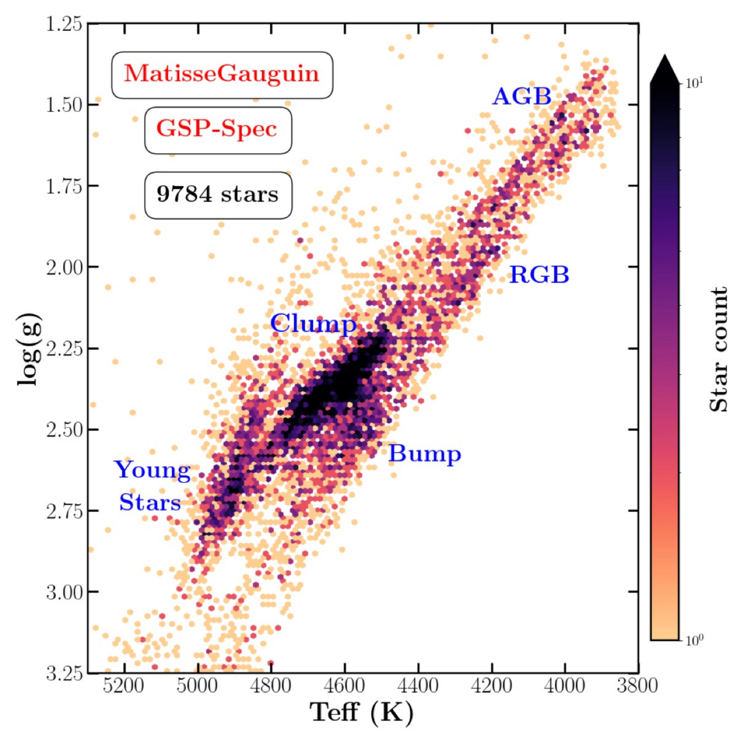
Parameter	p_0	p_1	p_2	p_3	p_4
log(g)	0.4496	-0.0036	-0.0224		
[M/H]	0.274	-0.1373	-0.0050	0.0048	
$[M/H]_{OC}$	-0.7541	1.8108	-1.1779	0.2809	-0.0222

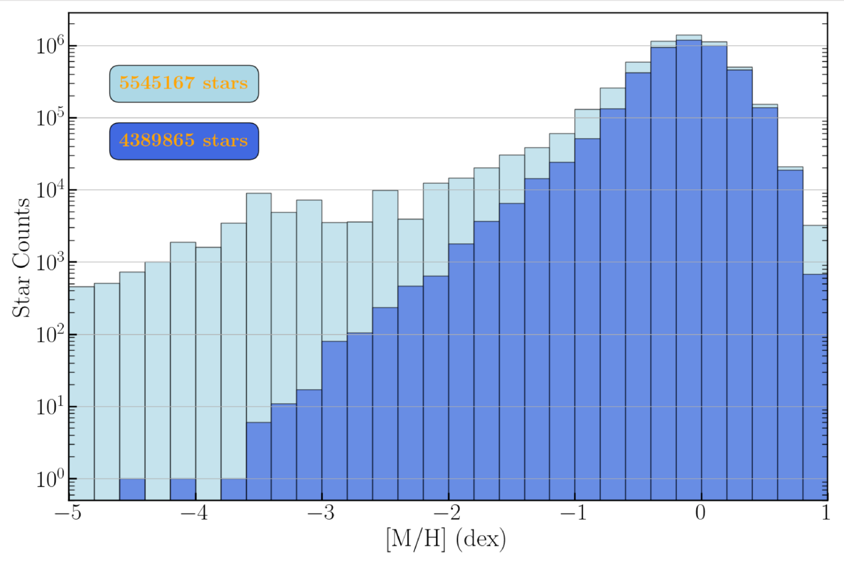
Element	p_0	p_1	p_2	p_3	p_4	Recommended interval		*extrapol* flag
	As a function of log(g)					Min log(g)	Max log(g)	
[α/Fe]	-0.5809	0.7018	-0.2402	0.0239	0.0000	1.01	4.85	0
[Ca/Fe]	-0.6250	0.7558	-0.2581	0.0256	0.0000	1.01	4.85	0
[Mg/Fe]	-0.7244	0.3779	-0.0421	-0.0038	0.0000	1.30	4.38	0
[S/Fe]	-17.6080	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 $t = T_{\text{eff}}/5750$					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

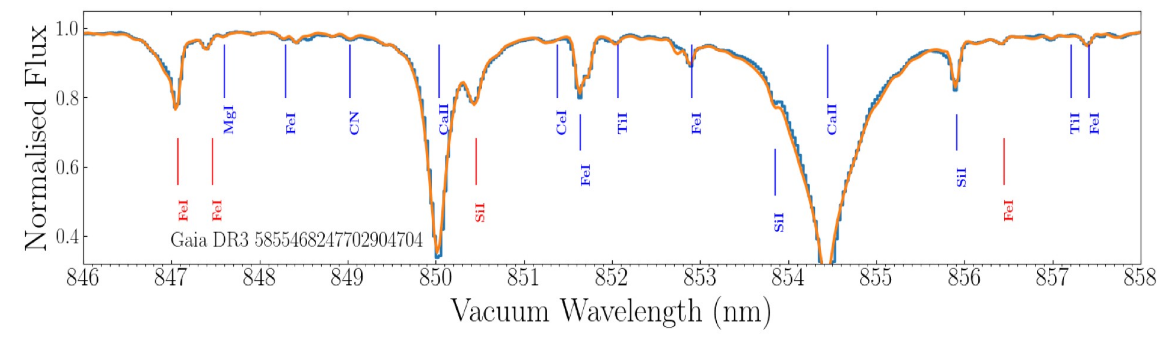
• Recio-Blanco et al. 2023

Spectral analysis methodology, tips and examples of usage









Related Gaia DR3 Papers

Gaia DPAC

Astronomy & Astrophysics
Special issue

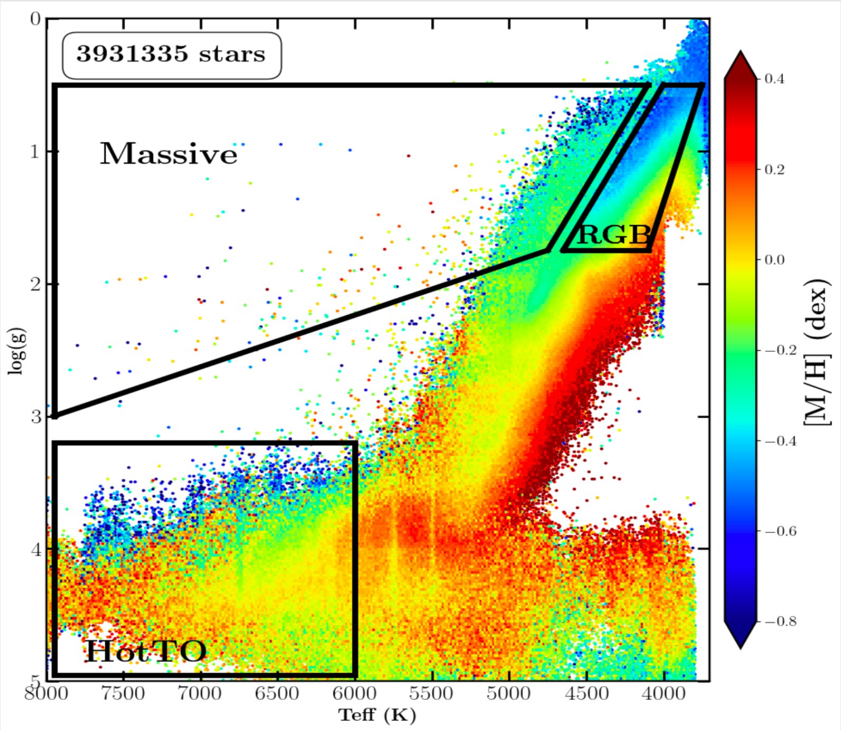
- Gaia Collaboration, Recio-Blanco et al. 2023

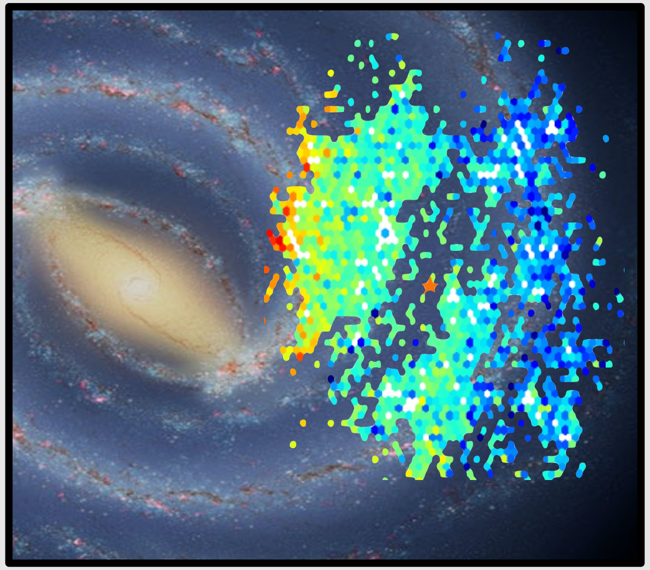
Gaia Data Release 3

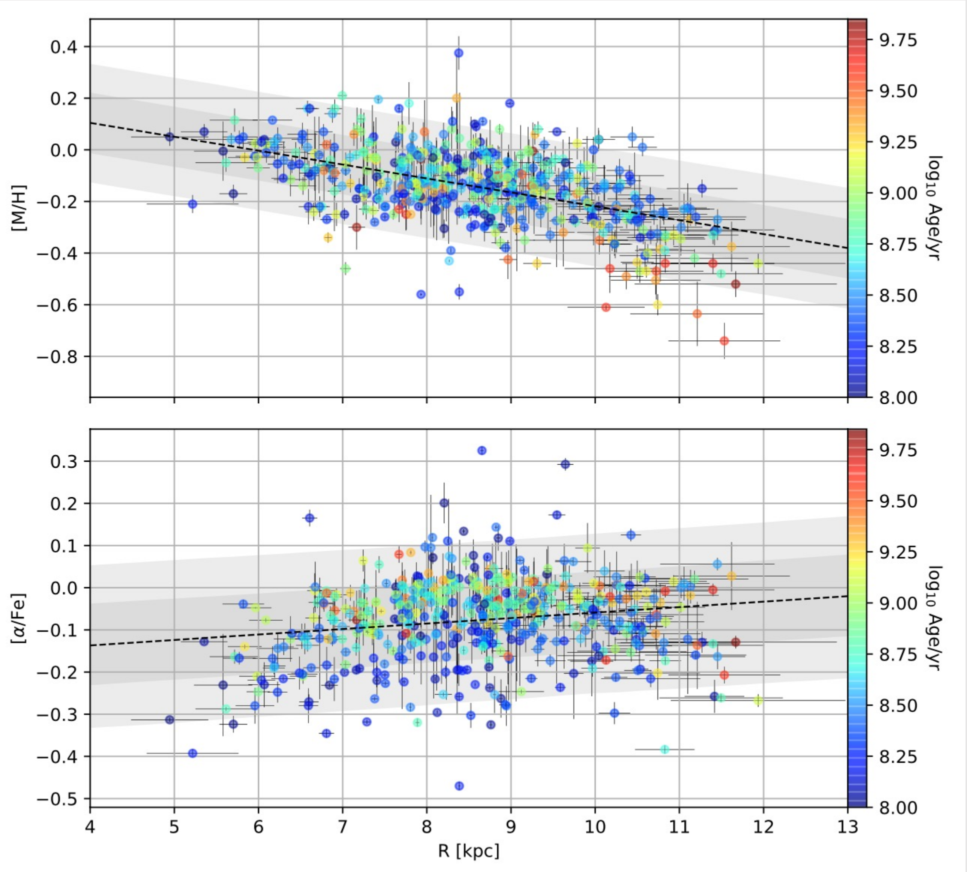
Chemical cartography of the Milky Way

Performance verification on Galactic physics

Selection function illustration

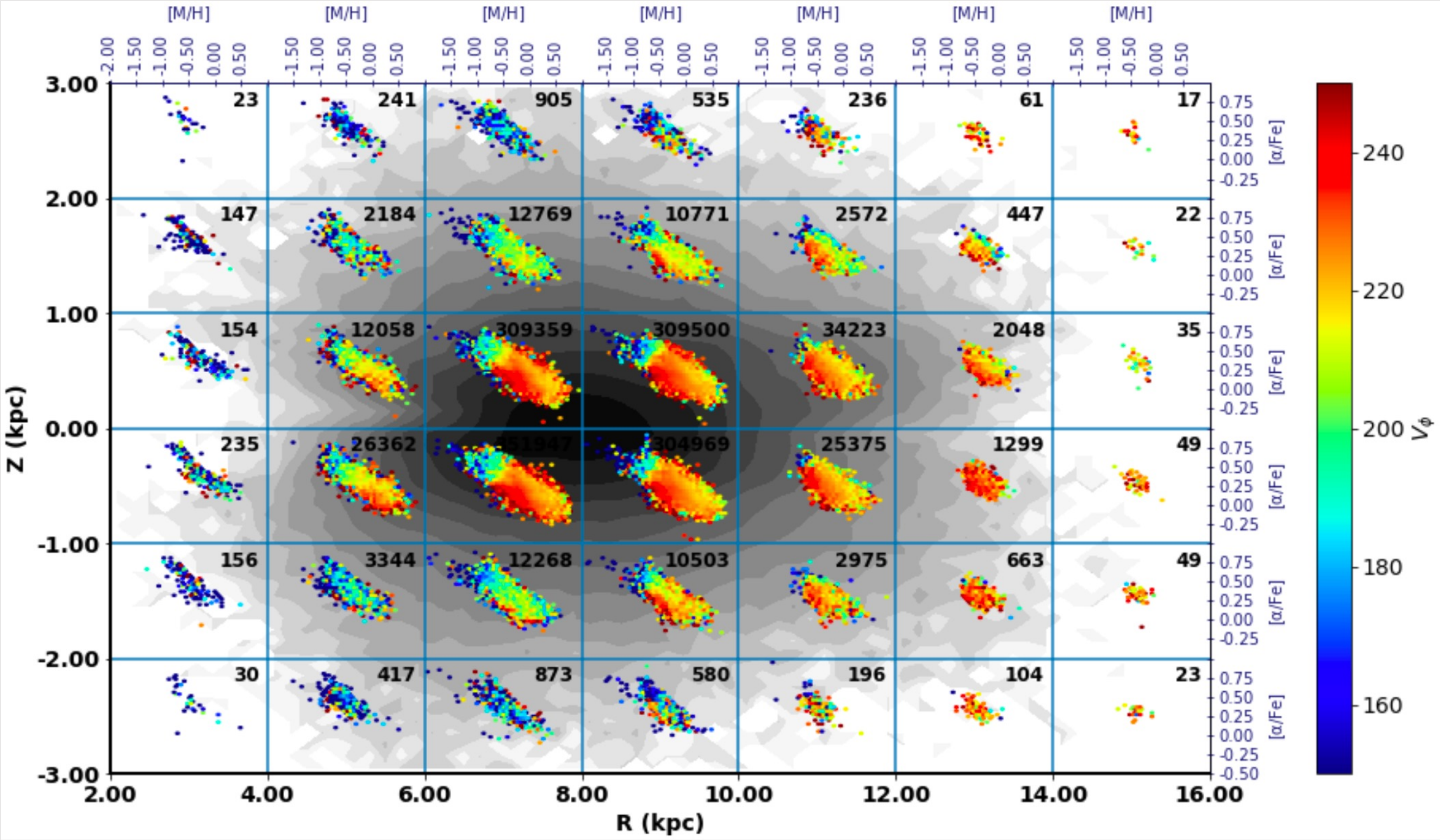






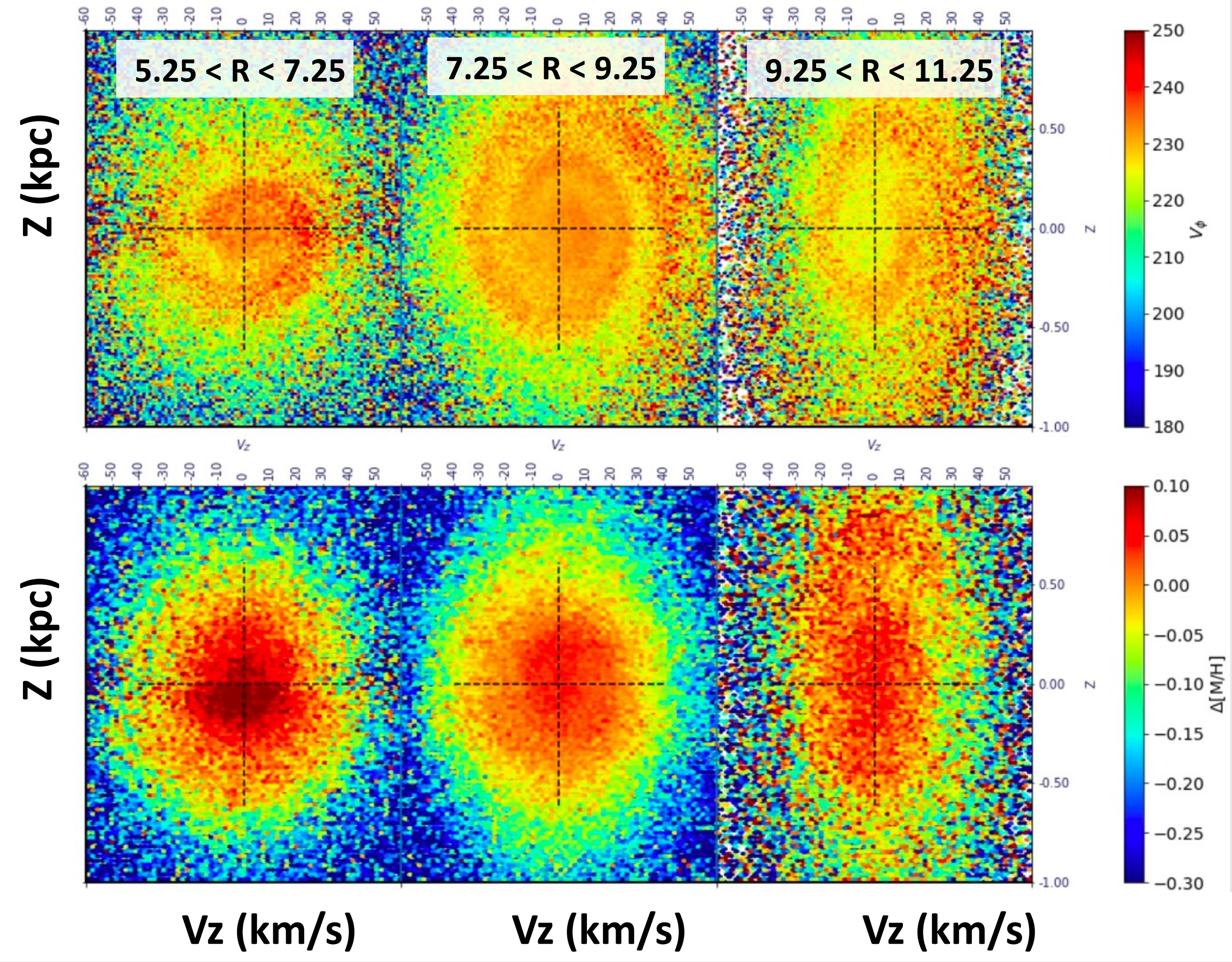
Galactic disc: structure and chemical gradients

Vertical and radial cartography of [alpha/Fe] vs. [M/H] colour coded with Galactic azimuthal velocity



Thin disc stars are found at 3 kpc from the plane in the outer regions !

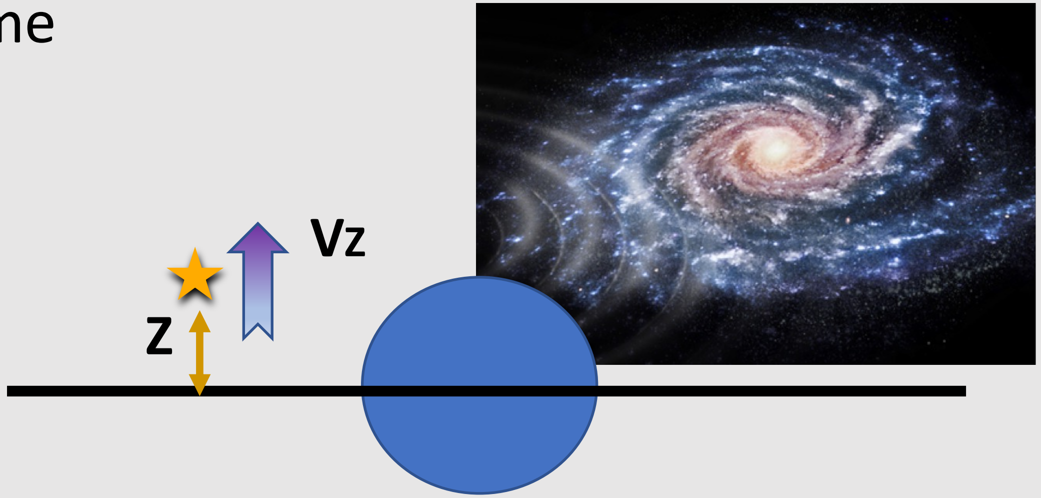
Chemical markers of disc perturbations:
kinematics and phase spiral as a function of R



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

Wave-like perturbation (Antoja et al. 2018):
- disc-crossing satellite (Binney & Schoenrich 2018, Bland-Hawthorn et al. 2019)
- bar's buckling (Koperskov et al. 2019)

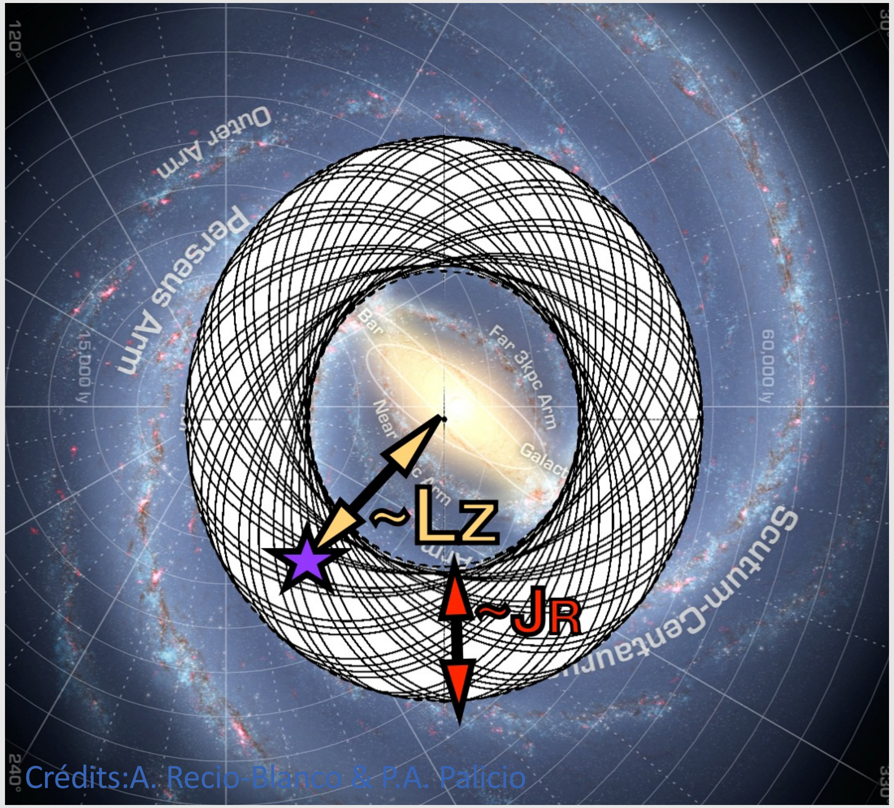
Correlation of thin disc phase spiral **with metallicity excess** detected for the first time

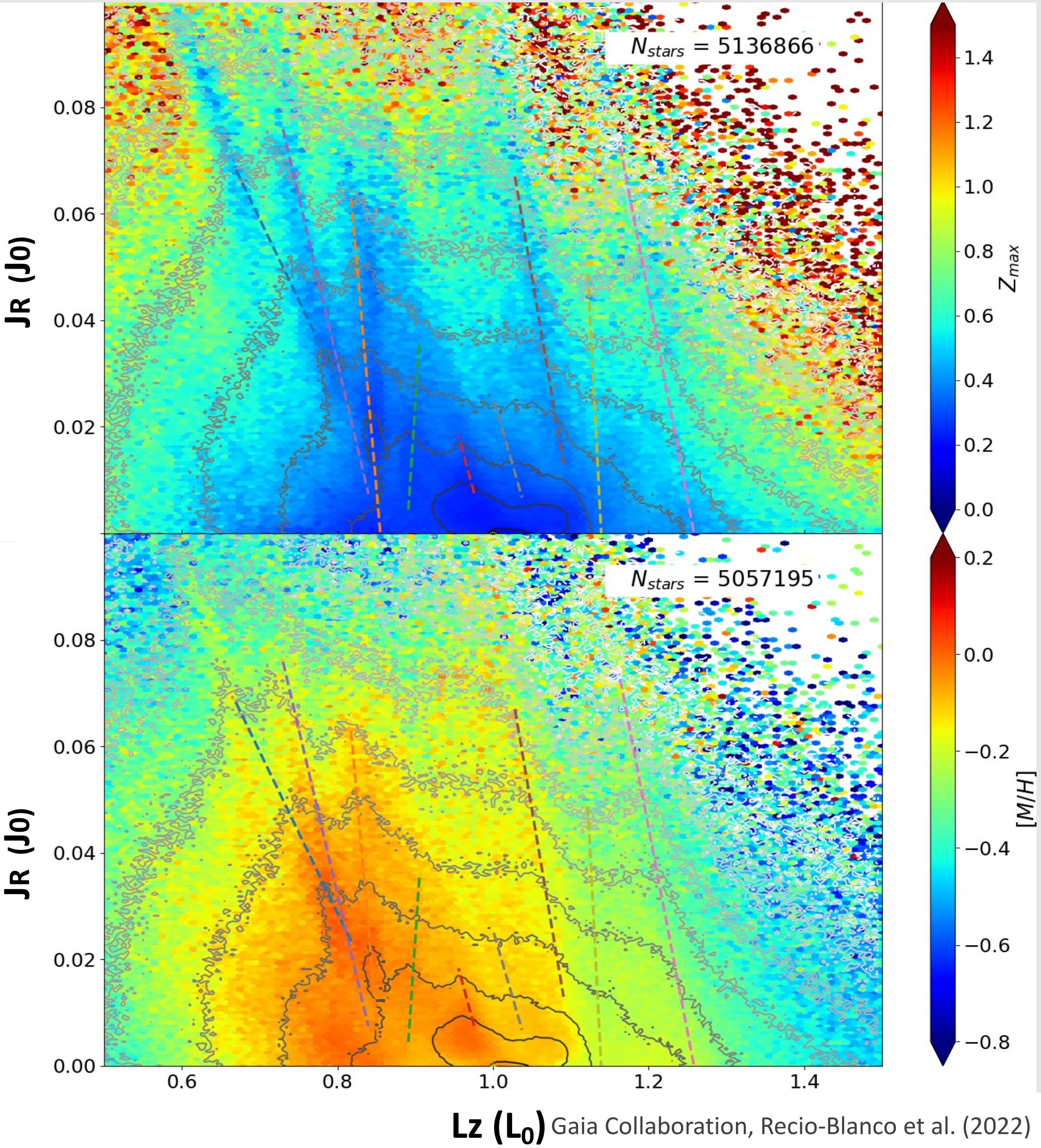


Chemical markers of disc perturbations:
orbital space

Ridges of higher stellar density:

- orbits closer to the plane
- metallicities higher than surrounding median values.

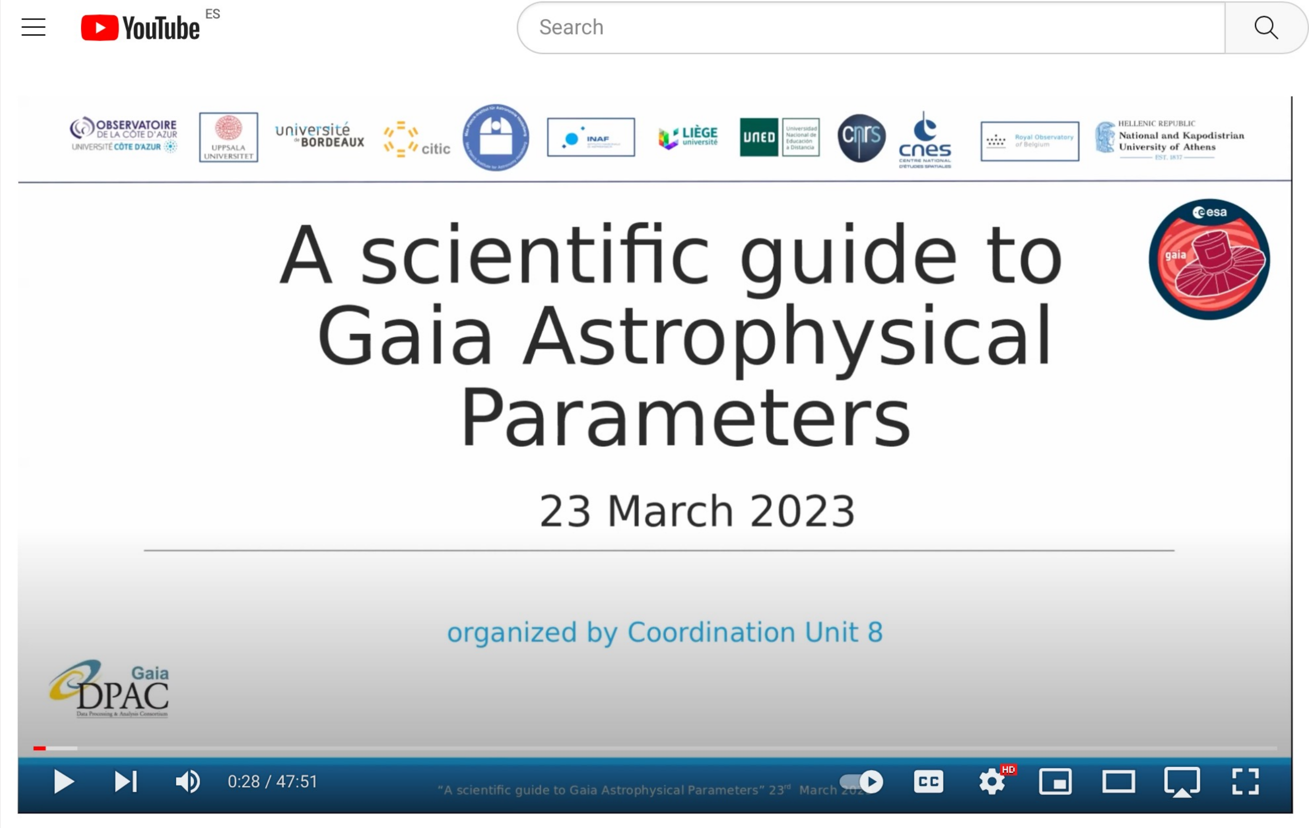




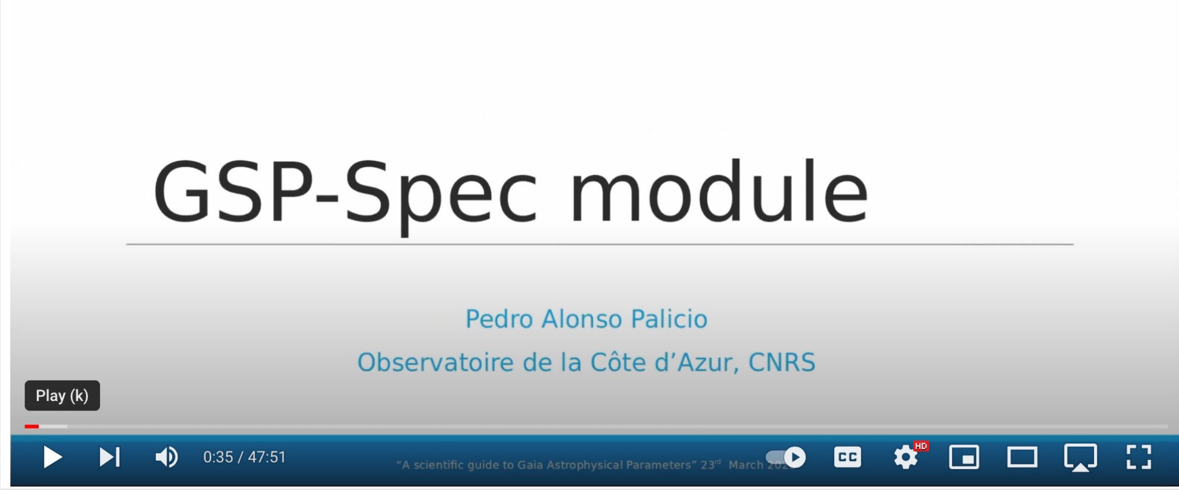
Gaia Collaboration, Recio-Blanco et al. (2022)

Documentation and webinars

- **Gaia DR3 documentation,** chapter 11 Astrophysical Parameters, Ulla et al. (2022)
- **Gaia Coordination Unit 8, webinars:** GSPspec by Pedro A. Palicio



GSPSpec by P. A. Palicio



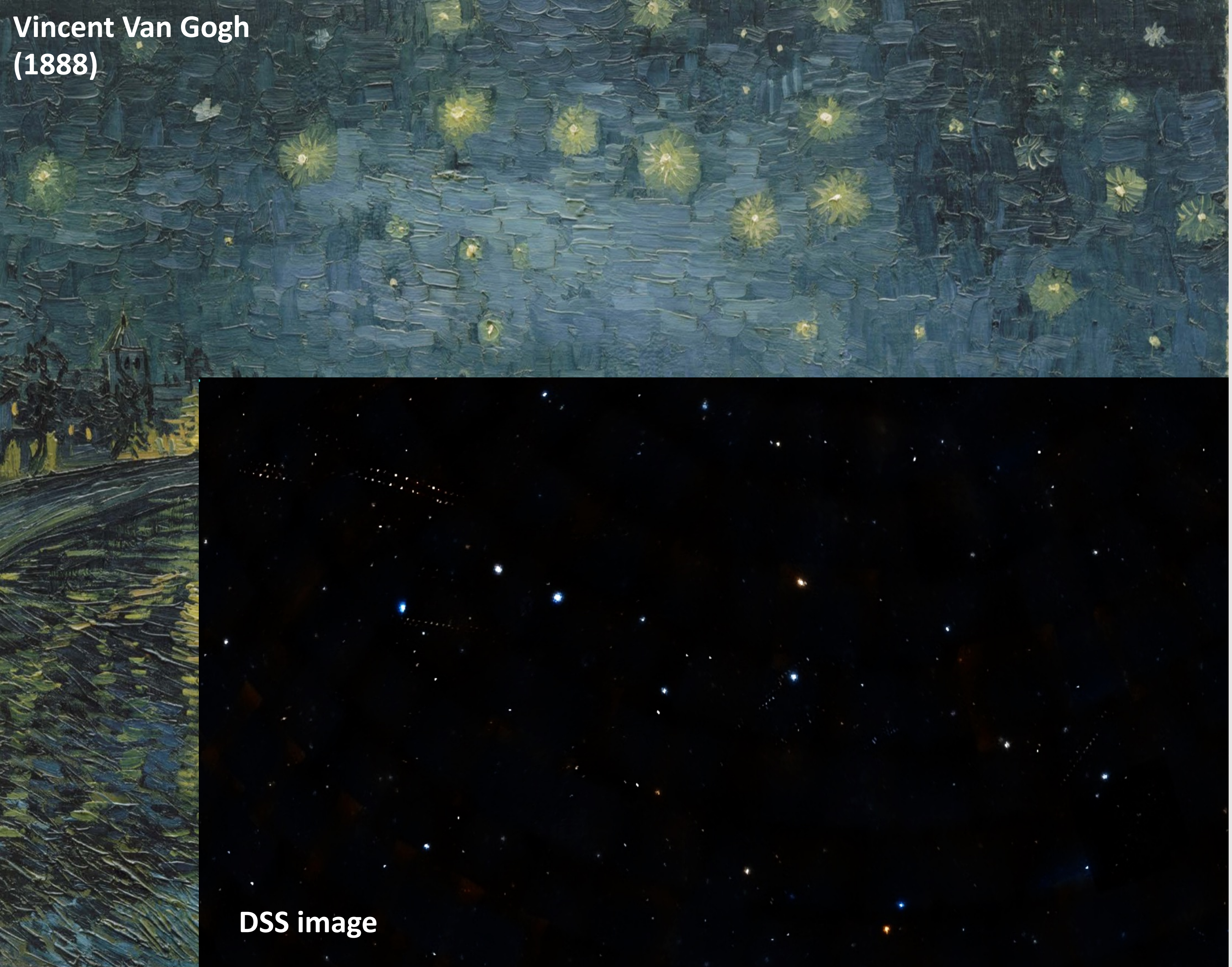
1. RVS parametrization in a nutshell

2. Why is it unique ?

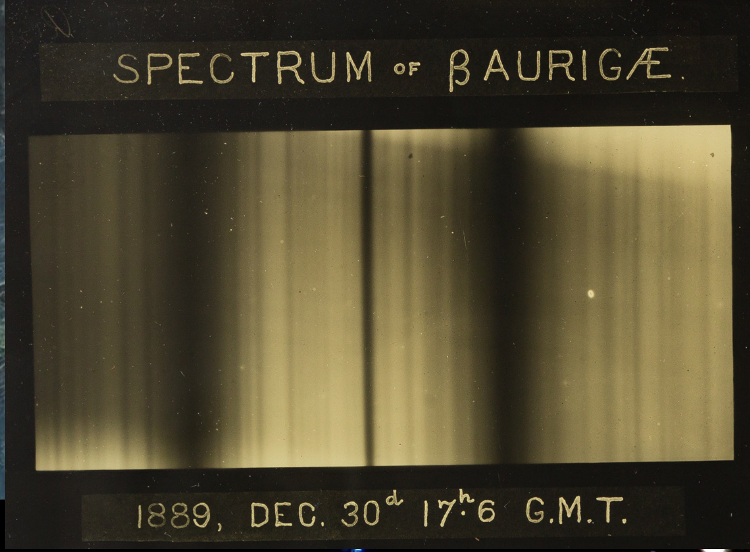
Physics:

RVS spectroscopy adds to Gaia's astrometric classical approach, a physical approach of modern astrophysics

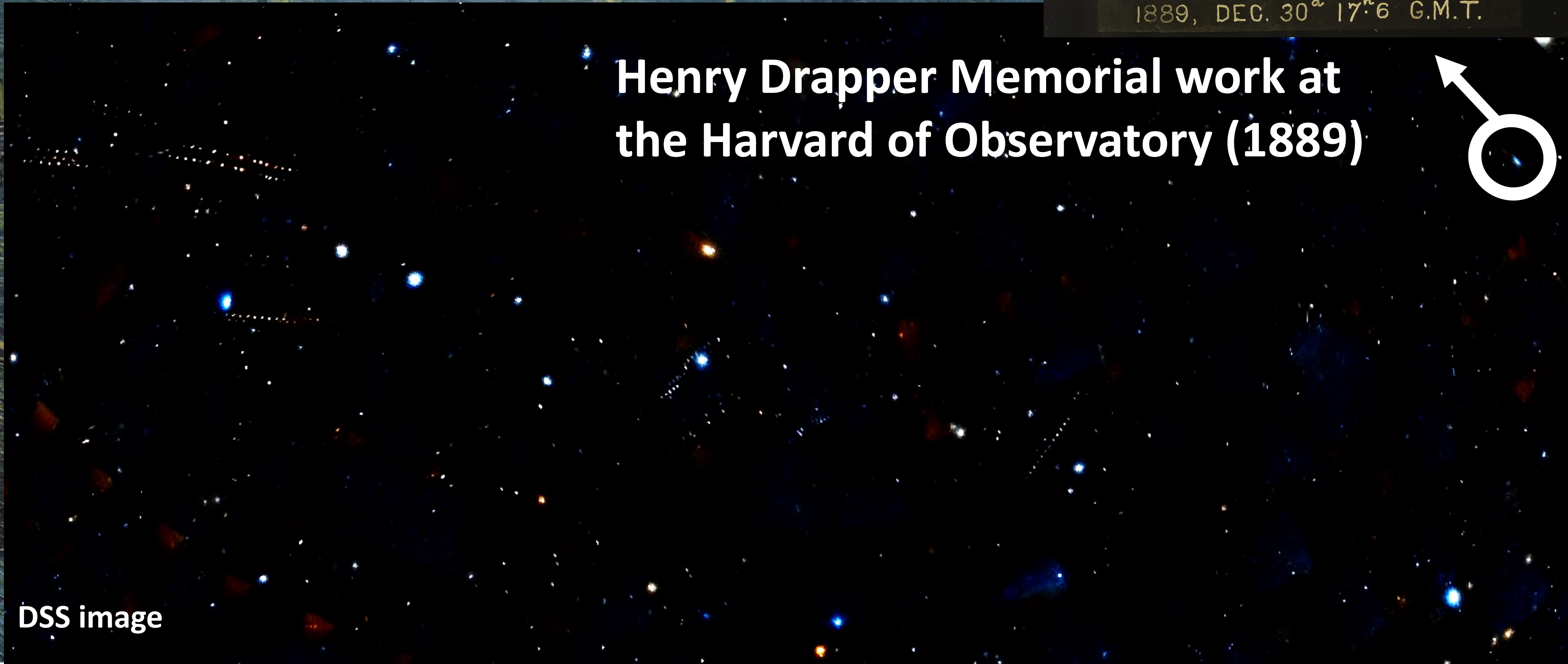

Vincent Van Gogh
(1888)


Vincent Van Gogh
(1888)
DSS image


Vincent Van Gogh
(1888)



Henry Drapper Memorial work at the Harvard of Observatory (1889)


DSS image

All sky spectroscopic survey with high number statistics

Gaia GSPspec data everywhere!

Gaia GSPspec

Teff = 3760K

log g = 0.41 cm/s^2

[M/H] = -0.66 dex

[alpha/Fe] = 0.14 dex

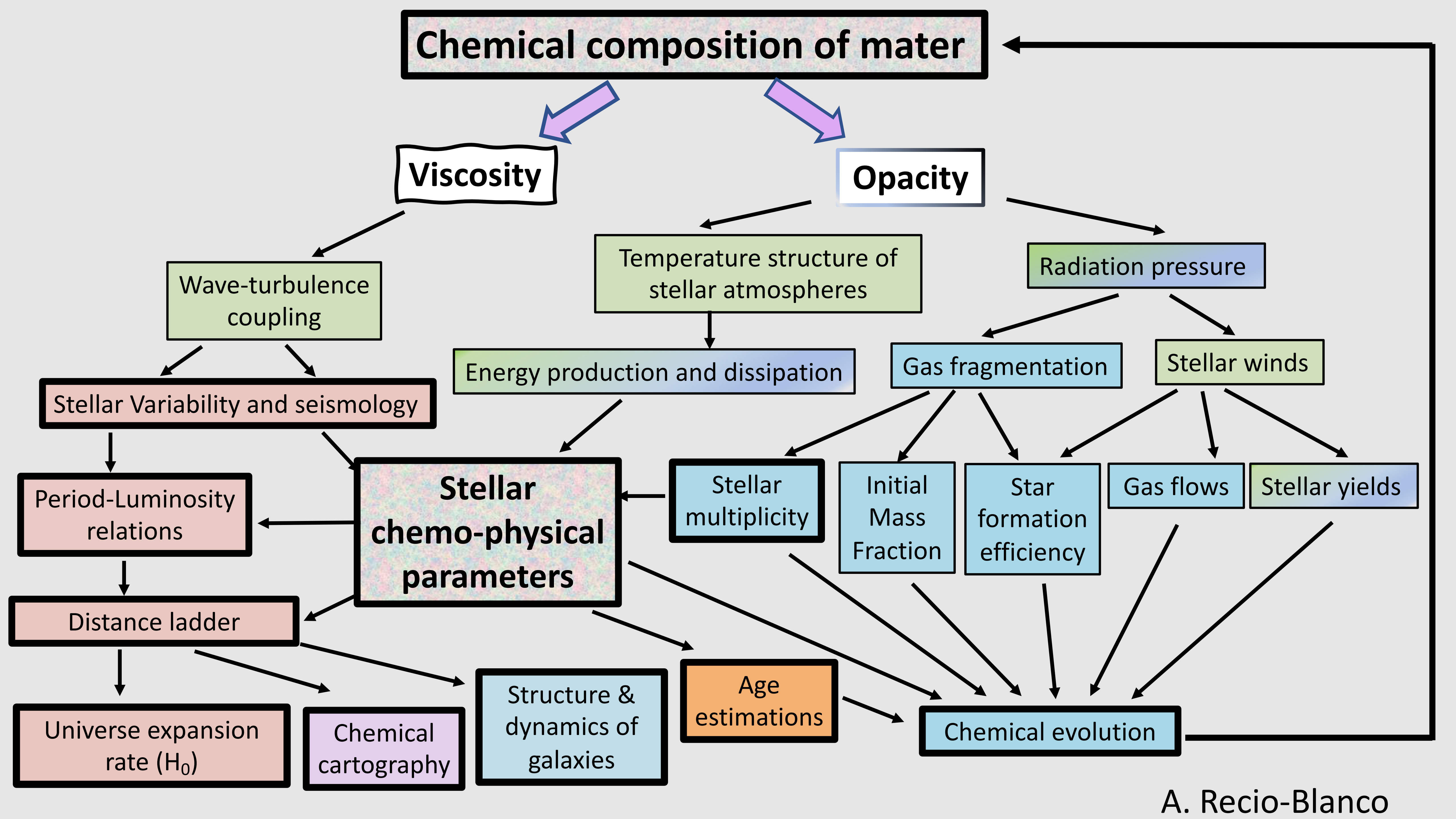
[Ca/Fe] = 0.19 dex

[Nd/Fe] = 0.59 dex

[Cr/Fe] = 0.3 dex

[Ce/Fe] = 0.34 dex

Gaia DPAC


Chemical composition of mater
Viscosity
Opacity
Wave-turbulence coupling
Temperature structure of stellar atmospheres
Radiation pressure
Energy production and dissipation
Gas fragmentation
Stellar winds
Stellar Variability and seismology
Stellar chemo-physical parameters
Stellar multiplicity
Initial Mass Fraction
Star formation efficiency
Gas flows
Stellar yields
Period-Luminosity relations
Distance ladder
Age estimations
Chemical evolution
Universe expansion rate (H_0)
Chemical cartography
Structure & dynamics of galaxies
A. Recio-Blanco

1. RVS parametrization in a nutshell

2. Why is it unique ?

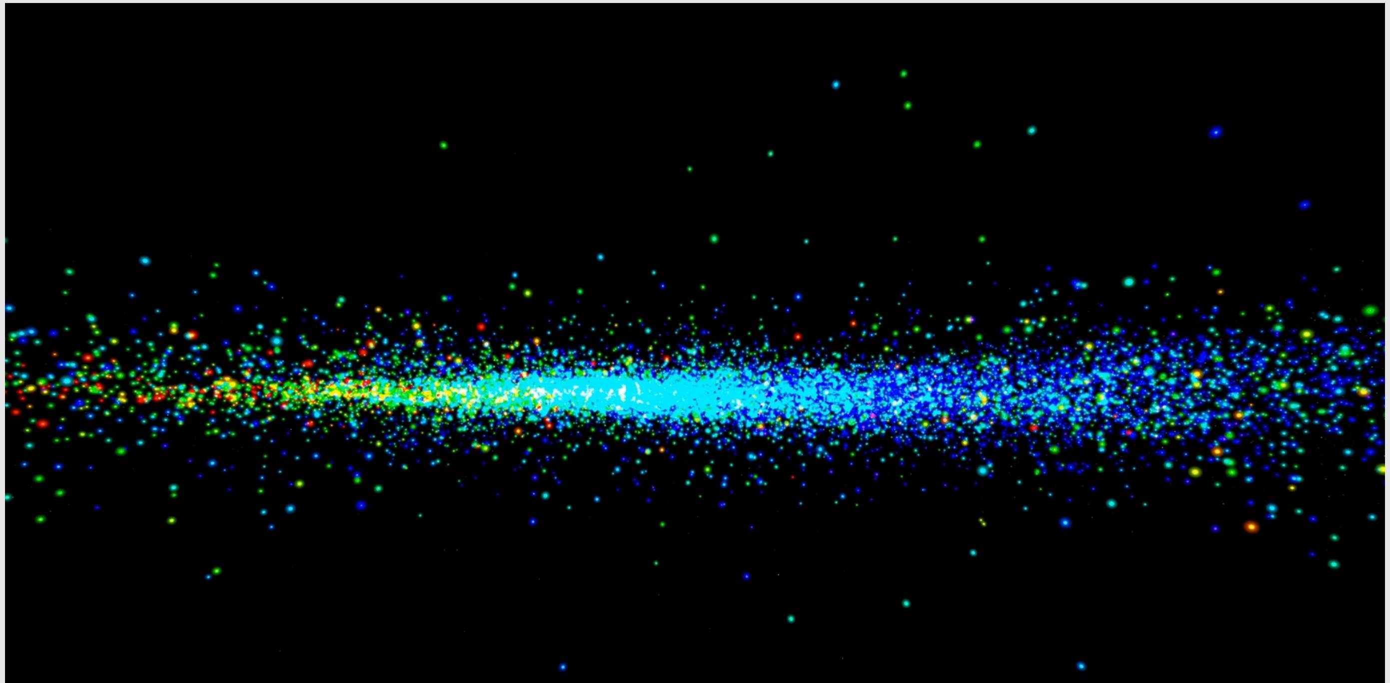
Physics

Diversity

Medium resolution spectroscopy coupled to high nb statistics increases dimensionality of parameter space to unprecedented levels

Diversity

5.6 million parametrized stars means exploring the queue of the distributions



Crédits: ESA/Gaia/DPAC, S. Jordan et al.
Gaia Collaboration, Recio-Blanco et al. (2022)

S-type, R-type, C-type stars
Blue Loop, RC, tip RGB stars
heavy-element enhanced stars
extremely metal-poor stars
accreted stars
exoplanet hosts
variables
binaries (non spectroscopic)
thin disc stars at 4 kpc from the Galactic plane
... and probably your favourite targets at G<14 mag

1. RVS parametrization in a nutshell

2. Why is it unique ?

Physics

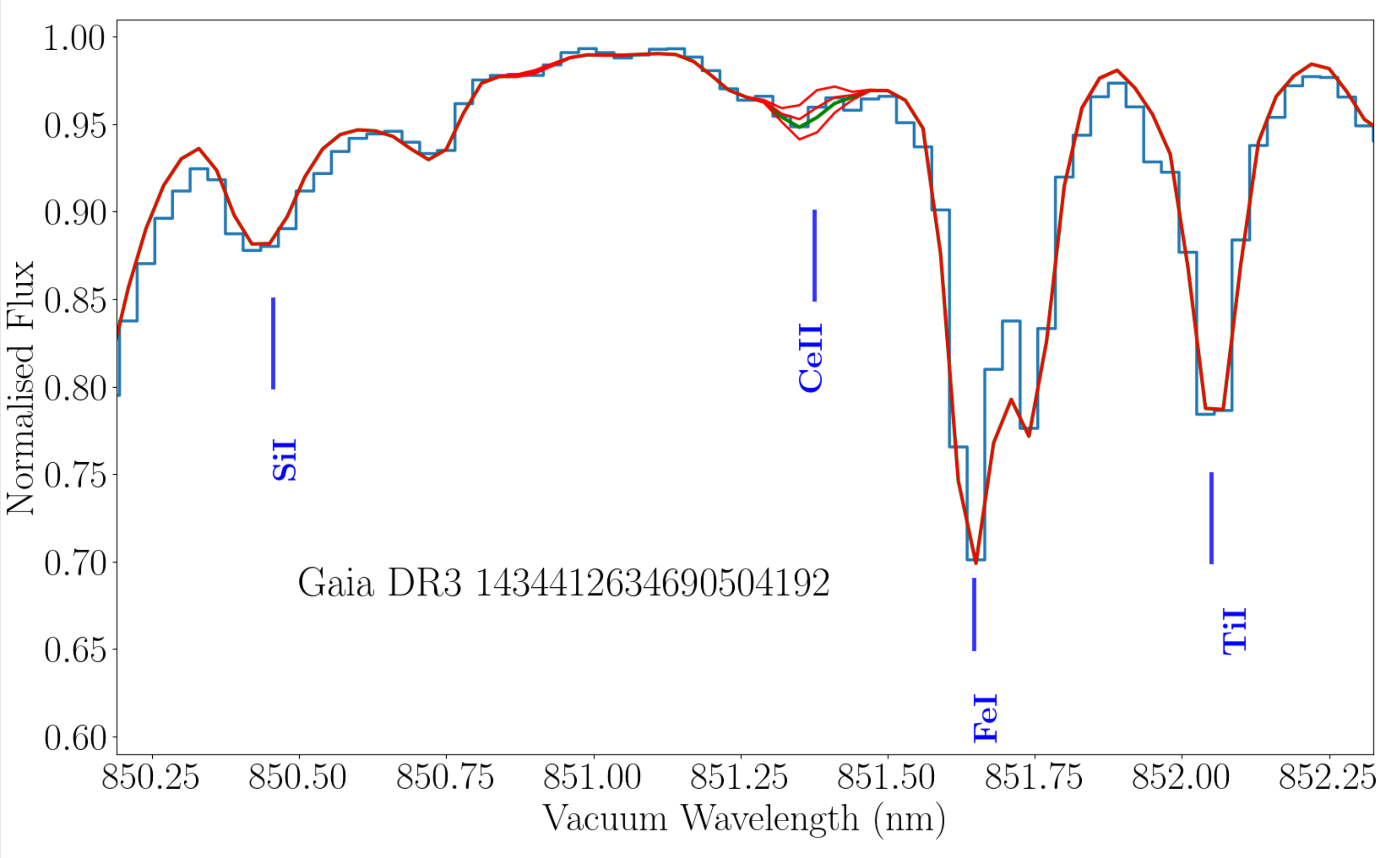
Diversity

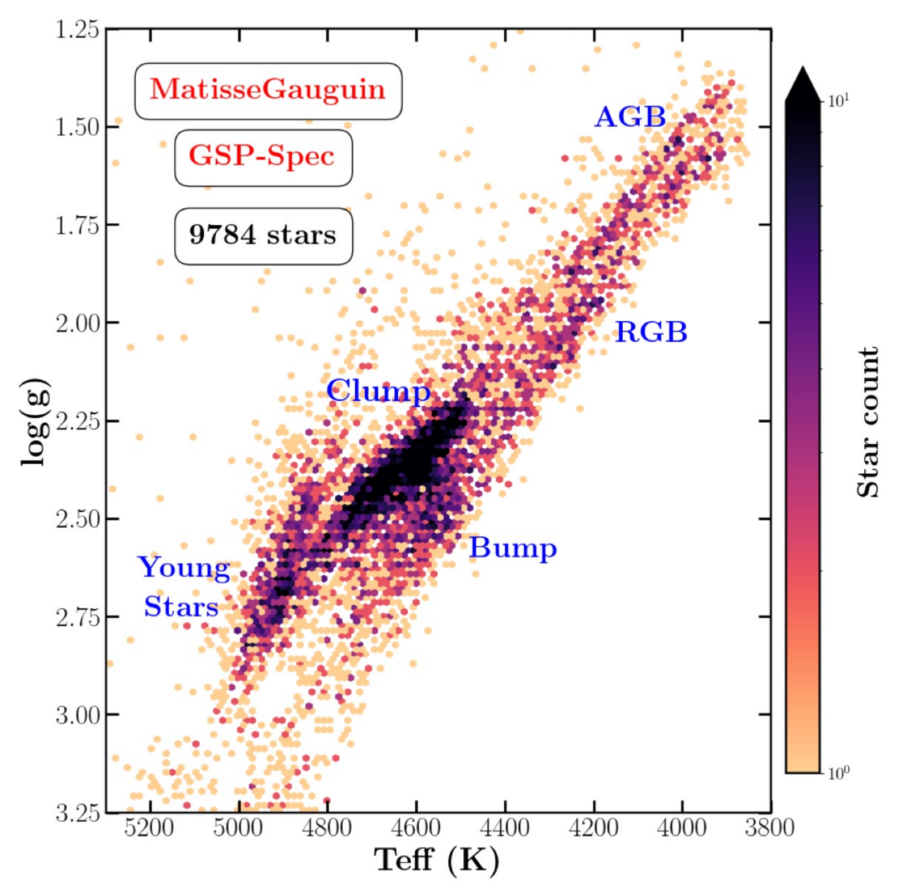
Precision (spectral fidelity + homogeneous treatment):

RVS allows a stellar parametrization of quality comparable to ground-based data of higher resolution/spectral coverage

Precision

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



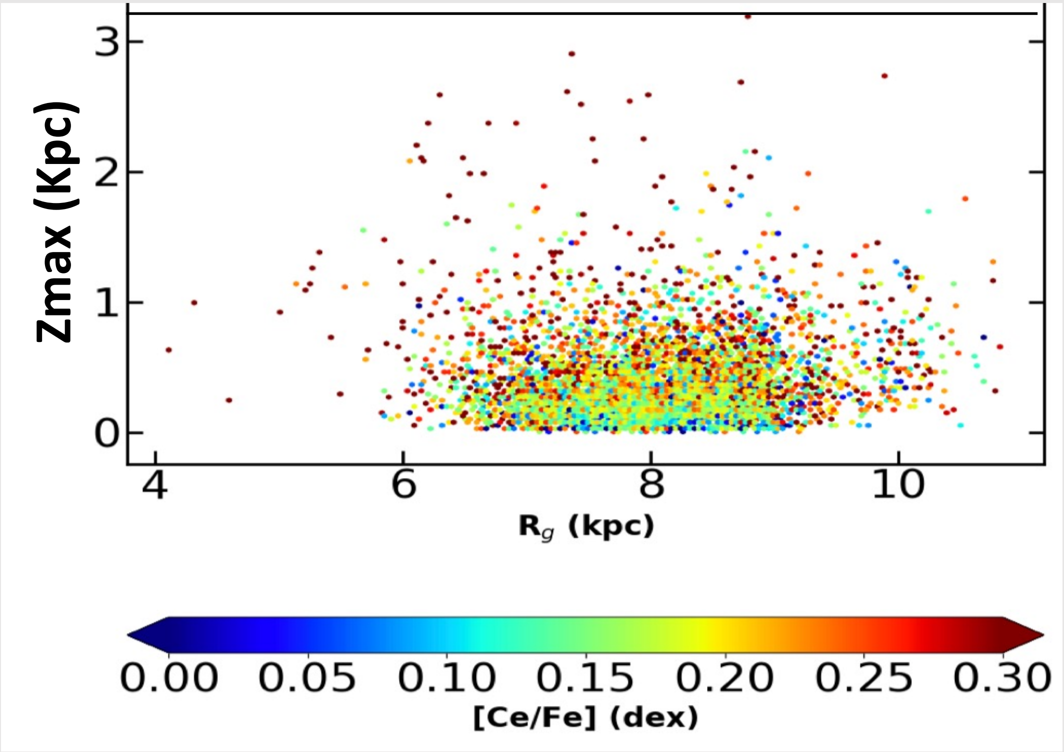


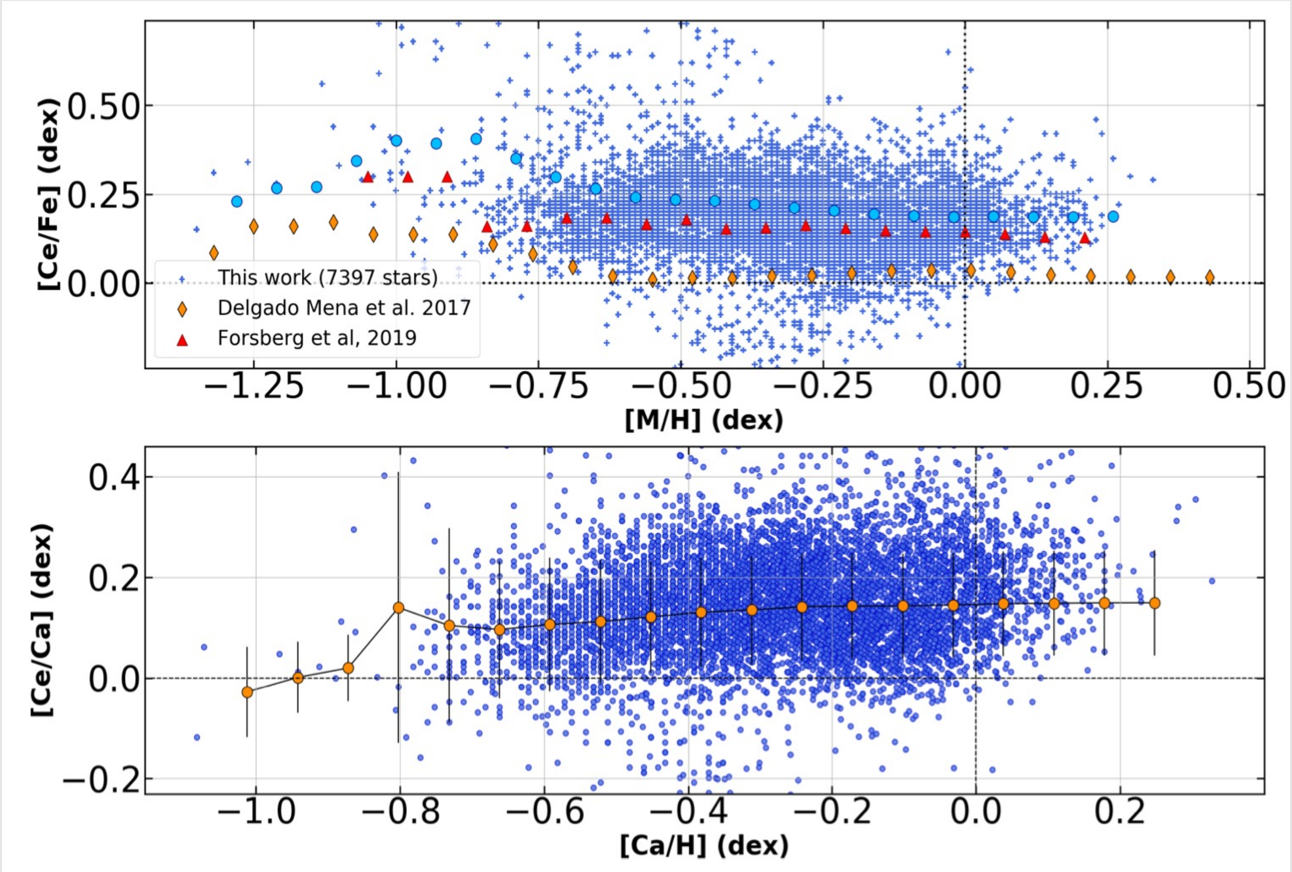
Recio-Blanco et al. 2023

Precision : Heavy element abundances

Contursi et al. (2022)

Heavy elements: Cerium





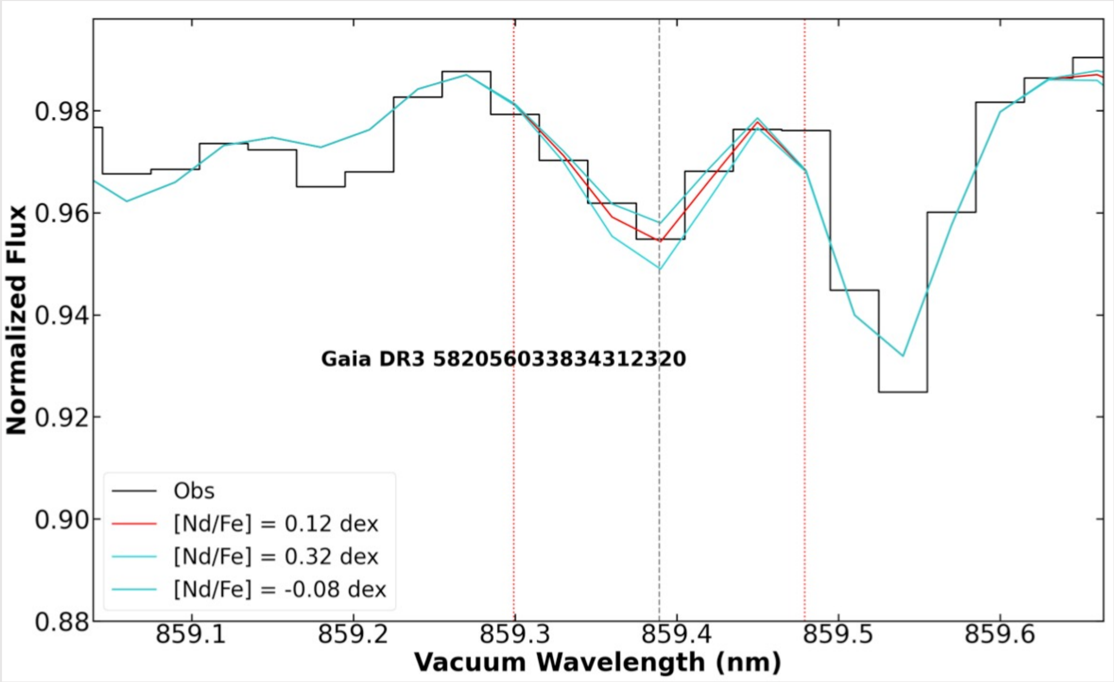
Flat [Ce/Fe] radial gradient and positive vertical gradient

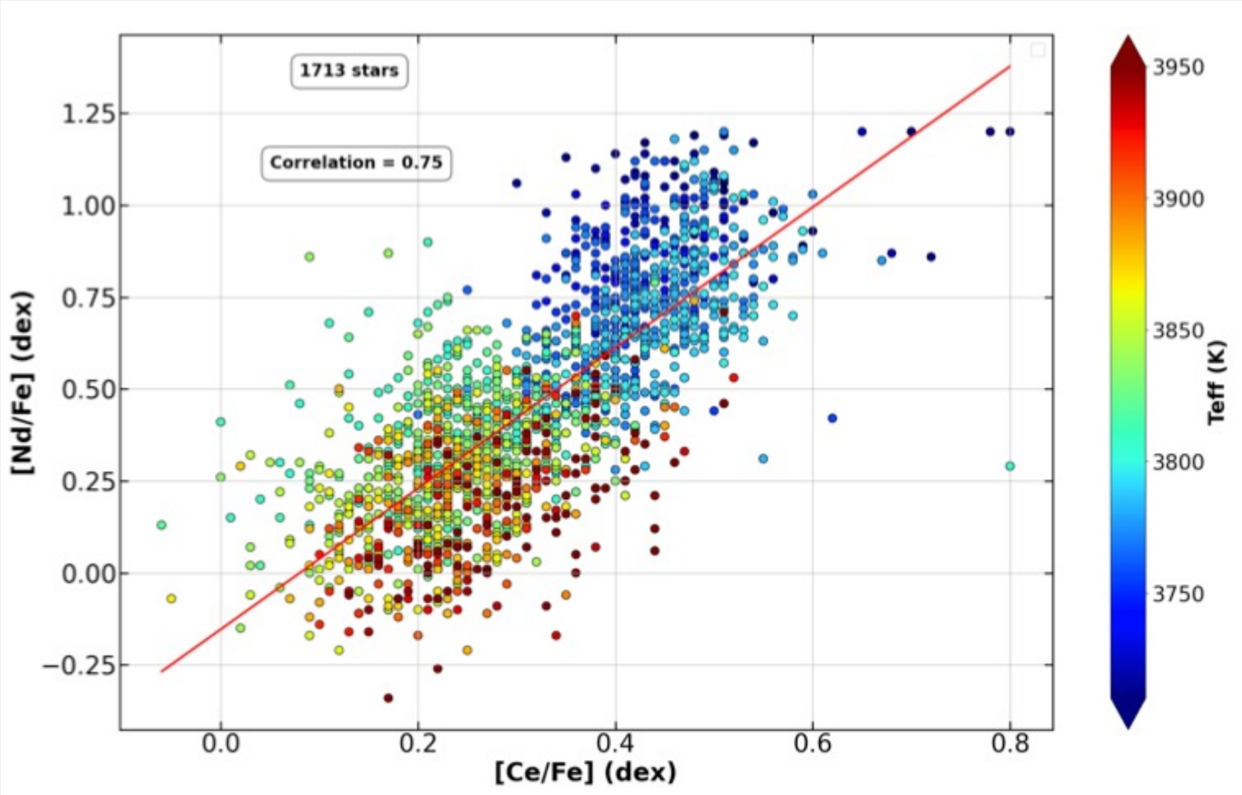
Slightly possitive [Ce/Ca] trend vs. [Ca/H] -> AGB stars are the main responsibles for Cerium abundances in the disc.

Precision : Heavy element abundances

Heavy elements: Neodymium

Contursi et al. (2023)





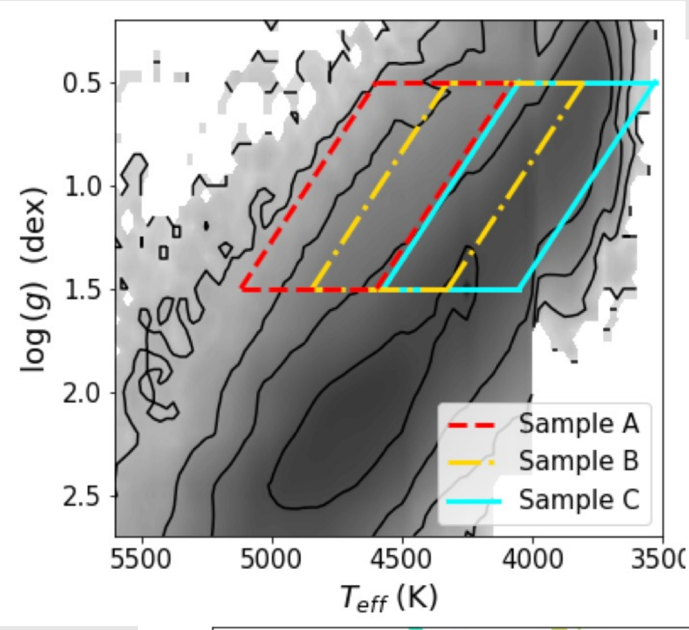
AGB production of s-process elements:

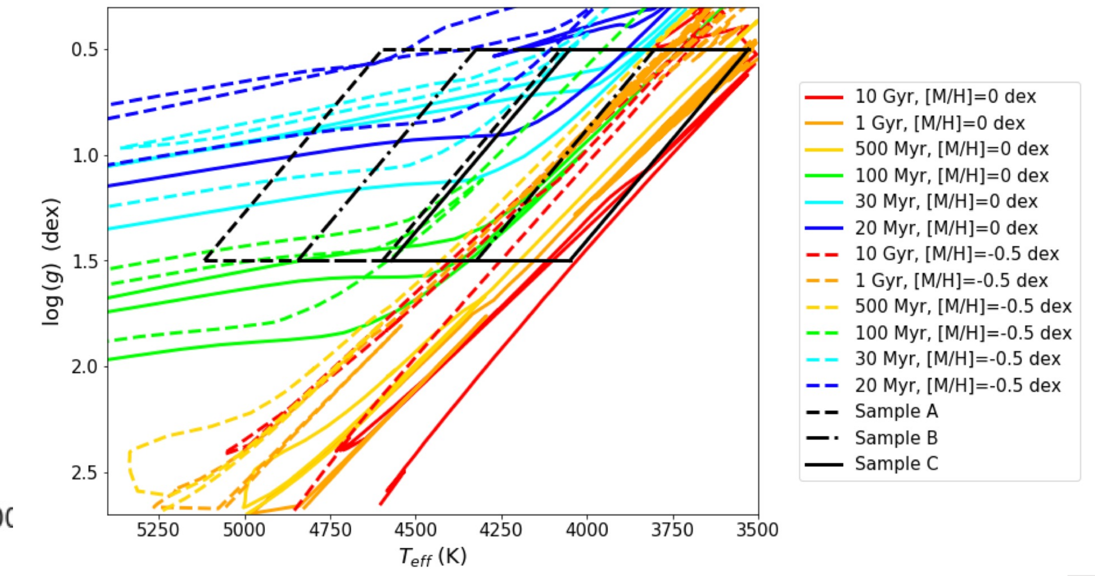
Higher Ce and Nd abundances for more evolved AGB stars of similar metallicity.

Precision : Chemical signature of spiral arms & azimuthal gradients

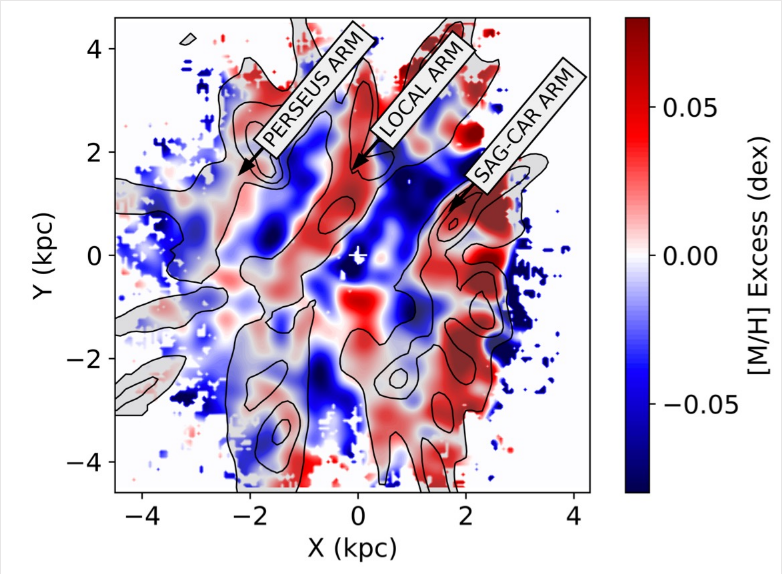
High enough precision and nb statistics to select stars in different age bins.

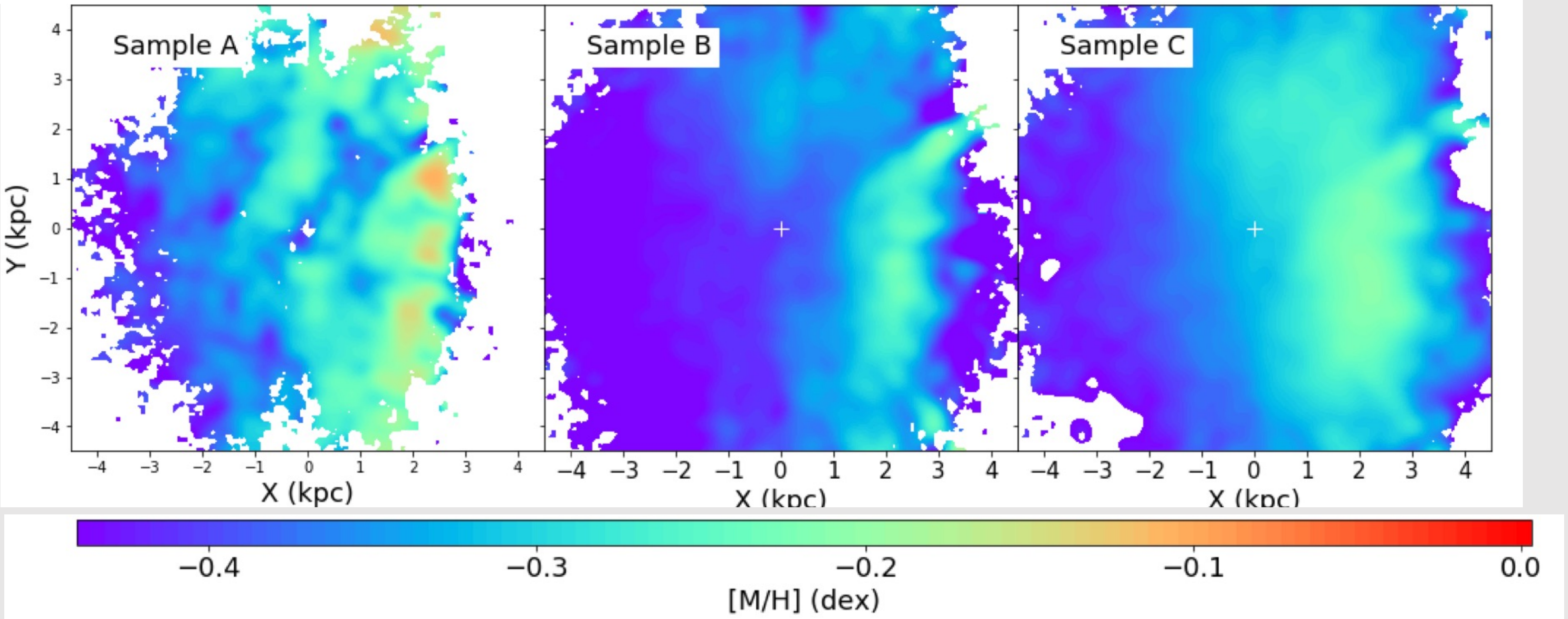
Chemical signature of the Spiral Arms





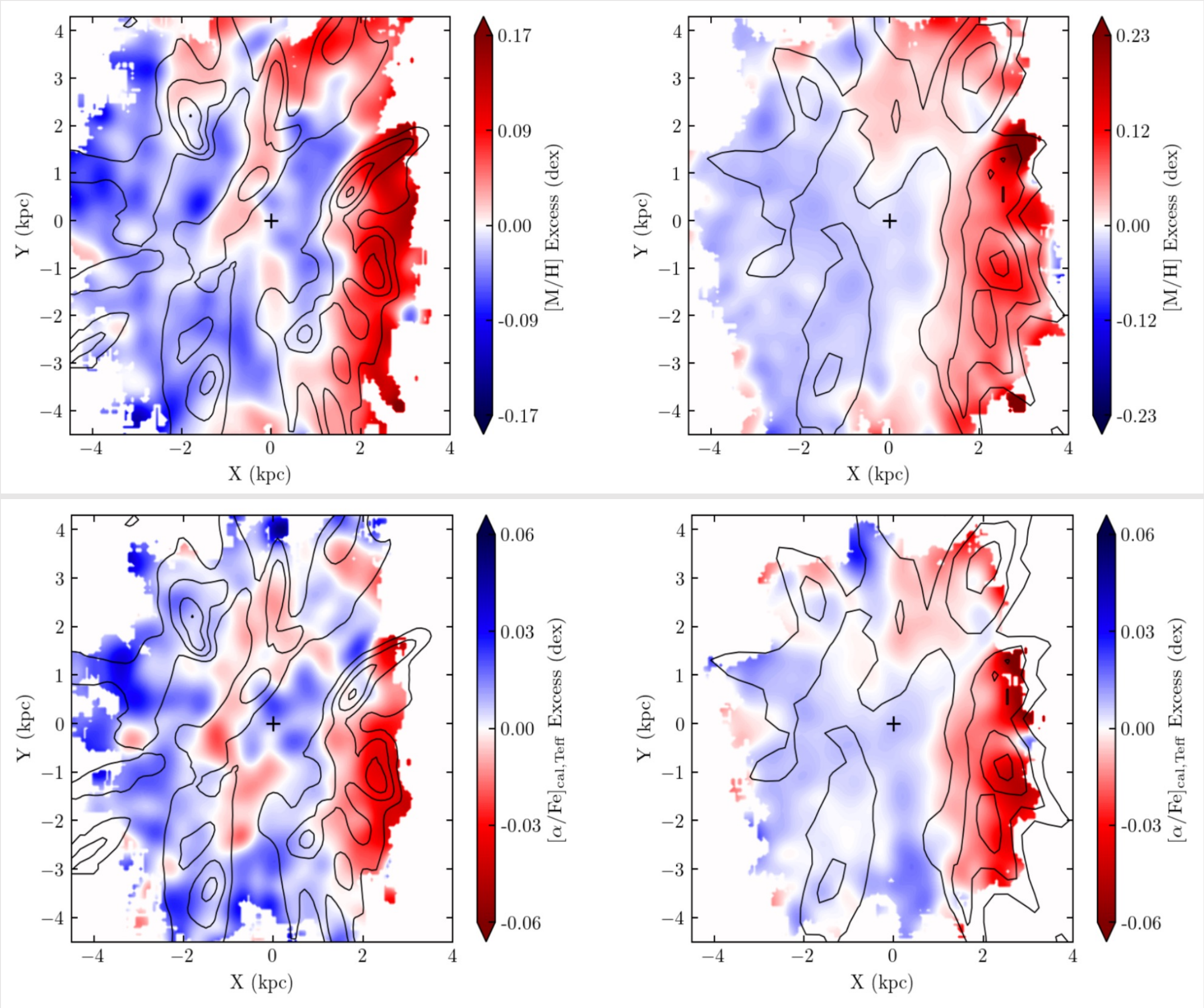
Poggio et al. (2022)





Precision : Chemical signature of spiral arms & azimuthal gradients

Age<1Gyr **Age>1Gyr**



Barbillon et al. (2023, in prep.)

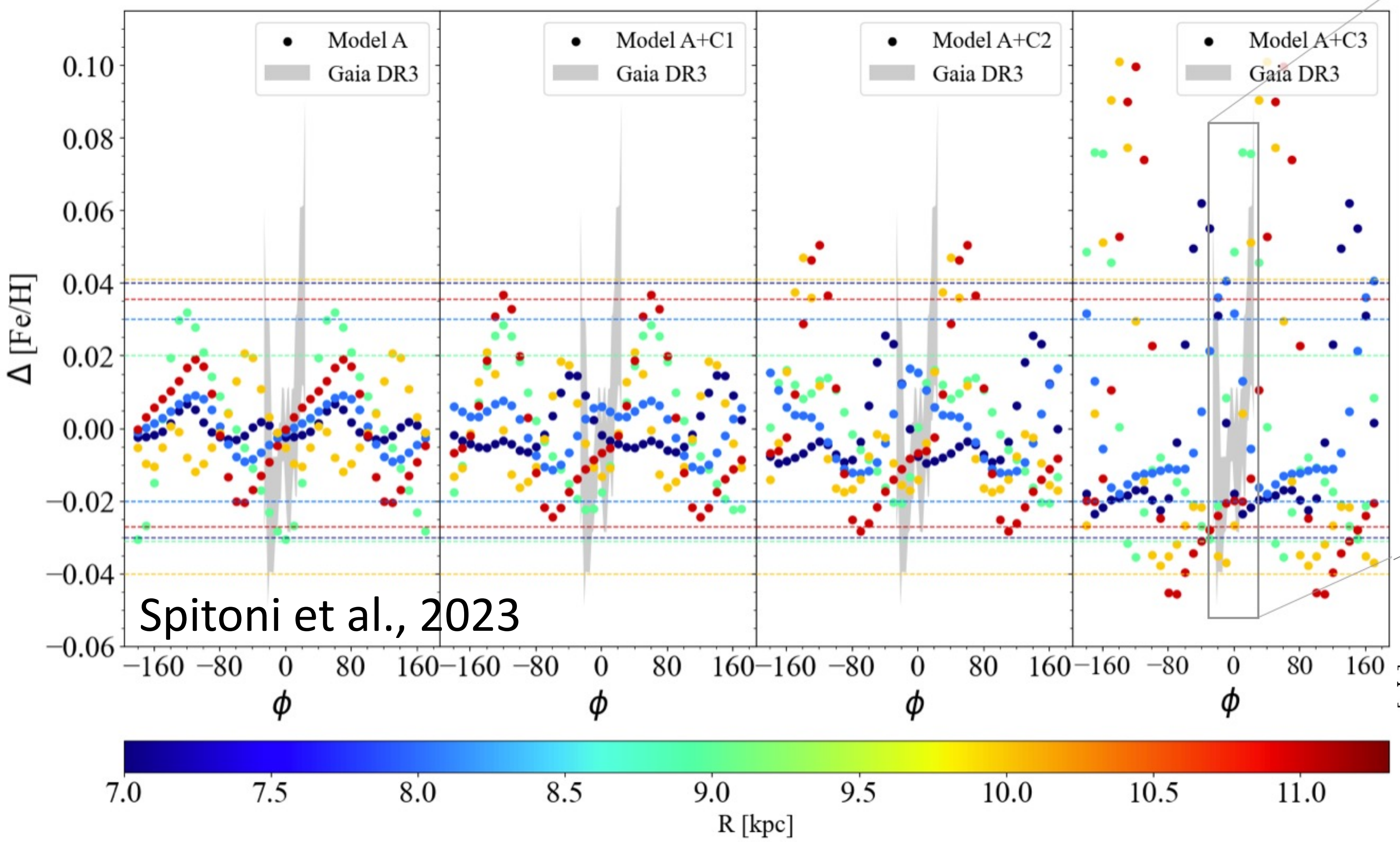
Metallicity signatures both **in the young** (Poggio et al. 2023) **in the old population** (Barbillon et al., in prep.)

The spiral arms signature is **visible in the relative abundance of α-elements with respect to iron.**

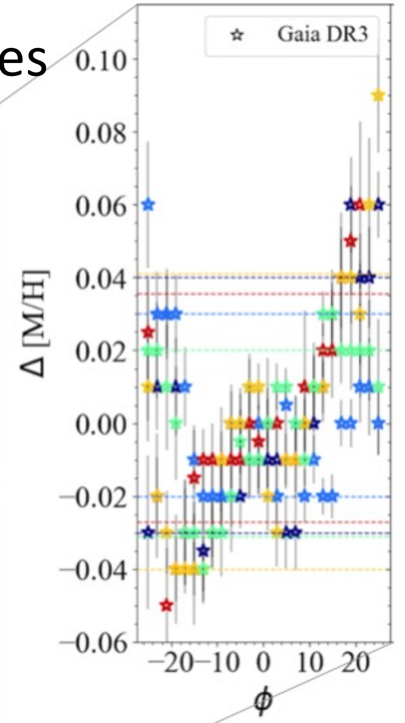
Precise α-element abundances

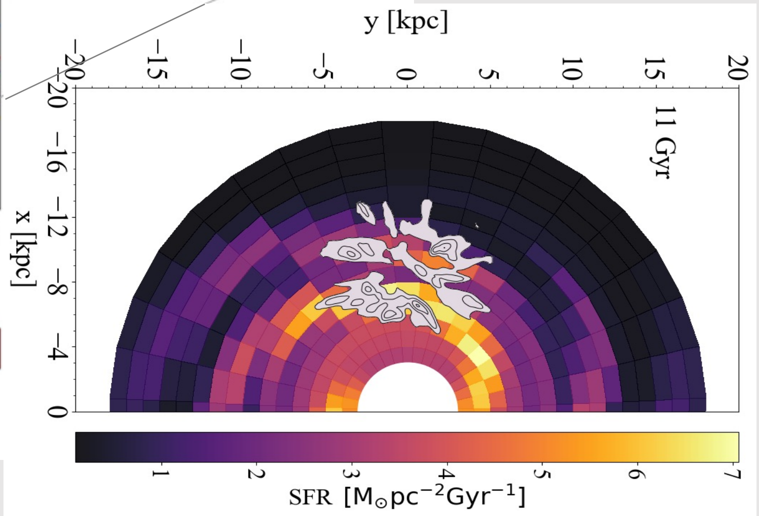
Precision : Chemical signature of spiral arms & azimuthal gradients

2D Chemical evolution models predict the spiral arms chemical signatures



Spitoni et al., 2023



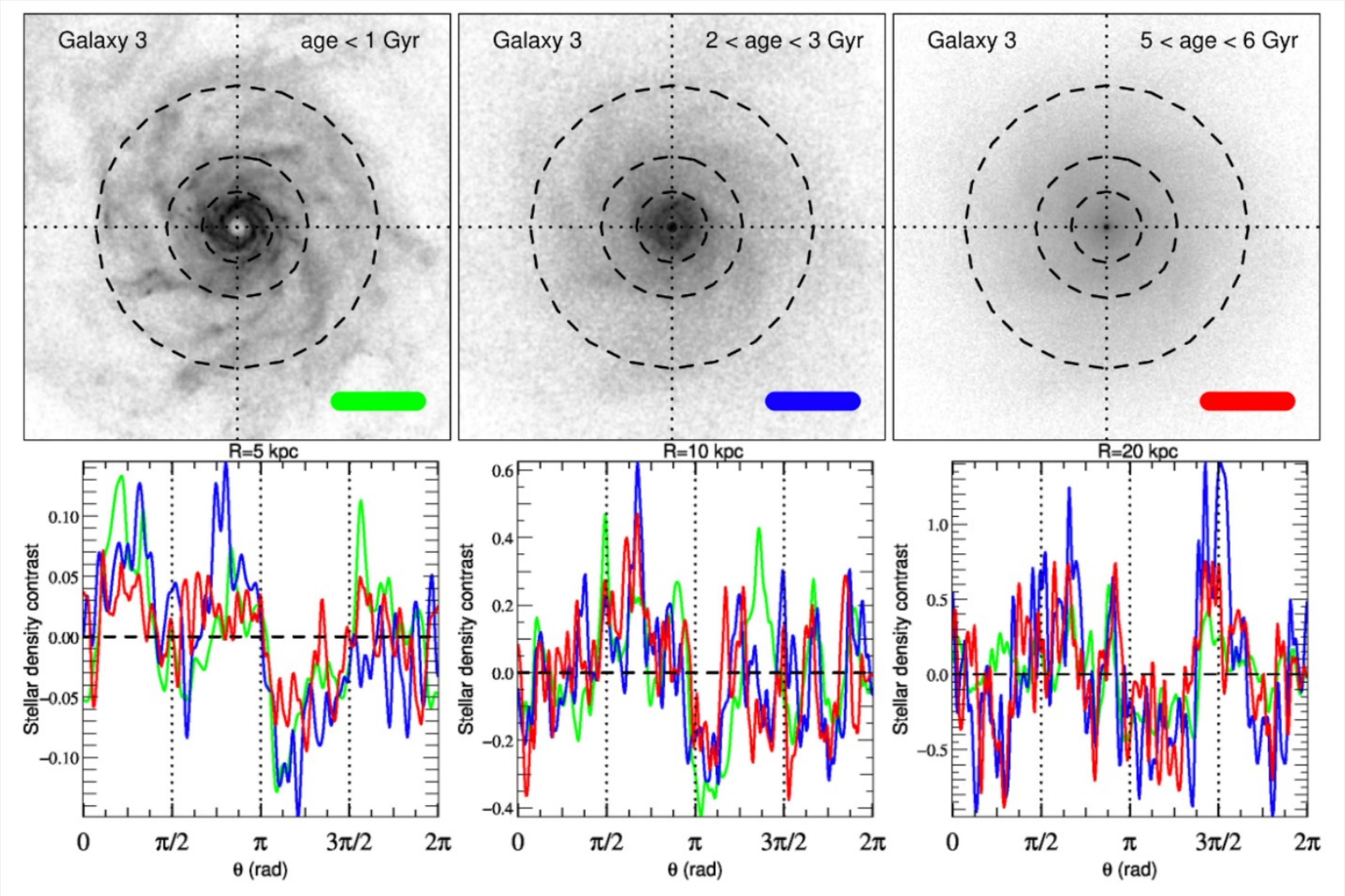


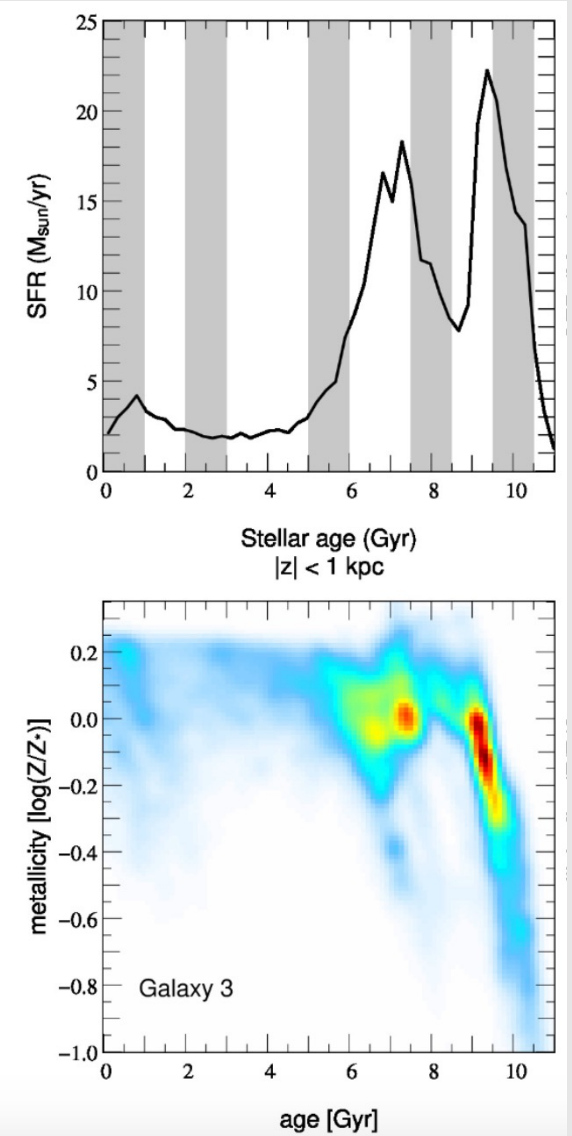
Precision : Chemical signature of spiral arms & azimuthal gradients

Zoom-in cosmological simulations (New Horizons)

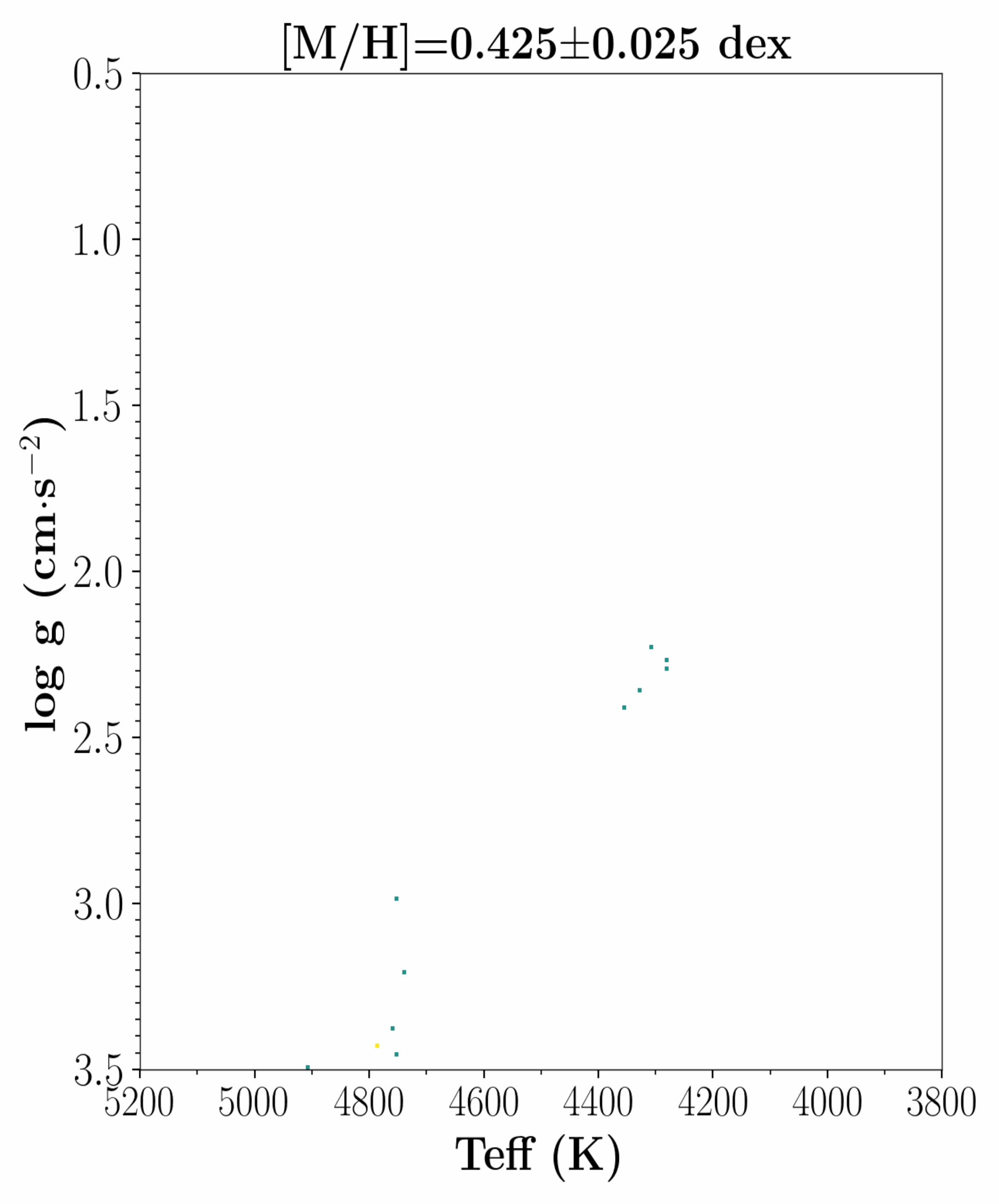
Peirani et al., in prep.

Spiral structure detected in several galaxies for stars as old as 6 Gyr

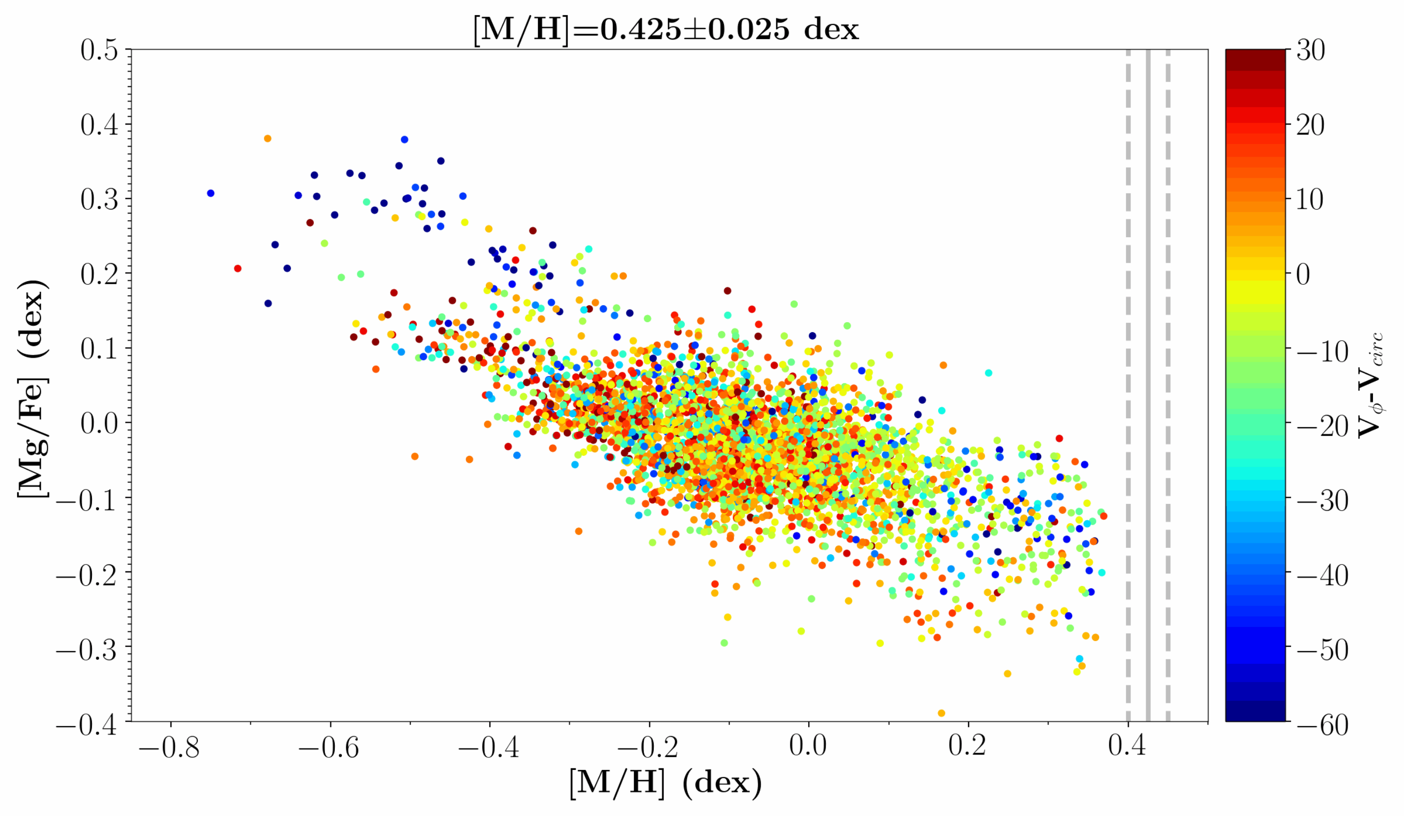




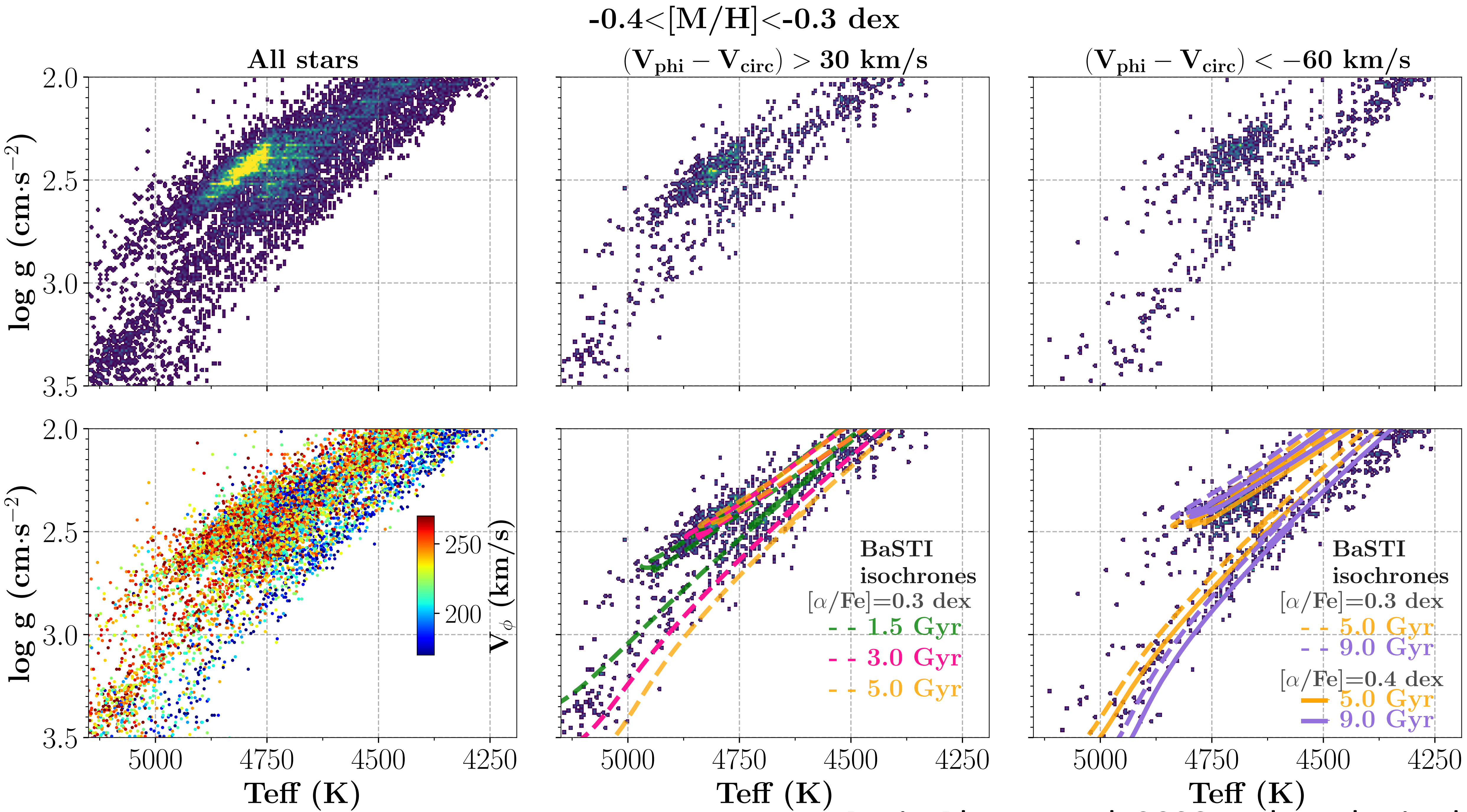
Precision : Bimodal disc RBG and RC & chemical sequences



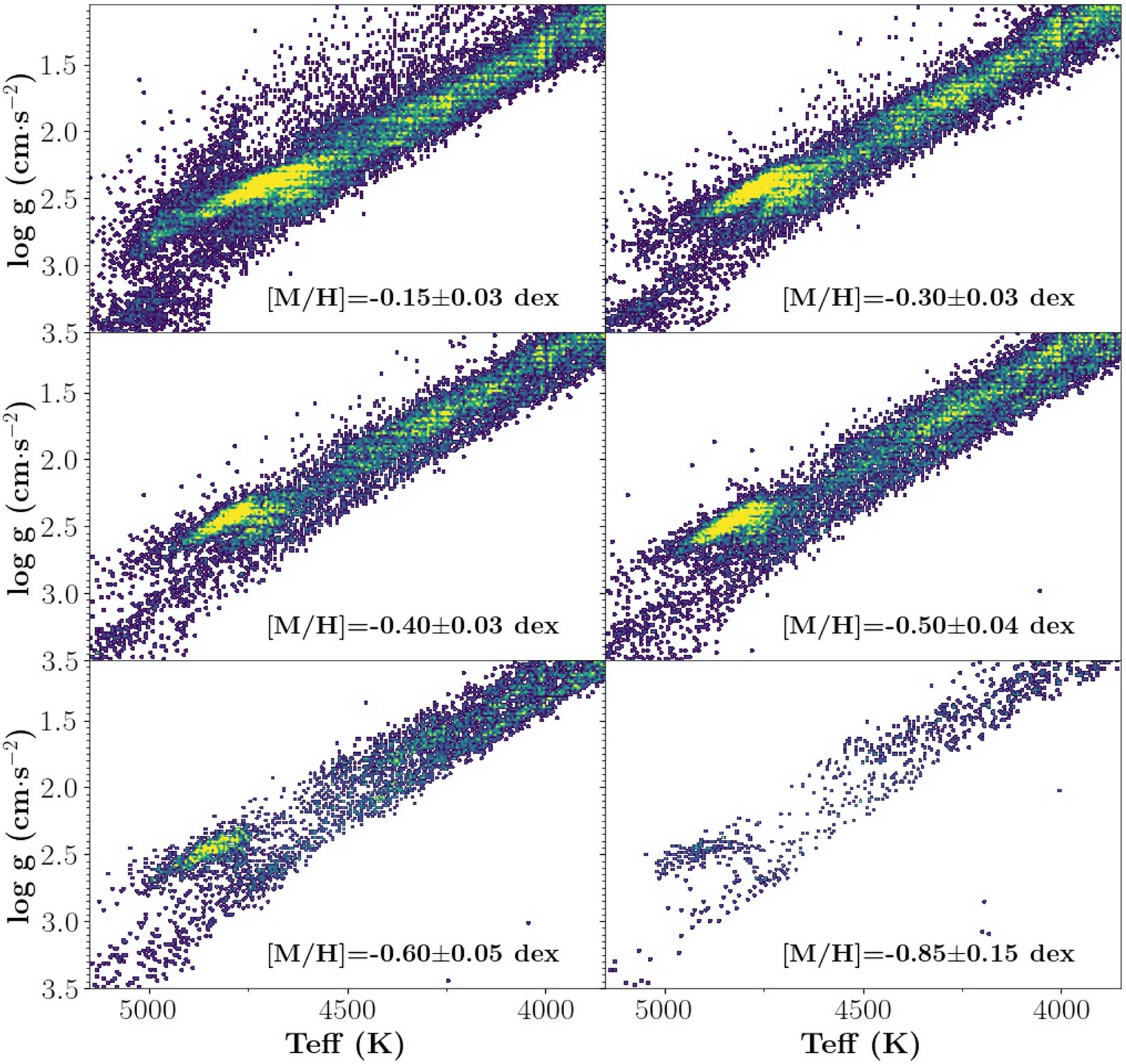
Gaia GSPspec : mono-abundance disc populations



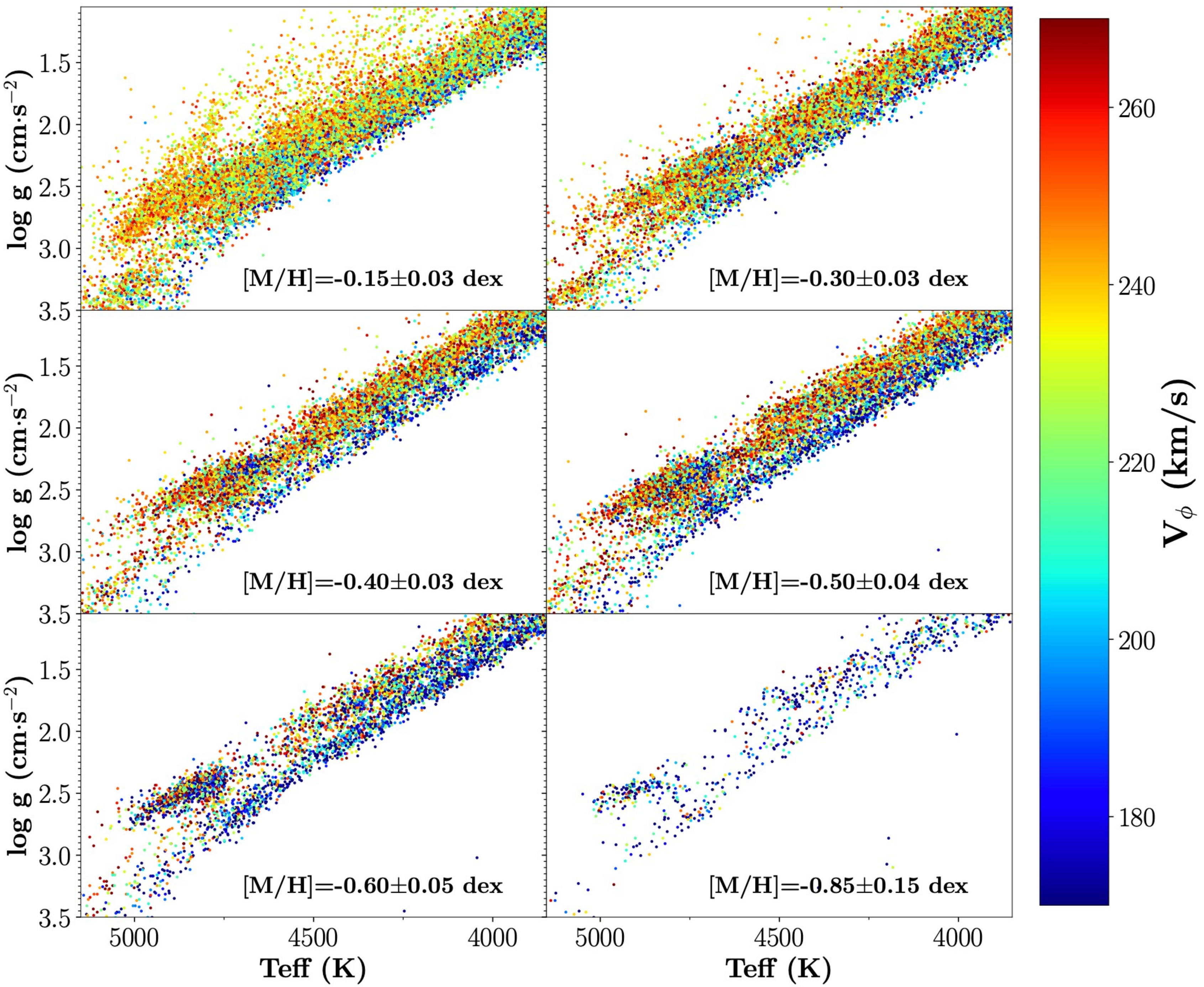
Recio-Blanco et al. 2023, to be submited



Recio-Blanco et al. 2023, to be submited

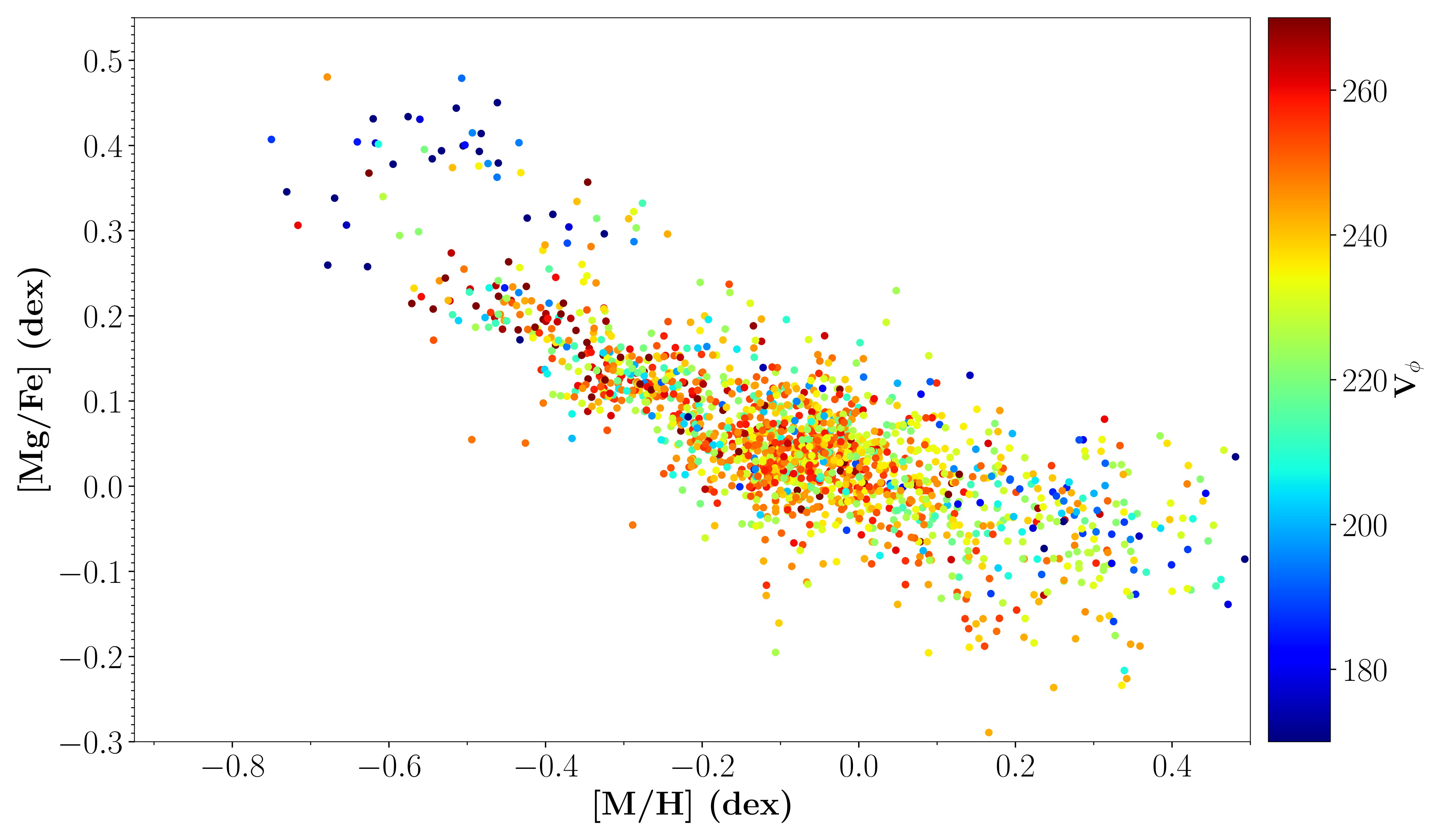


Recio-Blanco et al. 2023, to be submited



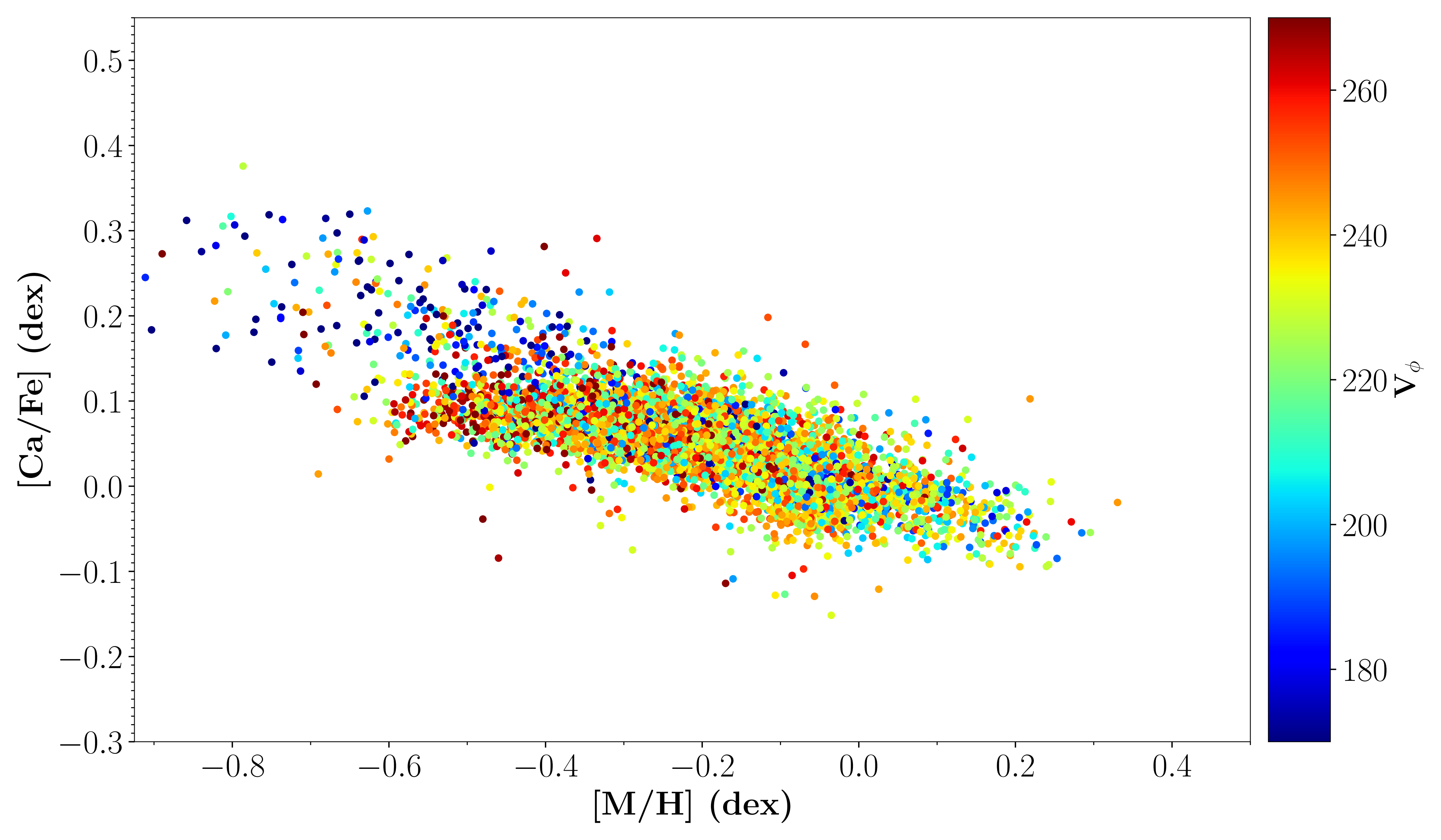
Recio-Blanco et al. 2023, to be submited

Precision : Bimodal disc RBG and RC & chemical sequences



Recio-Blanco et al. 2023, to be submited

Precision : Bimodal disc RBG and RC & chemical sequences



Recio-Blanco et al. 2023, to be submited

Precision : Bimodal disc RBG and RC & chemical sequences

Important! The "separation" power between thin/thick disc sequences depends on the lifetimes of the chemical element sources (short-lived versus long-lived ones)

This is supported by:

- **Chemical evolution models:**

  Prantzos et al. 2023, Spitoni et al. 2023
- **Observations by different spectroscopic surveys:**

  Gaia-ESO Survey (Mikolaitis et al. 2014)

  AMBRE project (de Laverny et al. 2012, Prantzos et al. 2023)

  APOGEE data (Abdurro'uf et al. 2022)

  ....

Precision : Bimodal disc RBG and RC & chemical sequences

Important! The "separation" power between thin/thick disc sequences depends on the lifetimes of the chemical element sources (short-lived versus long-lived ones)

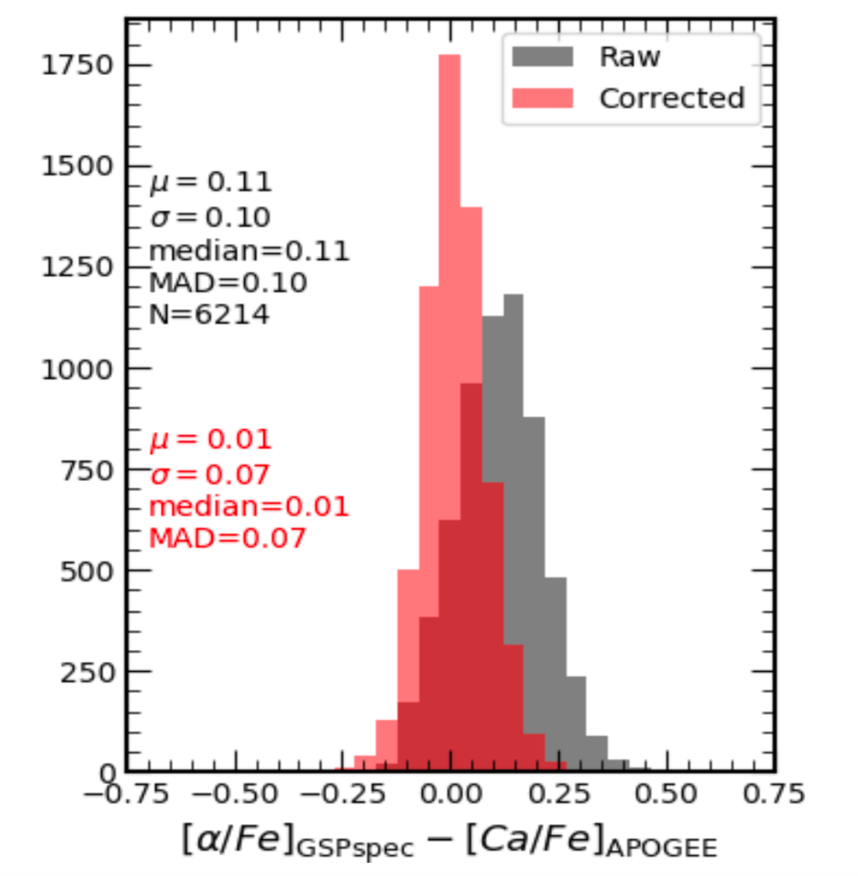
Warning for data driven parametrization methods applied to RVS spectra, but trained on a different catalogue

If the method loosely separates thin/thick discs using CaT lines

=> it is probably **not estimating [Ca/Fe]** abundances from the RVS data, **but just producing a potential [Mg/Fe] abundance assuming the underlying Ca-Mg relation in the training set**.

Precision : Bimodal disc RBG and RC & chemical sequences

Important! The "separation" power between thin/thick disc sequences depends on the lifetimes of the chemical element sources (short-lived versus long-lived ones)

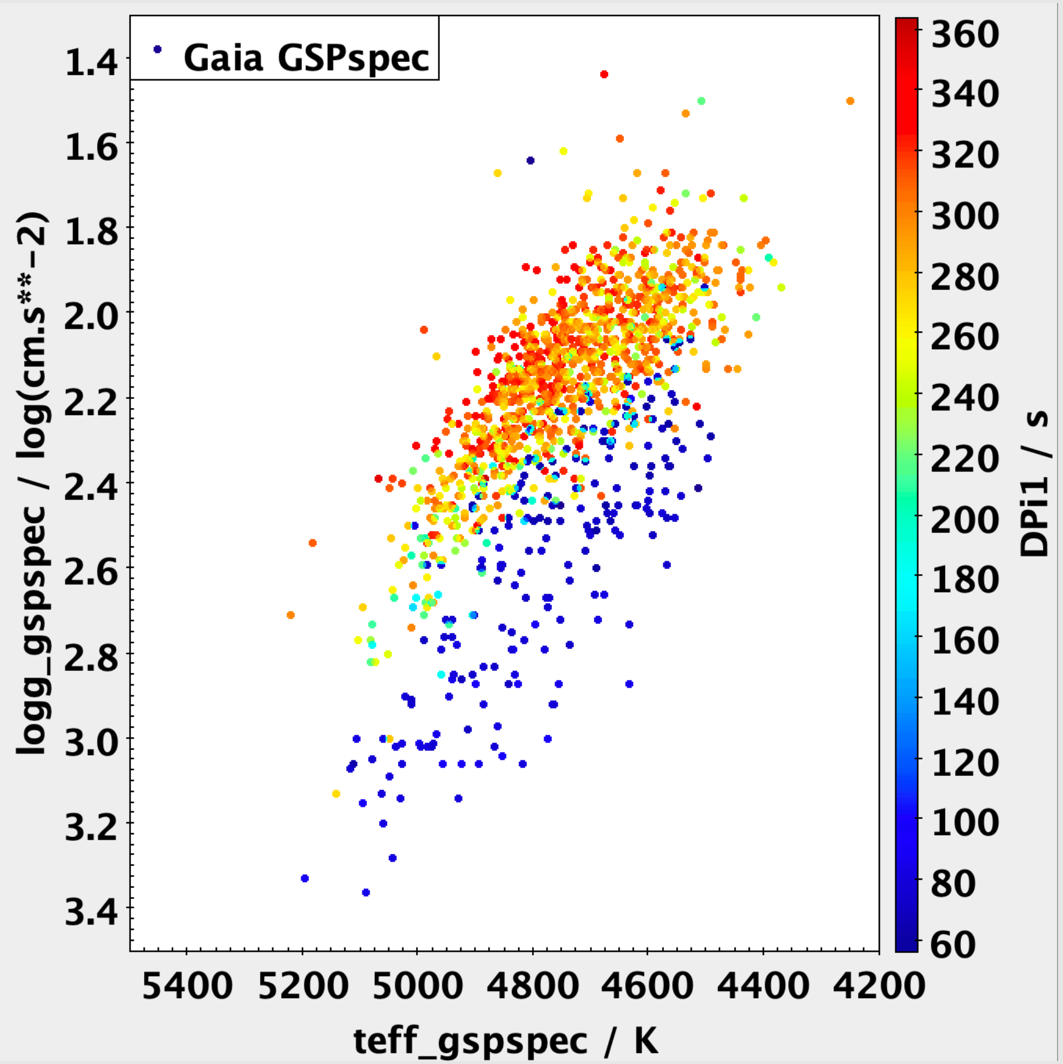


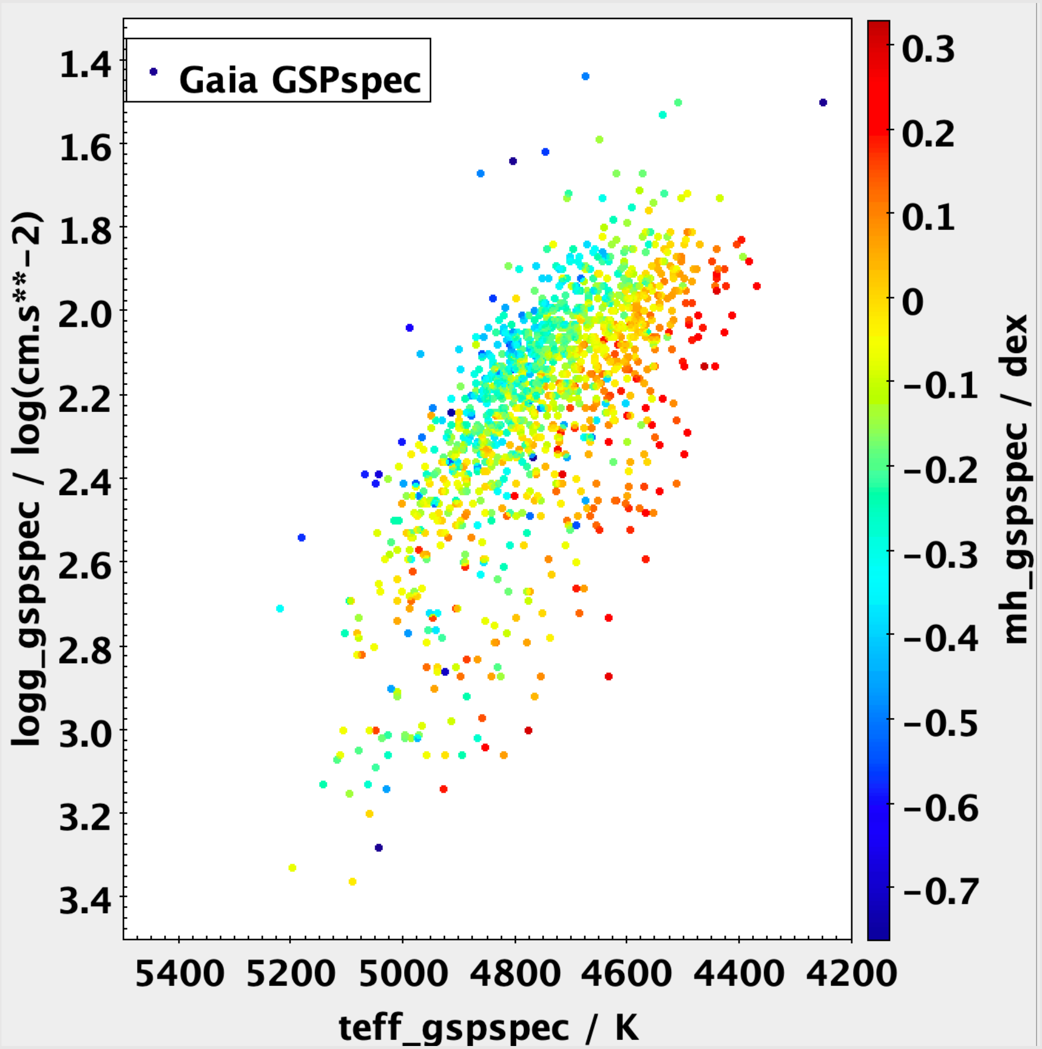
The GSPspec α diagnostic is dominated by the calcium lines

In GSPspec $[\alpha/Fe]$ = [Ca/Fe]

Precision : comparison with asteroseismology

Gaia/GSPspec + Kepler (colour code on Delta π & metallicity)





Conclusions

- **The Gaia future is bright:**
  - only ¼ of the data analysed in DR3!
  - RVS data SNR increasing

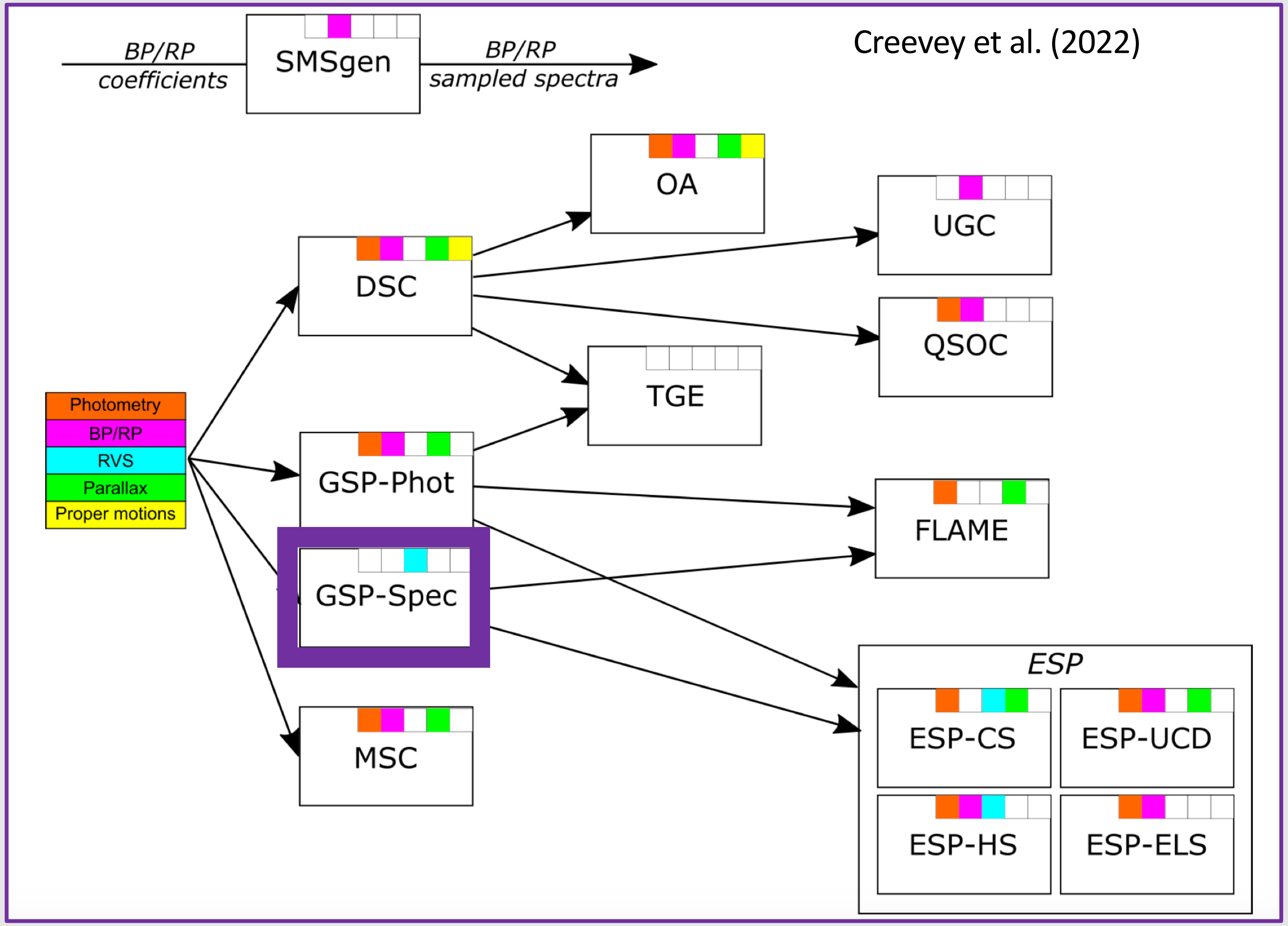
- **Much larger chemo-dynamical catalogues to come:**
  - 5.6 million stars with chemo-physical parameters in DR3 (2022)
  - ~ 35 million stars in DR4 (end 2025)
  - ~100 million stars in DR5 (2030)

- **Gaia RVS offers high precision parametrization**
  Quality comparable to ground-based data of higher resolution/spectral coverage and much **higher number statistics**

Gaia/RVS: a space spectroscopic survey

CU8/GSPspec: The chemical composition of 5.6 million stars

Apsis DPAC/CU8 pipeline



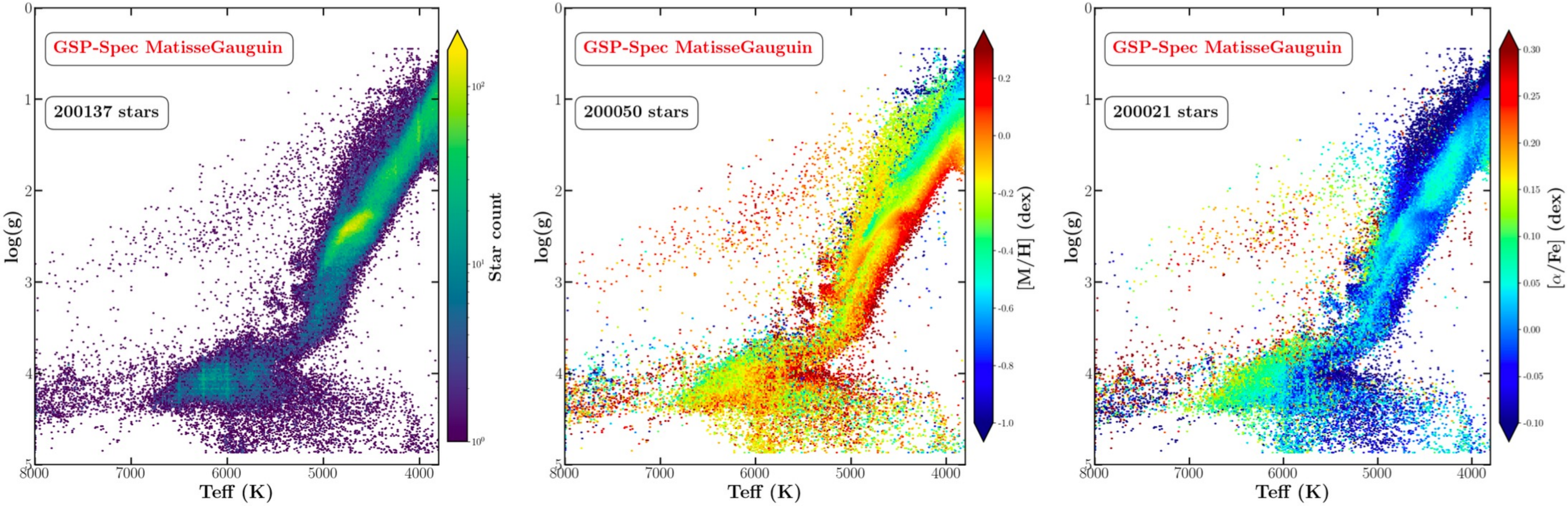
GSPspec (Recio-Blanco et al. 2022) is an up-stream module of the Astrophysical parameters inference system (Creevey et al. 2022)

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

Gaia/RVS: high precision Kiel diagrams

SNR>150

High quality parameter flags

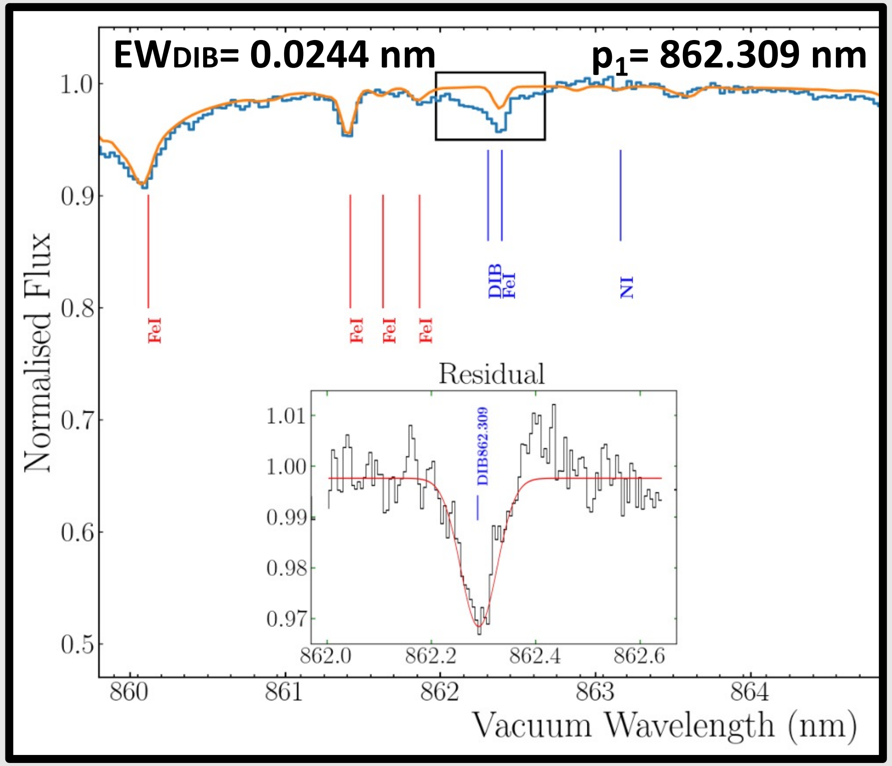


Recio-Blanco et al. (2022)

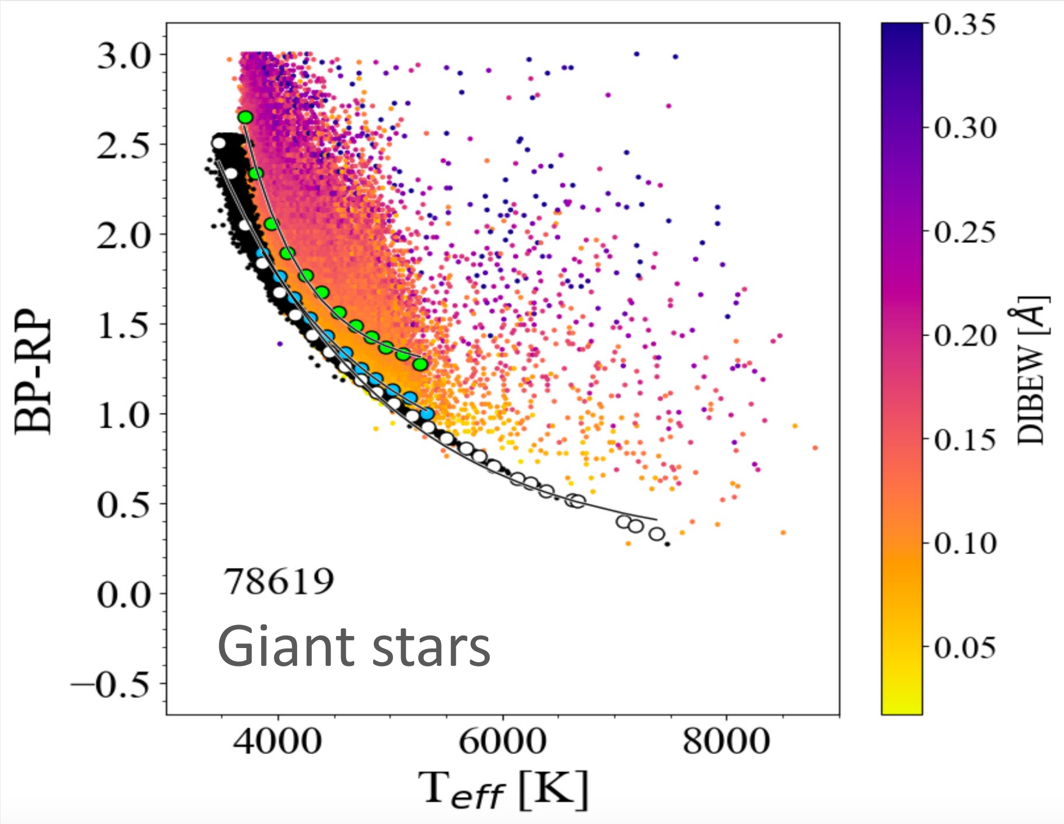
Gaia/RVS: a space spectroscopic survey

High quality spectra: **continuous observations for 3 years, no atmosphere, control of systematics, ...** Gaia is not a ground-based survey!

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



Recio-Blanco et al. (2022)

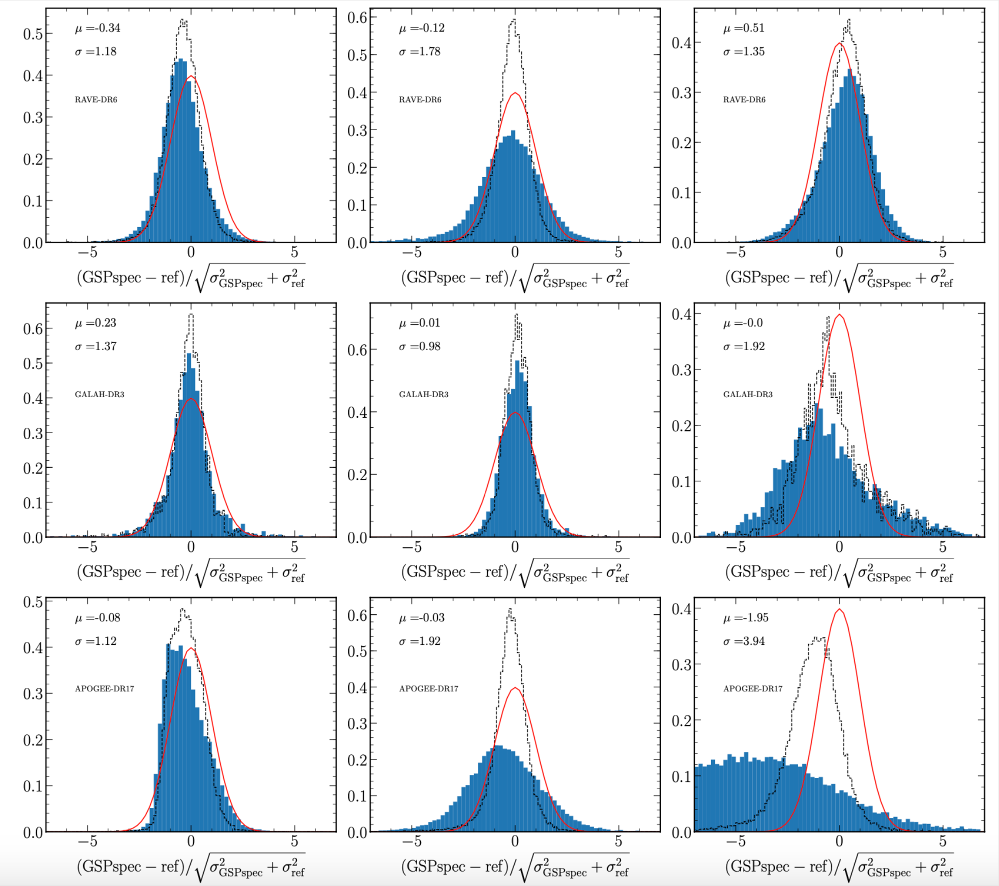


No Teff-absorption denegeneracy

Gaia/RVS: a space spectroscopic survey

CU8/GSPspec: Comparison with ground-based surveys

	$T_{\rm eff}$	log(g)	[M/H]	$\log(g)_{\rm calibrated}$	$[M/H]_{\rm calibrated}$	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)



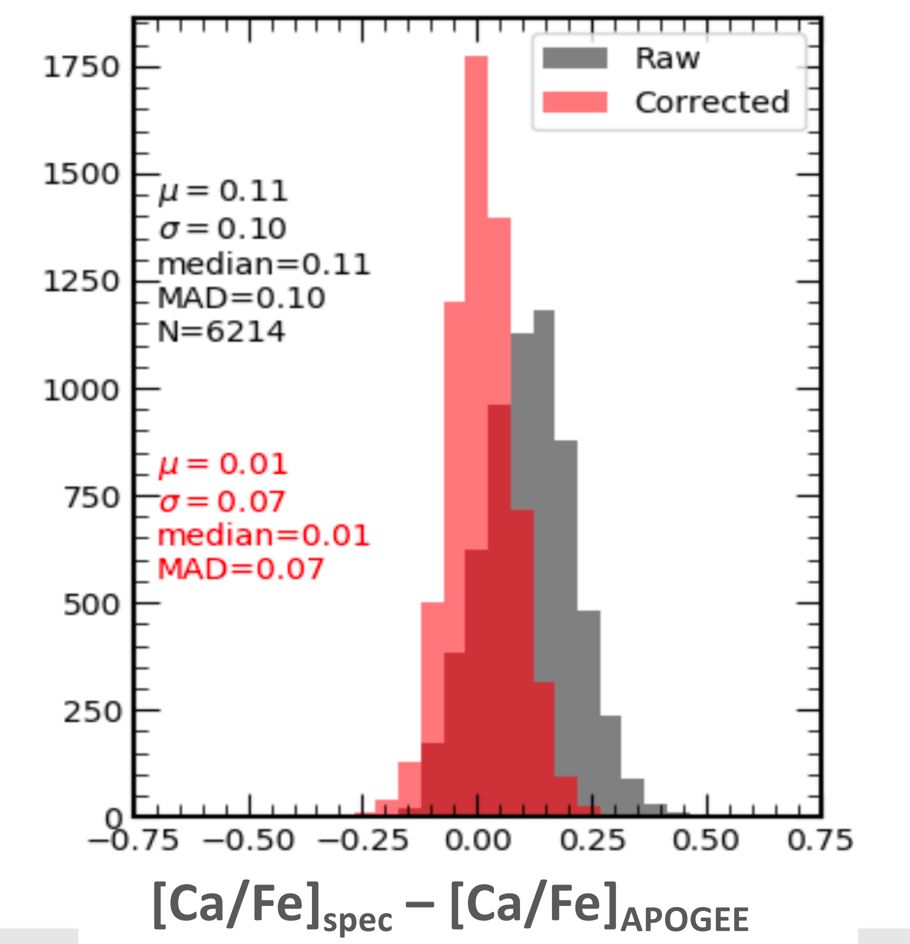
General very good agreement

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

Gaia/RVS: a space spectroscopic survey

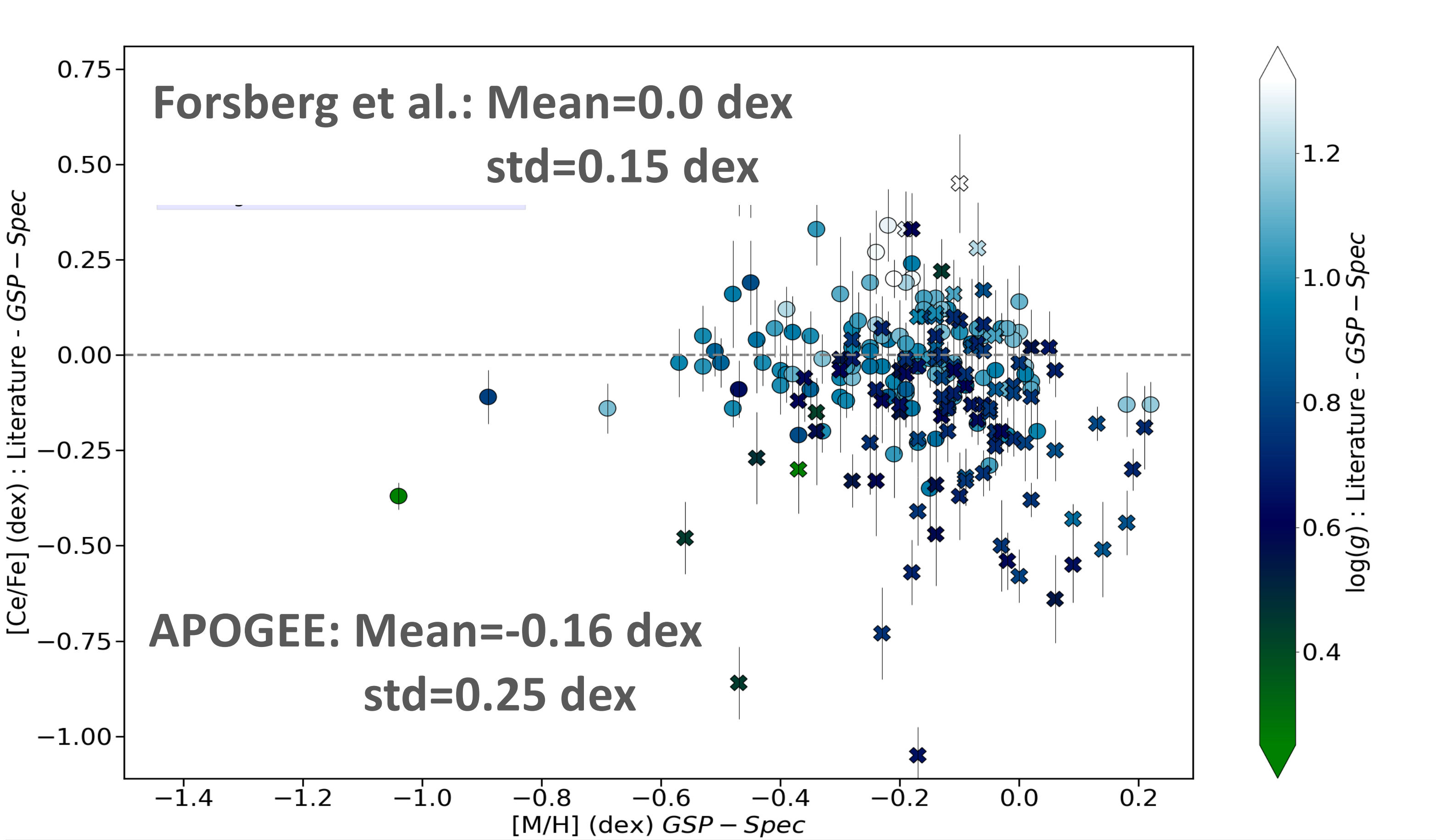
CU8/GSPspec: Comparison with ground-based surveys

[Ca/Fe]



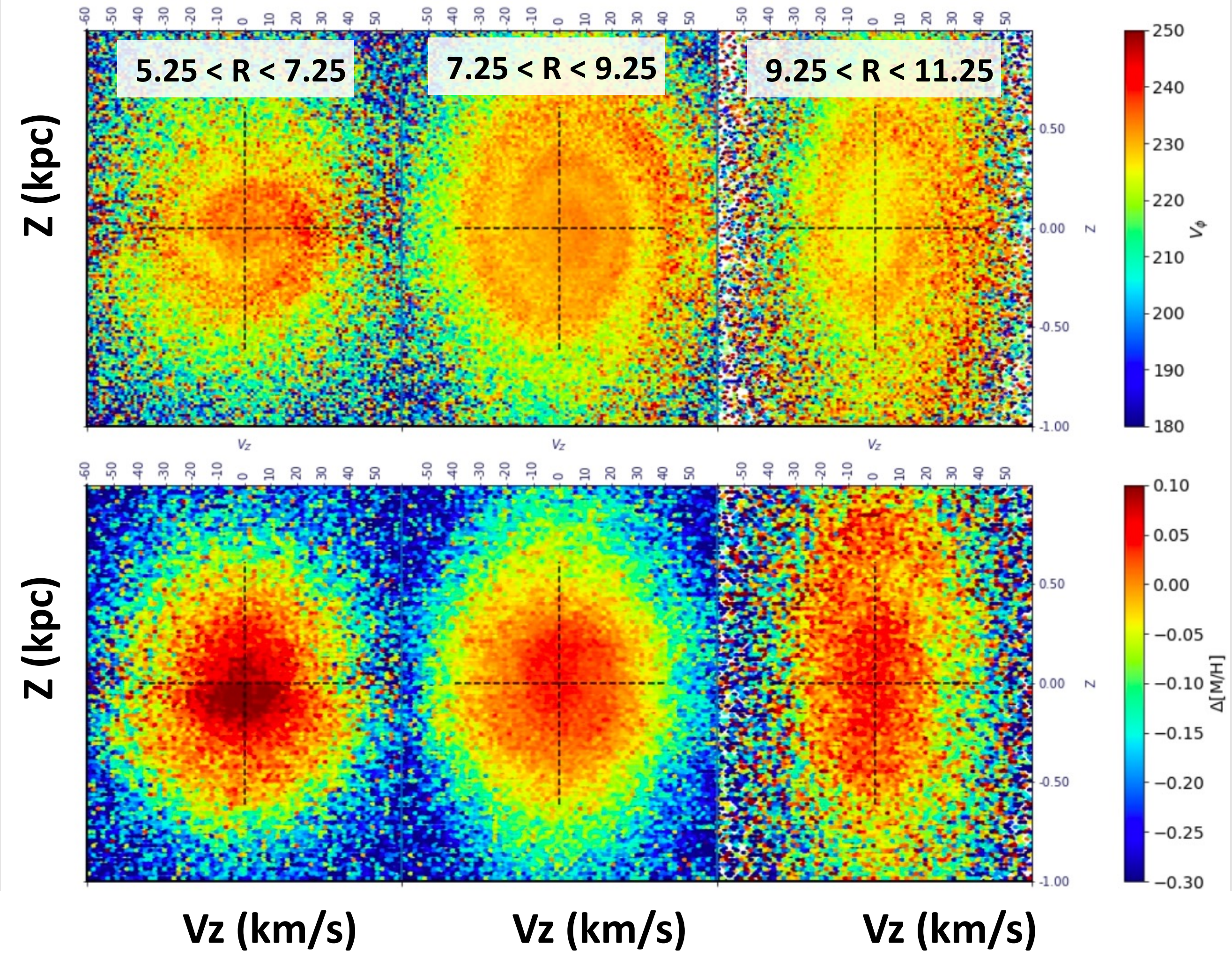
Recio-Blanco et al. (2022)

[Ce/Fe]



Contursi et al. (2022)

Chemical markers of disc perturbations:
kinematics and phase spiral as a function of R

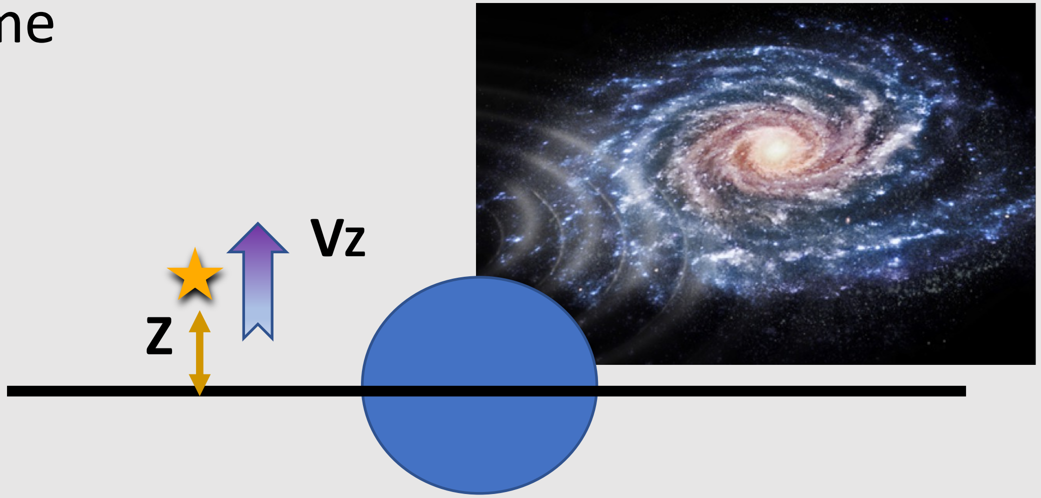


Crédits: Gaia Collaboration, Recio-Blanco et al. (2022)

Wave-like perturbation (Antoja et al. 2018):

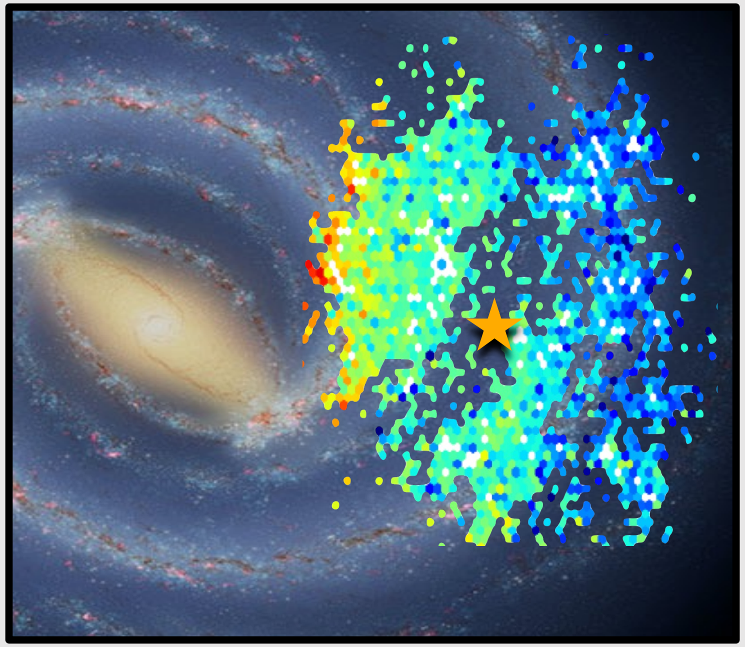
- disc-crossing satellite (Binney & Schoenrich 2018, Bland-Hawthorn et al. 2019)
- bar's buckling (Koperskov et al. 2019)

Correlation of thin disc phase spiral **with metallicity excess** detected for the first time

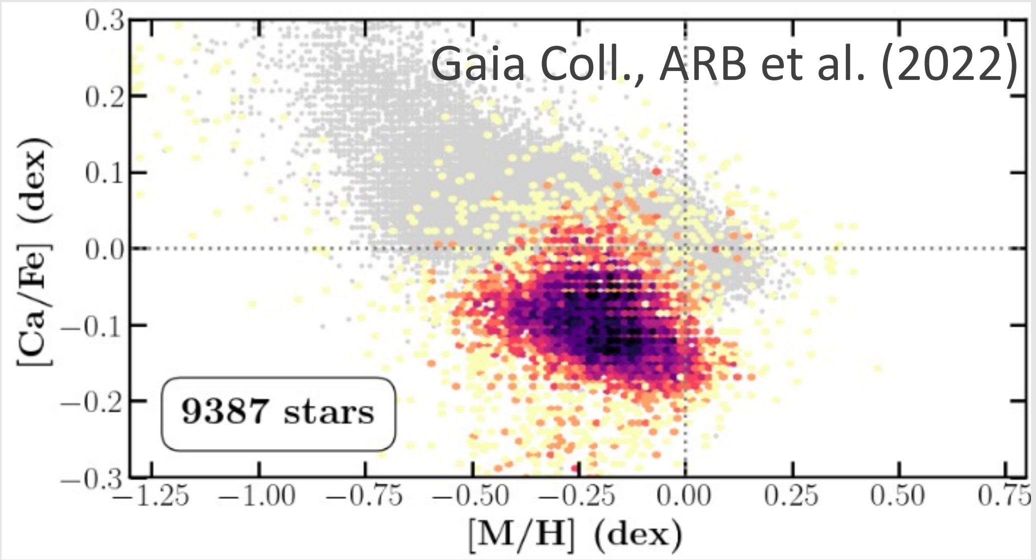


Galactic disc: a young chemically impoverished population?

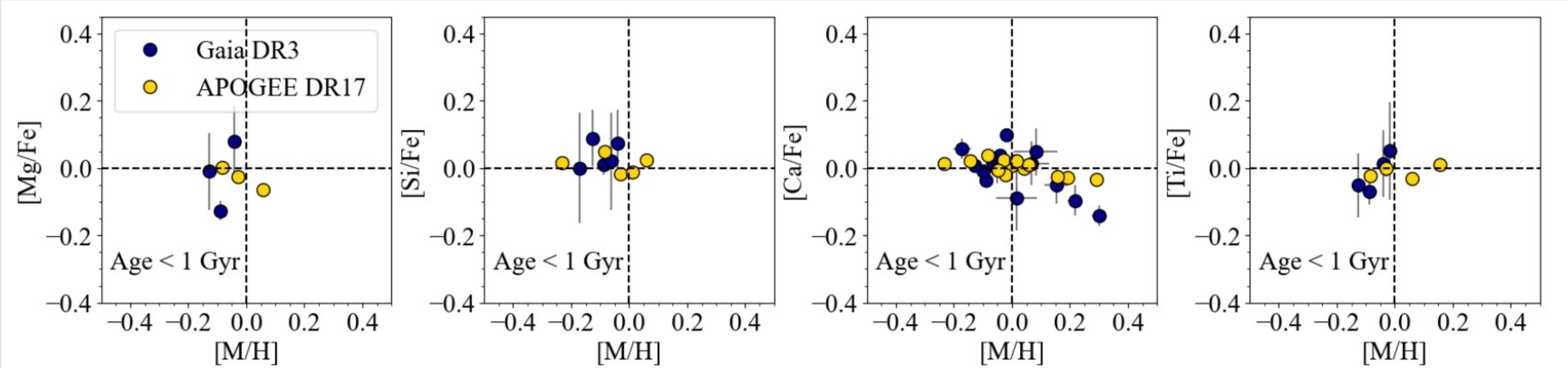
Young stellar populations in the spiral arms

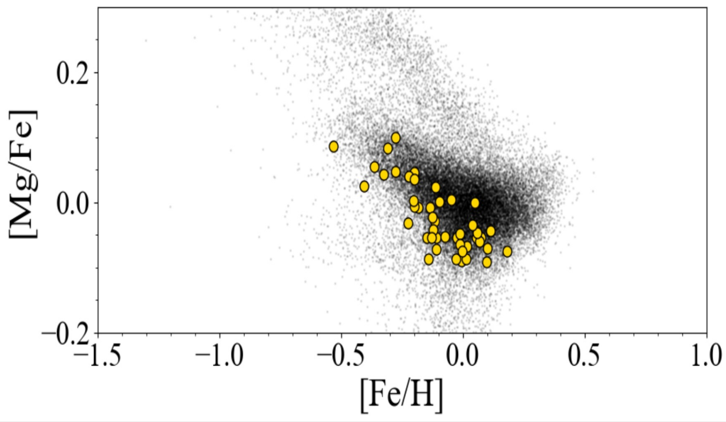


Chemical impoverishment ?



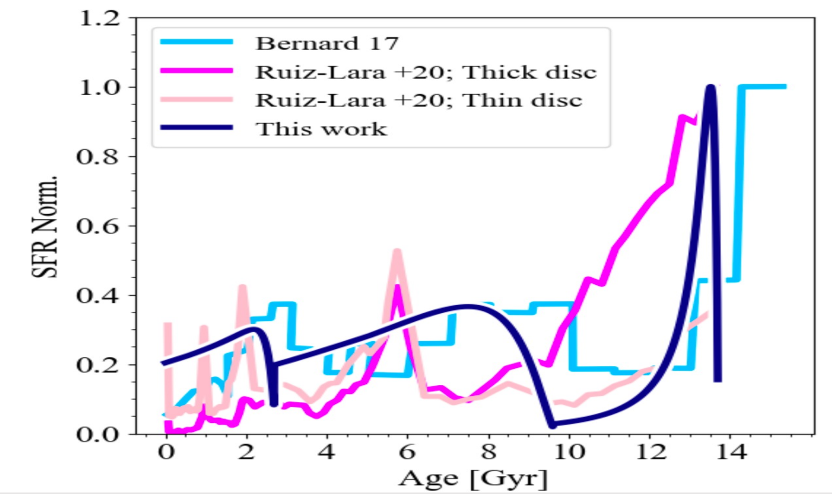
Depletion consistent with other HR surveys (APOGEE)





Spitoni, ARB et al. (2022)

Galactic disc: a young chemically impoverished population?

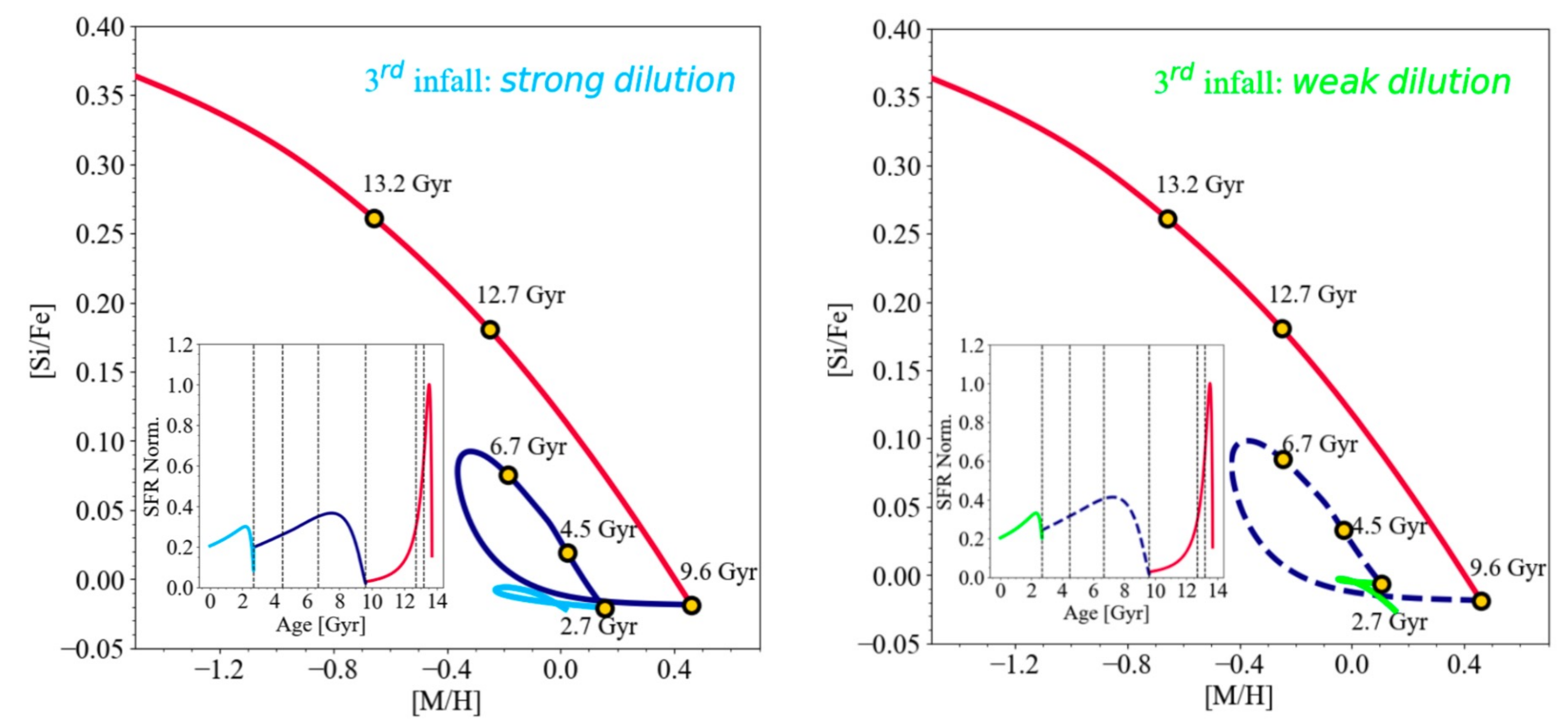


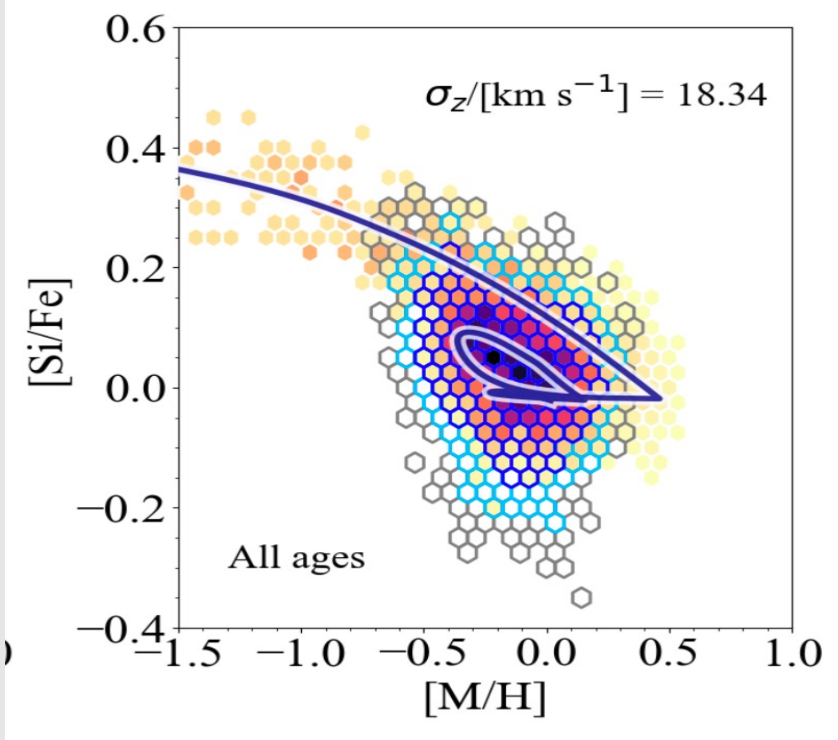
Spitoni et al. models

Galaxy formed by separated accretion episodes, **modelled by decaying exponential infalls of gas.**

Recent infall of gas related to thin disc star formation history and **chemically depleted young populations**

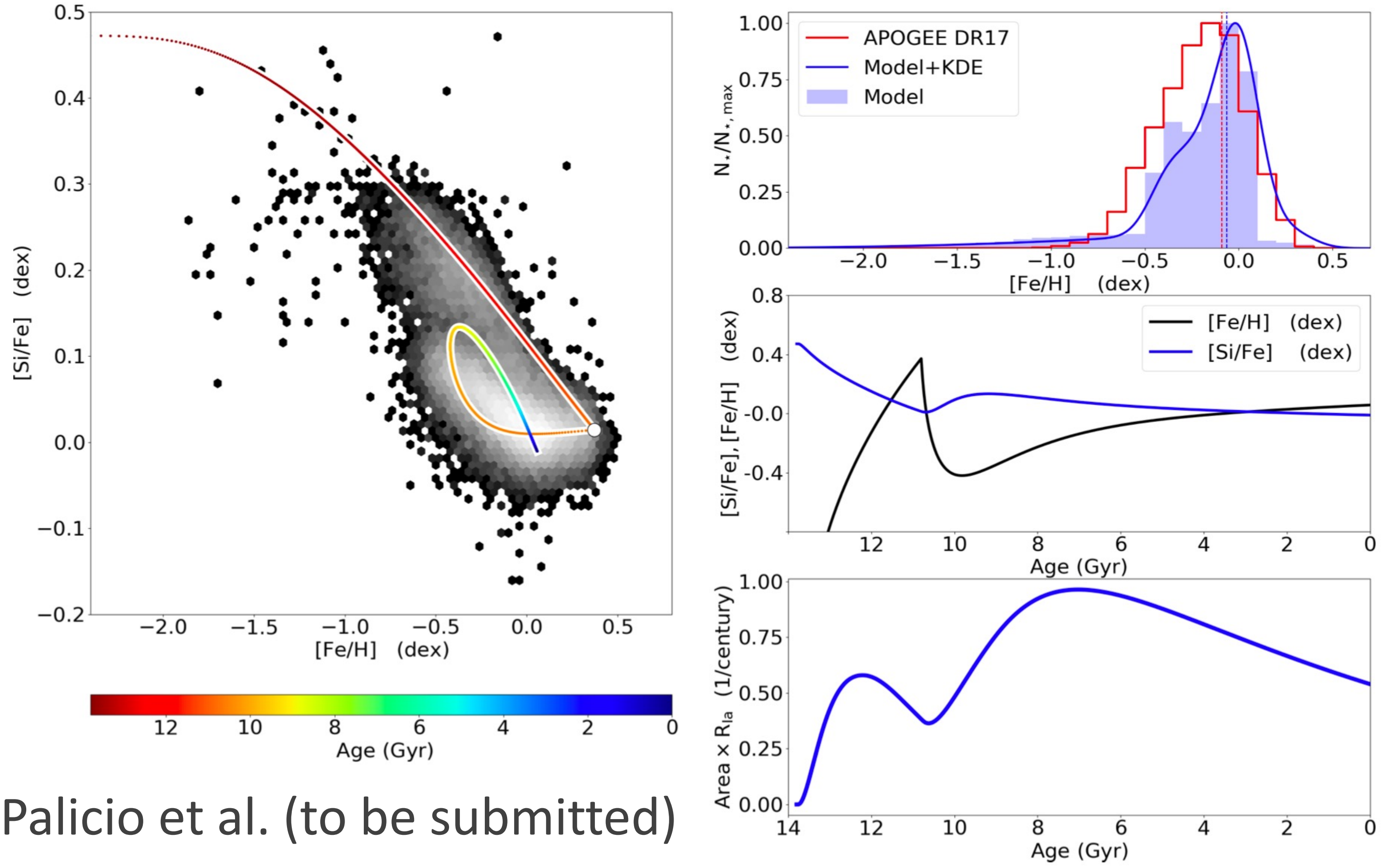
Spitoni, ARB et al. (2022)





Galactic disc: an analytical chemical model including Type Ia SN

Chemical evolution model integrated by extending the instantaneous recycling approximation with the contribution of Type Ia SNe



Palicio et al. (to be submitted)

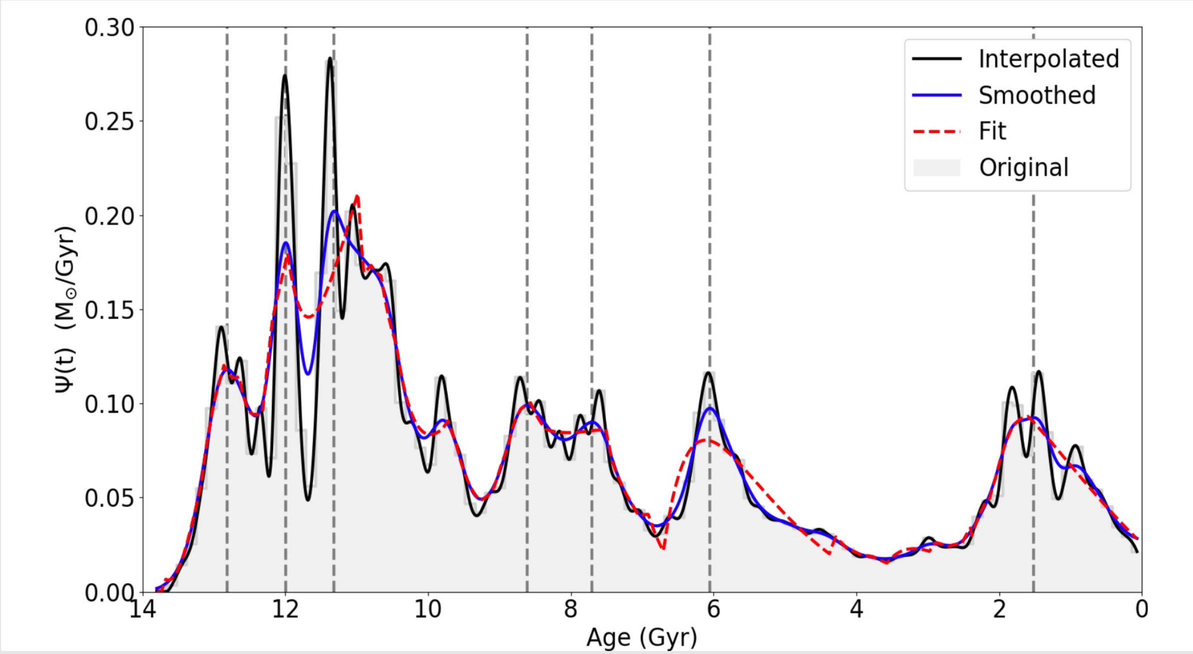
Extra term in the modelling depending on the Delay Time Distribution (DTD).

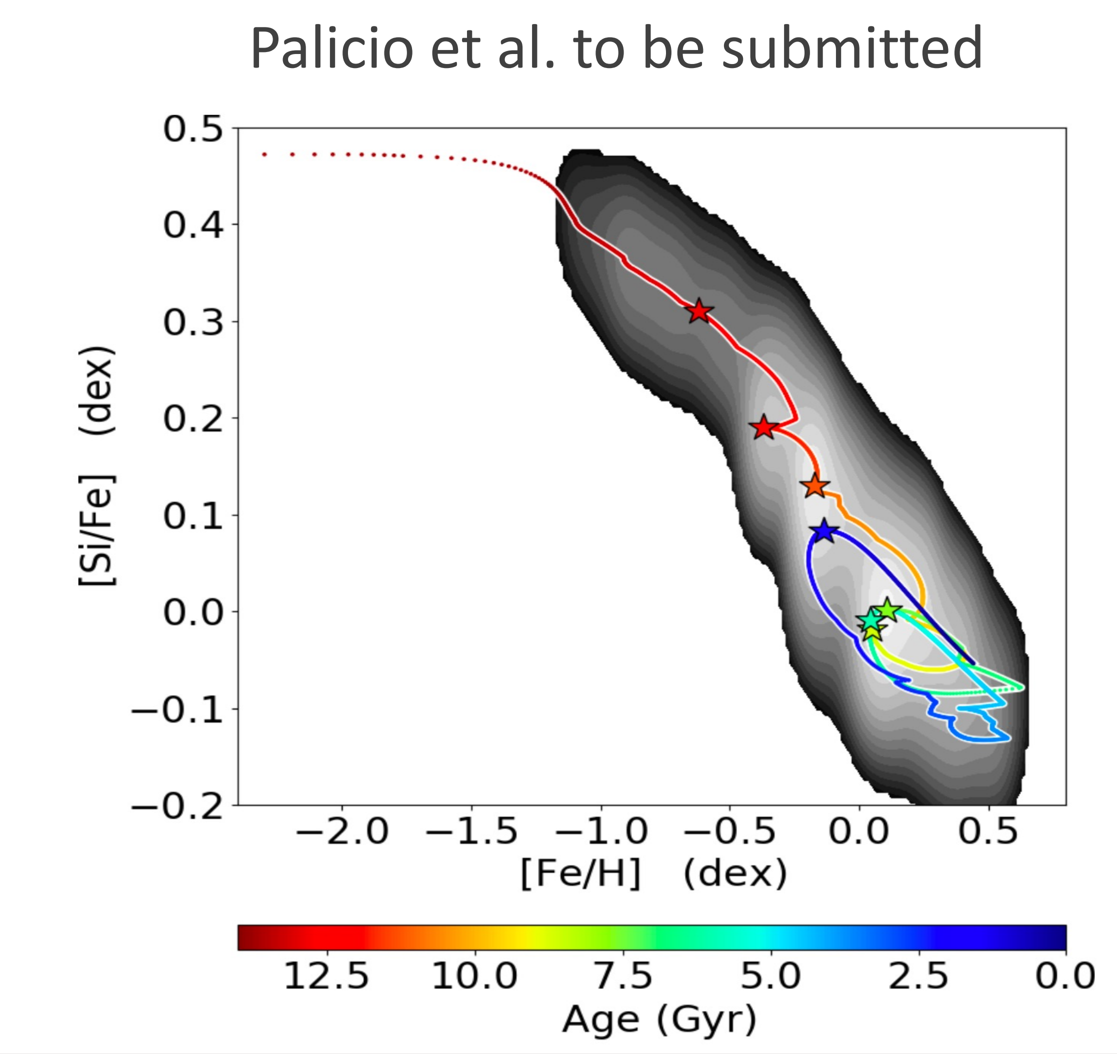
Four different DTDs are considered, either analyticaly or as a superposition of Gaussian, exponential and 1/*t* functions using a restricted least-squares fit.

Galactic disc: an analytical chemical model including Type Ia SN

Used to model the chemical evolution of the GALACTICA Milky Way-like simulated galaxy (Park et al. 2021) from its star formation history.

Extracted from a zoom-in hydrodynamical simulation in a cosmological context (S. Peirani) spatial resolution and sub-grid models as in NewHorizon simulation as in Dubois et al. 2021.





Chemo-dynamics with individual element abundances

Gaia collaboration, ARB et al. (2022)