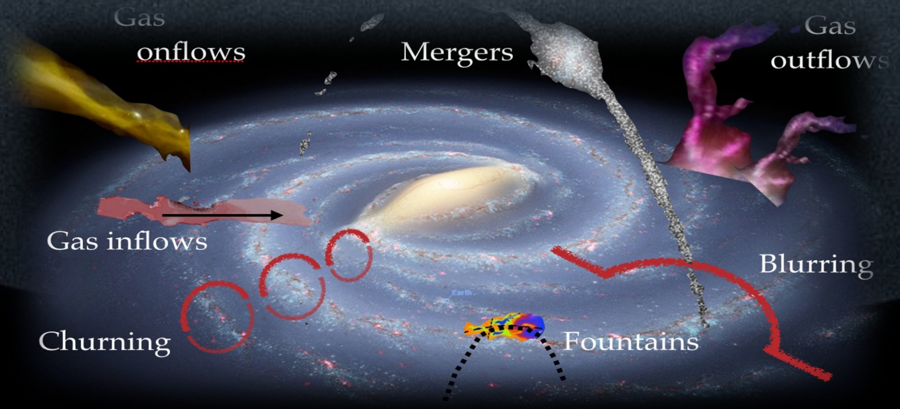
Ecology of the Milky Way and Gaia chemistry

Alejandra Recio-Blanco
Observatoire de la Côte d'Azur (Lab. Lagrange)



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

Horizon 2020 research
No 101004214

MARIE CURIE ACTIONS

In collaboration with:

Patrick de Laverny

and

Pedro A. Palicio (CNES post-doc)

Eloisa Poggio (Marie Curie Fellow)

Emanuele Spitoni (EU H2020 EXPLORE post-doc)

Gabriele Contursi (PhD)

In collaboration with:

Patrick de Laverny

and

Marie Barbillon
(M2 MAUCA)

Elisa Denis
(M2 MAUCA)

Pedro
A. Palicio
(CNES post-doc)

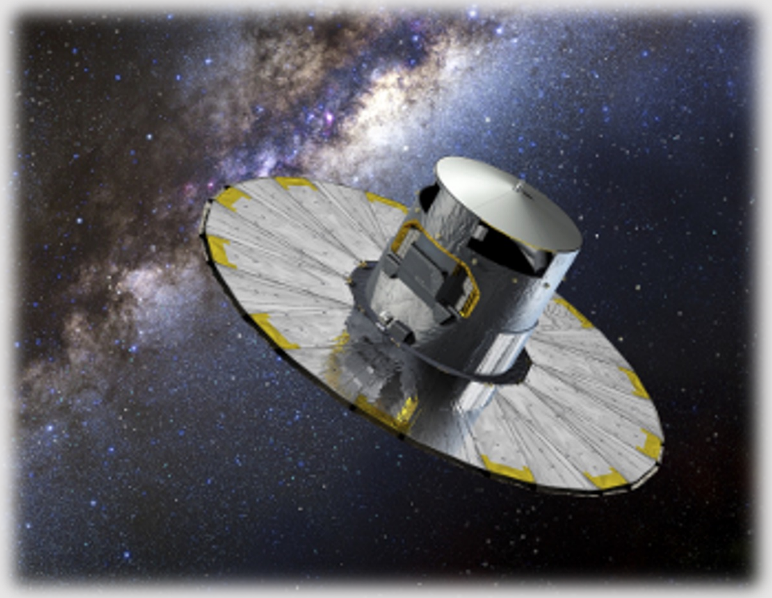
Eloisa
Poggio
(Marie Curie
Fellow)

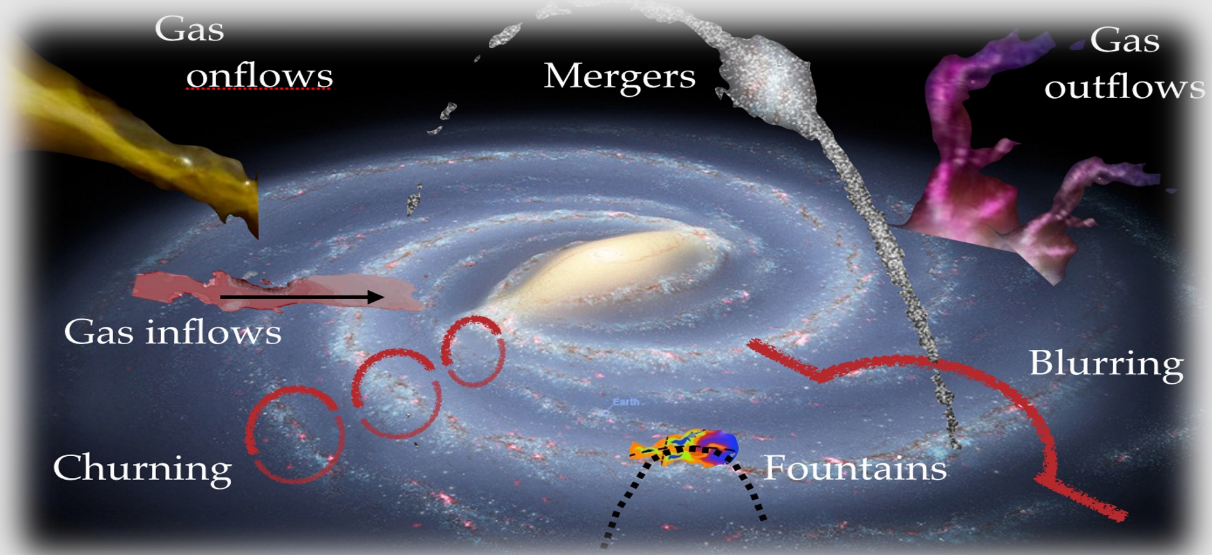
Emanuele
Spitoni
(EU H2020
EXPLORE post-doc)

Gabriele
Contursi
(PhD)

Outline of the talk

1. The Gaia revolution: roots and keys
2. The chemical cartography of the Milky Way
3. The Galactic disc(s):
    - structure and chemical gradients
    - kinematic disturbances
    - spiral arms pattern(s)
4. Conclusions





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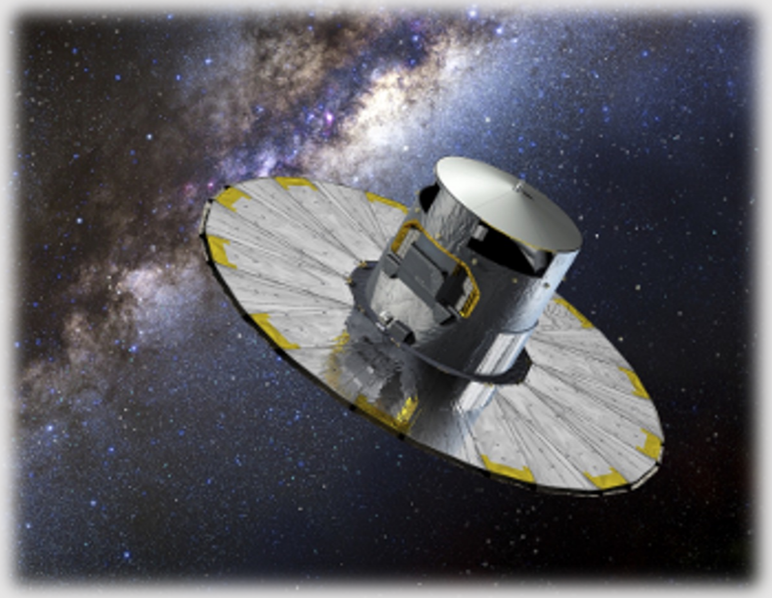
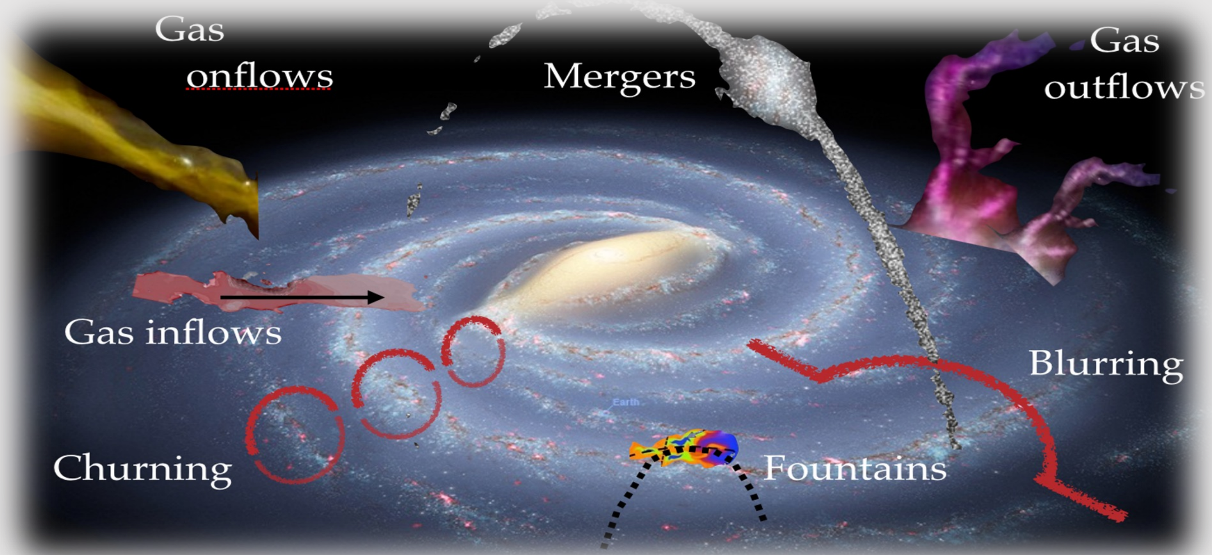


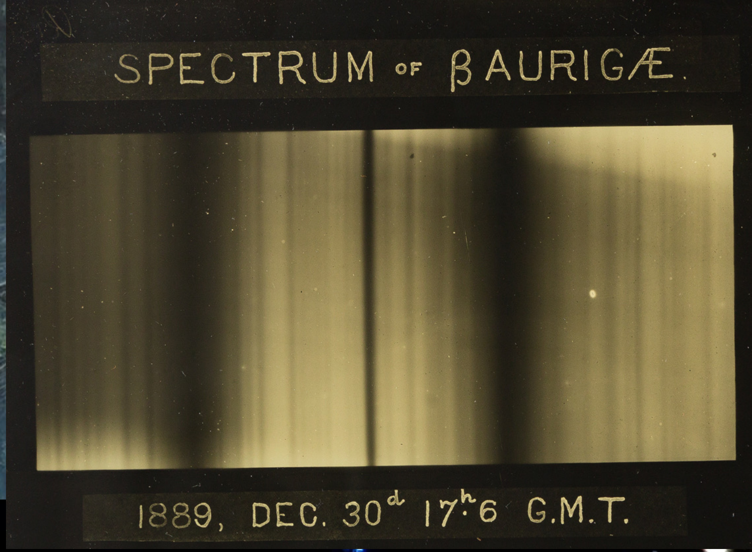



Vincent Van Gogh
(1888)


Vincent Van Gogh
(1888)

DSS image


Vincent Van Gogh
(1888)

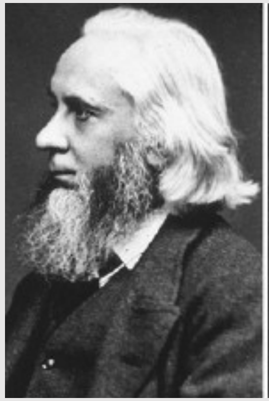

SPECTRUM OF β AURIGÆ.
1889, DEC. 30d 17h.6 G.M.T.


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

Spectroscopy

Angelo Secchi

William Huggins



Margaret Lindsay Huggins

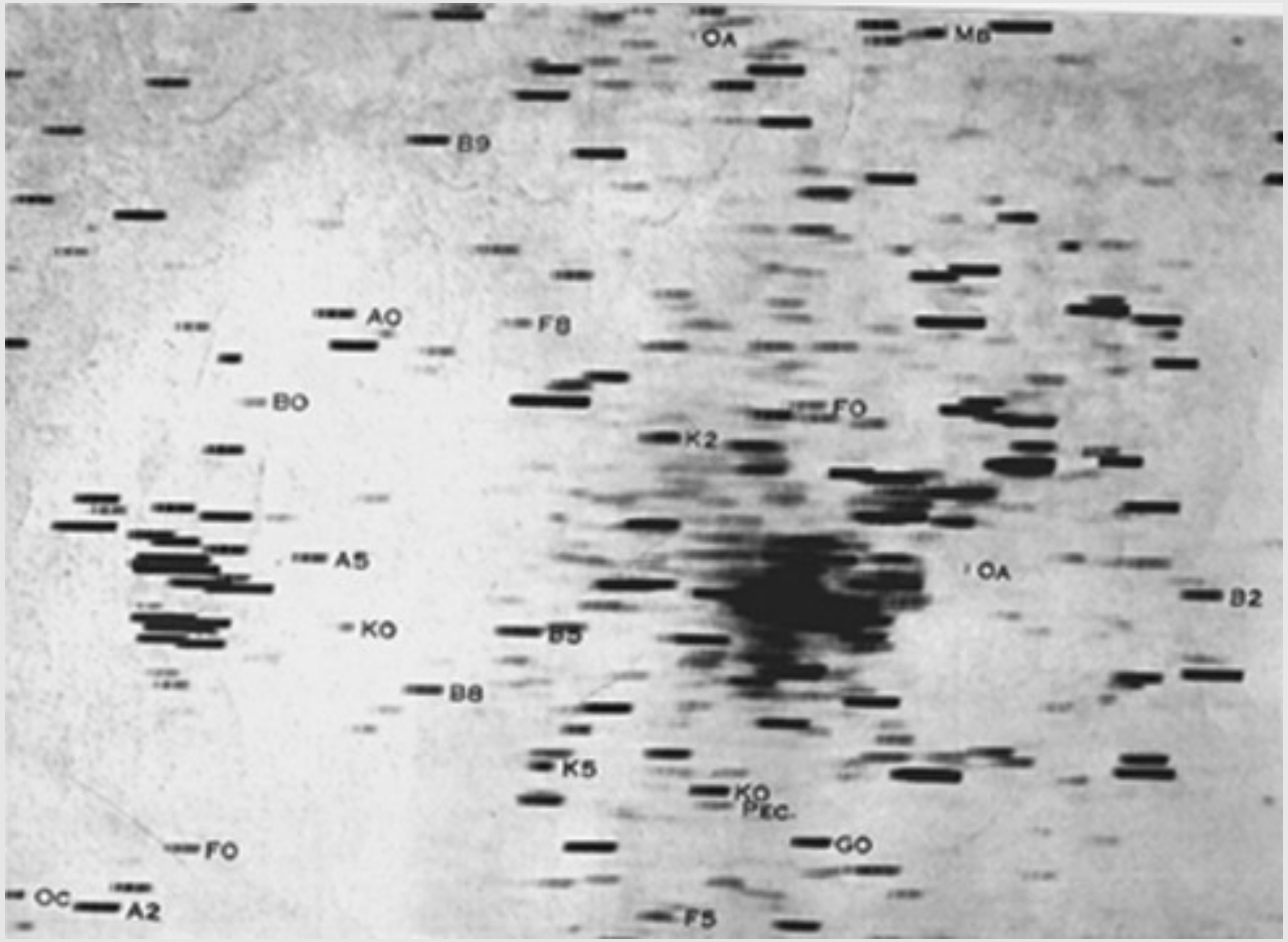
The Harvard computers

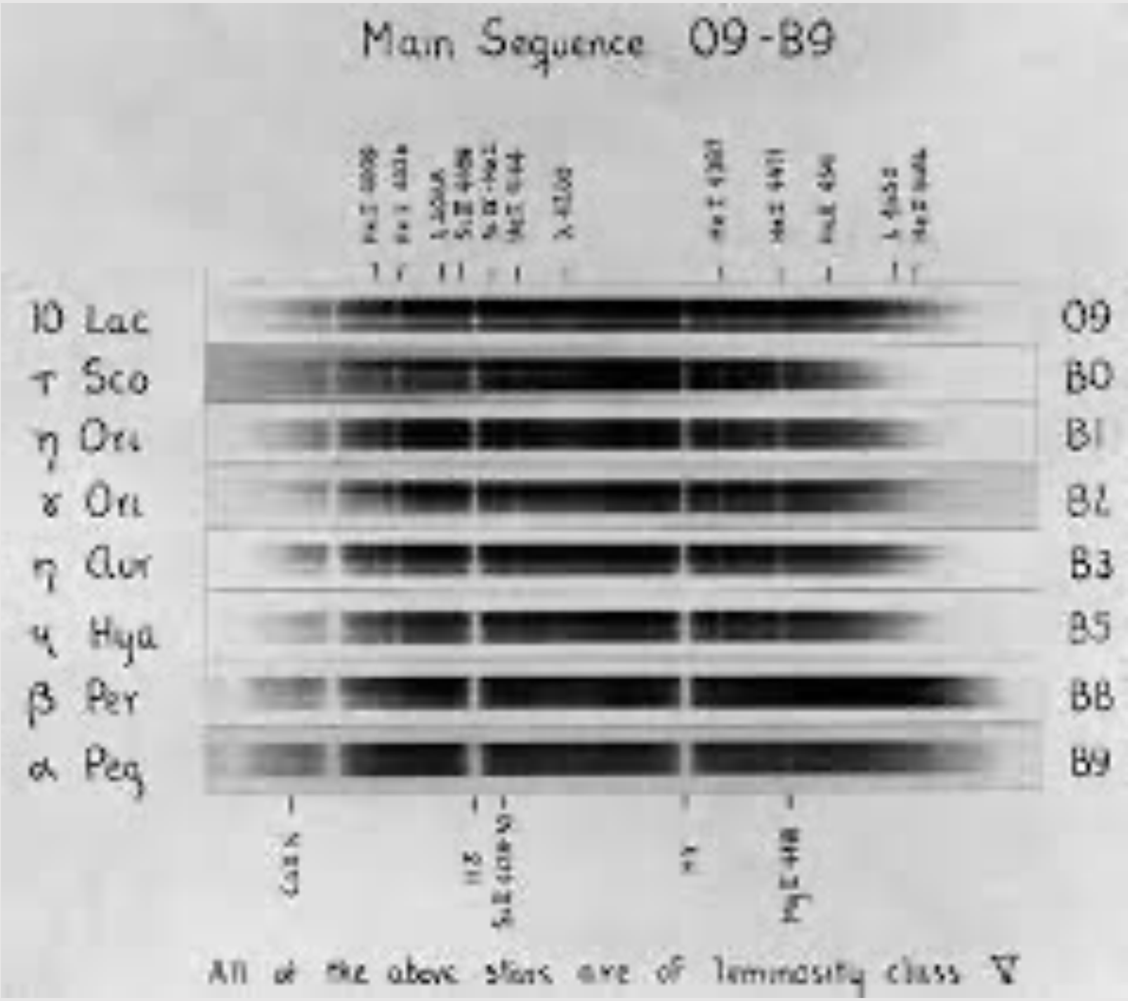
Antonia Maury

Annie Jump Cannon

Charles Pickering

Spectroscopy



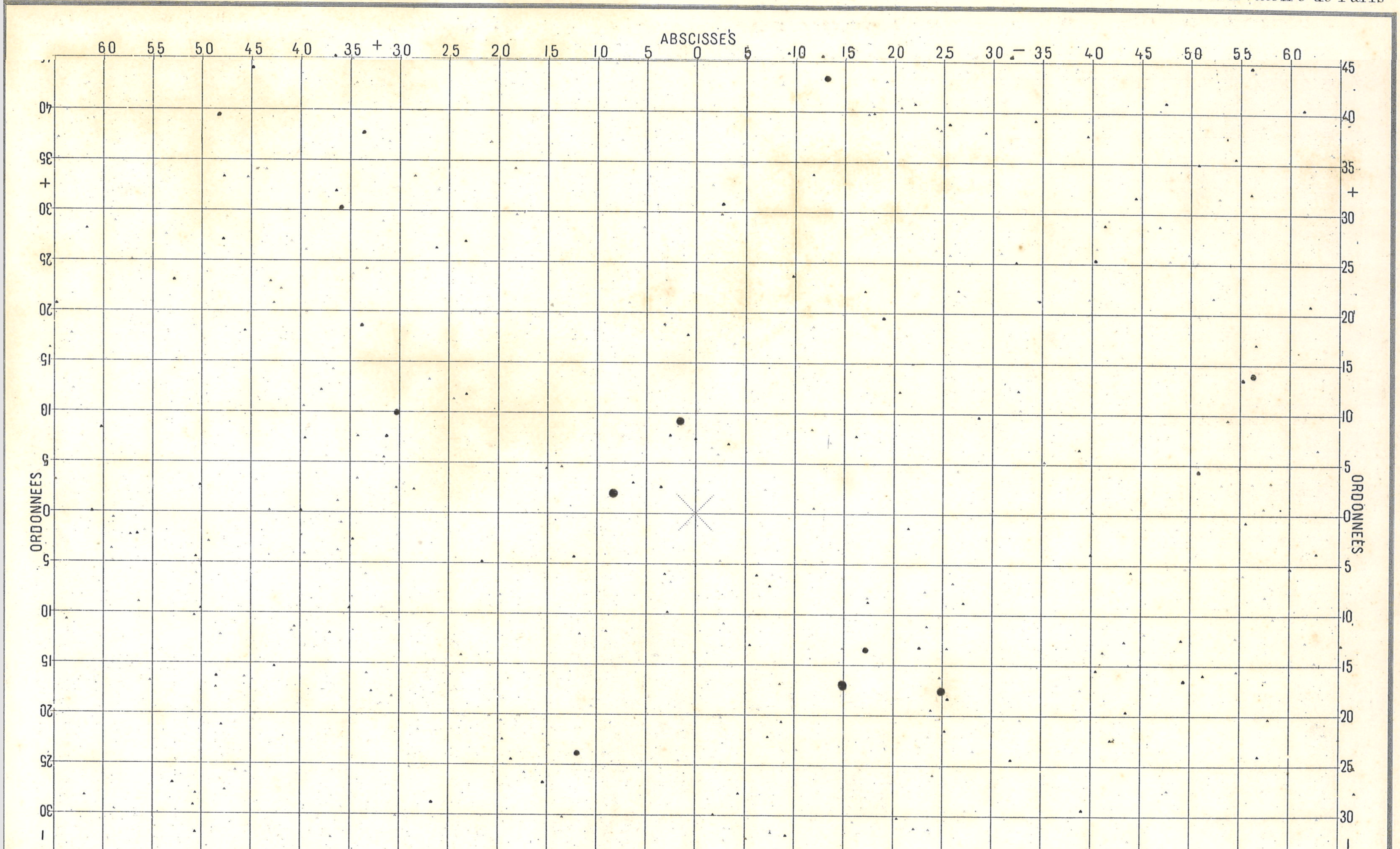


CARTE PHOTOGRAPHIQUE DU CIEL

Position du centre pour 1900 $\begin{cases} \text{Æ} = 12^h 48^m \\ D = +\ 20^\circ \end{cases}$

Zone +20° N° 97

Observatoire de Paris



Atomic Physics Spectroscopy

- **Stellar physical parameters**
- **Chemical composition**
- **Line-of-sight velocity -> 3D motions**

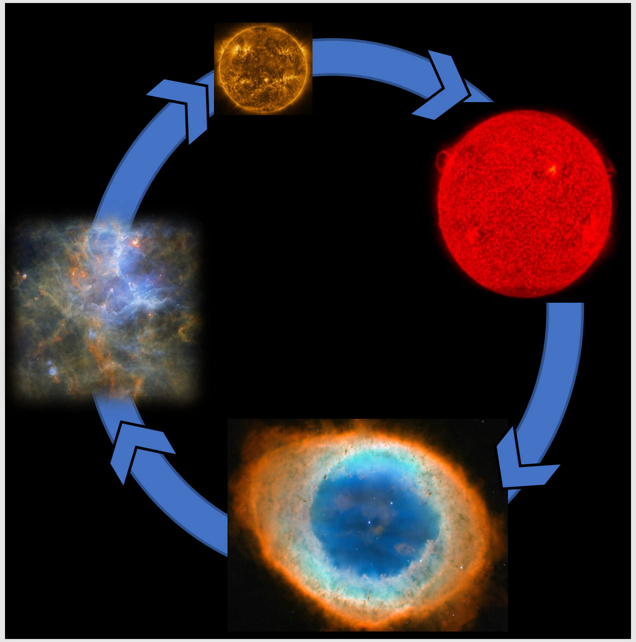
Cecilia Payne

George Gamow

Hans Bethe

Margaret Burbidge

Atomic Physics Spectroscopy



- Stellar physical parameters
- Chemical composition
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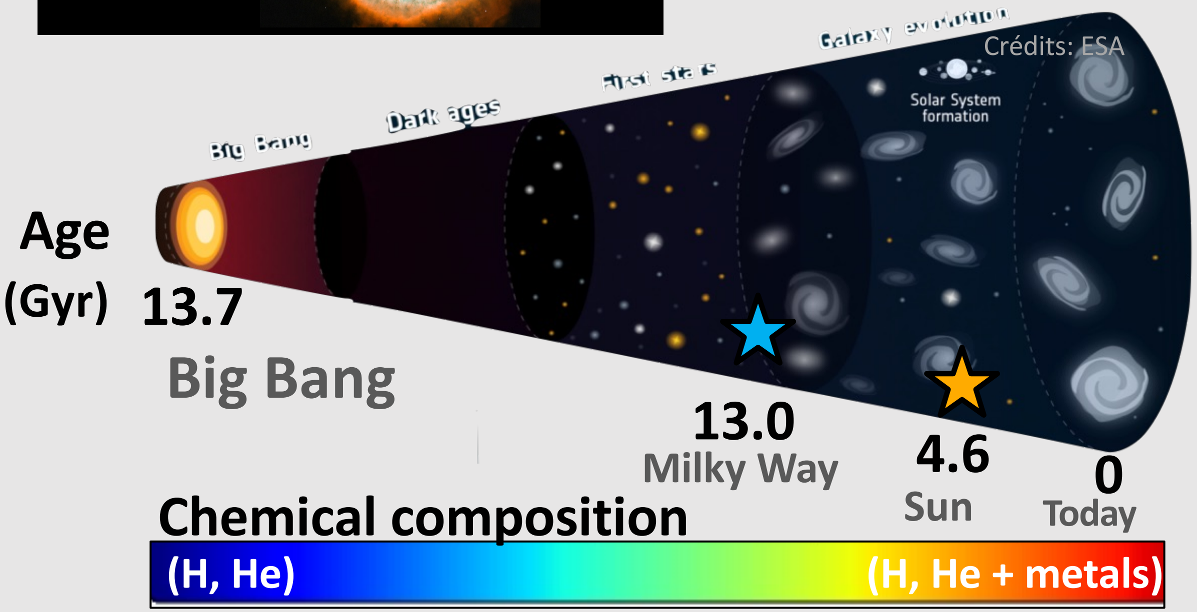
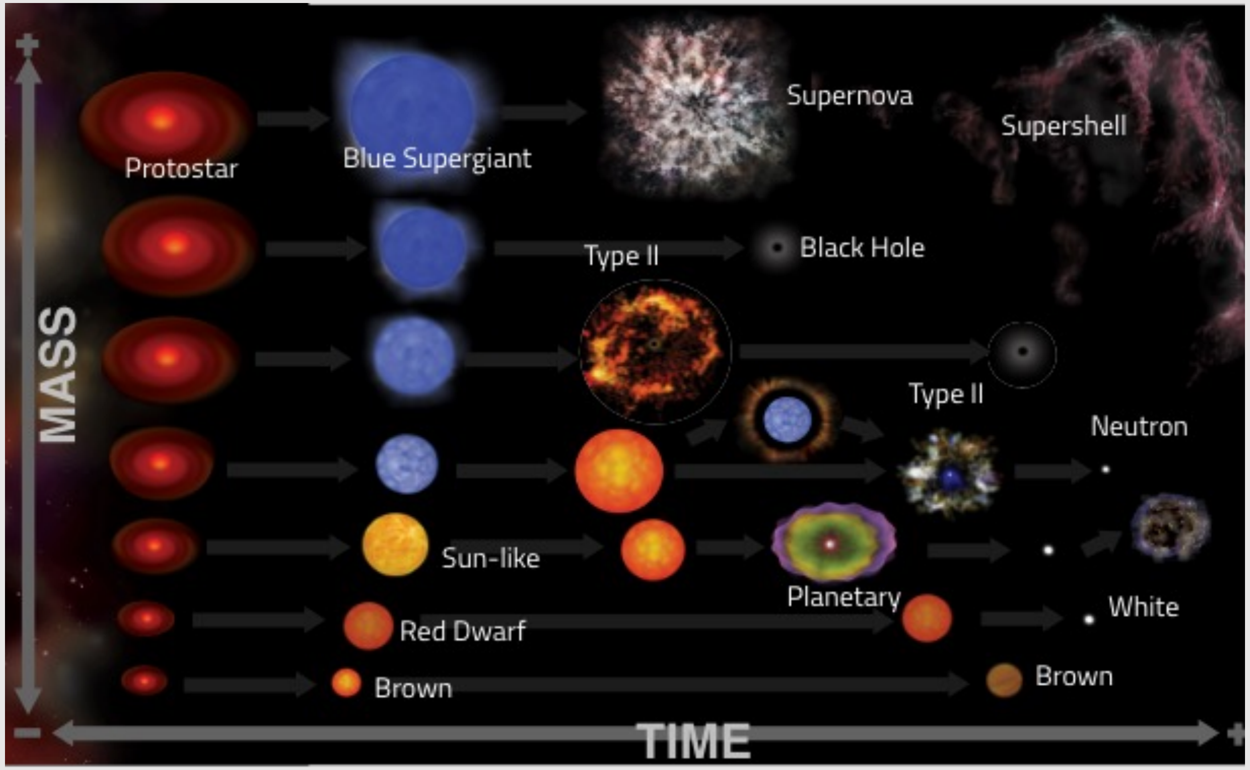
Evolution





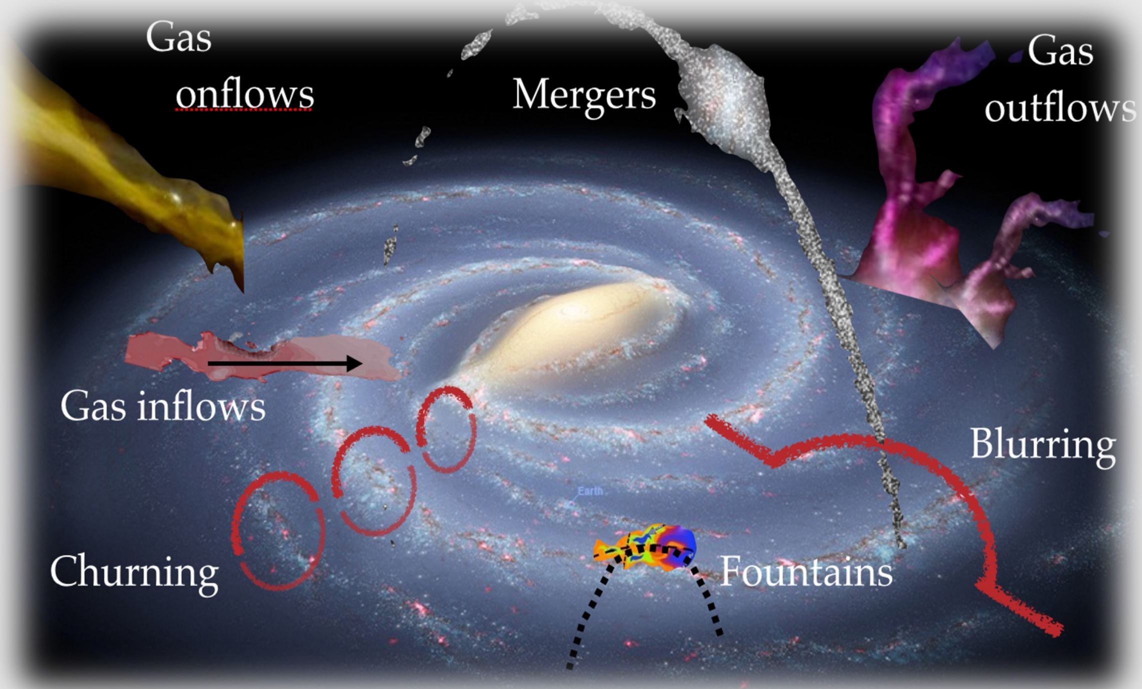
Gaia revolutions: roots and keys

Gaia combines the **astrometric** approach of **classical astronomy** with the **physical** approach of **modern astrophysics.**

This is enhanced by:

- High number statistics
- High precision
- Time series observations

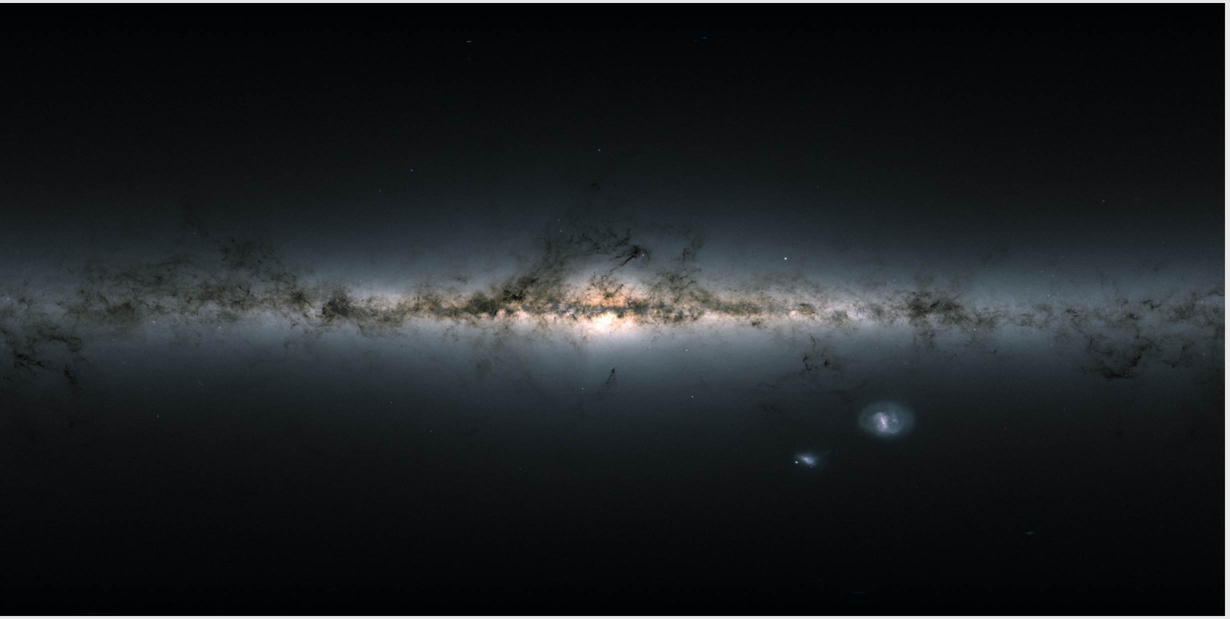
Detailed evolution of the Galaxy in its environment

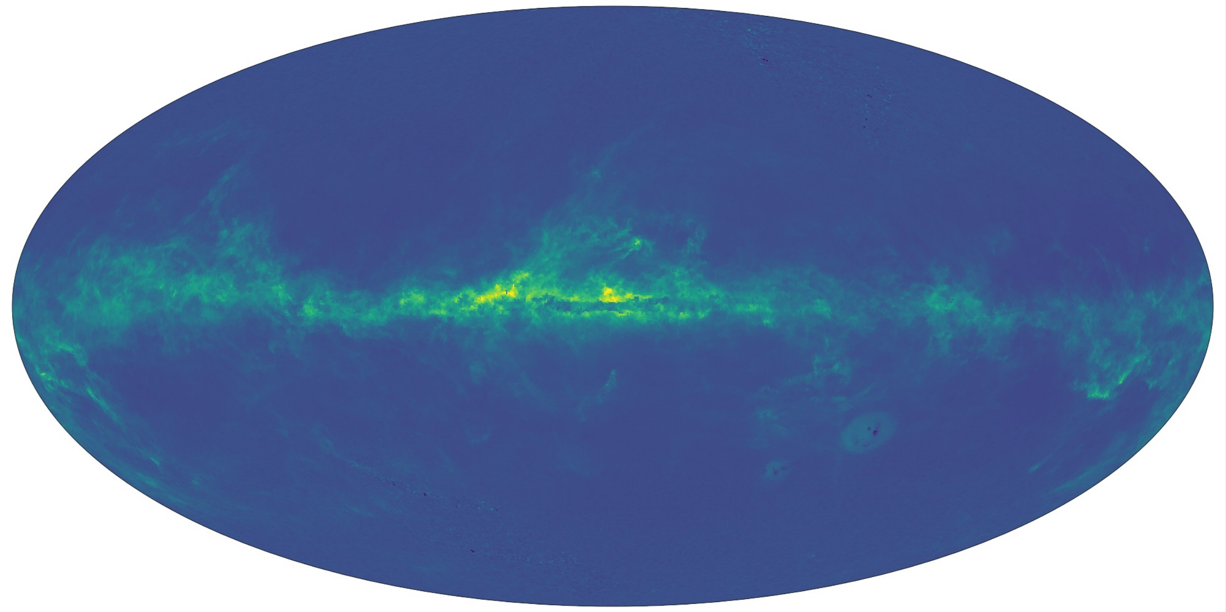


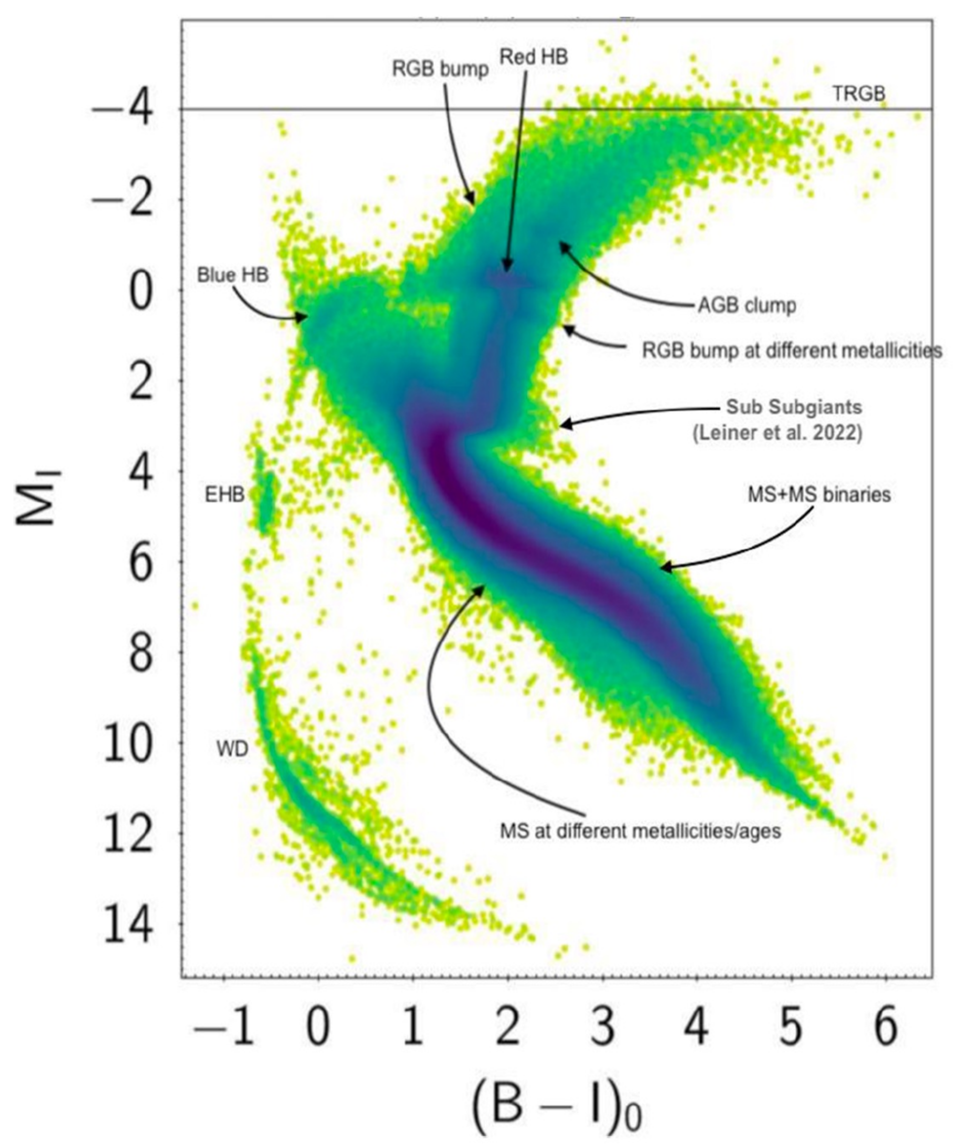
The keys of the Gaia revolution

- Parallaxes: the depth of the sky...
- **Number statistics:** 1.8 billion stars (astrometry+photometry)
  33 million stars (spectroscopy) Nb increasing!

Photometry





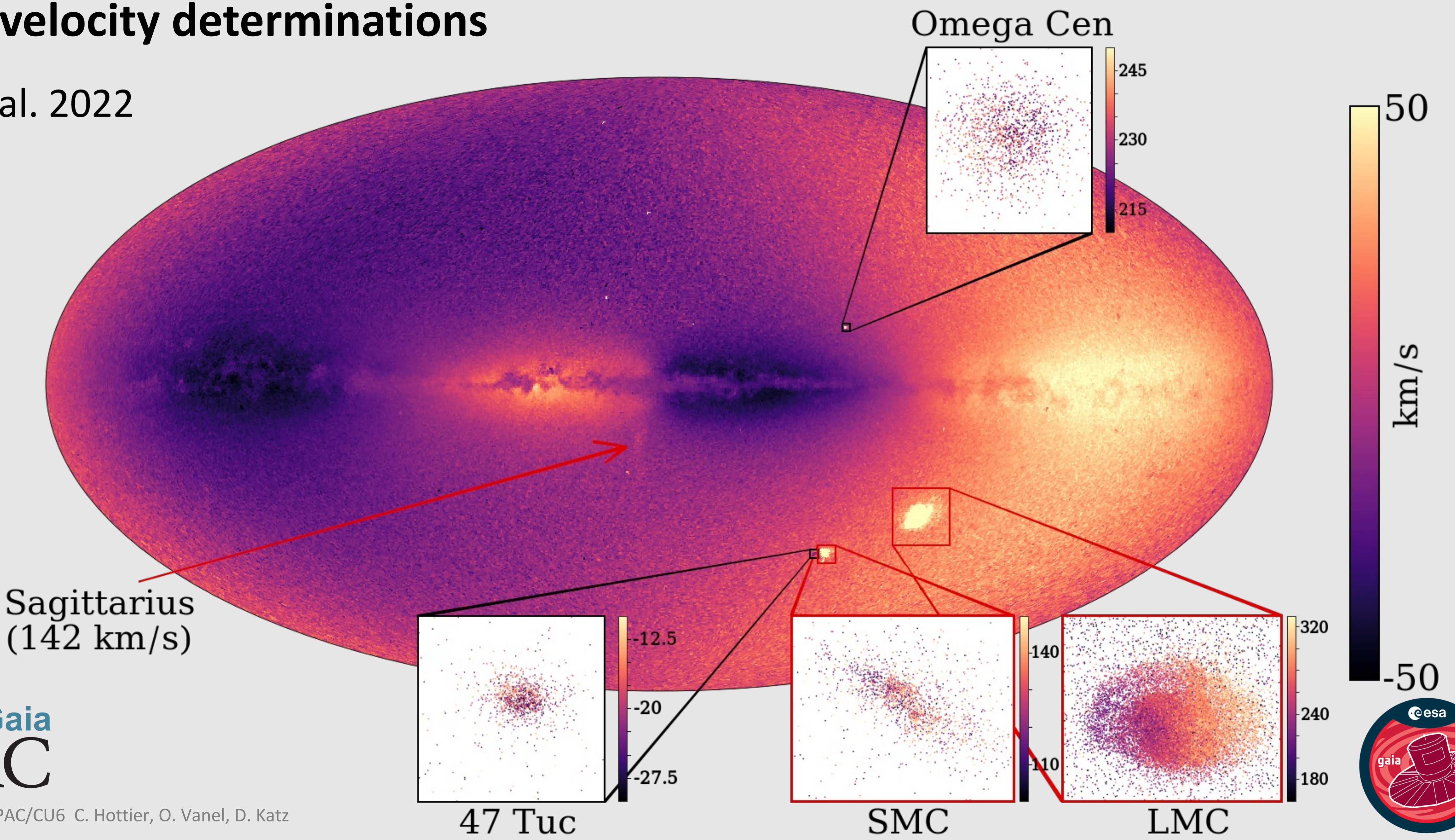


Gaia Collaboration, Montegriffo et al. 2022

Gaia DR3: 33.6 milion stars with radial velocity determinations

Spectroscopy

Katz et al. 2022



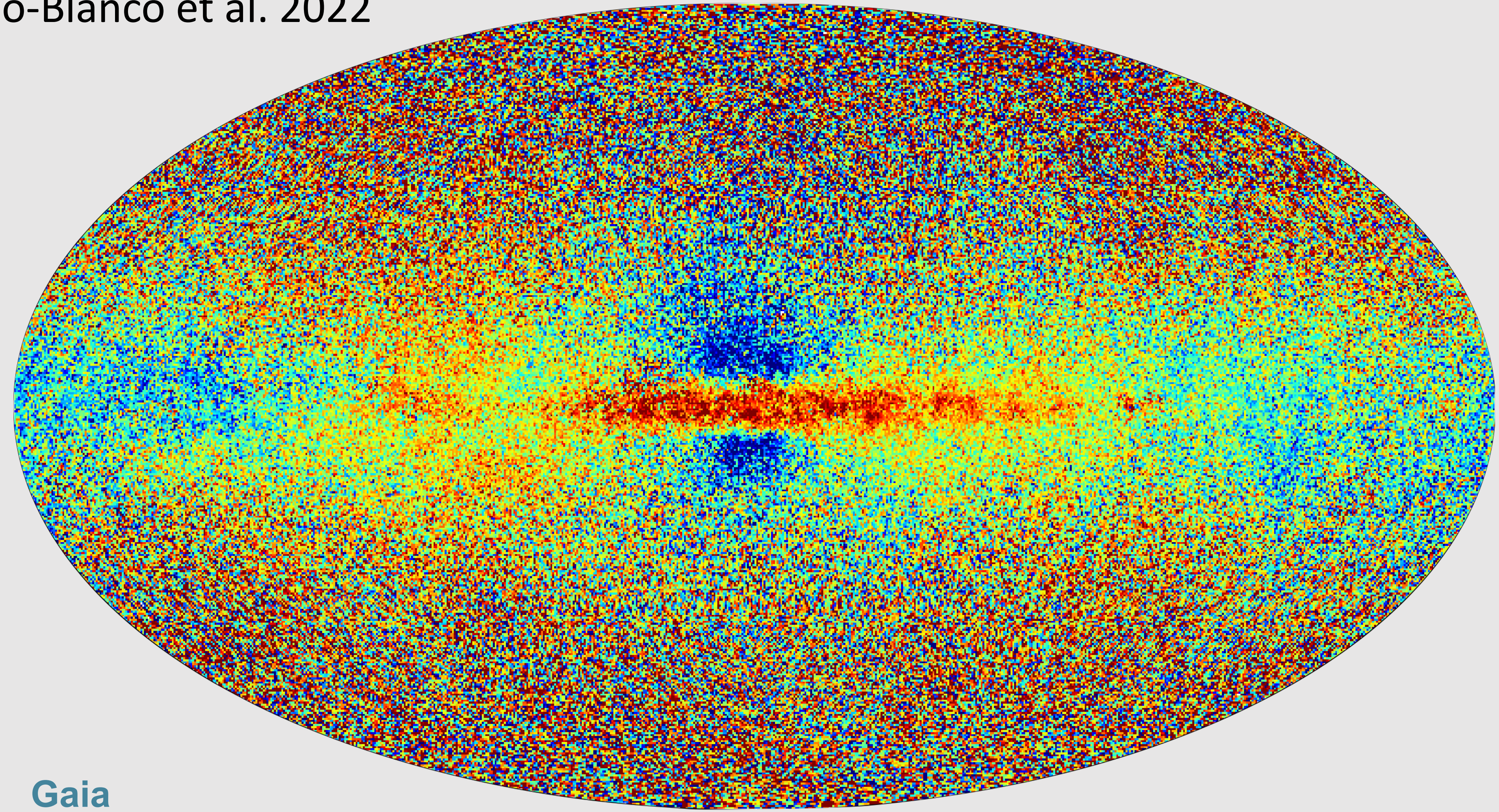
Gaia DPAC

Credits: ESA/GAIA/DPAC/CU6 C. Hottier, O. Vanel, D. Katz

Gaia DR3: 5.6 milion stars with chemo-physical parameters

Spectroscopy

Recio-Blanco et al. 2022



Gaia Collaboration, Recio-Blanco et al. 2022

Gaia DPAC

esa gaia

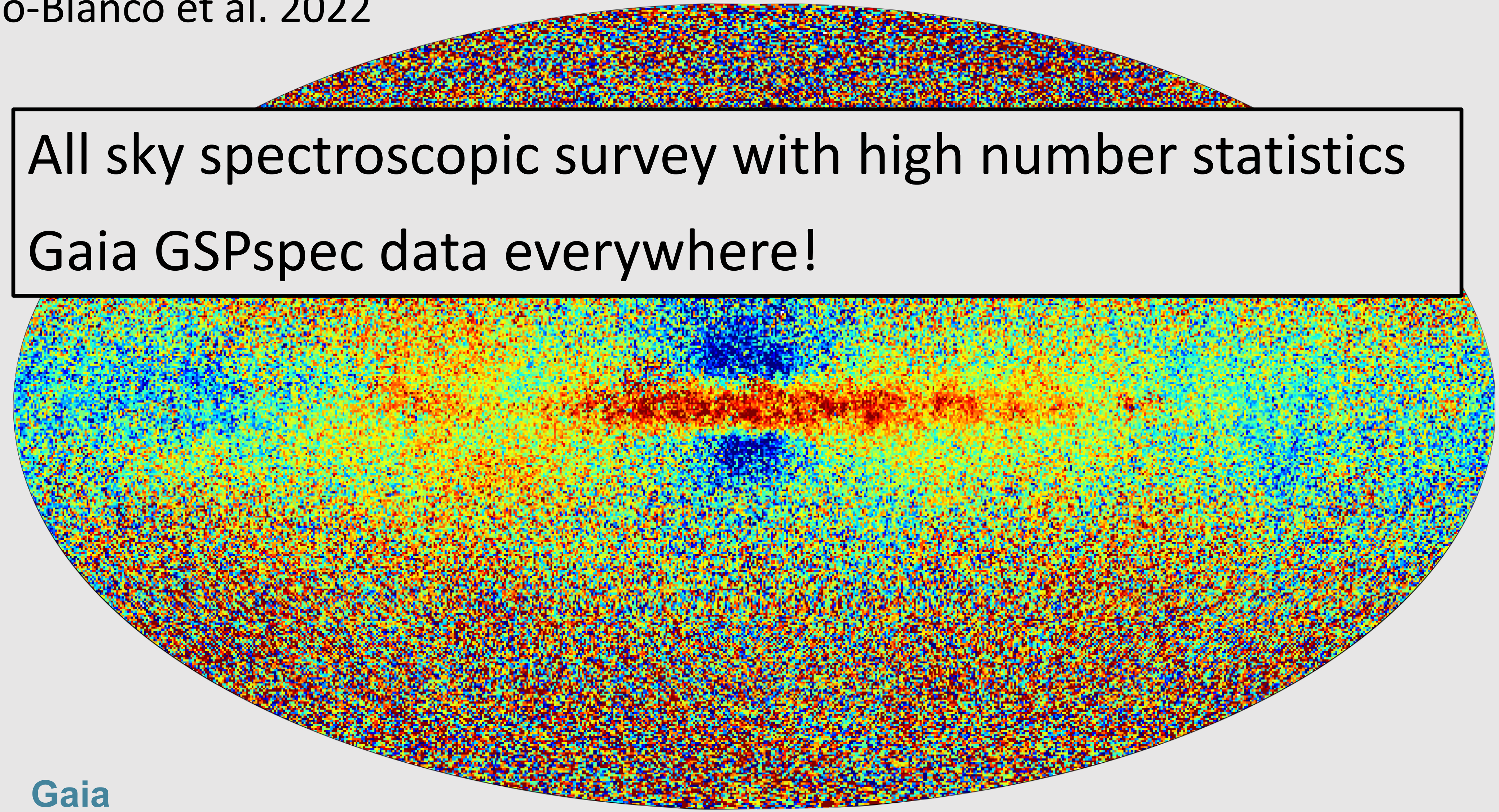
Gaia DR3: 5.6 milion stars with chemo-physical parameters

Spectroscopy

Recio-Blanco et al. 2022

All sky spectroscopic survey with high number statistics

Gaia GSPspec data everywhere!

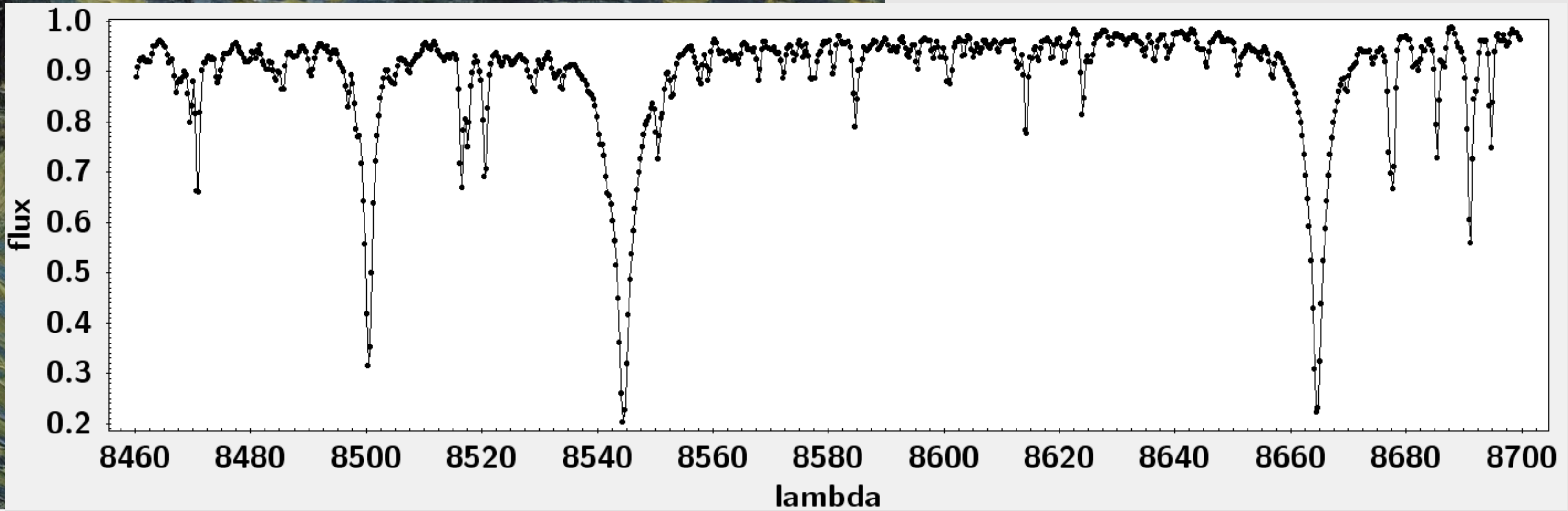


Gaia Collaboration, Recio-Blanco et al. 2022


Vincent Van Gogh
(1888)

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



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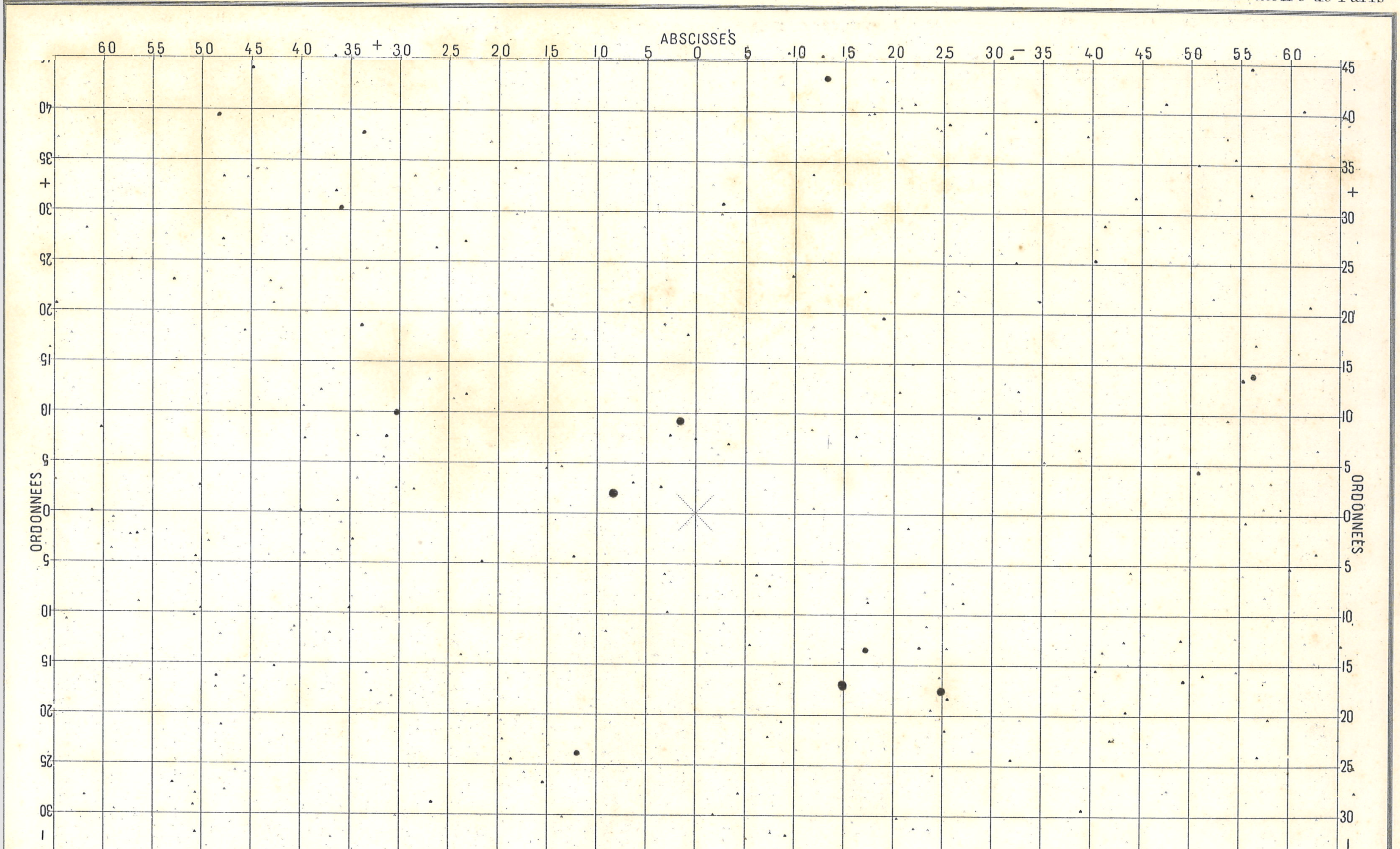
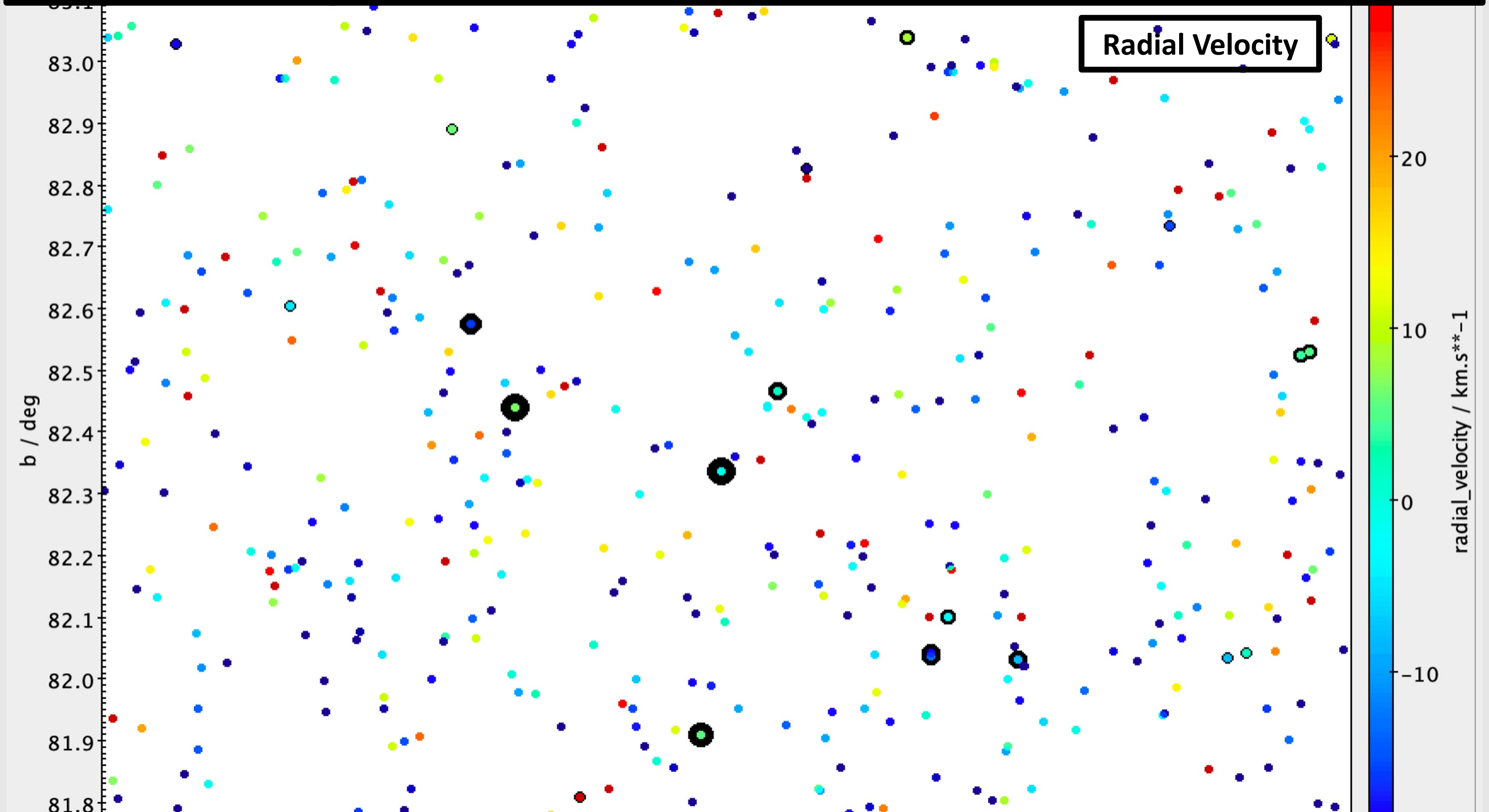
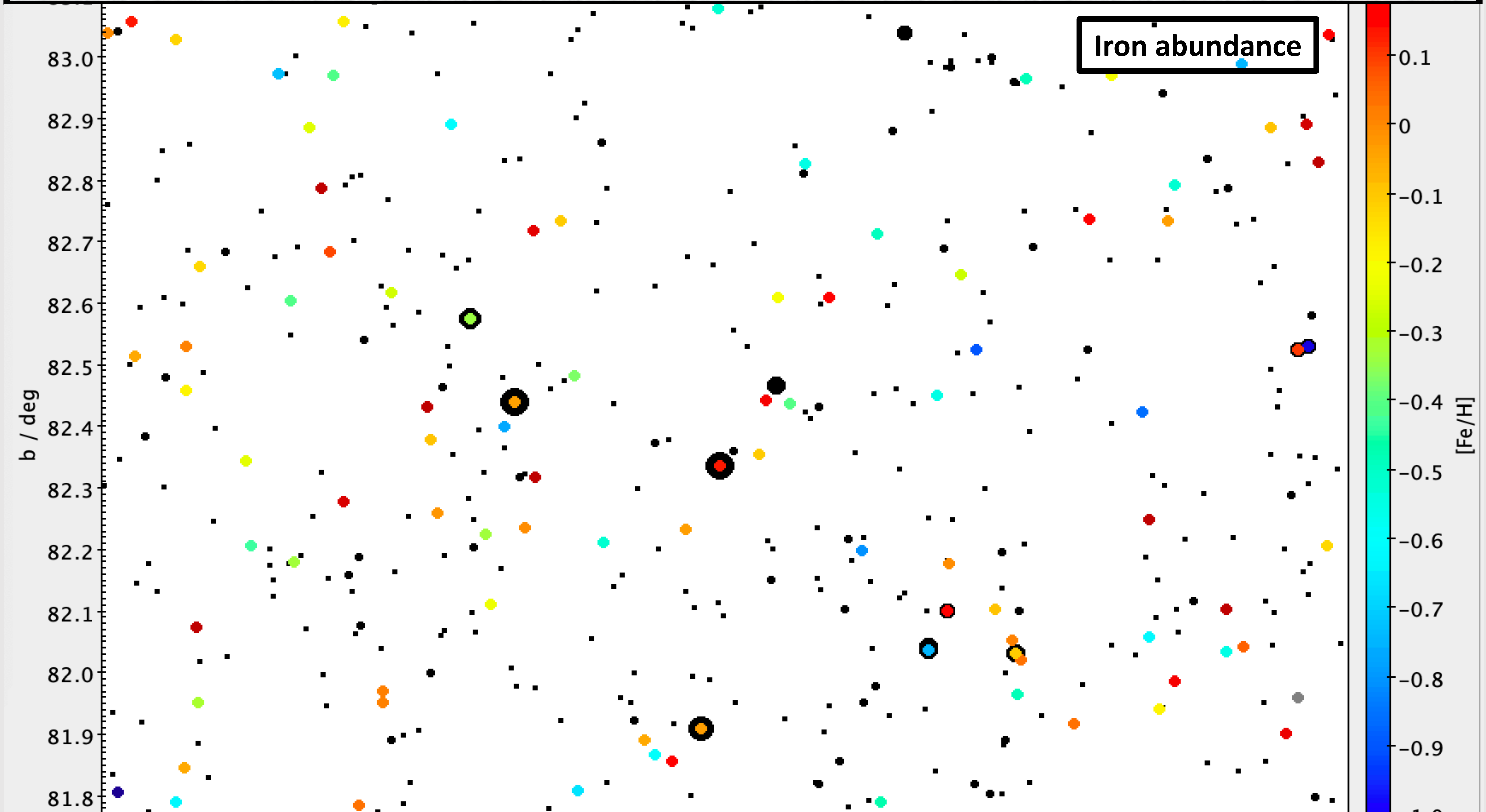


Carte Gaia RVS - DR3 2022



Carte Gaia RVS - DR3 2022



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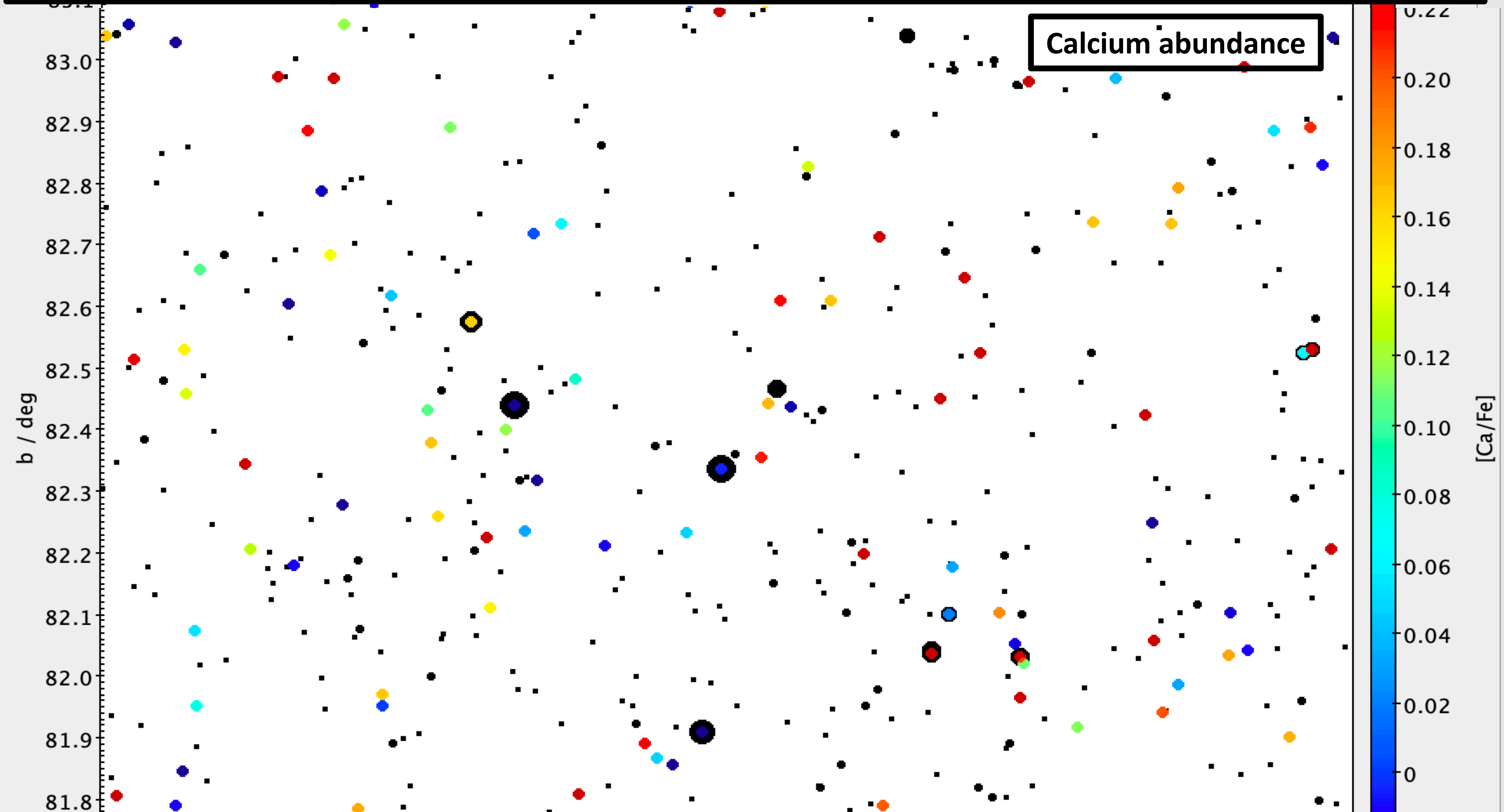

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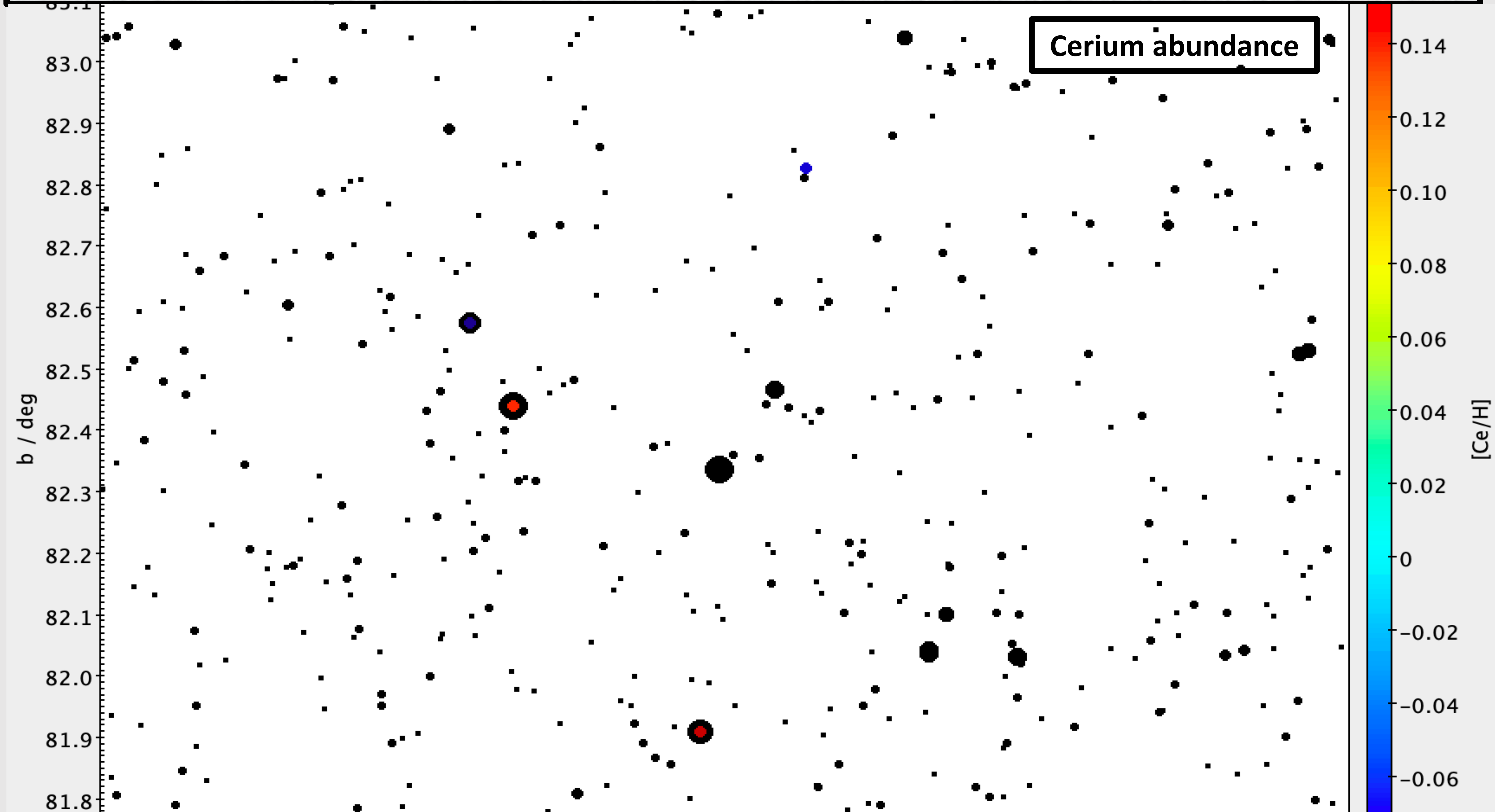
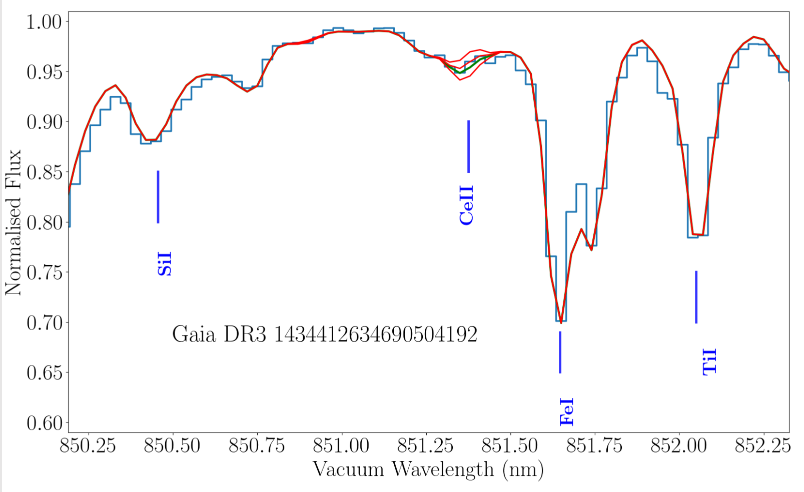


The keys of the Gaia revolution

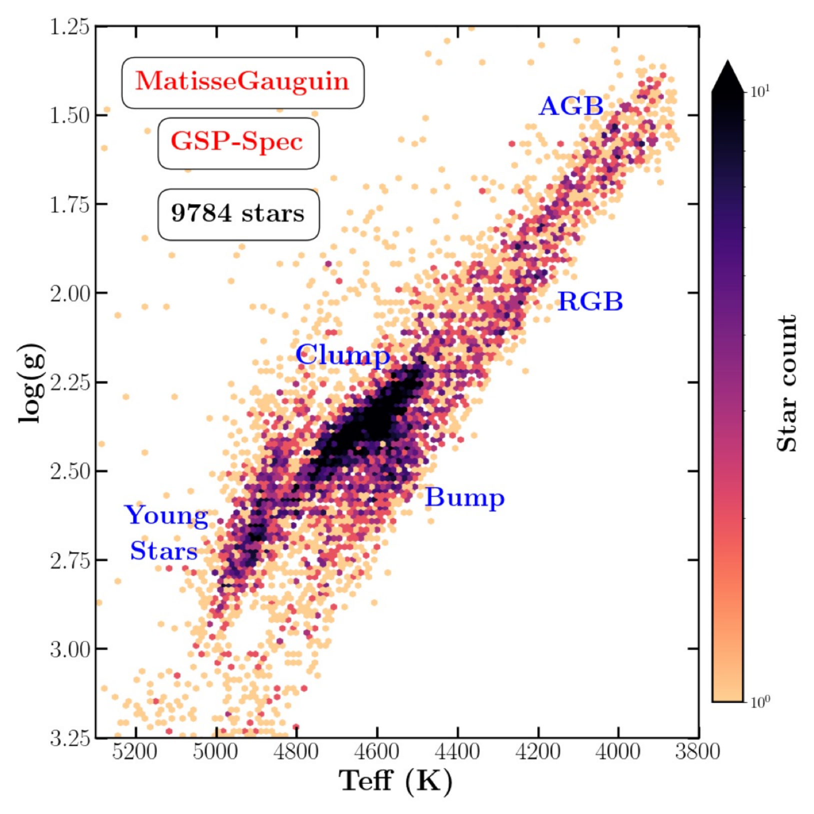
- Parallaxes: the depth of the sky...
- **Number statistics:** 1.8 billion stars (astrometry+photometry)
  33 million stars (spectroscopy) Nb increasing!
- **Stability and precision:** space observations (no Earth's atmosphere)
  extremely good control of systematics

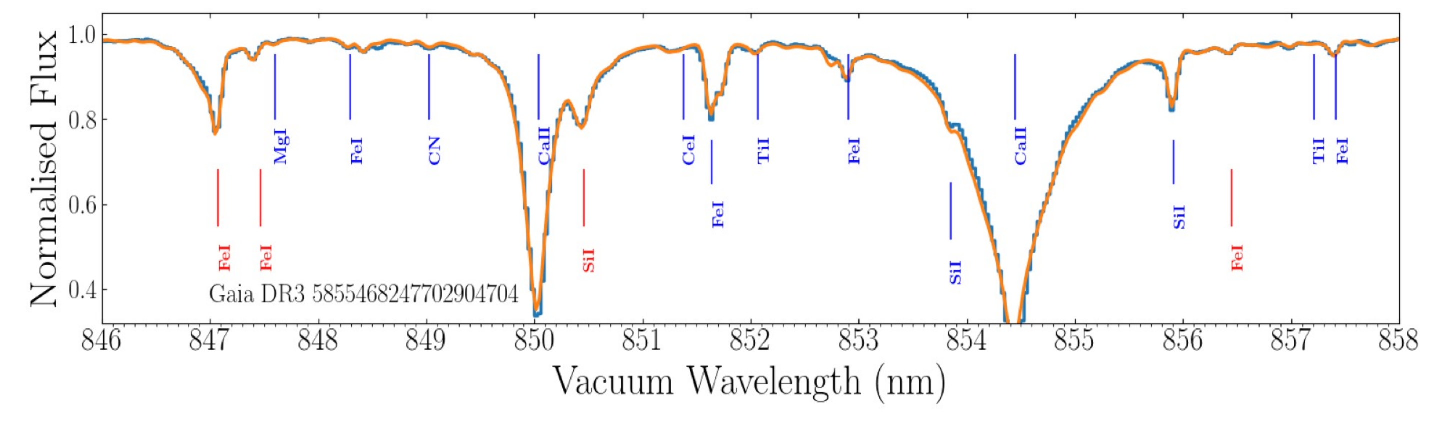
The keys of the Gaia revolution

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



Parametrization quality comparable to ground-based surveys of higher spectral resolution and wavelength coverage.

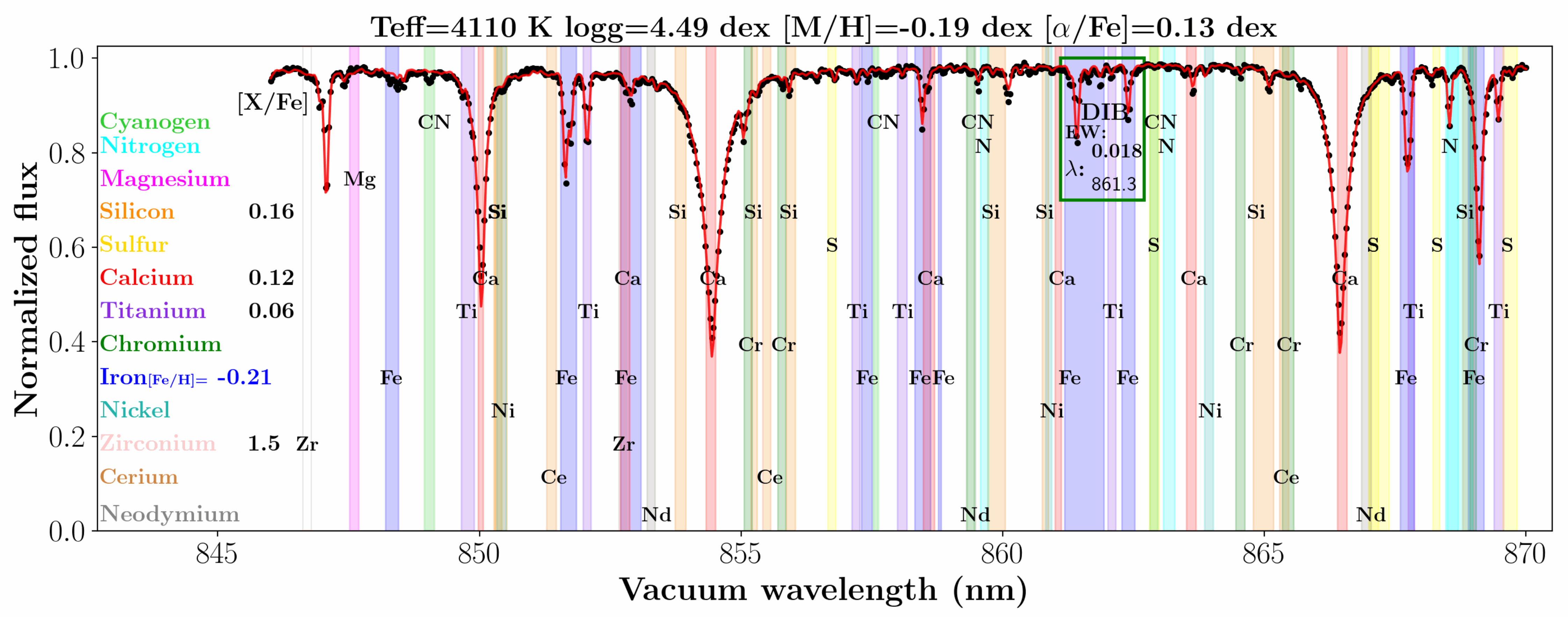




Recio-Blanco et al. 2022

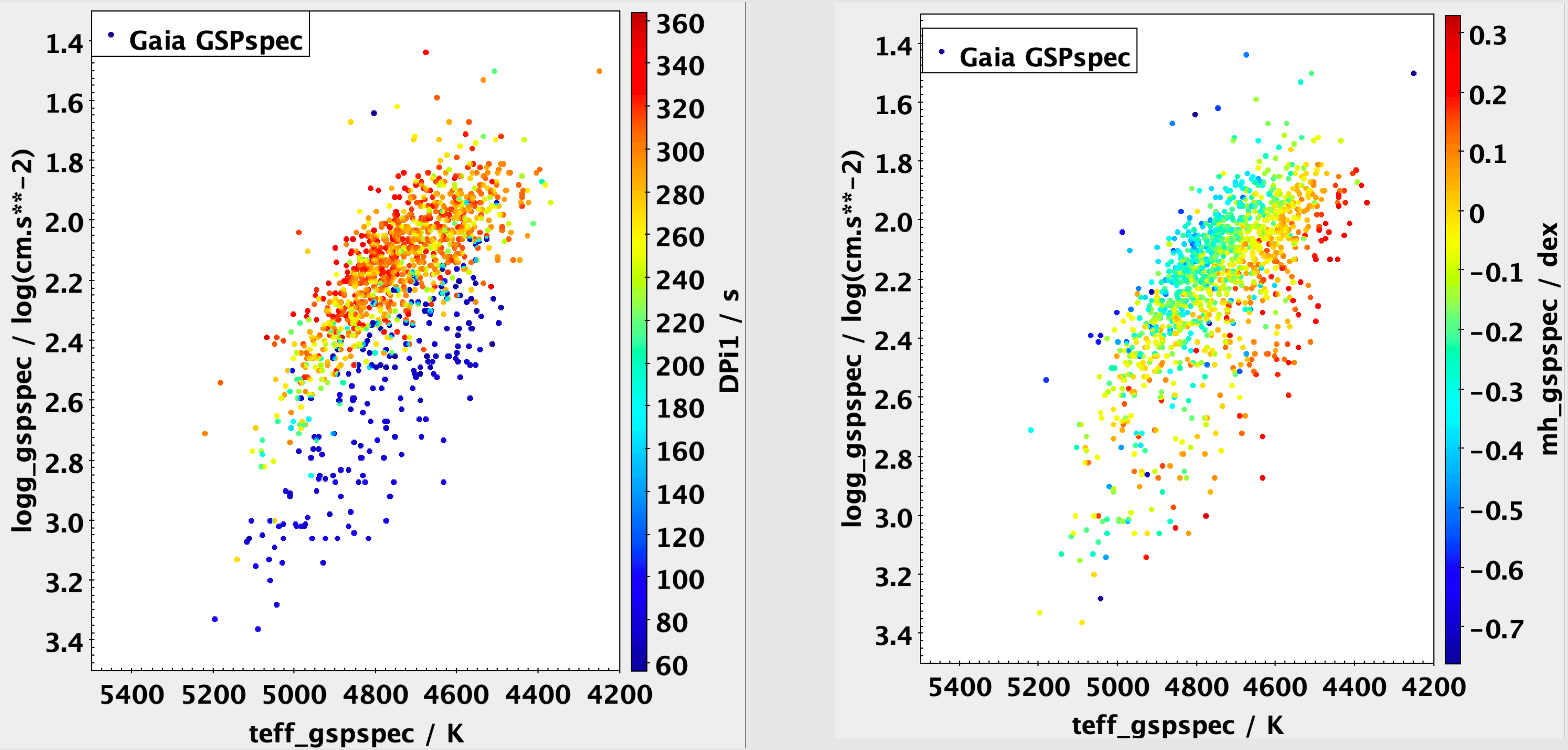
Gaia/RVS: a space spectroscopic survey

CU8/GSPspec: The chemical composition of 5.6 million stars

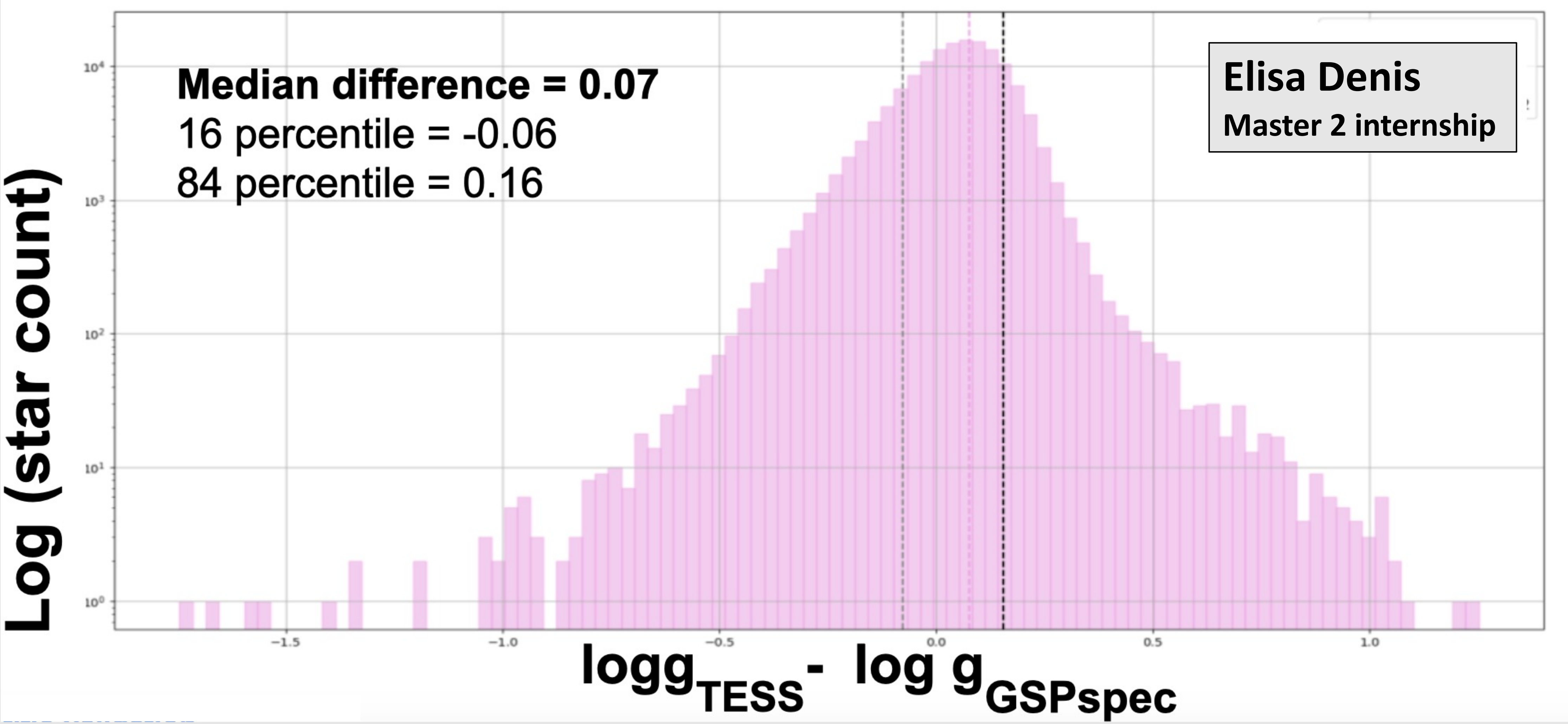


Credits:ESA/GAIA/DPAC-CU8-CU6 Recio-Blanco and the GSPspec team

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



Gaia/GSPspec + TESS: comparison of precision in log g



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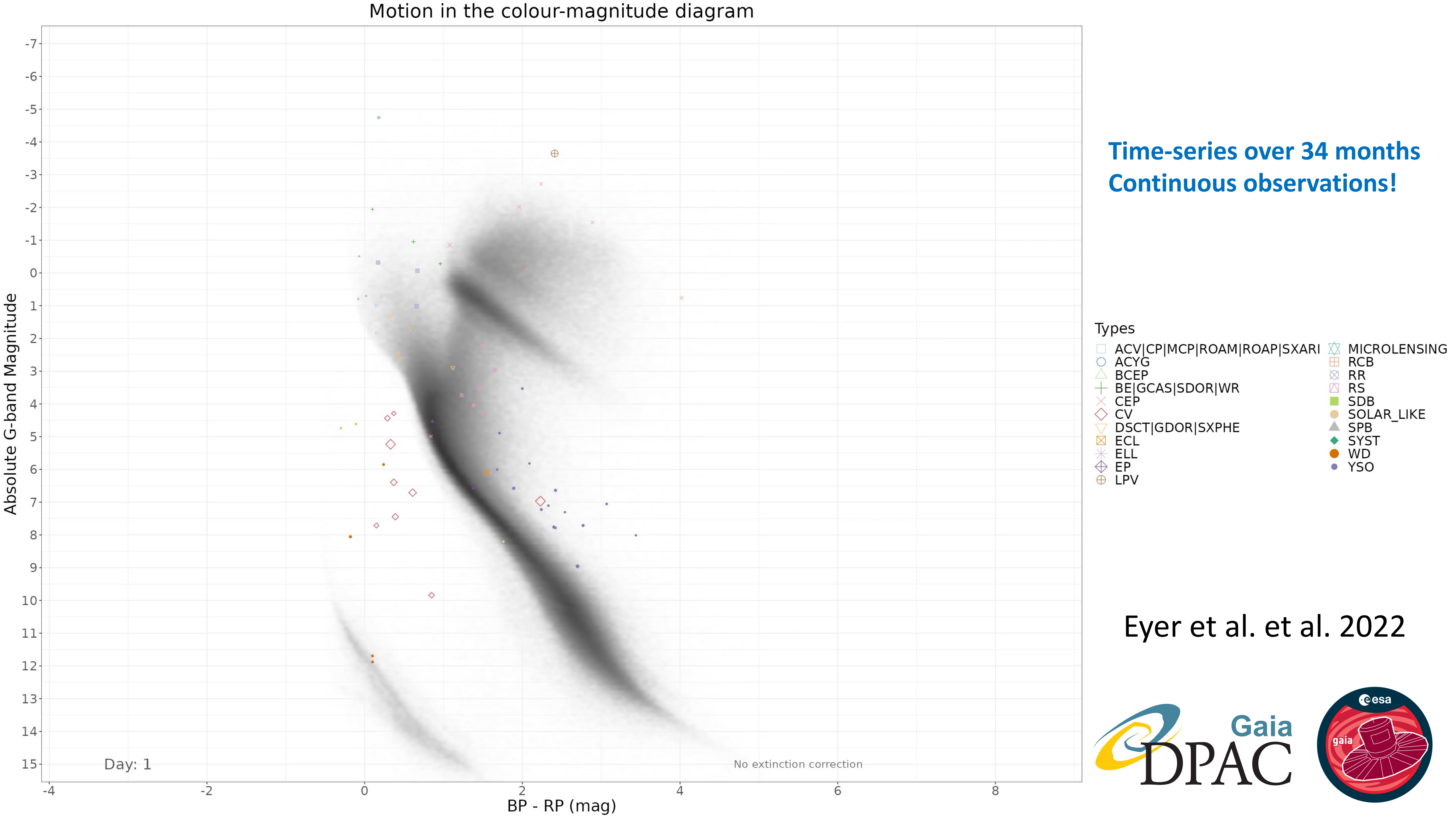
- **Stability and precision:** space observations (no Earth's atmosphere)
  extremely good control of systematics
- Time-series (continuous observations for years): **evolution!**
  - Proper motions
  - Solar System acceleration
  - Stellar variability
  - Binaries and their orbital solutions


Motion in the colour-magnitude diagram
Absolute G-band Magnitude
BP - RP (mag)
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
-4
-2
0
2
4
6
8
Day: 1
No extinction correction
Types
ACV|CP|MCP|ROAM|ROAP|SXARI
ACYG
BCEP
BE|GCAS|SDOR|WR
CEP
CV
DSCT|GDOR|SXPHE
ECL
ELL
EP
LPV
MICROLENSING
RCB
RR
RS
SDB
SOLAR_LIKE
SPB
SYST
WD
YSO
Time-series over 34 months
Continuous observations!
Eyer et al. et al. 2022
Gaia
DPAC
esa
gaia

Outline of the talk

1. The Gaia revolution: roots and keys
2. The chemical cartography of the Milky Way
3. The Galactic disc(s):
   - structure and chemical gradients
   - kinematic disturbances
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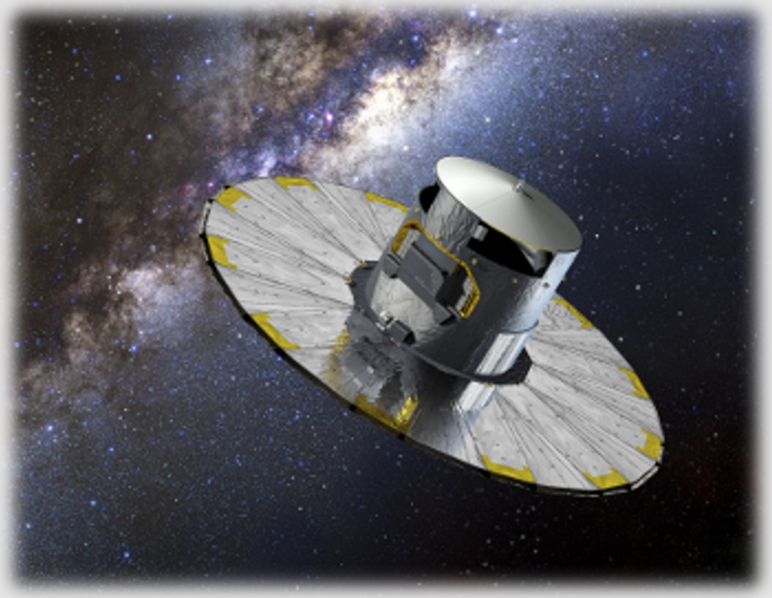
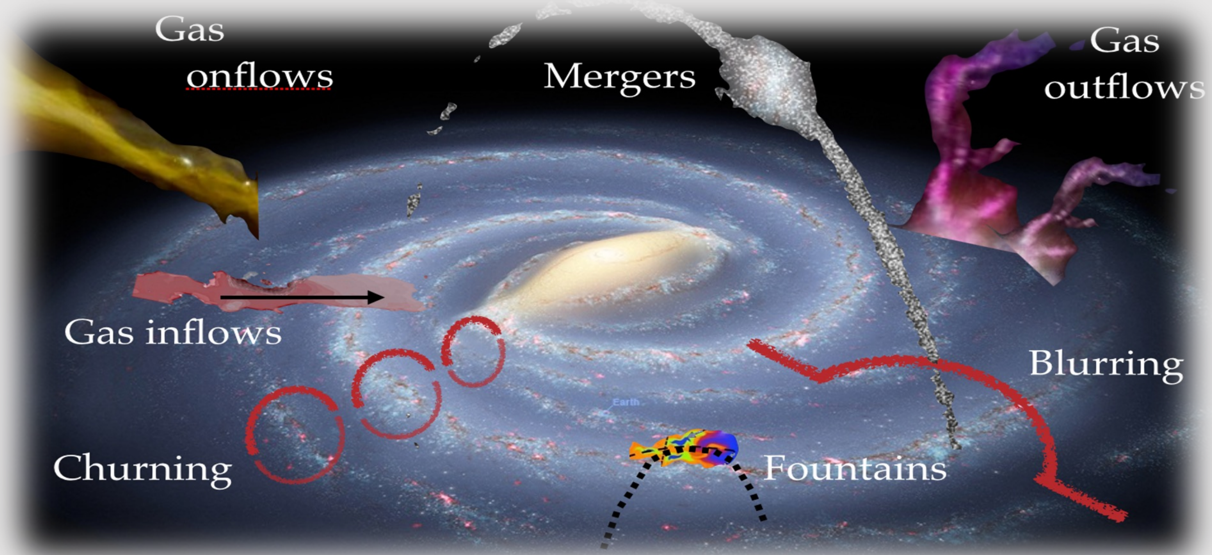
4. Conclusions





Workshop 7 RVS Working Group, 11-12 Dec 2003

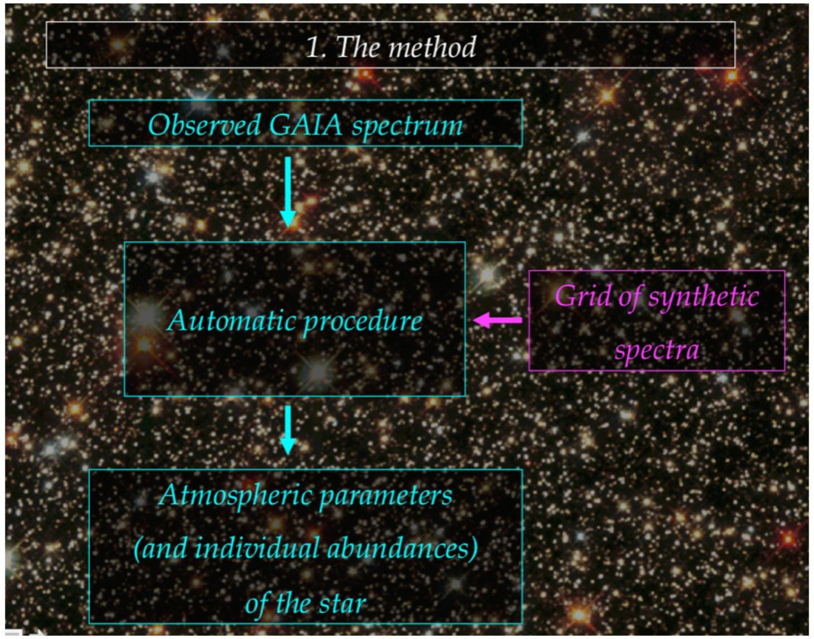
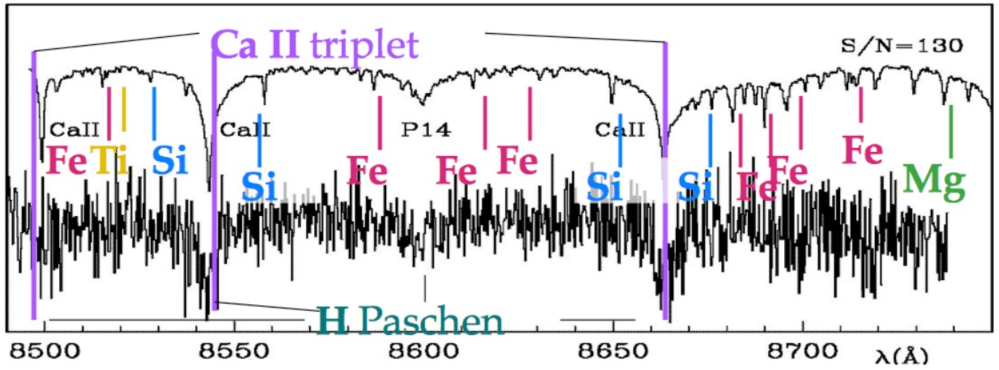


Photo during ESA external fellowship

copy-right Eric Lagadec (PhD student)!

DPAC creation in 2006 **First CU8 DPAC meeting**

Generalized Stellar Parametrizer – Spectroscopy (GSP-spec) GWP-S-823-0000



Alejandra Recio-Blanco *on behalf of the GSP-spec group*
Nice, 16-17 March 2006

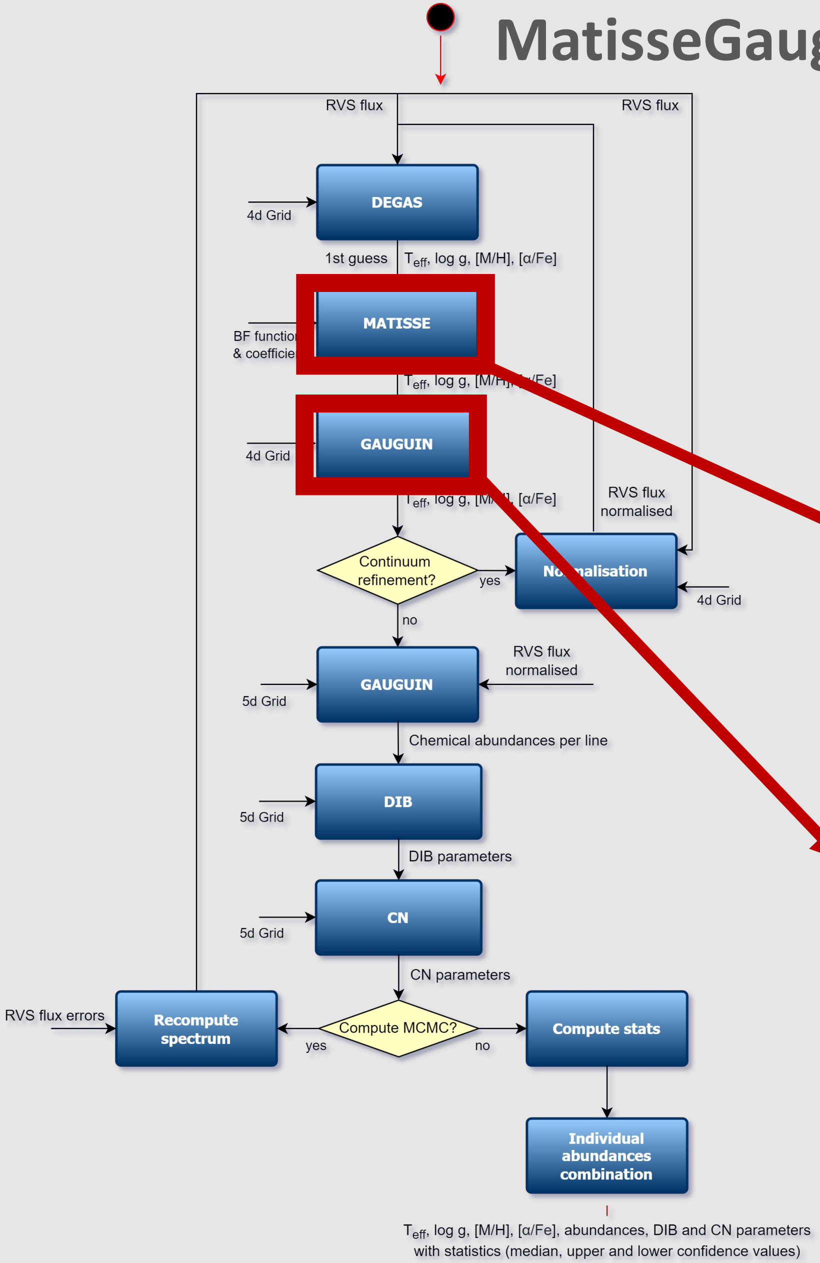
Brussels, 2011

When we started, automated spectra parameterization practically did not exist… and almost nobody cared!

Gaia/RVS/GSPspec

GSPspec (Recio-Blanco et al. 2022)

MatisseGauguin



AstrophysicalParameters table in the Gaia Archive

Atmospheric Parameters

Individual chemical abundances

Differential CN EW

Diffuse Interstellar Band parameters

Matisse: Projection method

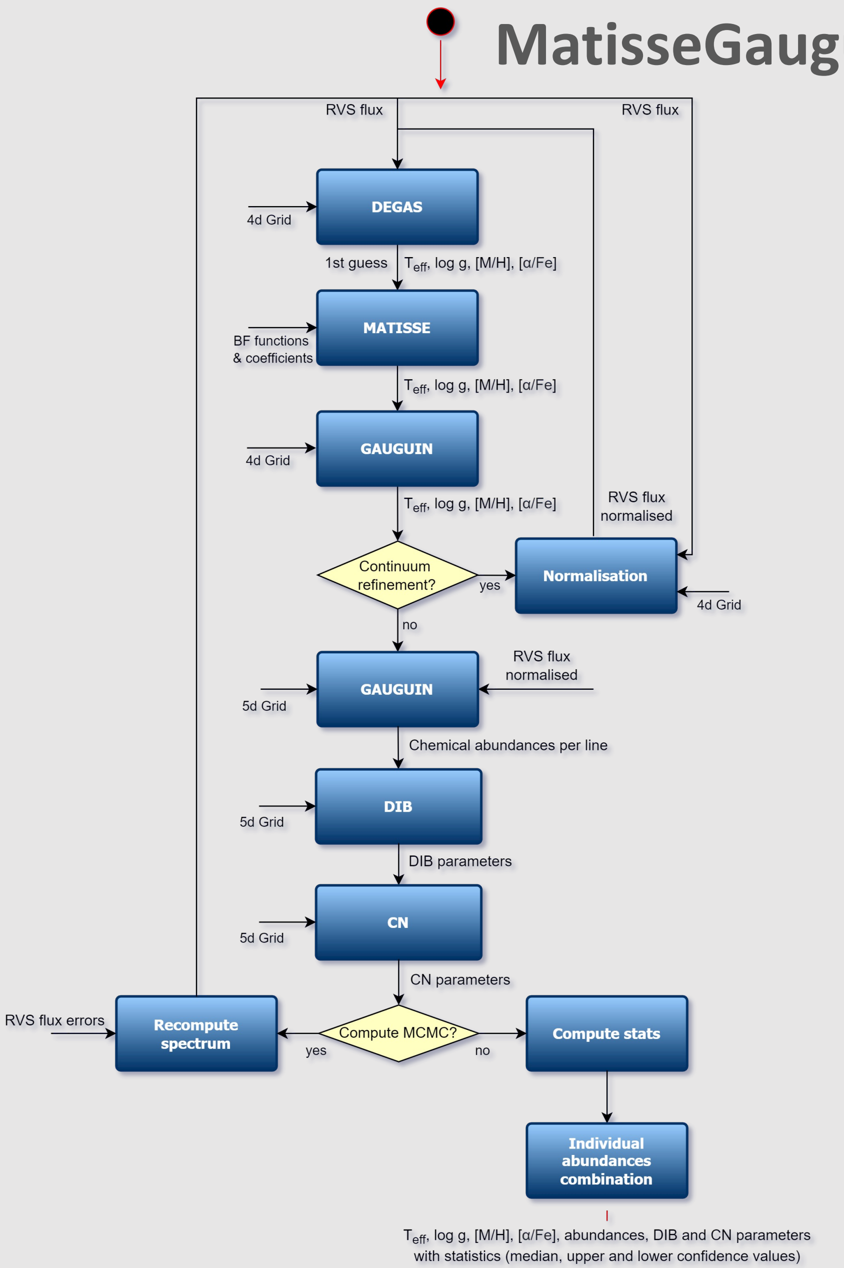
ARB, Bijaoui & de Laverny (2006)

Gauguin: Gauss-Newton algorithm

Bijaoui, ARB, de Laverny, Ordenovic (2012)

Gaia/RVS/GSPspec GSPspec (Recio-Blanco et al. 2022)

MatisseGauguin



AstrophysicalParameters table in the Gaia Archive

Atmospheric Parameters

Individual chemical abundances

Differential CN EW

Diffuse Interstellar Band parameters

DR3 operations at DPCC (CNES-Toulouse)

6.9 million spectra treated

50 MC realisations of each RVS spectrum -> APs uncertainties

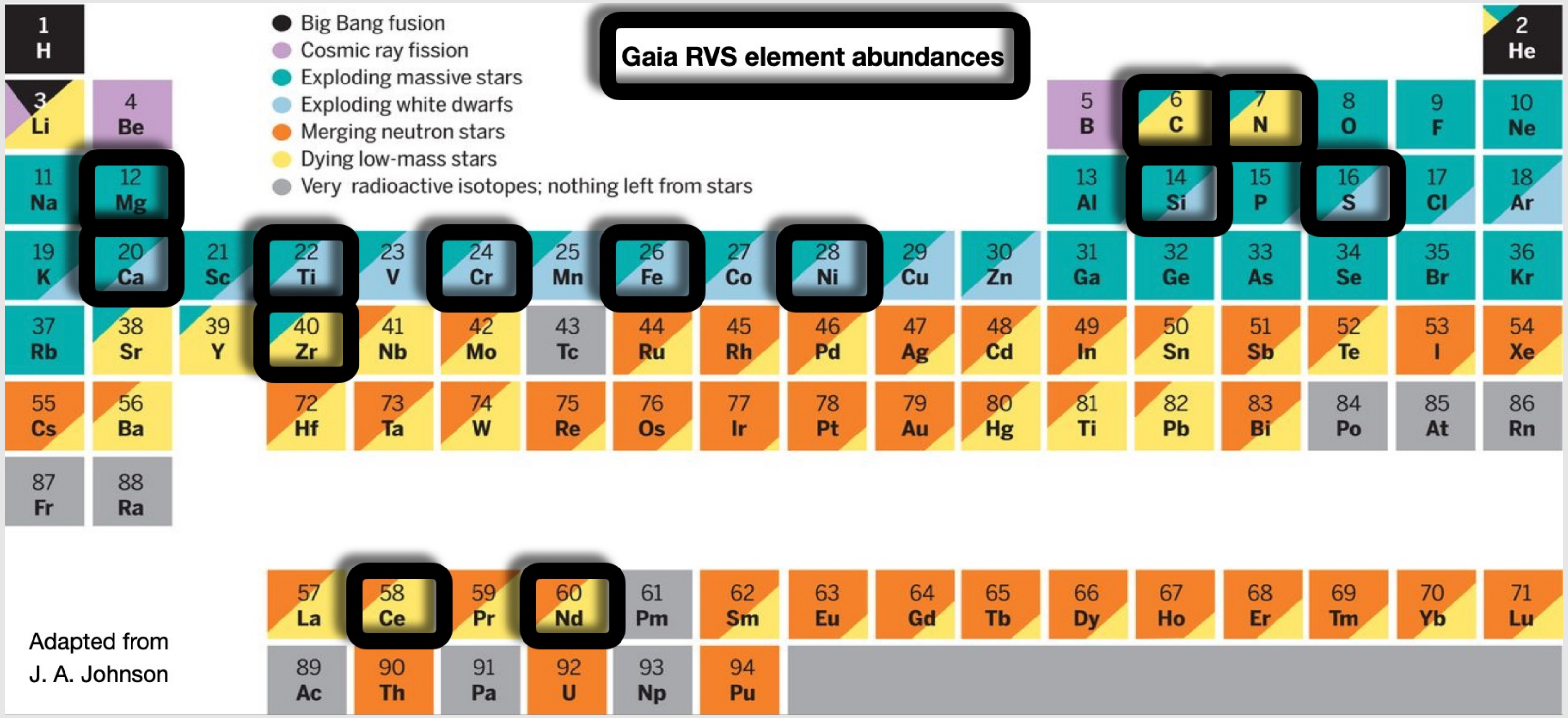
110 000 h spread on 2100 cores

Execution time= 150h

One second per spectrum

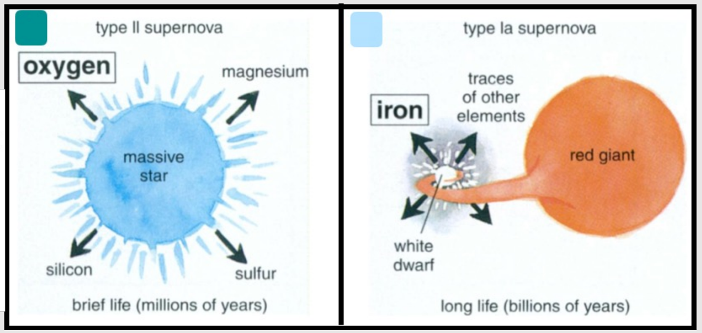
Galactic alchemists

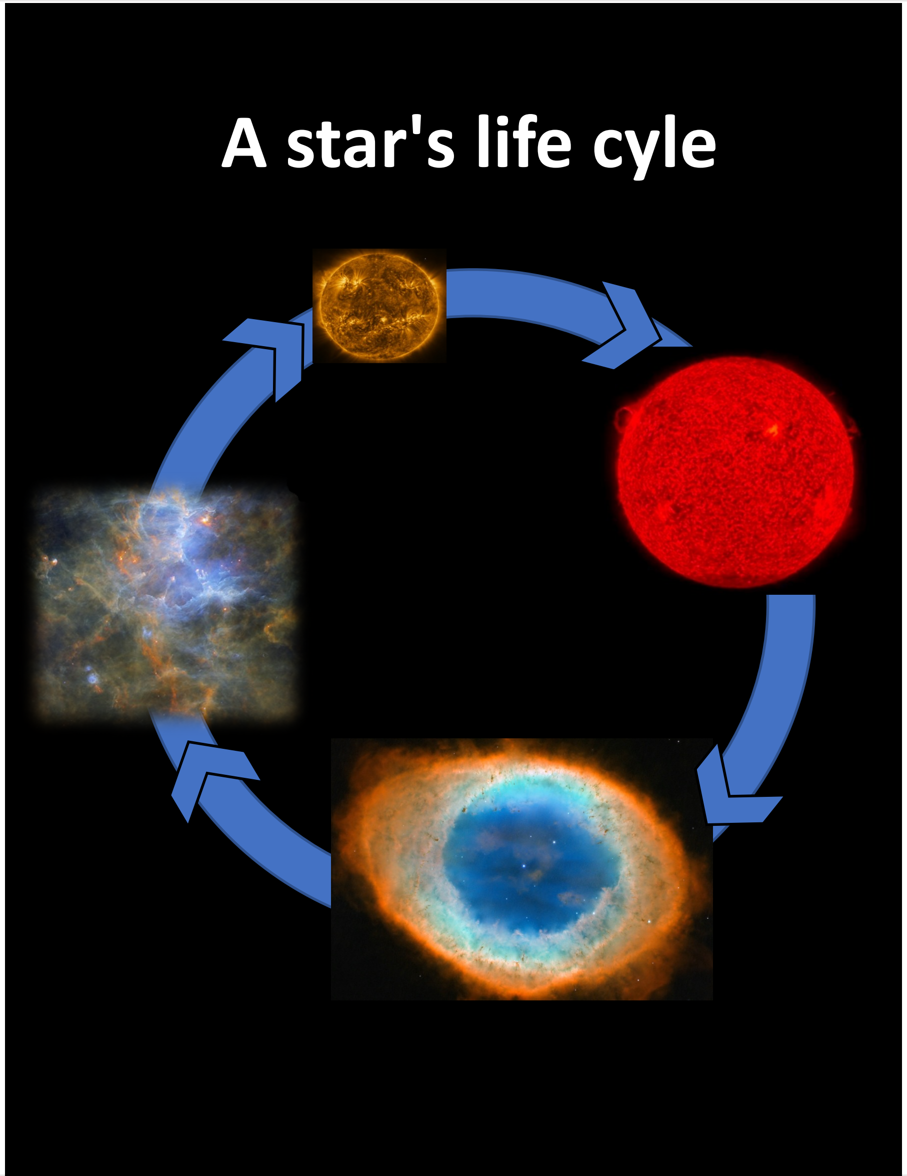
Different nucleosynthetic channels



Adapted from J. A. Johnson

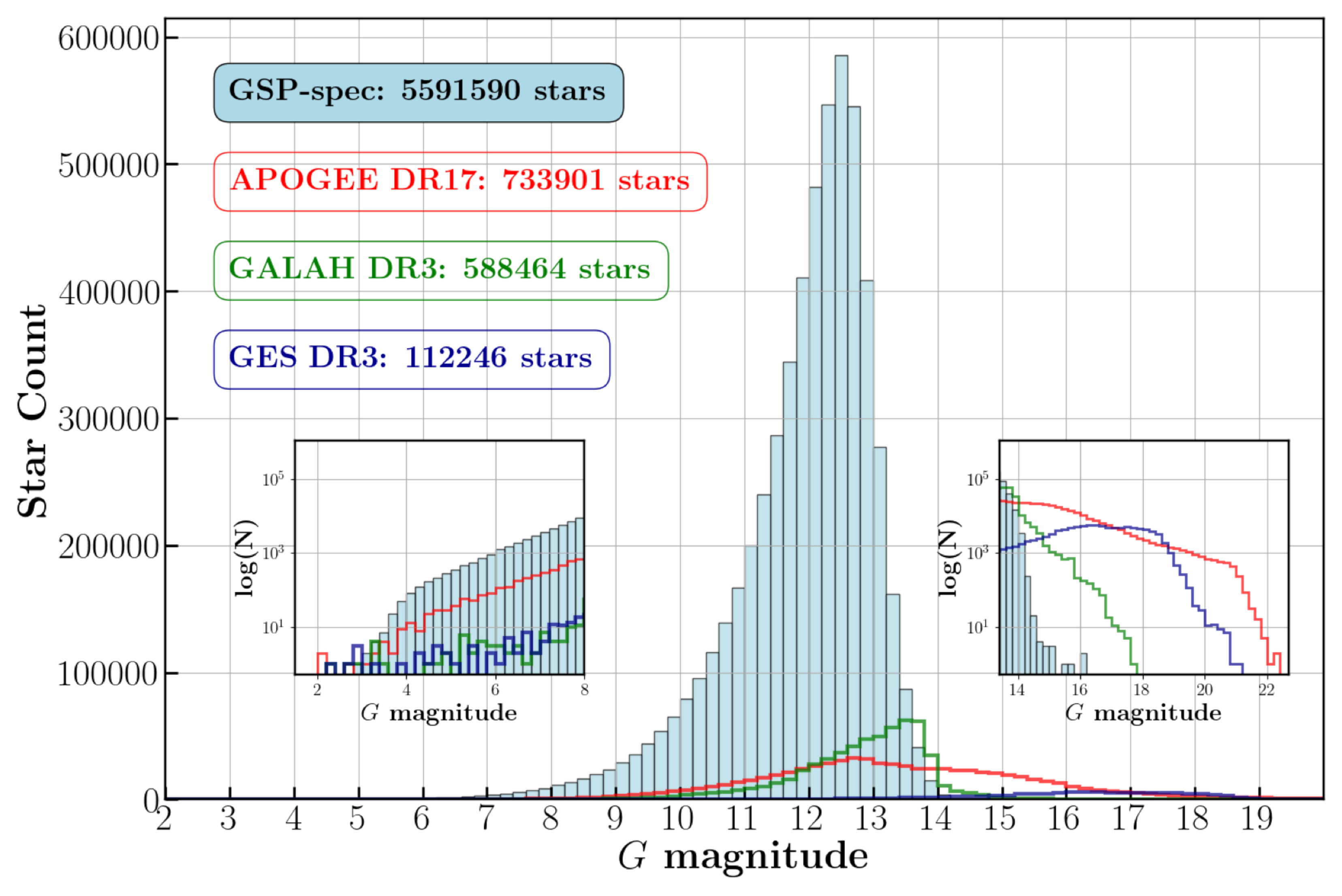
credits C. Chiappini





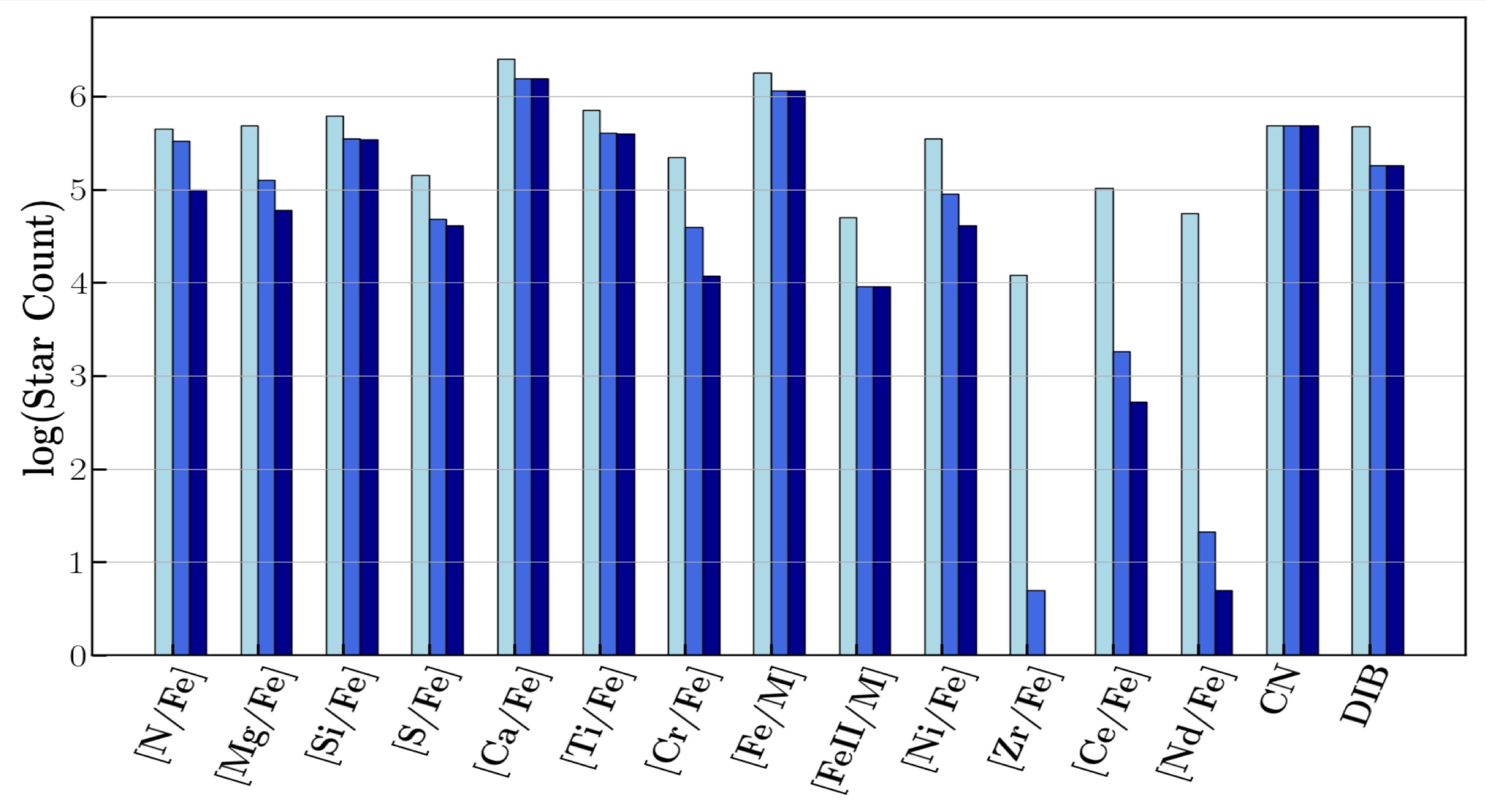
Gaia/RVS: a space spectroscopic survey

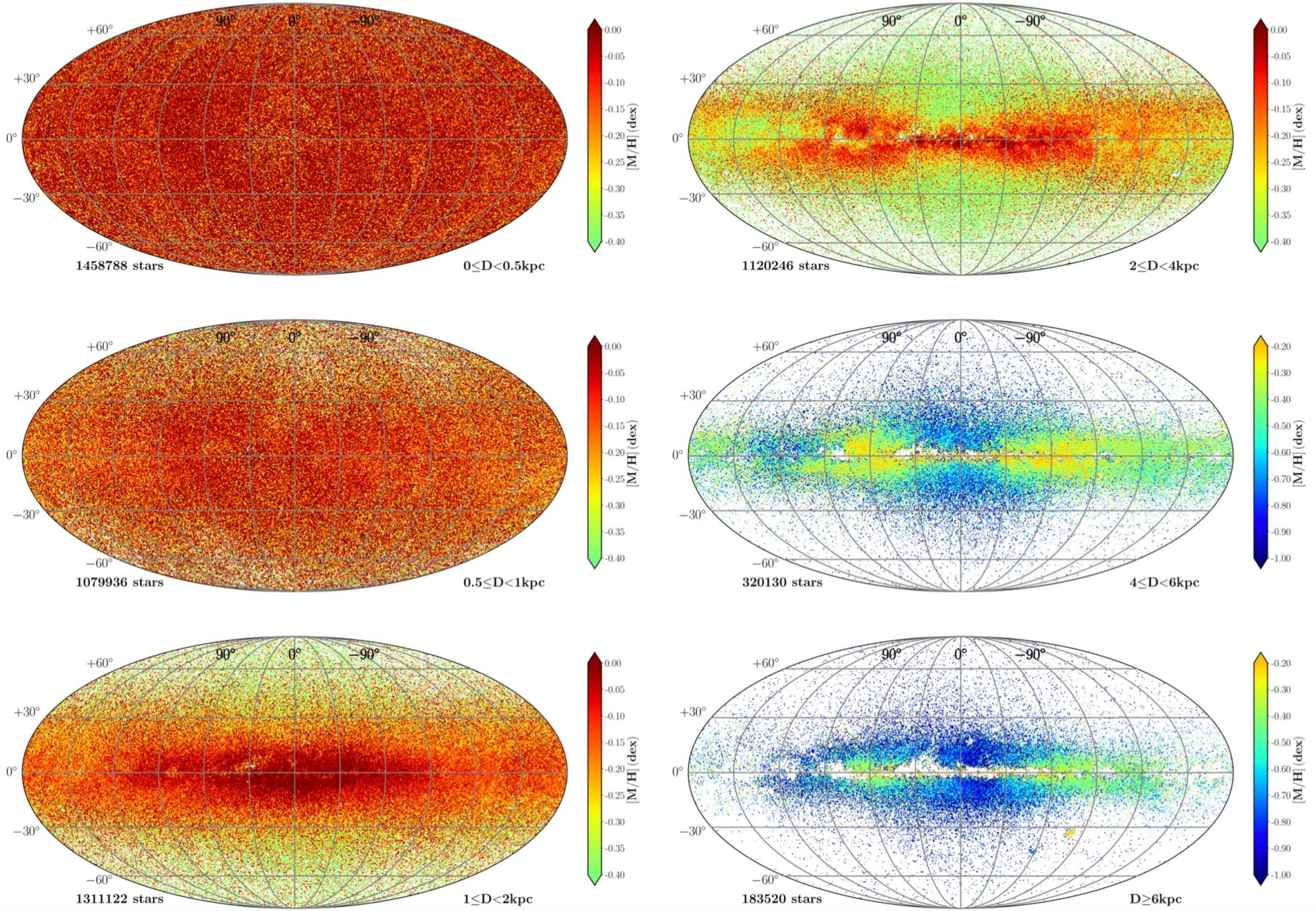
CU8/GSPspec: The chemical composition of 5.6 million stars



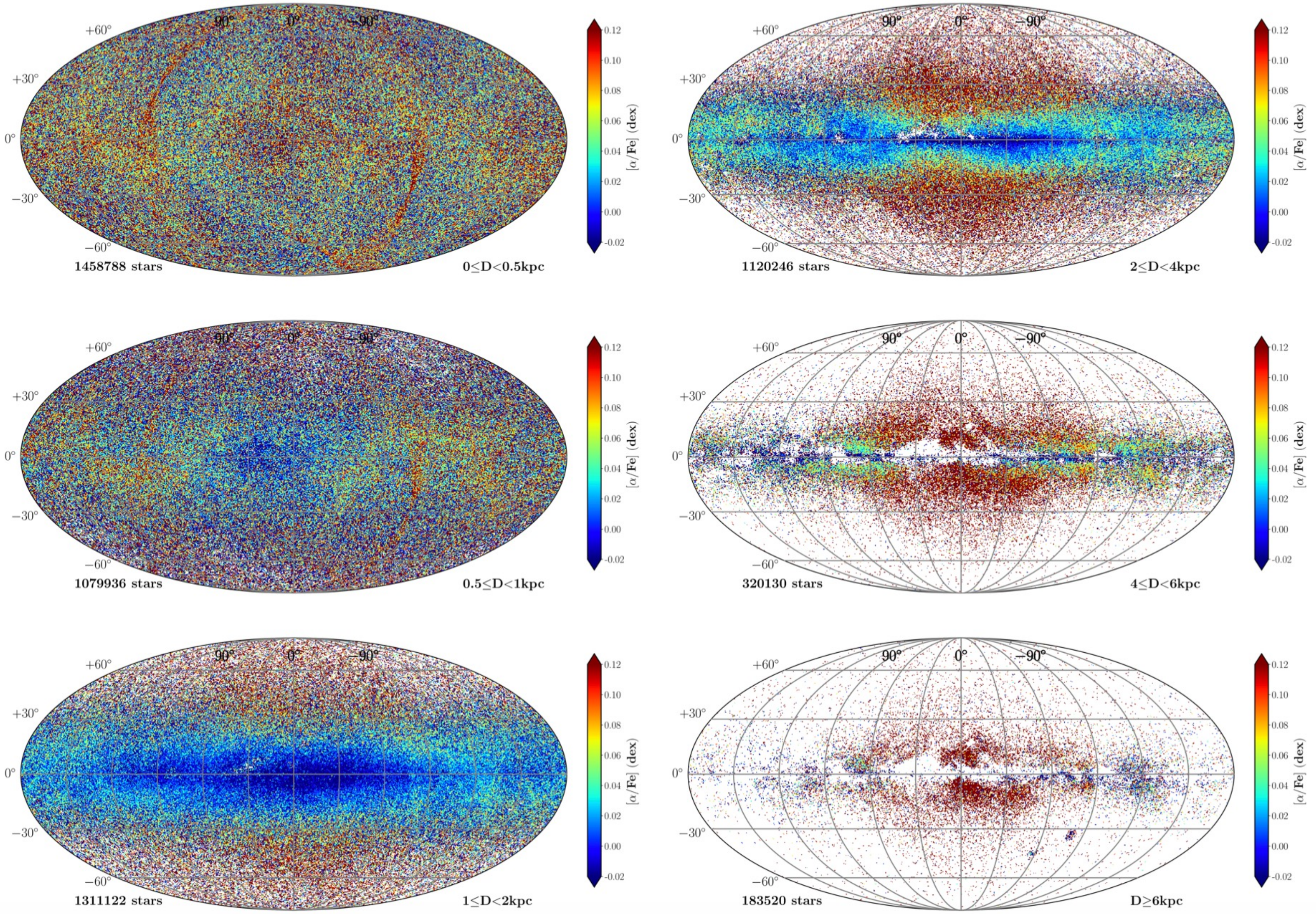
Gaia/RVS: a space spectroscopic survey

CU8/GSPspec: The chemical composition of 5.6 million stars





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



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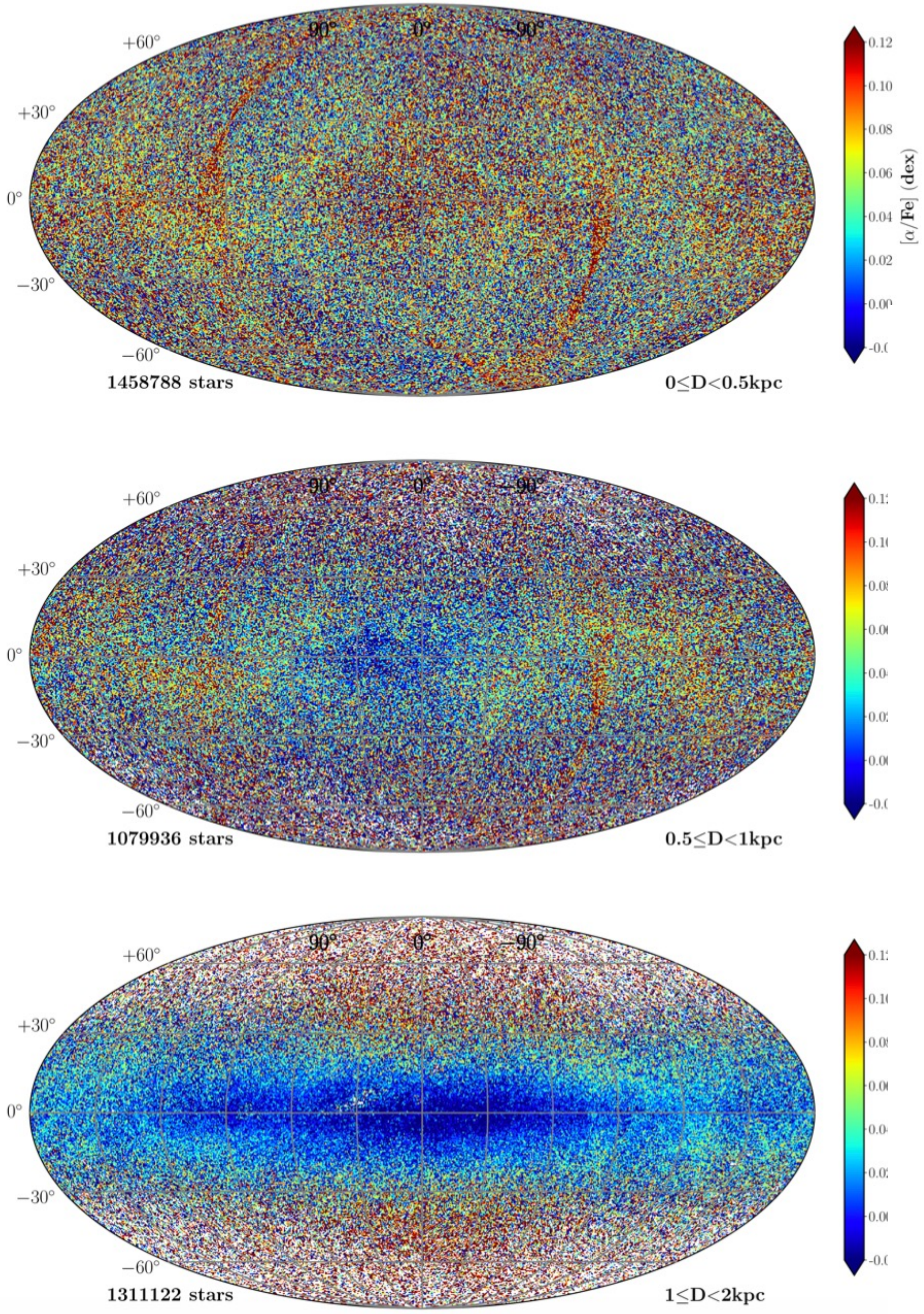

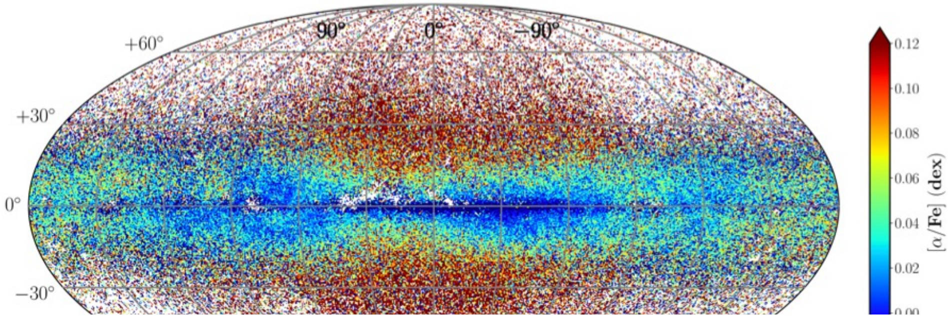

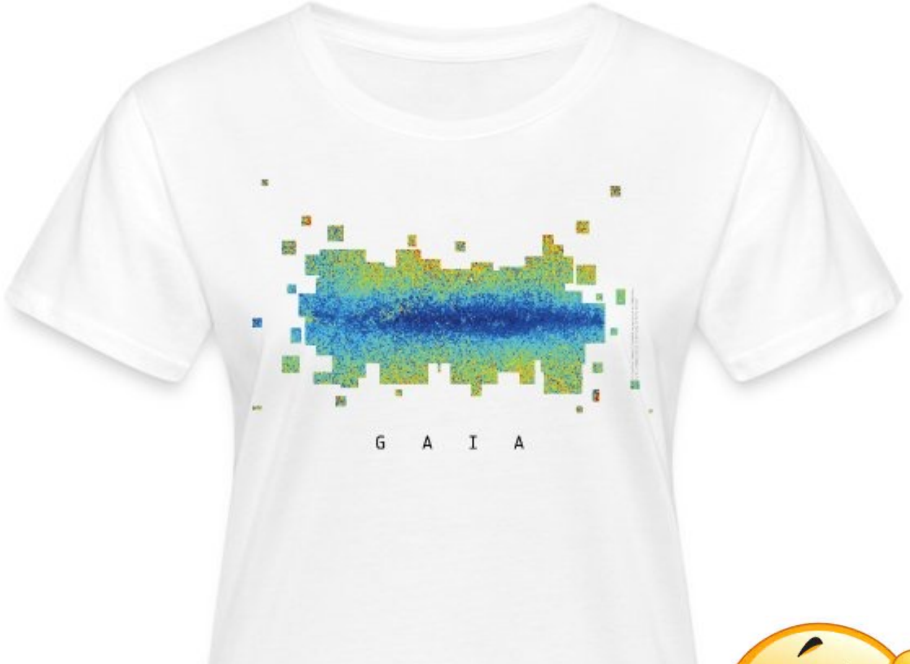

ESA shop!!!

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

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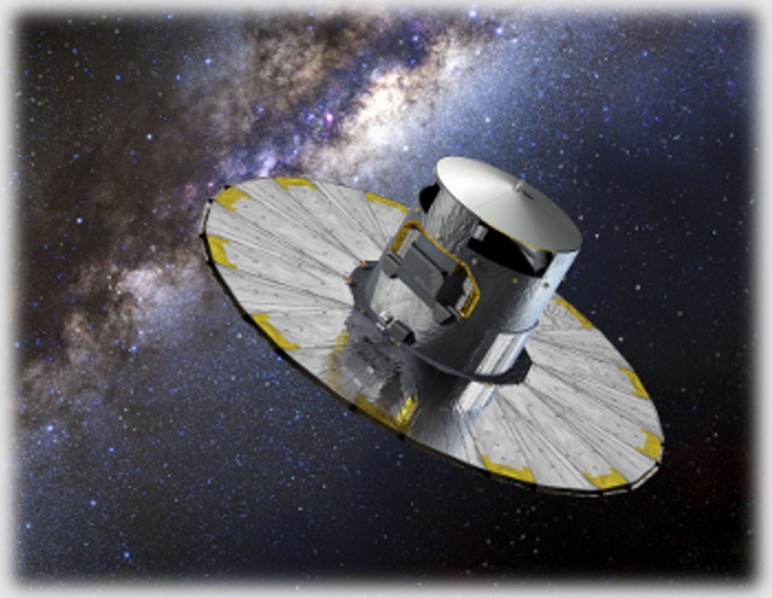
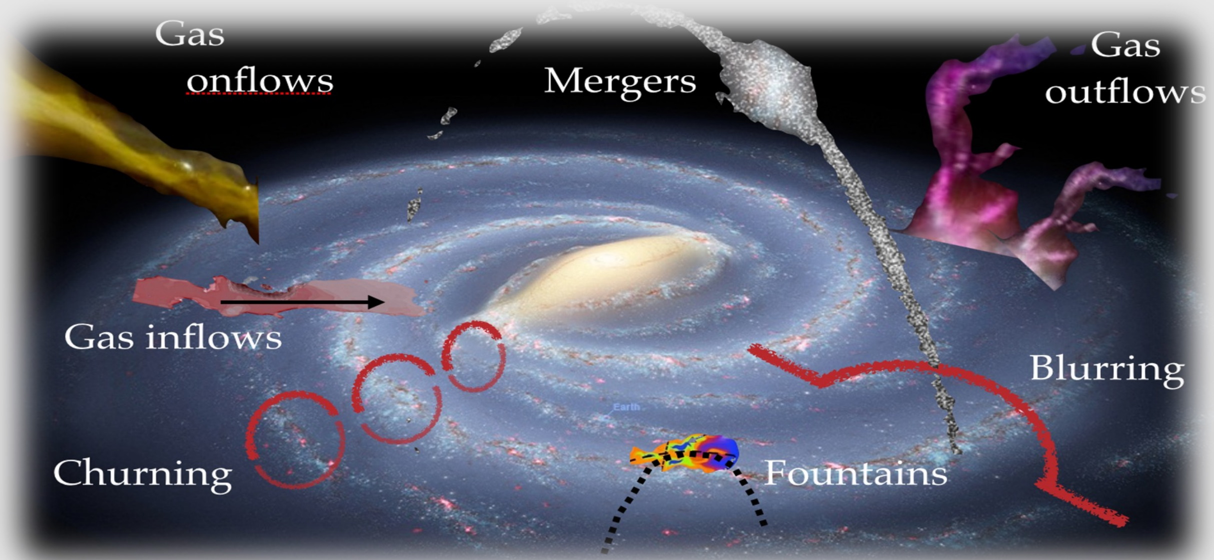
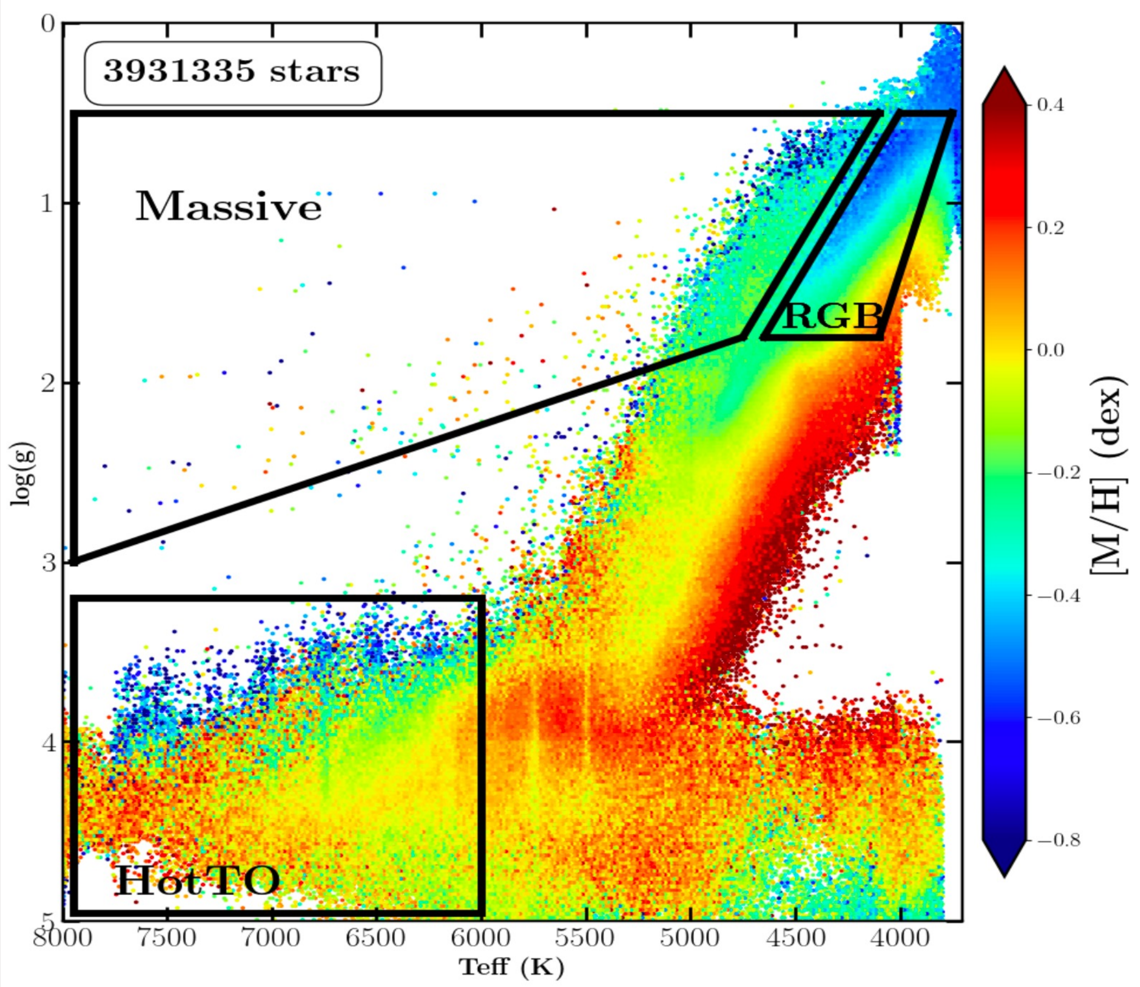


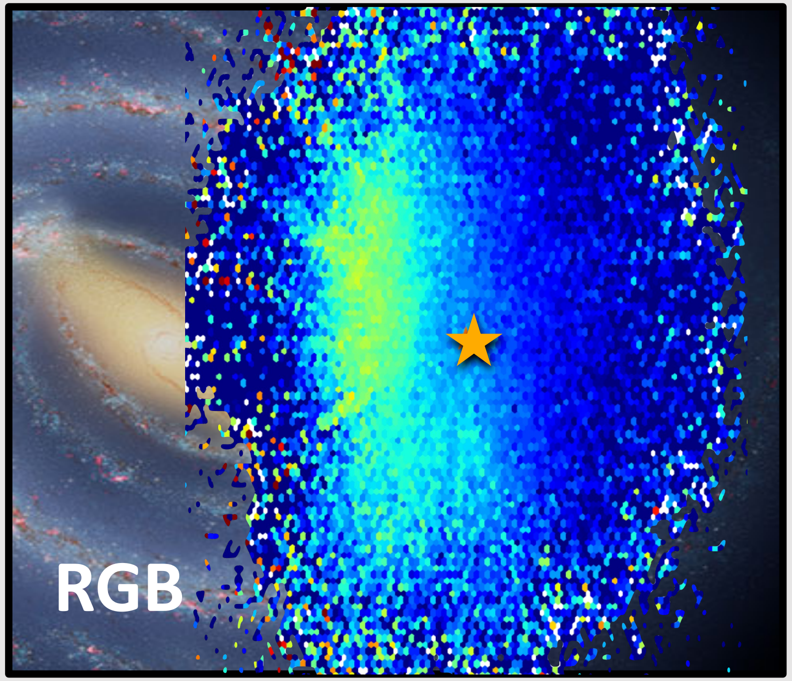


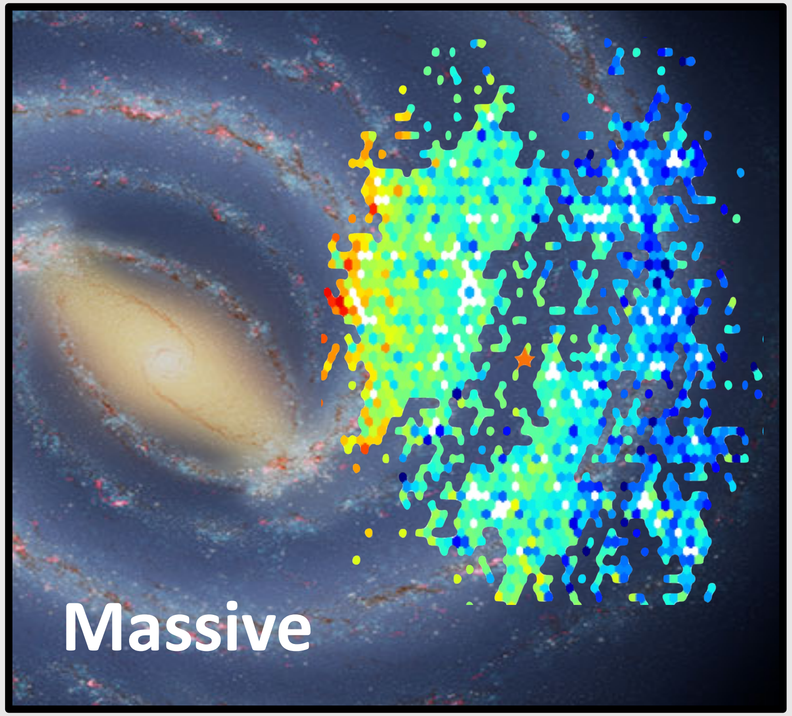
Galactic disc: landscapes

Selection function



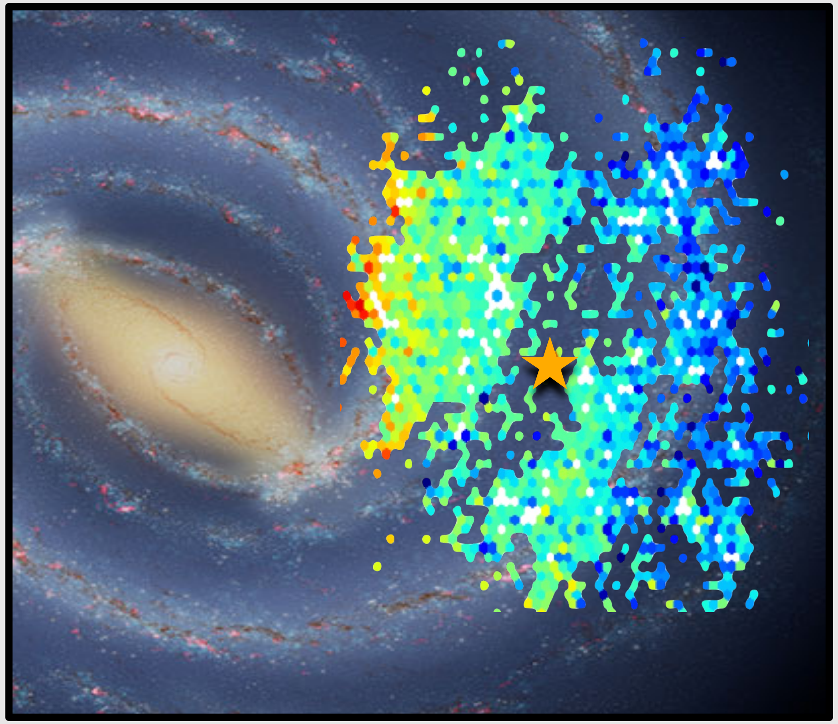
Gaia Collaboration, ARB et al. (2022)

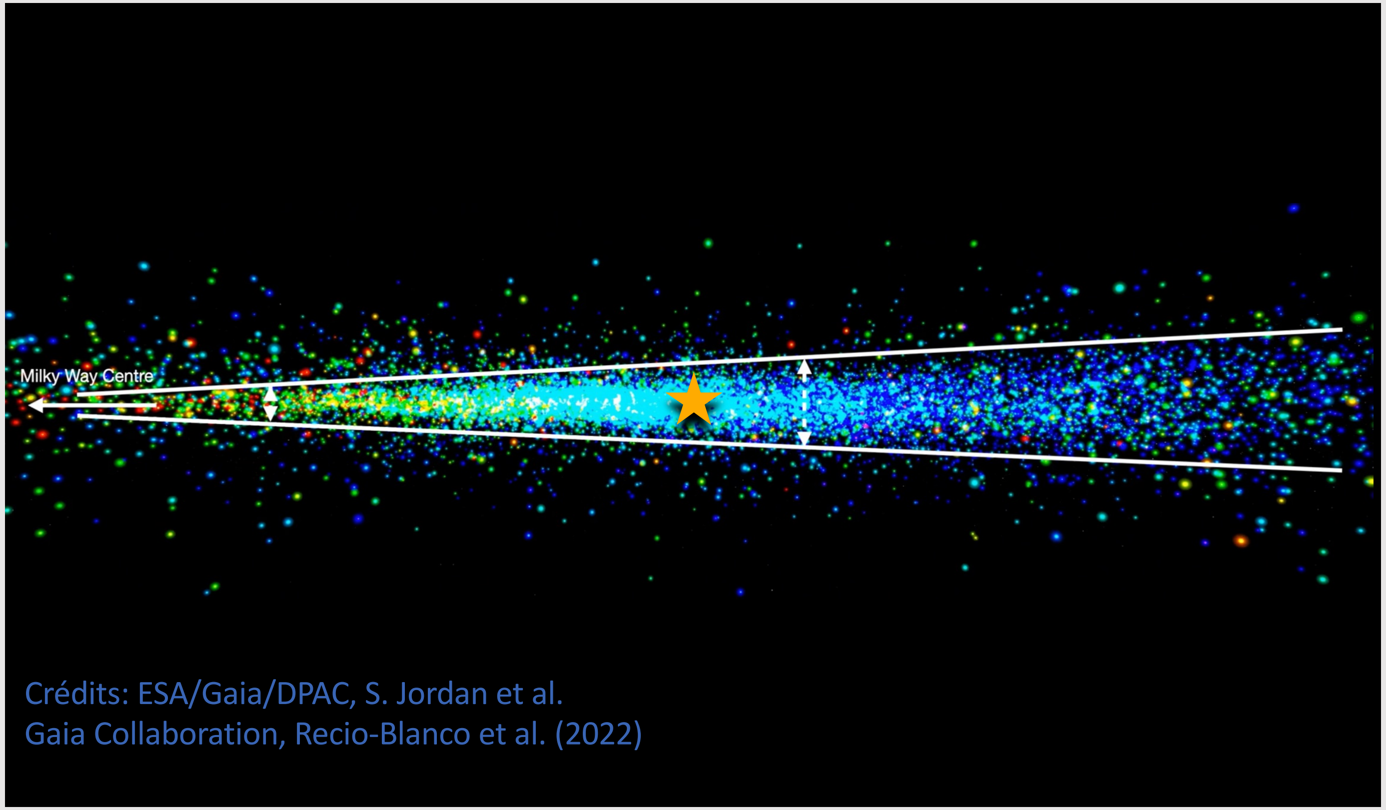




Galactic disc: structure and chemical gradients

Young stellar populations in the spiral arms



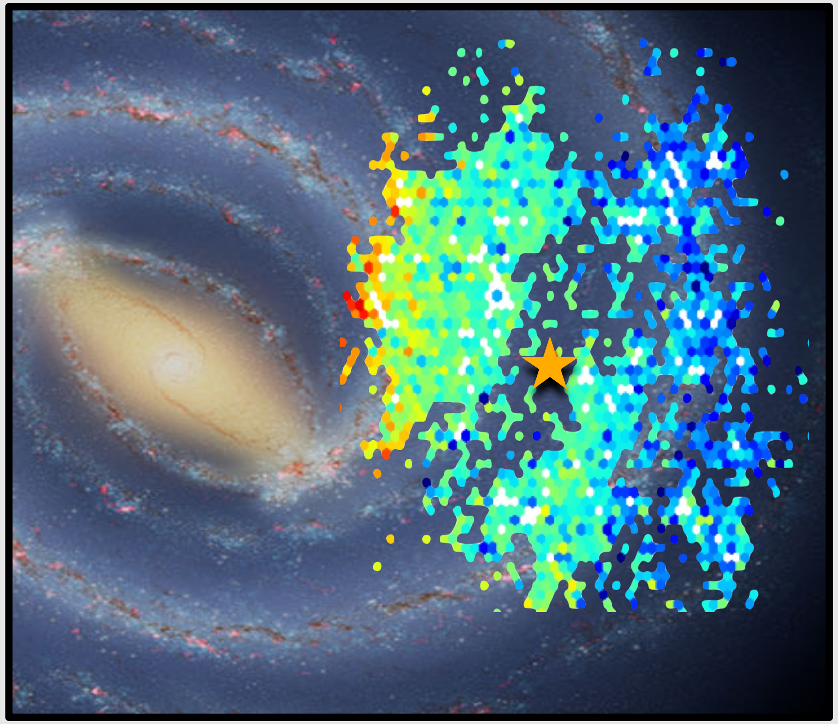


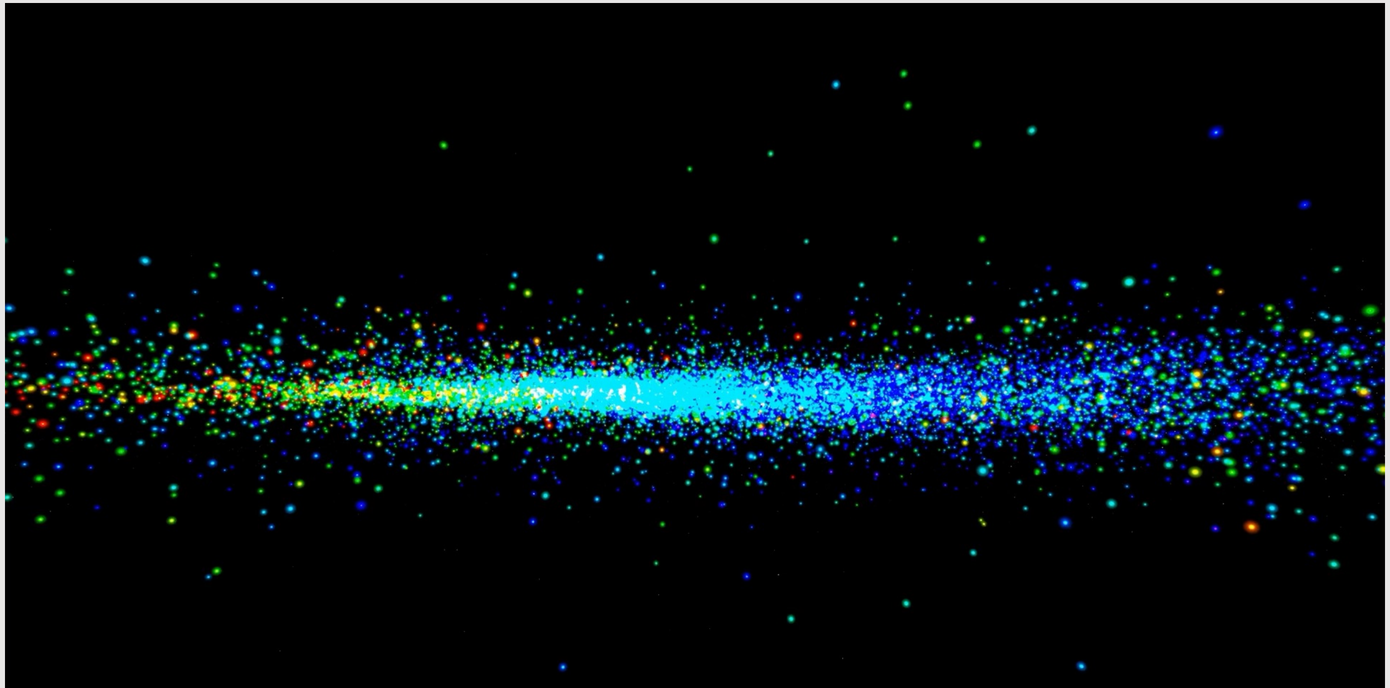
The thin disc

- Radial chemical gradient -> precise quantification with different tracers
- The flare: the thin disc gets thicker as we move outwards

Galactic disc: structure and chemical gradients

Young stellar populations in the spiral arms





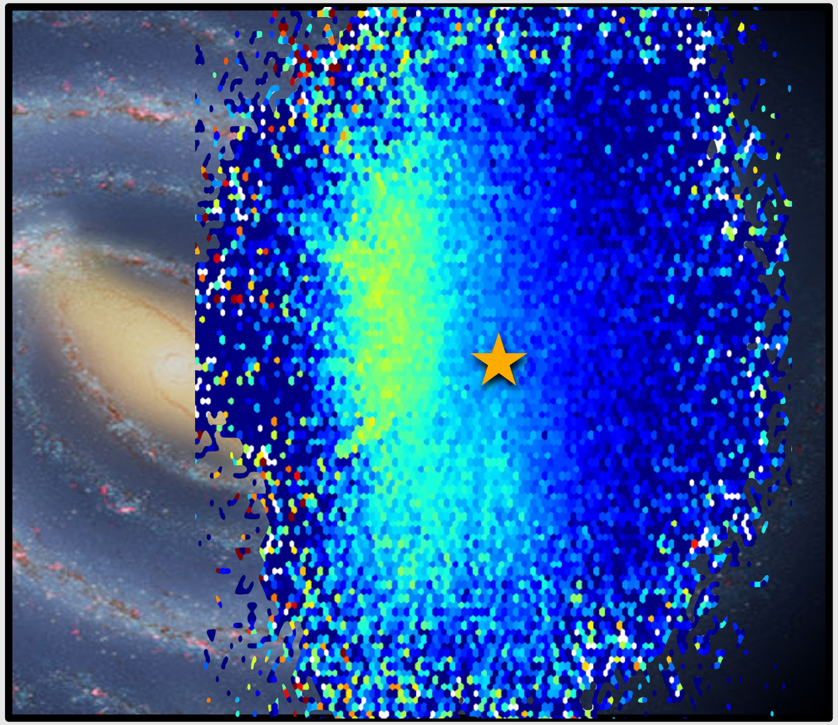
Crédits: ESA/Gaia/DPAC, S. Jordan et al.
Gaia Collaboration, Recio-Blanco et al. (2022)

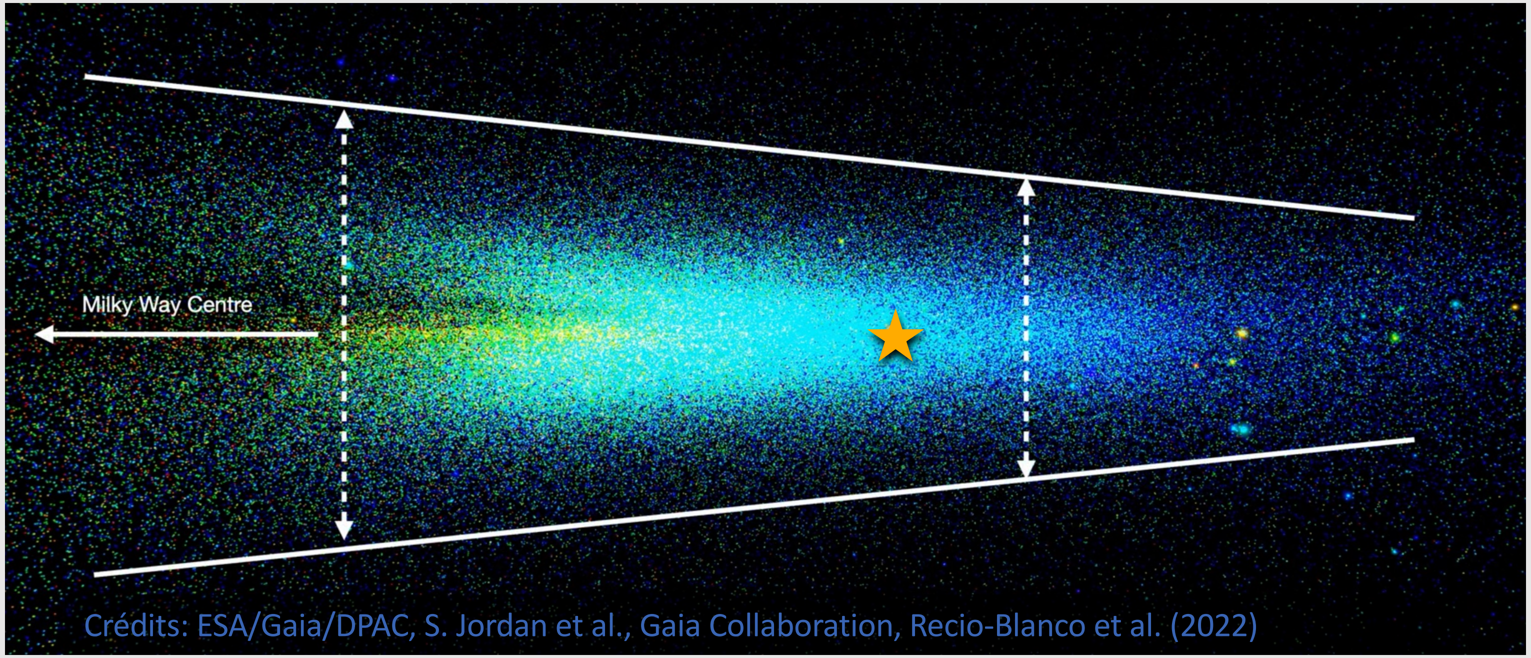
We couple chemistry and orbits thanks to DR3 radial velocities

Katz et al. (2022)

Galactic disc: structure and chemical gradients

Global view of the disc : luminous RGB stars



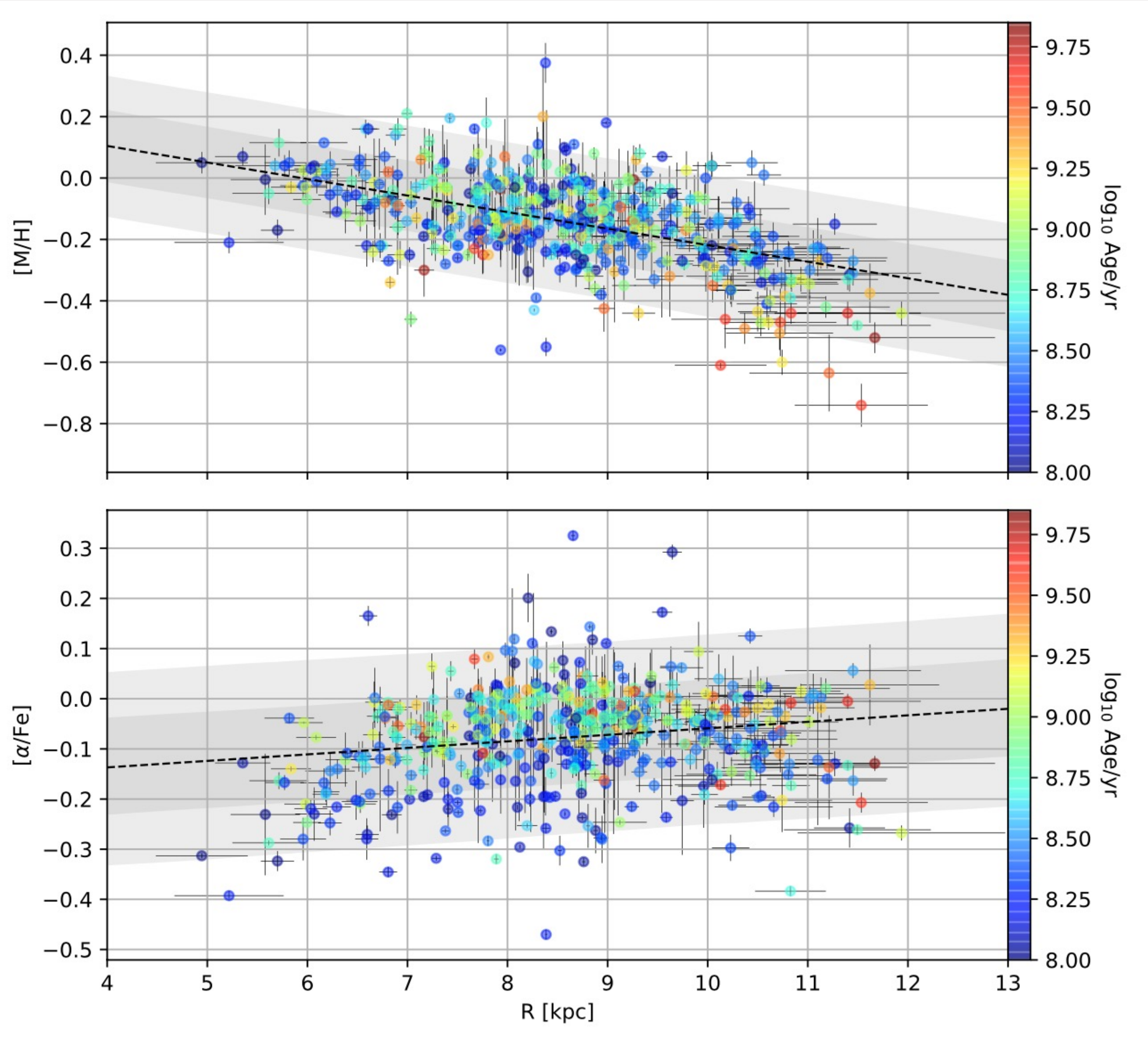


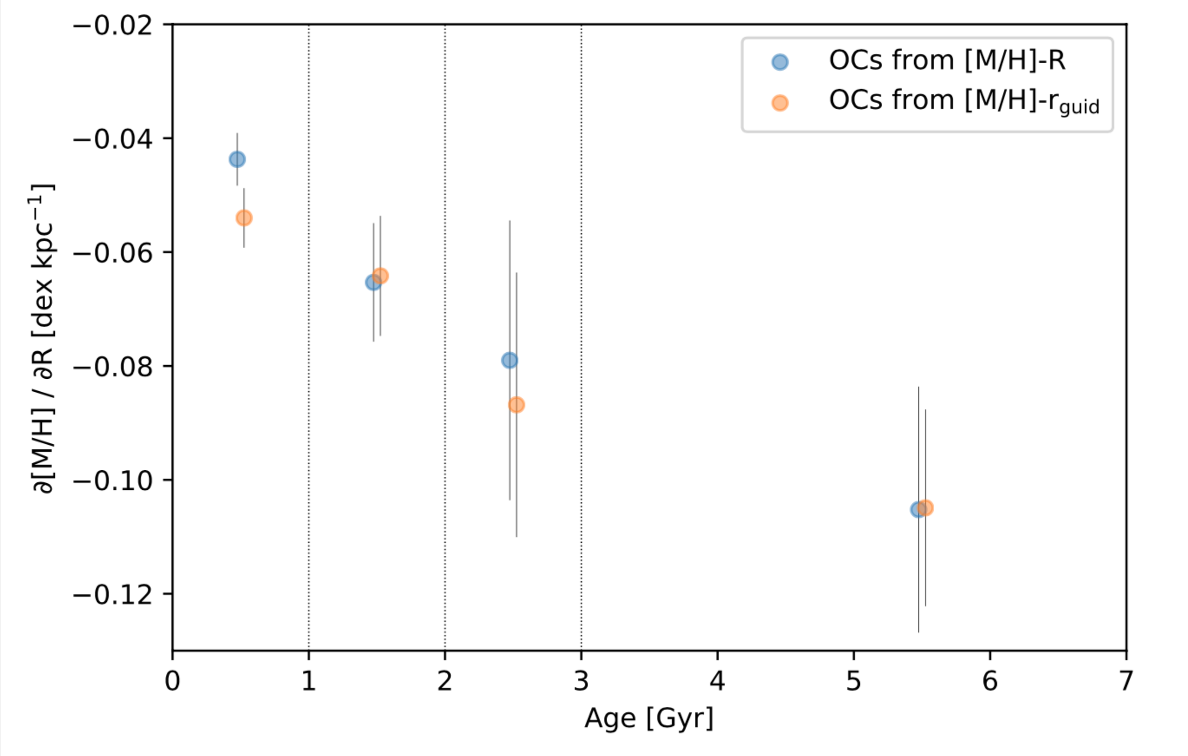
Crédits: ESA/Gaia/DPAC, S. Jordan et al., Gaia Collaboration, Recio-Blanco et al. (2022)

We observe the disc vertical chemical gradient.

Strong symmetry above/below the Galactic plane

Galactic disc: Open clusters





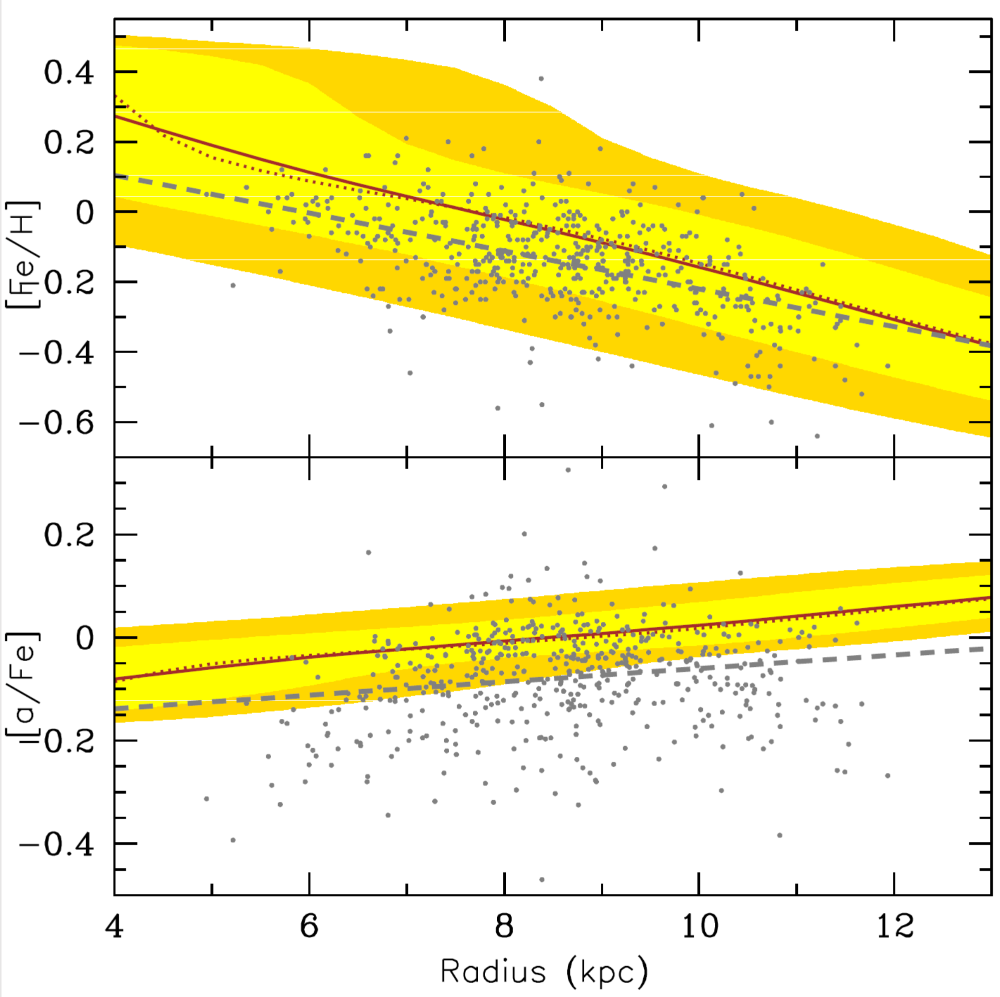
687 open clusters in the Gaia DR3 chemical database

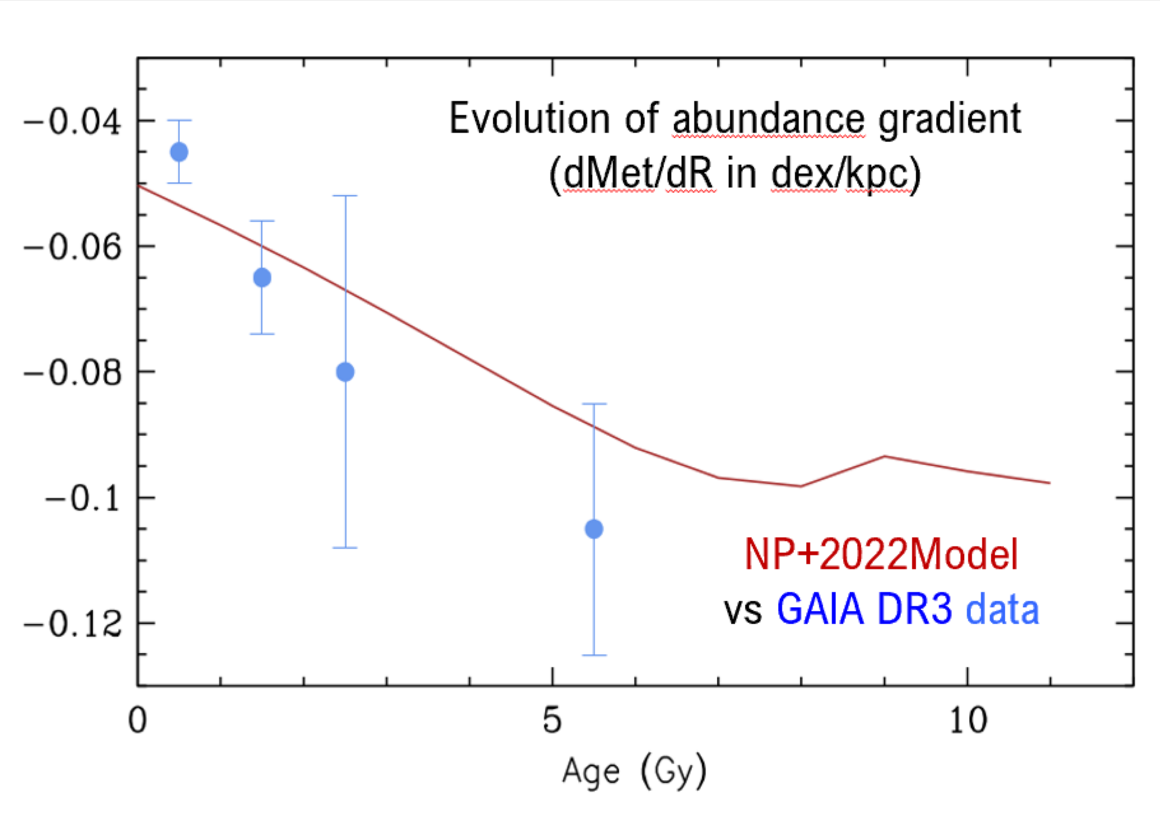
Gaia Collaboration, Recio-Blanco et al. (2022)

Galactic disc: Open clusters

Prantzos et al. chemical evolution model

Multi-zone semi-analytical models + radial migration

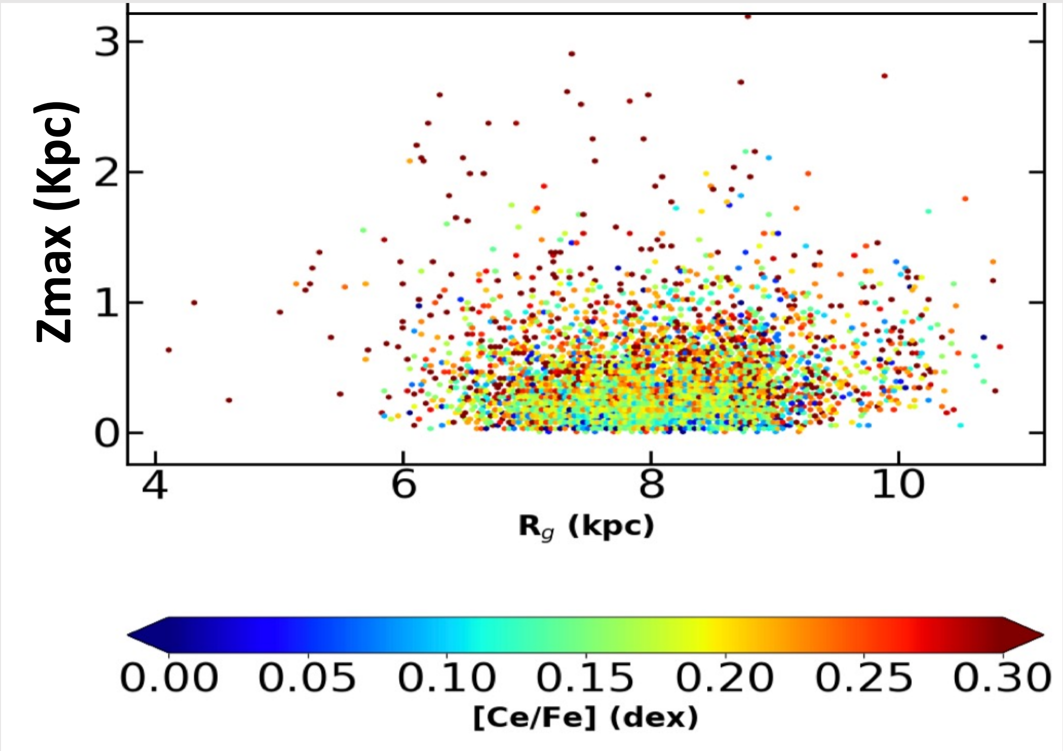




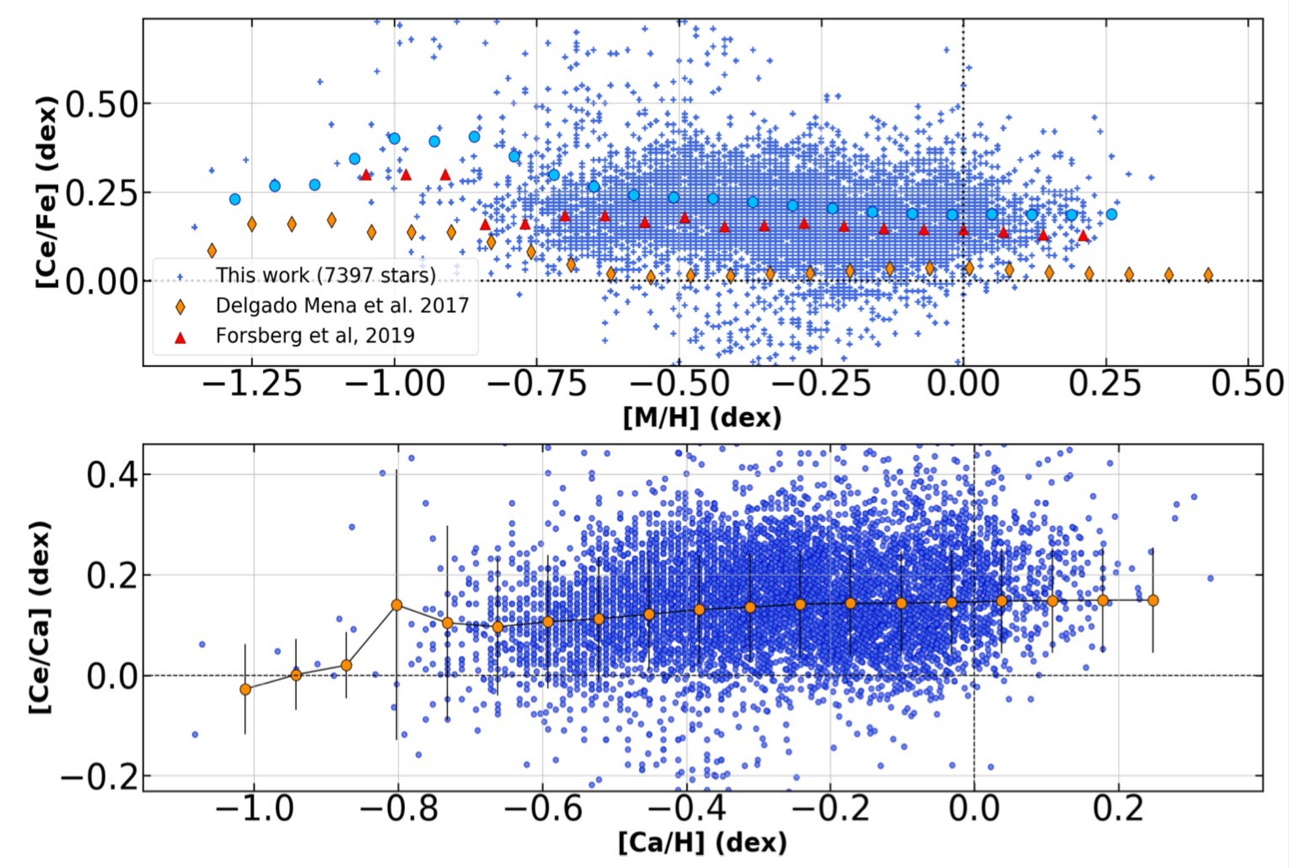
Prantzos et al. (2023)

Galactic disc: structure and chemical gradients

Heavy elements: Cerium



Contursi et al. (2022)



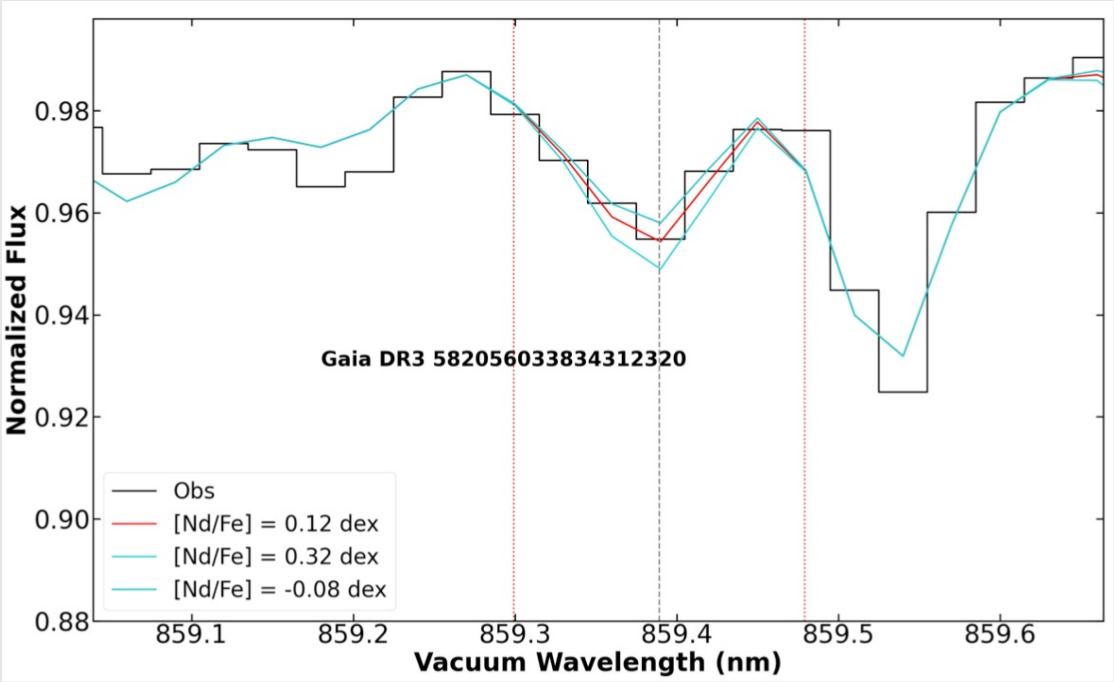
Flat [Ce/Fe] radial gradient and positive vertical gradient

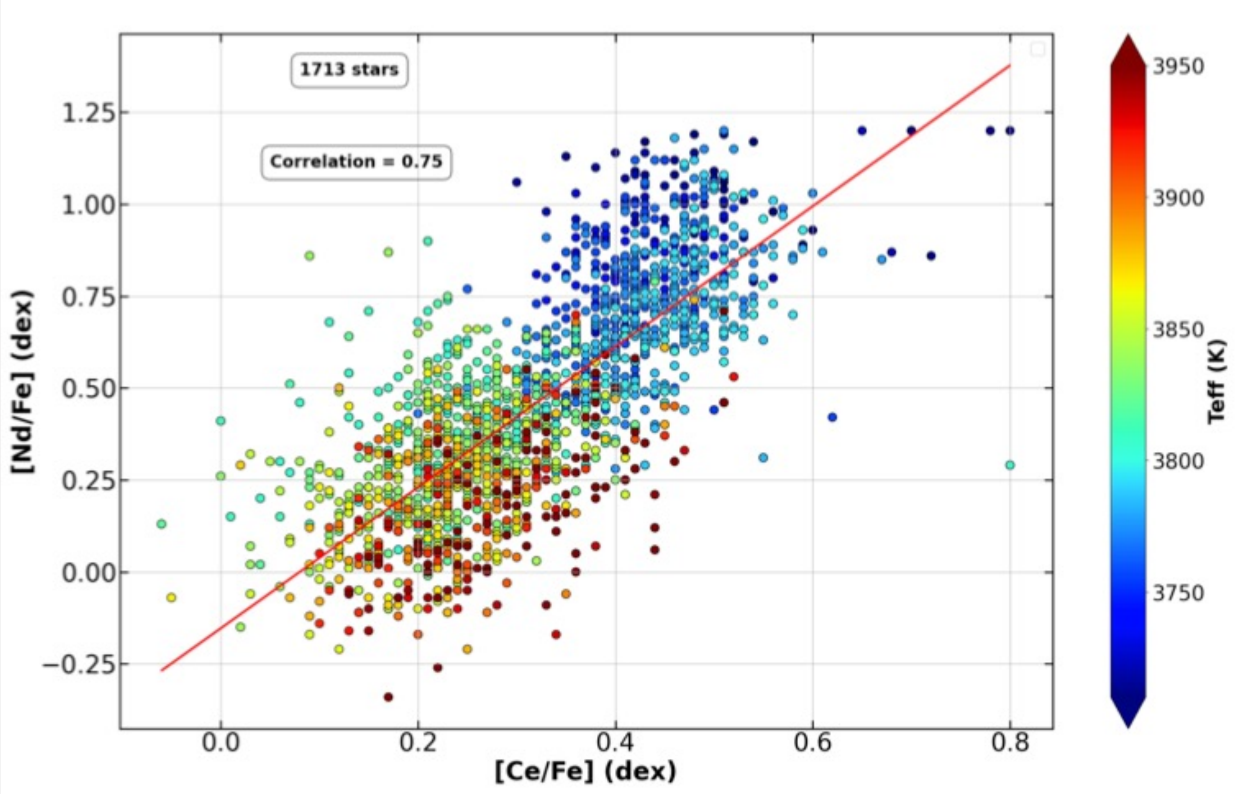
Slightly possitive [Ce/Ca] trend vs. [Ca/H] -> AGB stars are the main responsibles for Cerium abundances in the disc.

Galactic disc: structure and chemical gradients

Heavy elements: Neodymium

Contursi et al. (2023, in prep.)



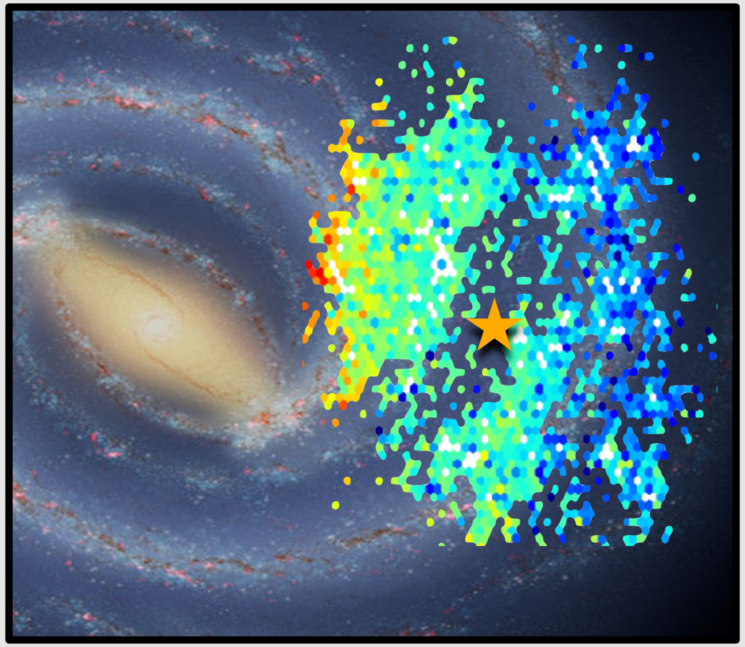


AGB production of s-process elements:

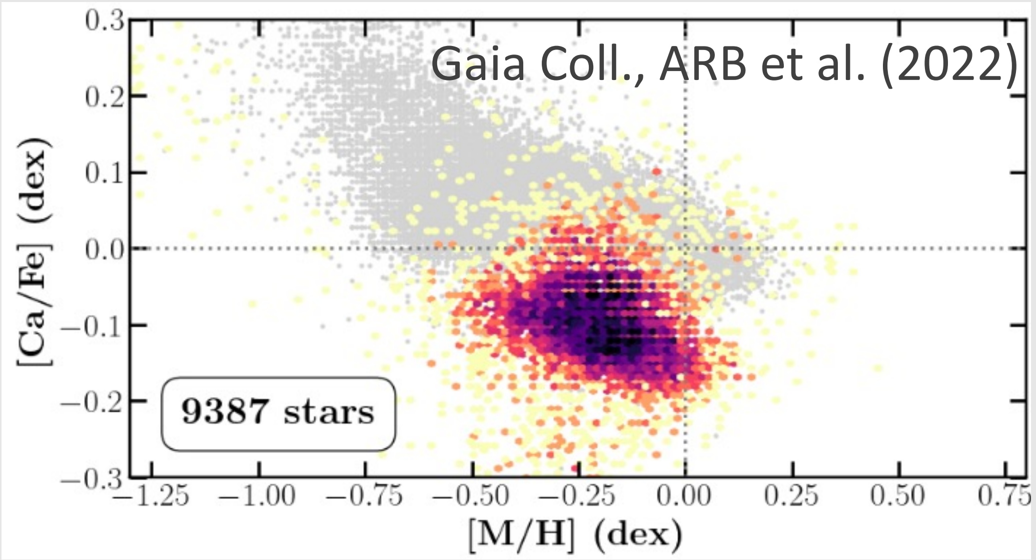
Higher Ce and Nd abundances for more evolved AGB stars of similar metallicity.

Galactic disc: a young chemically impoverished population?

Young stellar populations in the spiral arms

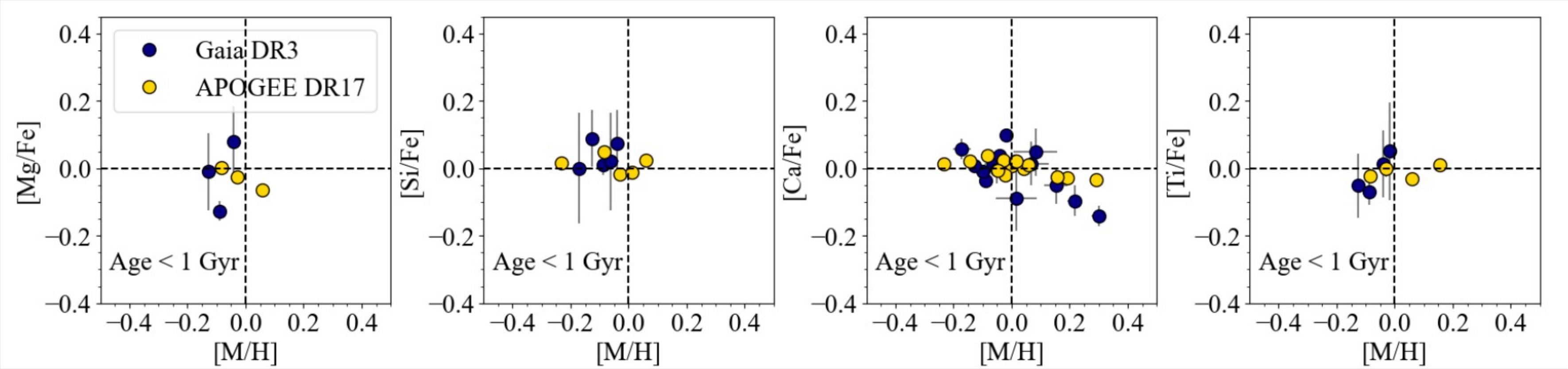


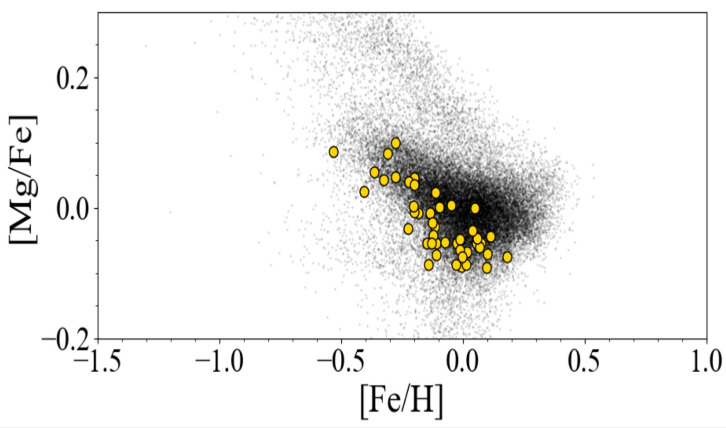
Chemical impoverishment ?



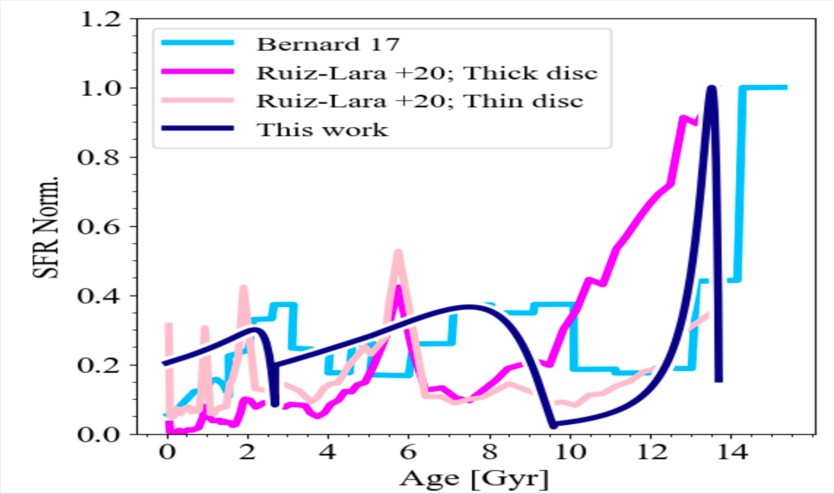
Depletion consistent with other HR surveys (APOGEE)

Spitoni, ARB et al. (2022)





Galactic disc: a young chemically impoverished population?

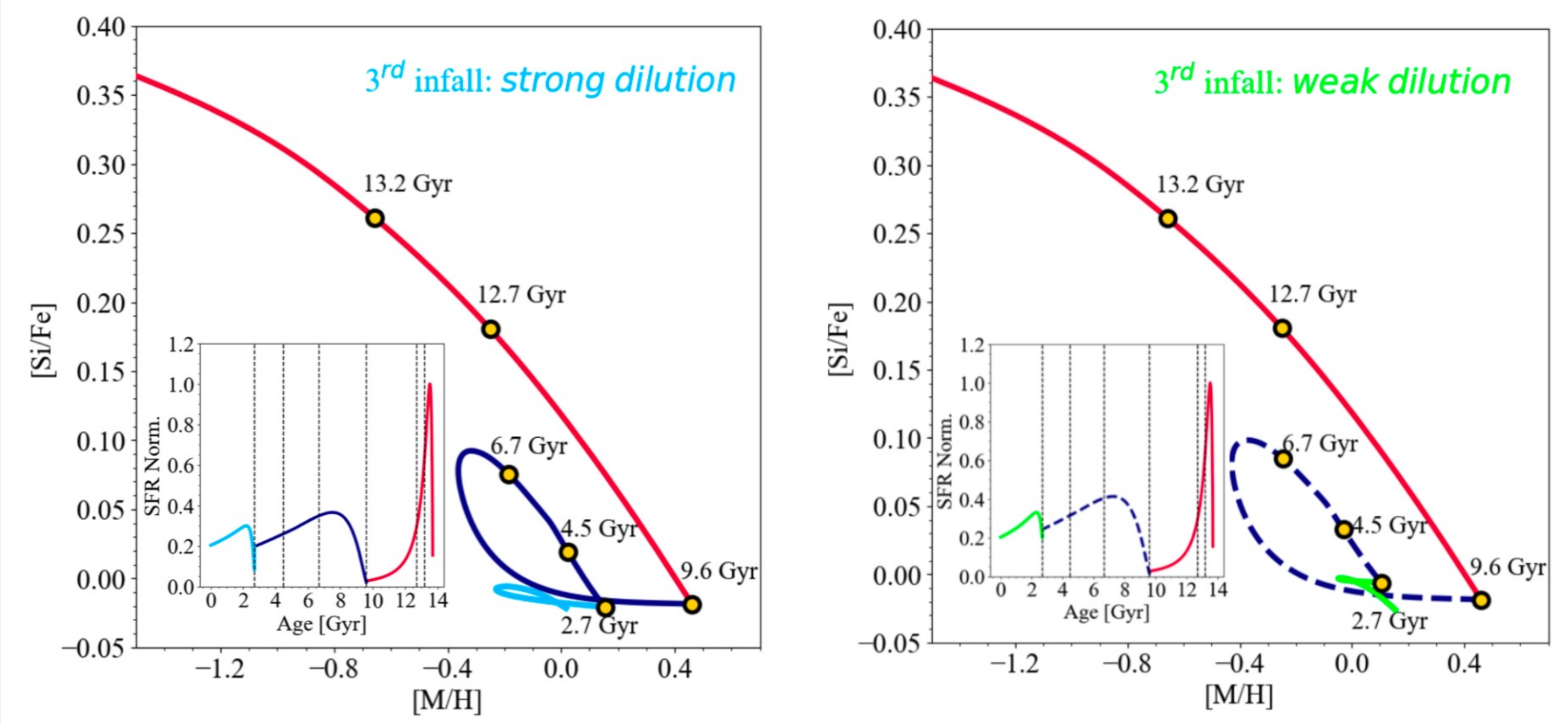


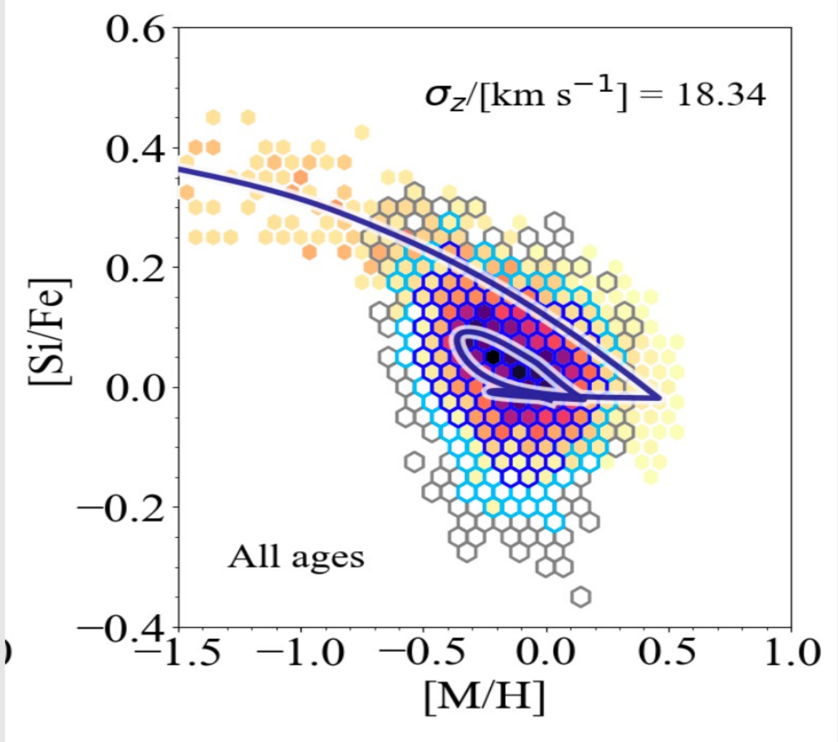
Spitoni et al. models

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

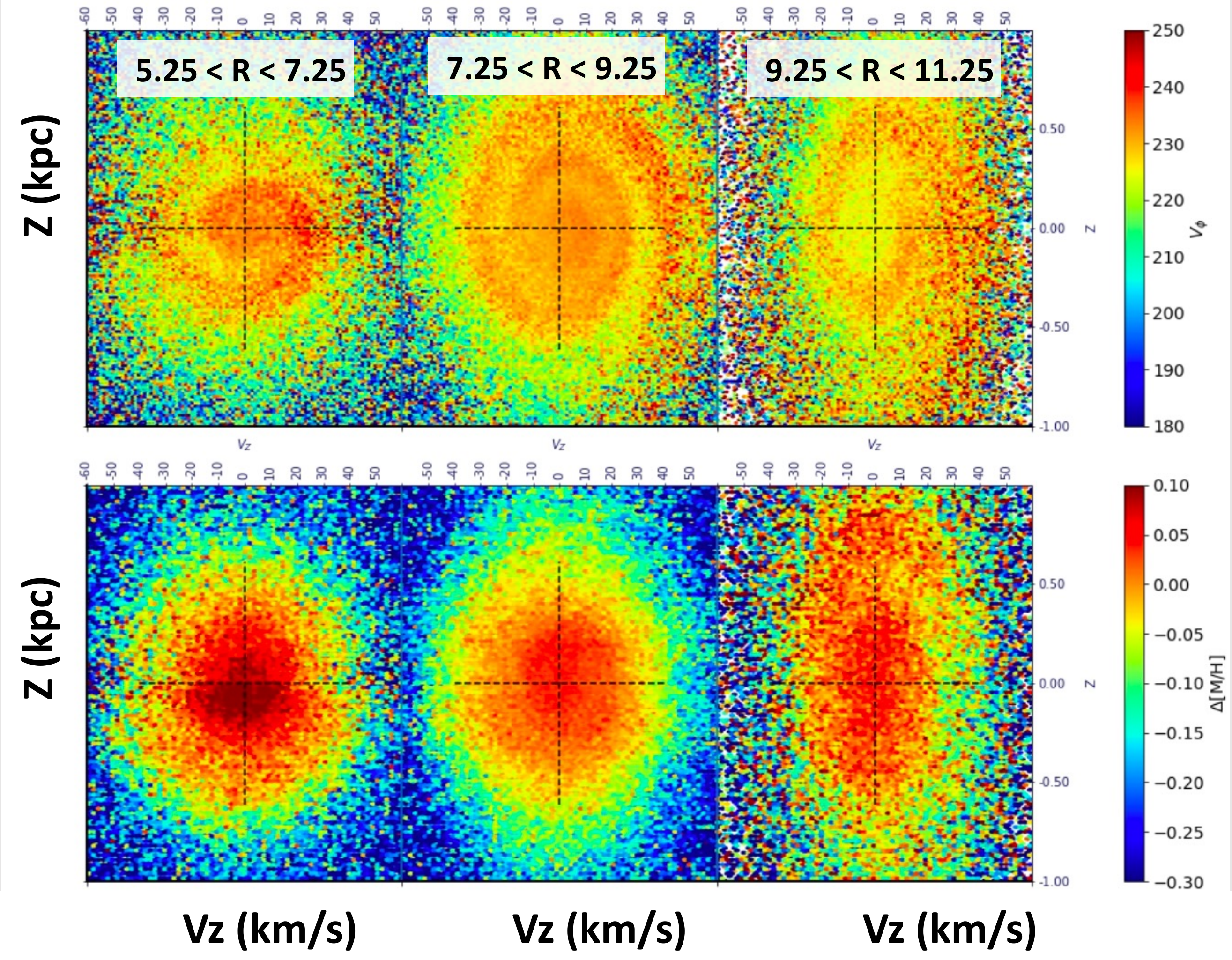
Recent infall of gas related to thin disc star formation history and **chemically depleted young populations**

Spitoni et al. (2022)





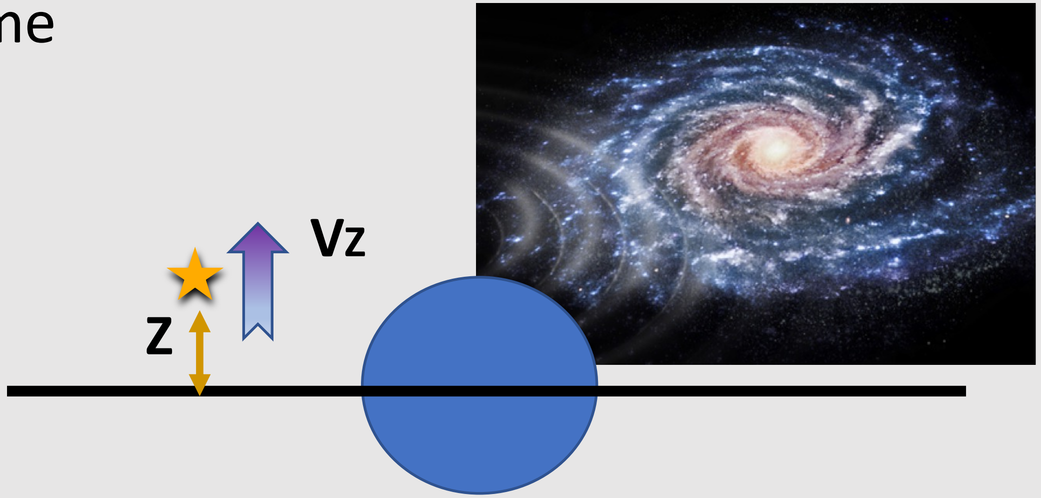
Chemical markers of disc perturbations:
kinematics and phase spiral as a function of R



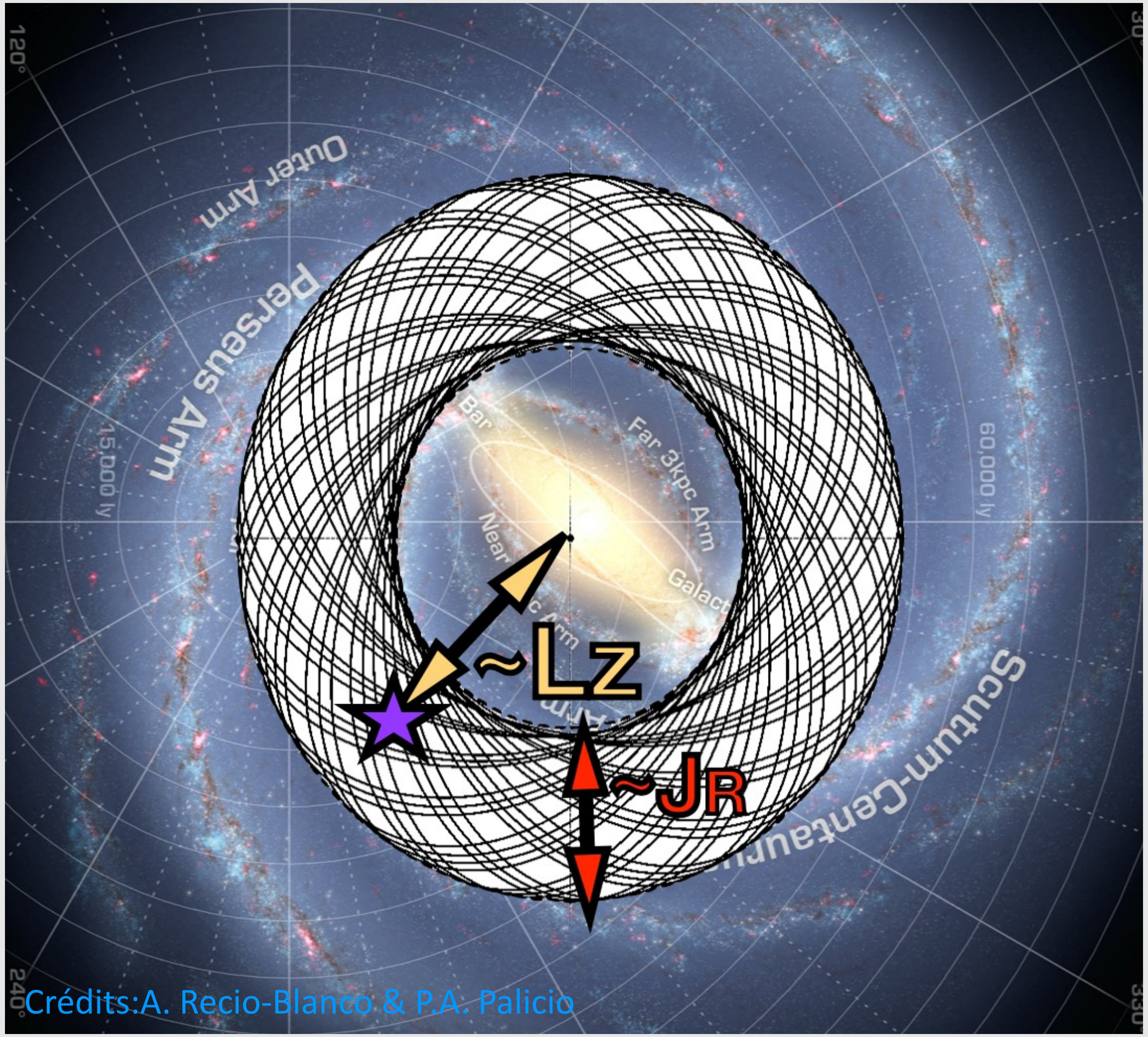
Crédits: Gaia Collaboration, Recio-Blanco et al. (2022)

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



Chemical markers of disc perturbations:
orbital space



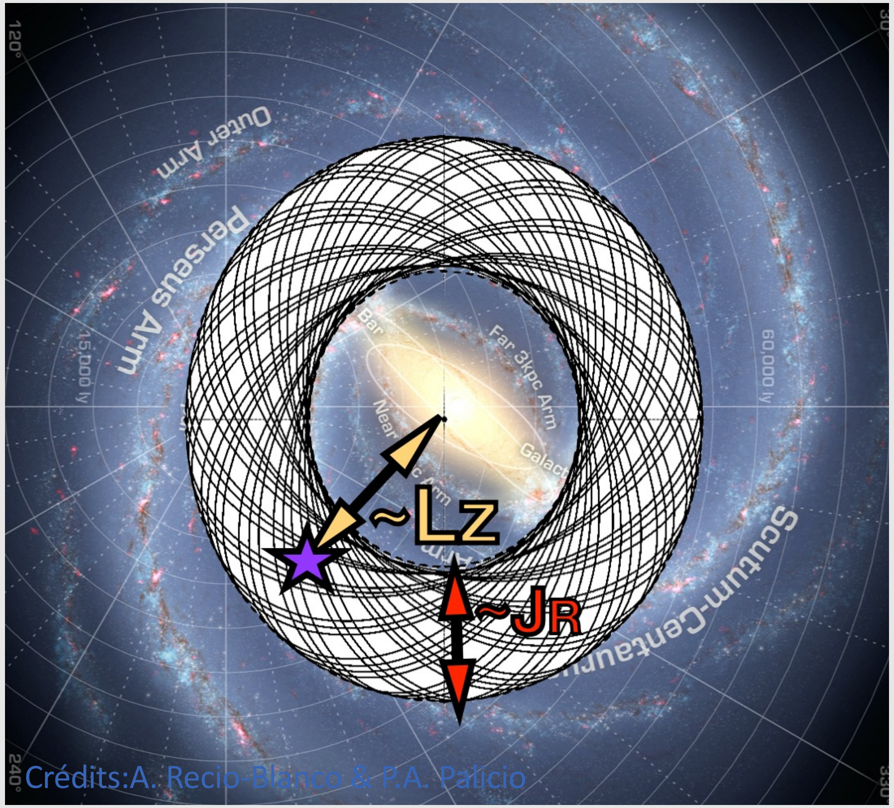
The actions (J_R, J_Z, L_Z) in static potentials are integrals of motion that characterise the orbit of the stars.

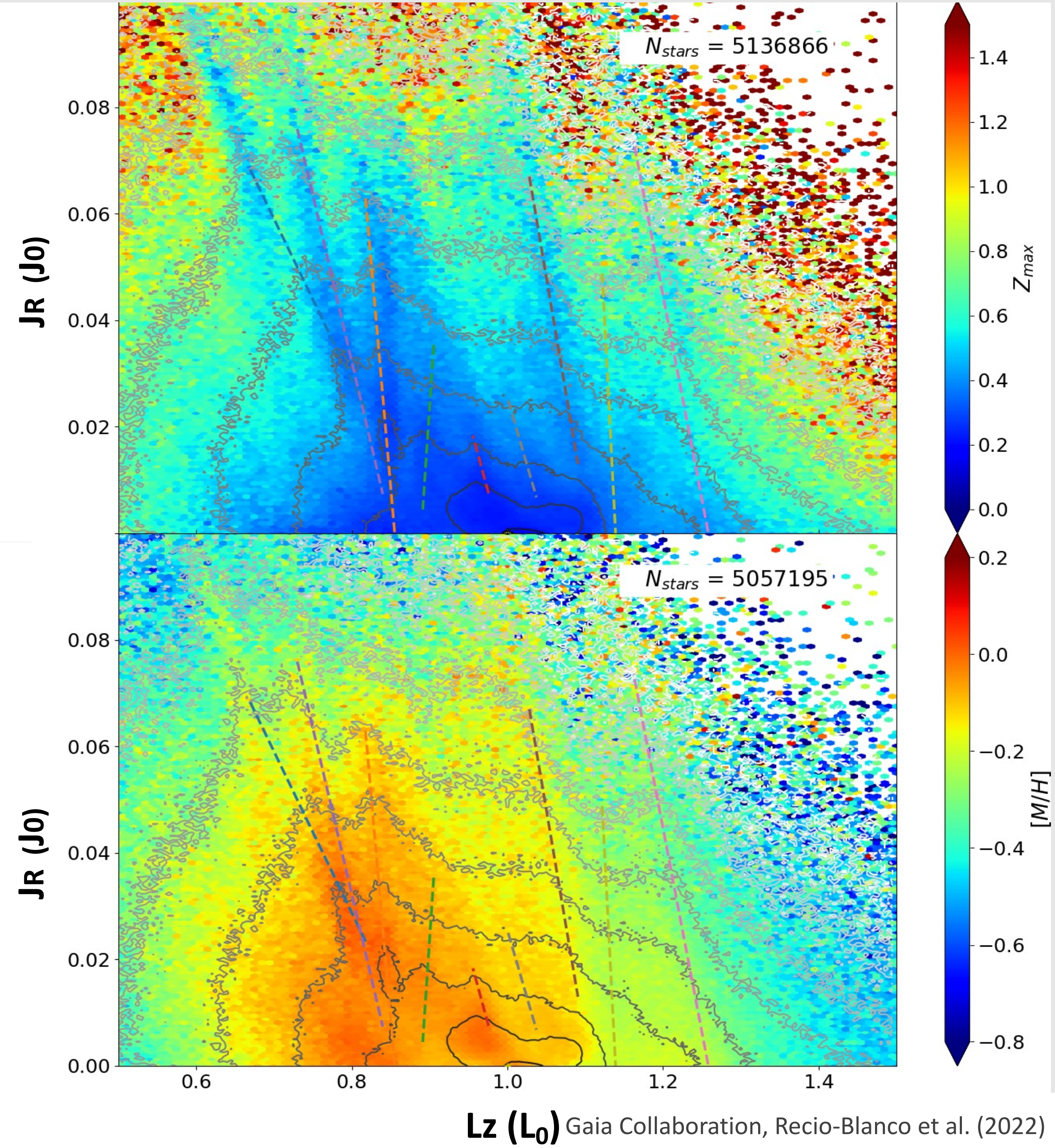
- $\boldsymbol{J_R}$ characterises the **radial amplitude** of the epicyclic orbits
- the **angular momentum L_Z** sets the **guiding raidus** a more robust estimate of the typical Galactic distance of the star than the present-day Galactocentric radius R.

Chemical markers of disc perturbations: orbital space

Ridges of higher stellar density:

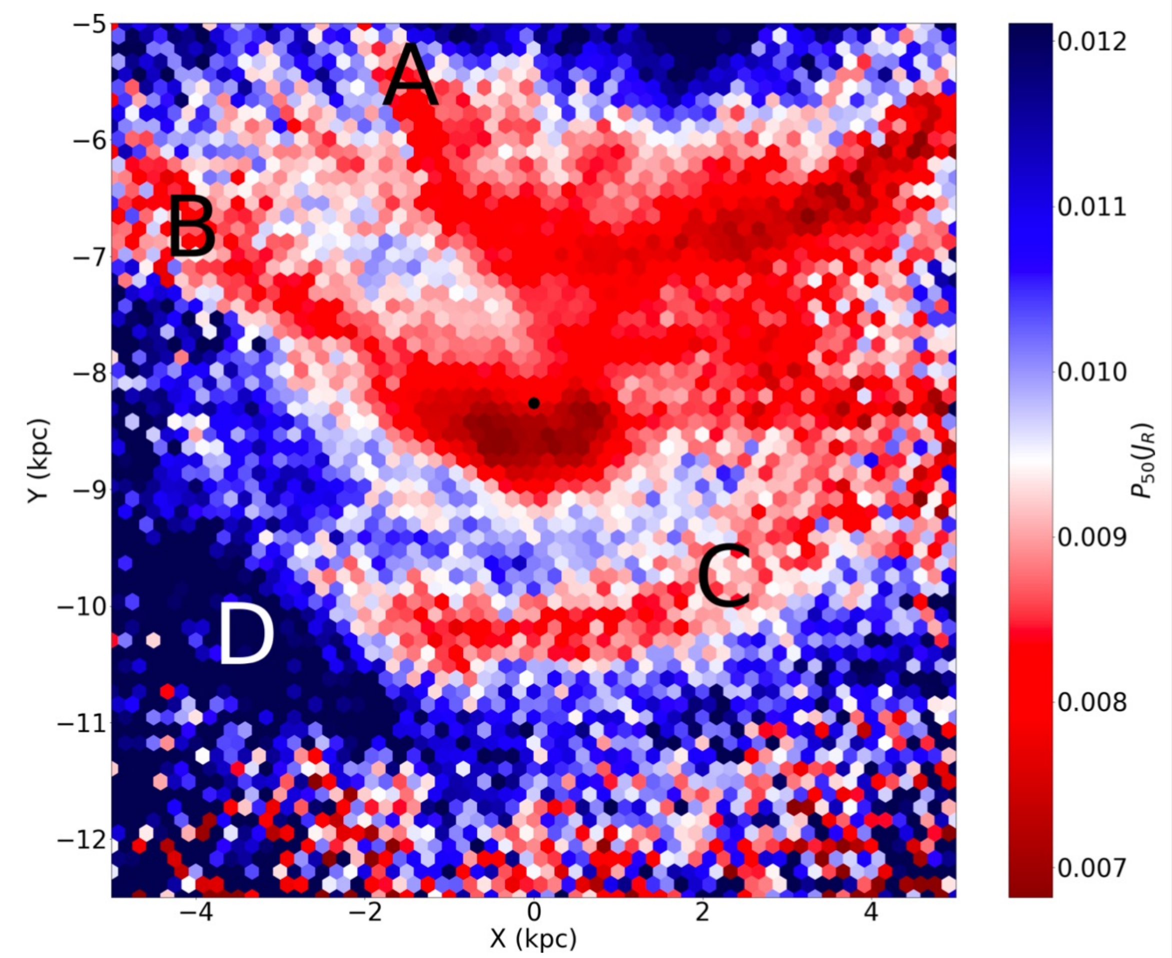
- orbits closer to the plane
- metallicities higher than surrounding median values.





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

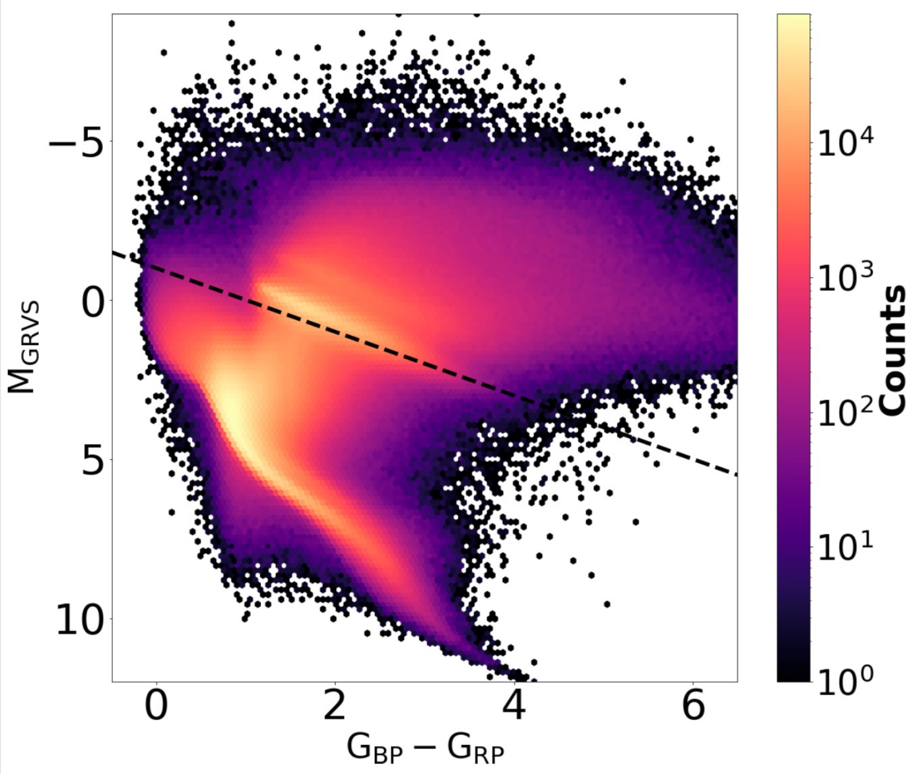
Spiral arms : signatures in orbits, density and metallicity



Radial action J_R ~ orbit's excentricity

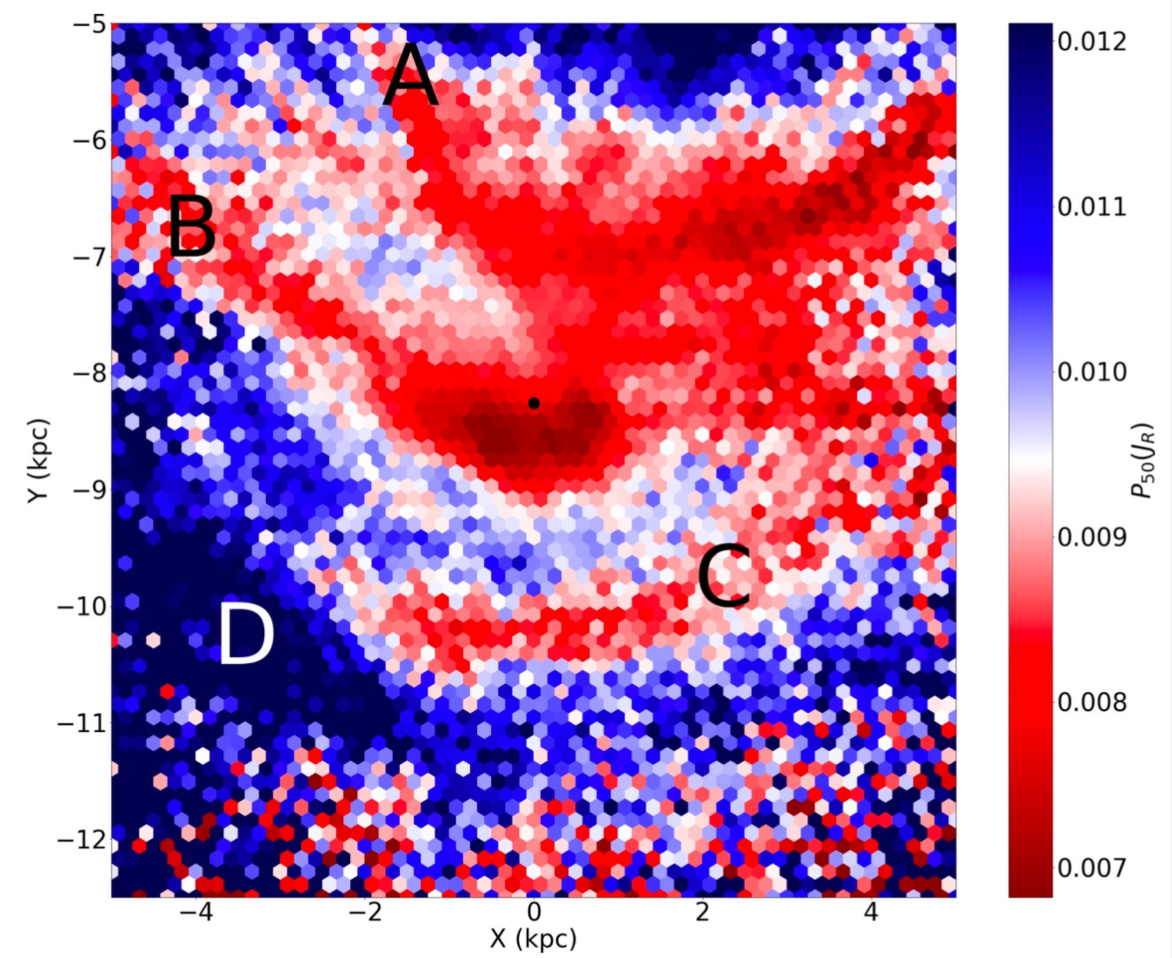
Lower J_R (red) means more circular

Spiral-like structures in J_R for (old) giant stars

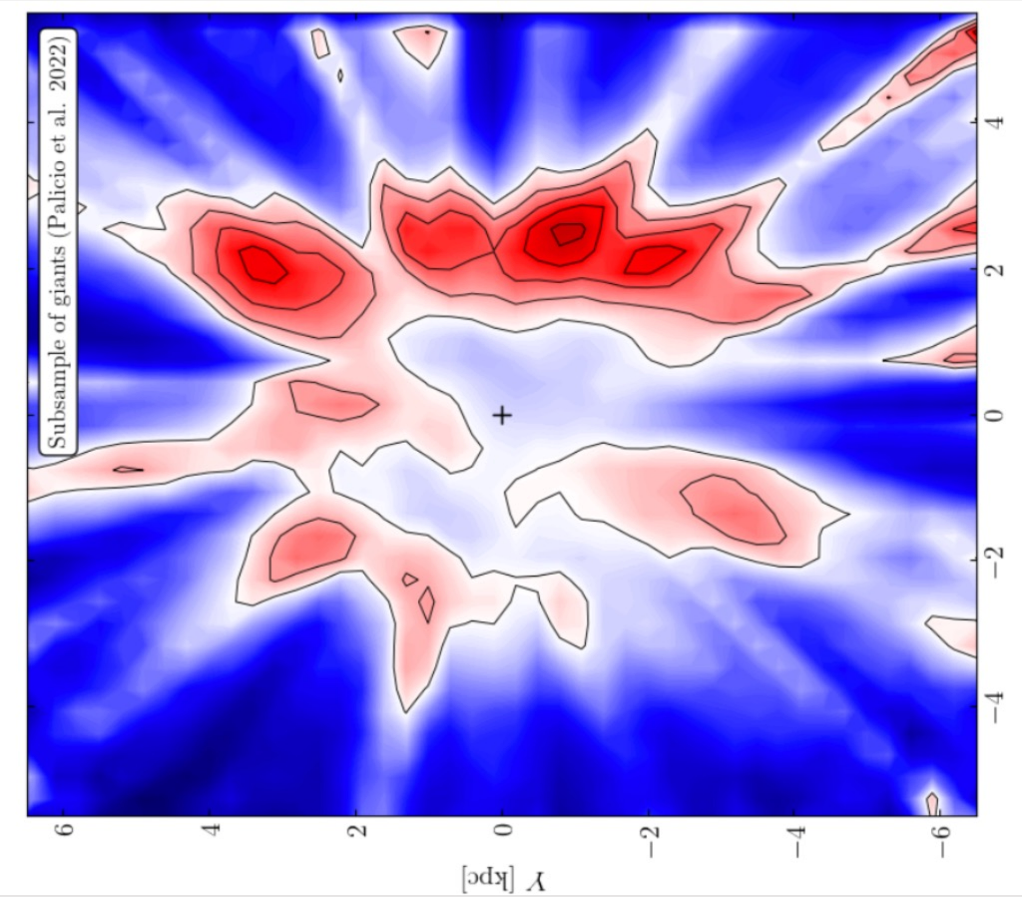


Palicio et al. (2023a)

Spiral arms : signatures in density, metallicity and orbits



Spiral arms detected in stellar density for old stars (Age>1Gyr)



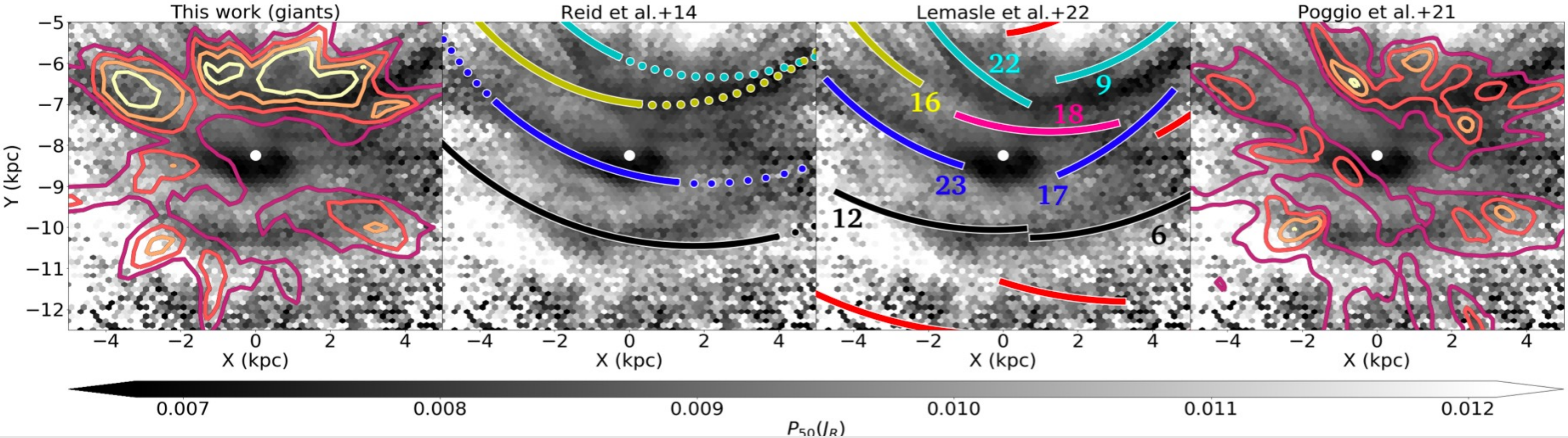
Palicio et al. (2023a)

Adapted from Palicio et al. (2023a) by M. Barbillon

Spiral arms : signatures in density, metallicity and orbits

Correlation of the J_R pattern **with different spiral arms tracers** (in stellar density).

Old	**Young**		
Giant stars	Masers	Cepheids	Upper Main Sequence

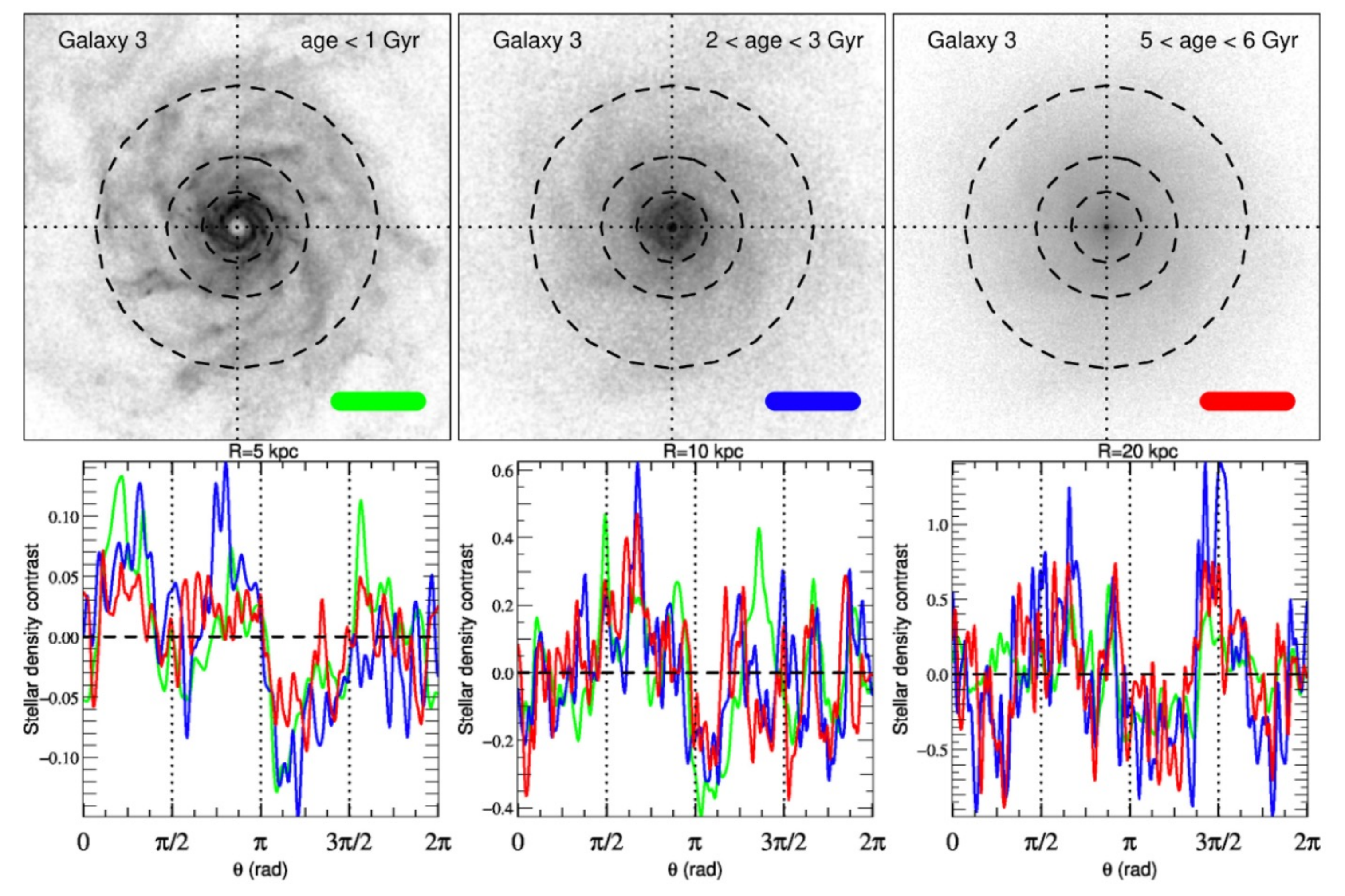


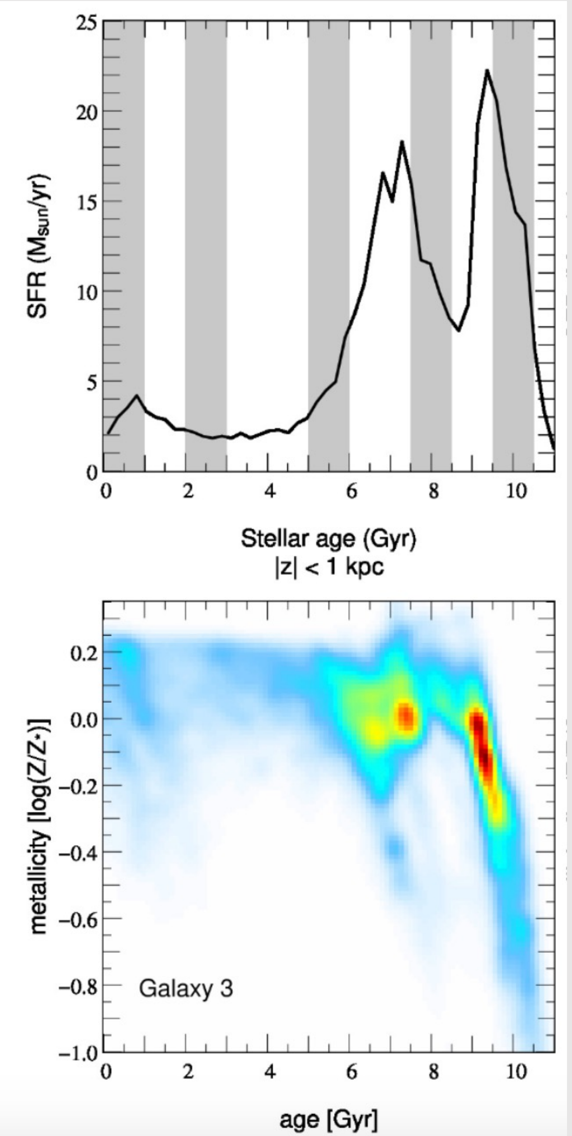
Palicio et al. (2023a)

Spiral arms : signatures in density, metallicity and orbits

Zoom-in cosmological simulations (New Horizons) **Peirani et al., in prep.**

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



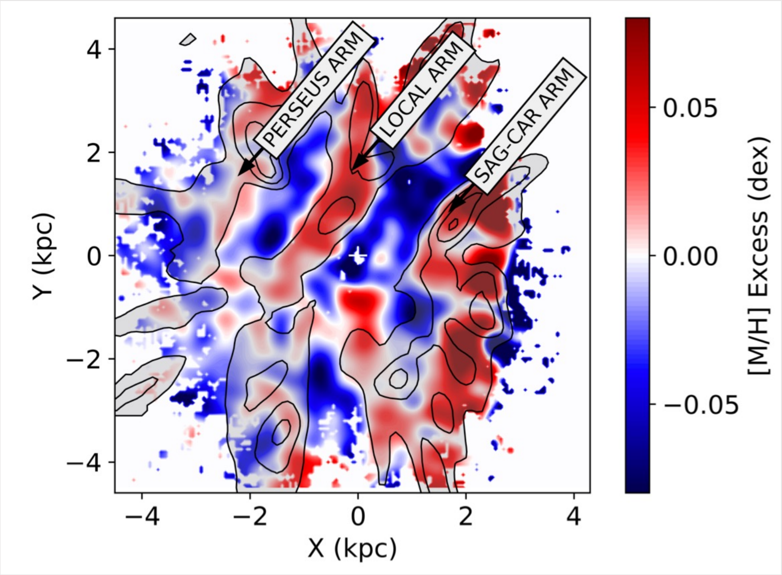


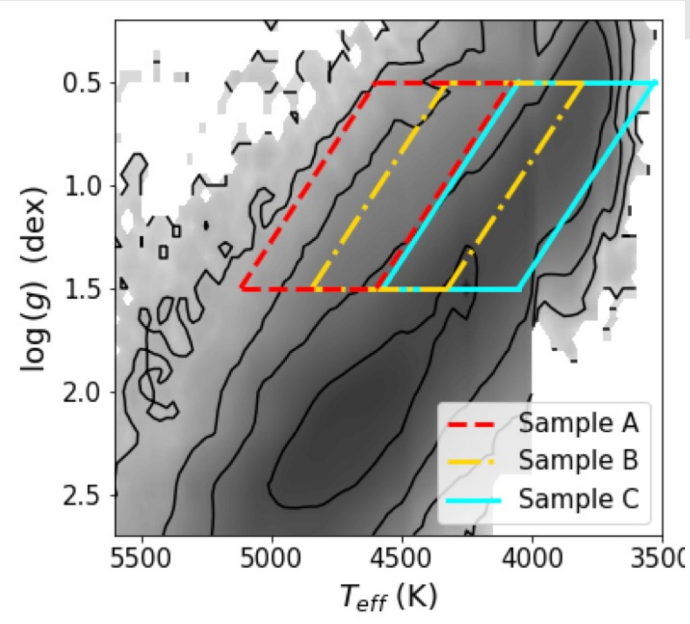
Spiral arms : signatures in density, metallicity and orbits

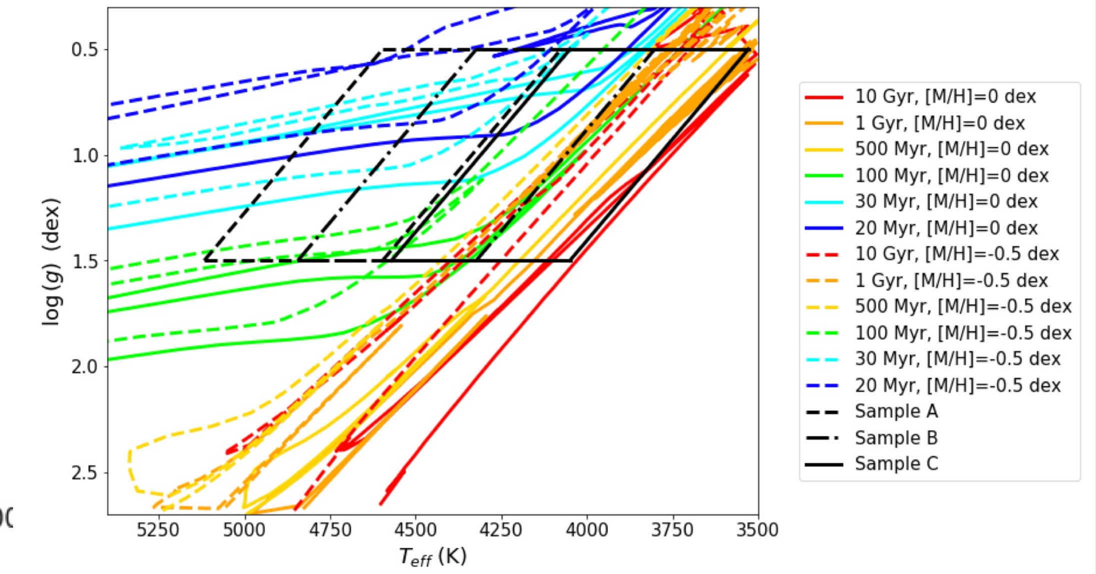
High enough precision and nb statistics to select stars in different age bins.

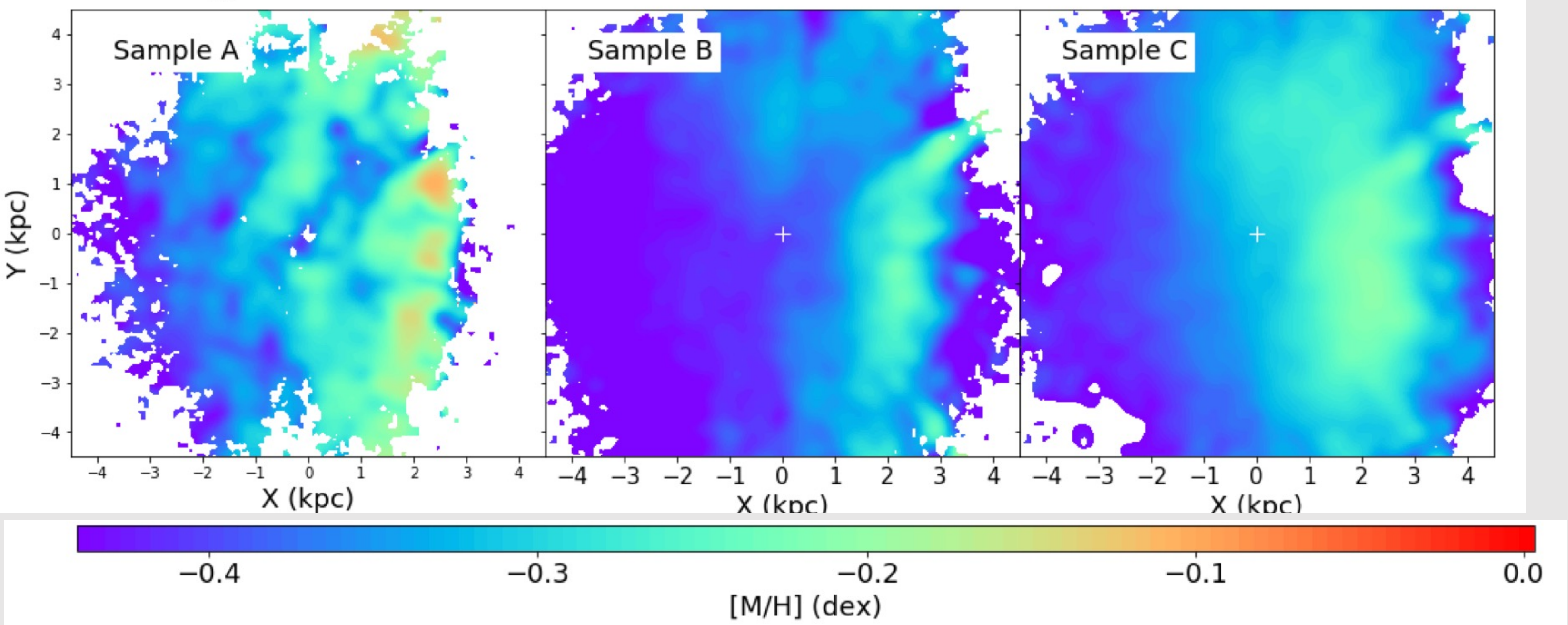
Chemical signature of the Spiral Arms

Poggio et al. (2022)



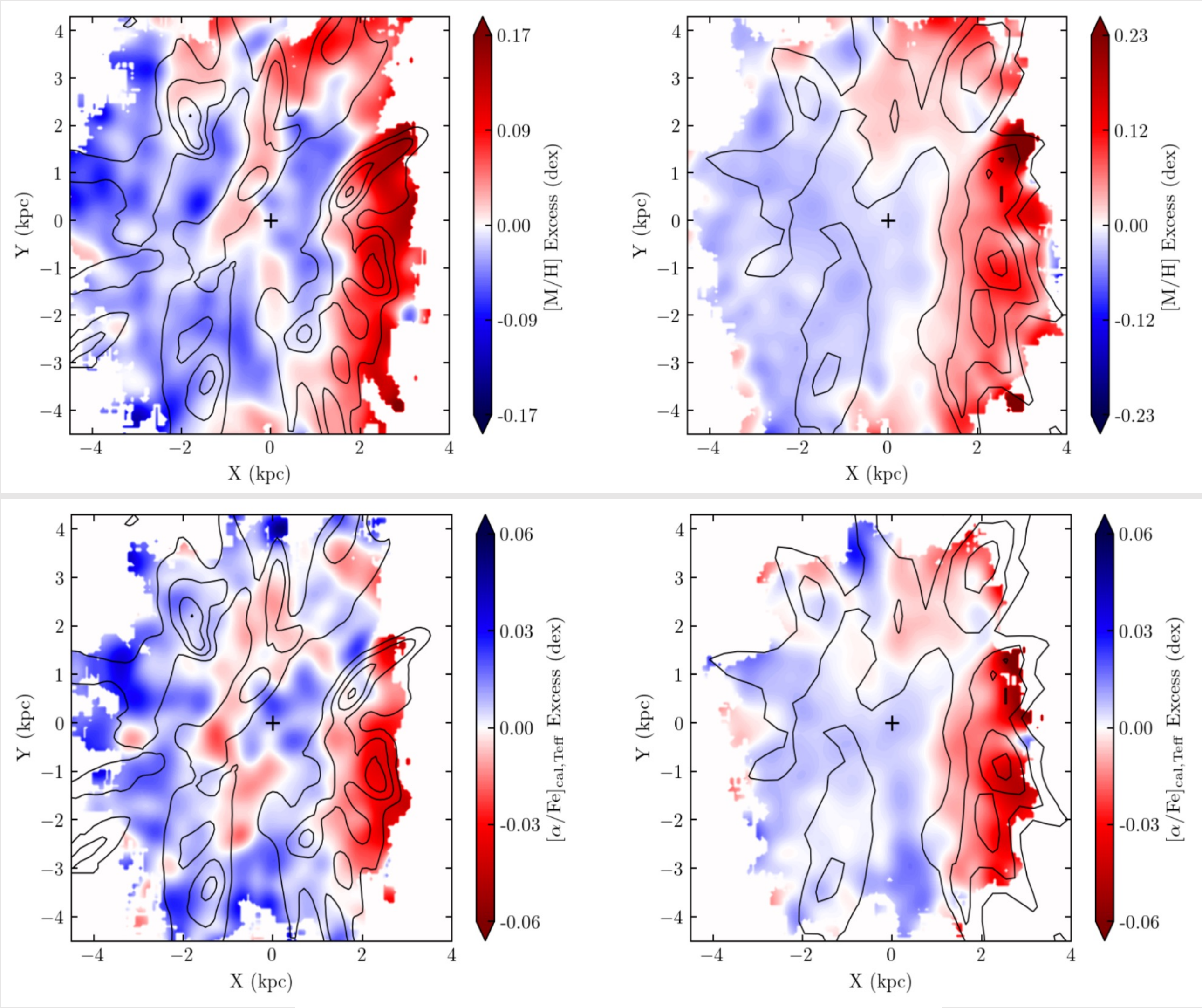






Spiral arms : signatures in density, metallicity and orbits

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



Barbillon et al., in prep.

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

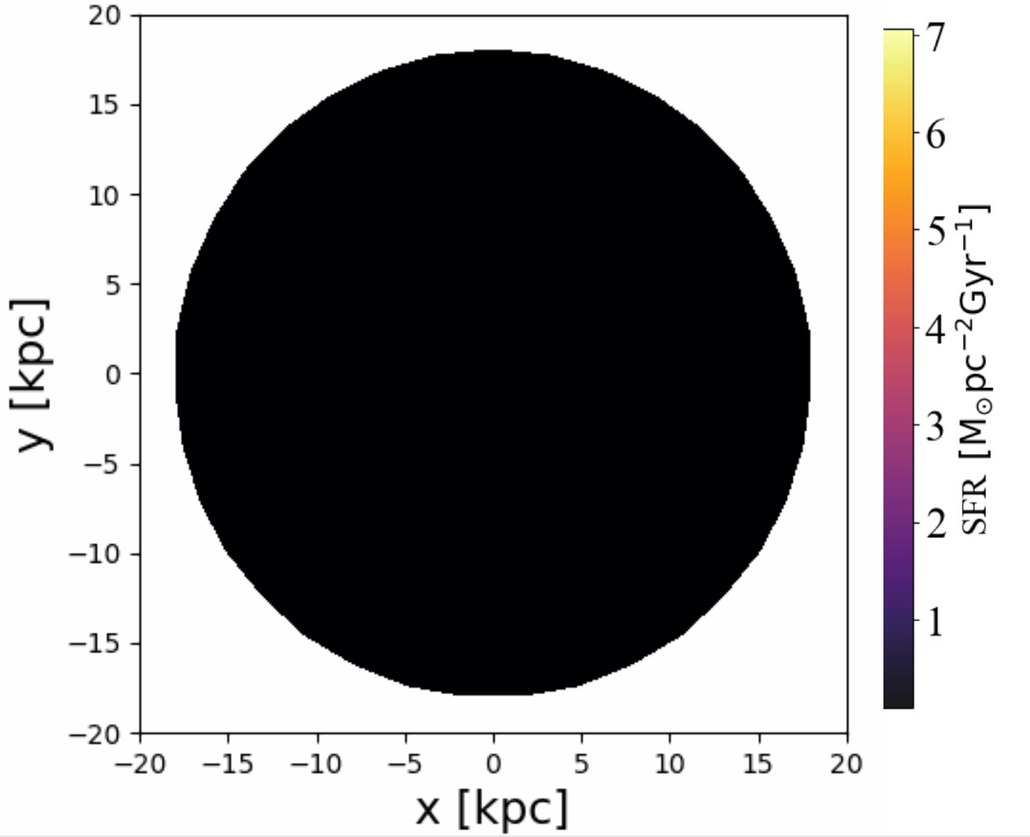
The spiral arms signature is **visible in the relative abundance of α-elements with respect to iron.**

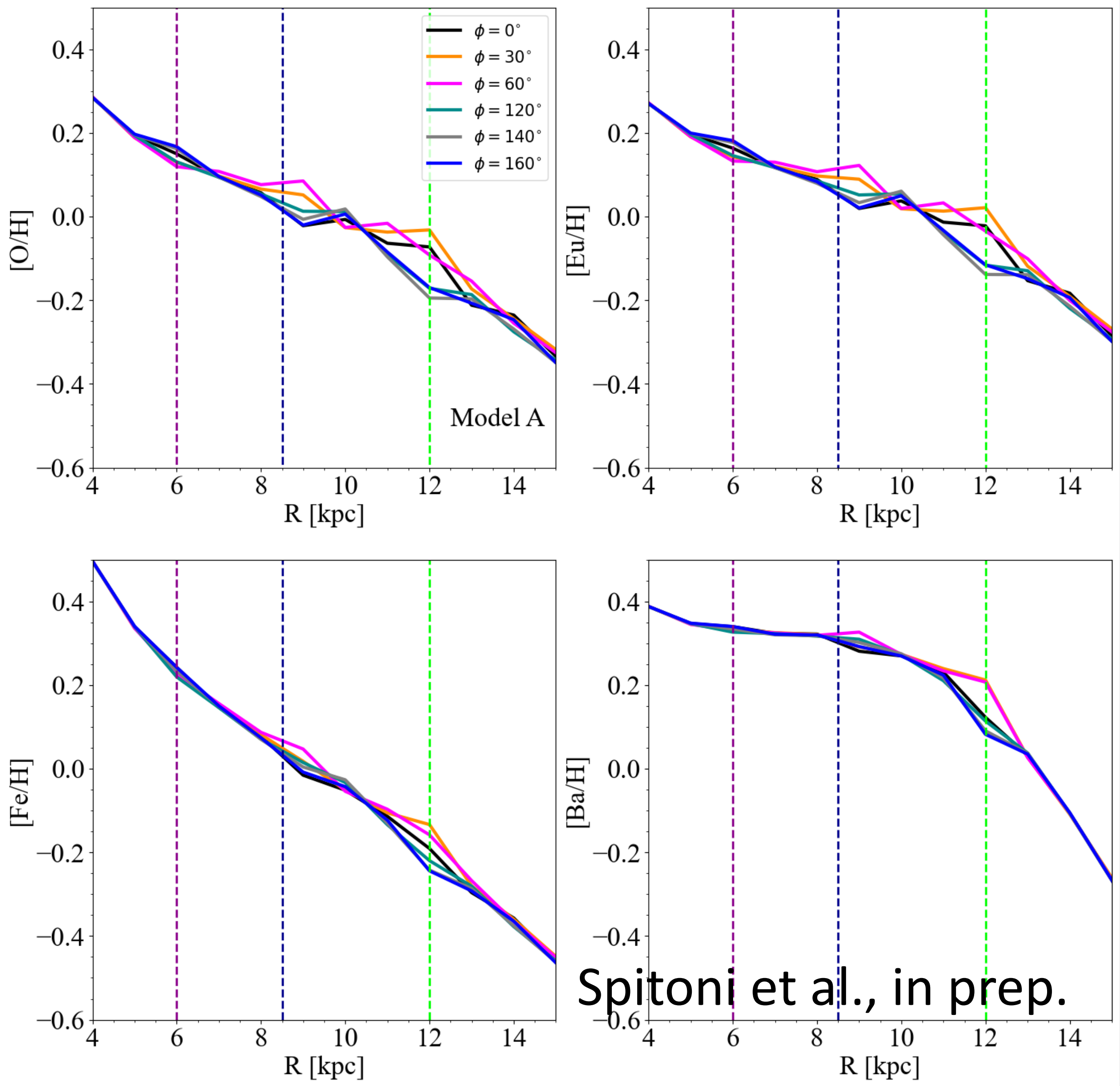
The fluctuation in α-elements is higher than in iron.

Spiral arms : signatures in density, metallicity and orbits

2D chemical evolution model

Elements synthesised on short time scales (i.e., oxygen and europium) exhibit larger abundance fluctuations.





Spitoni et al., in prep.

Spiral arms : signatures in density, metallicity and orbits

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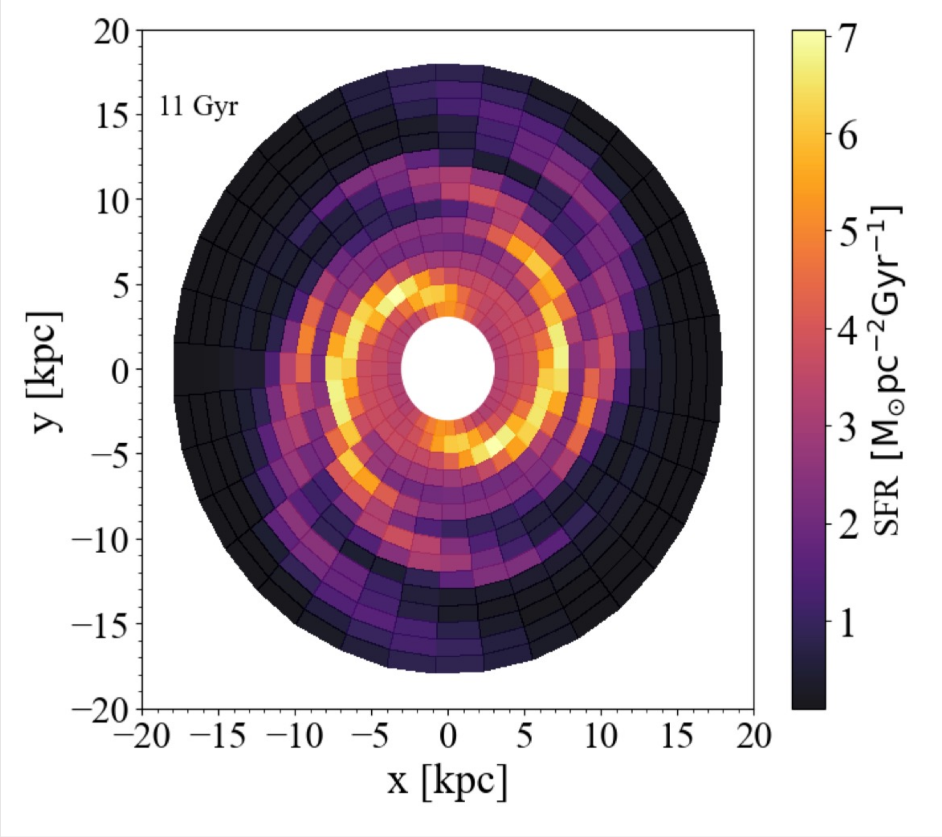
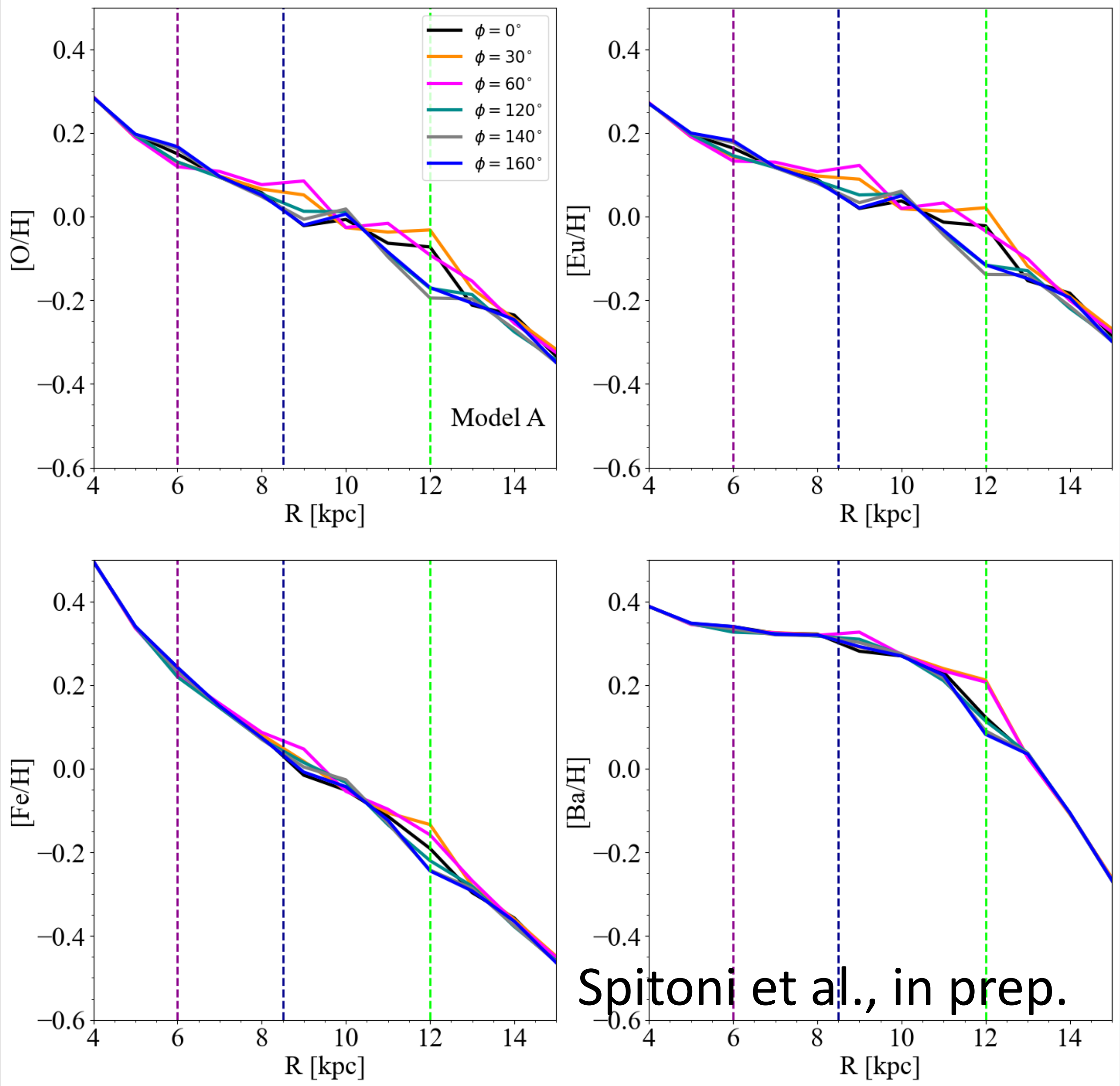
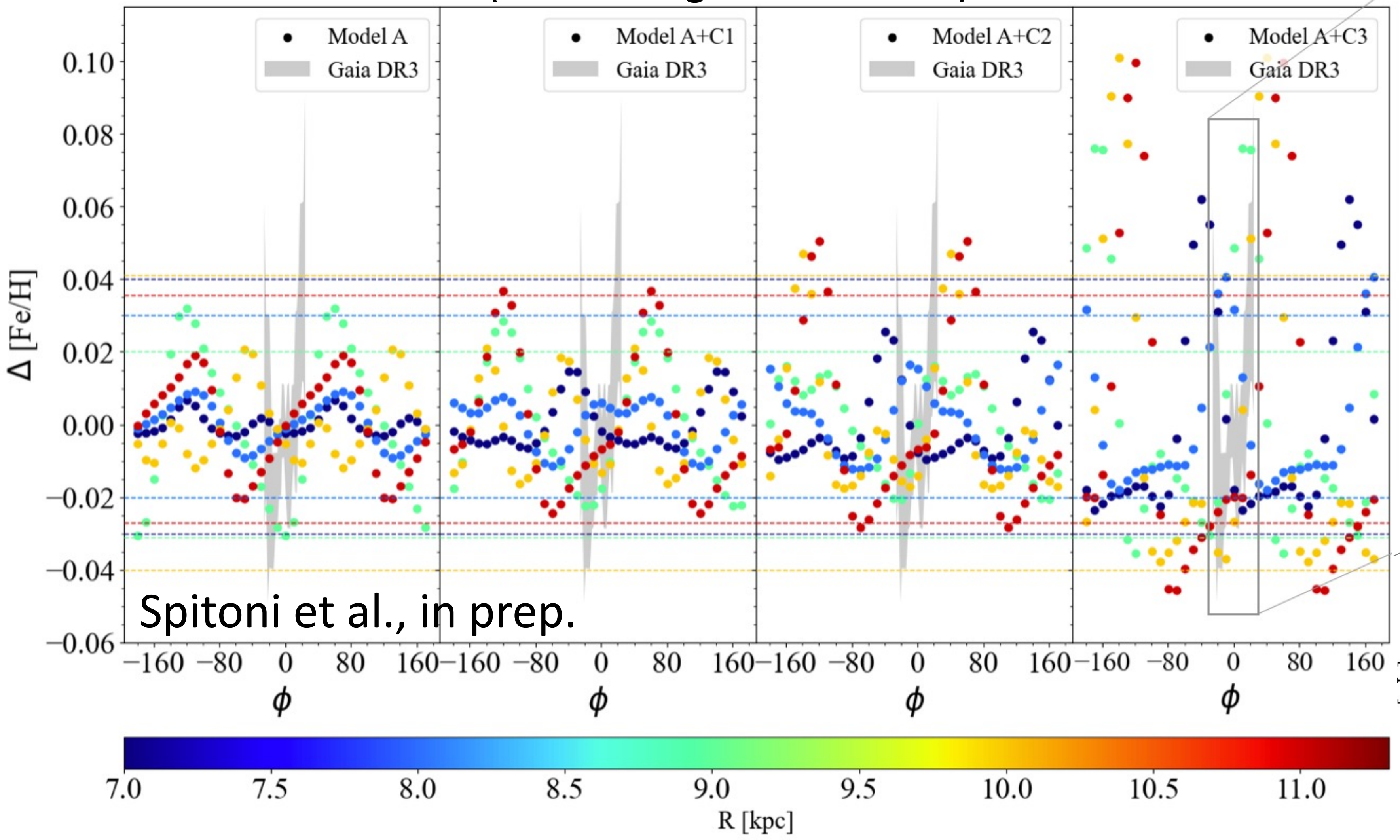




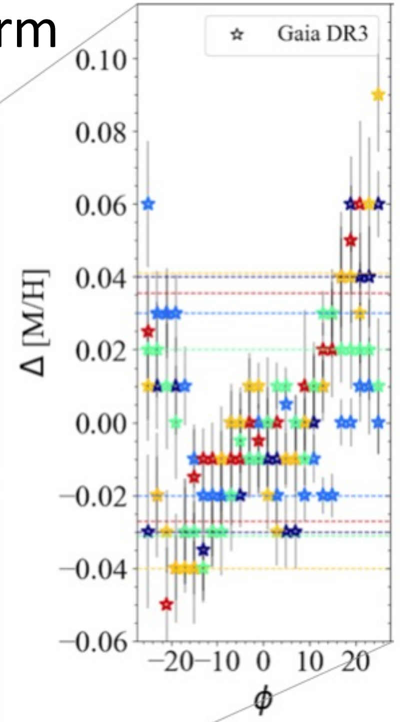
Spitoni et al., in prep.

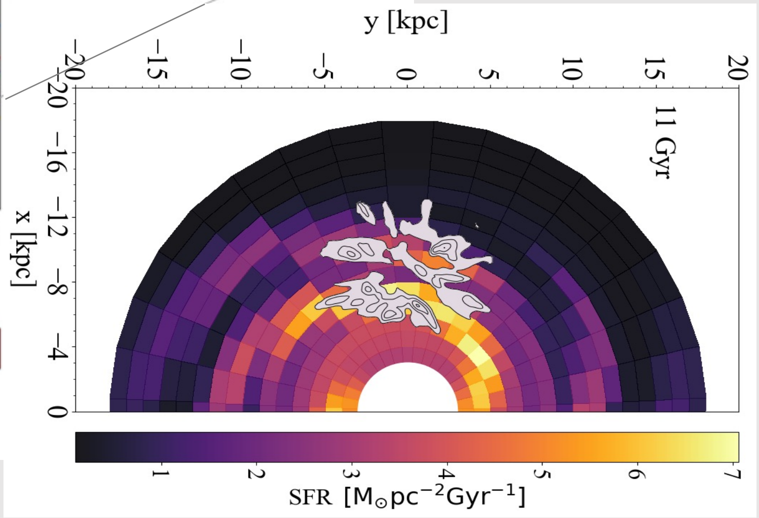
Spiral arms : signatures in density, metallicity and orbits

Agreement with Gaia observations if at most recent times the spiral arm structure is transient (co-rotating with the disc).



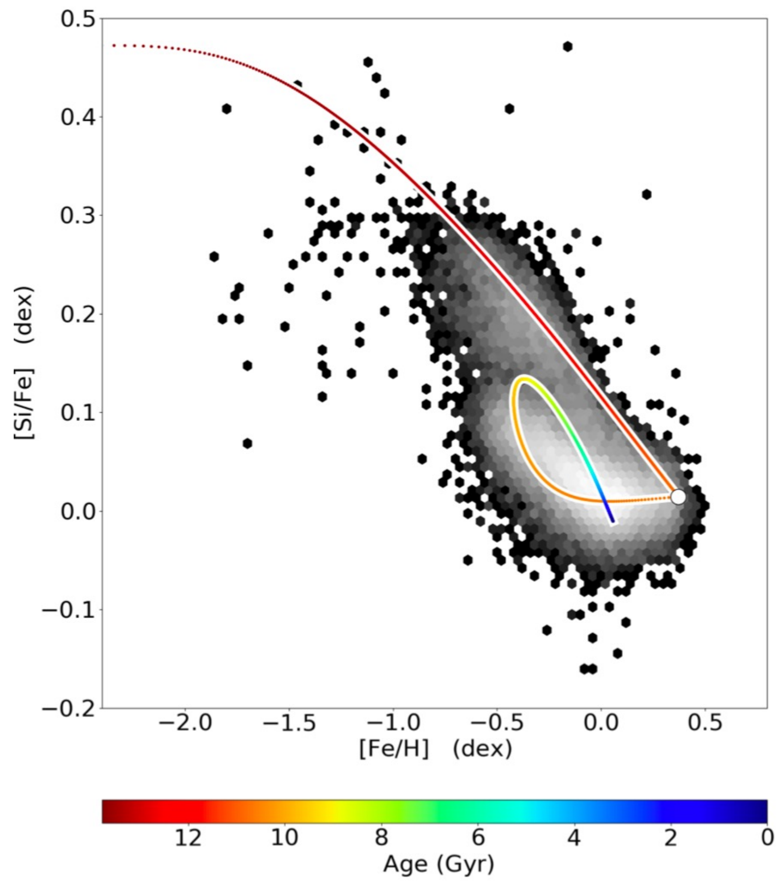
Spitoni et al., in prep.

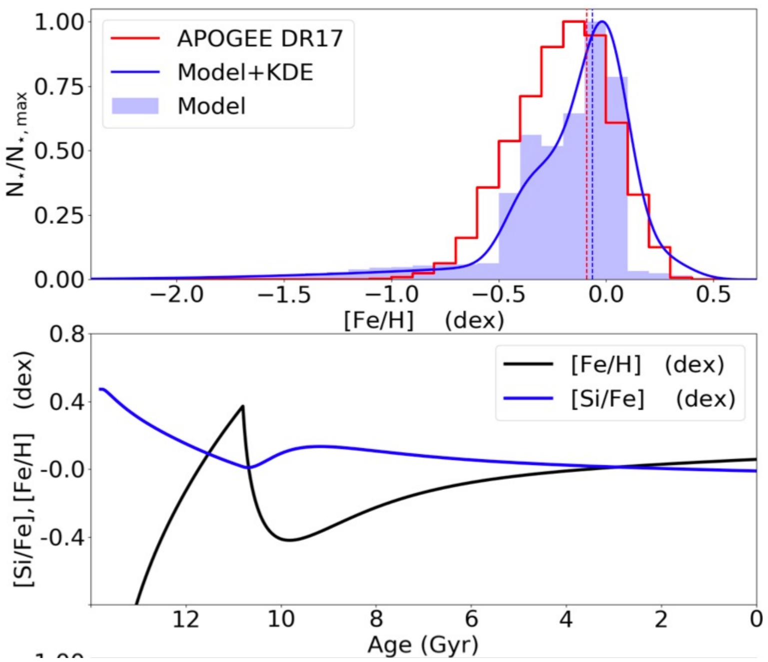




Spiral arms : signatures in density, metallicity and orbits

What is this telling us about Milky Way's building up and evolution?
Comparison with simulations including robust chemical predictions, thoroughly exploring the parameter space.





Palicio et al. (2023b)

An analytical chemical model including Type Ia SN

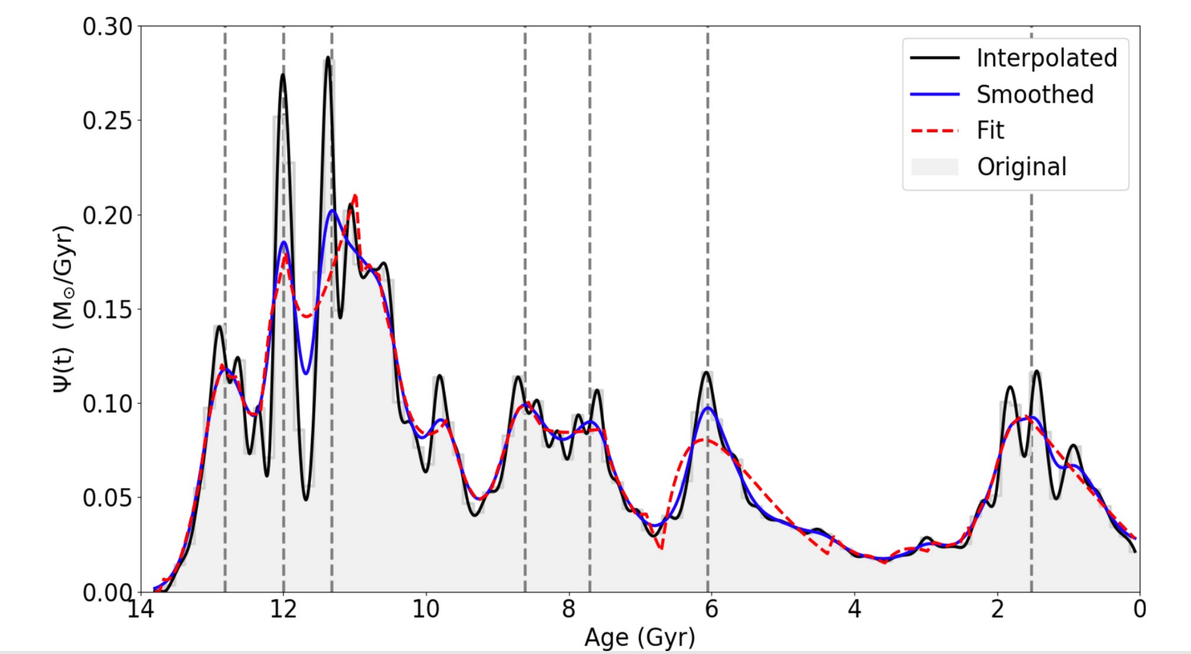
Chemical evolution model integrated by extending the instantaneous recycling approximation with the contribution of Type Ia SNe

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

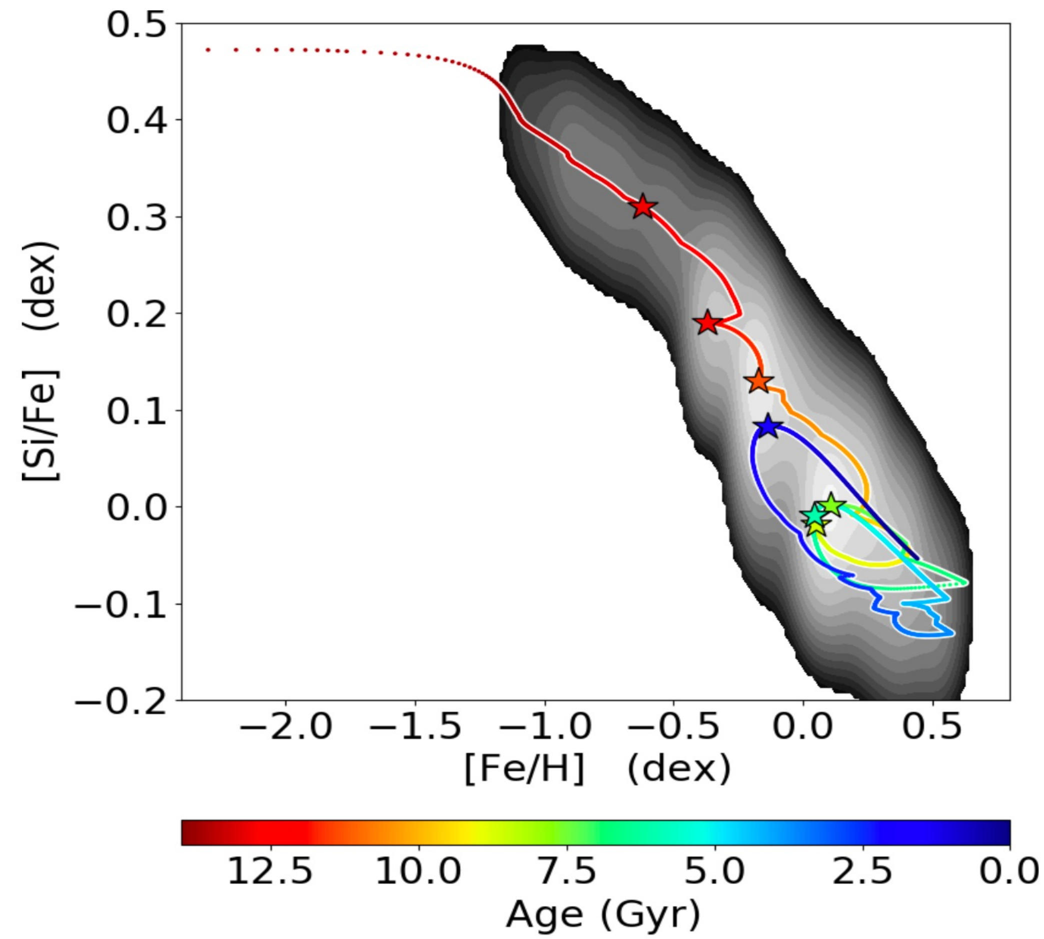
Galactic disc: an analytical chemical model including Type Ia SN

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.

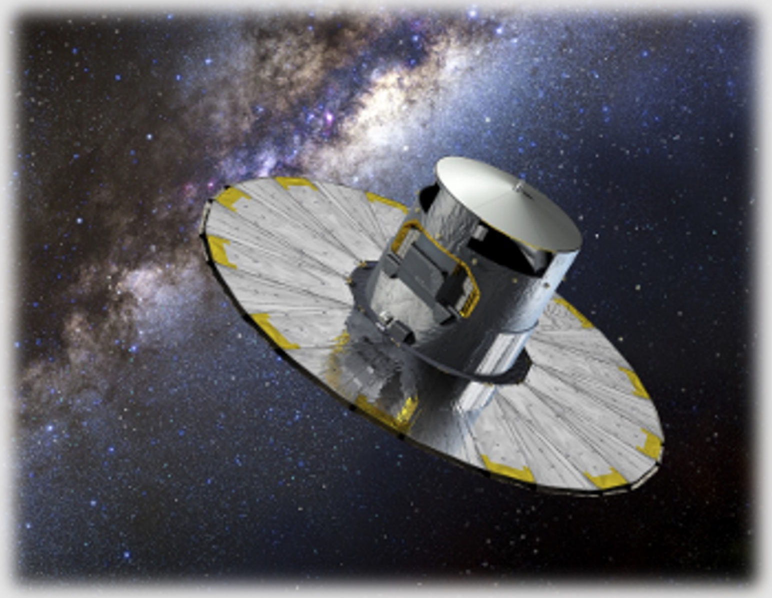


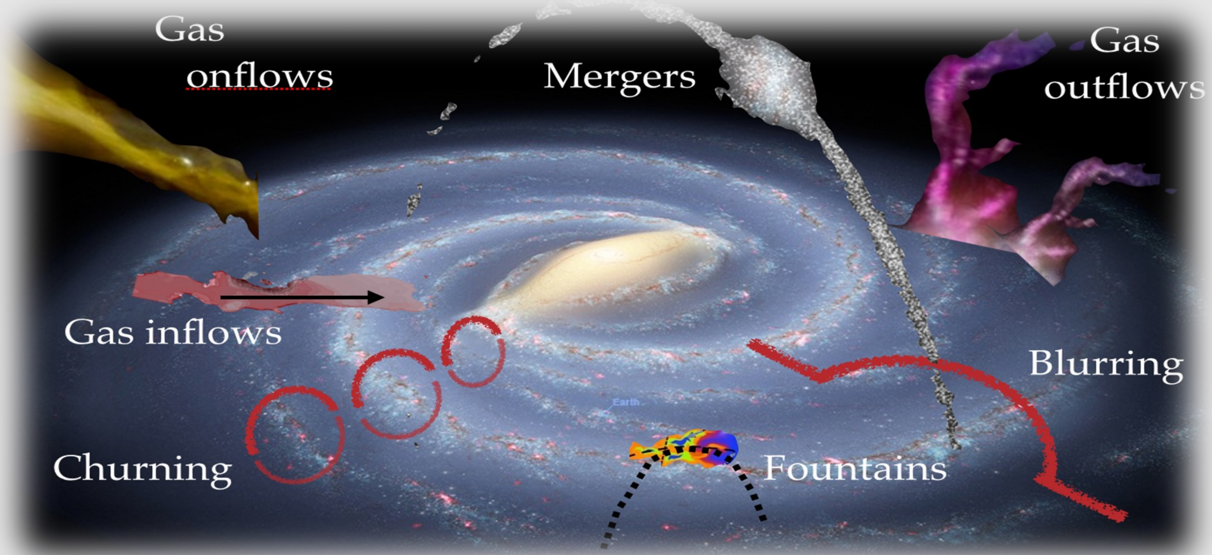
Palicio et al. (2023b)



Outline of the talk

1. The Gaia revolution and its keys
2. The chemical cartography of the Milky Way
3. The Galactic disc(s):
   - structure and chemical gradients
   - kinematic disturbances
   - spiral arms pattern(s)
4. Accretion of satellites in the Halo
5. Conclusions

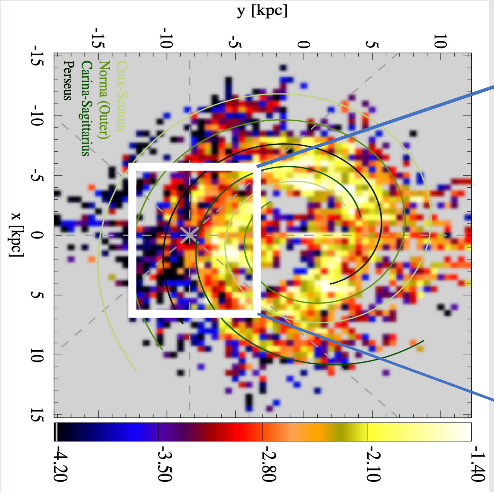


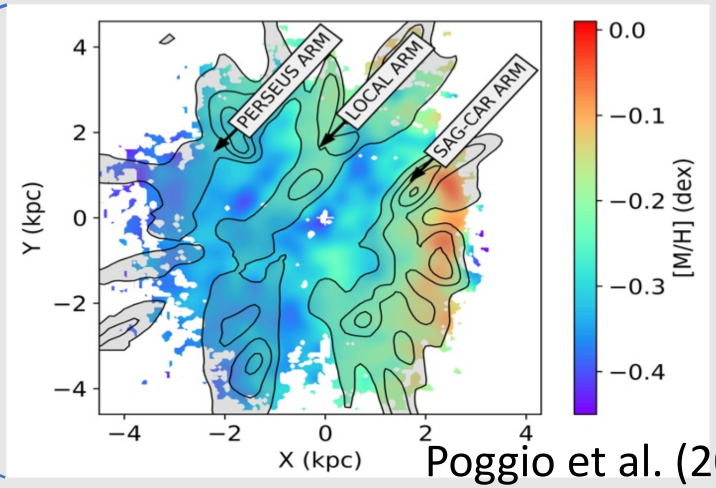


Conclusions

- The Milky Way disc has strong bisymmetric signatures (bar/spiral arms) that are probably long living
  - Can we link this to the star formation/accretion history?
  - Test evolution parameters with zoom-in cosmological simulations
- The classical radial chemical gradients in the disc are an approximation of a more complex 2D distribution:
  - Can we link this to star formation rate estimates?

Elia et al. (2022)
SFR estimates from
HERSCHEL data





Poggio et al. (2022)

Conclusions

- Chemical composition is crucial to improve our understanding of baryon physics.
- It is central to many physical processes as it modifies:
  - Opacity -> stellar temperature and colours
  - Viscosity -> turbulence, stellar interiors -> asteroseismology
  - Stellar evolutionary paths -> age estimates
  - Pulsation periods -> distance ladder
  - Dust production -> ISM
  - Stellar yields
  - ...

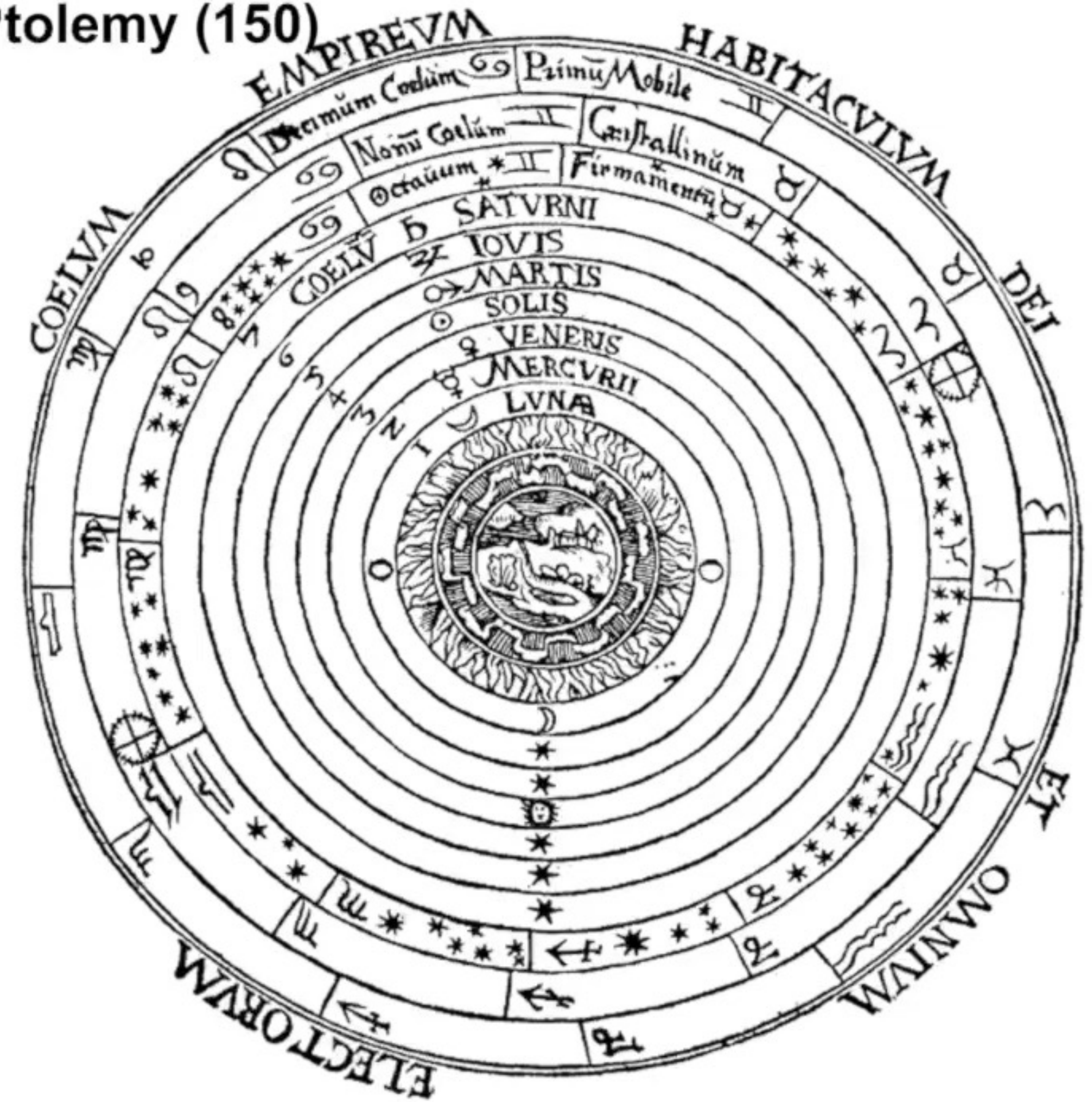
Conclusions

- The Gaia future is bright:
  - only ¼ of the data analysed in DR3!
  - end of cold gas (operational phase) Jan-March 2025
  - 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)
- Complementary ground based HR spectroscopy (WEAVE+4MOST) 5-10 million

Conclusions

- Time-series chemo-physical parameters for cepheids and RRLyrae from DR4
  New Gaia DPAC task force
- Standard candles will increase the precision of Gaia distances towards the bulge, the outer disc, the halo and the surrounding satellites.
- In 2030 Gaia will have recorded 10 years of the Milky Way history!
- Important to keep synergy with models and simulations, including in a cosmological context
- Gaia will be a crucial catalogue for LISA (spiral arm detection with GW?)

Ptolemy (150)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