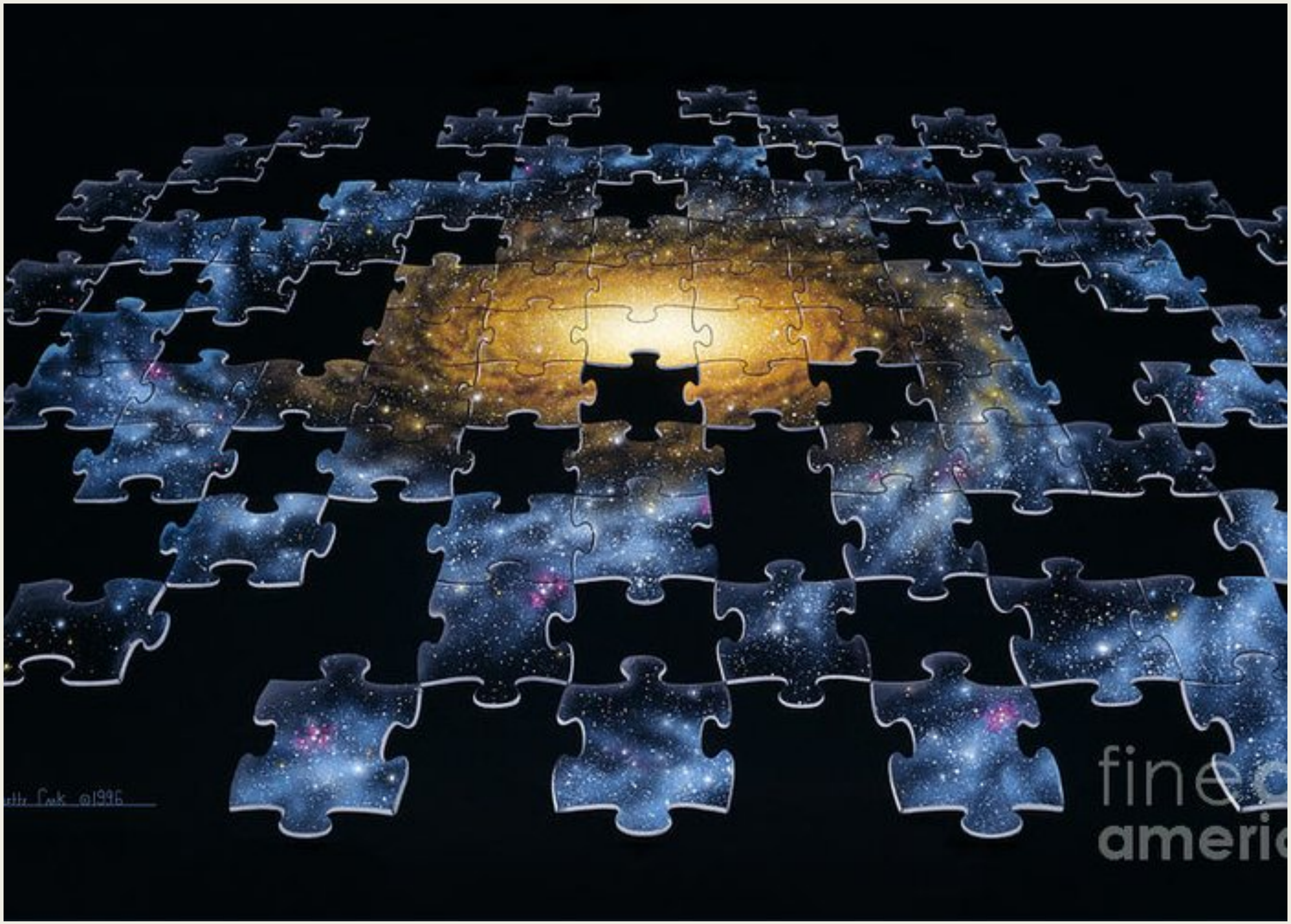
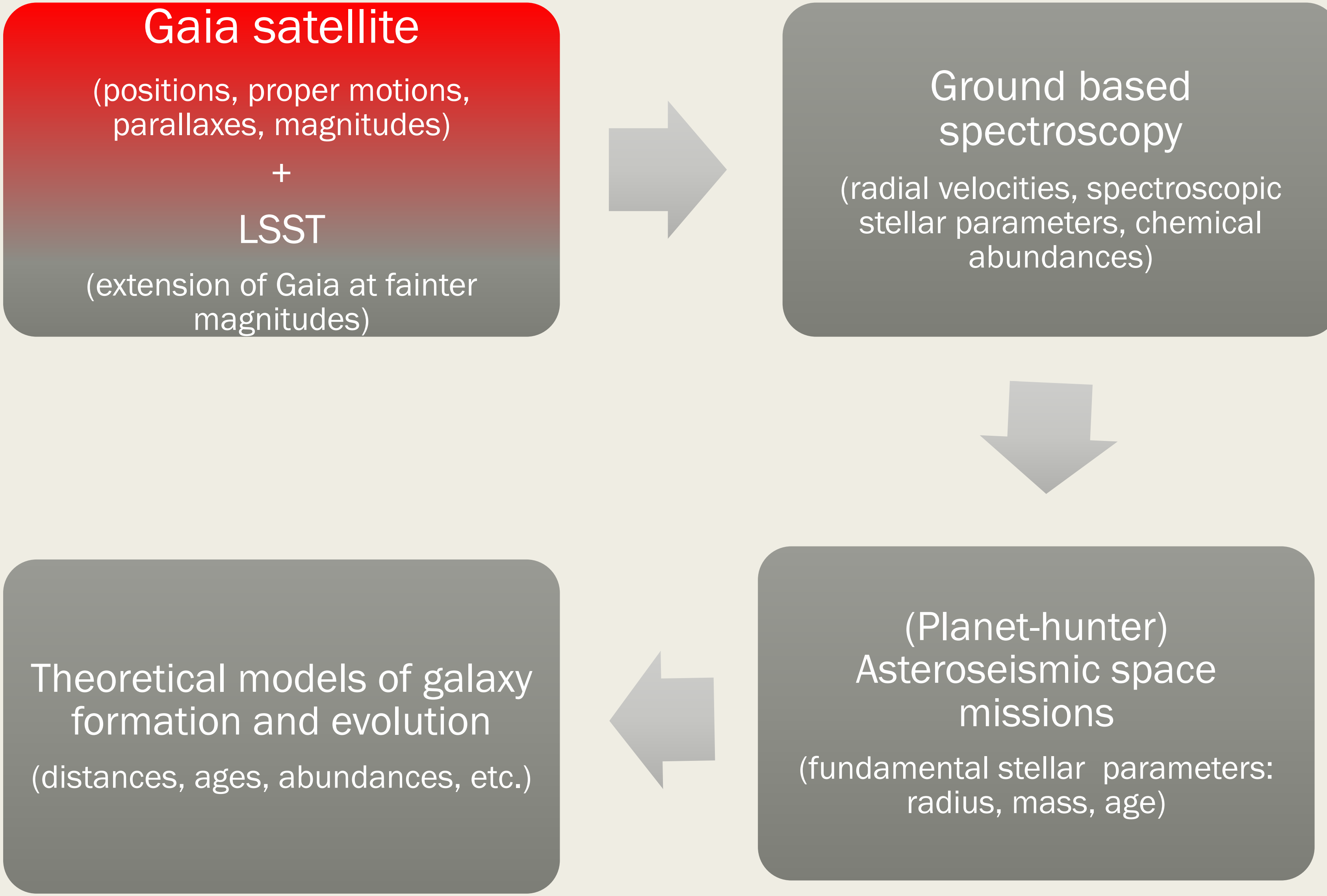
THE GOLDEN AGE OF GALACTIC ASTRONOMY

Lezione XII- Fisica delle Galassie

Laura Magrini

Now, we can collect a large number of the pieces of the MW puzzle….




Gaia satellite
(positions, proper motions, parallaxes, magnitudes)
+
LSST
(extension of Gaia at fainter magnitudes)
Ground based spectroscopy
(radial velocities, spectroscopic stellar parameters, chemical abundances)
(Planet-hunter) Asteroseismic space missions
(fundamental stellar parameters: radius, mass, age)
Theoretical models of galaxy formation and evolution
(distances, ages, abundances, etc.)

Gaia Satellite and System

- ESA mission
- Launch: 19 December 2013
- Launcher: Soyuz–Fregat from French Guiana
- Orbit: L2 Lissajous orbit
- Lifetime: 5 years (1 year potential extension)
- Downlink rate: 4 - 8 Mbps

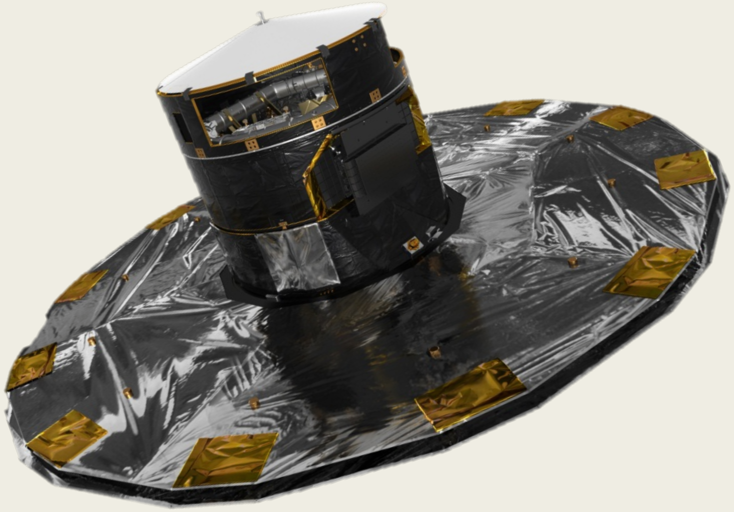


Figure Soyuz: Arianespace; figure Gaia: ESA - C. Carreau

First release: 14 September 2016
Gaia DR1 contents Gaia DR1 overview page
Second release: 25 April 2018
Gaia DR2 contents Gaia DR2 overview page
Third release: Early Gaia EDR3: Q3 2020 Gaia DR3: H2 2021

Gaia: products

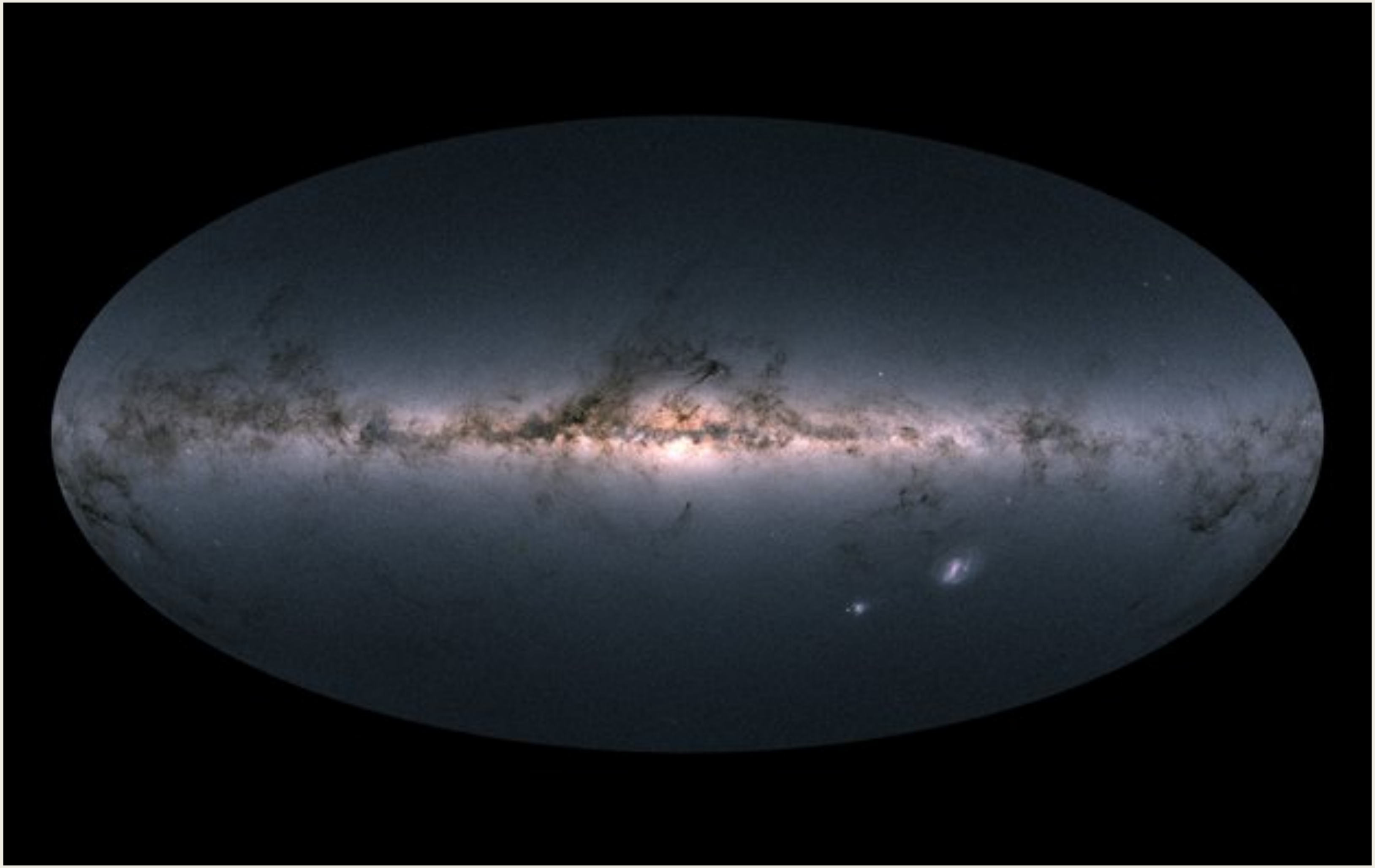
- **Astrometry (G < 20 mag):**
  - completeness to 20 mag ⇒ $>10^9$ stars
  - accuracy: 26 μarcsec at G=15 mag (Hipparcos: 1 milliarcsec at 9 mag)

⇒ *global accuracy, with optimal use of observing time*

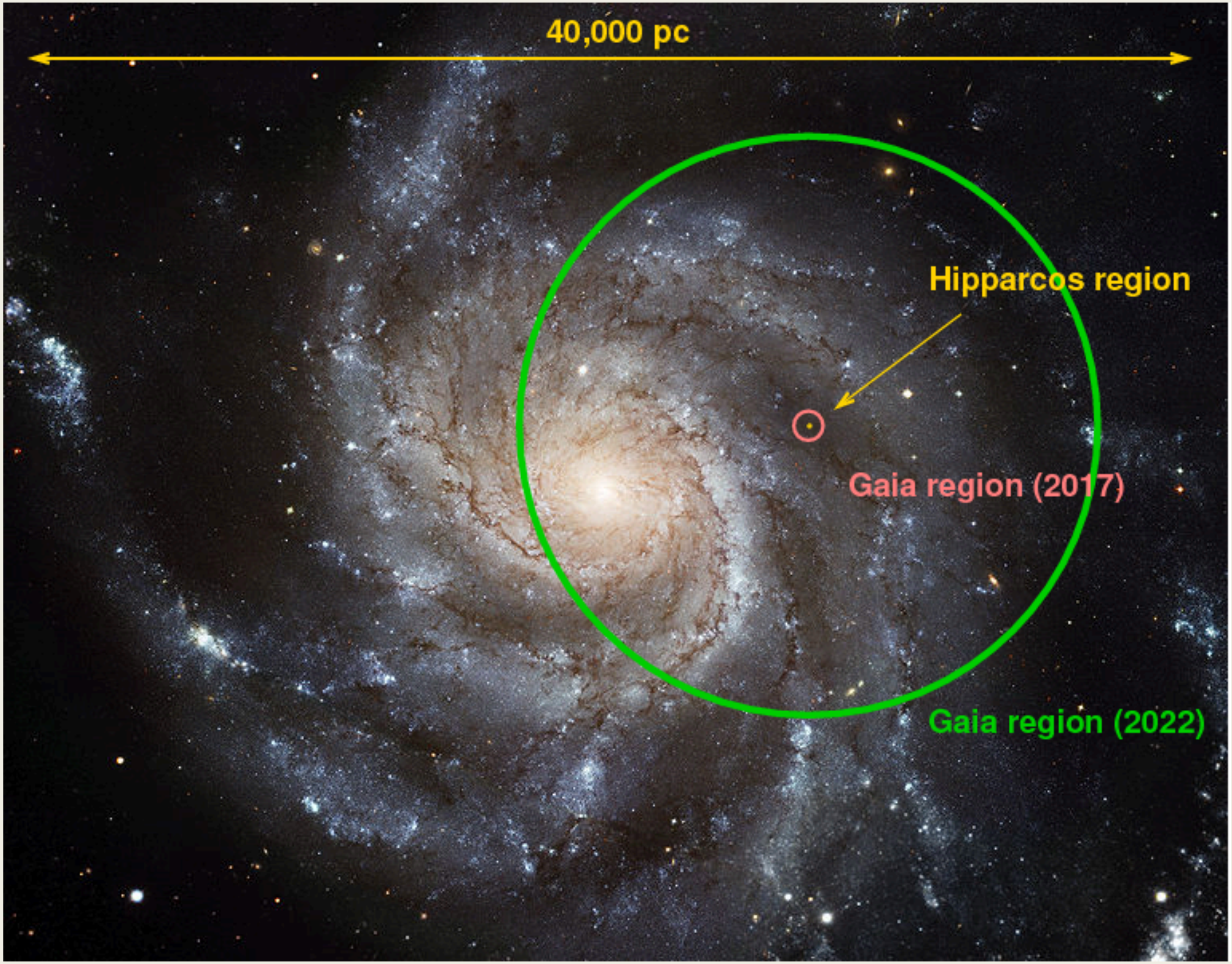
- **Photometry (G < 20 mag):**
  - astrophysical diagnostics (low-dispersion photometry) + chromaticity
    - ⇒ ΔT_{eff} ~ 100 K, log g, [Fe/H] to 0.2 dex, extinction (at G=15 mag)

- **Radial velocity (G_{RVS} < 16 mag):**
  - accuracy: 15 km s^{-1} at G_{RVS}=16 mag
  - application:
    - third component of space motion, perspective acceleration
    - dynamics, population studies, binaries
    - **spectra for G_{RVS} < 12 mag: chemistry, rotation**
    - Ca triplet (845-872 nm) at R = ~10,800

The Milky Way as seen by Gaia



From Hipparcos to Gaia



Gaia DR2

→ HOW MANY STARS WILL THERE BE IN THE SECOND GAIA DATA RELEASE?
esa
position & brightness on the sky
1 692 919 135
surface temperature
161 497 595
red colour
1 383 551 713
blue colour
1 381 964 755
parallax and proper motion
1 331 909 727
radius & luminosity
76 956 778
amount of dust along the line of sight
87 733 672
radial velocity
7 224 631
14 099
Solar System objects
550 737
variable sources

Deeper than Gaia: LSST

Observation period: 2022-2032

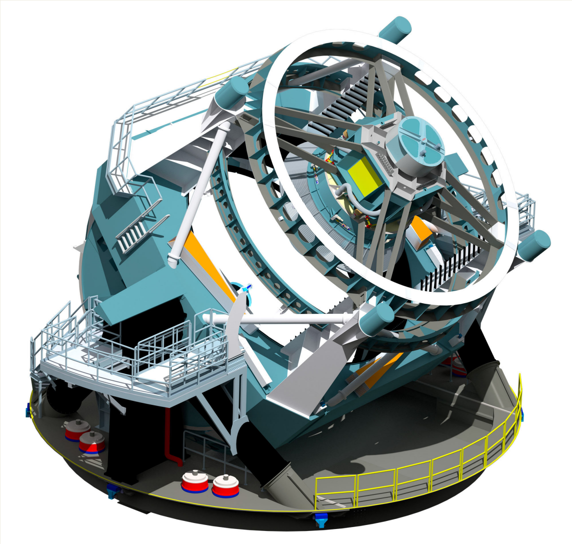
Sky coverage: 25 000 deg^2

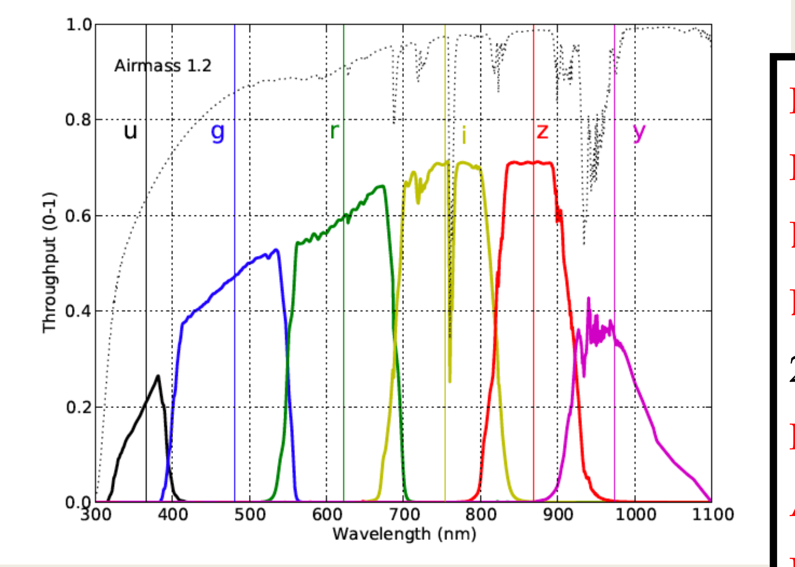
Telescope: 8.4 m (6.5m)

FoV: 9.6 degree^2

Website: https://www.lsst.org/

(Ivezic et al. 2008)





Multiband photometry: u, g, r, i, z, y

Number of objects: 37 x 10 ^{9}

Limiting magnitudes: 26.1, 27.4, 27.5, 26.8, 26.1, 24.9

Limiting magnitudes single visit: 23.4, 24.6, 24.3, 23.6, 22.9, 21.7

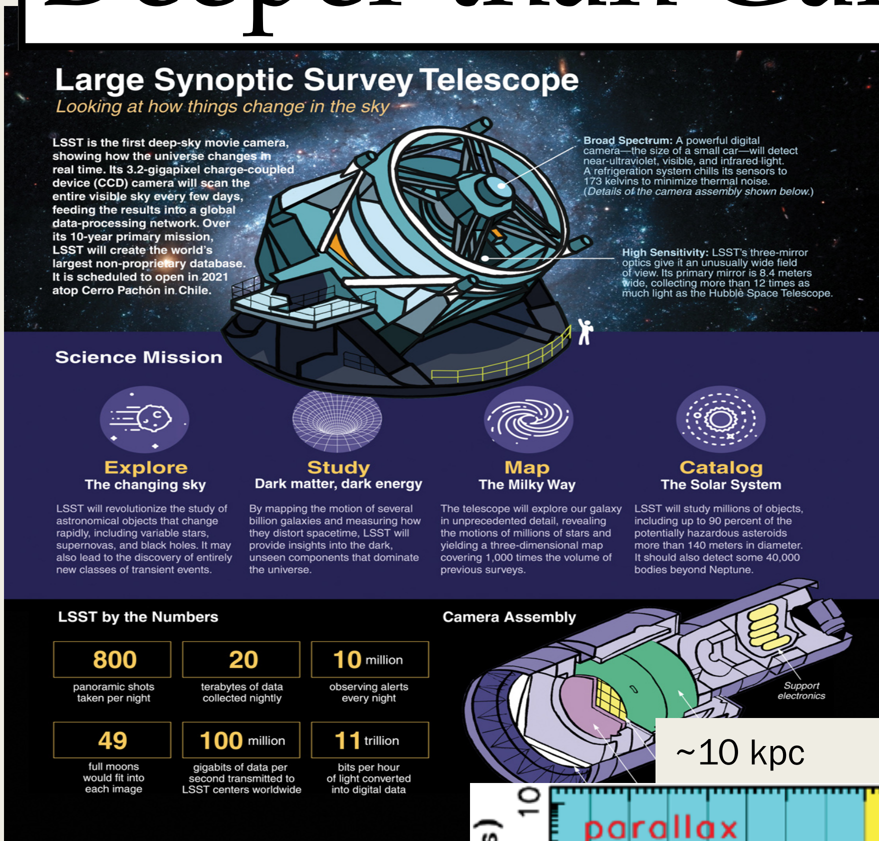
N. visits: 56, 80, 184, 184, 160, 160

Astrometry: mag limit 24

Parallaxes: 0.6-2.9 mas (21-24 mag in r band)

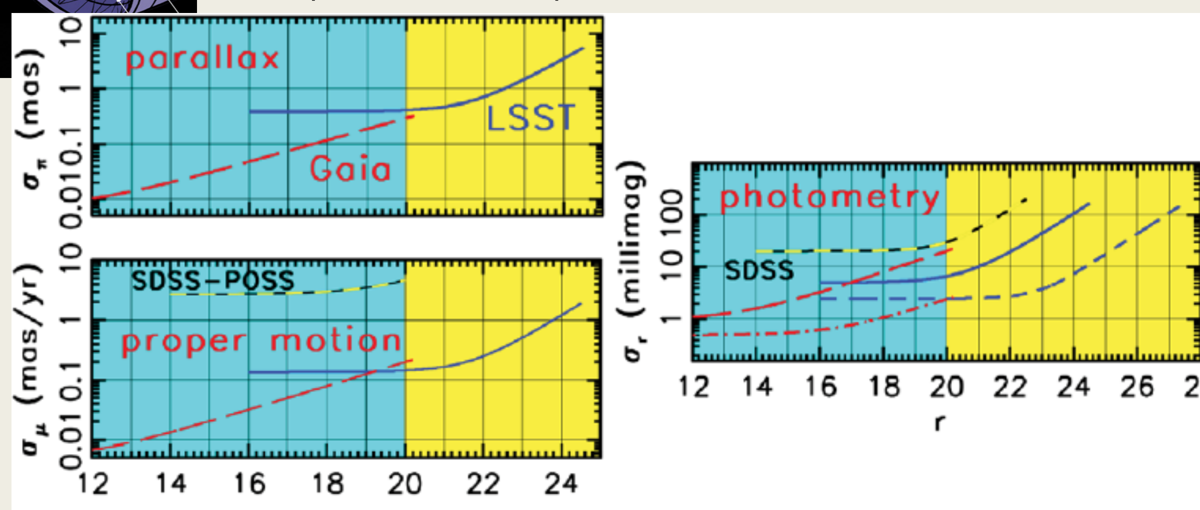
Proper motion: 0.2-1.2 mas/yr (21-24 mag in r band)

Deeper than Gaia: LSST



- Variability
- Transients
- Deep photometry
- Proper motions and parallaxes

~10 kpc ~60 kpc



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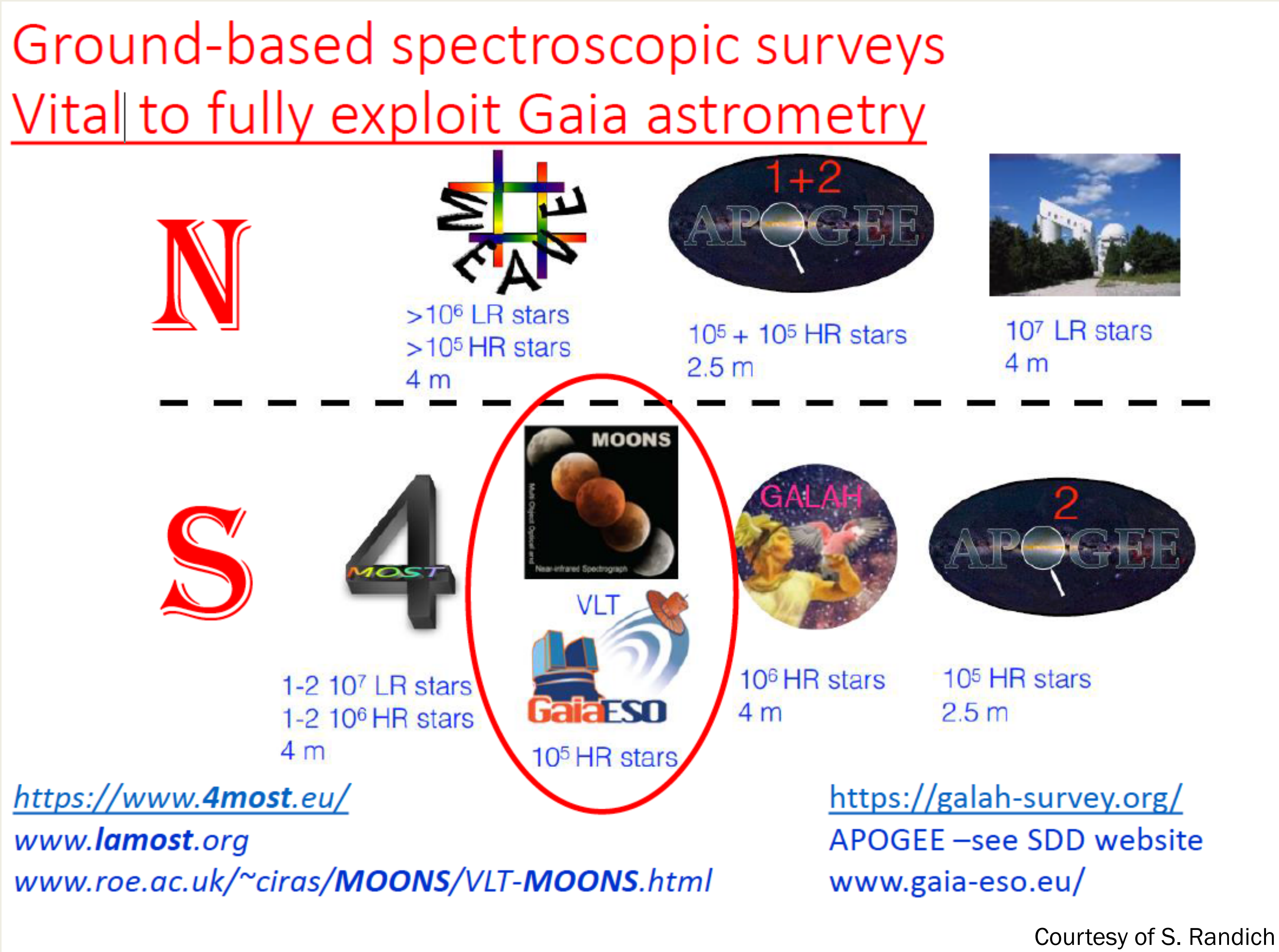
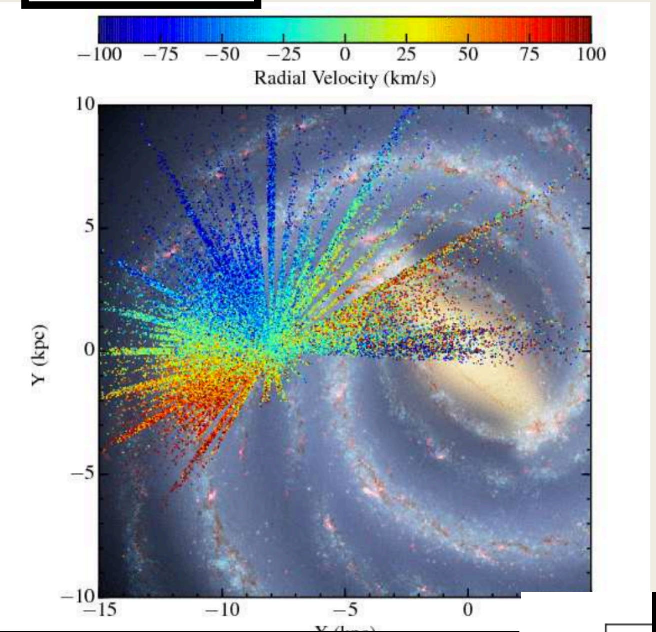
The large spectroscopic surveys



The observed fields

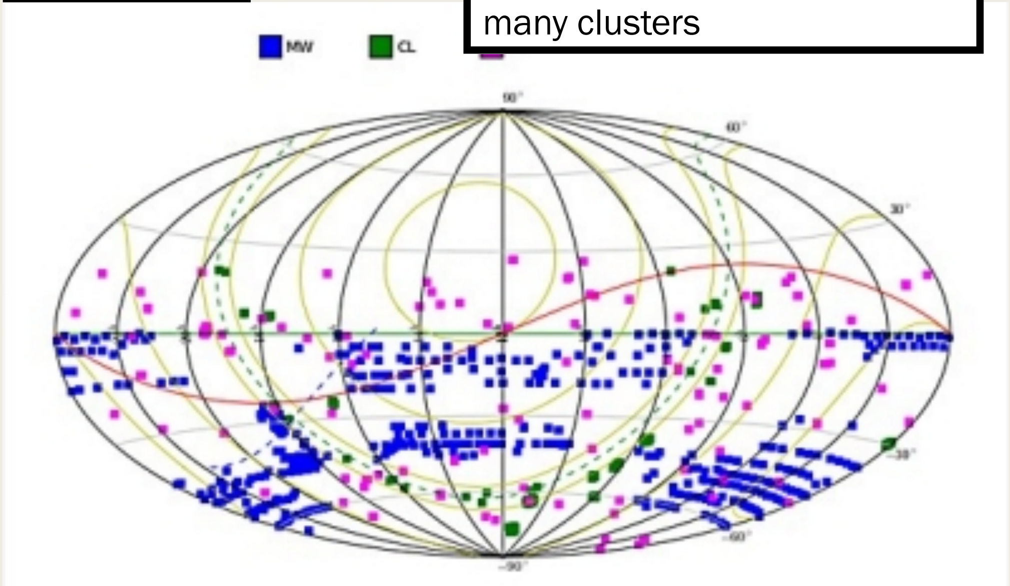
APOGEE



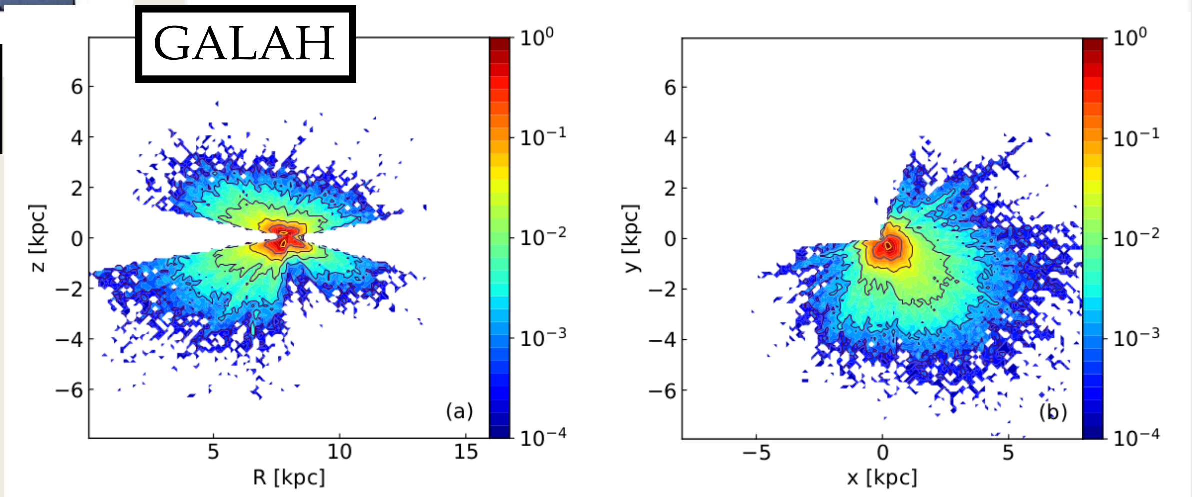
100000 red giant stars in the thin and thick discs

Gaia-ESO

100000 stars in the thin and thick discs, bulge, halo + many clusters



GALAH

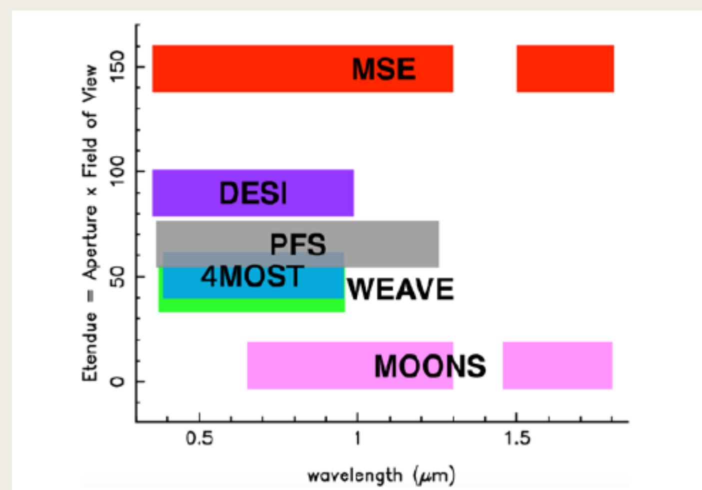


1 million stars 77% thin-disk stars, 22% thick-disk stars, 0.8% bulge stars, and 0.2% halo stars

Future spectroscopic surveys:

WEAVE, 4MOST, MOONS and MSE (MaunasKea Spectroscopic Explorer)

- Large number of objects
- Large fields of view
- Towards the near infrared
- Medium/low spectral resolution



How to put together all these surveys?

- Intra-survey calibration samples
- Inter-calibration samples

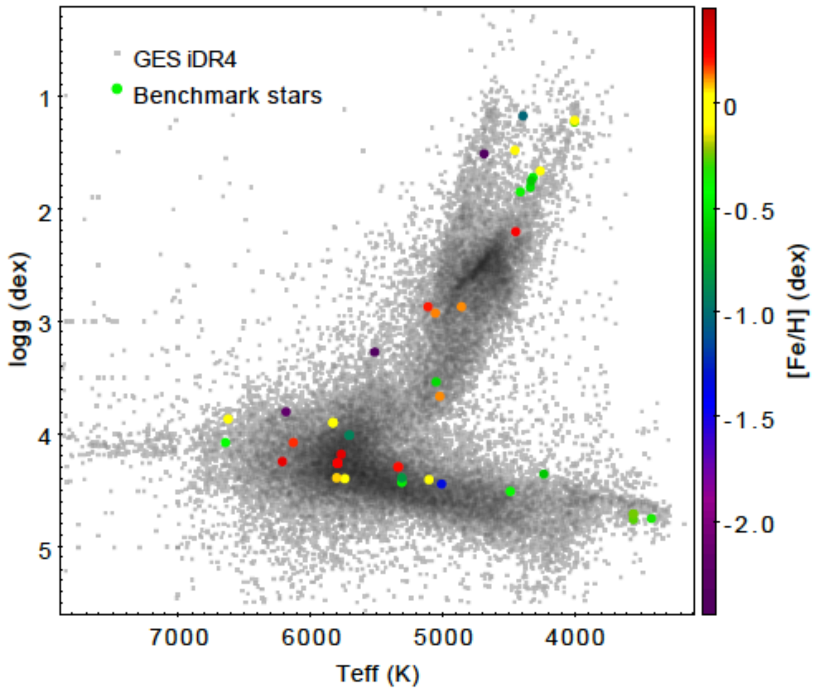


Fig. 8. Position on the $T_{\rm eff} - \log g$ plane of the *Gaia* FGK benchmark stars (Heiter et al. 2015b, see also Sect. 4.1) analyzed in iDR4, colored according to their [Fe/H]. A few of the cooler benchmarks ($T_{\rm eff}$ < 4000 K) described in Sect. 4.2 were also analyzed in iDR4. The whole GES iDR4 sample is reported in the background as smaller gray squares.

From Pancino et al. 2018

- Gaia benchmark stars
- Photospheric parameters independent of spectroscopy
- Observed by several surveys
- Star clusters: observed by several surveys

How to put together all these surveys?

- Intra-survey calibration samples
- Inter-calibration samples

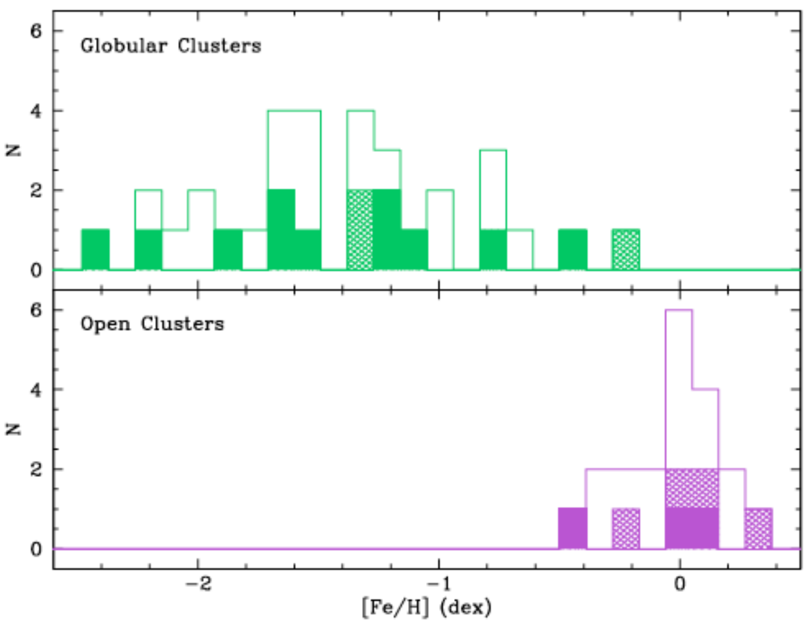
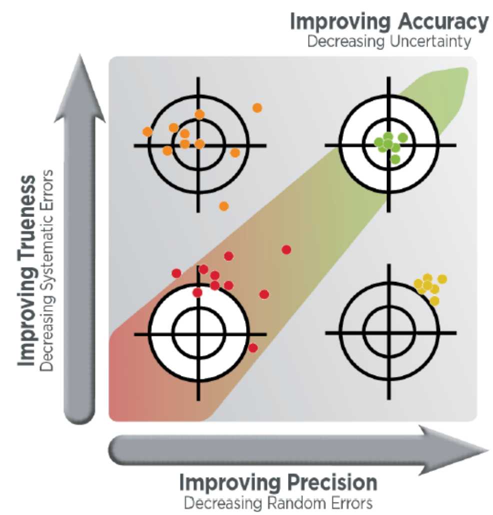


Fig. 11. Metallicity distribution of calibrating clusters: *the top panel* shows GCs and *the bottom panel* OCs. Heavily shaded histograms show clusters included in iDR4; lightly shaded histograms clusters that will be included in future releases (see also Tables 8 and 7); empty histograms represent a pool of viable candidates to complete the coverage. A few of them might be selected in the next observing runs, depending on observations scheduling and data homogenization needs.

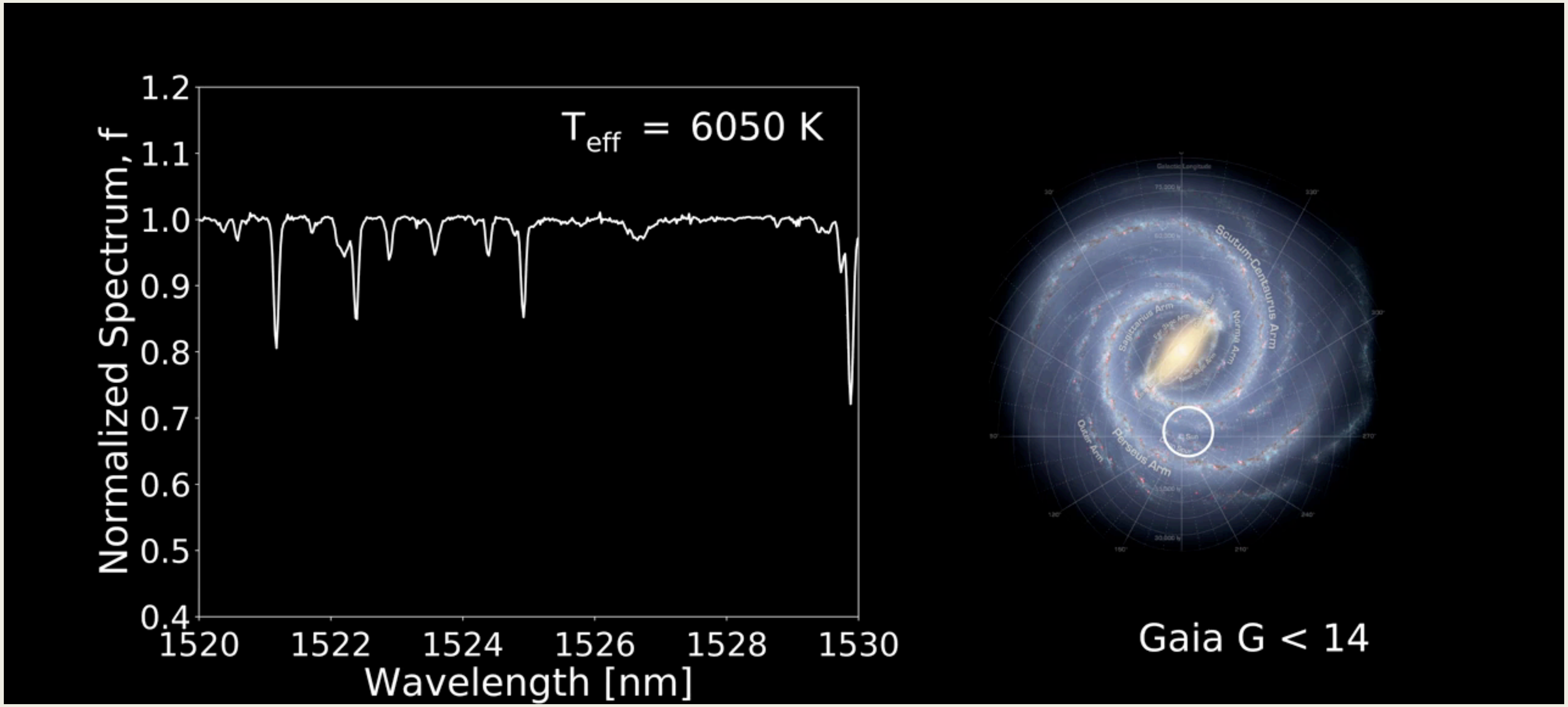
From Pancino et al. 2018

- Open and globular star clusters
- Internal consistency
- Covering the whole metallicity range



Courtesy C. C. Worley

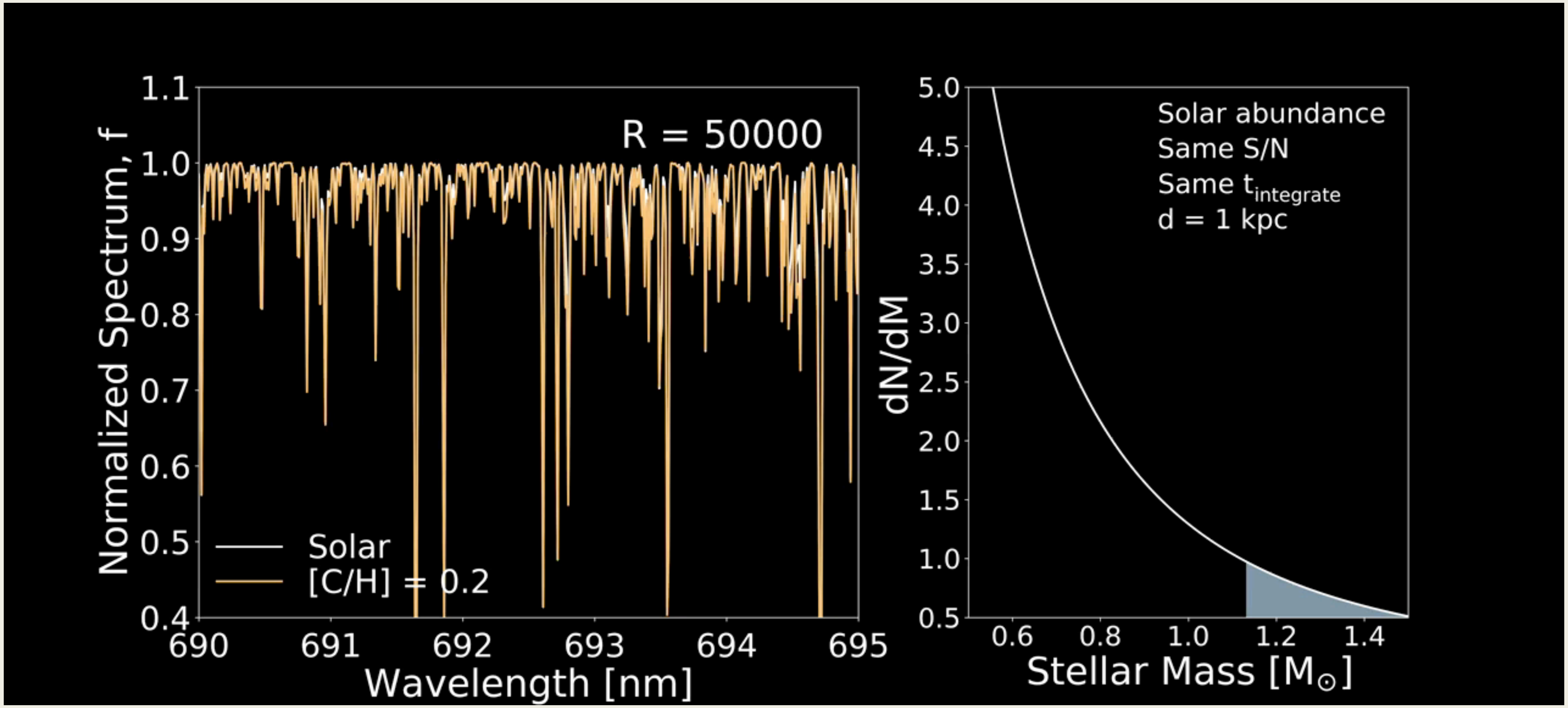
Extending our horizon in the MW



- New surveys go towards lower spectral resolution
- Fitting the full spectra is a *necessity* to get more information
- The farther stars that can be observed are cool giant stars, and they have blended features

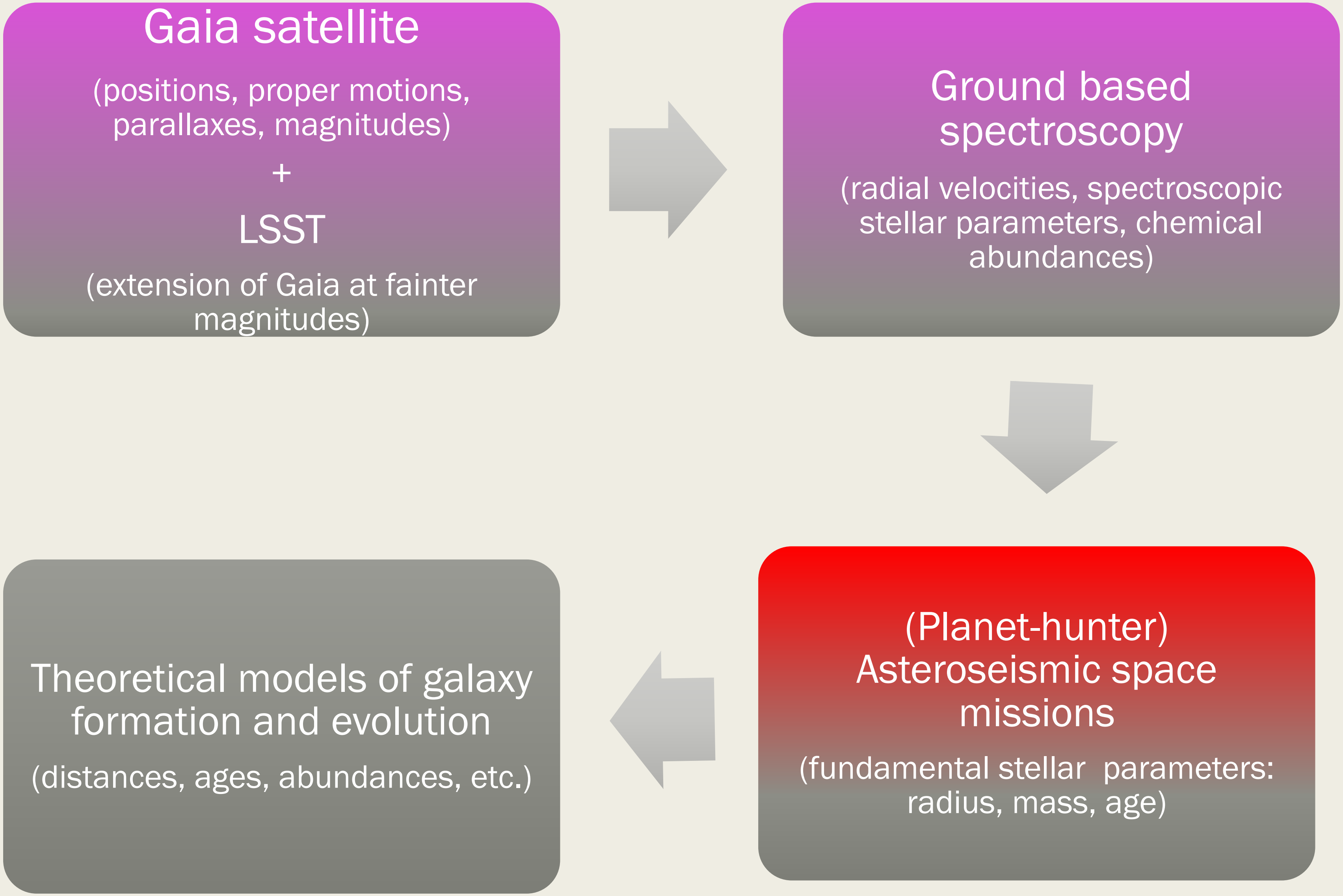
Courtesy of Y. Ting

Going to medium/lower resolution



Sample lower mass stars → Higher sampling rate

Courtesy of Y. Ting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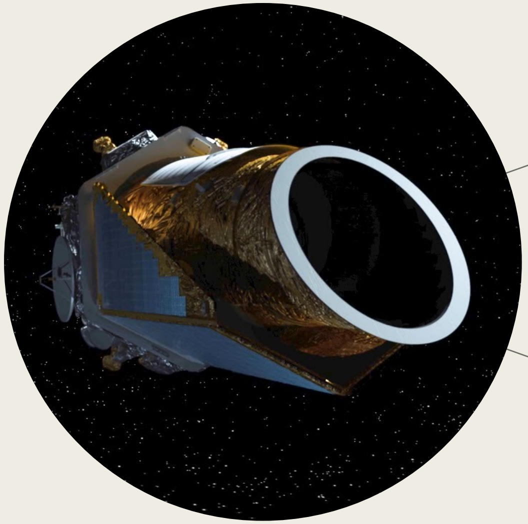
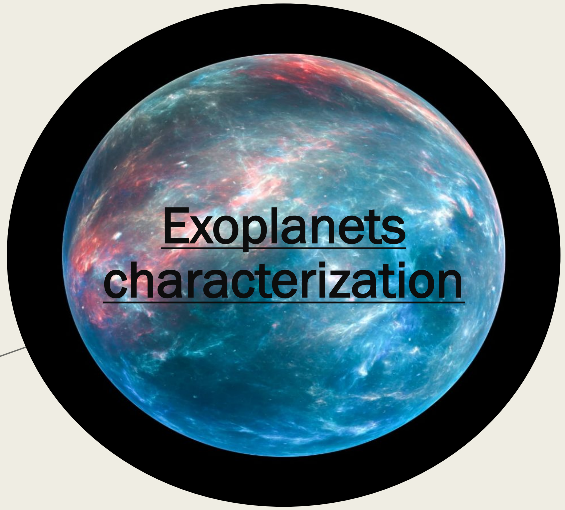
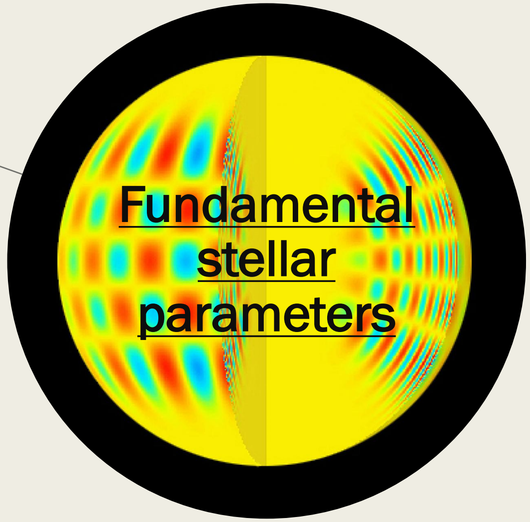
The fundamental parameter of stars

Space missions:
CoRoT, Kepler (K2), TESS, PLATO







The fundamental parameter of stars

Asteroseismology allows to see inside stellar interiors by observing global oscillation modes.

The field of asteroseismology has experienced a prolific two decades resulting from the influx of data from ground-based networks such as WET, OGLE, ASAS, DSN, and space missions such as MOST, BRITE, **CoRoT, Kepler, K2, soon to be followed by TESS and PLATO**

→ **Ages and Masses of stars**

→ **Very difficult to measure from ground based observations**

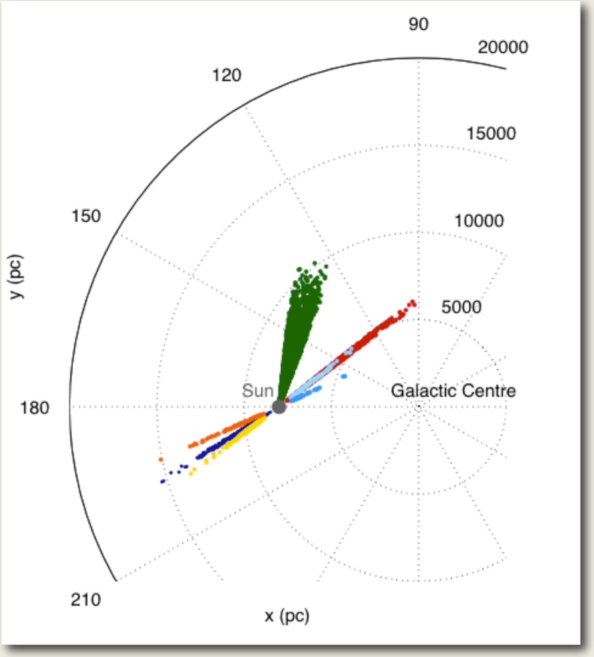
→ **Fundamental constraints to understand the formation and evolution of the MW**

The space missions:

CoRoT (Convection, Rotation and planetary Transits) was the first space mission dedicated to exoplanetary research and designed for this purpose (2006-2012)

The two main objectives were:

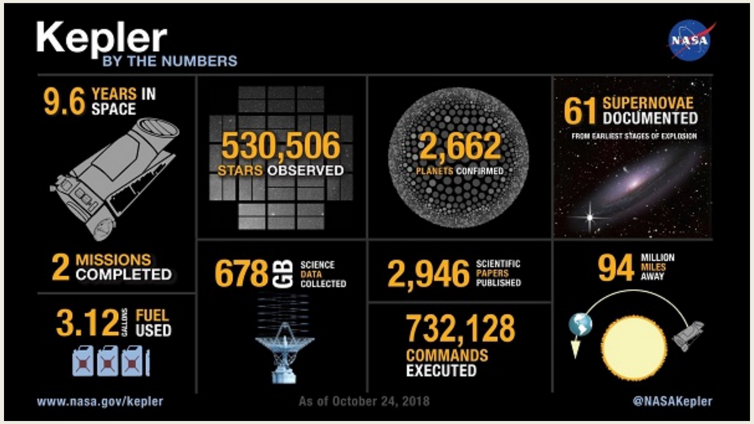
- to search for extrasolar planets with short orbital periods (more massive than the Earth)
- **to perform asteroseismology by measuring solar-like oscillations in stars.**



K2 (Kepler 2)

Together with the search fro exoplanets, the aim of K2 is to characterize the internal stellar structure and fundamental properties of stars with astereoseismology:

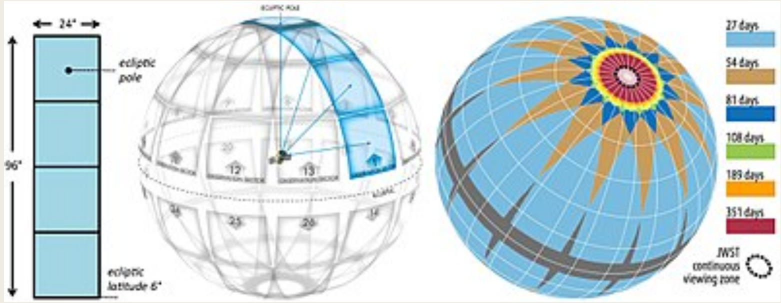
- The on-board instrument is a photometer to monitor the brightness of main sequence stars in a fixed field of view



The space missions:

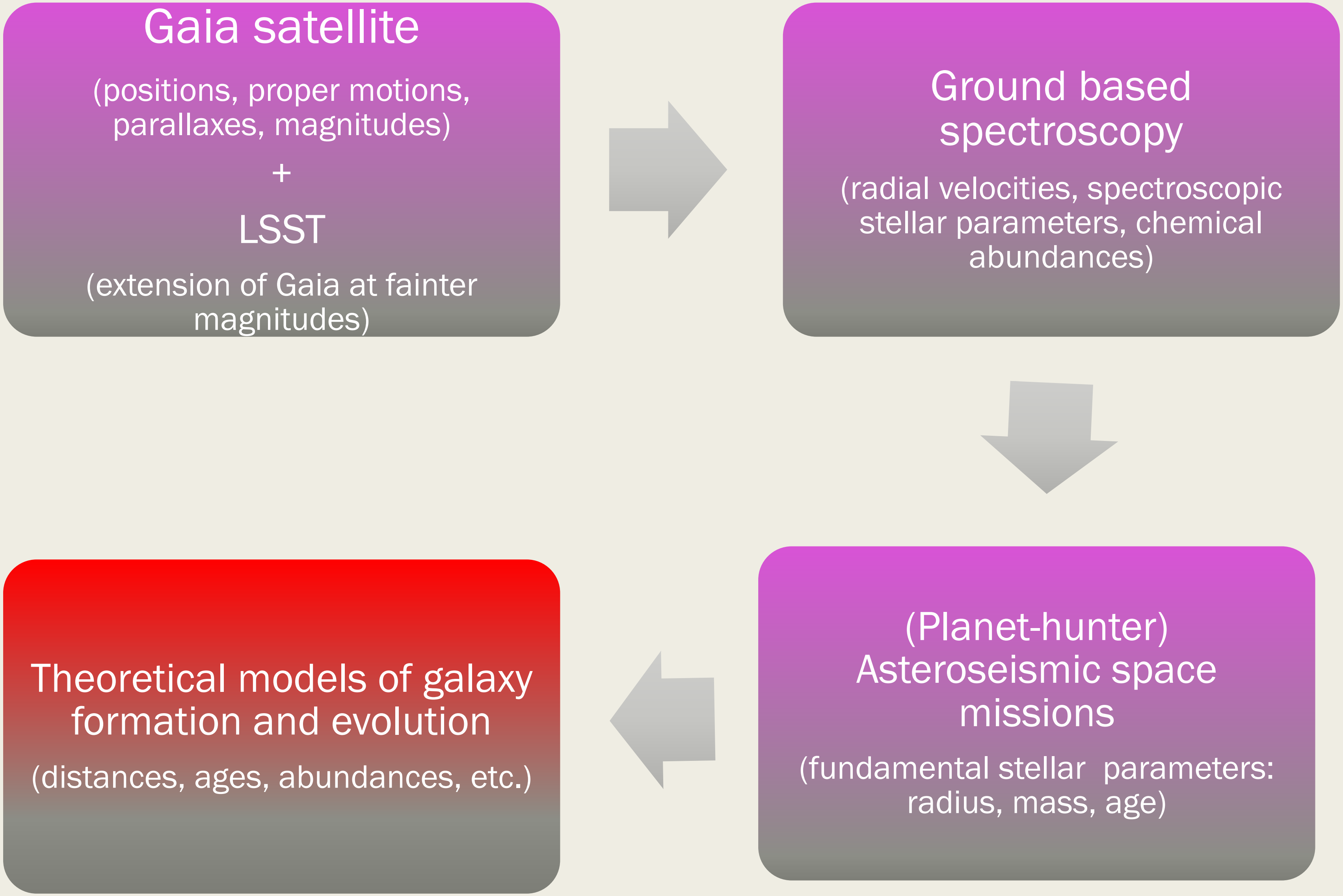
The **Transiting Exoplanet Survey Satellite** (**TESS**) is a space telescope for NASA's Explorers program (2018), designed to search for exoplanets using the transit method in an area 400 times larger than the *Kepler* mission

- The TESS covers 85% of the sky
- G, K, and M-type stars with apparent magnitudes brighter than magnitude 12.[
- 500,000 stars, including **astereoseismology.**



PLAnetary Transits and Oscillations of stars (**PLATO**) is a space telescope (ESA, launch in 2026)

- search for planetary transits for up to one million stars (magnitudes between 4 and 11)
- to study stellar oscillations or seismic activity in stars to measure **stellar masses and evolution** and enabling the precise characterization of the planet host star, including its **age**.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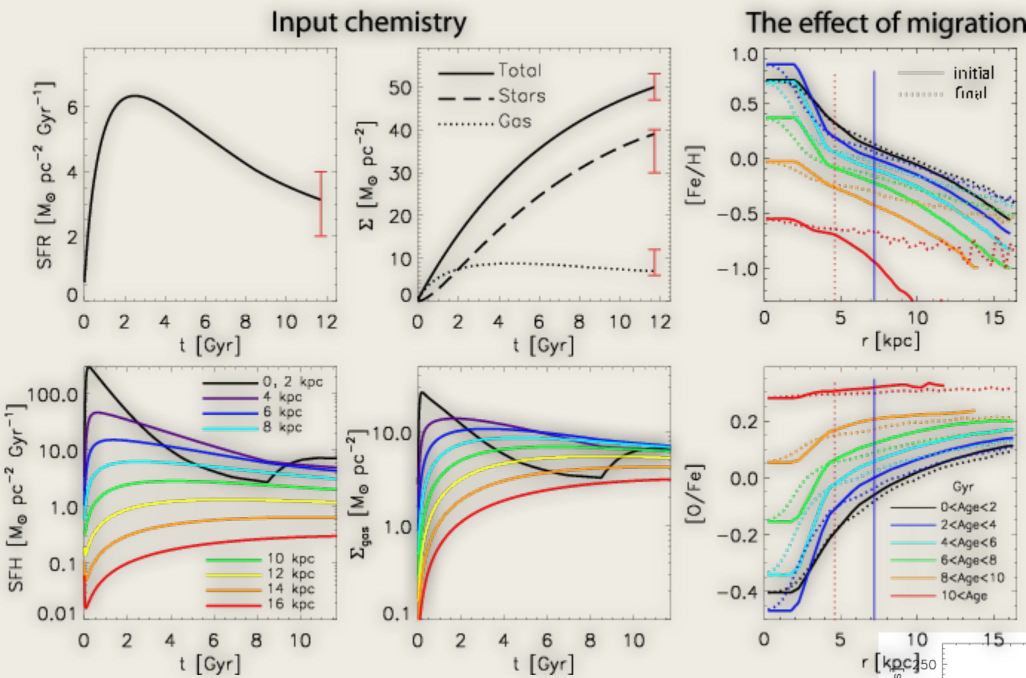
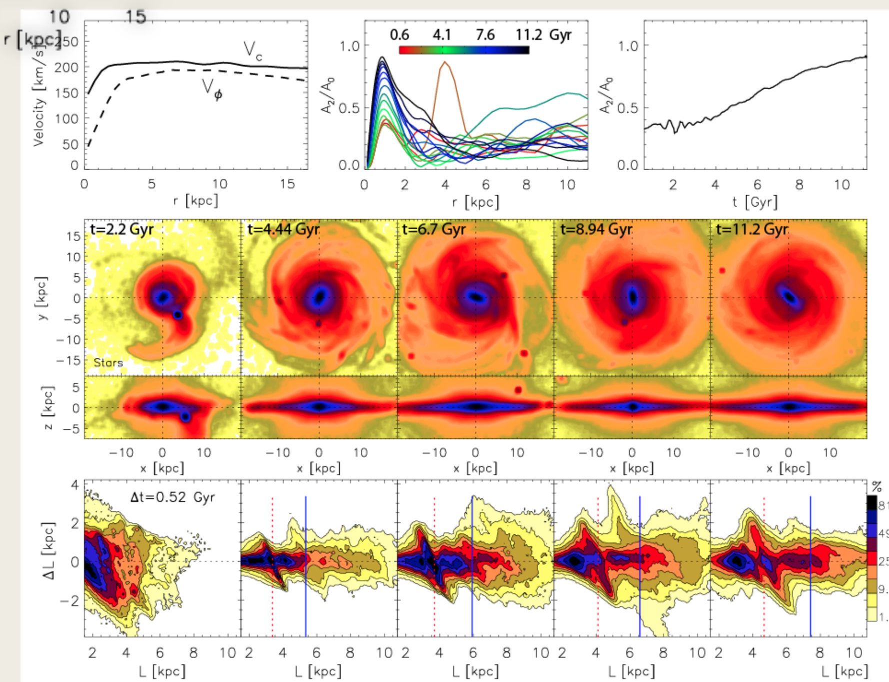


The main goal of **Galactic Archaeology** is understanding the formation and evolution of the basic Galactic components.



Let's have a try!
What we need:

- Installing Topcat

- Topcat is a popular astronomical tool for manipulating tables of data. It started under the UK Starlink project, was extensively developed under AstroGrid, and now continues to be developed by Mark Taylor in Bristol. You can read about and download Topcat at the official website

- http://www.star.bristol.ac.uk/~mbt/topcat

- ***Tutorial:* Exploring Gaia DR2 data with TOPCAT and STILTS** Available as PDF script or LaTeX source code (github).

What we need: All data from large spectroscopic survey are public!!!

- Downloading data from spectroscopic surveys:

- APOGEE:

https://www.sdss.org/dr15/data_access/bulk/#APOGEECatalogData

- GaiaESO:

https://www.eso.org/qi/catalogQuery/index/121

- GALAH:

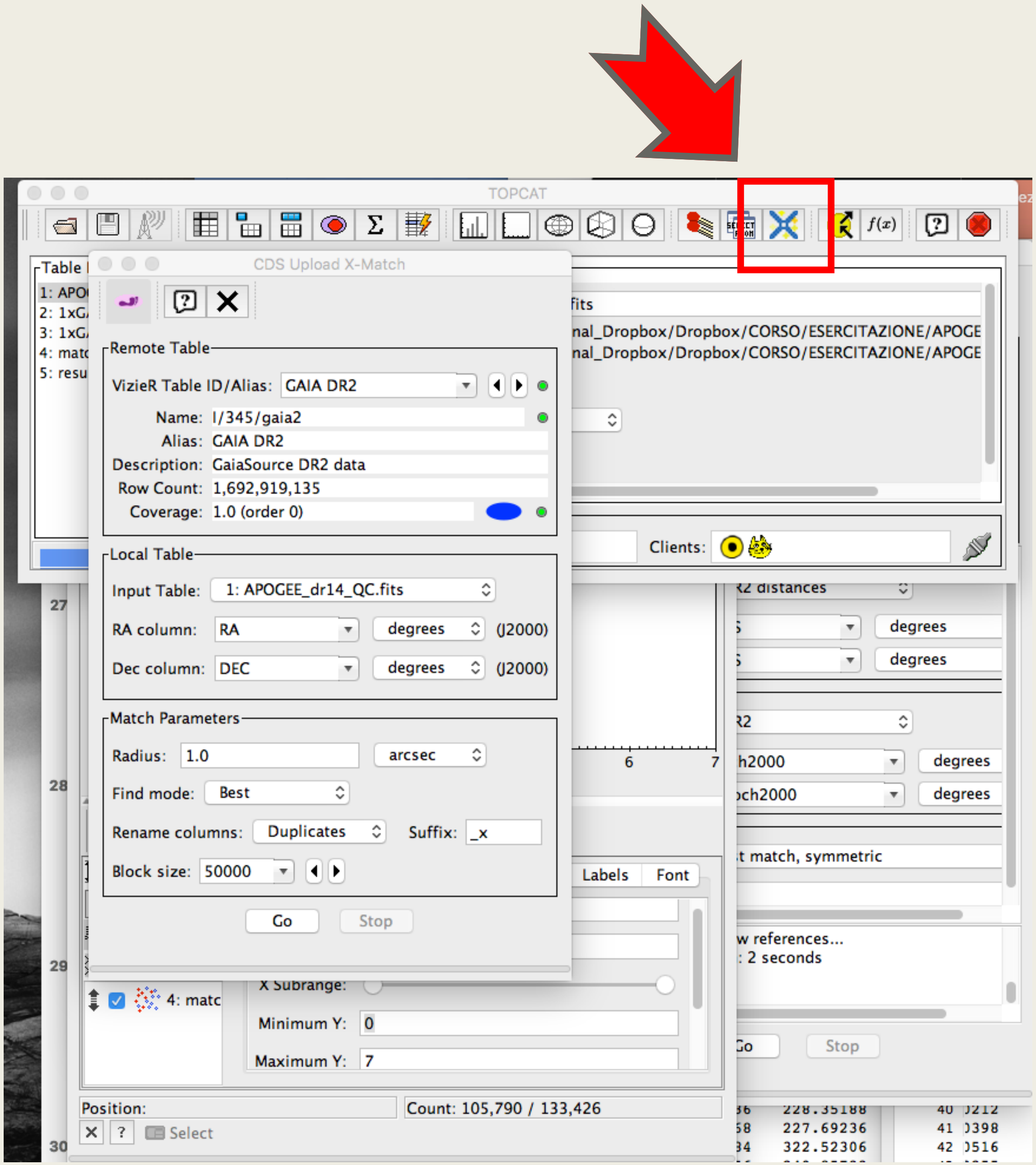
https://docs.datacentral.org.au/galah/

Esercitazione 1

- Combining the APOGEE data with the Gaia dr2 data
- Computing the distances (from parallaxes)
- Compute [Alpha/Fe]
- Separate thin and thick disc stars
- Computed Galactocetric distances
- Build the MDFs (thin vs thick disc, at different Rgc)

What we need: cross-match with the Gaia DR2 catalogue

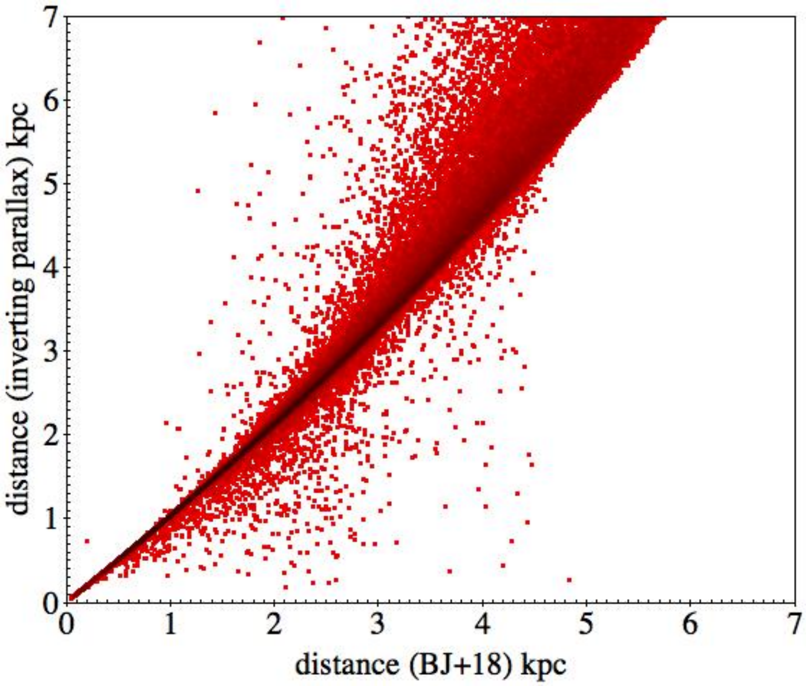
- Cross-match with Topcat:
- Gaia DR2
- Gaia DR2 distances



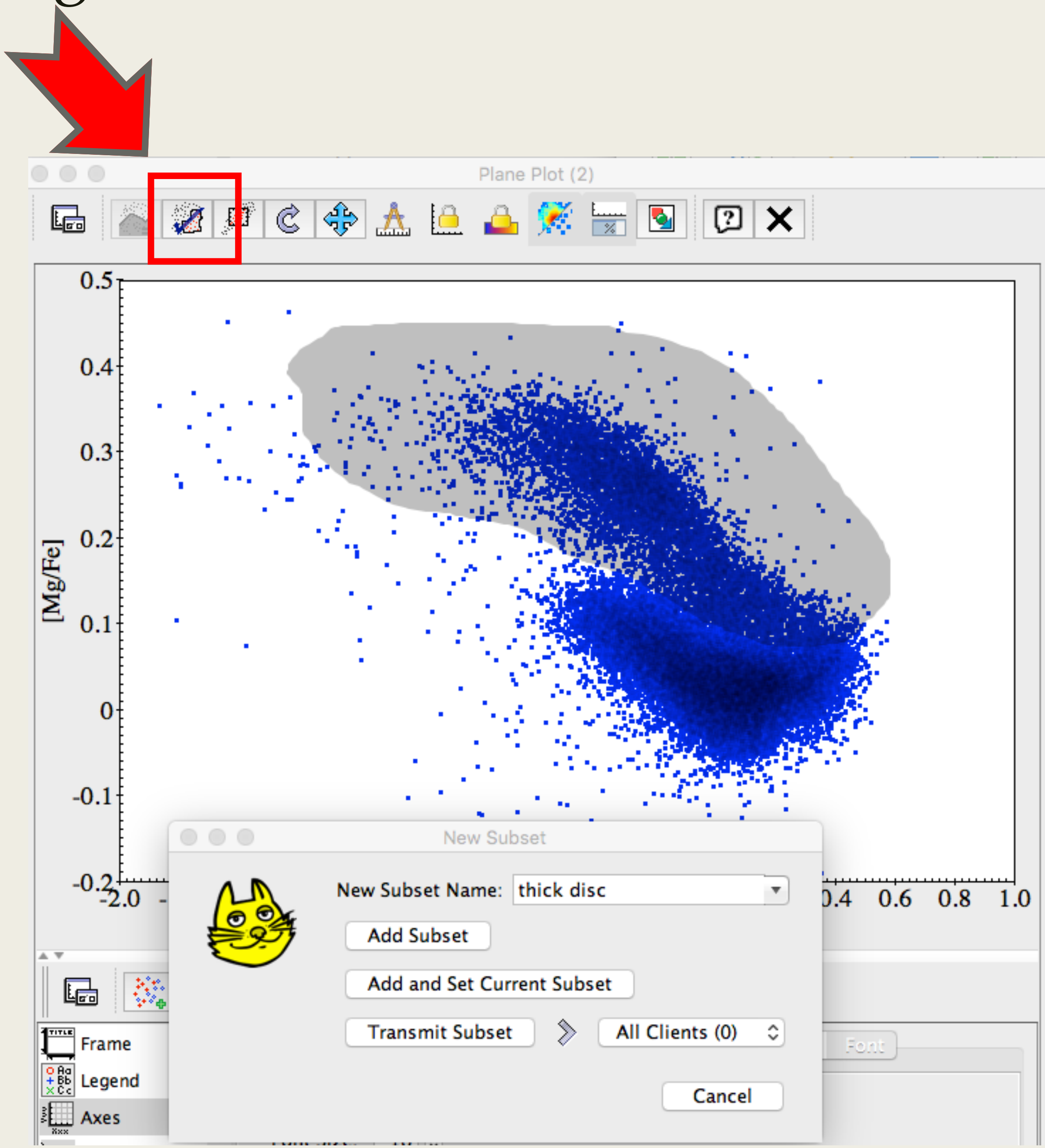
Comparing distances:

- Distances computed inverting parallaxes

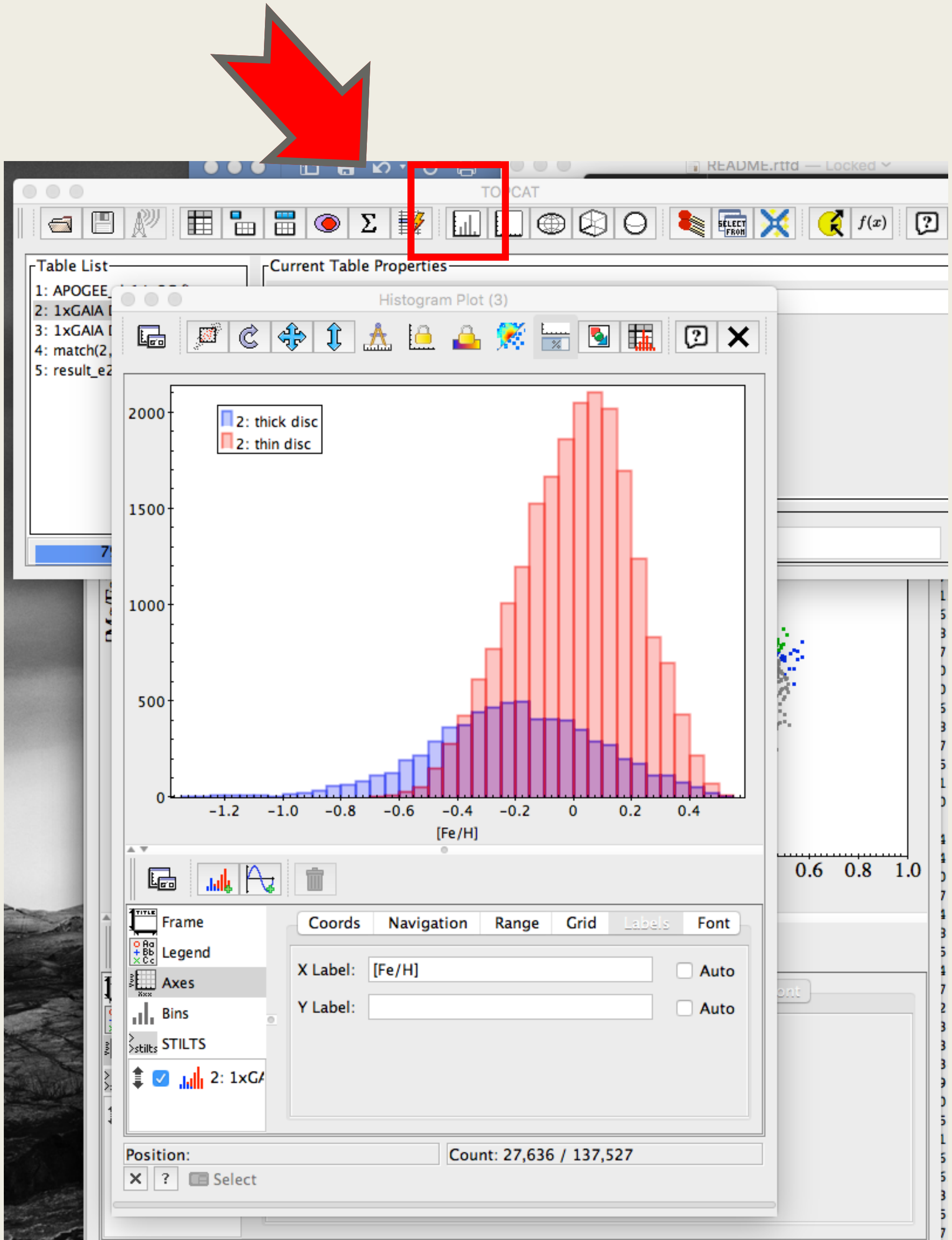
- Distances that account for the nonlinearity of the transformation and the asymmetry of the resulting probability distribution model (from Bailer-Jones et al. 2018)



Selecting stars in the thin and thick discs



MDF of solar neighborhood stars in the thin and thick discs



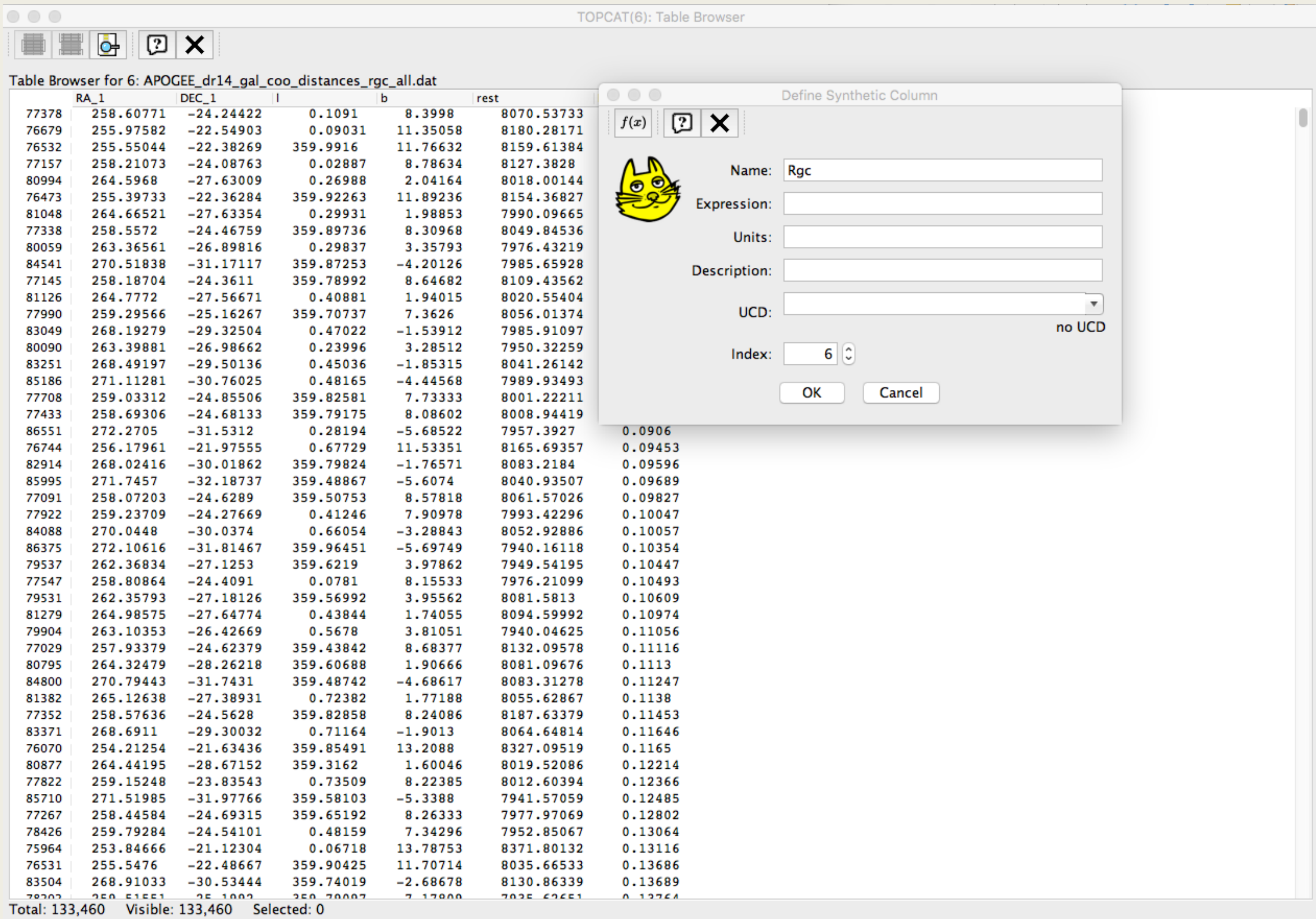
MDF in different part of the Galaxy: computing the R_{gc}

- Compute the Galactocentric distances
- D(Sun)=8.00 kpc
- Distance projected on the galactic disk
- d = D(Sun) – Distance x cos(b) x cos(l)
- Deprojected on the sun-Galactic-centre line
- $R_{gc} = (Distance^2 + (d*cos(b)*sin(l))^2)^{0.5}$

- If we know the distance (Distance) and the Galactic coordinate (l and b), we can compute the Galactocentric distance

MDF in different part of the Galaxy: computing the R_{gc}

- Add new columns where we can insert algebrical expressions

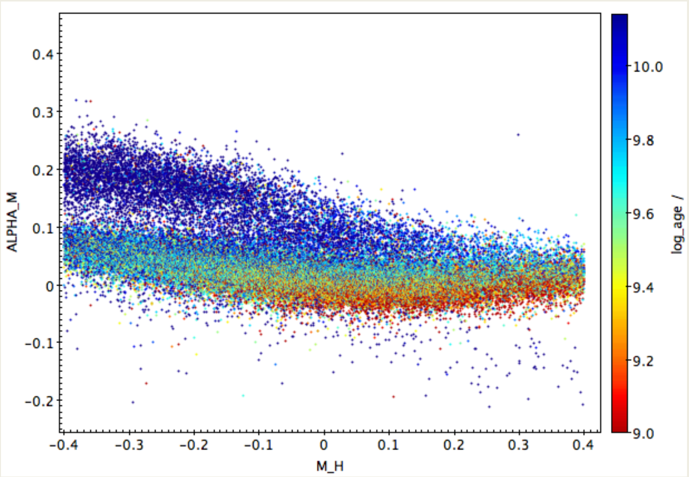


	RA_1	DEC_1	l	b	rest	
77378	258.60771	-24.24422	0.1091	8.3998	8070.53733	
76679	255.97582	-22.54903	0.09031	11.35058	8180.28171	
76532	255.55044	-22.38269	359.9916	11.76632	8159.61384	
77157	258.21073	-24.08763	0.02887	8.78634	8127.3828	
80994	264.5968	-27.63009	0.26988	2.04164	8018.00144	
76473	255.39733	-22.36284	359.92263	11.89236	8154.36827	
81048	264.66521	-27.63354	0.29931	1.98853	7990.09665	
77338	258.5572	-24.46759	359.89736	8.30968	8049.84536	
80059	263.36561	-26.89816	0.29837	3.35793	7976.43219	
84541	270.51838	-31.17117	359.87253	-4.20126	7985.65928	
77145	258.18704	-24.3611	359.78992	8.64682	8109.43562	
81126	264.7772	-27.56671	0.40881	1.94015	8020.55404	
77990	259.29566	-25.16267	359.70737	7.3626	8056.01374	
83049	268.19279	-29.32504	0.47022	-1.53912	7985.91097	
80090	263.39881	-26.98662	0.23996	3.28512	7950.32259	
83251	268.49197	-29.50136	0.45036	-1.85315	8041.26142	
85186	271.11281	-30.76025	0.48165	-4.44568	7989.93493	
77708	259.03312	-24.85506	359.82581	7.73333	8001.22211	
77433	258.69306	-24.68133	359.79175	8.08602	8008.94419	
86551	272.2705	-31.5312	0.28194	-5.68522	7957.3927	0.0906
76744	256.17961	-21.97555	0.67729	11.53351	8165.69357	0.09453
82914	268.02416	-30.01862	359.79824	-1.76571	8083.2184	0.09596
85995	271.7457	-32.18737	359.48867	-5.6074	8040.93507	0.09689
77091	258.07203	-24.6289	359.50753	8.57818	8061.57026	0.09827
77922	259.23709	-24.27669	0.41246	7.90978	7993.42296	0.10047
84088	270.0448	-30.0374	0.66054	-3.28843	8052.92886	0.10057
86375	272.10616	-31.81467	359.96451	-5.69749	7940.16118	0.10354
79537	262.36834	-27.1253	359.6219	3.97862	7949.54195	0.10447
77547	258.80864	-24.4091	0.0781	8.15533	7976.21099	0.10493
79531	262.35793	-27.18126	359.56992	3.95562	8081.5813	0.10609
81279	264.98575	-27.64774	0.43844	1.74055	8094.59992	0.10974
79904	263.10353	-26.42669	0.5678	3.81051	7940.04625	0.11056
77029	257.93379	-24.62379	359.43842	8.68377	8132.09578	0.11116
80795	264.32479	-28.26218	359.60688	1.90666	8081.09676	0.1113
84800	270.79443	-31.7431	359.48742	-4.68617	8083.31278	0.11247
81382	265.12638	-27.38931	0.72382	1.77188	8055.62867	0.1138
77352	258.57636	-24.5628	359.82858	8.24086	8187.63379	0.11453
83371	268.6911	-29.30032	0.71164	-1.9013	8064.64814	0.11646
76070	254.21254	-21.63436	359.85491	13.2088	8327.09519	0.1165
80877	264.44195	-28.67152	359.3162	1.60046	8019.52086	0.12214
77822	259.15248	-23.83543	0.73509	8.22385	8012.60394	0.12366
85710	271.51985	-31.97766	359.58103	-5.3388	7941.57059	0.12485
77267	258.44584	-24.69315	359.65192	8.26333	7977.97069	0.12802
78426	259.79284	-24.54101	0.48159	7.34296	7952.85067	0.13064
75964	253.84666	-21.12304	0.06718	13.78753	8371.80132	0.13116
76531	255.5476	-22.48667	359.90425	11.70714	8035.66533	0.13686
83504	268.91033	-30.53444	359.74019	-2.68678	8130.86339	0.13689

Esercitazione 2

$$\log[Age(yr)] = 10.54(\pm 0.06) + 2.61(\pm 0.10)[C/N].$$

- Measuring ages with [C/N] as a chemical clock
- [C/N]=[C/Fe]-[N/Fe]
- Select stars with 2.4 < log g < 3.4
- Select stars with -0.4<[Fe/H]<+0.4
- Apply the relationship in the [alpha/Fe vs [Fe/H] plane
- What can we say about the ages of stars in the thin and thick discs?



Esercitazione 3

- Elements for which IRA is not valid

- Select elements that are not immediately recycled in the ISM

- Can you find elements produced similarly to iron (iron-peak elements)? How are their[X/Fe] vs [Fe/H] diagrams?

- Elements produced by SNII and SNIa (e.g. Si, Ca, Ti, how do they behave with respect to O and Mg?