Gaia Follow-up projects: the power of spectroscopy

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Overview

The power of Gaia and Spectroscopic follow-up

GES

WEAVE

Many talks/posters during this week about other surveys and GES specific aspects (Jeffries, Smiljanic, Lanzafame, Casamiquela, Sacco...)
Unveiling the complex history of the MW assembly and internal evolution is still one of the main interest of astrophysics.

However the specific questions we ask have evolved substantially.

Diagnostics: Kinematics + chemistry of stars + distance + ages

Metallicity from photometry / spectroscopy

Large amount of data requires ad-hoc modeling: hard to separate the different components

The selection function importance

The presence of radial migration in the disks has lead to a different way of describing stellar populations using chemical abundances as tag: Mono-abundance vs mono-age populations (Bovy+2016, Minchev 2017)

Data driven models (Anderson + 2017, Leistedt+2017)
MW key questions

Structure formation on sub-galactic scale

Halo: variation of halo properties with distance from the center (Deason, Belokurov & Evans 2011; Ablimit & Zhao 2018, Fernandez-Alvar et al. 2015, Carollo et al. 2007, 2010; Beers et al. 2012)
- What is the total mass of the Milky Way? What is the shape of the Galactic gravitational potential? (Battaglia + 2015, Koposov+ 2009)
- Where are the most metal-poor stars in the Milky Way, what are their properties, and what do they tell us about the physics of the early Universe? (Caffau+2011)
- dSph and UDFs: the role of disrupted dwarfs (Fabrizzio+2015, Tolstoy+2009)

Disks: respective roles of hierarchical formation and secular evolution in shaping the Galaxy? what are the roles of spirals (+ number of arms, pitch angle, pattern speed?) and the bar (length, pattern speed?) (Helmi+2006, Schoenrich & Binney 2009, Minchev+2015)

Dark matter: How much substructure does the Galactic dark matter distribution have with: in 20–50 kpc? How do they interact with cold streams? (Yoon + 2011)
The Gaia revolution

Gaia Data Release 2
25.4.2018, ILA Berlin

Gaia Collaboration, Brown Vallenari et al 2018
Galactic Archeology

A wealth of information from ground and space based and surveys

- **Pan-STARRS** (Kaiser+2010, $\delta$>-30, no u filter), **Sky mapper** (Keller 2012)
- **Gaia, LSST** (Ivezic+ 2014, 2022, $r=24.5$, 30,000sq deg), **PLATO, TESS**
- **Lisa, Gaia, LSST**: 100,000 ultra-compact binary WDs to trace the barionic mass in disk and bulge (Korol 2018)

Spectroscopic surveys: GES, RAVE, APOGEE, GALAH, SDSS, SEGUE, Lamost, 4MOST, MOONS, WEAVE...
Gaia DR2 new view of the Halo

- Kinematically selected halo stars having $\text{[Fe/H]} > -1$ (Bonaca +2017)
- Local Halo merging history from TGAS+ RAVE (Helmi 2017, Myeong+2017)
- Accretion events with DR2 found in the halo using a variety of data (Belokurov et al. 2018; Myeong et al. 2018a,b; Deason et al. 2018; Kruijssen et al 2018, Koppelman+ 2018, Lancaster+2018...)
- Haywood +2018: using Nissen &Schuster metallicity confirm that red sequence is thick disk
- Gaia Sausage/Enceladus retrograde stars are on the blue sequence(Helmi+2018)
Gaia+SDSS data: Gaia Sausage contributing to 50% mass of the halo within 25 Kpc (Belokurov+2018, Lancaster+2018, Kruijssen+2018)

100,000 stars DR2+APOGEE within 5 Kpc (Helmi+ 2018)

In the inner 30 Kpc the stellar halo could be largely dominated by a single, ancient, extremely radial merger 10 Gyr ago

[alpha/FeH] different from thick disk: long lasting SF

High mass progenitor : $10^{9-10}$ Mo
GES in a nutshell

- **GIRAFFE**: $R = 16000 - 25000$
  - Bulge: mostly giant stars (clump and RGB), $I = 15$
  - Halo/thick disc: FG TO stars ($17 < r < 18$);
  - Thin disc – RVs for dynamics; $I < 19$
- **UVES parallel**: $R = 42,000$, SNR > 20 SN: unbiased 5000- star sample.
  - $M_V \sim 5.5$, $\Rightarrow$ unbiased survey to 1kpc at $V = 15$
- 60-70-Ocs in UVES ($V < 16$): GIRAFFE ($G < 19$)
The challenge

- 5 groups of people using different analysis methods (EW, spectral synthesis) → 15 pipelines (Smiljanic+2014, Lanzafame+2015)
  - (MATISSE, SME: Valenti & Piskunov1996; FERRE: Allende Prieto et al. 2006 codes for GIRAFFE spectra, and about a dozen different methods for UVES spectra)

- More methods means more information
- Common line list (Heiter+ 2015, Heiter +in preparation)
- Common stellar models (MARCS)
- Selection function vs Vista HS Stonkute et al. (2016)
- Set of calibration objects (Pancino+2017)
  - to Identify the dominant systematic variables
  - to identify both systematic method errors and random errors
  - Add seismic data for precision and systematics
  - Share calibration across all the Surveys

- Calibrators: RV standards; Gaia benchmark stars (Jofre’2014, Hawkins+2016); Clusters: (20) hot vs. cool; PMS vs. MS vs. evolved;
  - CoRoT – Kepler asteroseismic gravities and ages
<table>
<thead>
<tr>
<th></th>
<th>$T_{\text{eff}}$</th>
<th>$\log g$</th>
<th>[Fe/H]</th>
<th>Num:</th>
<th>$\log g_{\text{sc}}$</th>
<th>Num$_{\text{sc}}$:</th>
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<td><strong>APOGEE</strong></td>
<td>$-30\pm277$</td>
<td>$-0.22\pm0.60$</td>
<td>$0.08\pm0.44$</td>
<td>711</td>
<td>$0.03\pm0.29$</td>
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<td>$4\pm342$</td>
<td>$-0.35\pm0.70$</td>
<td>$0.05\pm0.52$</td>
<td>190</td>
<td>$0.06\pm0.31$</td>
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<td>$-0.05\pm0.37$</td>
<td>$0.16\pm0.14$</td>
<td>221</td>
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<td><strong>GAIA-ESO</strong></td>
<td>$243\pm477$</td>
<td>$-0.12\pm0.89$</td>
<td>$0.25\pm0.93$</td>
<td>53</td>
<td>$0.17\pm0.64$</td>
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<td>$613\pm659$</td>
<td>$-0.82\pm0.93$</td>
<td>$-0.10\pm0.30$</td>
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<td>$52\pm266$</td>
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<td>$0.16\pm0.69$</td>
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<td>$-0.39\pm0.45$</td>
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<td>$-0.59\pm0.29$</td>
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<td>$111\pm196$</td>
<td>$0.15\pm0.51$</td>
<td>$0.01\pm0.18$</td>
<td>169</td>
<td>$-0.18\pm0.90$</td>
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<td><strong>LAMOST</strong></td>
<td>$30\pm325$</td>
<td>$0.12\pm0.48$</td>
<td>$0.05\pm0.27$</td>
<td>2700</td>
<td>$0.14\pm0.40$</td>
<td>557</td>
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<td>$-4\pm364$</td>
<td>$0.08\pm0.49$</td>
<td>$0.00\pm0.27$</td>
<td>2026</td>
<td>$0.24\pm0.45$</td>
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<td>$58\pm208$</td>
<td>$0.16\pm0.36$</td>
<td>$0.09\pm0.15$</td>
<td>987</td>
<td>$0.06\pm0.33$</td>
<td>33</td>
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<tr>
<td><strong>GALAH</strong></td>
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<td>$0.00\pm0.50$</td>
<td>$-0.02\pm0.33$</td>
<td>1700</td>
<td>$0.04\pm0.45$</td>
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<tr>
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<td>$-0.07\pm0.45$</td>
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<tr>
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<td>$-6\pm144$</td>
<td>$0.06\pm0.35$</td>
<td>$0.04\pm0.13$</td>
<td>663</td>
<td>$0.06\pm0.32$</td>
<td>613</td>
</tr>
</tbody>
</table>
Disk Vertical metallicity gradient

Indication of formation model (disk heating spiral arms and mergers)
(Chiappini+2001, Schoenrich 2009, Rix & Bovy 2013...)

Agreement between different surveys and with Schlesinger et al. 2014, Xiang 2015, Cheng 2003, Duong 2018 (GALAH)

Boeche et al. (2014) -0.112±0.007 dex kpc RAVE Z<2kpc
Soubiran et al. (2008): -0.31±0.03 dex/ kpc

**Fig. 11.** Vertical metallicity gradients calculated for all sources in each survey belonging to ALR (left) and AGR (right). The slope estimated for each survey is also shown in the plots. The gradient for the combined sample of surveys is shown for ALR and AGR.
Bulge

- Several papers supporting the boxy/peanut X-shaped component in the metal-rich population, with bar-like kinematics (Rojas-Arriagada+2014 Williams+2016)
- Low-Alpha stars found in the Bulge with chemical pattern similar to thin disk. A thin disk contribution to the Bulge? (Recio-Blanco+2017)
- Two populations from large sample of high resolution spectroscopy (Babusiaux 2010, but see Ness 2013)
- Vertical metallicity gradients in both
- Metal rich has a bar-like kinematics and consistent with X-shape → overlap with thin disk in [Mg/Fe] vs [Fe/H] → formed by secular evolution of the thin disk
- Metal poor has isotropic kinematics and no X-shape
- Confirmed recently Schultheis+2017 (APOGEE)
Discreteness of thin/thick disk in elemental abundances
in agreement with APOGEE (Hayden +2015)
Thin/thick disk intersect at solar metallicity
The knee is constant with RGC\rightarrow thick disk formed in a single episode, not inside-out
Three sub-populations in the thin disk

Different spatial and kinematical properties of the metal poor component

Mild increase of overall chemical and dynamical properties between the groups is smooth suggesting a mild early disk evolution and inside-out scenario

Fig. 3. GMM decomposition of Gaia-ESO survey and APOGEE samples in the \([\alpha/M] \text{ vs. } [M/H]\) plane. Points depict the APOGEE working sample. Contour lines draw the density distribution of Gaia-ESO survey GMM data groups. A vertical shift of \(\Delta[\alpha/M] = 0.1\) dex was applied to the APOGEE sample to obtain a better agreement between the two data
Radial metallicity gradient in the inner disk
- From 12 Ocs: $-0.10 \pm 0.02$ dex kpc (Jacobson+2016)
- Old Ocs in SV have higher $[\text{Fe/H}]$ than the younger ones
- Super-metal-rich stars in the Solar V (Minchev+2013; Anders +2016)
Fig. 5. Radial distributions of [Fe/H] for our open cluster sample (first panel: filled circles in grey the youngest clusters, age < 2 Gyr, and in blue the oldest ones), for the Netopil et al. (2016)’s open clusters with high-resolution metallicities (second panel: filled hexagons in grey the youngest clusters, age < 2 Gyr, and in blue the oldest ones), for the APOGEE (Cunha et al. 2016) and Cantat-Gaudin et al. (2016)’s open clusters (third panel: green triangles and cyan squares, respectively), and for the Cepheids (fourth panel: stars and pentagons Martin et al. 2015; Genovali et al. 2014, 2015, respectively). The black curves represent the gradients of the elements over Fe in the K15-improved model at the present time – updated with the new yields of the present work – while the red and blue ones correspond to 2 Gyr and 5 Gyr ago, respectively.
Do we have alpha-enhancement in the outer disk? (Sestito 2008, Hayden 2015, Magrini 2017)

O and Mg different channels $\rightarrow$ different trends $\rightarrow$ confirmed by APOGEE (Donor+ 2018)

O from massive stars: no migration, but impact of bar driven radial gas flow (R<6Kpc)

$[\alpha/Fe]$ is an average value (Magrini+2017)
Young OC metallicity gradient

![Graph showing radial metallicity distribution](image)

**Fig. 8.** Radial metallicity distribution of regions younger and older than 100 Myr compared with the model of Minchev et al. (2014) for the age interval between 0 and 2 Gyr including radial migration (blue line).
Ocs Parameter revision

- Parallax-Pms revision for 150 OCs in the inner 2 Kpc in DR1 and 1200 in DR2 (Cantat-Gaudin+2018)
- Ages for 80 Ocs (Gaia collab, van Leeuwen+, 2017, 2018 Cantat+2018)
- Upmask(Krone-Martins 2014)
- Gaia+GES for 8 clusters(Randich +2017)

Fig. 11. Left: location of the OCs projected on the Galactic plane, using the distances derived in this study. The yellow dots indicate the objects newly identified in this study. Right: same sample of OCs, colour-coded by age (as listed in MWSC). Superimposed is the spiral arms model of Reid et al. (2014).
### WEAVE Characteristics

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<table>
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</thead>
<tbody>
<tr>
<td><strong>Telescope, diameter</strong></td>
<td>WHT, 4.2m</td>
</tr>
<tr>
<td><strong>Field of view</strong></td>
<td>2° ø</td>
</tr>
<tr>
<td><strong>Number of fibers</strong></td>
<td>960 (plate A)/940 (plate B)</td>
</tr>
<tr>
<td><strong>Fiber size</strong></td>
<td>1.3”</td>
</tr>
<tr>
<td><strong>Number of small IFUs, size</strong></td>
<td>20 x 11”x12” (1.3” spaxels)</td>
</tr>
<tr>
<td><strong>LIFU size</strong></td>
<td>1.3’x1.5’ (2.6” spaxels)</td>
</tr>
<tr>
<td><strong>Low-resolution mode resolution</strong></td>
<td>5750 (3000–7500)</td>
</tr>
<tr>
<td><strong>Low-resolution mode wavelength coverage (Å)</strong></td>
<td>3660–9590</td>
</tr>
<tr>
<td><strong>High-resolution mode resolution</strong></td>
<td>21000 (13000–25000)</td>
</tr>
<tr>
<td><strong>High-resolution mode wavelength coverage (Å)</strong></td>
<td>4040–4650, 4730–5450, 5950–6850</td>
</tr>
</tbody>
</table>

70% of 5 years telescope time; 1 year proprietary time
Primary Science Surveys

- **WEAVE GA Goals:**
  - To complement Gaia
  - To complement 4MOST, MOONS (in the North)
  - Bridge the gaps in APOGEE footprints

- **GA Surveys:**
  - LR Halo/LR disk
  - HR halo/HR disk/OC

- **Stellar, Circumstellar, and Interstellar Physics (SCIP):** 1200 sq deg on the disk (b<3-4 deg) to probe massive stars, ISM, YSO+ Great Cygn Rift star formation

- **Characteristics:**
  - Continuous sky coverage to sample global phenomena
  - High statistics
WEAVE performances

- Surveys to acquire accurate Vr (2 km/s) (and stellar parameters, incl. Metallicity at 0.2 dex) for 15<G<20
  - Defined the LR mode of WEAVE:
- Surveys to determine accurate stellar parameters and detailed chemistry (at 0.1 dex) for G>11-17
  - Defined the HR mode of WEAVE:
WEAVE GA at glance

LR disk: $|b|<6 \cdot 10^6$ stars
LR Halo: 10,000 sq deg

HR disk: 1,800 deg$^2$ with $15<|b|<30^\circ$ to insure coverage of discs
HR halo: 5000 deg$^2$
WEAVE HR in contest

APOGEE - WEAVE - GES

N=300,000

N=1.8 \times 10^6 \text{ WEAVE-HR}

N=100,000

N_{\text{halo}} \sim 6.10^4
N_{\text{thick}} \sim 8.10^5
N_{\text{thin}} \sim 1.10^6

Kordopatis+ 2016
WEAVE – 4MOST excellent complementarity
4MOST 2 LRH and 1HR (3 passbands)
WEAVE HR products

- WEAVE can measure stellar parameters and individual abundances in all main nucleosynthetic channels to $V=16$, i.e. closely matching the Gaia’s most precise sphere (distances, ages)
- $T_{\text{eff}}$, $\log(g)$, $V_{\text{rad}}$, $V_{\text{sini}}$
- Nucleosynthetic channels:
  - Lithium $\rightarrow$ young objects
  - iron peak (Fe, Ni, Cr, Co, Zn),
  - alpha elements (C, Mg, Si, Ca, [O I] ...),
  - neutron-capture slow and rapid elements (Zr, Y, Sr, Ba, La, Nd, Eu),
  - odd elements (Na, Al, Sc)

| High-resolution mode wavelength coverage (Å) | 4040–4650, 4730–5450, 5950–6850 |
WEAVE Timeline

- Now Operation Rehearsal
- First science light: 2019
- Surveys begin: T0+3 months
- WEAVE main instrument at WHT
- 5 years of WEAVE surveys (70% of available time), plus TAC time (30%) which may also include using WEAVE
- Open time PIs will have full access to WEAVE calibration data
Conclusions

- We are just at the beginning of the scientific exploitation of Gaia
- GES and WEAVE are complements to Gaia and present and upcoming surveys with a strong legacy value

More exciting science to come