Galactic Kinematics & Statistical Stellar Ages

Melissa Ness
Columbia University & Center for Computational Astrophysics, New York

Sagan workshop, July 2022
Outline

1. The Milky Way Data Revolution
2. The Populations in the Milky Way Galaxy in the Gaia era
3. Statistical Stellar Ages
Outline

• The Milky Way Data Revolution

• The Populations in the Milky Way Galaxy in the Gaia era

• Statistical Stellar Ages
Circa 2004 — The Geneva Copenhagen survey

~17,000 G, F dwarfs in solar neighbourhood
  • ages, proper motions, metallicities, velocities — Nordstrom+ 2004
  • solar neighbourhood metallicity distributions, age-metallicity & age-velocity relations
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Holmberg+ 2009
Circa 2004 — The Geneva Copenhagen survey

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“upside-down” formation (Bird+ 2021, Wisnioski+ 2015) + disk heating (radial migration, molecular clouds, mergers)
Circa 2004 — The Geneva Copenhagen survey

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“Unlikely to be superseded until the Gaia mission (Perryman et al. 2001) and/or the RAVE project (Steinmetz 2003)”
2022: Realising the Milky Way as a test of Galaxy Formation
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  - \( p(\text{age, mass, chemical composition, orbits}) \)

All sky-density map of the 1.1 billion sources in Gaia (ESA/Gaia/DPAC/U.Lisbon)
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    - stellar spectra

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  - stellar spectra
  - satellite missions measuring movement

All sky-density map of the 1.1 billion sources in Gaia (ESA/Gaia/DPAC/U.Lisbon)
The Milky Way in a cosmological context & stars as stellar-planetary architectures
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- An inventory of information across a huge range of spatial and temporal scales
The Milky Way in a cosmological context & stars as stellar-planetary architectures

- An inventory of information across a huge range of spatial and temporal scales
- Mapping (ages, velocities, metallicities)
- Planets

Gaia (astrometry) + Ground based spectroscopic surveys +

JWST, MUSE, ELTs, LIGO, LISA, TESS, Kepler, Vera Rubin, Nancy Grace Roman Space Telescope

Sagan, 2022

Melissa Ness
Where is the Milky Way spectra coming from?

- Millions of spectra from a multitude of surveys — different $\lambda$, Resolution, spatial coverage:
  - Completed/current: APOGEE, GALAH, Gaia-ESO, RAVE, Gaia, LAMOST, SEGUE
  - Future/Current: Gaia, SLOAN V, MOONS, 4-MOST, WEAVE
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- Deliverables from spectra:
  - $V_{\text{rad}}$
  - $\text{Teff, logg, [Fe/H]}$ (stellar parameters) & $[X/Fe]$ (chemical compositions)
SDSS V Milky Way Mapper - 5 million stars across the Milky Way
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- **SDSS V Milky Way Mapper 2022-2027**
- A holistic view of the Galaxy — P.I. Juna Kollmeier (see Kollmeier et al., 2017)
- Milky Way Mapper is 5 million stars in the IR (R=22,500) and many programs
- Galactic Genesis makes up the majority continuous, contiguous map of the disk (below)
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- Age,
- Fe (Sn1a)
- $\alpha$-abundance (SnII)
- distances,
- velocities,
- orbits
- [Kollmeier+ 2017]
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**Stellar Astrophysics (SA) & Stellar System Architecture (SSA)**
- target known multi-star and planetary systems
- target stars with asteroseismic detections
- volume limited sample of stars < 100 pc
- young stars in clusters
Outline

• The Milky Way Data Revolution

• The Populations in the Milky Way Galaxy

• Statistical Stellar Ages
Milky Way Architecture

- Galactic halo
- Galactic disk
- Gas and dust
- Open cluster
- Galactic bulge
- Galactic center
- Globular clusters
- O, B stars
- Sun
- Emission nebula

30 kpc
8 kpc
4 kpc

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Milky Way Architecture

Different populations show different abundances and have different orbital properties
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Different populations show different abundances and have different orbital properties

Stellar halo
1% of stellar mass but time capsule of early formation

Disk
75% of stellar mass and record of assembly process

Bulge
24% of stellar mass and signature of formation events
The stellar halo

- Eggen, Linden-Bell and Sandage (1962)
The stellar halo

More eccentric

Eggen, Linden-Bell and Sandage (1962)
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More metal poor
The stellar halo

Gaia+spectroscopic surveys -> substructure & ‘in-situ’ and ‘accreted’

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The stellar halo

Gaia+spectroscopic surveys -> substructure & ‘in-situ’ and ‘accreted’

Helmi+ 2018: **Gaia-Encedaleus or Saussage**
(see also Belokurov+ 2018, Myeong+ 2018, Deason+ 2018)

Also noted by Nissen & Schuster (2010)
Industry in identifying & understanding halo field structures

e.g. Feuillet+ 2021, di Matteo + 2019, Buder+ 2022, Lane+ 2022, Bird+ 2021, An+ 2021, Das+ 2020, Deason+ 2019, Mackereth+ 2019
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The MW halo is almost entirely composed of substructure
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Abundances to organise into progenitors, ex-situ, in-situ and related — Horta+ 2022 (APOGEE survey + Gaia)
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Streams and possible dark-matter sub halo interaction:
GD1 (PANSTARRS and GAIA) — Price-Wheelan & Bonaca 2018, Bonaca+ 2018, (also see Banik & Bovy + 2019)

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The Milky Way disk

“Thin” and “Thick” disk
Gilmore & Reid 1983

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The Milky Way disk

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(Bensby 2004)

Saglia

300pc scale height

1350pc scale height
The Milky Way disk

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SnIa

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SnIIa

300pc scale height

1350pc scale height

log space density

[Fe/H]

[\text{n}/\text{Fe}]

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The Milky Way disk

Gilmore & Reid 1983

300pc scale height

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SnIa

SnII

(Bensby 2004)
The Milky Way disk

“High” and “Low” alpha-disks (fast v slow star formation)
(see also Fuhrmann 1998, Gratton+ 2000, Tautvaisine+ 2001,

“Thin” and “Thick” disk
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SnIa

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[S/N/Fe] [Fe/H] log space density

0 2000 4000
distance (pc)
The Milky Way disk

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From APOGEE DR17 (Horta+ 2022)
Empirical landscape of the Milky Way disk-bulge
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SnII

SnIa

Eilers+ 2022
Empirical landscape of the Milky Way disk-bulge

Sagan, 2022

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R=2kpc

Eilers+ 2022

Sagan, 2022
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Eilers+ 2022
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R=2kpc  R=8kpc  R=17kpc

Eilers+ 2022

Sagan, 2022

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Solar neighbourhood = bimodality

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High-\(\alpha\) sequence concentrated to the inner region, thicker spatially

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In the disk, stars are born…and move over time…

- Stars form in clusters, with presumably identical abundances

Armillotta et al., 2018
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Armillotta et al., 2018

these disperse in forming the disk

Ruth Nungarrayi Spencer
In the disk, stars are born…and move over time…

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These disperse in forming the disk

- one prospect to trace back disk assembly — chemical tagging (Bland-Hawthorn & Freeman 2010)
- identify individual stars across the disk from the same birth sites using large vector of chemical abundances
Chemical tagging is difficult - but we can use joint-information
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Stellar abundances are very correlated (spectra is low dimensional in the disk)

e.g. Weinberg+ 2021, Ting & Weinberg+ 2021, Griffiths+ 2021, Ness+2022
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“see” cluster dissolution
(and test cluster dissolution processes i.e. Kamdar+ 2019)
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[Graphs showing correlation and distribution of abundances]
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Phase-space spiral a signature of a perturbation such as Sagittarius dwarf galaxy tidal interaction (i.e. Binney & Schoenrich 2018, Laporte+ 2019, Khanna+ 2019, Hunt+ 2021, Bland-Hawthorn & Tepper-Garcia+ 2021, Gandhi+ 2021+, others)
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N-body disk (Li & Shen 2015)
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Dissipational collapse
(Debattista+ 2016)
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Cosmological
(Buck+ 2020, Fragkoudi+2020)
The Milky Way Bulge

Simulations predict a bulge formed from the disk will be boxy/X-shaped

& a consequence of orbit families from dynamical instabilities
We see this X-shape in the Milky Way

Milky Way bulge is 27 degrees with respect to our line of sight

*Milky Way bulge is 27 degrees with respect to our line of sight
We see this X-shape in the Milky Way

image credit: (Lang - unwise photometry)

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Observing many “rare” stars
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Observing many “rare” stars

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- But - we see Li-rich stars — requiring a production mechanisms — such as planet engulfment
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Enrichment from planet engulfment:
- on the sub-giant branch
- (1-4-1.6 solar masses)

**Statistical Significance of Enrichment**

![Graph showing statistical significance of enrichment.](image)

*Sores-Furtado+ 2021*
Observing many “rare” stars

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8000 Li-rich stars in LAMOST identified directly from spectra

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Sores-Furtado+ 2021

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Wheeler+ 2021
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How are ages typically measured?

(also see talk by Marina Kounkel)
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small nearby samples: Gaia will provide here
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**giants**: asteroseismology: Kepler, CoRoT = mass

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Haywood et al., 2013
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Giants: asteroseismology: Kepler, CoRoT = mass

Small nearby samples: Gaia will provide here

Giant masses $\rightarrow$ giant ages

(1)

Proxy for age

Haywood et al., 2013

Sagan, 2022
Main sequence turn-off ages
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Gaia will provide high-precision (~10-15 percent) ages for stars within < 2kpc (turnoff)
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Age-date different halo populations:
11,000 halo MSTO H3 + Gaia (Bonaca+ 2020) Ages from MINESWEEPER - Cargile+ 2020)
Main sequence turn-off ages

Gaia will provide high-precision (~10-15 percent) ages for stars within < 2kpc (turnoff)

Turning point (also seen in Feuillet+ 2020, Lu+ 2021) due to Sgr-mass merger + radial migration (Lu+ 2022)

Age-date different halo populations: 11,000 halo MSTO H3 + Gaia (Bonaca+ 2020) Ages from MINESWEEPER - Cargile+ 2020)
Asteroseismic ages for red giants
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- precision age distributions of $\alpha$-sequences (2000 stars, Silva-Aguirre+ 2018)
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\[ \text{Normalized distributions} \]
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invert age-abundance gradients —> to get ages, given abundances —> also see
  - Moya+ 2022
  - Feuillet+2018, Hayden+2021, Sharma+ 2021

Melissa Ness
Sagan, 2022
We can now measure ages for giants spectroscopically.

regime change:
from stars in the solar
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regime change: from stars in the solar neighbourhood....

large, vast maps ↓

20kpc

6kpc
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APOGEE

Sagan, 2022

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\[ Z=0.020 \ Y=0.280 \]

APOGEE

20kpc
6kpc
Reference set of stars with known mass
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- label “bad” data using models built from “good data” (bad = low SNR, low-resolution)
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An incomplete list…

How *The Cannon* works on spectra (and other data-driven label transfer)

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\[ f_{n\lambda} = g(l_n|\theta_\lambda) + \text{noise} \]

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*Teff, logg, [Fe/H]*

*photon noise + fit of spectral model*

*spectral model*

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Relates stellar labels $l$ to stellar flux $f$, at each wavelength $\lambda$.

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Uses \( n \) reference objects with known labels \( l \) to build a model *Training*

Relates stellar labels \( l \) to stellar flux \( f \), at each wavelength \( \lambda \).

That model is then used to infer the stellar labels for the remaining stars in the survey *Test*

*see also DD-Payne Ting+ 2019, Xiang+ 2019, ASTRO-NN Leung+ 2018*
The APOGEE example: to infer \((\text{Teff}, \log g, [\text{Fe/H}])\)

\[ R = 22,500, \text{H-band (1.5-1.7\,\mu m)} \]
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**Training set:** 540 open and globular cluster stars, labels from ASPCAP, \(-2.5 < [\text{Fe/H}] < 0.5\)

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120,000 stars from APOGEE

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\begin{align*}
\text{f}_{n\lambda} &= a_{\lambda} + b_{\lambda}(\text{Teff})_n + c_{\lambda}(\text{logg})_n + d_{\lambda}([\text{Fe/H}])_n + \\
& \quad e_{\lambda}(\text{Teff} \cdot \text{logg})_n + f_{\lambda}(\text{Teff} \cdot [\text{Fe/H}])_n + g_{\lambda}([\text{Fe/H}] \cdot \text{logg})_n + \\
& \quad h_{\lambda}(\text{Teff})^2_n + i_{\lambda}(\text{logg})^2_n + j_{\lambda}([\text{Fe/H}]^2)_n + \text{noise}_{\lambda} \\
\text{f}_{m\lambda} &= a_{\lambda} + b_{\lambda}(\text{Teff})_m + c_{\lambda}(\text{logg})_m + d_{\lambda}([\text{Fe/H}])_m + \\
& \quad e_{\lambda}(\text{Teff} \cdot \text{logg})_m + f_{\lambda}(\text{Teff} \cdot [\text{Fe/H}])_m + g_{\lambda}([\text{Fe/H}] \cdot \text{logg})_m + \\
& \quad h_{\lambda}(\text{Teff})^2_m + i_{\lambda}(\text{logg})^2_m + j_{\lambda}([\text{Fe/H}]^2)_m + \text{noise}_{\lambda}
\end{align*}
How well does this work?
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(i) Take-one-out test to measure how well you can infer the labels
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(ii) Examine generated model vs observed spectra for test objects
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To learn age: reference set of stars with known mass
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stellar parameters from APOGEE spectra with ASPCAP
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\[ M = \left( \frac{\nu_{\text{max}}}{\nu_{\text{max,\odot}}} \right)^3 \left( \frac{\Delta \nu}{\Delta \nu_{\odot}} \right)^{-4} \left( \frac{T_{\text{eff}}}{T_{\text{eff,\odot}}} \right)^{1.5} \]
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— Cannon model that is used to determine masses for rest of APOGEE giants —
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— Cannon model that is used to determine masses for rest of APOGEE giants —

Go from mass to age with stellar evolution models
Origin of mass information

![Graph showing normalized flux vs. wavelength for different masses. The graph compares the normalized flux of two different masses: 0.7 Msun (dashed black line) and 3.3 Msun (solid blue line). The wavelength is measured in Angstroms (Å).]
Origin of mass information

Martig et al., 2016, (see also Masseron & Gilmore 2015)

mass dependent dredge up -> alters CN abundances
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mass dependent dredge up -> alters CN abundances

Models can leverage this indirectly or directly using [C/N/-age] calibration with asteroseismic stars or clusters
e.g. Spoo+ 2022, Casali+ 2017, Martig+ 2016
Ages: inside out formation and flaring of the disk

75,000 stars from APOGEE DR16
Ages: inside out formation and flaring of the disk

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(Ness et al., 2016 and also see Martig et al., 2016, Das & Sanders et al., 2018, Lu+2021)
Ages: inside out formation and flaring of the disk

75,000 stars from APOGEE DR16

Milky Way Mapper - Ages for 4 million stars including hundreds of thousands in the bulge & propagate ages to other surveys given stars in common

(Ness et al., 2016 and also see Martig et al., 2016, Das & Sanders et al., 2018, Lu+2021)
Putting everything together - ages are key
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- Measure **radial migration & inside-out formation** of the disk (e.g. Frankel+ 2018, 2019)
- **Modelling the joint abundance-age-spatial** distribution across the disk (e.g. Sharma+ 2021)
- Measuring **dynamical heating** across the Milky Way (e.g. Mackereth+ 2019, Ting+ 2019)
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- The relationship between **orbits and abundances and ages** (e.g. Gaia-Collaboration 2022, Viscasillas-Vazquez+ 2022, Manea+ 2022, Espinoza-Rojas+ 2021, Lu+ 2021, Hayden+ 2020, Gandhi+ 2019, Beane+ 2018)
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- **Age-metallicity** relations across the disk (e.g. Xiang+ 2022, Lu+ 2021, Feuillet+ 2019)
- **Age dating the disk z-vz spiral** from a perturbing impulse (e.g. Bland-Hawthorn+ 2019)
- **Age dating the bulge compared to the disk** (e.g. Bovy+ 2019, Sit+ 2020, Hasselquist+ 2020, Surot+ 2019, Valenti+ 2018)
Planet engulfment signatures: hidden in abundances of mono-age-metallicity groups?
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*open clusters with 20 measured abundances*
Planet engulfment signatures: hidden in abundances of mono-age-metallicity groups?

open clusters with 20 measured abundances

A metric to compare the ‘chemical distance’ of pairs of stars within open clusters
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A metric to compare the ‘chemical distance’ of pairs of stars within open clusters

\[
\chi^2_{nn'} = \sum_{i=1}^{I} \frac{[x_{ni} - x_{n'i}]^2}{\sigma_{ni}^2 + \sigma_{n'i}^2}.
\]

where the indices \( n \) and \( n' \) denote the two stars, \( i \) the elements, and \( x_{ni} \) the measurements with uncertainty \( \sigma_{ni} \).
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Most pairs are chemically indistinguishable in 20 elements.
Planet engulfment signatures: hidden in abundances of mono-age-metallicity groups?

A metric to compare the ‘chemical distance’ of pairs of stars within open clusters

$\chi^2_{nn'} = \sum_{i=1}^{I} \frac{[x_{ni} - x_{n'i}]^2}{\sigma^2_{ni} + \sigma^2_{n'i}}$.

where the indices $n$ and $n'$ denote the two stars, $i$ the elements, and $x_{ni}$ the measurements with uncertainty $\sigma_{ni}$.

most pairs are chemically indistinguishable in 20 elements

But some pairs of stars born together have large abundance differences. Why? (e.g. planet engulfment? Oh+ 2018)

Ness et al., 2018
Next Frontiers

architectures <- ages, kinematics, abundances
Next Frontiers

architectures <- ages, kinematics, abundances

Gaia
Next Frontiers

architectures <- ages, kinematics, abundances
Next Frontiers

architectures <- ages, kinematics, abundances

Gaia + Ground based spectroscopic surveys

Sagan, 2022
Next Frontiers

architectures <- ages, kinematics, abundances

Gaia

Ground based spectroscopic surveys
Next Frontiers

architectures <- ages, kinematics, abundances
Next Frontiers

architectures <- ages, kinematics, abundances

Gaia + Ground based spectroscopic surveys + opportunity <- ages, kinematics, abundances

JWST
TESS
Kepler
ELTs
Nancy Grace Roman Space Telescope
Vera Rubin Observatory