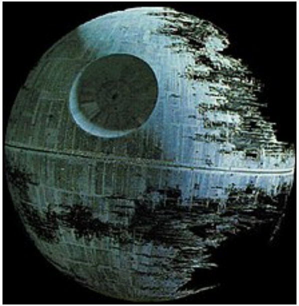
Observational foundations of stellar dynamics

Eugene Vasiliev

Institute of Astronomy, Cambridge

45th Heidelberg Physics Graduate Days, October 2020

What is a star?



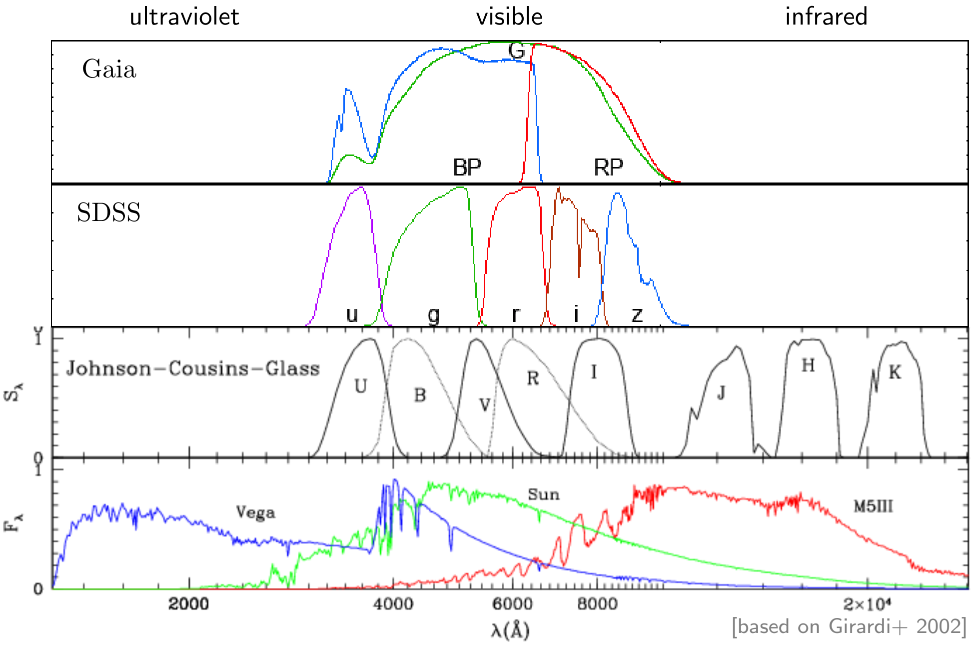
in stellar dynamics:

● a point mass with additional properties

What is a star?

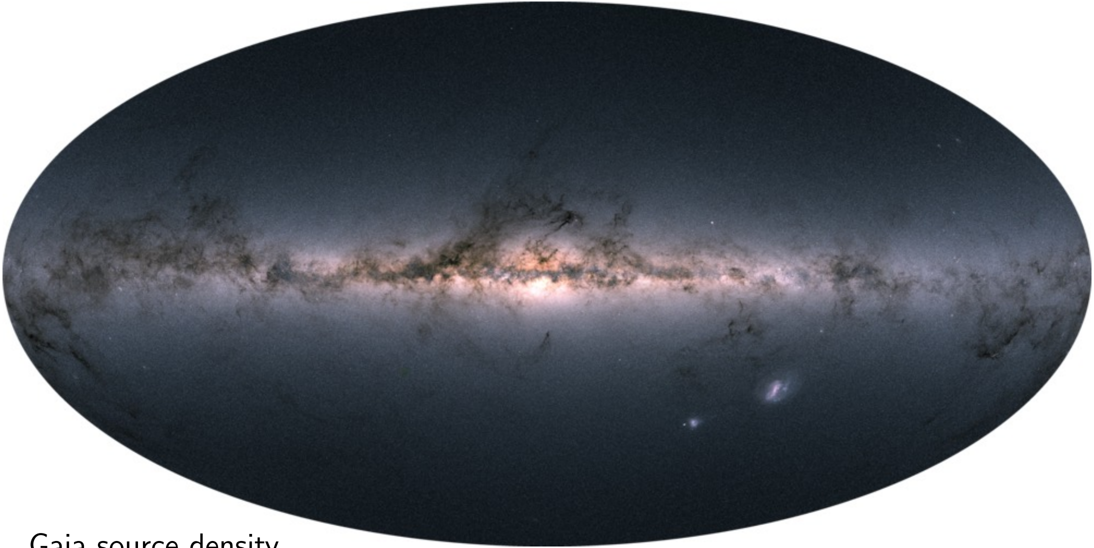
- position $\mathbf{x}$
- velocity $\mathbf{v}$
- mass m
- radius R $= 0$ [remember, it's a point mass!]
  $\Leftrightarrow$ surface gravity $\log g$
- [effective] temperature T
- luminosity L (more generally: broad-band spectrum – luminosity in several photometric bands $\Rightarrow$ magnitudes, colours)
- chemical composition:
  metallicity $Z = [\mathrm{Fe/H}] \equiv \log_{10} \left(N_{\mathrm{Fe}} / N_{\mathrm{H}} \right)_{\mathrm{star}} / \left(N_{\mathrm{Fe}} / N_{\mathrm{H}} \right)_{\mathrm{Sun}}$,
  abundances of other elements [X/Fe]
- age

Photometry



[based on Girardi+ 2002]

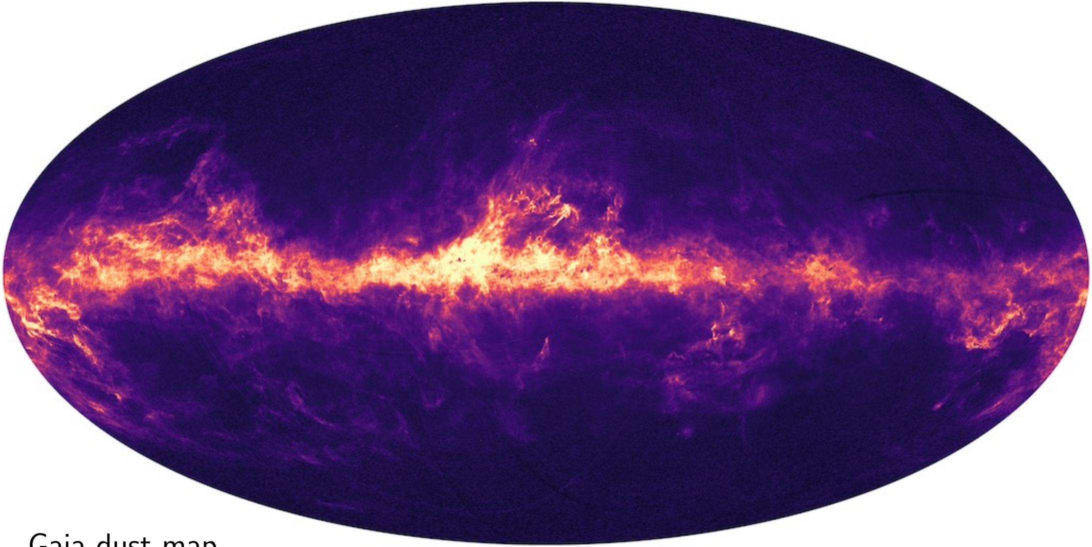
Photometry: dust extinction and reddening



Gaia source density

[credit: ESA]

Photometry: dust extinction and reddening

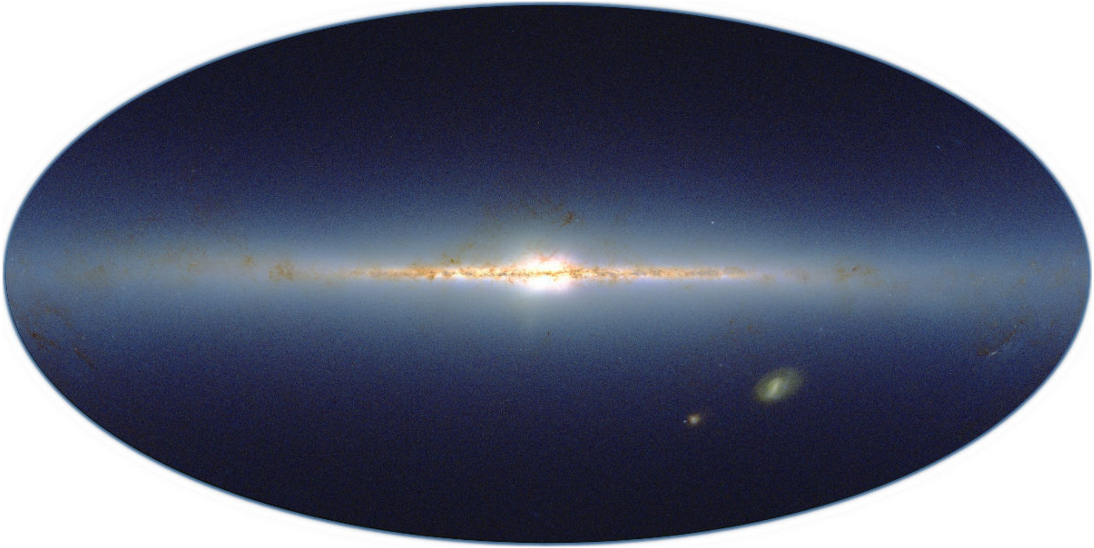


Gaia dust map

0 extinction: A_G [mag] 2.5

[credit: ESA]

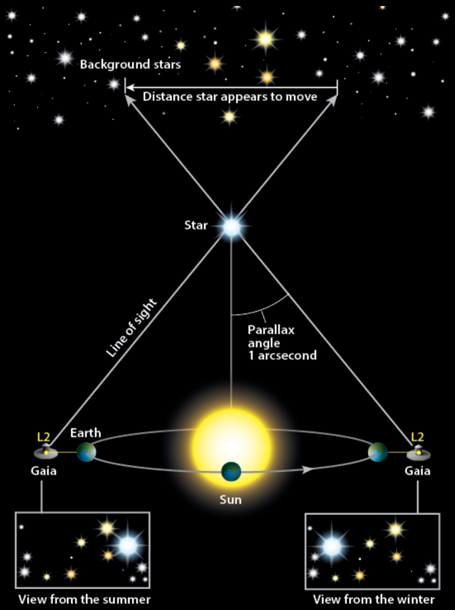
Photometry: dust extinction and reddening

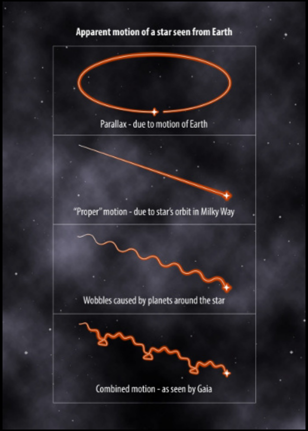


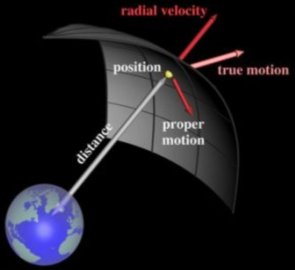
2MASS infrared survey (early 2000s)

[credit: NASA]

Astrometry







Position on the sky α, δ
Parallax $\varpi = 1/\text{distance}$
Proper motion μ_α, μ_δ
Line-of-sight velocity $v_{\rm los}$
Binary orbit parameters

Astrometry

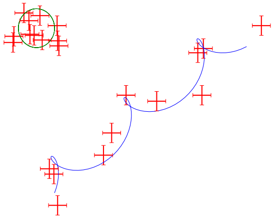
To measure the absolute proper motion of a star, one needs

- repeated observations of its location with a baseline of a few years;
- an absolute reference frame (e.g., tied to extragalactic objects).

Ground-based astrometry was used for decades, but is largely obsolete now after Gaia DR2, except highly extincted regions of the Galactic bulge – here ground-based near-IR observations are the only possibility (e.g., the VIRAC catalogue [Smith+ 2018], or as an extreme example, GRAVITY interferometry).

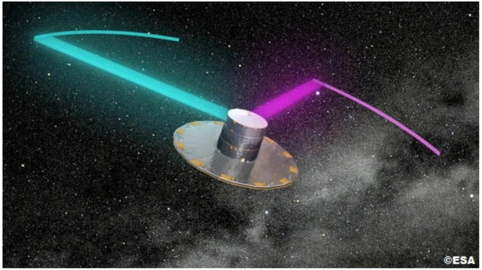
HST-based astrometry is superior for faint sources and crowded fields.

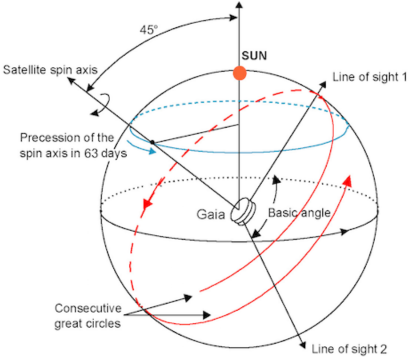
In both cases, extra steps are needed to determine *absolute* proper motions, though these are not always needed (e.g., relative motions are sufficient for studying the internal kinematics of star clusters).

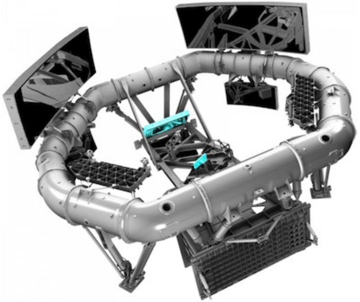


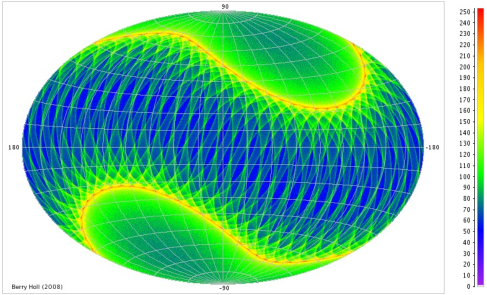
Relative accuracy of proper motion $\mu = V_{\mathrm{sky}}/D$ is usually better than that of parallax $\varpi = 1/D$, and improves faster with time:
error $\epsilon_\mu \propto T^{-1}\, N_{\mathrm{obs}}^{-1/2} \propto N_{\mathrm{obs}}^{-3/2}, \quad \epsilon_\varpi \propto N_{\mathrm{obs}}^{-1/2}$.

How Gaia astrometry works



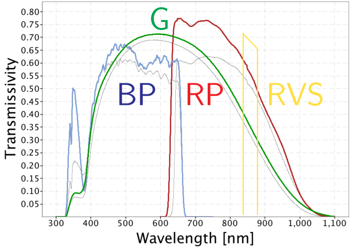






Overview of Gaia mission

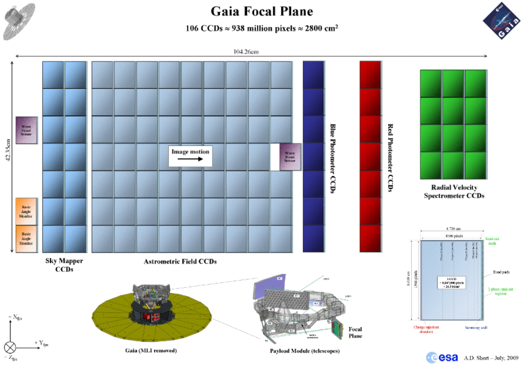
- Launched end 2013, duration up to 10 yr
- Scanning the entire sky every few weeks
- Astrometry for sources down to 21 mag
- Broad-band photometry/low-res spectra
- Line-of-sight velocity down to ~ 15 mag (end-of-mission)



Data release 2 (DR2, April 2018):

- based on 22 months of observations
- 1.3×10^9 stars with full astrometry
- 1.4×10^9 stars with two colours
- 7.2×10^6 stars with $V_{\rm los}$
- 0.5×10^6 variable stars

Next comes EDR3 (Dec 2020): improving astrometric precision for ϖ by a factor 1.4, μ by 2.2



[Source: ESA]

Spectroscopy

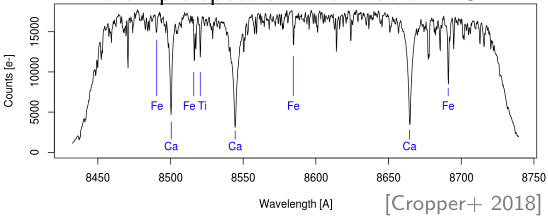
Two main tasks:

- measure line-of-sight velocities (often meaninglessly called "radial velocities") from Doppler shifts in spectral lines – e.g., Calcium triplet
- measure chemical abundances – usually requires relatively high resolution and/or large large wavelength coverage

Data products:

$v_{\rm los}$ (typical precision: from a fraction of km/s to tens of km/s);
metallicity [Fe/H]; abundances of α-elements (C, O, Mg, Si, Ca);
stellar parameters: effective temperature ($T_{\rm eff}$); surface gravity ($\log g$);
using stellar evolution models: ages and distances.

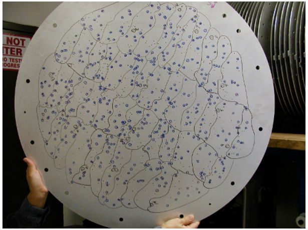
example spectrum from Gaia RVS

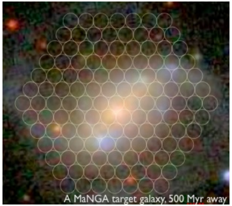


[Cropper+ 2018]

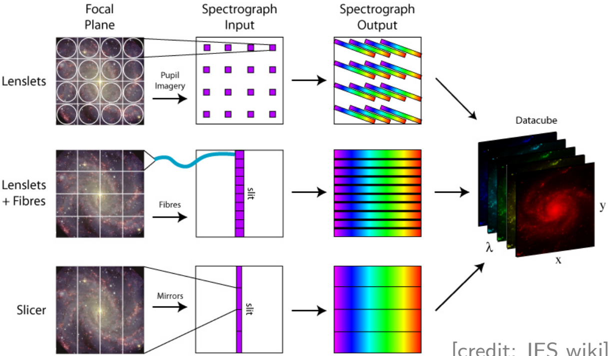
Multi-fiber and integral-field spectroscopic instruments

SDSS
(1000 fibers
per plate)
[video]





MaNGA IFU



[credit: IFS wiki]

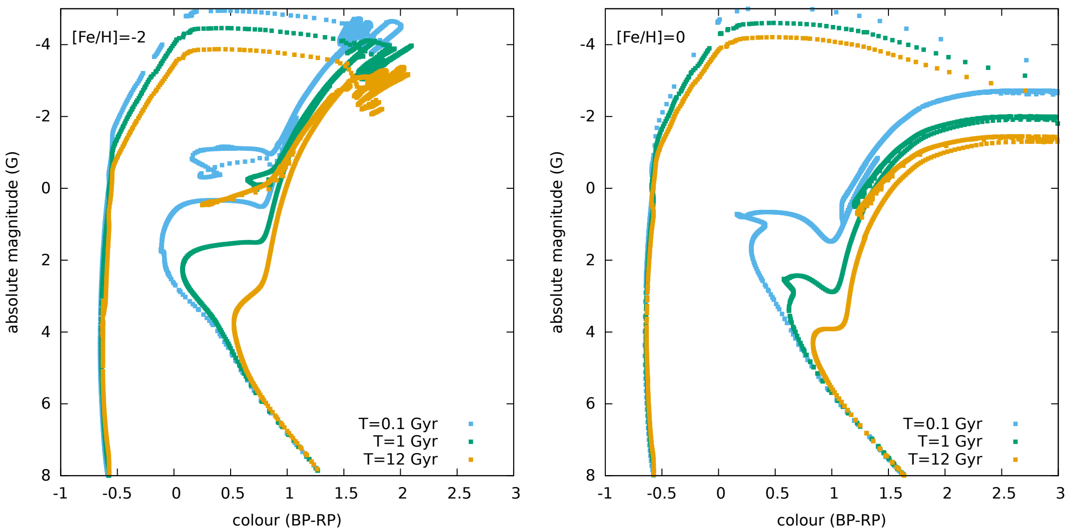
Integral-field spectroscopic instruments

Instrument	wavelength range	spectral res.	spatial res.	field of view	telescope
MUSE	4650 – 9300	≈ 3000	$0.''2$	$60'' \times 60''$	VLT 8 m
VIMOS	3600 – 10 000	200 – 2500	$0.''67$	$54'' \times 54''$	VLT 8 m
SAURON	4500 – 7000	≈ 1500	$0.''94$	$41'' \times 33''$	WHT 4.2 m
WEAVE	3700 – 9600	5000, 20 000	$1.''3$ $2.''6$	$11'' \times 12''$ $78'' \times 90''$	WHT 4.2 m
SAMI	3700 – 9500	1700 – 13 000	$1.''6$	$\varnothing 15''$	AAT 3.9 m
DensePak	3700 – 11 000	5000 – 20 000	$3.''0$	$30'' \times 45''$	WIYN 3.8 m
SparsePak	5000 – 9000	5000 – 20 000	$4.''7$	$72'' \times 71.''3$	WIYN 3.8 m
SITELLE	3500 – 9000	1 – 10 000	$0.''32$	$11' \times 11'$	CFHT 3.6 m
PPak	4000 – 9000	≈ 8000	$2.''7$	$74'' \times 64''$	Calar Alto 3.5 m
VIRUS-P	3500 – 6800	≈ 850	$4.''3$	$1.'7 \times 1.'7$	McDonald 2.7 m
VIRUS-W	4340 – 6040	2500, 6800	$3.''2$	$105'' \times 75''$	McDonald 2.7 m
MaNGA	3600 – 10 400	≈ 2000	$2.''0$	$12.''5$ – $32.''5$	APO 2.5 m

[adapted from Zou+ 2019]

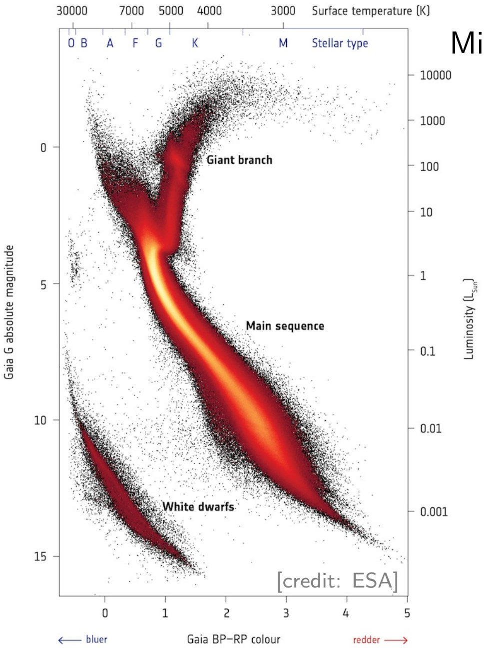
AO-assisted IFU					
MUSE-AO	4650 – 9300	≈ 3000	$0.''025$	$7.''5 \times 7.''5$	VLT 8 m
SINFONI	11 000 – 24 500	1500 – 4000	$0.''1$	$3'' \times 3''$	VLT 8 m
NIFS	9400 – 24 000	5000	$0.''1$	$3'' \times 3''$	Gemini N 8 m

Stellar evolution and isochrones



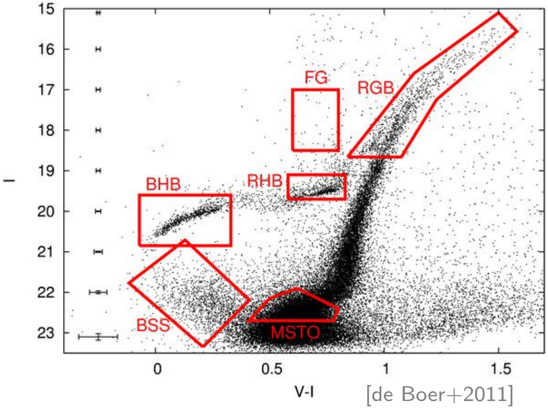
theoretical isochrones from MIST project [Dotter+2016, Choi+2016]

Observational colour–magnitude diagrams



Milky Way (Solar neighbourhood)

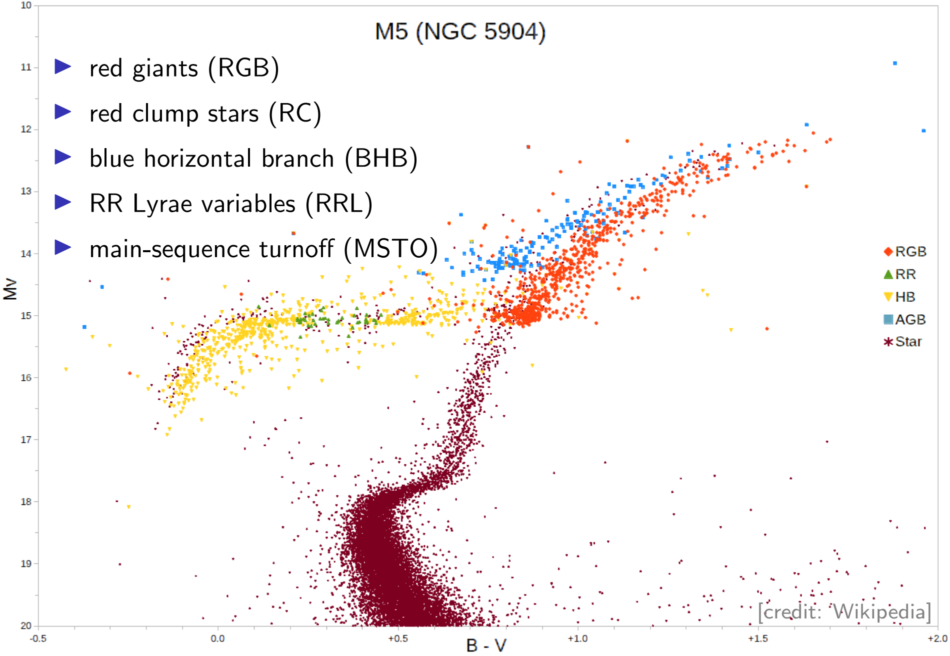
Sculptor dSph



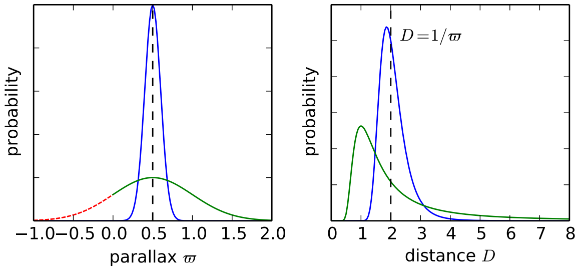
[de Boer+2011]

Important classes of stars

- red giants (RGB)
- red clump stars (RC)
- blue horizontal branch (BHB)
- RR Lyrae variables (RRL)
- main-sequence turnoff (MSTO)



Distance measurement



Individual stars:

- From parallax: $D \approx 1/\varpi$ – only good as long as $\epsilon_\varpi \ll \varpi$; error distribution is asymmetric
- From photometry (standard candles: Cepheids, RR Lyrae, RC, BHB, tip of the RGB, ...)
- From spectro-photometric and photo-astrometric modelling based on stellar evolution models (along with chemistry, masses, ages, ~~number of planets with alien life~~, etc.)

Stellar clusters, galaxies, ...

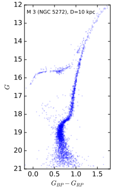
- resolved stellar populations: CMD fitting, standard candles
- semi-resolved: surface brightness fluctuations
- ...

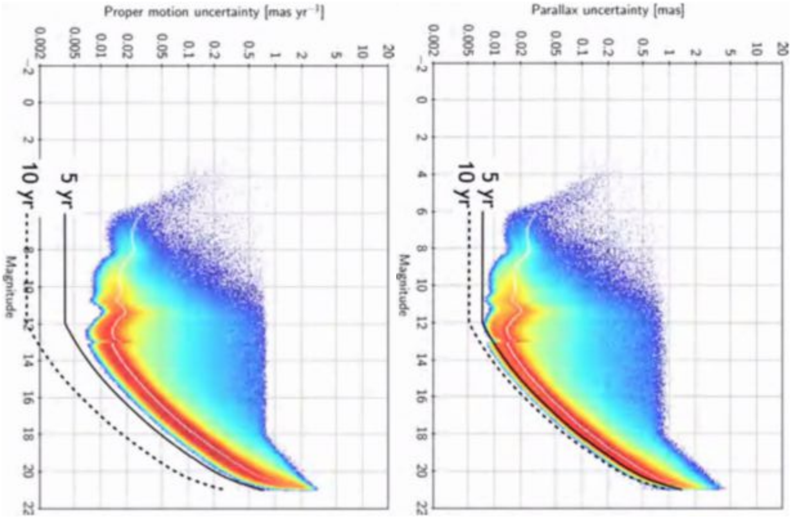
Velocity measurement

$v_{\rm los}$ usually measured with precision $\mathcal{O}(1$ km/s$)$,
but the sky-plane velocity is $v_{\rm sky} = D\,\mu$:
depends on both distance and proper motion

Gaia EDR3 accuracy [credit: A.Brown]

A typical star cluster
at a distance 10 kpc





1 5 25 km/s rel.err. 10% 100%

Density measurement

Couldn't be easier! just count stars...

but:

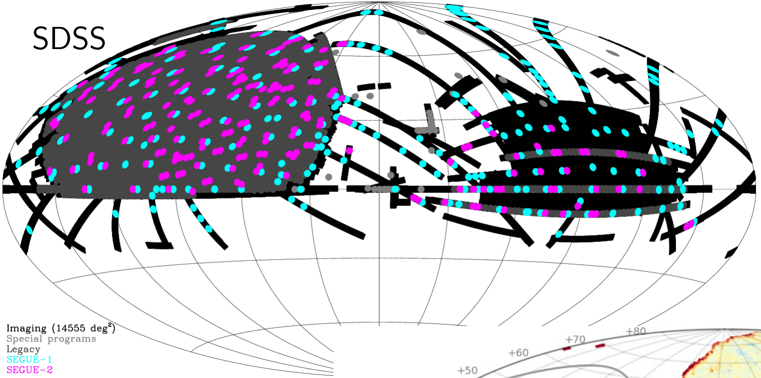
- limiting magnitude depends on distance ($\Rightarrow$ completeness)
- complicated by spatially variable extinction
- difficult to resolve faint stars in dense environment ($\Rightarrow$ crowding)
- not all potentially observable stars are recorded
  ($\Rightarrow$ survey selection function – sometimes simply uncomputable!)

In general, density is *more difficult* to measure reliably than kinematics!

Photometric surveys

Name	date	wavelength	coverage	telescope
2MASS	1997–2001	near-IR	all sky	Whipple obs (US), CTIO (Chile) 1.3m
WISE	2010	mid-IR	all sky	space 0.4m
SDSS	2000–2009	optical	1/3 sky	Apache Point 2.5m
PanSTARRs	2011–now	optical	3/4 sky	Hawaii 1.8m
Legacy surveys (DES, DECaLS, DECaPS, MzLS)	2013–now	optical	1/3 sky	Kitt Peak (US) 4m Blanco (Chile) 4m
VVV VHS	ongoing	near-IR	Galactic plane 1/2 sky (S)	VISTA (Chile) 4m
Gaia	2014–now	optical	all sky	space (L2) 1.2m
LSST	2023–	optical	1/2 sky (S)	Rubin obs. (Chile) 8m

Photometric surveys

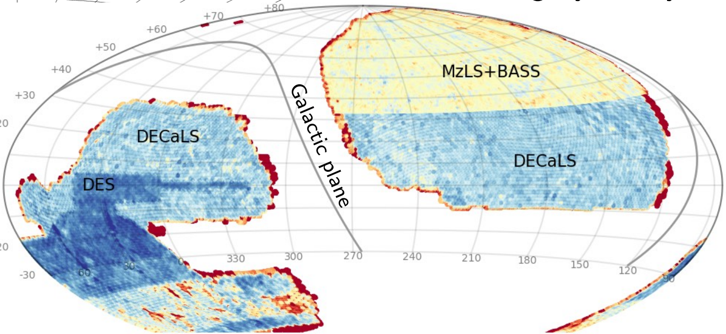


[Aladin Sky Atlas]

[LS Sky viewer]

[note: coordinate systems differ between these plots]

DES+Legacy surveys



Astronomical databases

Images are fun, but the real science is in catalogues, especially when cross-matching objects between different surveys.
Fortunately, most astronomical databases are publicly available (perhaps after some proprietary period).