Modern stellar dynamics, lecture 1: introduction, observational foundations

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Part III / MAst course, Winter 2022

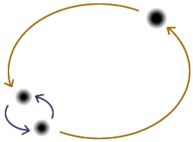
Plan of the course

- Introduction, observational foundations
- Structural properties of stellar systems, density and gravitational potential
- Orbits of stars; integrals of motion, action–angle variables
- Collisionless systems, Boltzmann equation and its moments – Jeans and virial equations
- Equilibrium models of stellar systems
- Mass modelling – inference on gravitational potential from stellar kinematics
- Collisional systems: two-body relaxation, evolution of star clusters
- Galaxy encounters, tidal streams and shells; galactic archeology

Literature:

- Binney J. & Tremaine S., *Galactic dynamics* (2nd ed.), Princeton Univ. press, 2008
- Bovy J., *Dynamics and astrophysics of galaxies*: galaxiesbook.org

Scope


planetary systems,
multiple stars
$N \sim \mathcal{O}(10)$


globular clusters

$N \sim 10^4 - 10^7$

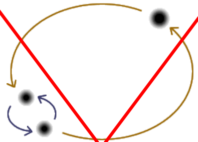

galaxies

$N \sim 10^7 - 10^{11}$

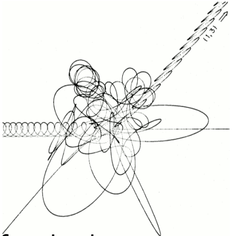

galaxy clusters

$N \sim 10^2 - 10^3$

Scope



~~planetary systems, multiple stars~~
~~$N \sim \mathcal{O}(10)$~~



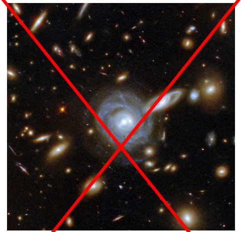
few-body encounters

globular clusters

$N \sim 10^4 - 10^7$

galaxies

$N \sim 10^7 - 10^{11}$



~~galaxy clusters~~

tidal streams

[mostly] continuum limit

- ✓ stars
- ✓ dark matter
- × gas

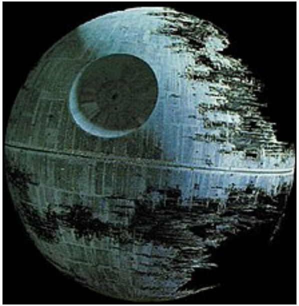
Characteristic scales

		
	globular clusters	galaxies
	$N \sim 10^4 - 10^7$	$N \sim 10^7 - 10^{11}$
Size	$\sim 10\,\mathrm{pc}$	stars: $\sim 1 - 10$ kpc halo: $\sim 10 - 100$ kpc
Velocity	$\sim 10\,\mathrm{km/s}$	$\sim 10 - 200$ km/s
Time	$\sim 10^6$ yr	$\sim 10^8$ yr

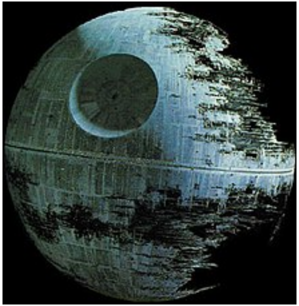
$\underbrace{\sim 10^6 \text{ yr} \qquad \sim 10^8 \text{ yr}}_{\text{dynamically old}}$

$$\frac{1\,\mathrm{pc}}{1\,\mathrm{Myr}} \approx 0.98\,\mathrm{km/s}$$

What is a star?



What is a star?

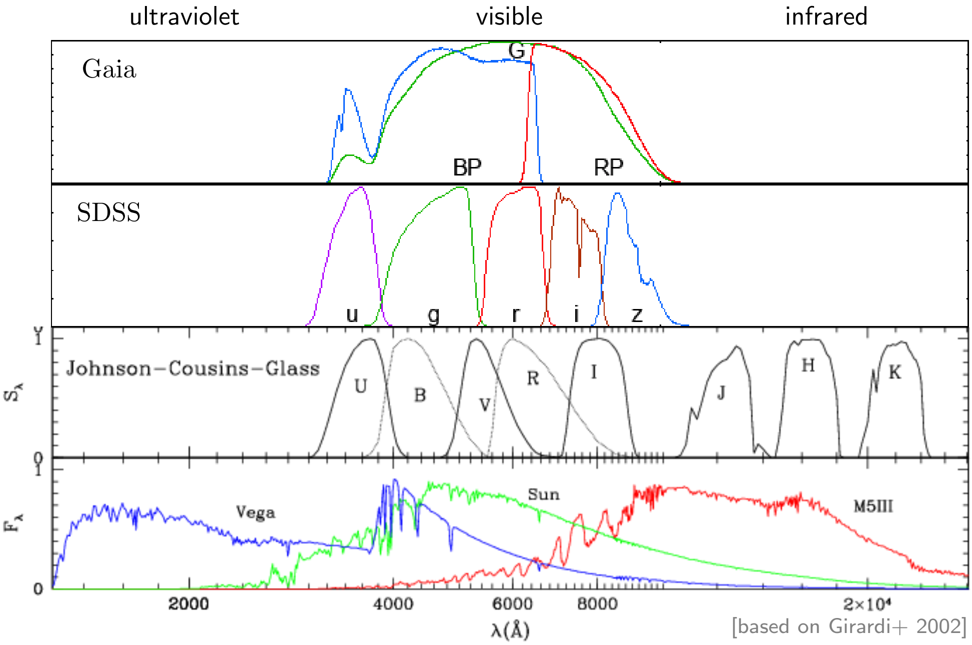


- in stellar dynamics:

  a point mass with additional properties:

position, velocity, mass, radius, luminosity, temperature, chemical composition, age, . . .

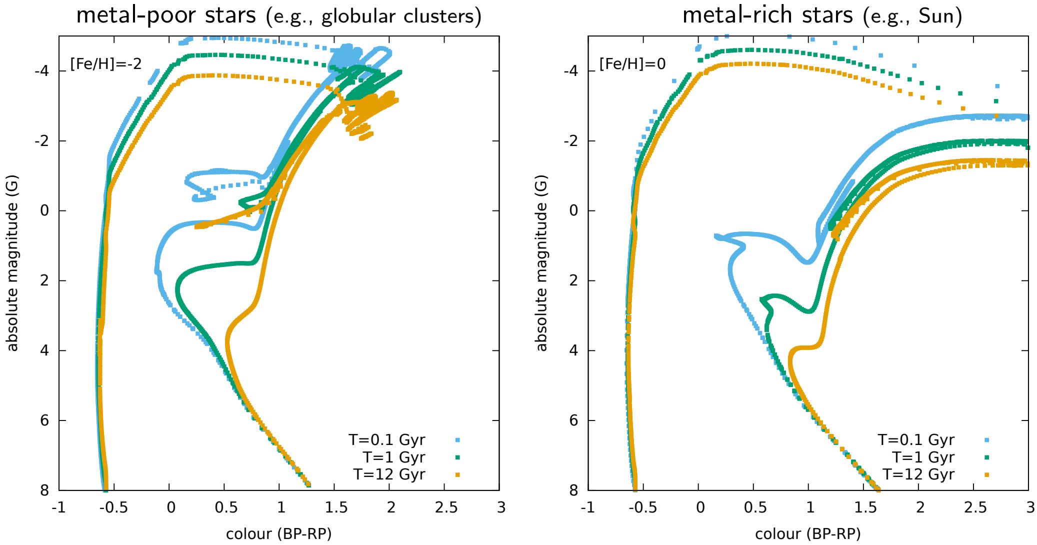
Photometry



[based on Girardi+ 2002]

Stellar evolution and colour-magnitude diagrams

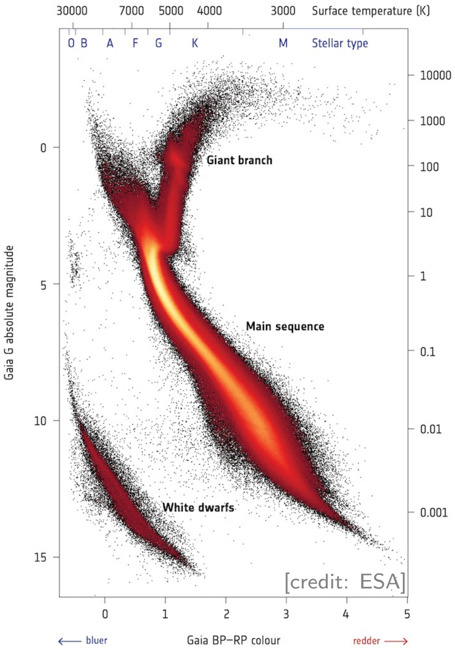
$$\text{metallicity } Z \equiv [\mathrm{Fe/H}] \equiv \log_{10}\left[\left(N_{\mathrm{Fe}}/N_{\mathrm{H}}\right)_{\mathrm{star}}/\left(N_{\mathrm{Fe}}/N_{\mathrm{H}}\right)_{\mathrm{Sun}}\right]$$



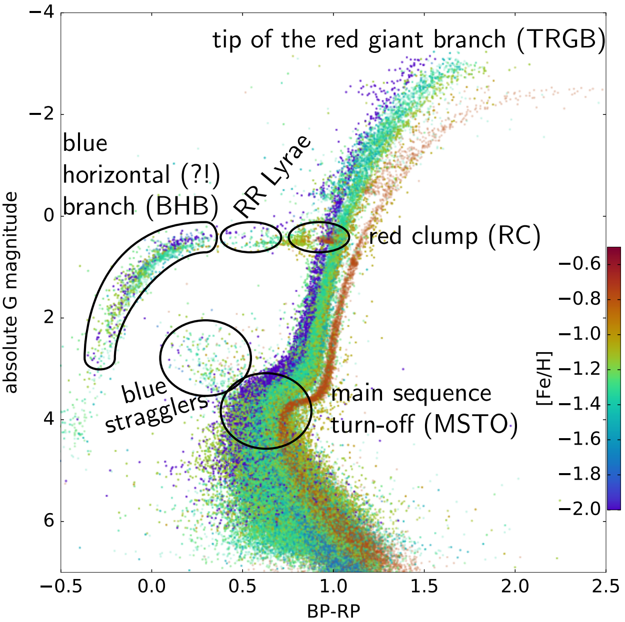
theoretical isochrones from MIST project [Dotter+2016, Choi+2016]

Observational colour–magnitude diagrams

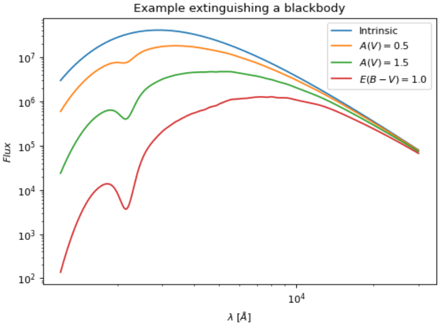
Solar neighbourhood



10 richest globular clusters

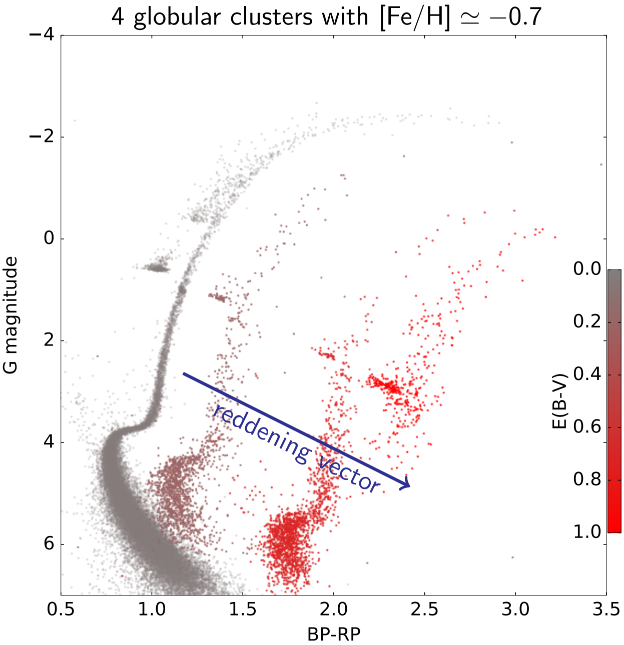


Photometry: dust extinction and reddening

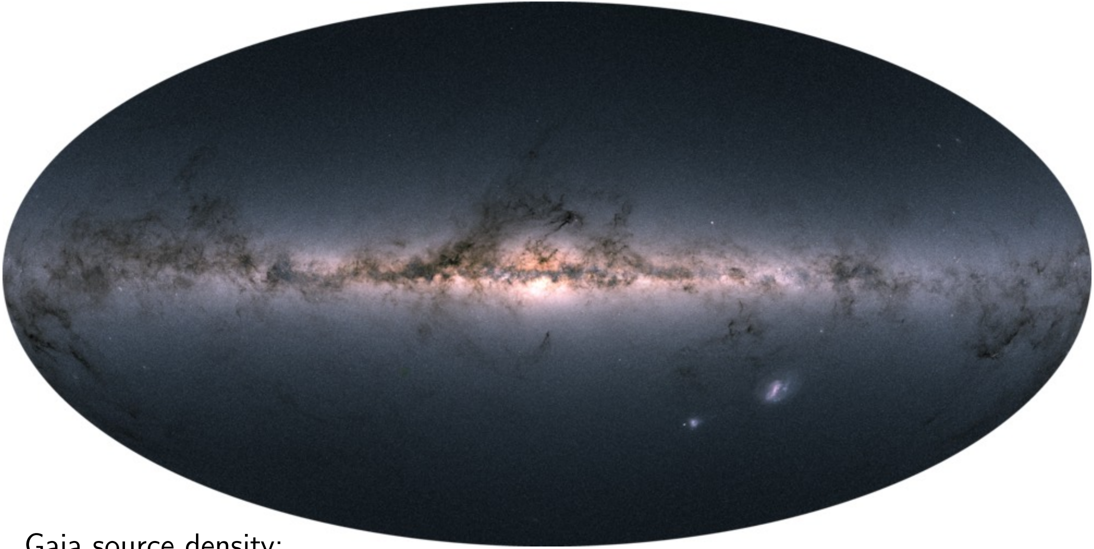


blue photons are more strongly attenuated than red photons ⇒ CMD is shifted down and right along the "reddening vector" (determined by the chosen colour bands) by an amount proportional to the overall extinction coefficient, usually expressed as

$$E(B-V) \equiv (B-V)_{\text{obs}} - (B-V)_{\text{true}}$$



Photometry: dust extinction and reddening

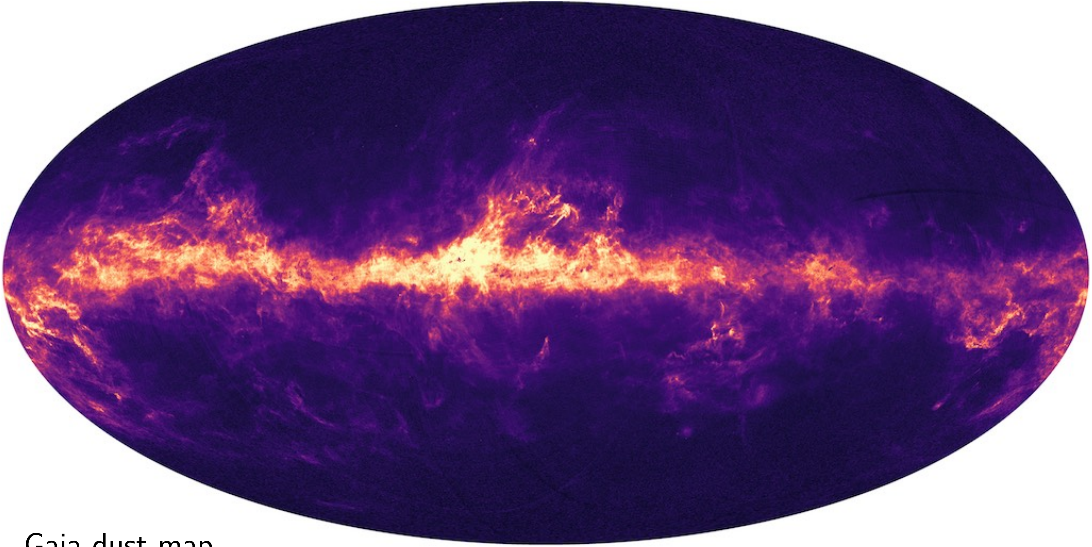


Gaia source density:

note the prominent dark lanes near the Galactic plane

[credit: ESA]

Photometry: dust extinction and reddening

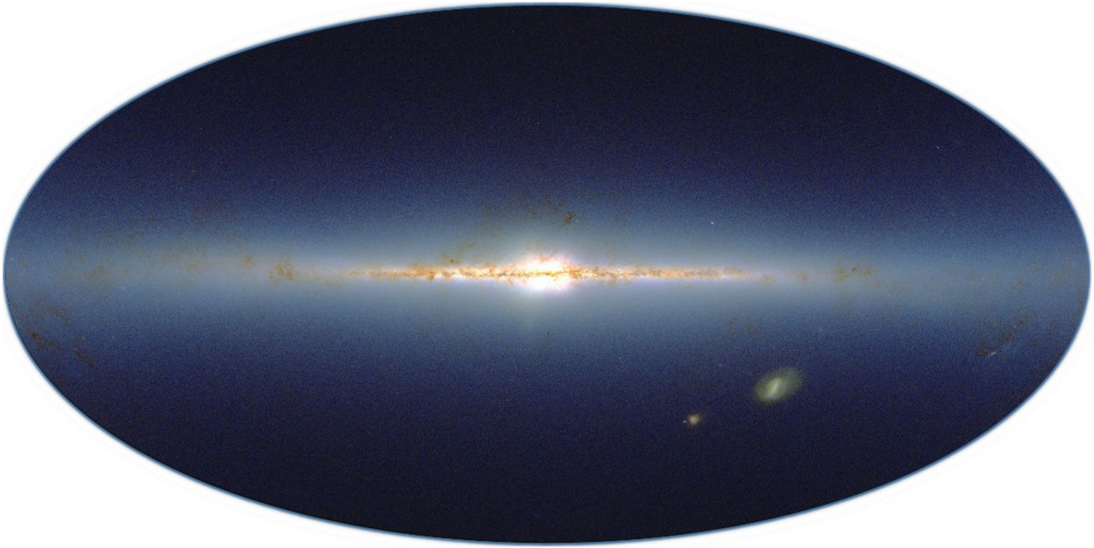


Gaia dust map

extinction: A_G [mag]

[credit: ESA]

Photometry: dust extinction and reddening



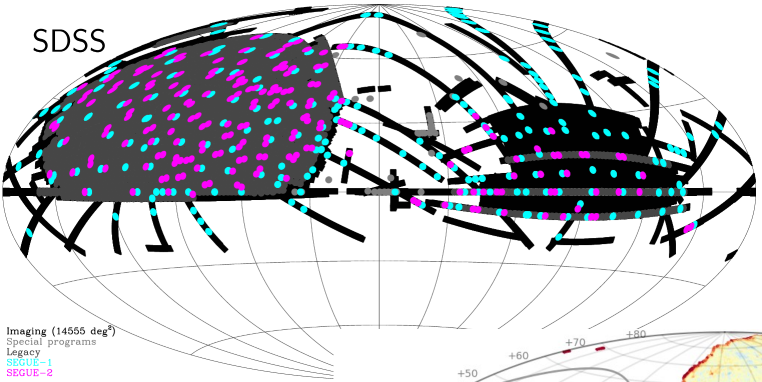
2MASS infrared survey (early 2000s)

[credit: NASA]

Photometric surveys

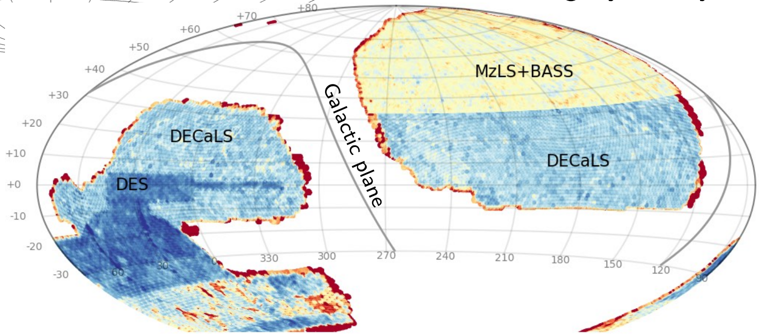
[Aladin Sky Atlas]

[LS Sky viewer]



[note: coordinate systems differ between these plots]

DES+Legacy surveys

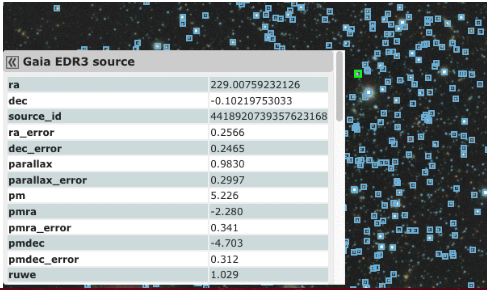


Photometric surveys

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

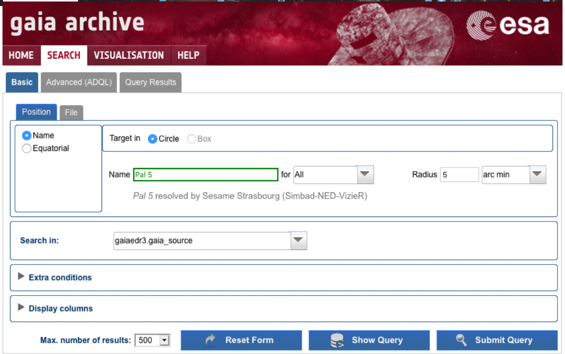
Photometric catalogues

$\Longrightarrow$



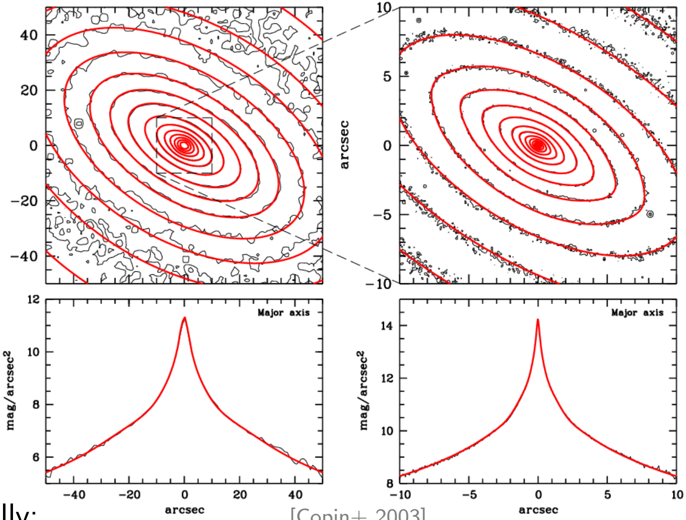
Gaia EDR3 source

ra	229.00759232126
dec	-0.10219753033
source_id	4418920739357623168
ra_error	0.2566
dec_error	0.2465
parallax	0.9830
parallax_error	0.2997
pm	5.226
pmra	-2.280
pmra_error	0.341
pmdec	-4.703
pmdec_error	0.312
ruwe	1.029



Typically one uses catalogues of individual objects (stars, galaxies) rather than raw images;
these can be queried from online databases using specific criteria and cross-matched with other catalogues

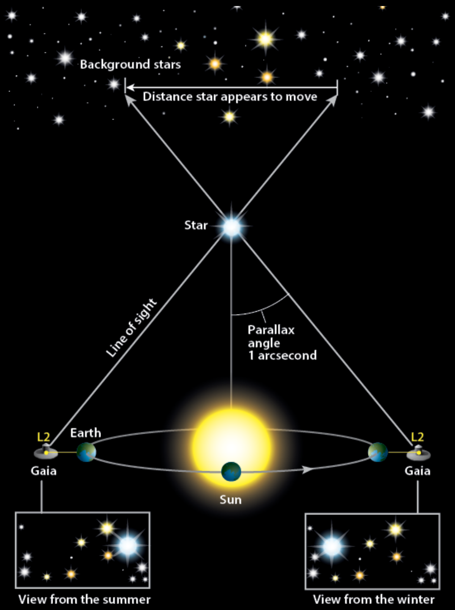
Photometry of unresolved stellar populations

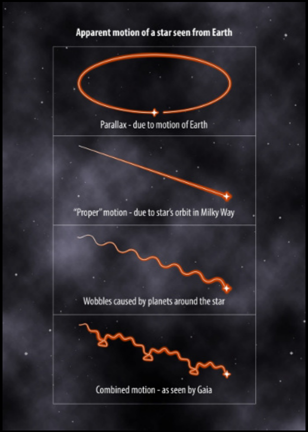


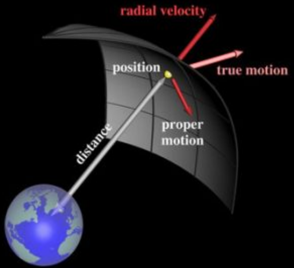
[Copin+ 2003]

Stars in external galaxies are typically not resolved individually; usually the image is converted into a parametric surface brightness profile

Astrometry







Position on the sky α, δ

Parallax $\varpi = 1/\text{distance}$

Proper motion μ_α, μ_δ

Line-of-sight velocity v_{los}

Binary orbit parameters

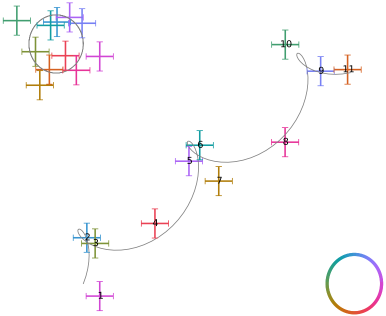
Astrometry

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

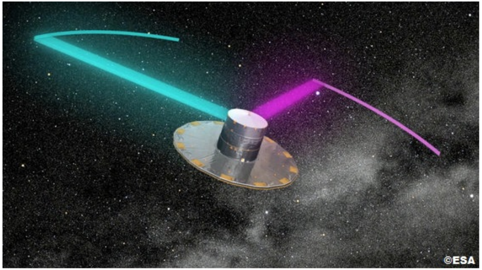
- repeated observations of its location with a baseline of a few years;
- an absolute reference frame (e.g., tied to extragalactic objects)
  (it is not necessary if one is interested only in the PM dispersion).

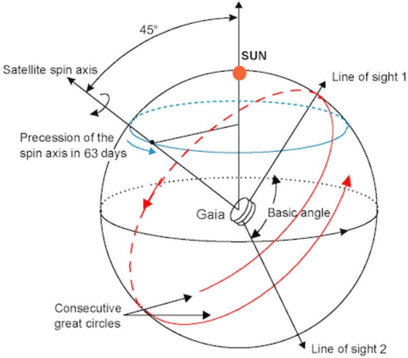
Gaia satellite is the main source of astrometric data today, complemented by *HST* (faint stars, dense systems, small field of view) and ground-based near-IR facilities (highly extincted regions in the Galactic centre).

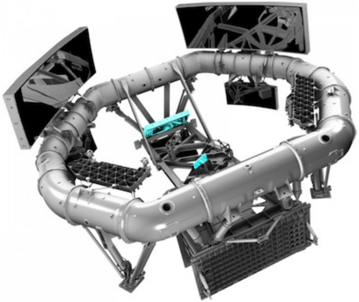
Relative accuracy of PM $\mu = V_{\rm sky}/D$
is usually better than that of parallax $\varpi = 1/D$,
and improves faster with time:
error $\epsilon_\mu \propto T^{-1}\, N_{\rm obs}^{-1/2} \propto N_{\rm obs}^{-3/2}, \quad \epsilon_\varpi \propto N_{\rm obs}^{-1/2}$.

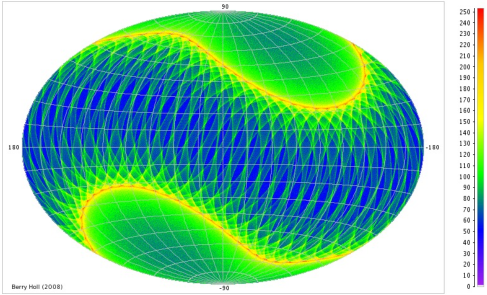


How Gaia astrometry works



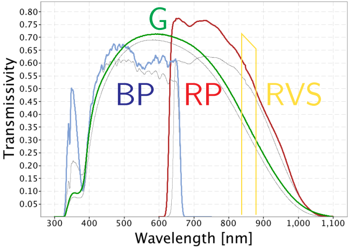






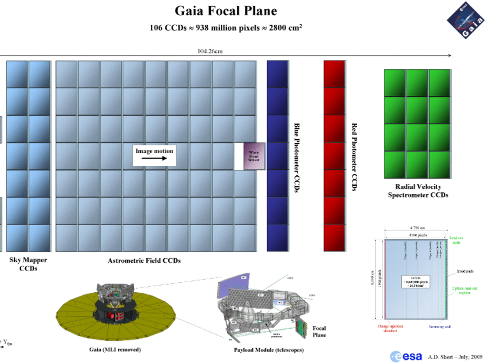
Overview of Gaia mission

- 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)



[Early] data release 3 (December 2020):

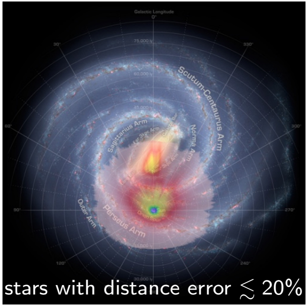
- based on 34 months of observations
- 1.5×10^9 stars with full astrometry
- 1.5×10^9 stars with two colours
- 7.2×10^6 stars with $V_{\rm los}$



[Source: ESA]

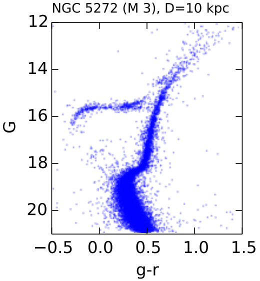
Full DR3 comes in Q2 2022:
increase $V_{\rm los}$ sample to 30×10^6,
provide low-res BP/RP spectra,
non-single-star orbital solutions

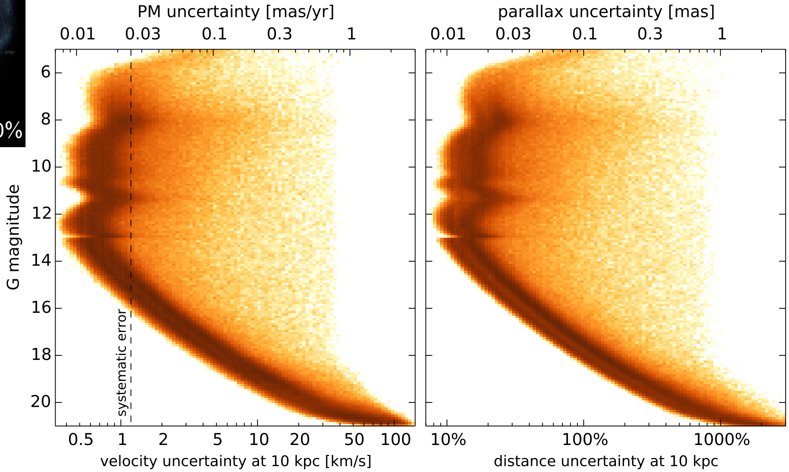
Gaia astrometric precision



relative parallax precision $\epsilon_\varpi/\varpi \le 20\% \;\Rightarrow$
$D \lesssim$ a few kpc for bright stars;

sky-plane velocity
$v_{\rm sky} = D\,\mu = 4.74\,{\rm km/s} \times (D/1\,{\rm kpc}) \times (\mu/1\,{\rm mas\,yr}^{-1})$





Spectroscopy of individual stars

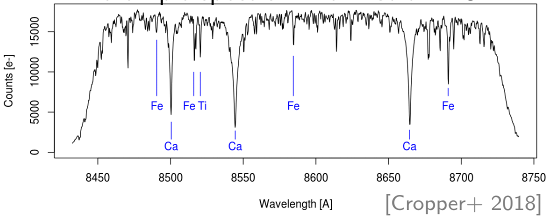
Two main tasks:

- 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.

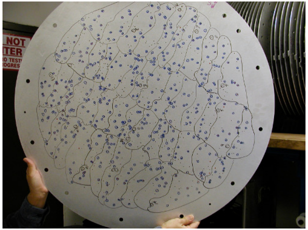
example spectrum from Gaia RVS

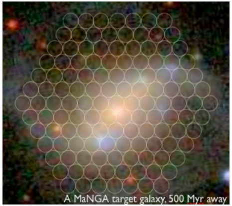


[Cropper+ 2018]

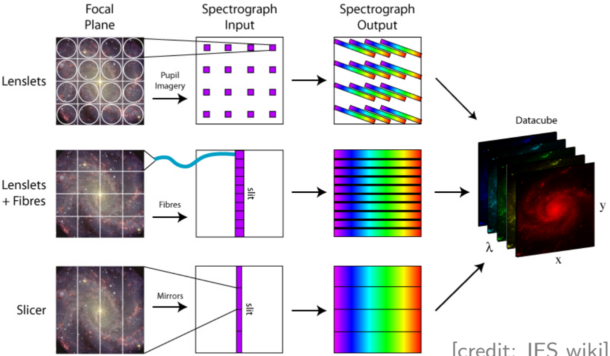
Multi-fiber and integral-field spectroscopic instruments

SDSS
(1000 fibers per plate)
[video]





MaNGA IFU



[credit: IFS wiki]

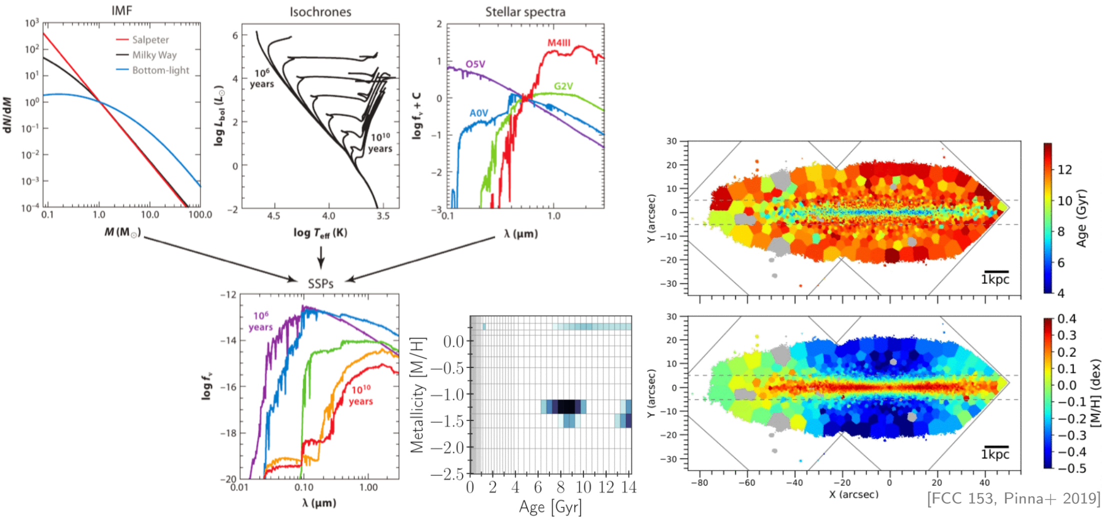
Integral-field spectroscopic instruments

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
NIRSpec	10 000 – 50 000	2700	$0.''1$	$3'' \times 3''$	JWST 6.5 m

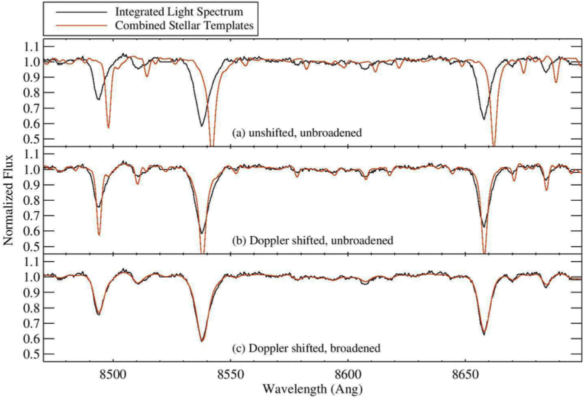
Analysis of IFU spectroscopic datacubes: stellar populations

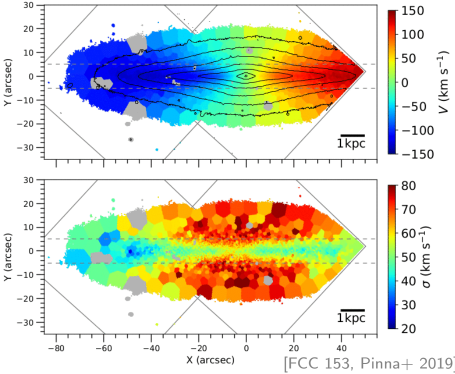


[FCC 153, Pinna+ 2019]

spectra of simple stellar populations (fixed age and chemical composition) ⊛ adjustable contribution of each SSP in the age & metallicity plane ⇒ spectrum in each spaxel

Analysis of IFU spectroscopic datacubes: velocity distribution





[FCC 153, Pinna+ 2019]

spectra of a few template stars $\circledast$ shift and broadening by adjustable velocity distribution function $\Rightarrow$ spectrum in each spaxel

Summary

- Scope of this course: structure and dynamics of stellar systems with $N \gg 1$ stars and dynamical time $\ll$ the age of the Universe
- Two rather different types of input data: resolved and unresolved stellar populations
- For individual stars, we can measure many properties, including all 6 phase-space coordinates (position $+$ velocity)
- For unresolved stellar systems, have to deal with 2d surface brightness profiles and line-of-sight velocity distributions (2$+$1d)