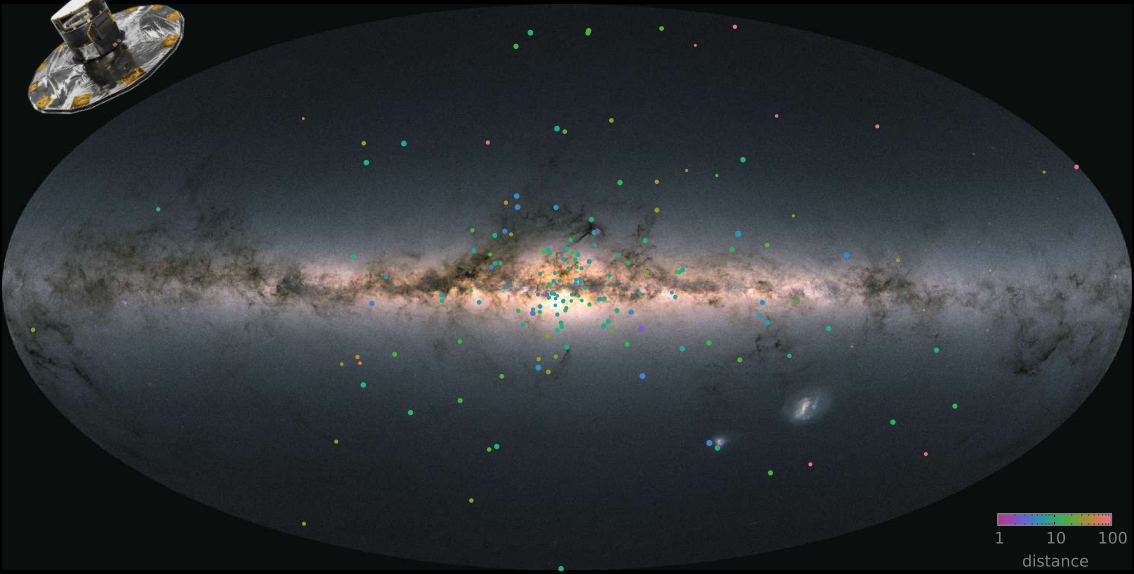
Dynamics of star clusters and streams



Eugene Vasiliev
Institute of Astronomy, Cambridge

Star clusters: the Gaia revolution online workshop, 6 October 2021

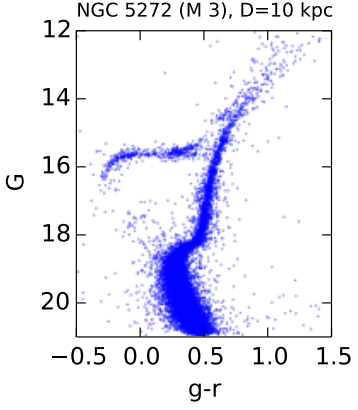
Gaia astrometric precision

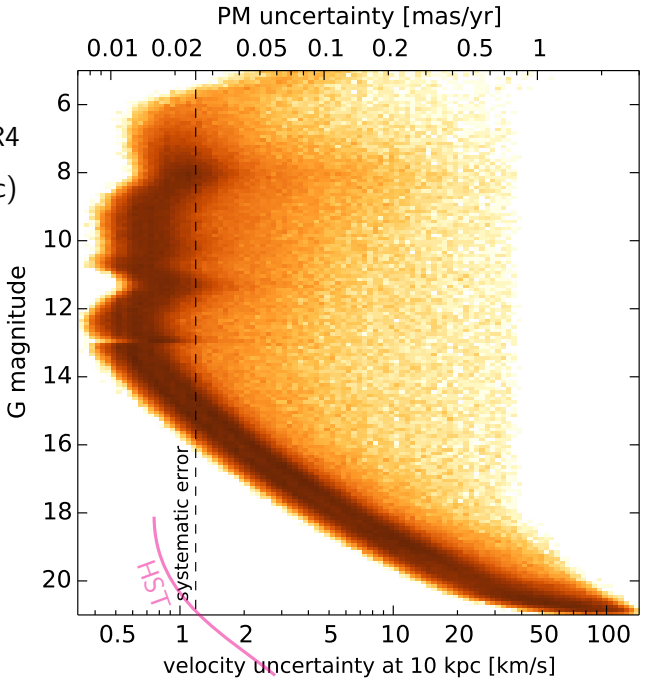
$\epsilon_\mu \gtrsim 0.01$ mas/yr in EDR3

$\epsilon_\mu \propto T^{-3/2}$:
expect 2.5× improvement in DR4

$1\,\mathrm{mas/yr} = 4.7\,\mathrm{km/s} \times (D/1\,\mathrm{kpc})$

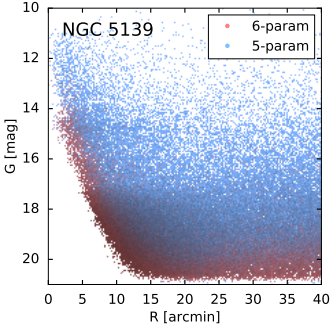
$\sigma \sim 2 - 10$ km/s in clusters

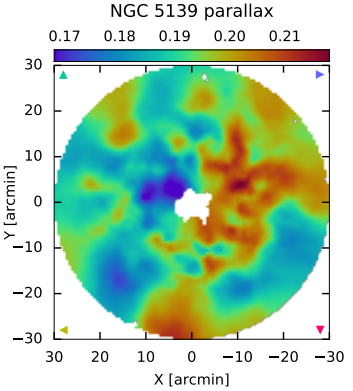


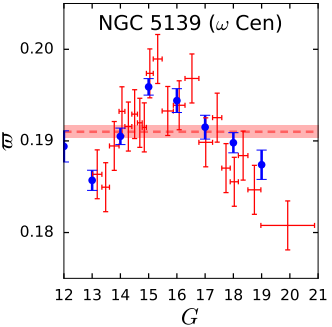


Gaia limitations and caveats

- poor completeness in dense regions ($\gtrsim$ 300 stars/arcmin^2) $\Rightarrow$ unsuitable for central regions of globular clusters, need HST and MUSE–AO;
- many quality indicators to filter out sources with unreliable astrometry;
- spatially correlated systematic errors in ϖ and μ at the level 0.01–0.03 mas on sub-degree scales;
- parallax not precise enough for objects beyond a few kpc (uncertainty about zero-point calibration and possible bias at the level 0.01 mas) $\Rightarrow$ have only 4d phase-space coords (or 5d with $v_{\rm LOS}$)

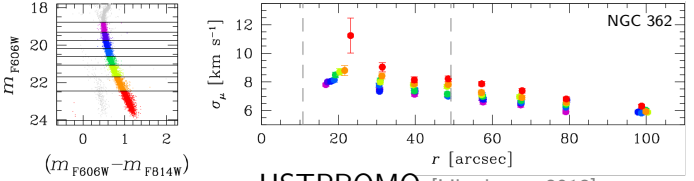




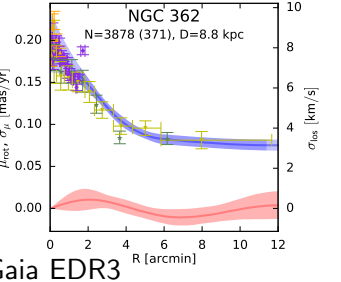


Internal kinematics of star clusters: rotation, dispersion

combination of $\sigma_{\rm PM}$ and $\sigma_{\rm LOS}$ $\Rightarrow$ dynamical distance measurement;
rotation in 3d $\Rightarrow$ effects of Galactic tidal field;
mass- and population-dependent kinematic differences $\Rightarrow$...

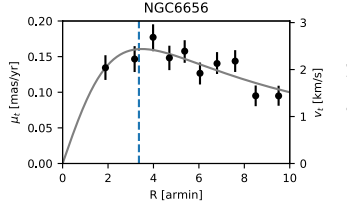


HSTPROMO [Libralato+ 2018]

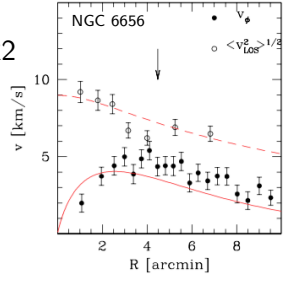


Gaia EDR3

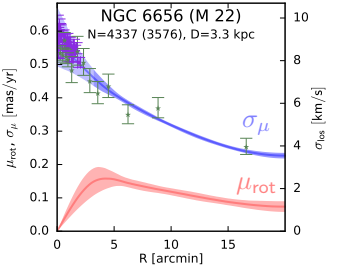
Gaia DR2



[Bianchini+ 2018]



[Sollima+ 2019]

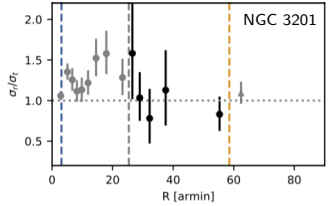


[Vasiliev & Baumgardt 2021]

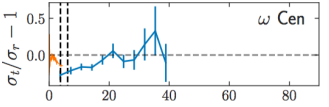
PM anisotropy profiles

variety of profiles, mostly weakly radial or isotropic

DR2



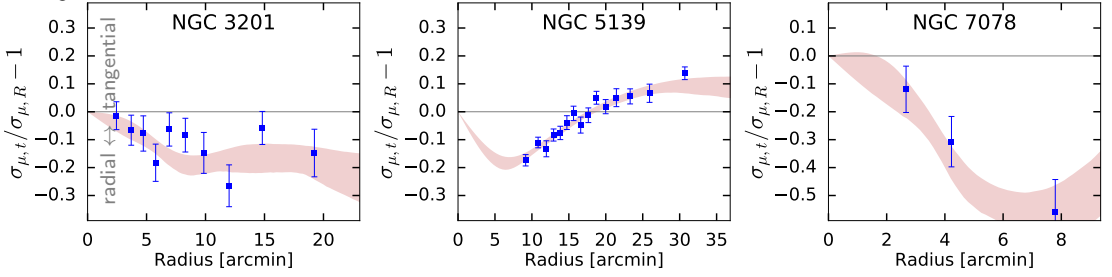
[Bianchini+ 2019]



[Jindal+ 2019]

strong radial anisotropy in the outer region – consequence of a core collapse?

EDR3



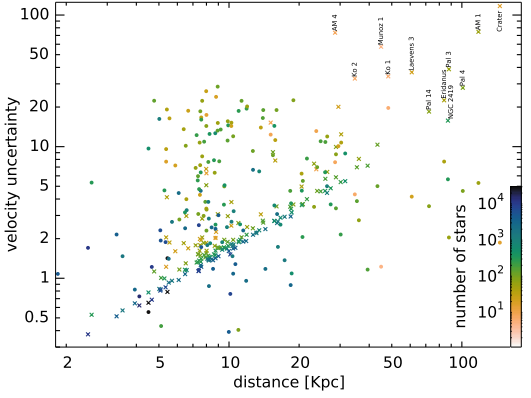
[Vasiliev & Baumgardt 2021]

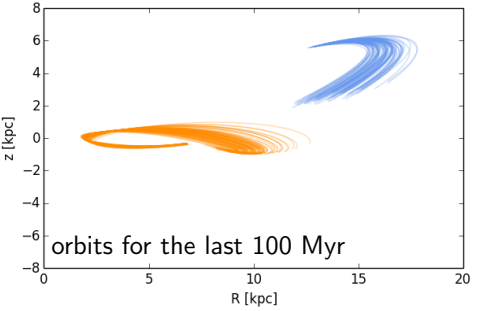
6d kinematics of star clusters

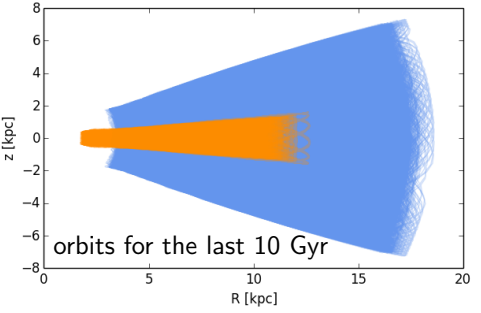
typical PM uncertainty: $\delta\mu \simeq 0.025$ mas/yr
distance uncertainty: $\sim$ a few percent

$$\frac{v}{\mathrm{km/s}} = 4.74 \frac{\mu}{\mathrm{mas/yr}} \frac{D}{\mathrm{kpc}}$$

distance uncertainty usually dominates

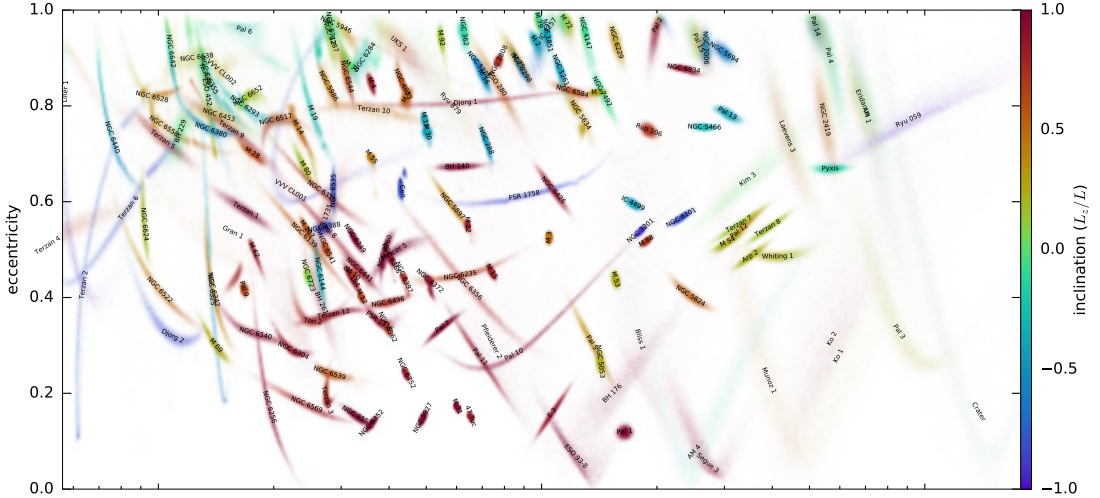






Orbits of globular clusters

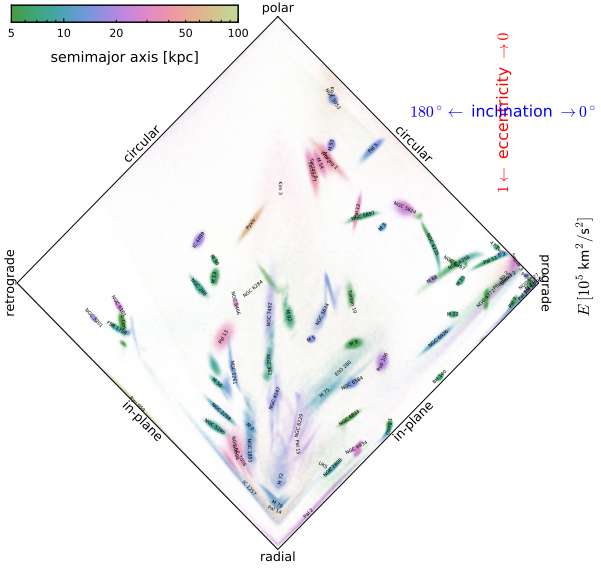
Each cluster is shown by a cloud representing its measurement uncertainties.
Need to assume a Galactic potential for this exercise, but the results are qualitatively similar for any reasonable choice.

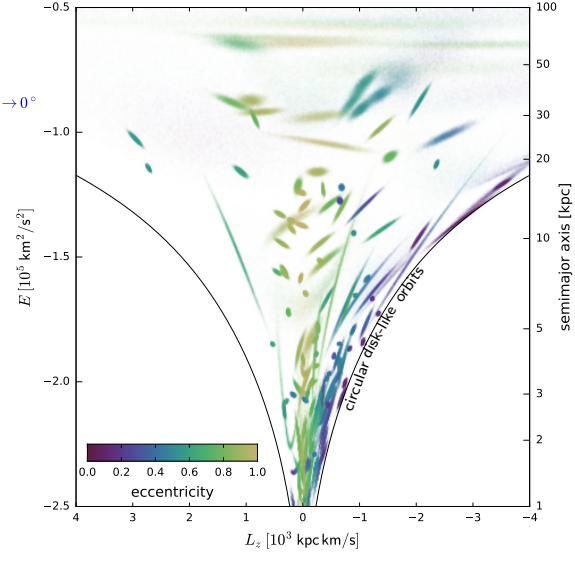


[Vasiliev & Baumgardt 2021]

Clusters in the space of integrals of motion

(energy, angular momentum, actions. . .)





Clusters in the space of integrals of motion

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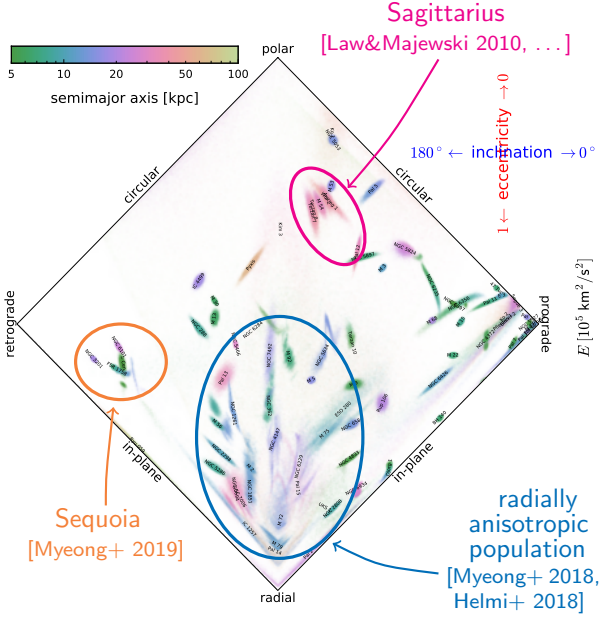
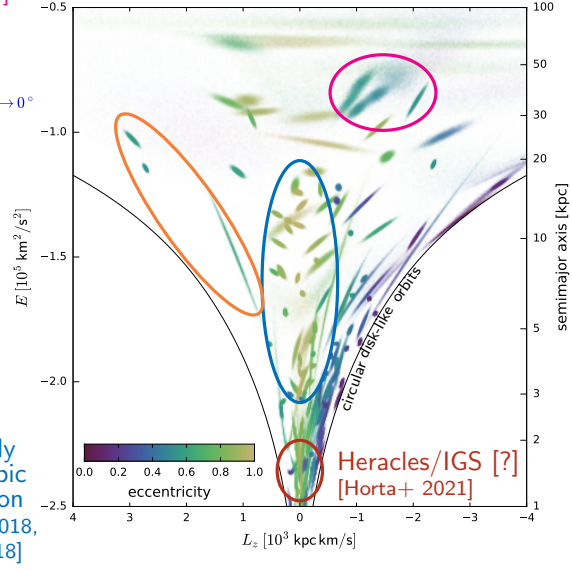
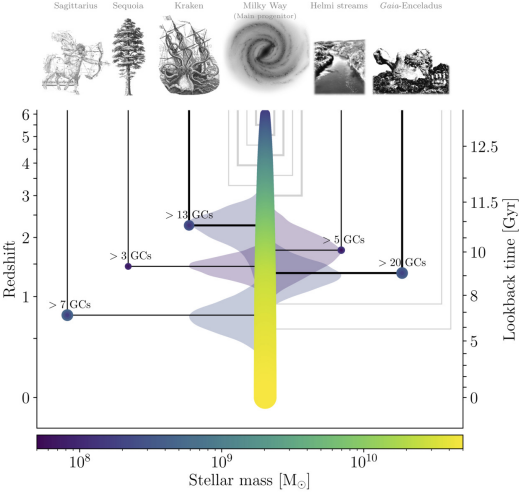


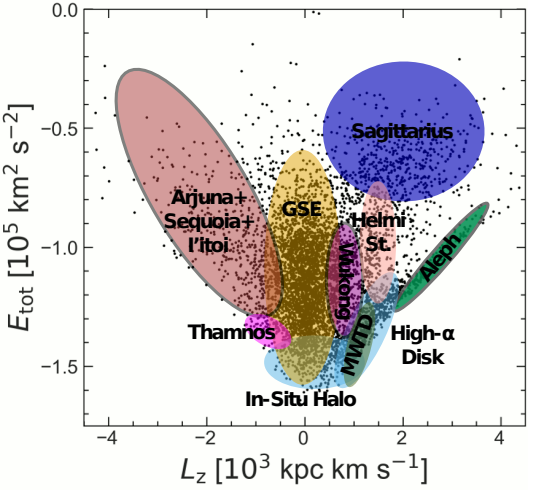


Galactic archeology with clusters, streams and halo stars

Reconstruction of the accretion history and progenitor properties



[Kruijssen+ 2020]



[Naidu+ 2020]

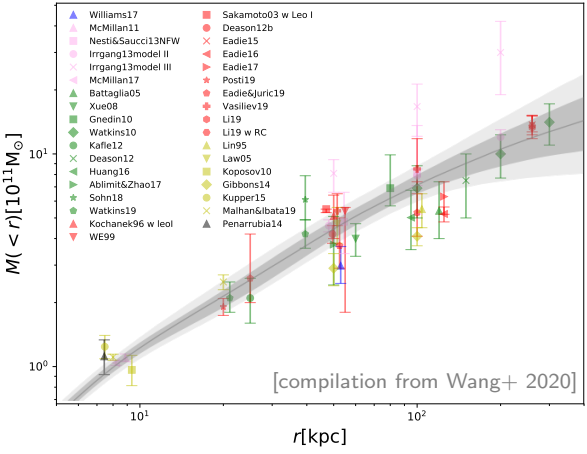
see also Massari+ 2019, Koppelman+ 2019, Forbes 2020, Yuan+ 2020, Malhan+ 2021, ...

Constraints on the Milky Way potential from globular clusters

Method:

simultaneously fitting the potential and the tracer distribution function, maximizing the likelihood of the observed sample of tracers under the assumption of dynamical equilibrium

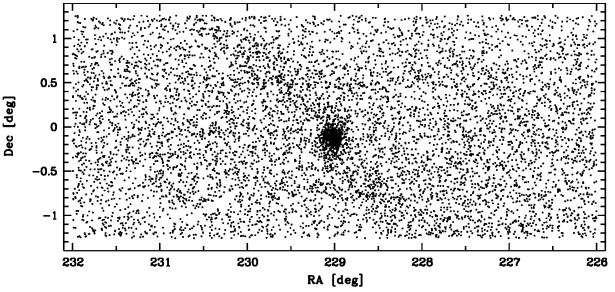
(in 2110.00018, using both globular clusters and satellite galaxies and compensating the perturbation induced by the LMC)



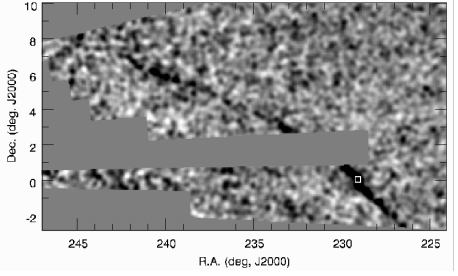
[see also Sohn+ 2018, Watkins+ 2019, Posti&Helmi 2019, Vasiliev 2019, Eadie&Juric 2019]

Tidal streams around globular clusters

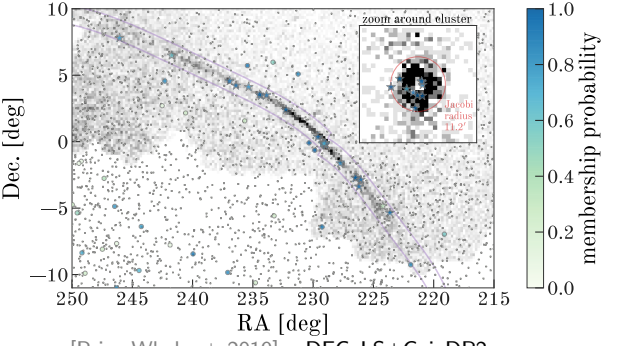
Pal 5: the archetypical stream



[Odenkirchen+ 2001] – SDSS commissioning data



[Grillmair&Dionatos 2006] – SDSS DR4



[Price-Whelan+ 2019] – DECaLS+GaiaDR2

Tidal streams around globular clusters

SDSS era:

- Pal 5 [Odenkirchen+ 2001]
- NGC 5466 [Belokurov+ 2006]

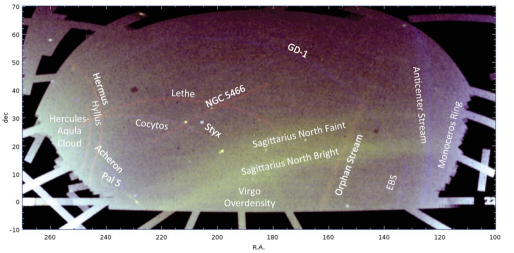
DECam era:

- NGC 288, 1261, 1851, 1904, 2808
  [Carballo-Bello+ 2018; Kuzma+ 2018; Shipp+ 2018]

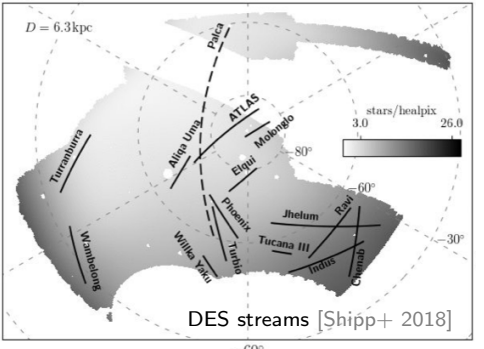
Gaia era:

- ω Cen [Ibata+ 2019]
- NGC 7099 [Sollima 2020]
- NGC 6341 [Thomas+ 2020]
- Pal 13 [Shipp+ 2020]
- and practically anything that was looked at*
  (but see Boldrini & Vitral 2021 for a counterexample)

see Tereza's poster

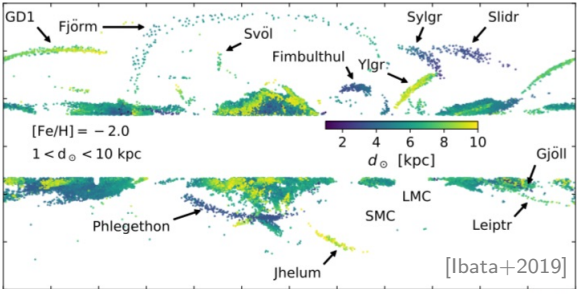


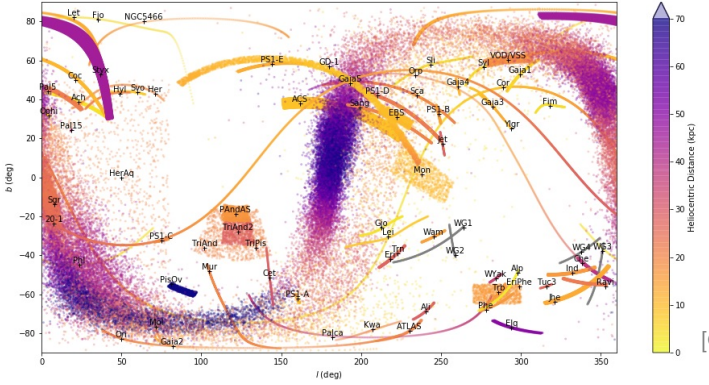
SDSS field of streams [Grillmair & Carlin 2016]



DES streams [Shipp+ 2018]

A census of stellar streams in the Milky Way



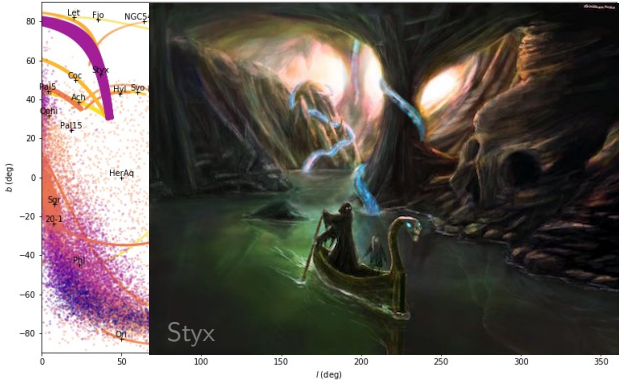


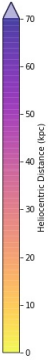
Stream name

Ylgr
Sylgr
Fjörm
Fimbulthul
Phlegethon
Styx
Kwando
Murrumbidgee
Chenab
Indus
Jhelum
Nix
Aliqa Uma
Willka Yaku
Turranburra
Orinoco
Wambelong
GD-1

[C.Mateu, GalStream database]

A census of stellar streams in the Milky Way





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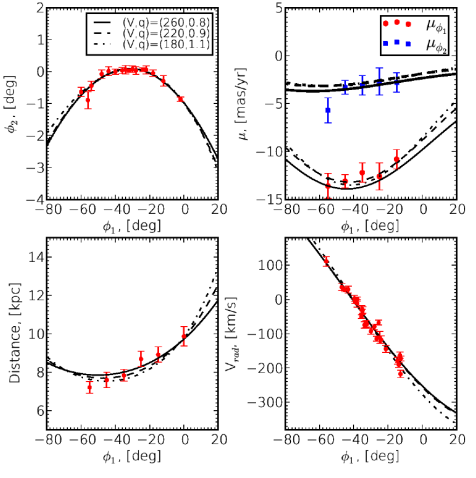
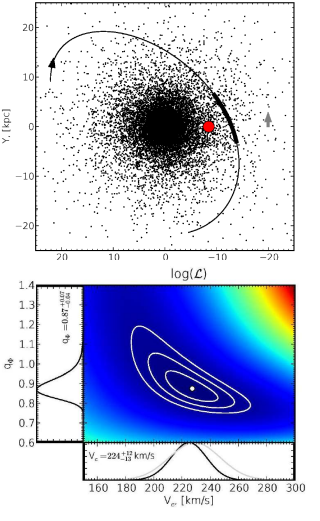
[C.Mateu, GalStream database]

Constraints on the Milky Way potential from stellar streams

Stars in a stream travel on [nearly] identical orbits $\Longrightarrow$
search for a best-fit potential reproducing the stream track

Example: GD-1 stream

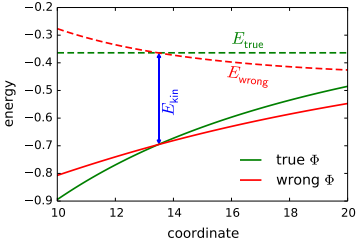


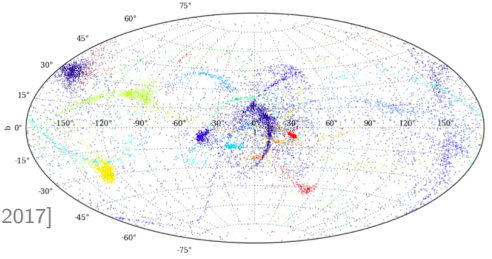


[Koposov+ 2010; see also Bowden+ 2015, Bovy+ 2016, Malhan&Ibata 2019, . . .]

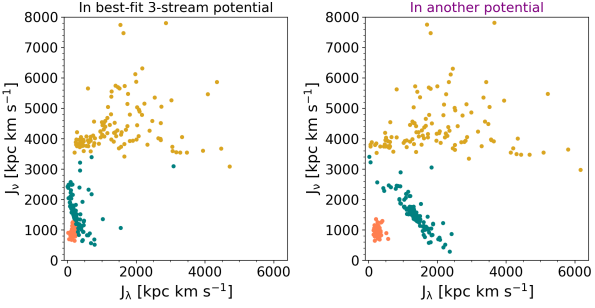
Constraints on the Milky Way potential from stellar streams

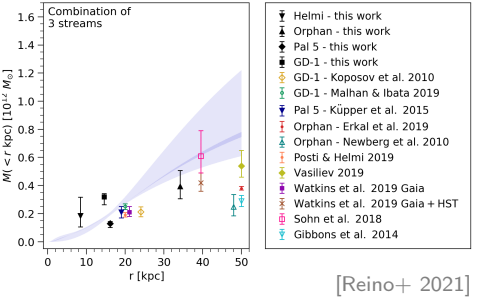
Another approach is to minimize the spread of stream members (or entropy) in the space of integrals of motion (e.g. $E - L$ or actions).





[Sanderson+ 2017]

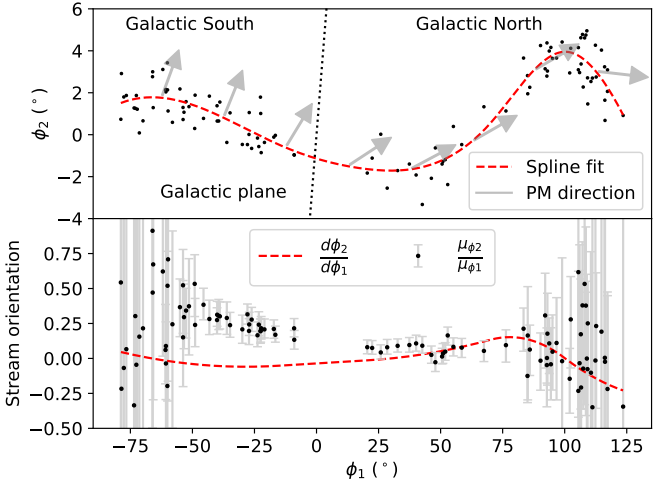


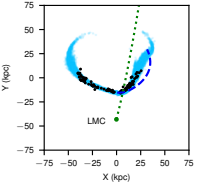


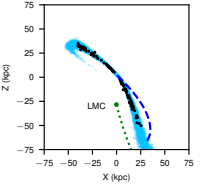
[Reino+ 2021]

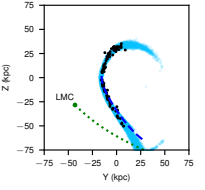
Effect of the LMC on streams

Orphan–Chenab stream: no remnant, spans $> 200^\circ$ on the sky.
Sky-plane velocity (reflex-corrected PM) is misaligned with the stream track; stream can be fitted only when taking LMC into account.







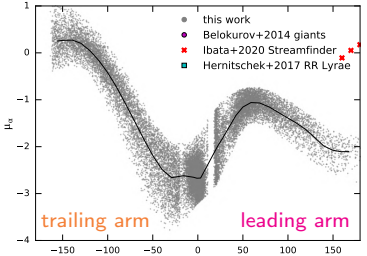


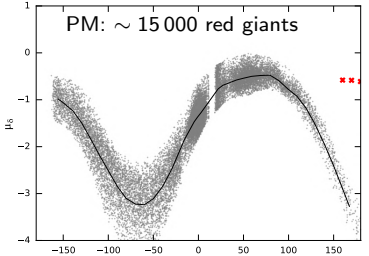
[Erkal+ 2019; see also Shipp+2021 for updated analysis with a few other streams]

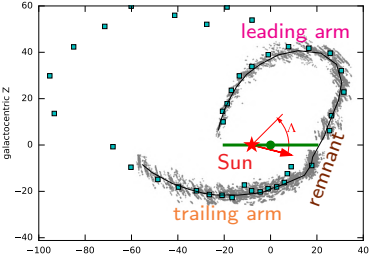
Effect of the LMC on streams

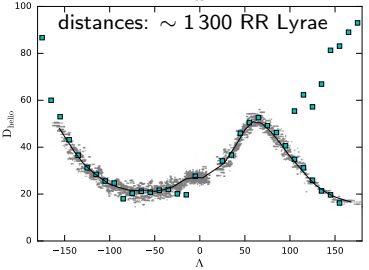
Sagittarius – the king of streams: a few $\times 10^8\, M_\odot$ remnant, $> 360^\circ$ on the sky.

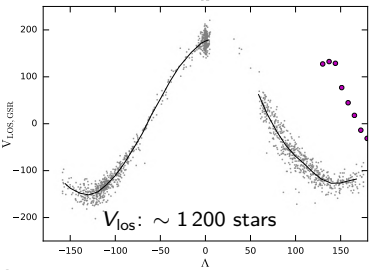
Extensively studied [Majewski+ 2003, Belokurov+ 2006, Law&Majewski 2010, Koposov+ 2012, Gibbons+ 2014, Fardal+ 2019; since Gaia DR2: Antoja+ 2020, Ramos+ 2020, Ibata+ 2020]

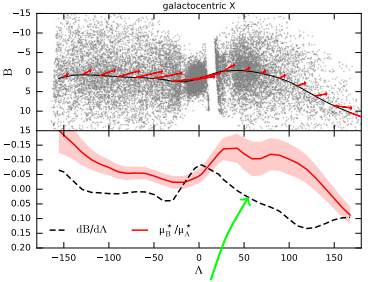












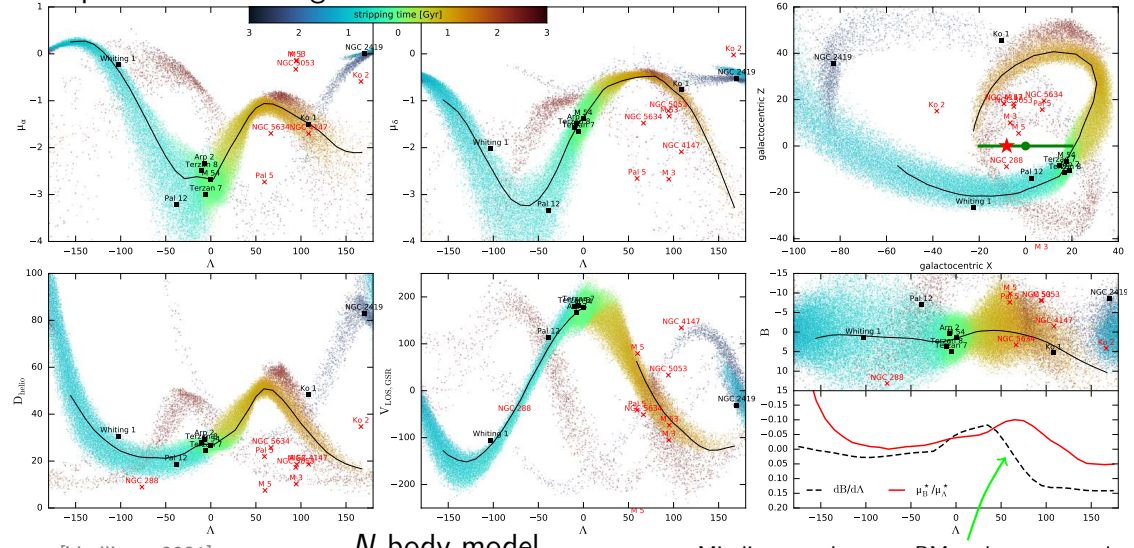
[Vasiliev+ 2021]

observations

Misalignment between PM and stream track

Effect of the LMC on streams

N-body fit of the Sgr stream and remnant in a flexible Milky Way potential and taking into account the effect of the LMC flyby to reproduce the leading arm shape and PM misalignment

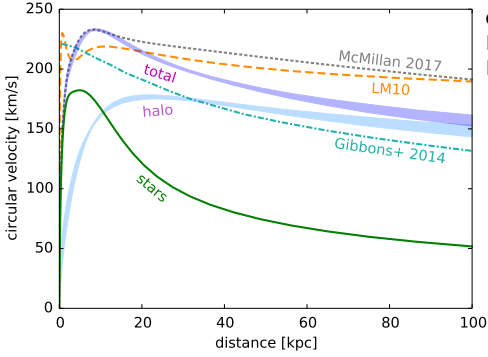


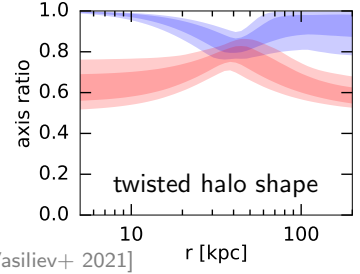
[Vasiliev+ 2021]

N-body model

Misalignment between PM and stream track

Constraints on the Milky Way potential from Sgr stream





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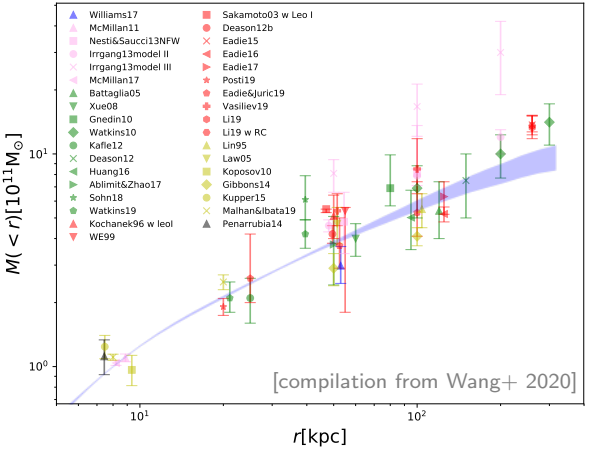
explored in many papers, e.g., Helmi 2004, Johnston+ 2005, Law & Majewski 2010, Deg & Widrow 2013, Gibbons+ 2014, Dierikx & Loeb 2017, Thomas+ 2017, Fardal+ 2019 ...



Mass within 100 kpc is $\sim$ 20% lower than inferred from kinematics of globular clusters and satellites

Summary: Gaia – the ongoing revolution

+ PM precision is already good enough to study internal kinematics in clusters up to ~ 10 kpc, and even a few satellite galaxies (LMC, SMC, Sgr); will improve 2.5$\times$ in DR4 and $\gtrsim 6\times$ by the end of 10-year mission!
− parallax precision and calibration is not yet precise enough beyond a few kpc;
+ high quality PM selection for spectroscopic follow-up of stream members and outskirts of clusters;
− central regions of clusters are too crowded (and likely will stay so);
¡ *Gaia* is great and will keep uncovering new phenomena **!**

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