Gaia science tour

Anthony Brown

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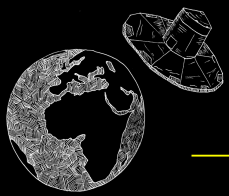
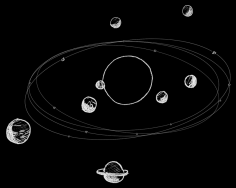
ESA/Gaia/DPAC

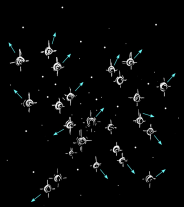
Credits: ESA



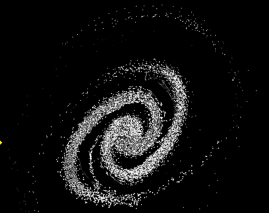
Earth & Gaia



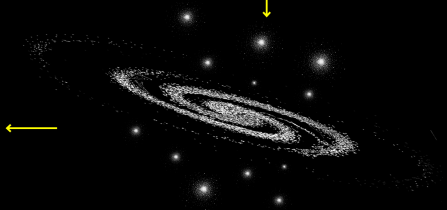
Solar System objects



Stars near the Sun

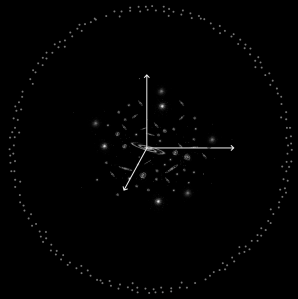


Milky Way: disc and bulge



Milky Way: halo and globular clusters

Nearby galaxies



Celestial reference frame: distant quasars

Impact of Gaia DR1 and DR2

Gaia DR1

- from 10^5 to 2 million high precision parallaxes and proper motions
- accurate all-sky positional reference frame to $G = 20.7$
- all-sky homogeneous white light photometry to $G = 20.7$

Gaia DR2

- 1.3 billion high precision, all-sky, homogeneous, parallaxes and proper motions to $G = 20.7$
  - precise geometric distances over several kpc around the Sun
- high precision, homogeneous, all-sky photometric survey to $G = 20.7$, three broad bands
- First realization of optical reference frame from extragalactic sources
- Large, all-sky, homogeneous, and precise radial velocity survey

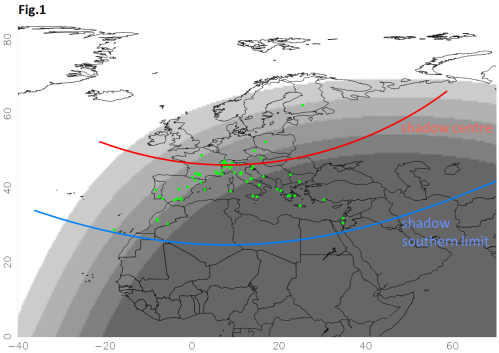
We are getting used to

- Looking up a parallax/ proper motion/ colour for any source in the sky
- Much more opportunity for stellar occultation campaigns based on very precise predictions
- Calibrating existing and future surveys onto Gaia astrometry/photometry
  - including surveys from 100 years ago

Following literature survey is a biased and very incomplete sample from the around 2000 papers using Gaia data since September 2016.

Gaia DR0 and Pluto

Pre-Gaia prediction



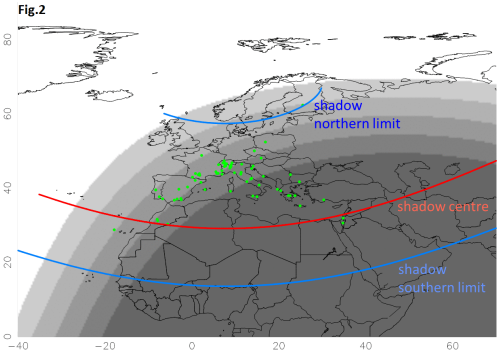
Credits: ESA/Gaia/DPAC/B. Sicardy (LESIA, Observatoire de Paris), D. Berard (LESIA, Observatoire de Paris), E. Meza (LESIA, Observatoire de Paris), R. Leiva (LESIA, Observatoire de Paris), A. Carbognani (Osservatorio Astronomico Valle d'Aosta - OAVdA, Italy), P. Tanga (Observatoire de la Côte d'Azur, Nice)

Occultation of UCAC 345-180315 by Pluto on July 19 2016

- Gaia position of UCAC 345-180315 released in summer 2016 (Gaia DR0)
- Occultation prediction improved
  - also using improved Pluto ephemeris from New Horizons flyby
- Successful occultation campaign thanks to Gaia position

Gaia DR0 and Pluto

Post-Gaia prediction



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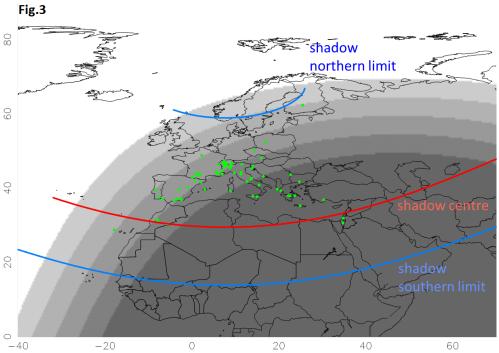
Gaia DR0 and Pluto

Actual track



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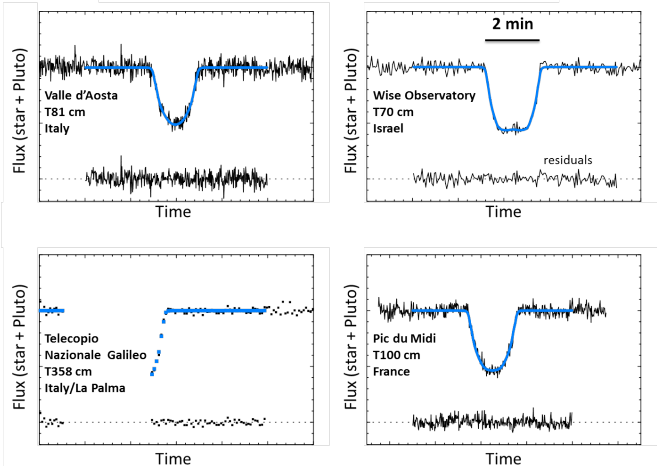
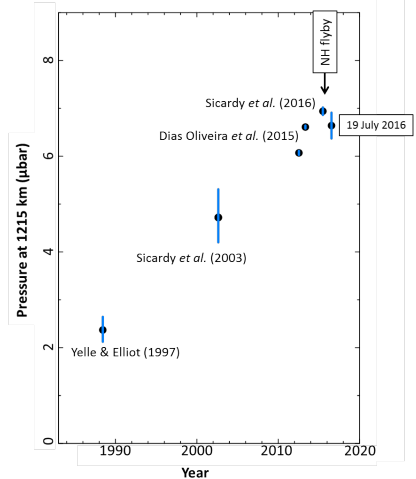
Gaia DR0 and Pluto

See http://www.cosmos.esa.int/web/gaia/iow_20160914





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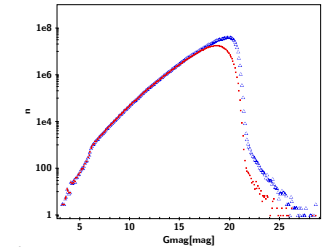
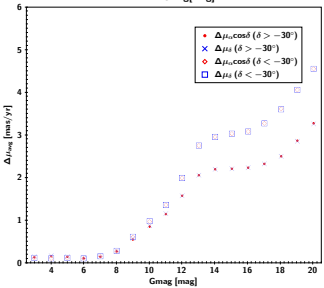
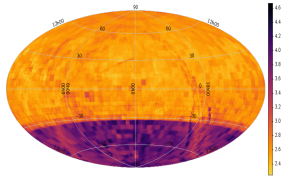
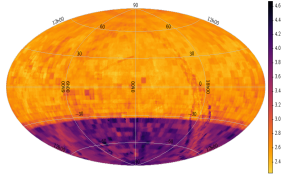
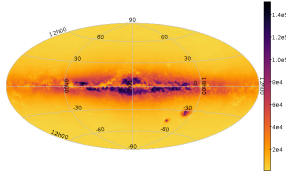
Hot Stuff for One Year











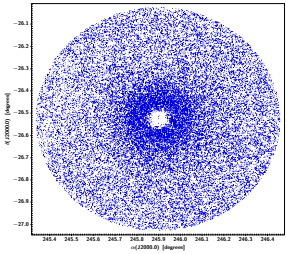
- 583 million proper motions prior to Gaia DR2
- Gaia DR1 – PPMXL combination

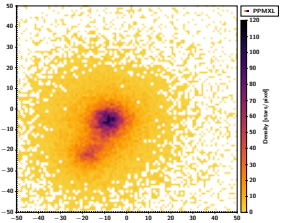
Altmann et al., 2017, A&A 600, L4 (arXiv:1701.02629)

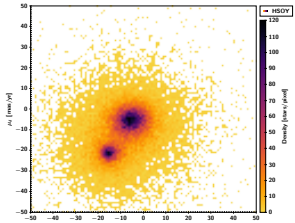
Hot Stuff for One Year

PPMXL

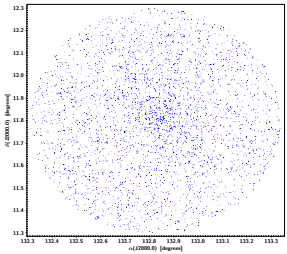
HSOY

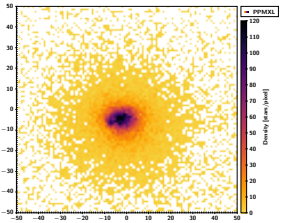


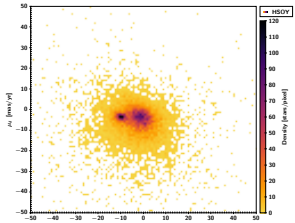




M4



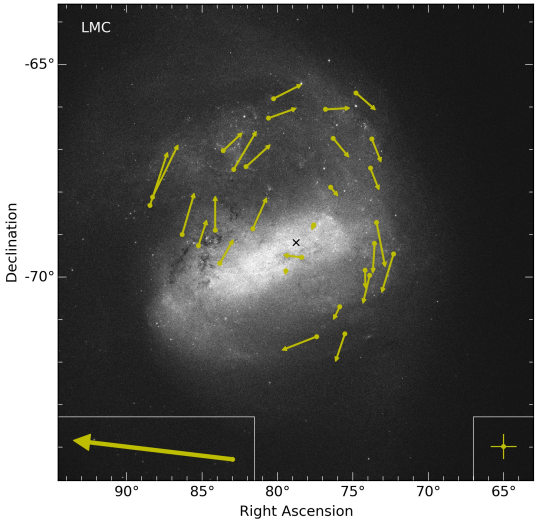




M67

Altmann et al., 2017, A&A 600, L4 (arXiv:1701.02629)

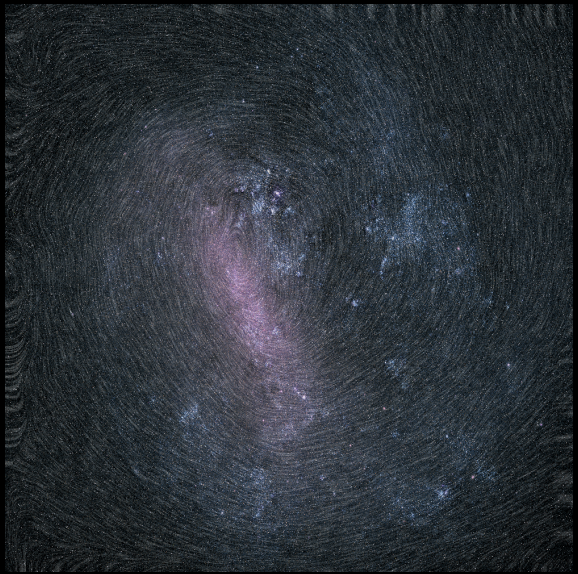
Large Magellanic Cloud kinematics



- Gaia DR1 proper motions of LMC and SMC stars consistent with HST result
- Residual kinematics in LMC show clear rotation pattern
  - also seen in HST studies
  - rotation curve from proper motions consistent with result from line-of-sight motions
  - Kinematic distance modulus of 18.54 ± 0.39

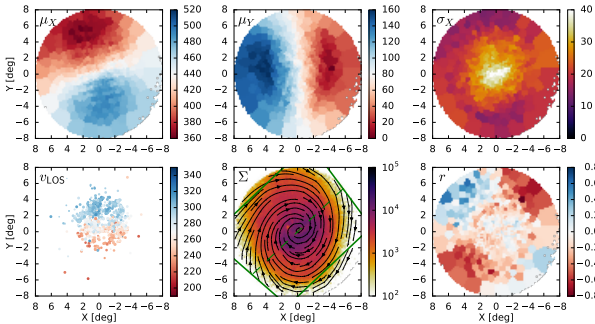
van der Marel & Sahlmann, 2016, ApJ 832, L32 (arXiv:1609.04395)

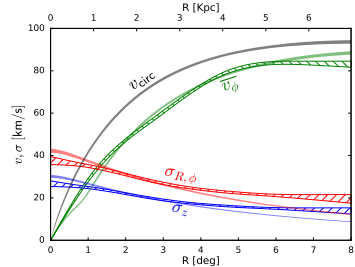
Gaia DR2 rotation field of LMC



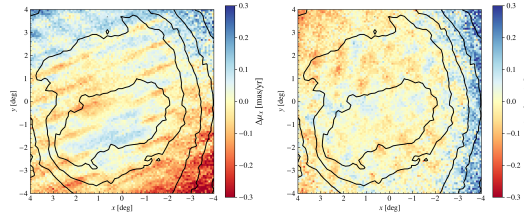
ESA/Gaia/DPAC

Gaia DR2 kinematics of LMC





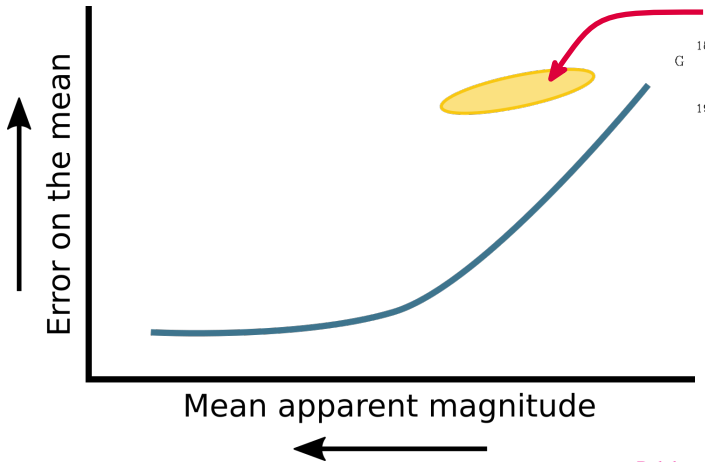
Vasiliev, 2018, MNRAS 481, L100 (arXiv:1805.08157)

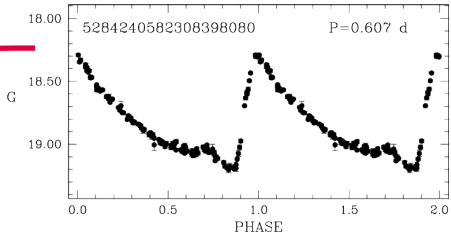


- Gaia DR2 contains proper motions for millions of LMC stars
- Rotation and dispersion profile
- Residual proper motion fields hints at dynamical effects of bar

Gaia Collaboration, Helmi et al., A&A, 2018, A&A 616, A12 (arXiv:1804.09381)

Magellanic clouds structure

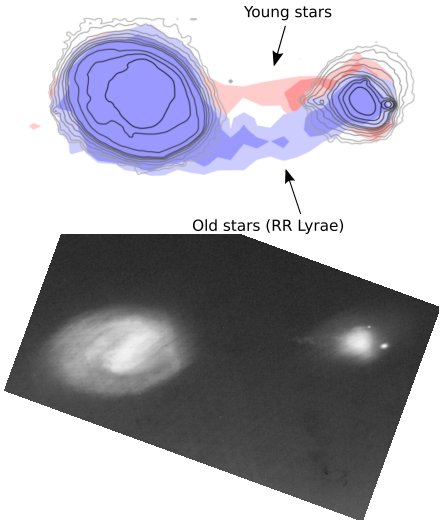




- Examine photometric error as function of magnitude
- Sources with apparently too large errors could be variable
- Select RR Lyrae all-sky without knowing light curves

Belokurov et al., 2017, MNRAS 466, 4711 (arXiv:1611.04614)

Magellanic clouds structure



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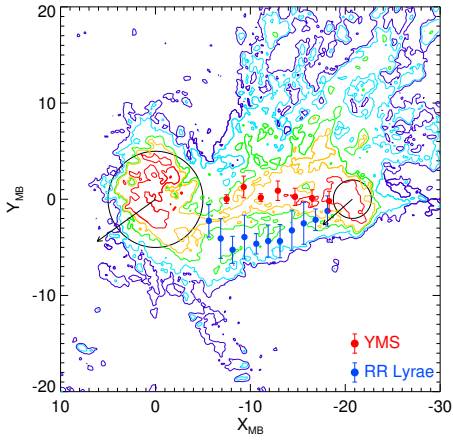
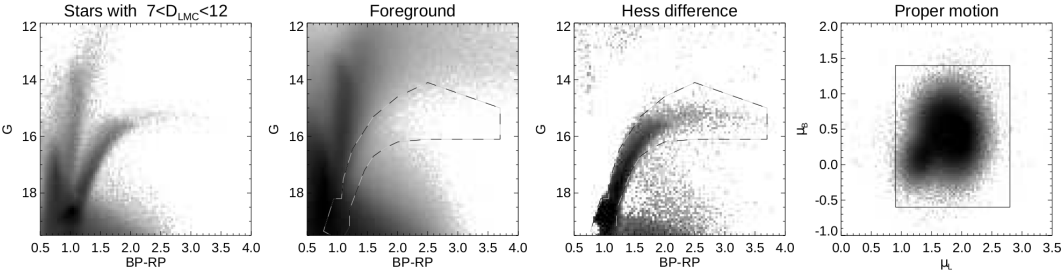


Jacyszyn-Dobrzeniecka et al. (arXiv:1904.07888, 1904.08220): no evidence for connecting bridge in their analysis of RRLs and Cepheids.

Clouds in arms

Belokurov & Erkal, 2019, MNRAS 482, L9 (arXiv:1808.00462)



- Gaia DR2 astrometry plus photometry allows for very clean selection of LMC/SMC red giants
  - removal of Milky Way foreground using parallaxes
- Red giant map reveals spiral arm-like structures around LMC
- Can be modelled as result of tidal effects of MW+SMC on the LMC
  - constraints on the properties and dynamical history of LMC/SMC

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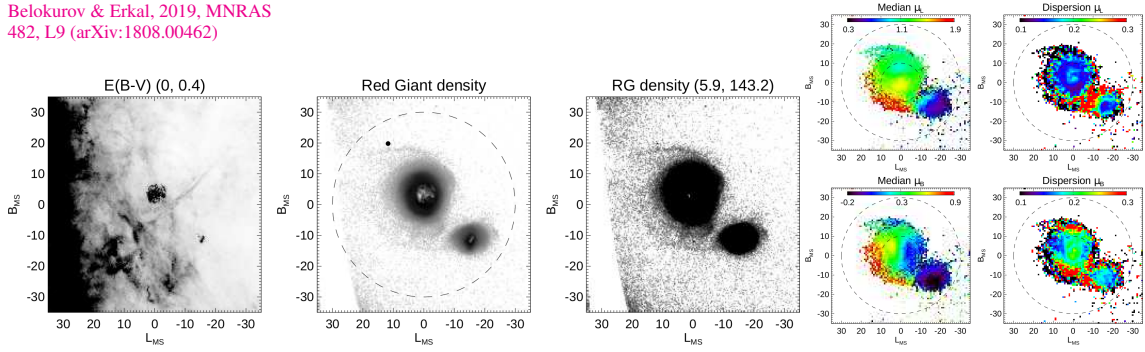

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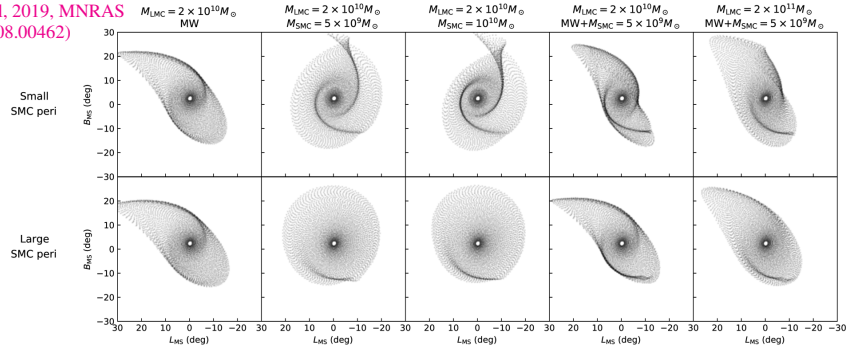

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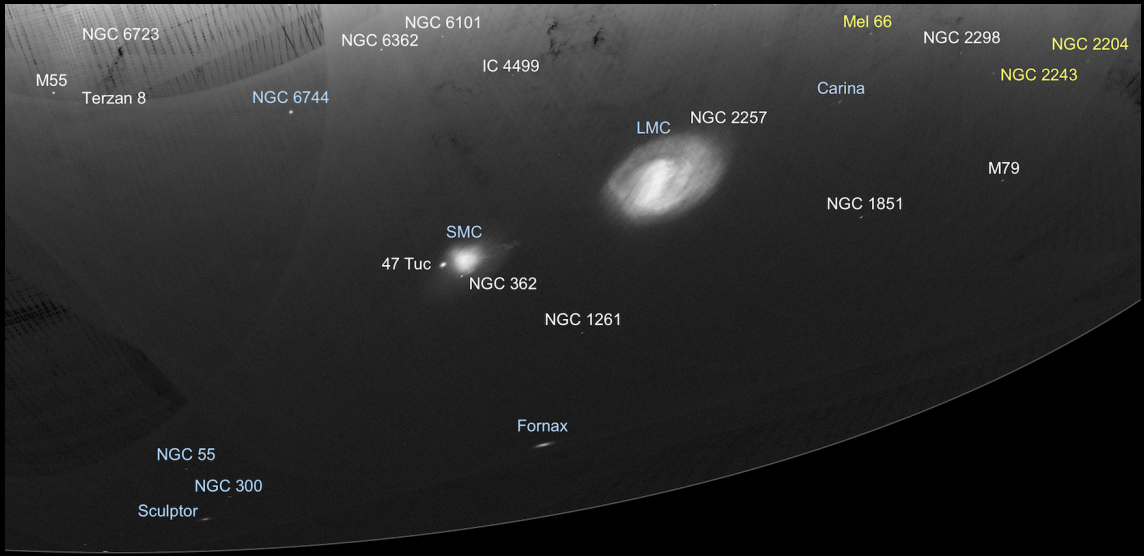
Stellar motions in the Sculptor dwarf: Gaia DR1 + HST



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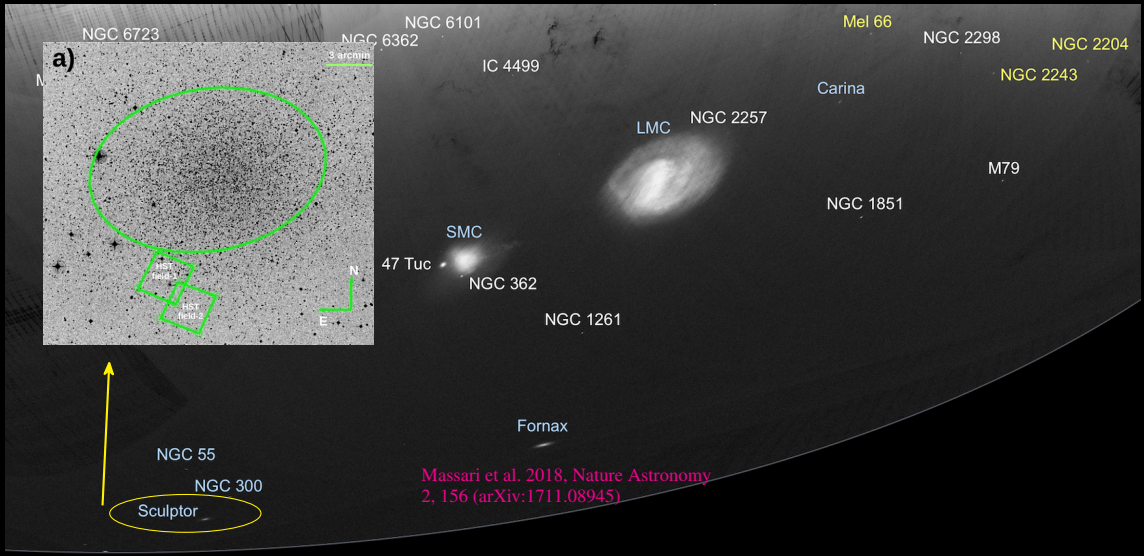

Massari et al. 2018, Nature Astronomy 2, 156 (arXiv:1711.08945)

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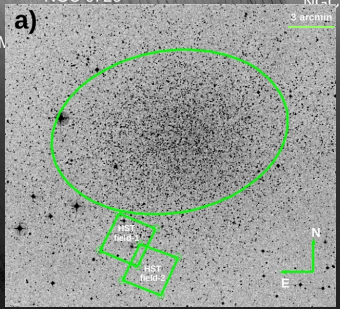

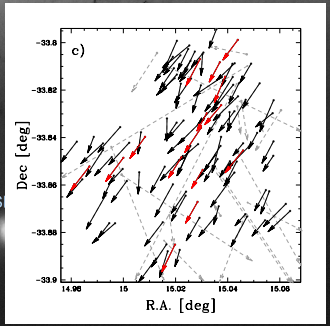

NGC 6723
NGC 6362
NGC 6101
Mel 66
NGC 2298
NGC 2204
NGC 2243
Carina
M79
NGC 1851
47 Tuc
Fornax
NGC 55
NGC 300
Sculptor

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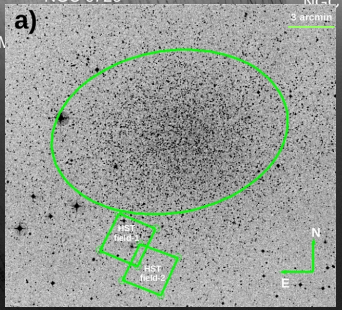

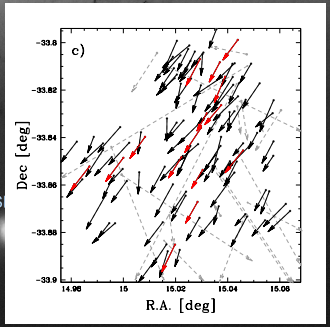

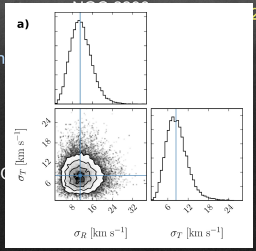

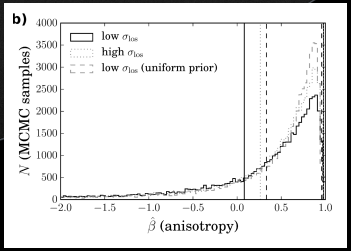

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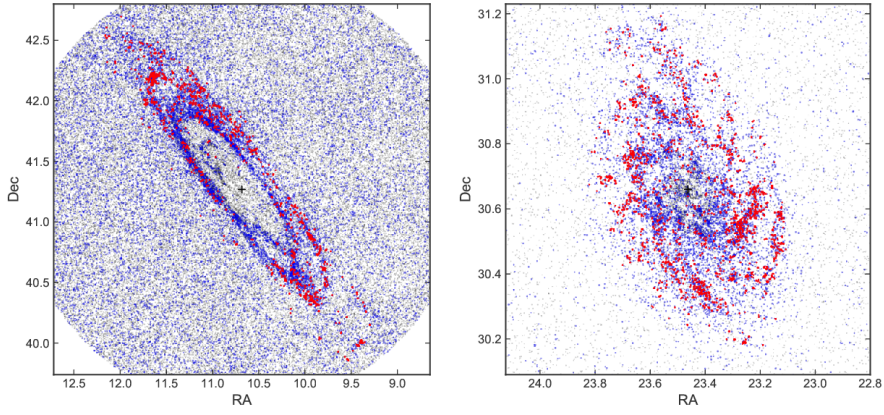
Rotation of Andromeda and Triangulum galaxies



van der Marel et al., 2019, ApJ 872 (arXiv:1805.04079)

- Averaging over carefully selected sample of stars allows measurement of rotation of M31 and M33
  - More precise measurement possible after nominal mission
  - Extension to 10 year Gaia mission would result in factor 12 gain in precision
- New insights into past and future of Milky Way - Andromeda system

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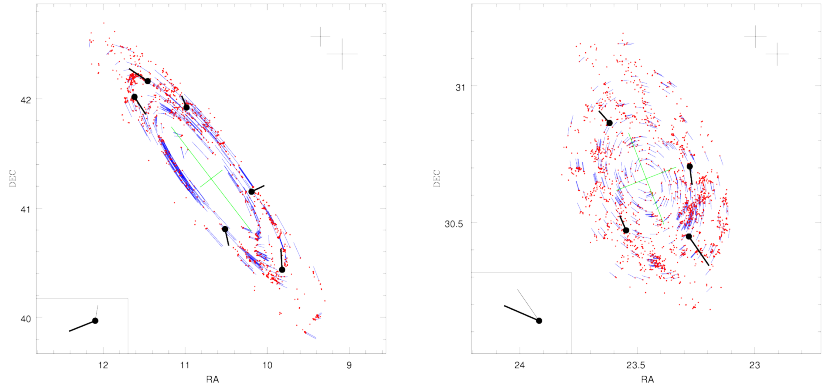

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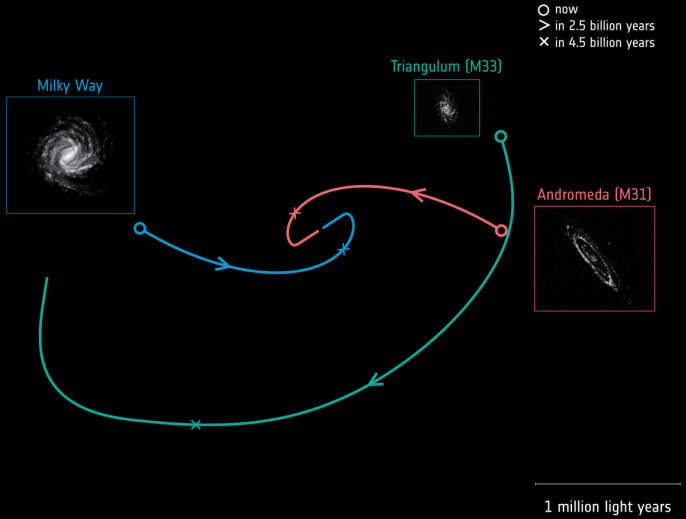
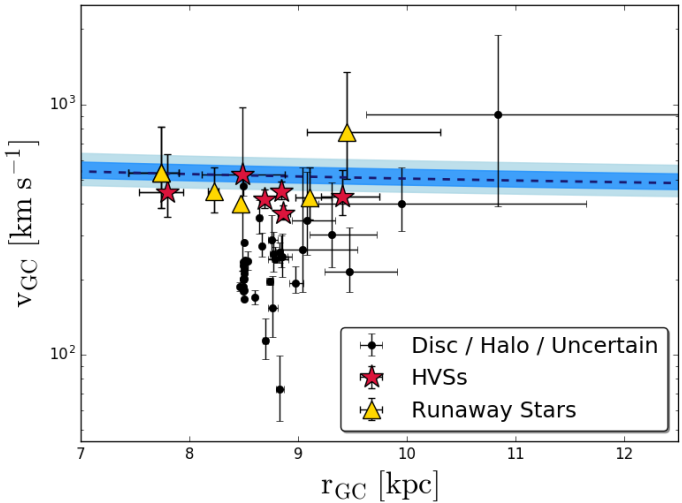


Credits: E. Patel, G. Besla (University of Arizona), R. van der Marel (STScI)

Hyper-velocity stars in Gaia DR1

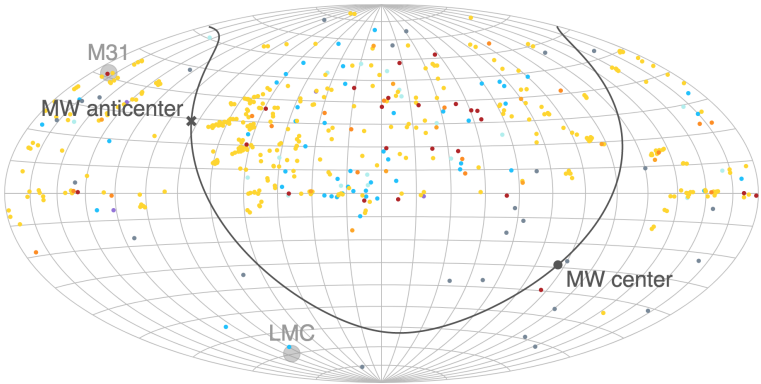


- Search TGAS for HVS with machine learning algorithm
- 14 stars with $V_{GC} > 400$ km s^{-1}
- 6 HVS candidates (orbits cross GC), one consistent with being unbound
- 5 runaway candidates with $400 < V_{GC} < 700$ km s^{-1}
- Great promise for future Gaia DRs
  - probe mass function and binary population at Galactic centre
  - shape and orientation Milky Way mass distribution

Marchetti et al., 2017, MNRAS 470, 1388 (arXiv:1704.07990)

Hypervelocity stars revisited with Gaia DR2

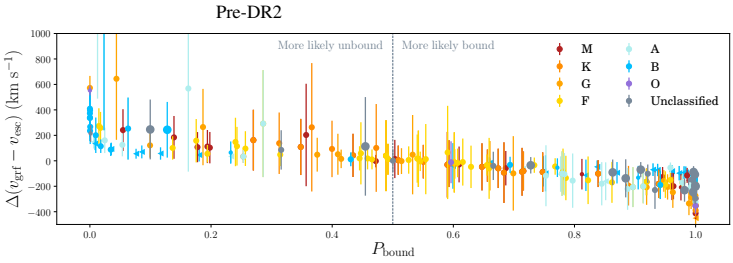
Boubert et al., 2018, MNRAS 279, 2789 (arXiv:1804.10179)

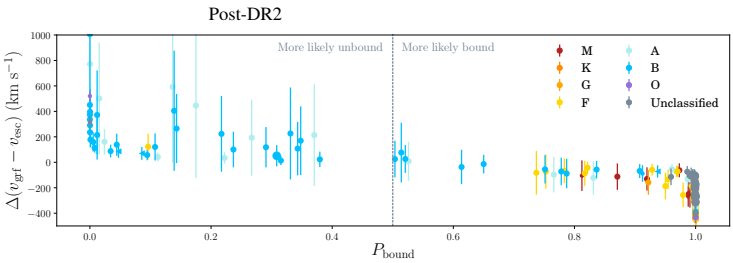


Candidate unbound stars
pre-Gaia DR2

Hypervelocity stars revisited with Gaia DR2

Boubert et al., 2018, MNRAS 279, 2789 (arXiv:1804.10179)



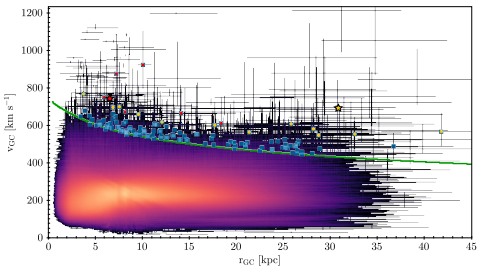


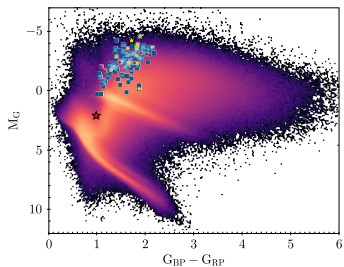
- Gaia DR2 cleans up the sample of unbound candidates
- Most late-type fast stars appear bound to Milky Way

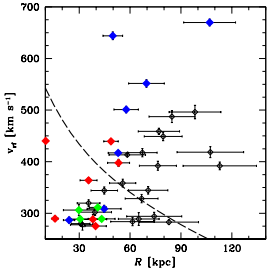
Hypervelocity stars revisited with Gaia DR2

Marchetti et al., 2018, MNRAS (arXiv:1804.10607)

Brown et al., 2018, ApJ 866 (arXiv:1805.04184)







- Gaia DR2 brings into focus the population of extreme-velocity stars in/around the Milky Way
  - ejected from galactic centre, disk (dynamical/binary star mechanisms)
  - accreted from infalling dwarf galaxies (e.g., LMC)
  - tails of stellar velocity distributions
- Probes of galactic centre environment, massive binary population in disk, accretion history, Milky Way mass and mass distribution

Hypervelocity stars revisited with Gaia DR2

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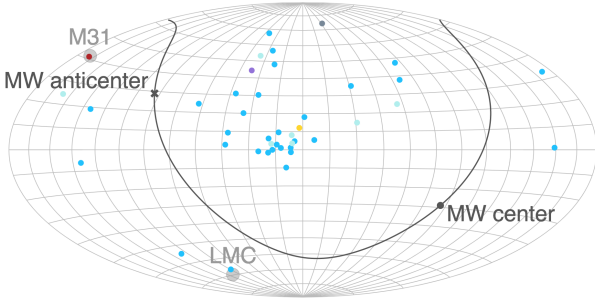
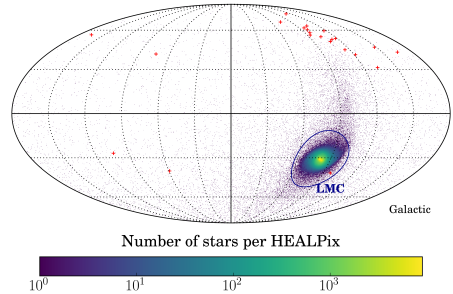


Simulated runaways from LMC
Boubert et al., 2017, MNRAS 469, 2151 (arXiv:1704.01373)



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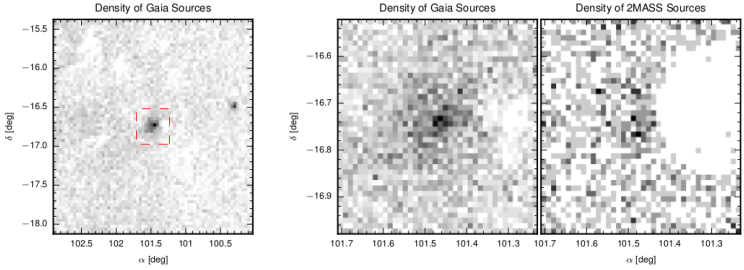
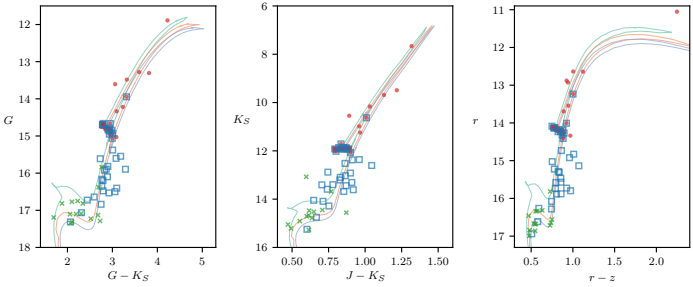
Gaia 1

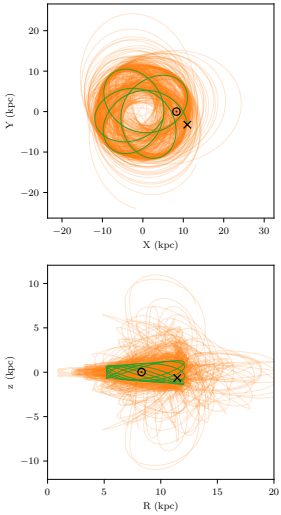


- Cluster hiding behind Sirius
- Power of all-sky, deep, high resolution, star-map

Koposov et al., 2017, MNRAS 470, 2702 (arXiv:1702.01122)

Gaia 1, Siriusly

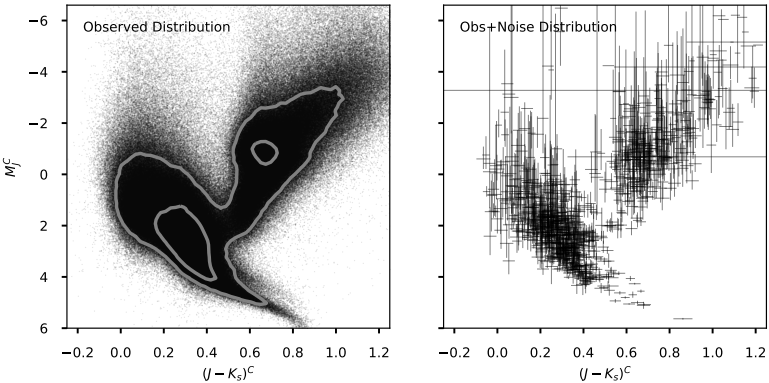




- ~ 3 Gyr old stellar cluster, $[\mathrm{Fe/H}] = -0.13 \pm 0.13$, $v_{\mathrm{rad}} = 58.30 \pm 0.22$ km s^{-1}
- Orbit: $e = 0.3 \pm 0.2$, $z_{\mathrm{max}} = 1.7^{+2.1}_{-0.9}$ kpc
- Koch et al. (arXiv:1709.04022): $[\mathrm{Fe/H}] = -0.62 \pm 0.1$ age ≈ 6 Gyr; thick disk member?
- Carraro (arXiv:1801.03997): cluster is in warped thin disk

Simpson et al., 2017, MNRAS 471, 4087 (arXiv:1703.03823)

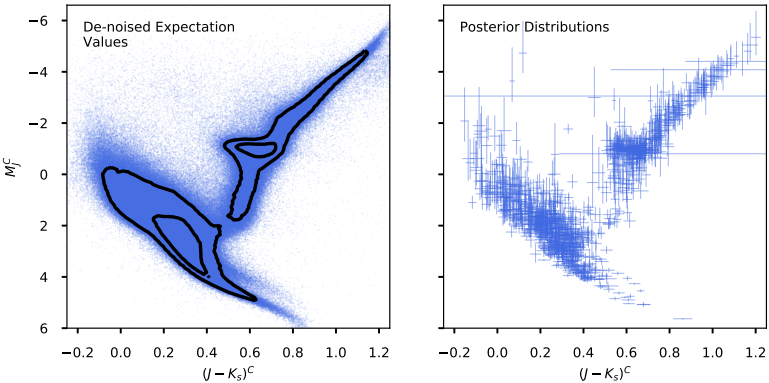
Data-driven models of stars



Anderson et al., 2018, AJ 156 (arXiv:1706.05055)

- Empirical Bayes analysis: use data itself to construct prior on CMD
- Posterior combines apparent magnitude, colour, parallax, dust map
  - improved precision on parallaxes
  - 'de-noised' CMD
- Illustrates optimal use of parallax information
- On the way to accurate empirical description of CMD

Data-driven models of stars



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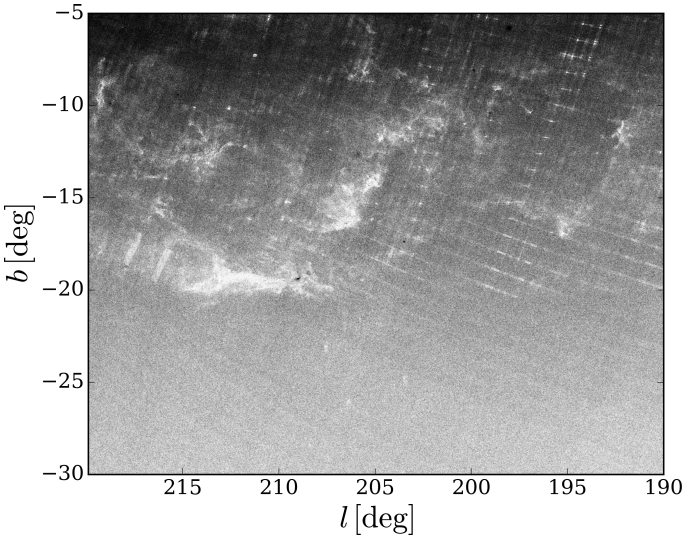
The Orion region in Gaia DR1



Zari et al., 2017, A&A 608, A148 (arXiv:1711.03815)

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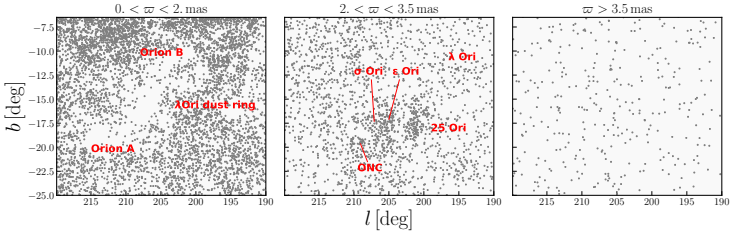

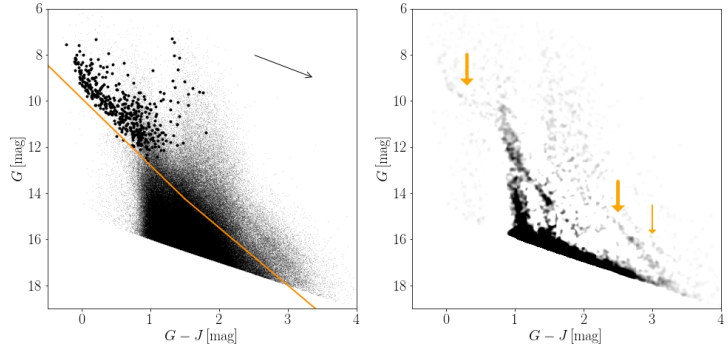

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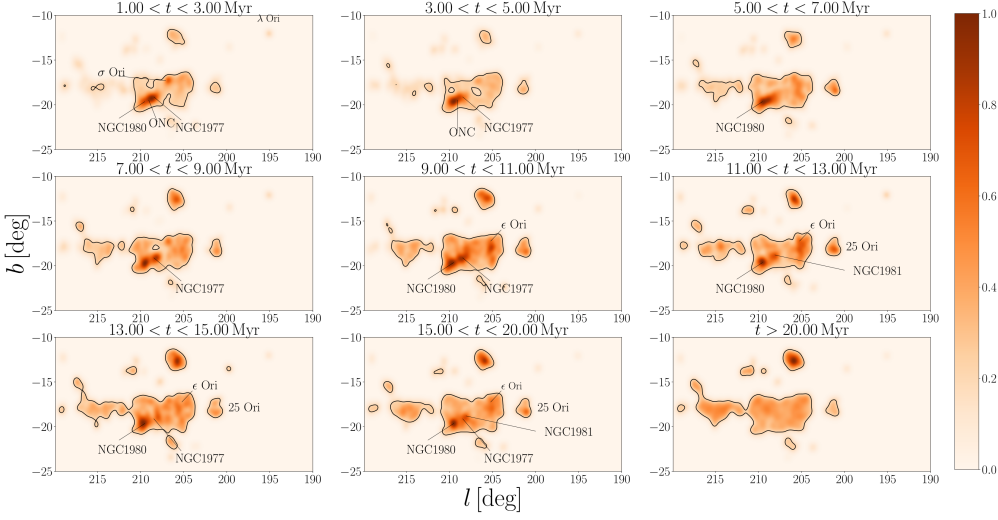

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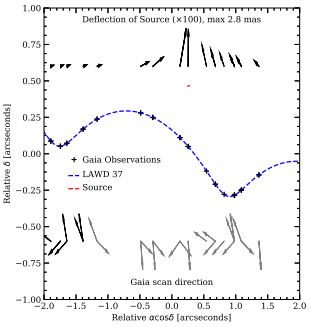
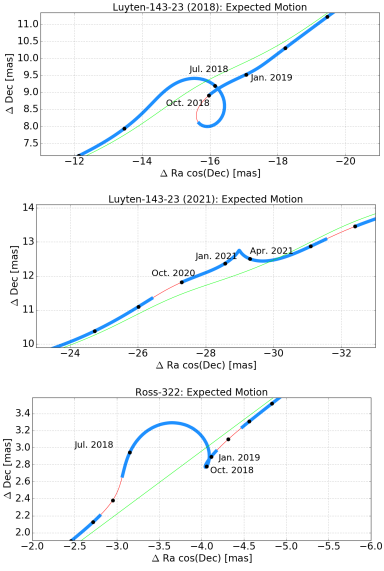
Astrometric micro-lensing predictions



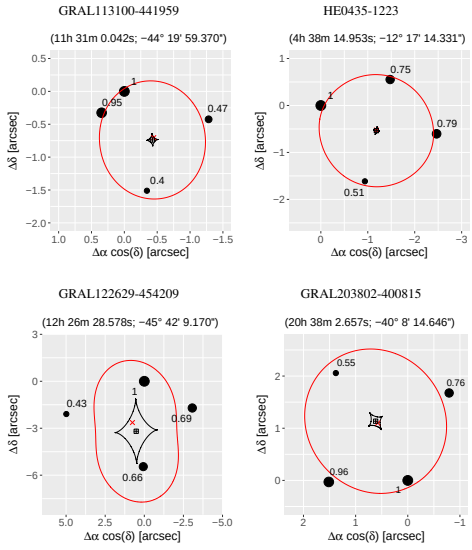
McGill et al., 2018, MNRAS 478, L29 (arXiv:1804.07049)

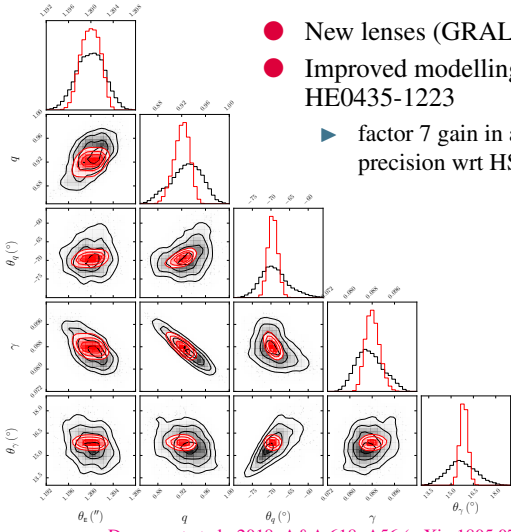


- Predict when nearby high-proper motion star (lens) passes in front of background star (source)
- Opportunity for mass determinations of the lens
  - From Gaia, HST, GRAVITY, Keck, LBT, etc

Klüter et al., 2018, A&A 615, L11 (arXiv:1805.08023)

Gaia DR2 as gravitational lens hunting ground





- New lenses (GRAL)
- Improved modelling HE0435-1223
  - factor 7 gain in astrometric precision wrt HST

Krone-Martins et al., 2018, A&A 616, L11 (arXiv:1804.11051)

Ducourant et al., 2018, A&A 618, A56 (arXiv:1805.07359)

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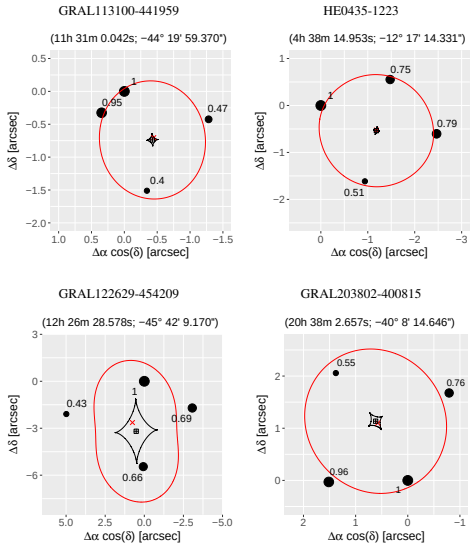

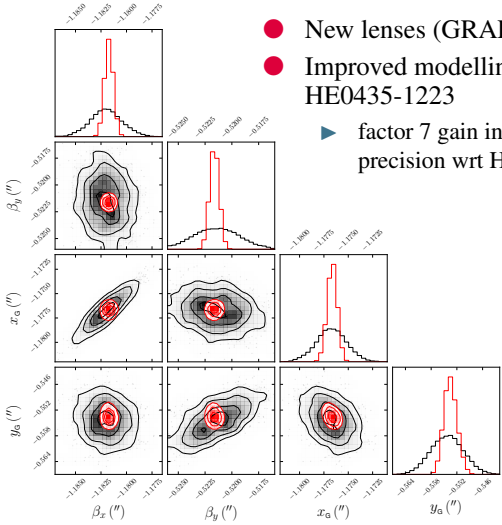

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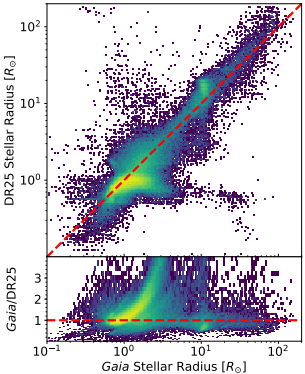
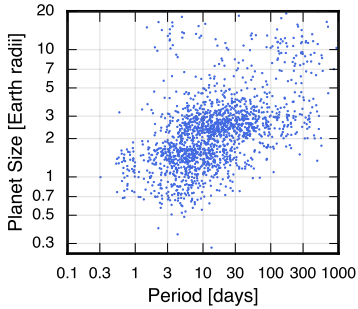
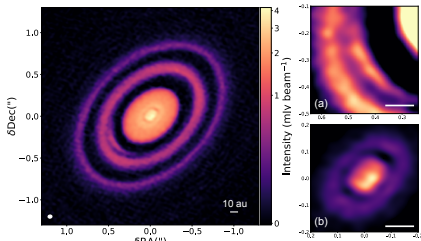
Stellar and exoplanet radii, protoplanetary disk sizes







- Strong improvement in Kepler exoplanet host star radii thanks to Gaia DR2 parallaxes (left, Berger et al., 2018, ApJ 866, arXiv:1805.00231)
- Radius gap in super-earth regime into sharper focus, two overlapping radius distributions (middle, Fulton & Petigura, 2018, AJ 156, arXiv:1805.01453)
- Example protoplanetary disk with star distance from Gaia DR2 (right, Isella et al., arXiv:1812.04047)