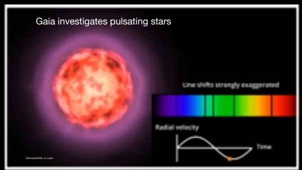
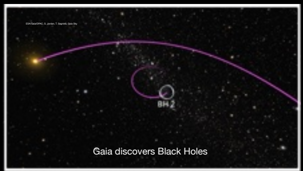
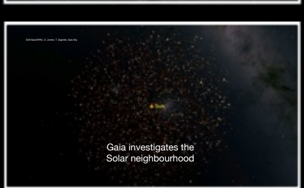
Stefan Jordan, Zentrum für Astronomie, Universität Heidelberg

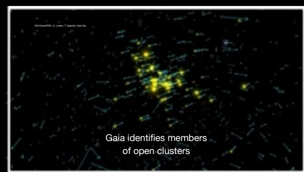
Gaia - The Mission, Instrument, Results and Impact

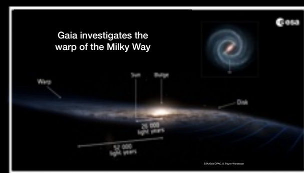
ISAPP School "Neutrinos and Dark Matter", 17.09.2024

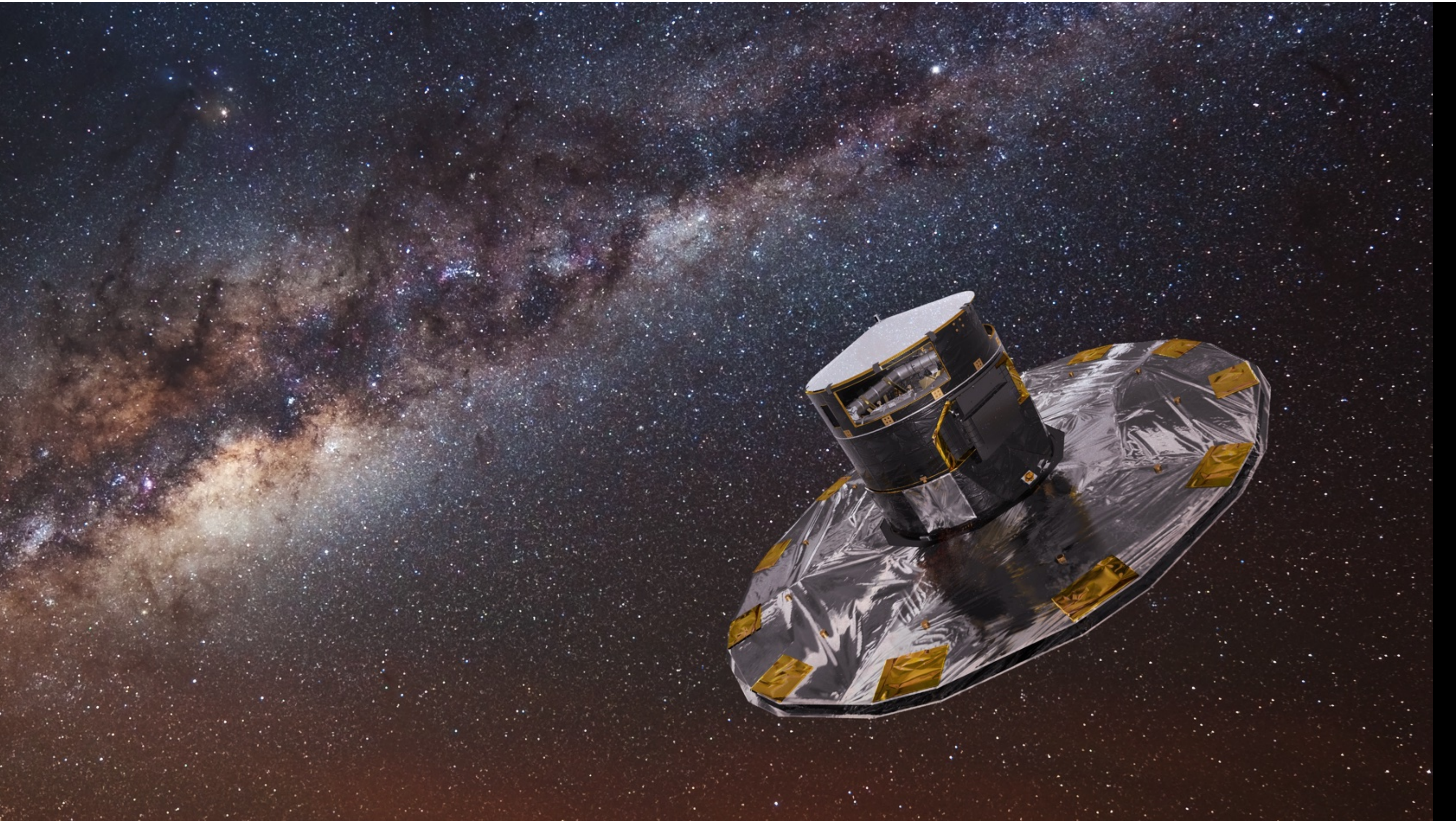












Stefan Jordan, Zentrum für Astronomie, Universität Heidelberg

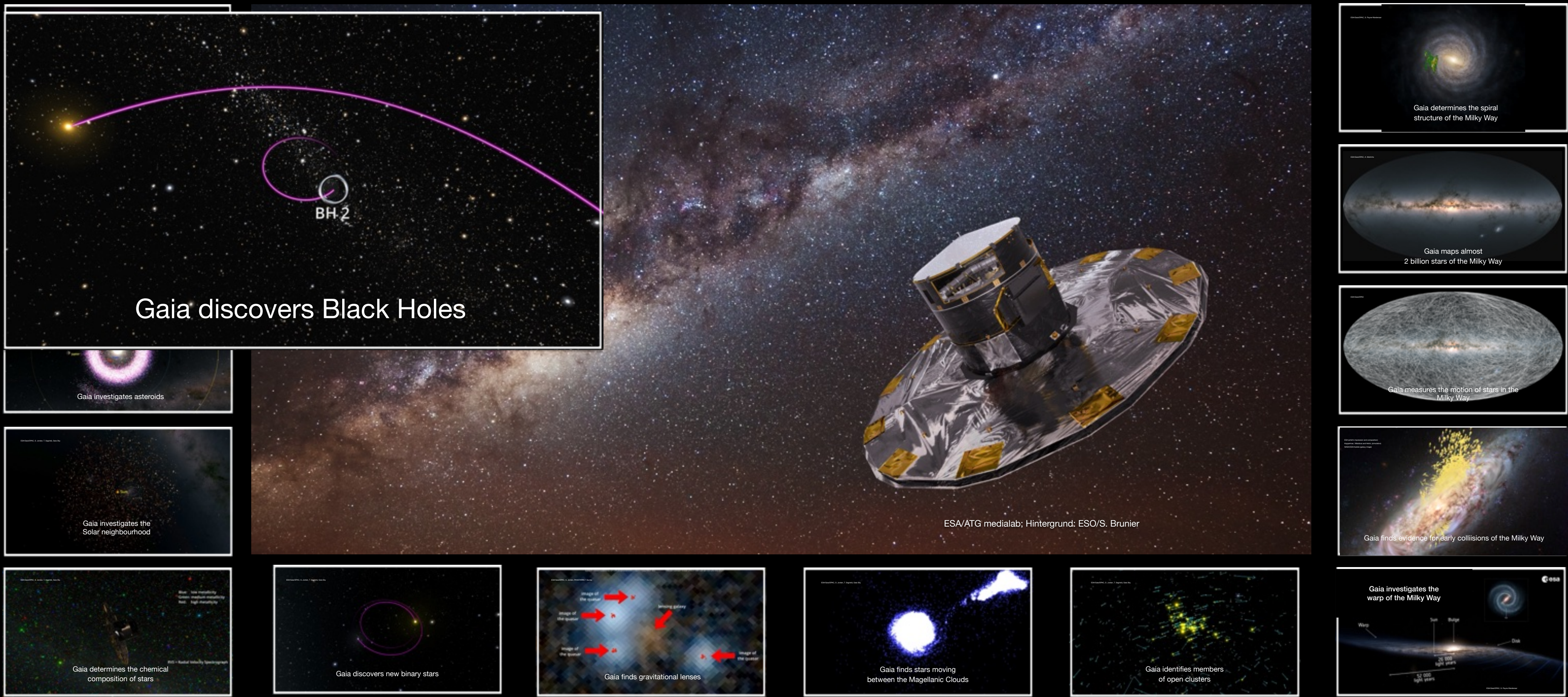
Gaia - The Mission, Instrument, Results and Impact

ISAPP School "Neutrinos and Dark Matter", 17.09.2024

Stefan Jordan, Zentrum für Astronomie, Universität Heidelberg

Gaia - The Mission, Instrument, Results and Impact

ISAPP School "Neutrinos and Dark Matter", 17.09.2024



Stefan Jordan, Zentrum für Astronomie, Universität Heidelberg

Gaia - The Mission, Instrument, Results and Impact

ISAPP School "Neutrinos and Dark Matter", 17.09.2024

Stefan Jordan, Zentrum für Astronomie, Universität Heidelberg

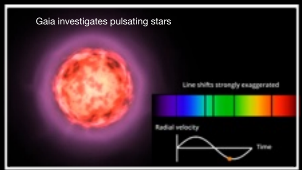
Gaia - The Mission, Instrument, Results and Impact

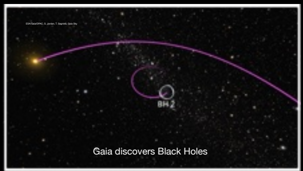
ISAPP School "Neutrinos and Dark Matter", 17.09.2024

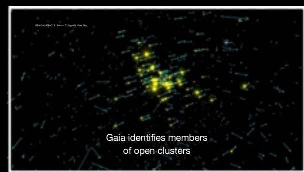
Stefan Jordan, Zentrum für Astronomie, Universität Heidelberg

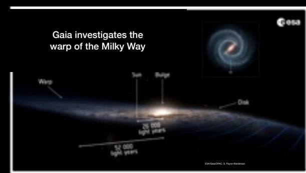
Gaia - The Mission, Instrument, Results and Impact

ISAPP School "Neutrinos and Dark Matter", 17.09.2024





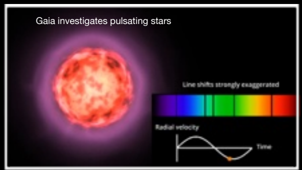


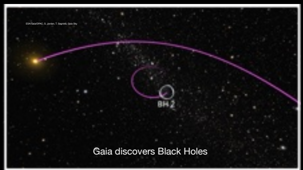


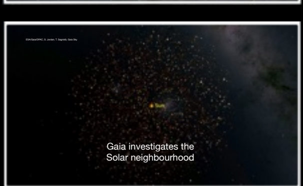
Stefan Jordan, Zentrum für Astronomie, Universität Heidelberg

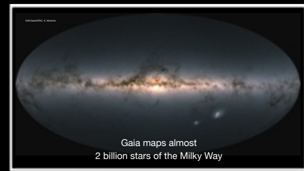
Gaia - The Mission, Instrument, Results and Impact

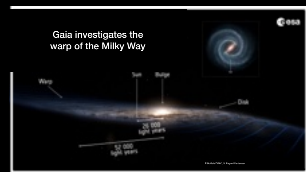
ISAPP School "Neutrinos and Dark Matter", 17.09.2024







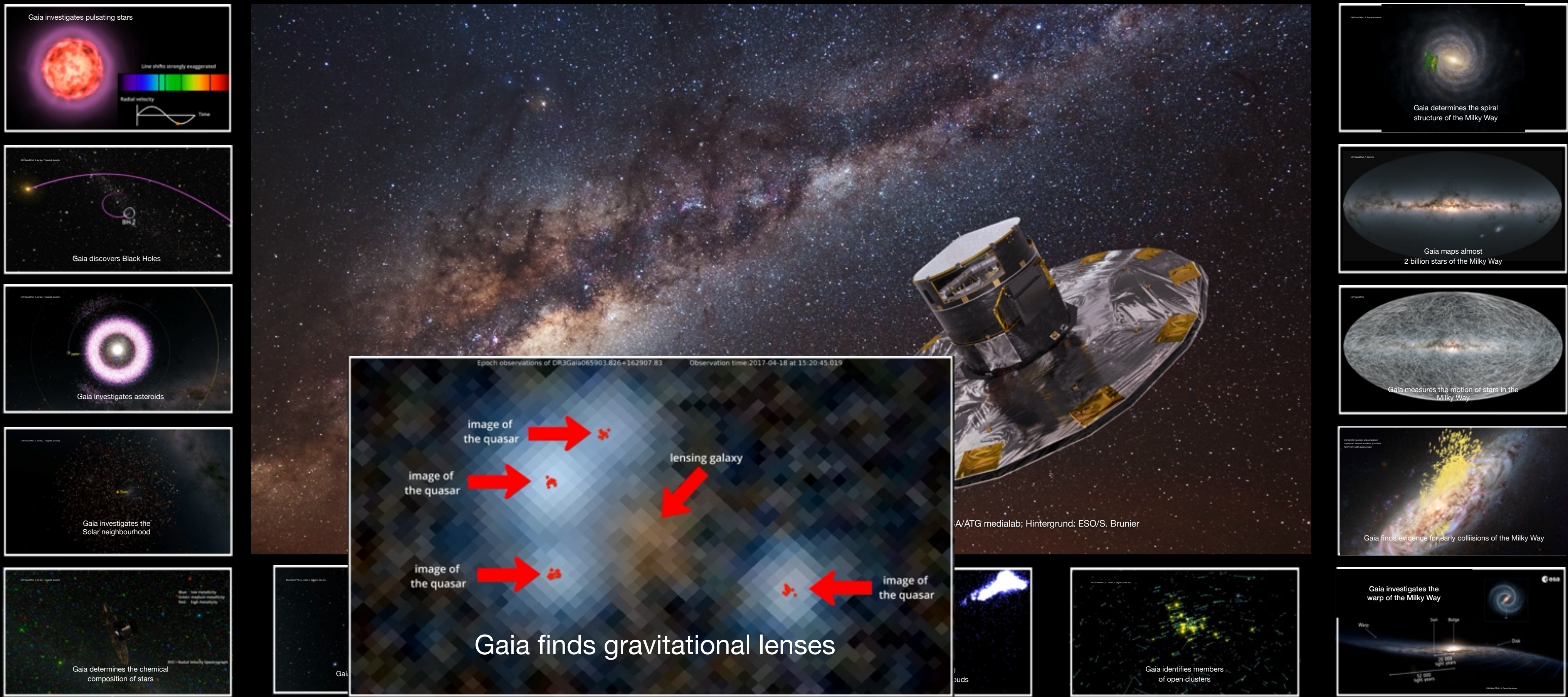




Stefan Jordan, Zentrum für Astronomie, Universität Heidelberg

Gaia - The Mission, Instrument, Results and Impact

ISAPP School "Neutrinos and Dark Matter", 17.09.2024



Stefan Jordan, Zentrum für Astronomie, Universität Heidelberg

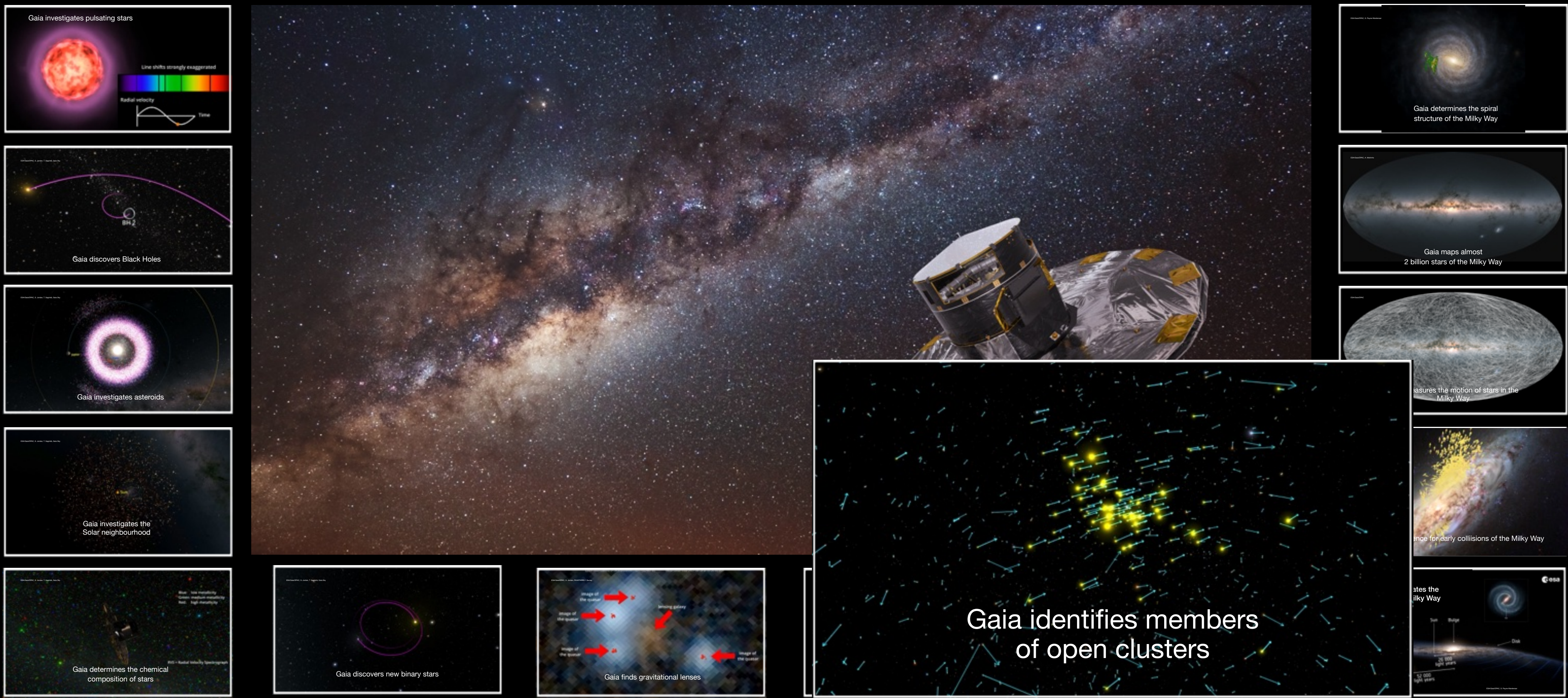
Gaia - The Mission, Instrument, Results and Impact

ISAPP School "Neutrinos and Dark Matter", 17.09.2024

Stefan Jordan, Zentrum für Astronomie, Universität Heidelberg

Gaia - The Mission, Instrument, Results and Impact

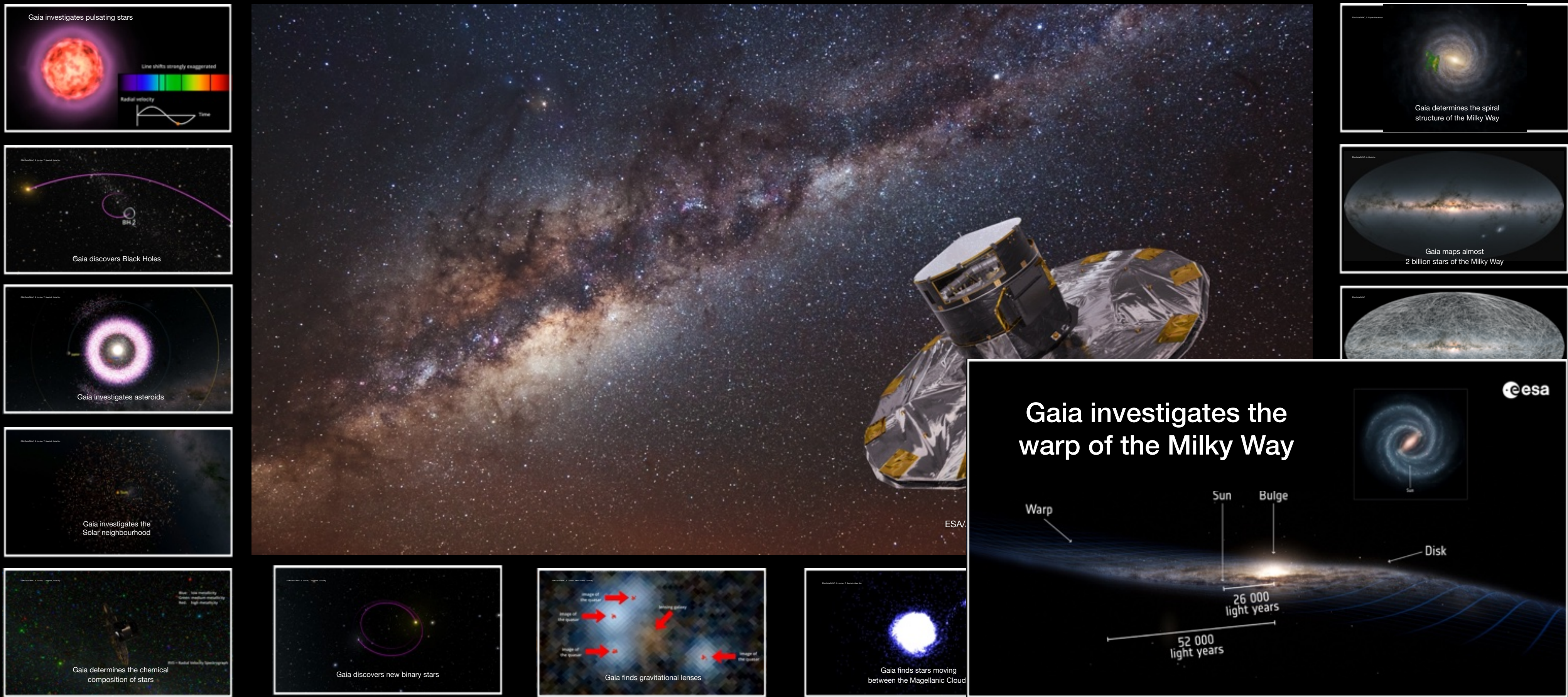
ISAPP School "Neutrinos and Dark Matter", 17.09.2024



Stefan Jordan, Zentrum für Astronomie, Universität Heidelberg

Gaia - The Mission, Instrument, Results and Impact

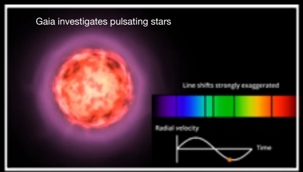
ISAPP School "Neutrinos and Dark Matter", 17.09.2024

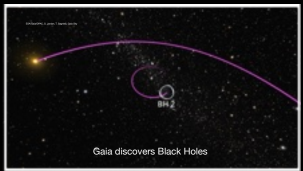


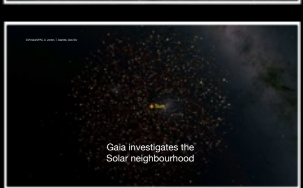
Stefan Jordan, Zentrum für Astronomie, Universität Heidelberg

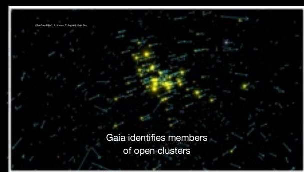
Gaia - The Mission, Instrument, Results and Impact

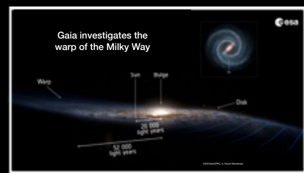
ISAPP School "Neutrinos and Dark Matter", 17.09.2024







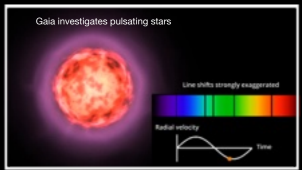


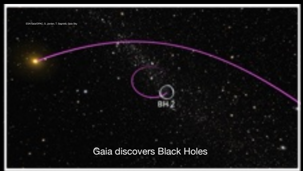


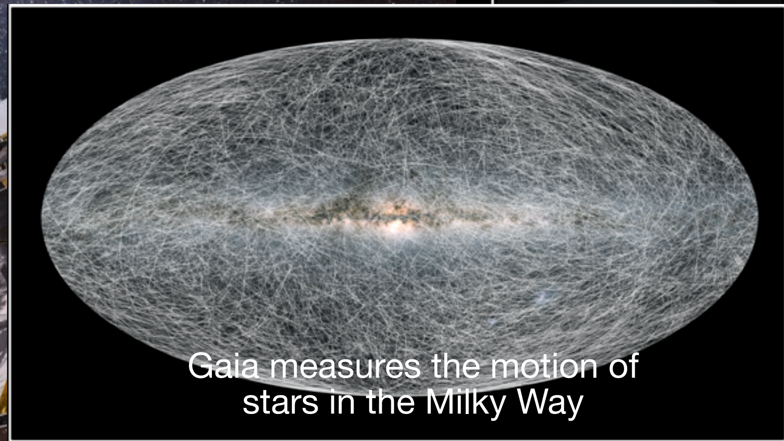
Stefan Jordan, Zentrum für Astronomie, Universität Heidelberg

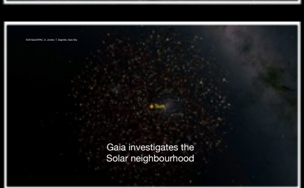
Gaia - The Mission, Instrument, Results and Impact

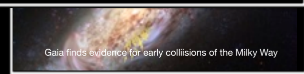
ISAPP School "Neutrinos and Dark Matter", 17.09.2024

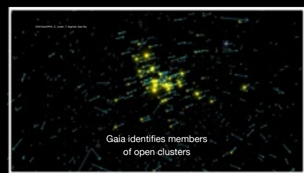


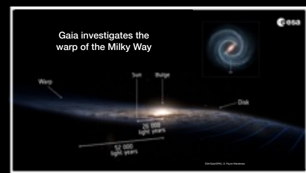








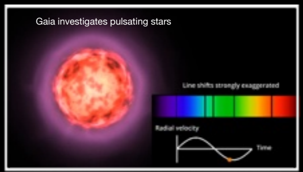


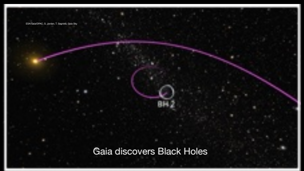


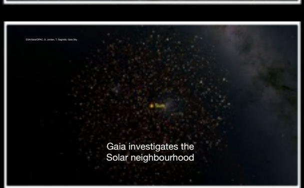
Stefan Jordan, Zentrum für Astronomie, Universität Heidelberg

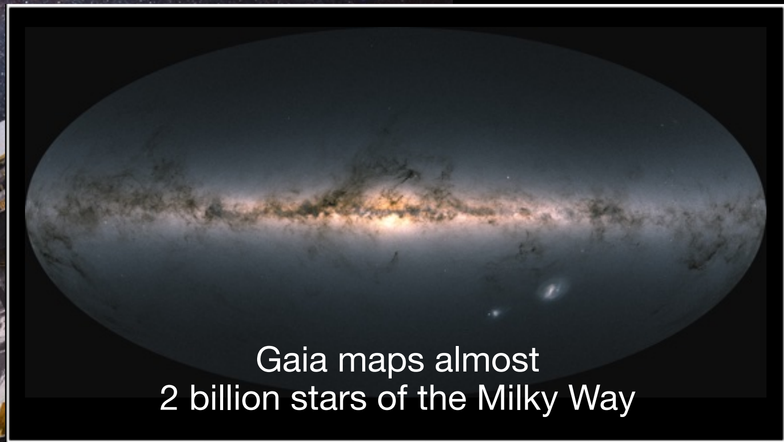
Gaia - The Mission, Instrument, Results and Impact

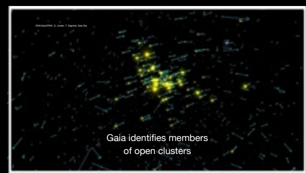
ISAPP School "Neutrinos and Dark Matter", 17.09.2024

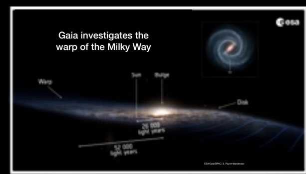








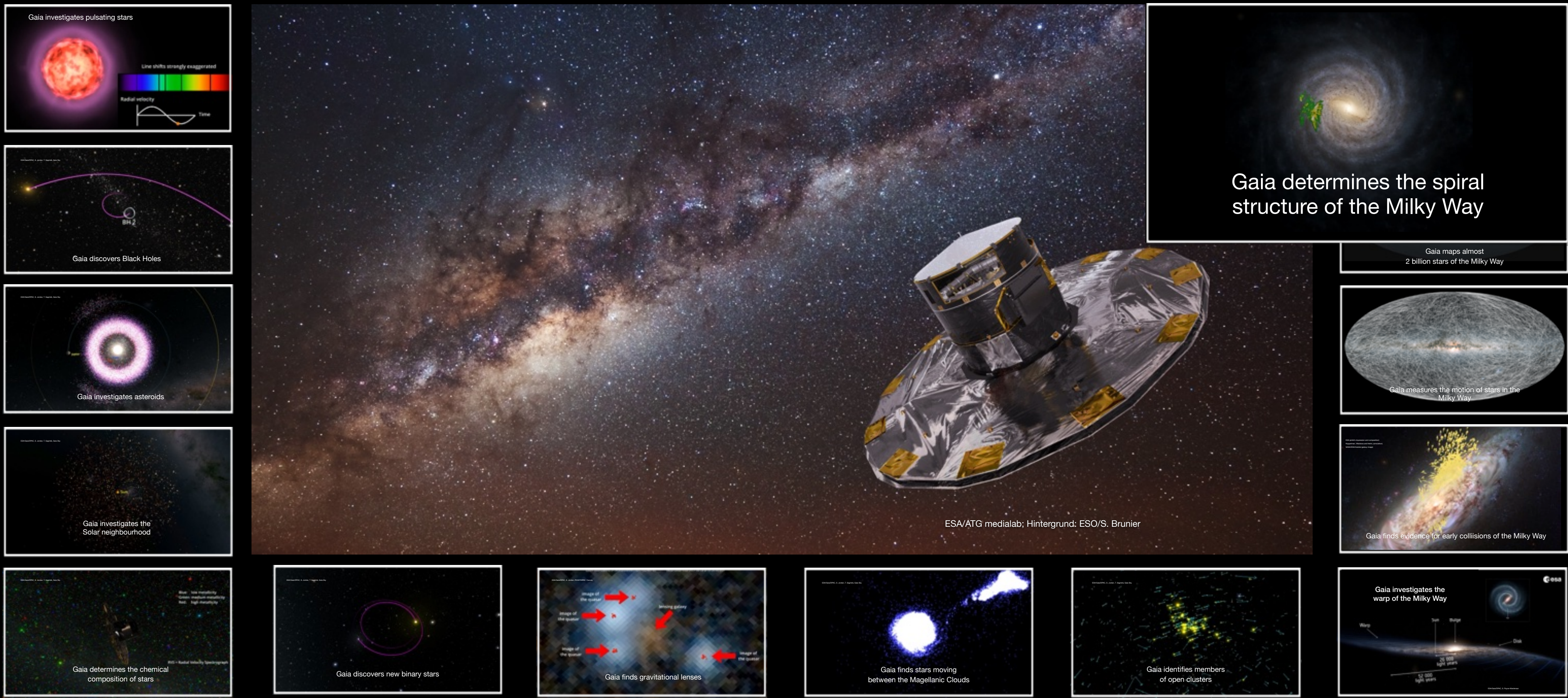




Stefan Jordan, Zentrum für Astronomie, Universität Heidelberg

Gaia - The Mission, Instrument, Results and Impact

ISAPP School "Neutrinos and Dark Matter", 17.09.2024



Gaia's Main Goals

Determination of the

- positions,
- motions, and
- distances (parallaxes)

of one billion stars

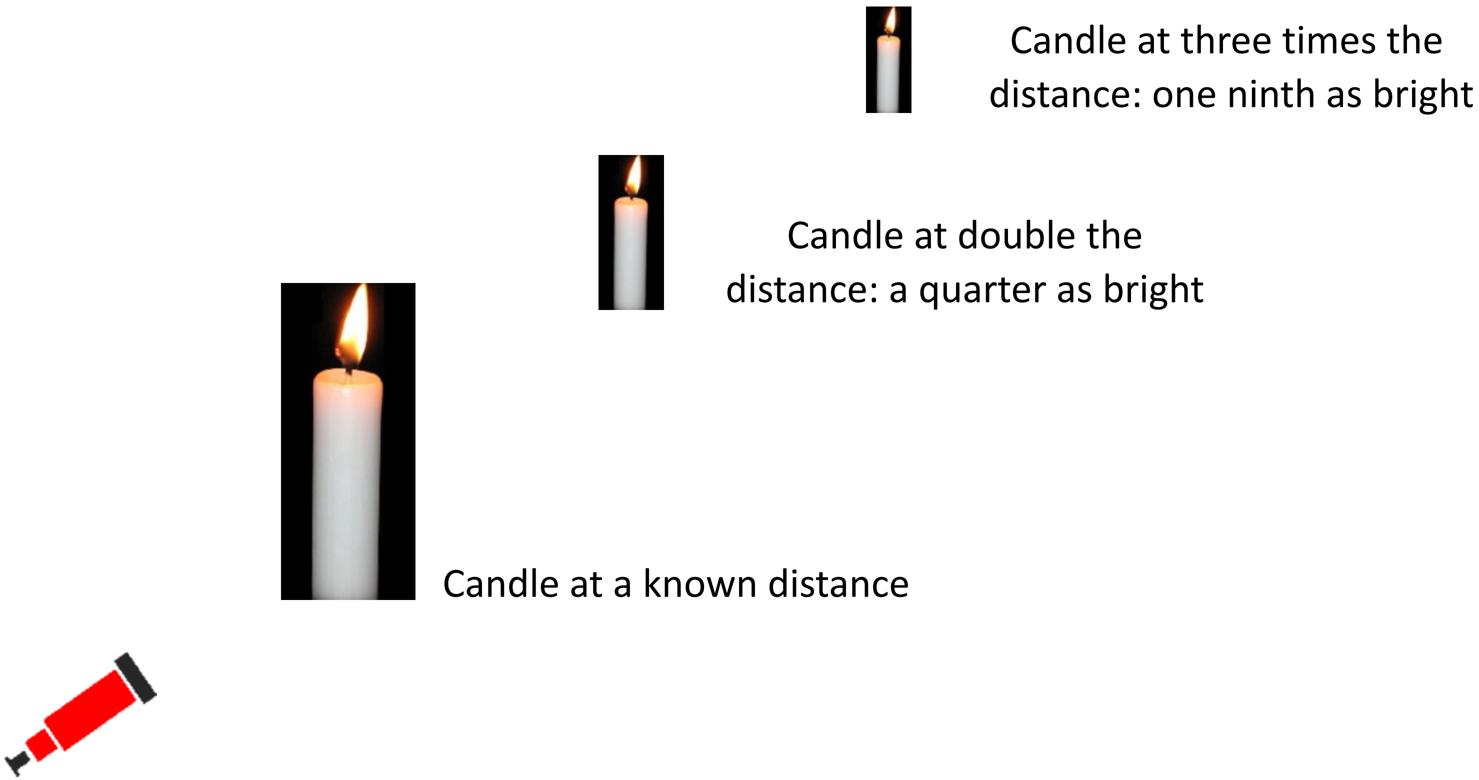
Additionally
the brightness and energy distribution (colours)

These are (practically) all stars up to magnitude 20
(i.e. brighter than a candle at a distance of 20000 km)

Photo: Johannes Wittek, Preetz, 14.3.2020

The brightness decreases with the square of the distance

- The brightness of a star (or a candle) decreases with the square of the distance.

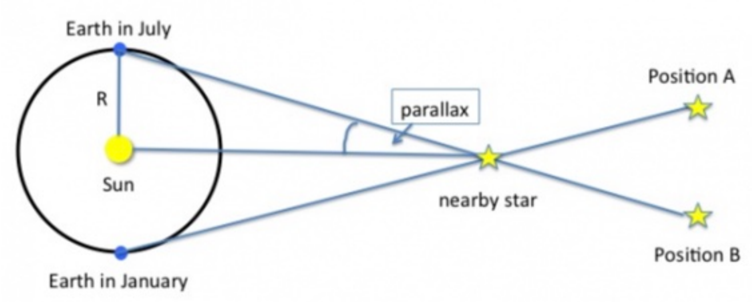



https://youtu.be/qdW53lYXObI

Only two independent distance-measuring methods

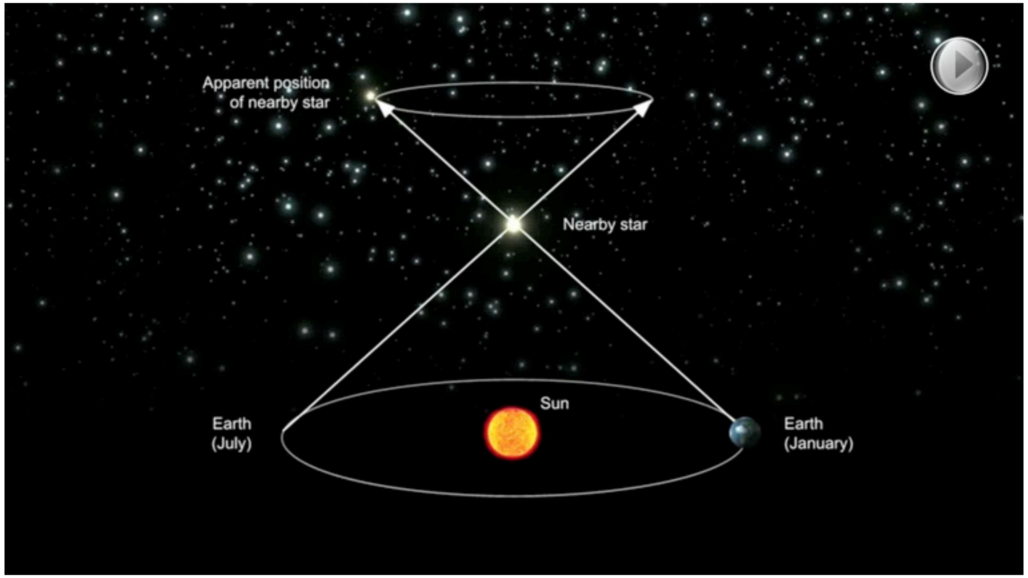
- Radar/Laser echos (travel time with velocity of light)
- Parallaxes (Triangulation)

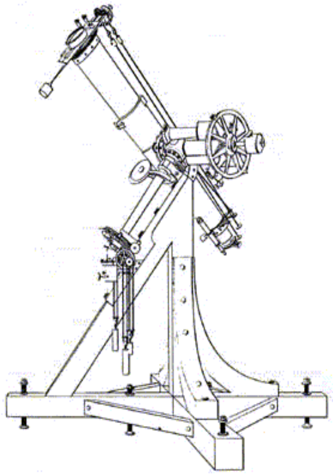
APOLLO
(Apache Point Observatory Lunar Laser-ranging Operation, New Mexico, 3.5m reflecting telescope)

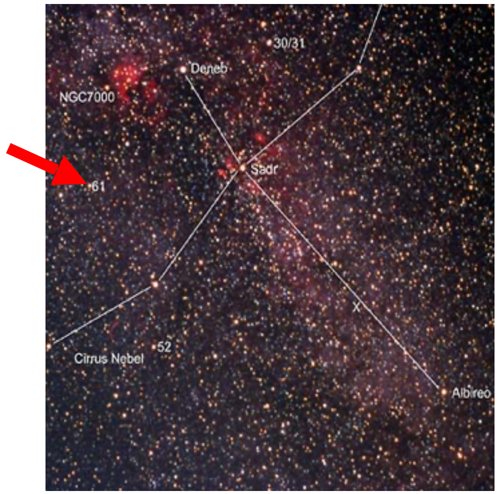


First significant measurement of a parallax

- Friedrich Wilhelm Bessel (1784-1846)
- 1838: Distance to the double star 61 Cygni
- Parallax: 0.31 arc seconds
- Distance: 11 light years

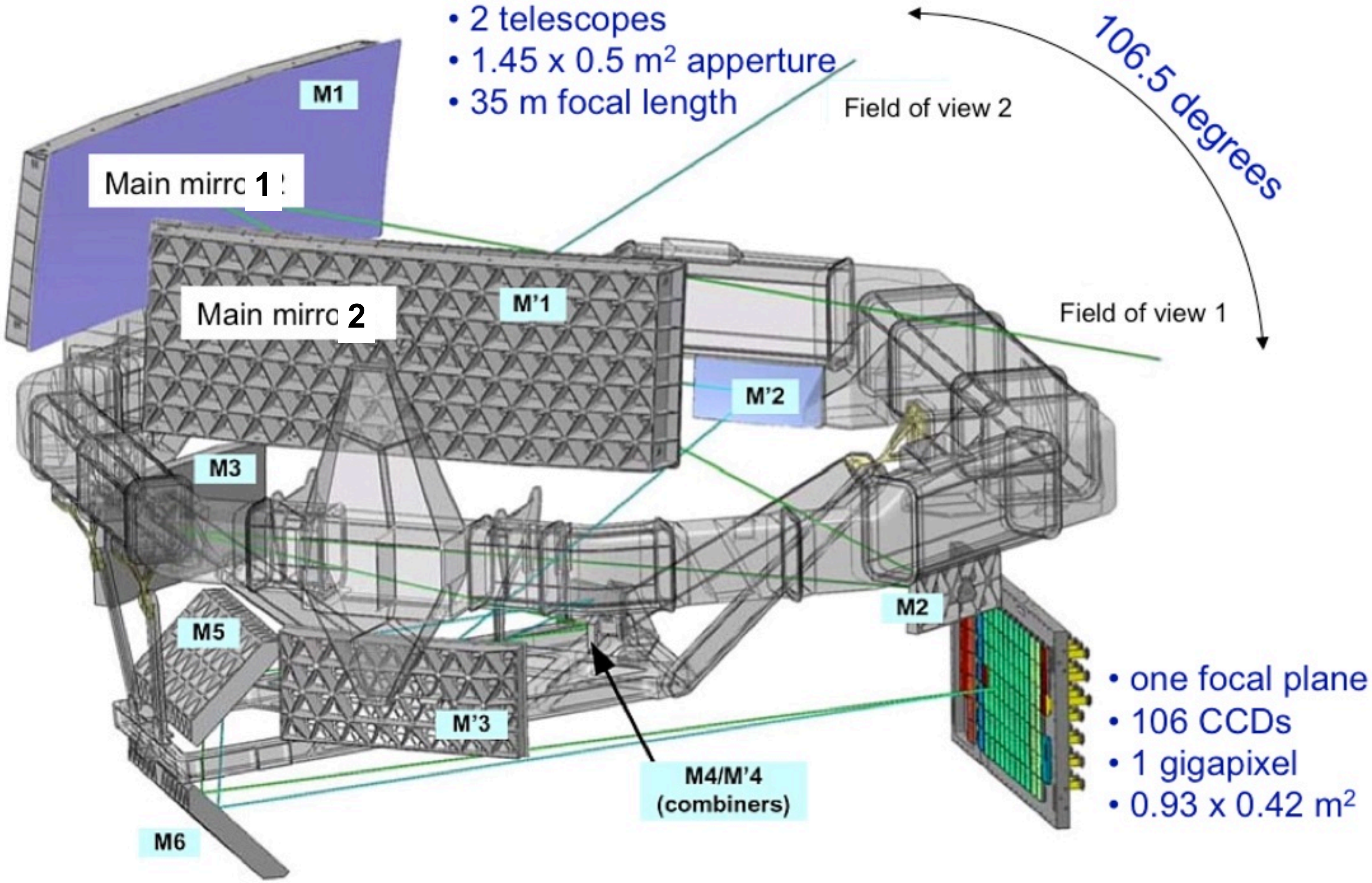






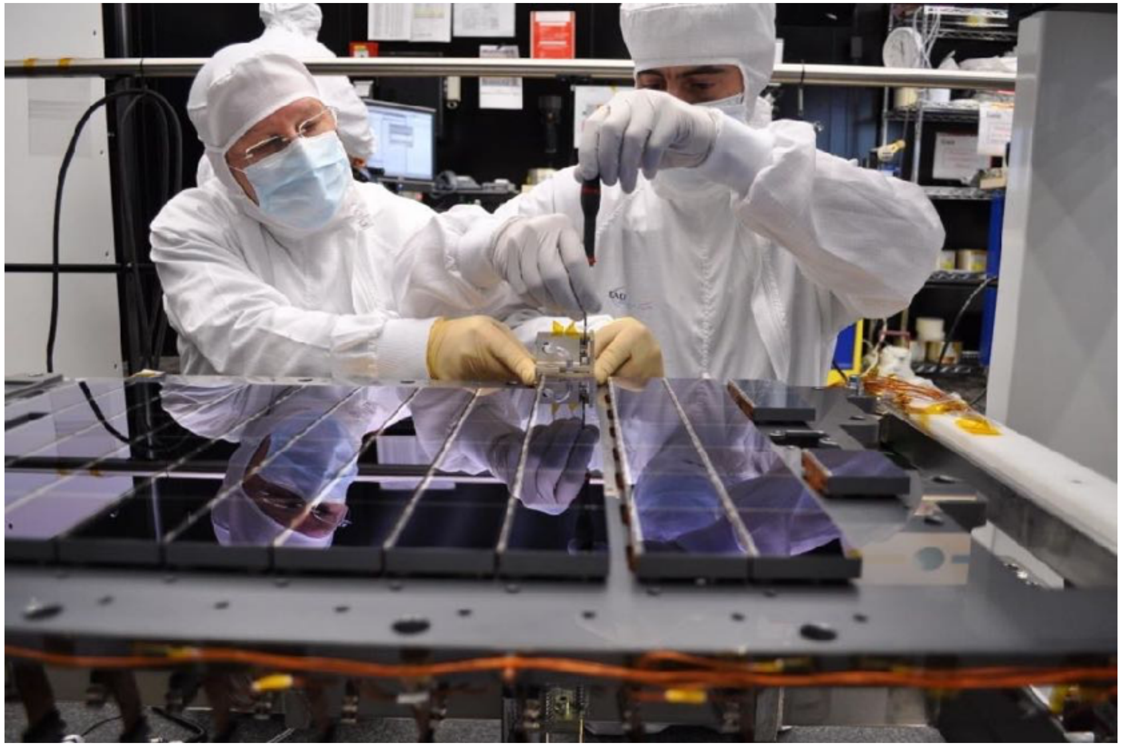
Gaia testing

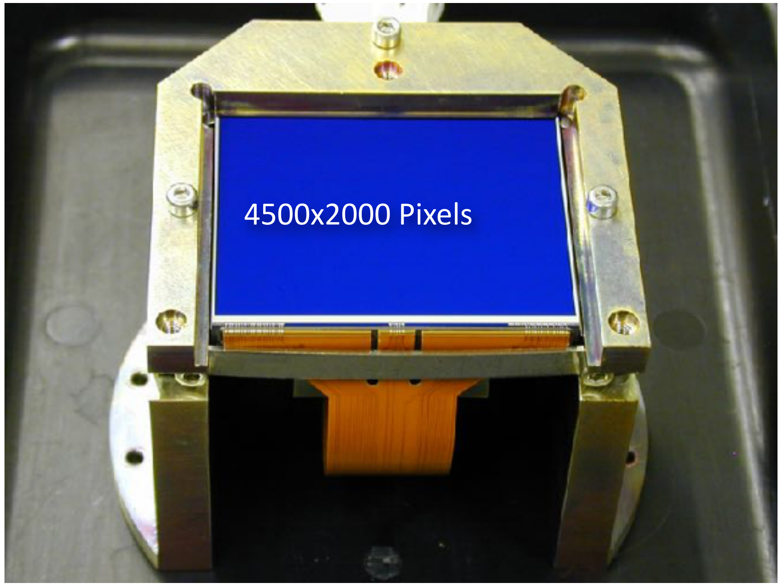
Gaia’s telescopes



One of the two main mirrors

Gaia's one-gigapixel camera

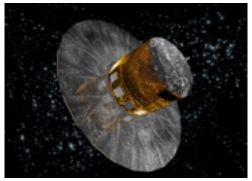


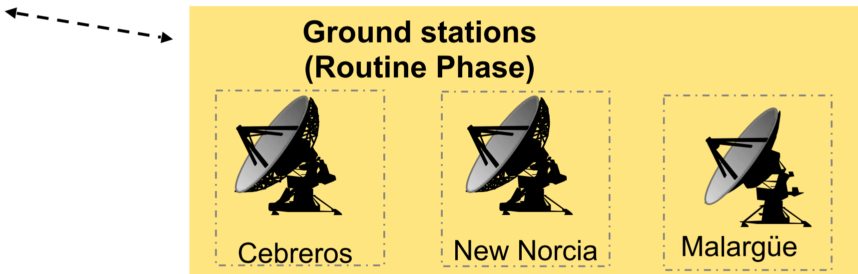


106 light-sensitive CCD detectors

ESA/Gaia/DPAC

Communication to ground





Spain Australia Argentina

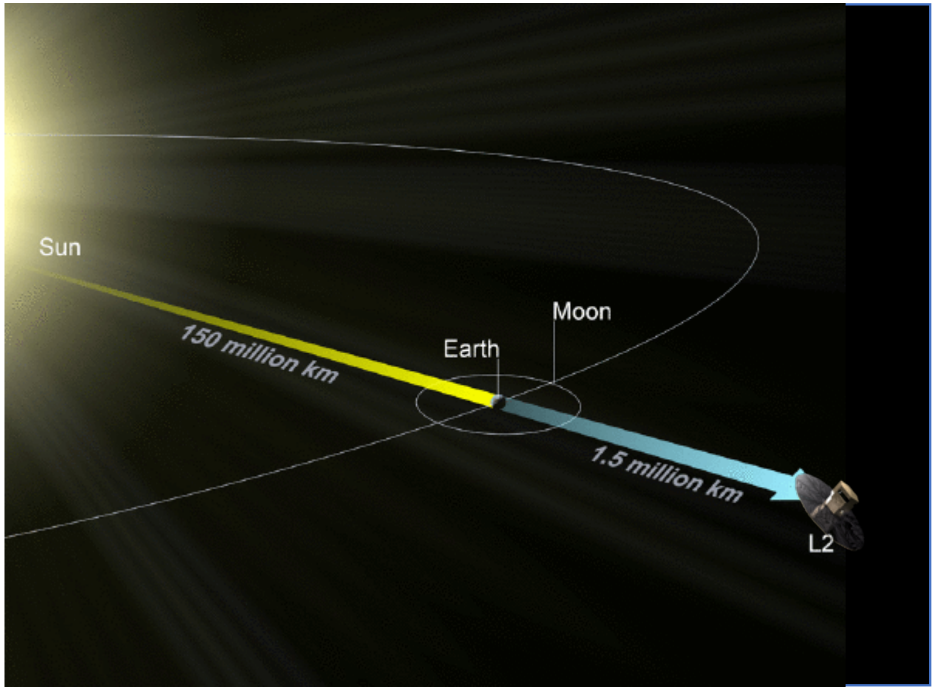
Telemetry:
3-8 Megabit per second

Der Start

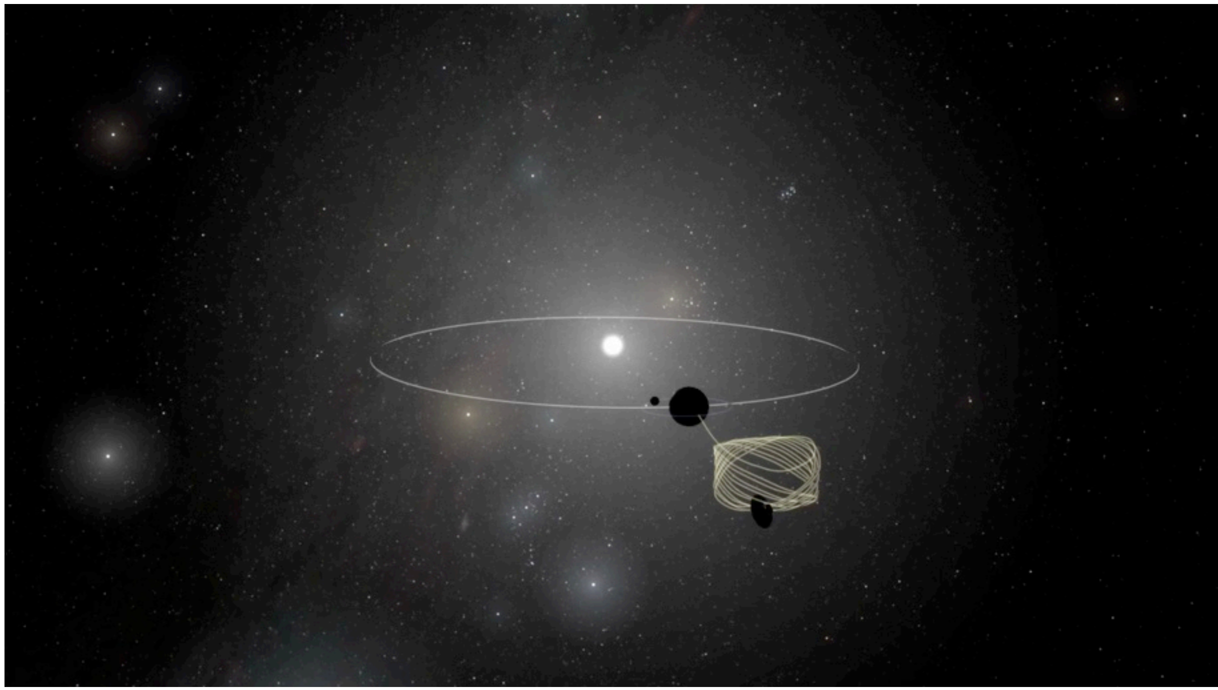
- **Sojus-Fregat**
- 47 Meter Höhe
- Startplatz: Sinnamary in Französisch-Guayana
- Start: 19. Dezember 2013

Gaia at the Sun-Earth Lagrange Point L2

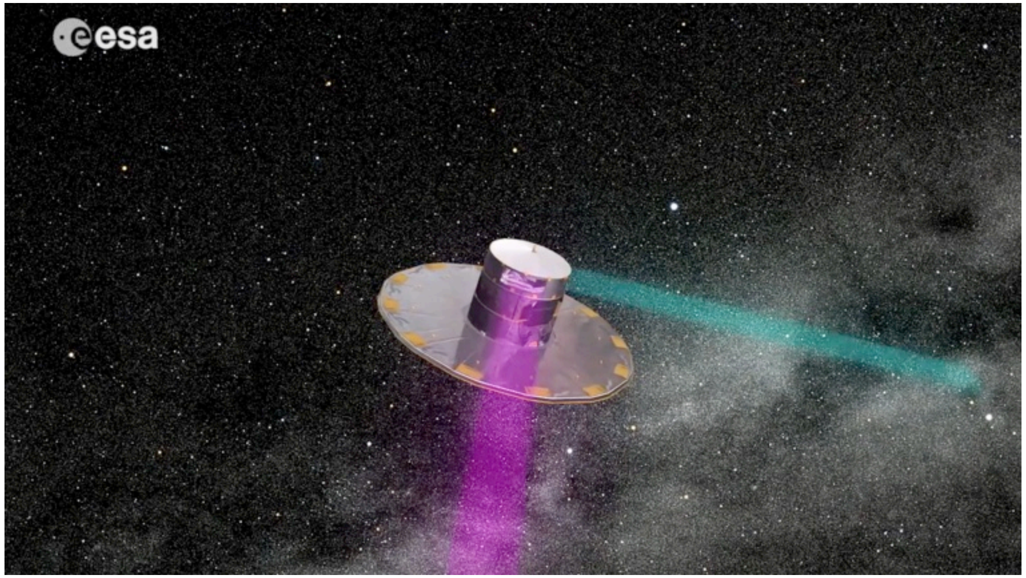
1.5 million km from the Earth



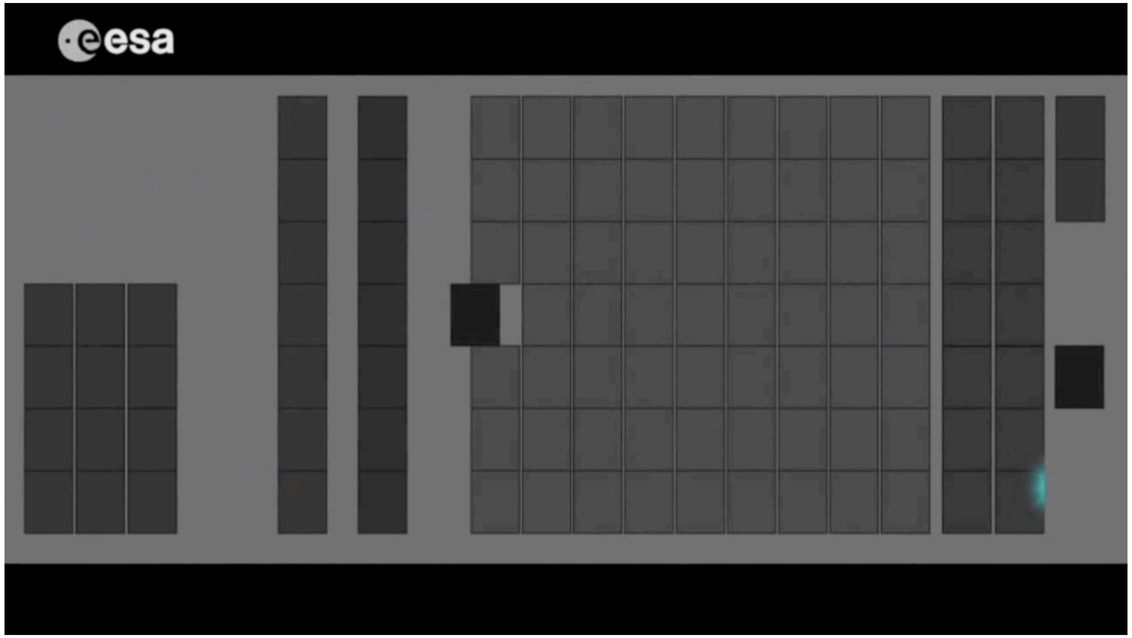
Animation with Gaia Sky: Toni Sagristà Sellés
(ARI/ZAH University of Heidelberg)
Software downloadable at
https://zah.uni-heidelberg.de/gaia/outreach/gaiasky/



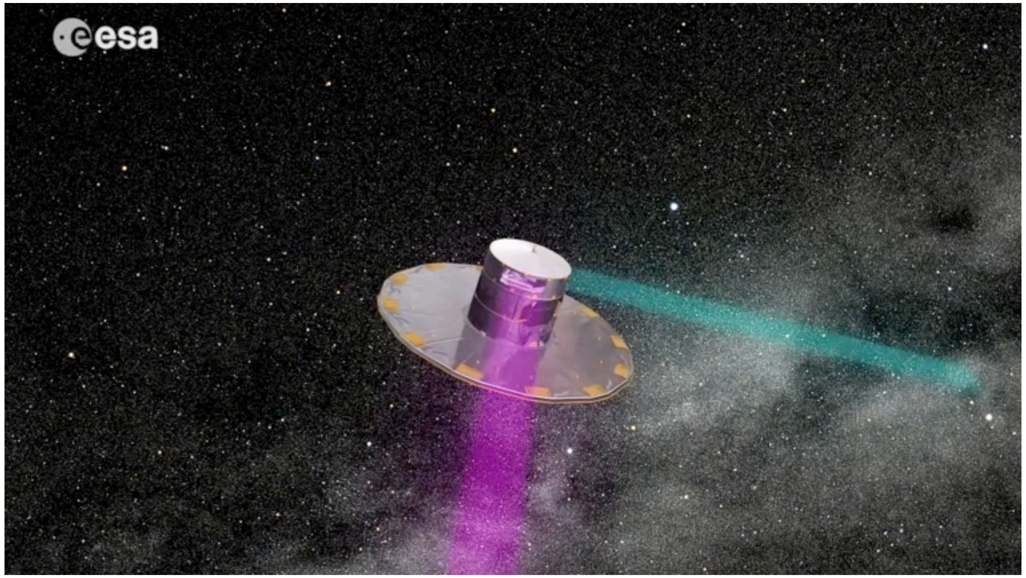
Scanning the sky, Focal plane

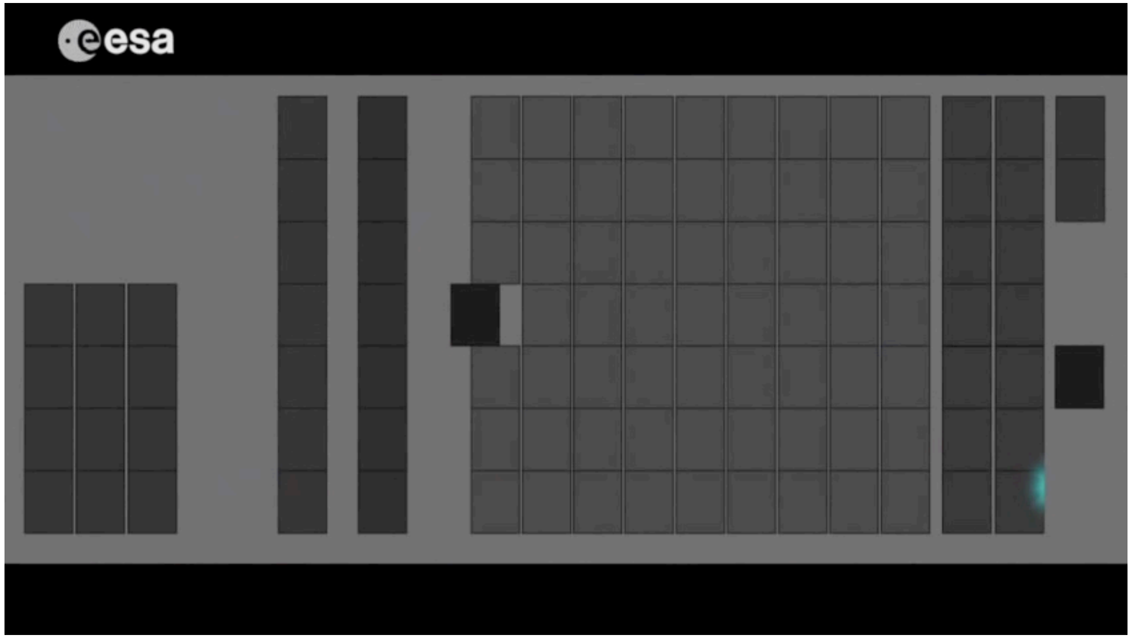


https://youtu.be/bbfb8VhH7L0

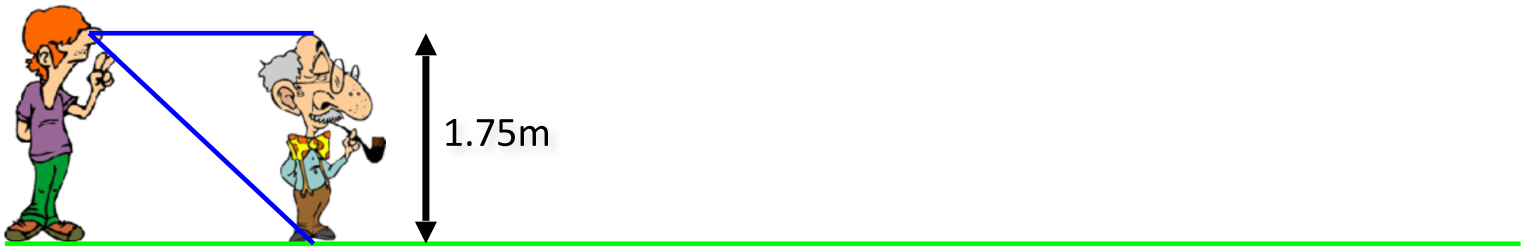


Scanning the sky, Focal plane



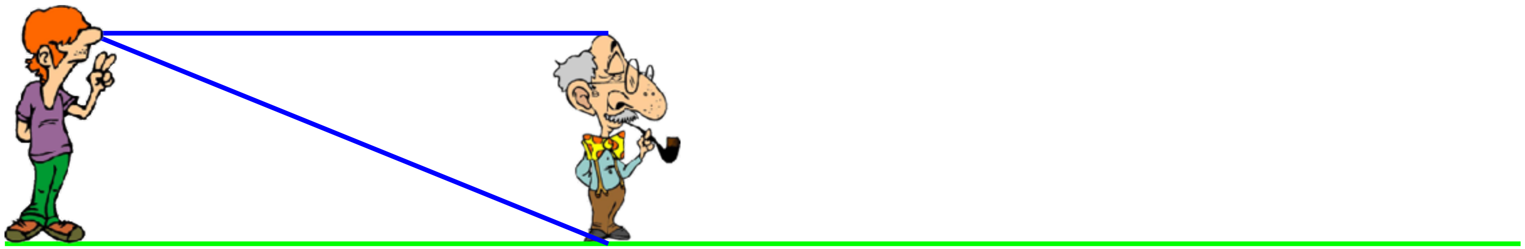


Parallax angles are tiny



200 metres distance
0.5 degrees

Parallax angles are tiny



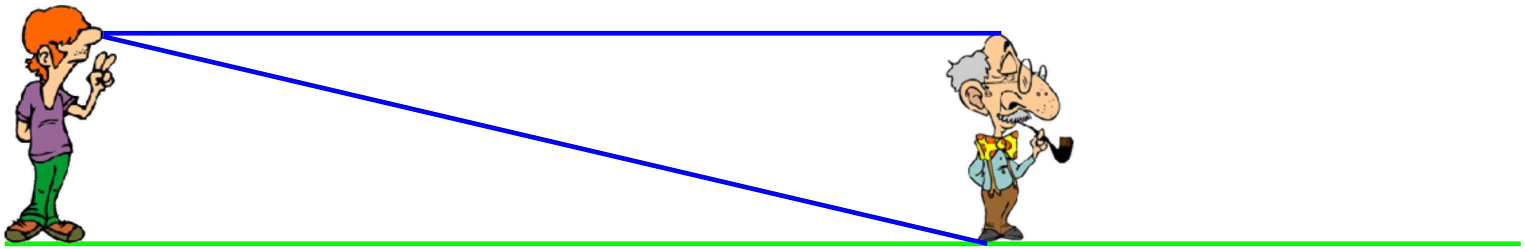
380 kilometres
1 arc second

An arcsecond is the 3600th part of a degree

The nearest star (Proxima Centauri) has a parallax of 0.77 arcseconds
(21 degrees in our hundred-thousand-fold exaggeration!)

Parallax angles are tiny

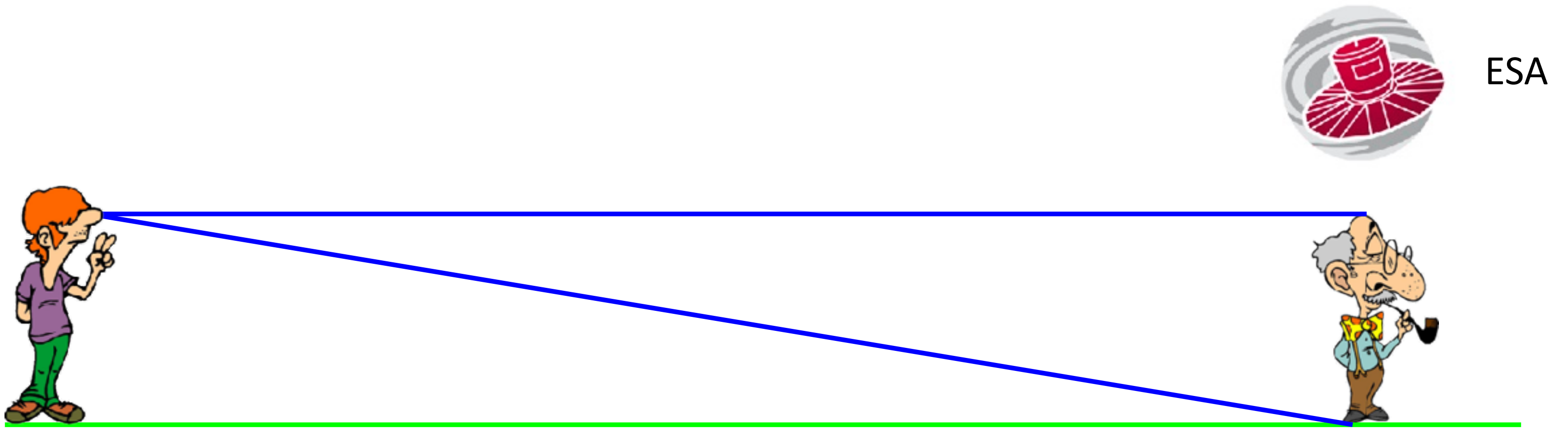
hipparcos ESA



380000 kilometres
1 milliarcsecond

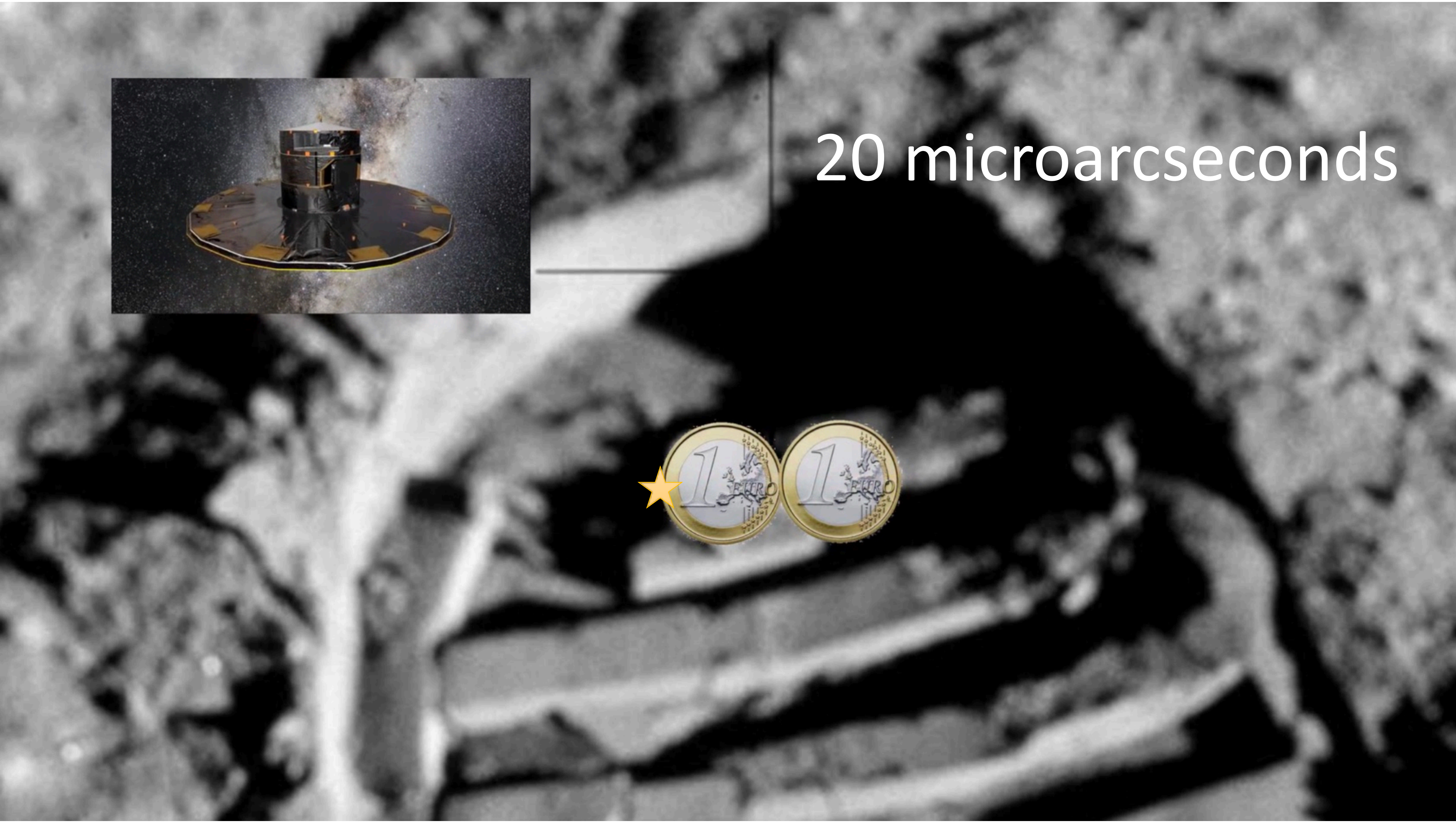
A milliarcsecond is one thousandth of a second of arc.

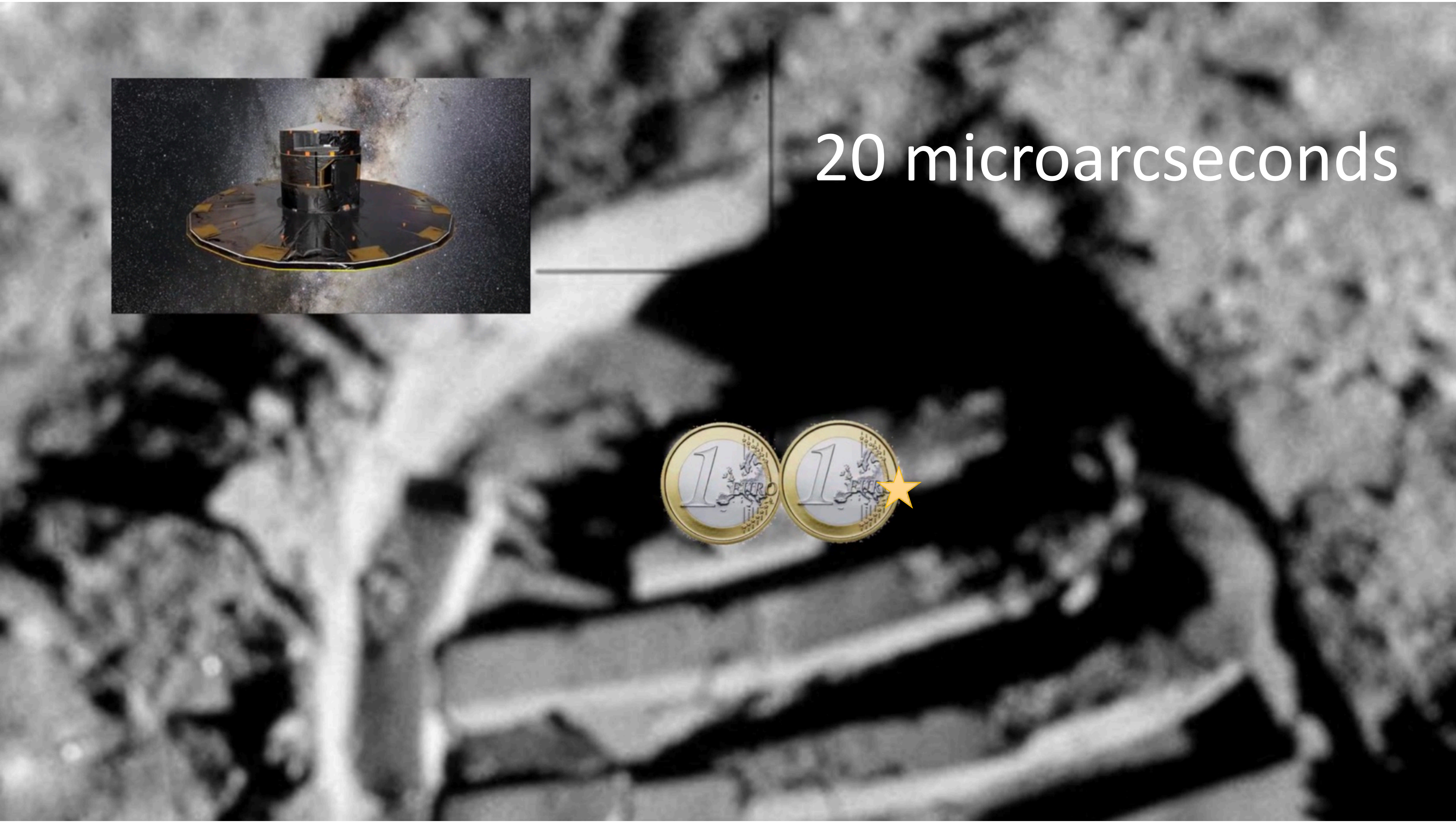
Parallax angles are tiny



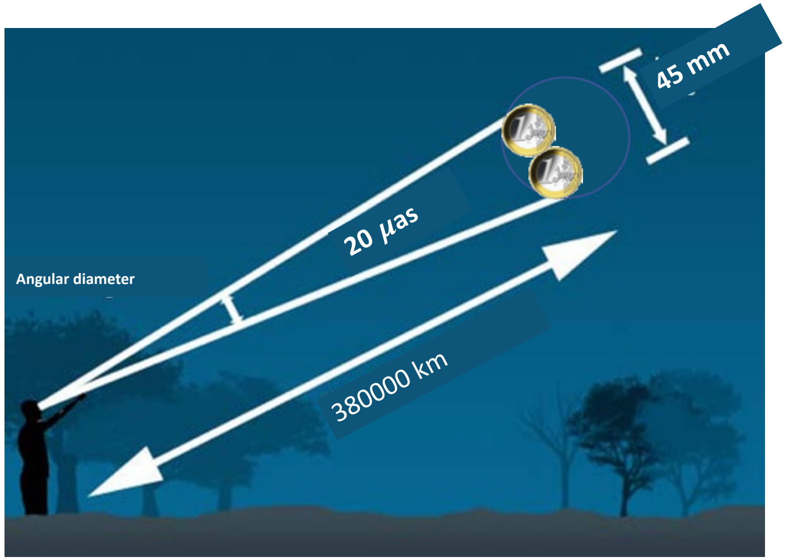
15 million kilometres
25 microarcseconds

A microarcsecond is one millionth of a second of arc.


20 microarcseconds


20 microarcseconds

Twenty arc seconds (20μas, goal for stars of 15th magnitude)



- Astrometry means angle measurement
- Target: 20 microarcseconds = 10^{-10} rad (radians)
- To avoid systematic errors: 10^{-11} rad
- Relative accuracy of 10^{-10} required
- Calibration to 10^{-10} required
- For a size of 2 m, this corresponds to 0.2 nm.
- 0.2 nm for instrument geometry and orientation
- With a thermal expansion coefficient of 10^{-6}/K, this corresponds to 10^{-4} K
- 20 μas = 333 ns; 10^{-10} relative time accuracy

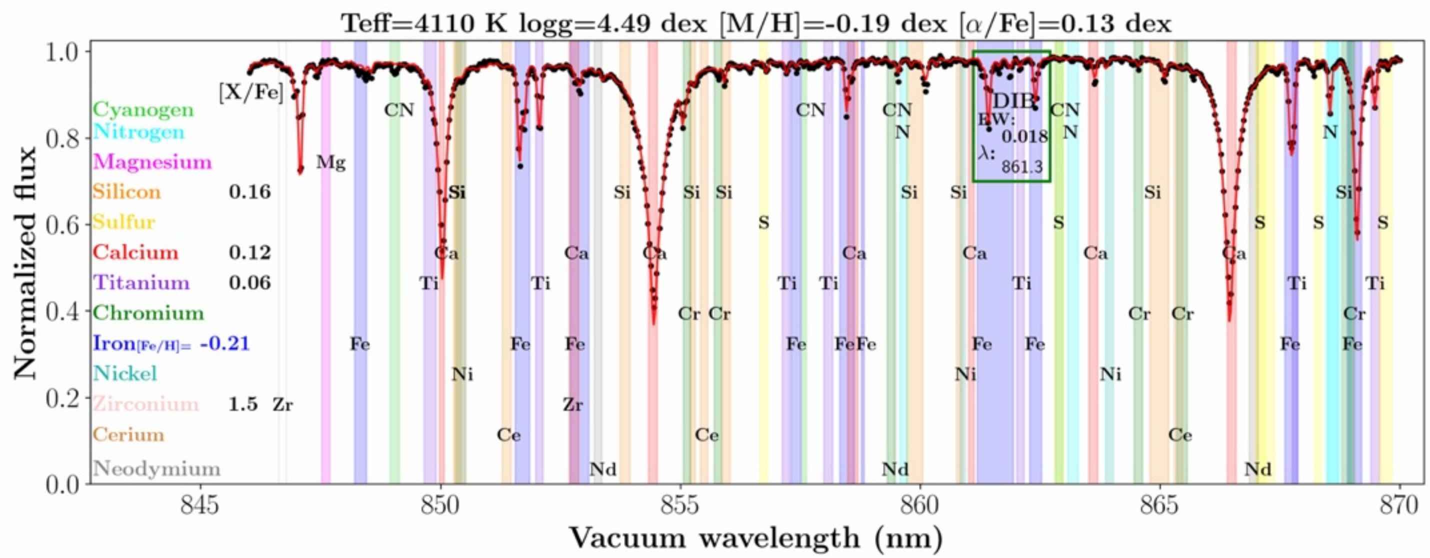
After U. Bastian

Spectra

Photo: Stefan Jordan

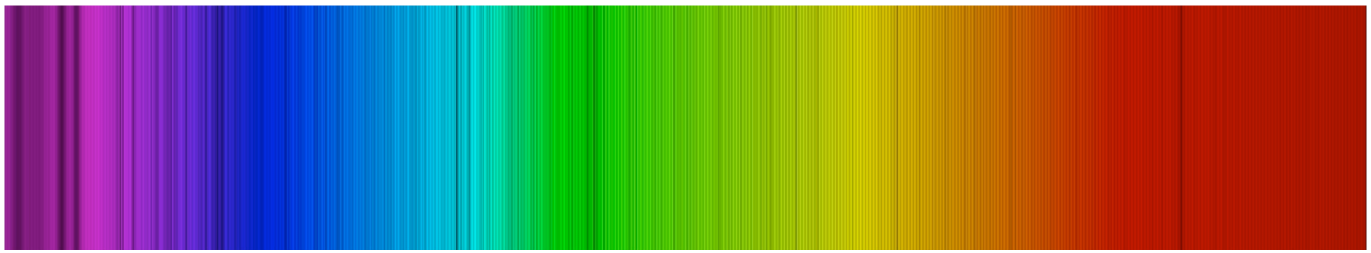
Heidelberg, 27.5.2011

Spectra for analysing light

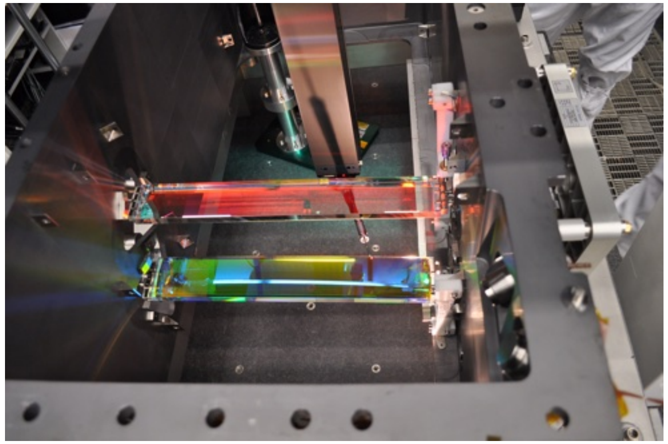


Spectrum of a star in the near infrared

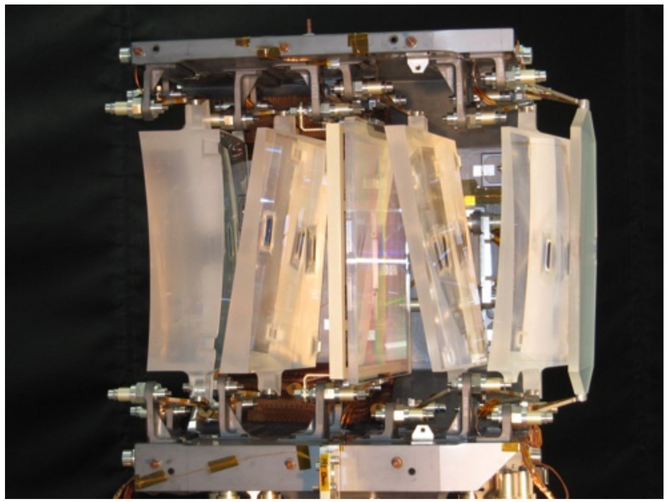
ESA/Gaia/DPAC-CU8, Recio-Blanco and the GSP-Spec team



The spectrum of the Sun in the visible

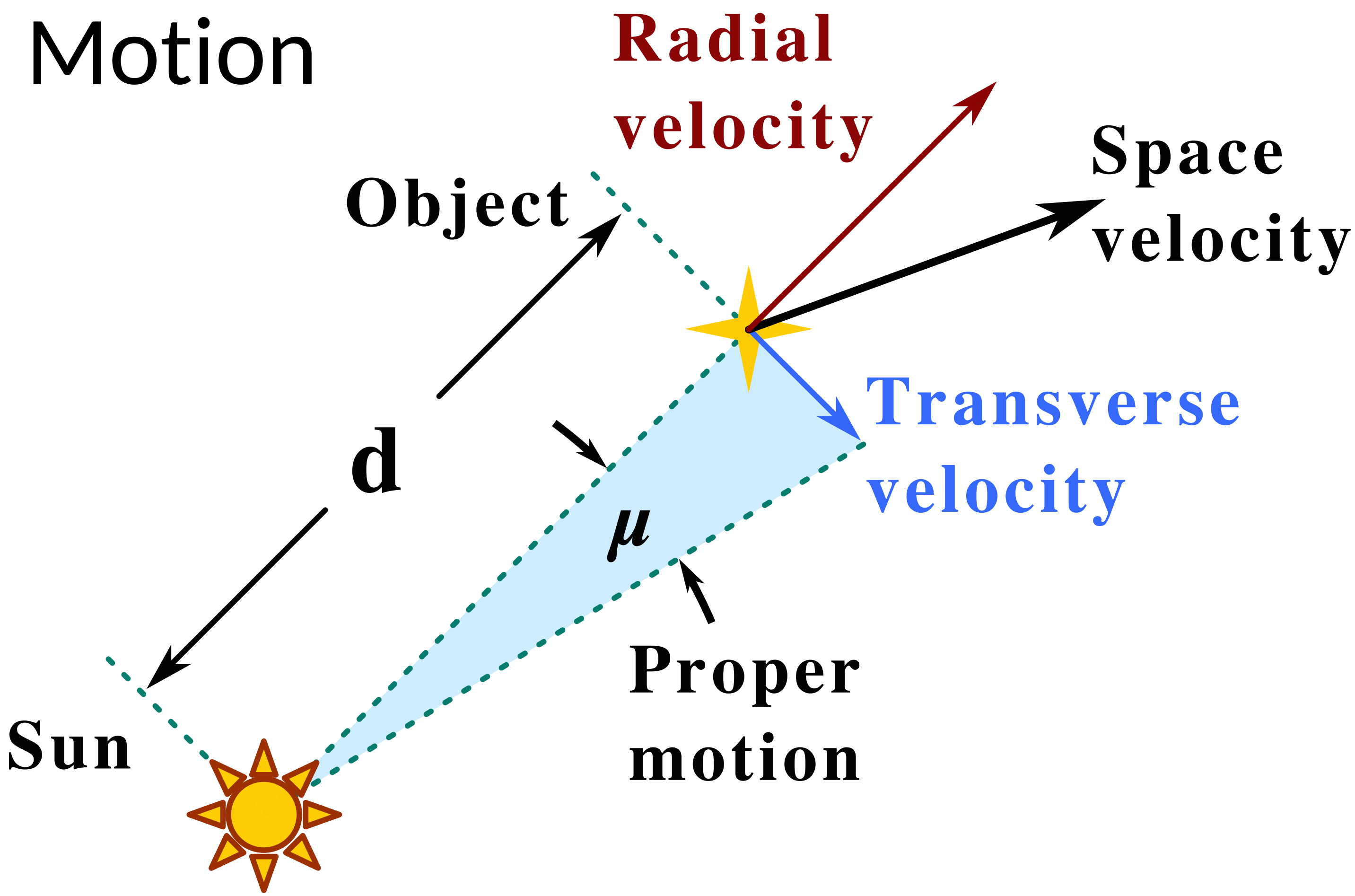


Blue and red photometer spectrograph



Radial velocity spectrograph

Space Motion



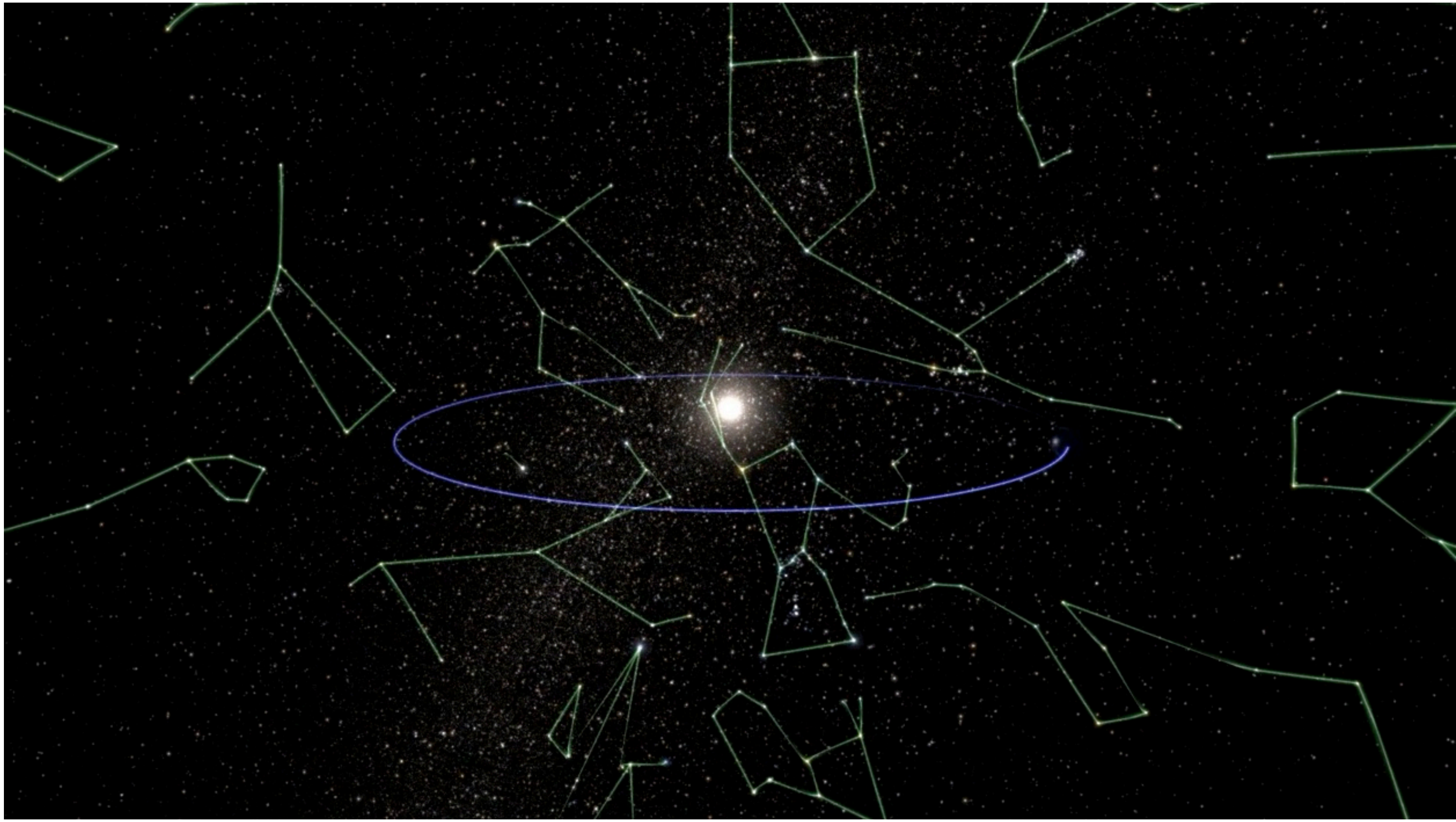
https:// /wikihttps://en.wikipedia.org/wiki/Proper_motion#/media/File:Proper_motion.svg

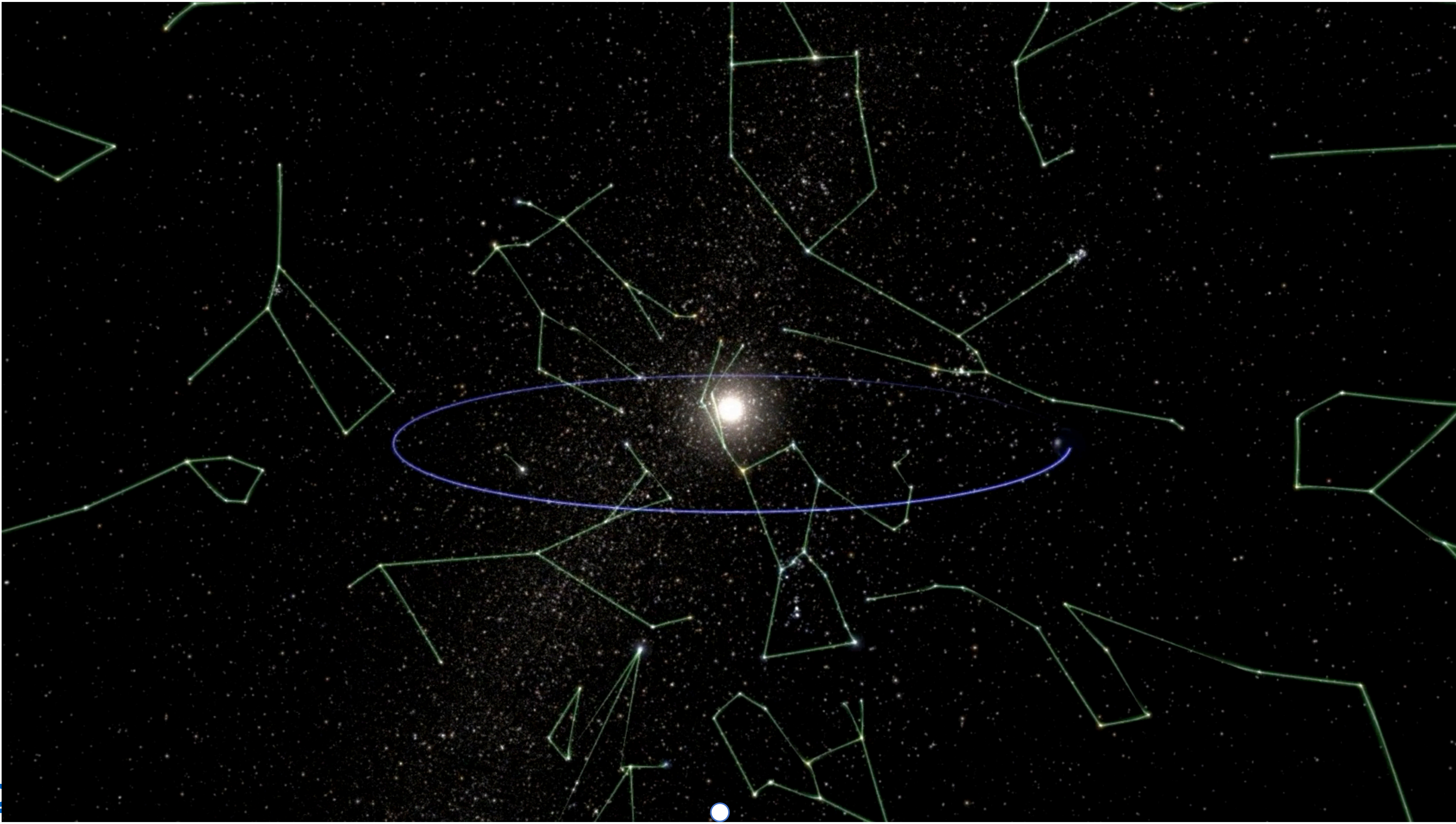
CURRENT DATE AND TIME	2024-09-17T09:22:43 (TCB)
MISSION STATUS	
Satellite distance from Earth (in km)	1,600,737
Number of days having passed since 25 July 2014	3707
Number of days in mission extension	1890
OPERATIONS DATA (collected since 2014/07/25)	
Volume of science data collected (in GB)	136,287
Number of object transits through the focal plane	258,876,153,148
Number of astrometric CCD measurements	2,551,779,223,881
Number of photometric CCD measurements	512,748,606,080
Number of spectroscopic CCD measurements	50,123,773,560
Number of object transits through the RVS instrument	16,840,769,964

https://www.cosmos.esa.int/web/gaia/mission-numbers

Video in which we assume that the parallaxes are 100,000 times larger than in reality

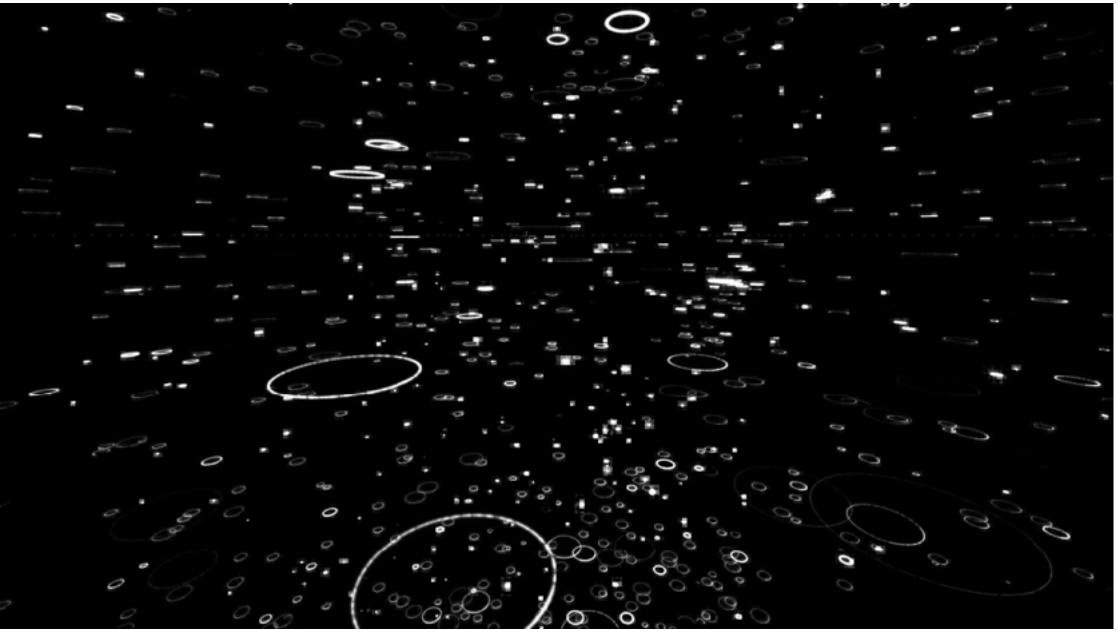
https://youtu.be/seiXLIh95IY



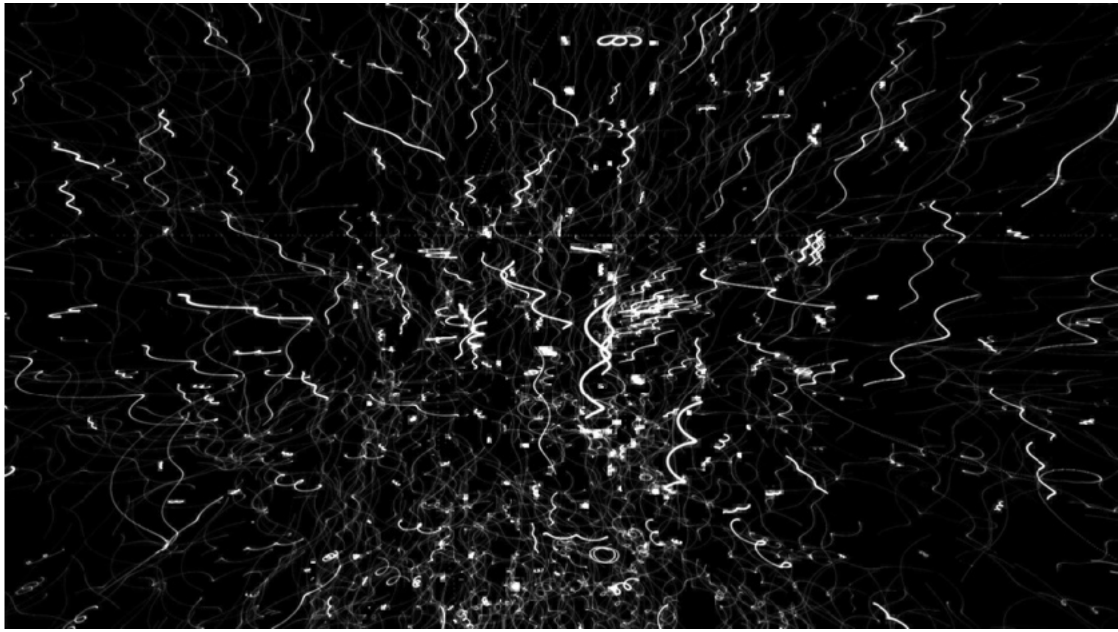


Video where we assume that the parallaxes are 100 000 times larger than in reality

“Long exposures“



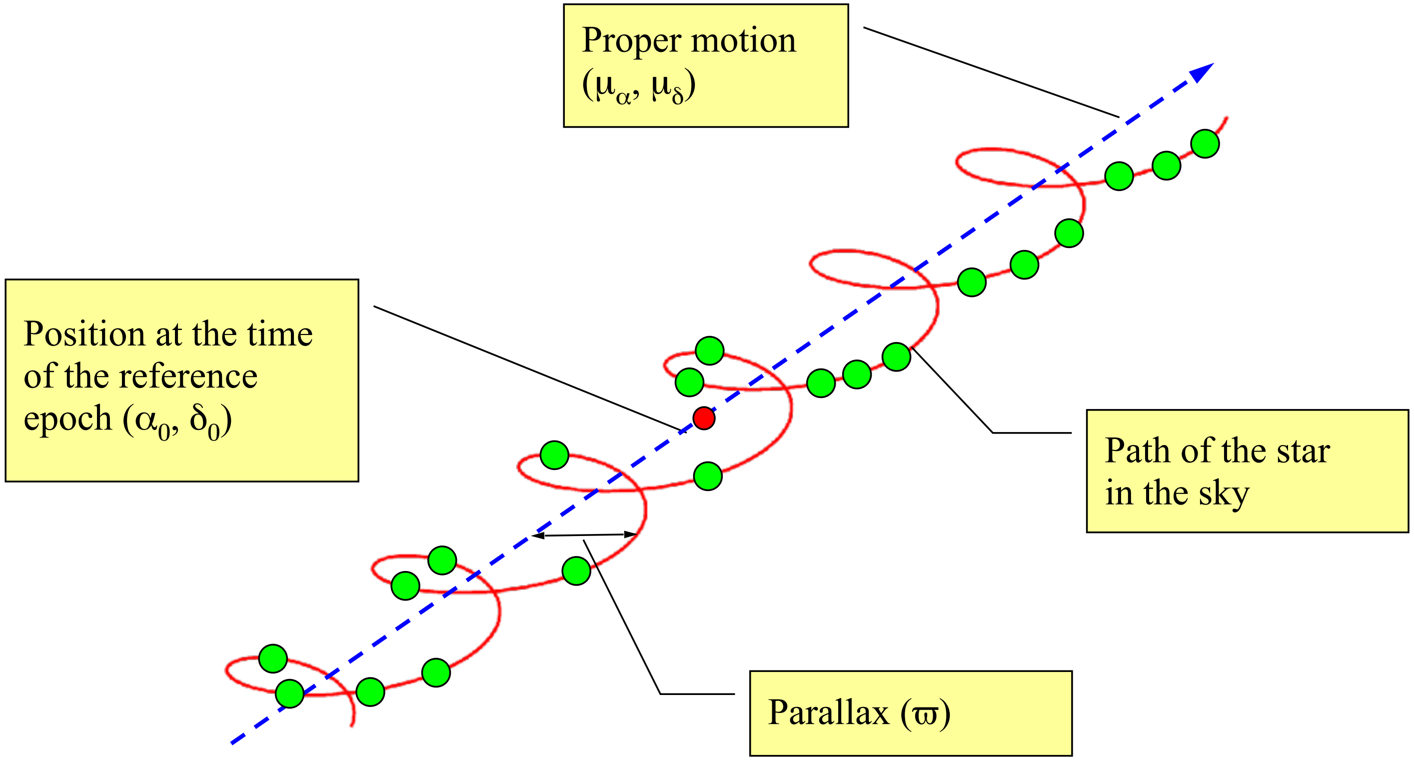
without proper motion, just parallax



parallax + proper motion

https://youtu.be/seiXLIh95IY

The motion of a single star



We need
five astrometric values
per star (single star)

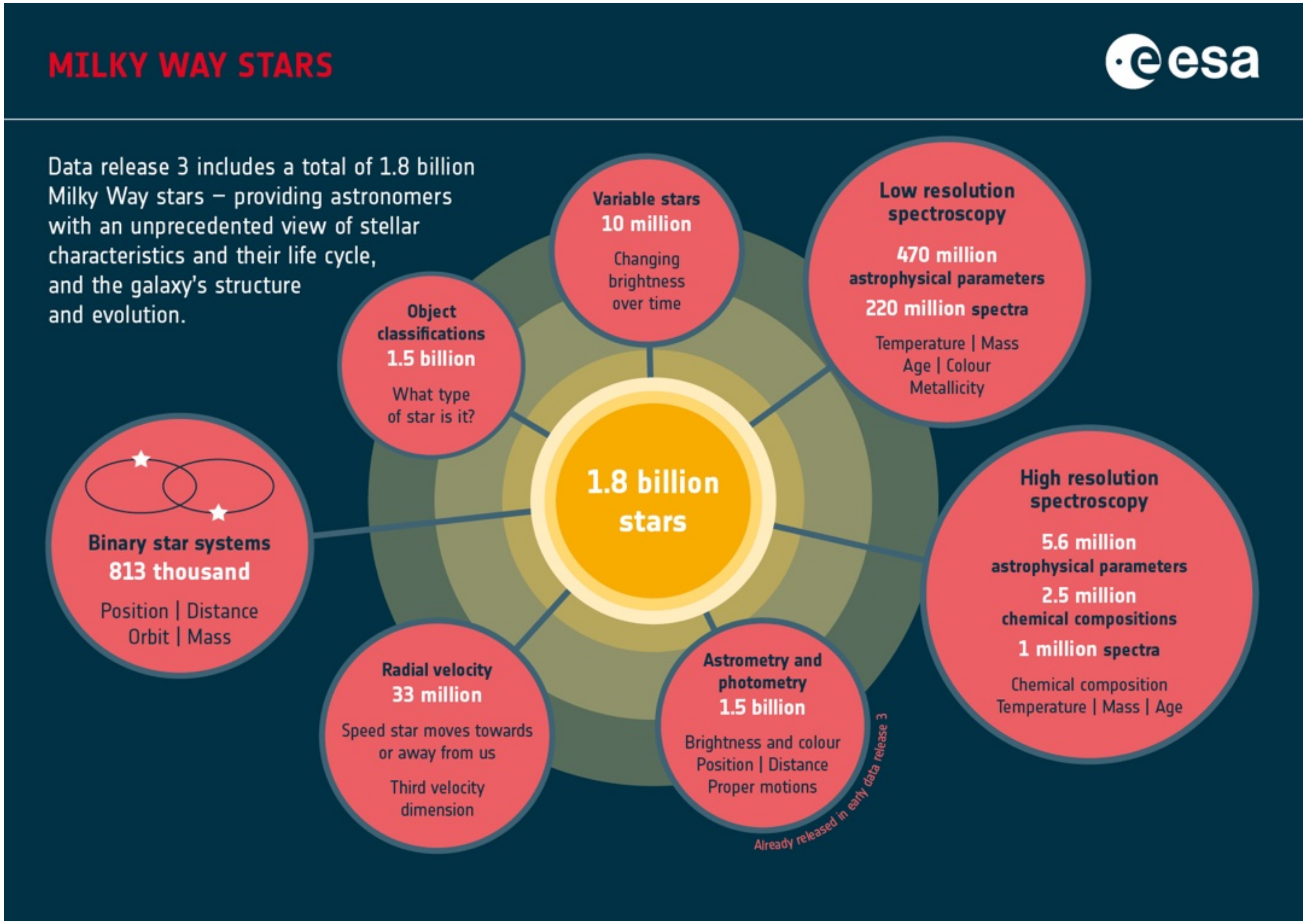
Why Gaia is so successful

- Precise parallaxes
    - ➢exact distances
        - with photometry, we obtain the true brightness of stars (luminosity) and how much energy a star emits on its surface
        - Angular diameters in the sky become spatial quantities
- Precise proper motions and radial velocities
    - ➢Study of the motions of stars
        - Finding star clusters, star streams
        - Motion structures in of the Milky Way (information about MW evolutionary history)
- Accurate photometry
    - ➢Energy distribution of the radiation over the wavelengths
    - ➢together with parallaxes provides information about the evolutionary states of stars
- Usability
    - ➢It is easy to access the data
    - ➢They are available to everyone

Publication of Gaia DR3

June 13, 2022, 12:00 CET

Content of Gaia Data Release 3



Content of Gaia Data Release 3

One random star

source_id	2032861317502068224
designation	Gaia DR3 2032861317502068224
other_ids	Gaia DR2 2032861317502068224 Gaia DR1 2032861313151022592
ra	295.790007803° +/- 0.02 mas
dec	30.677910246° +/- 0.03 mas
l	65.810499641°
b	3.518309377°
ecl_lon	306.399993720°
ecl_lat	50.908662007°
parallax	9.25 mas +/- 0.03 mas
pmra	3.25 mas/yr +/- 0.03 mas/yr
pmdec	4.40 mas/yr +/- 0.03 mas/yr
phot_g_mean_mag	6.08 mag
radial_velocity	-27.35 +/- 0.39 km/h
distance_gspphot	109.48 pc
ruwe	0.89
ag_gspphot	0.06 mag
ag_gspphot_lower	0.06 mag
ag_gspphot_upper	0.07 mag
astrometric_chi2_al	3.6e+3
astrometric_excess_noise	0.31 mas
astrometric_excess_noise_sig	116.06
astrometric_gof_al	-3.10
astrometric_matched_transits	42.00
astrometric_n_bad_obs_al	7.00
astrometric_n_good_obs_al	363.00
astrometric_n_obs_ac	370.00

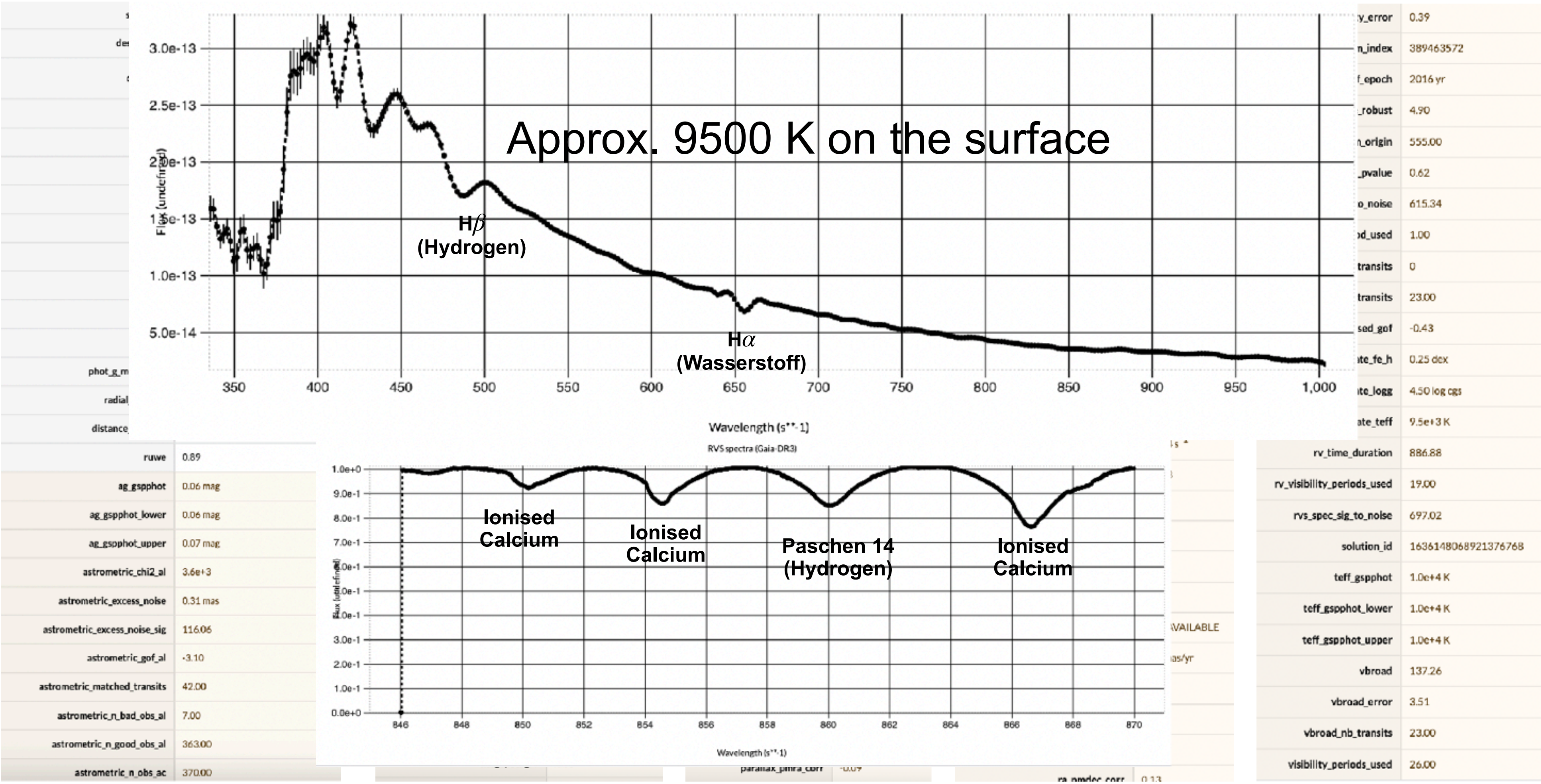
astrometric_n_obs_al	370.00
astrometric_params_solved	31.00
astrometric_primary_flag	false
astrometric_sigma5d_max	0.05 mas
azero_gspphot	0.07 mag
azero_gspphot_lower	0.06 mag
azero_gspphot_upper	0.07 mag
bp_g	-0.01 mag
bp_rp	-2.8e-3 mag
classprob_dsc_combmod_galaxy	5.8e-13
classprob_dsc_combmod_quasar	1.2e-13
classprob_dsc_combmod_star	1.00
dec_parallax_corr	0.13
dec_pmdec_corr	-0.20
dec_pmra_corr	0.07
distance_gspphot_lower	108.78 pc
distance_gspphot_upper	110.01 pc
duplicated_source	true
ebpminrp_gspphot	0.03 mag
ebpminrp_gspphot_lower	0.03 mag
ebpminrp_gspphot_upper	0.04 mag
g_rp	8.0e-3 mag
grvs_mag	6.05 mag
grvs_mag_error	5.0e-3 mag
grvs_mag_nb_transits	23.00
has_epoch_photometry	false
has_epoch_rv	false

has_mcmc_gspphot	true
has_mcmc_msc	true
has_rvs	true
has_xp_continuous	true
has_xp_sampled	true
in_andromeda_survey	false
in_galaxy_candidates	false
in_qso_candidates	false
ipd_frac_multi_peak	0
ipd_frac_odd_win	0
ipd_gof_harmonic_amplitude	0.01
ipd_gof_harmonic_phase	157.57 deg
libname_gspphot	A
logg_gspphot	3.97 log cgs
logg_gspphot_lower	3.97 log cgs
logg_gspphot_upper	3.98 log cgs
matched_transits	45.00
matched_transits_removed	16.00
mh_gspphot	-1.30 dex
mh_gspphot_lower	-1.32 dex
mh_gspphot_upper	-1.28 dex
new_matched_transits	20.00
non_single_star	0
nu_eff_used_in_astrometry	1.76 μm^{-1}
parallax_over_error	264.50
parallax_pmdec_corr	-0.16
parallax_pmra_corr	-0.09

phot_bp_mean_flux	5.1e+7 s^{-1}
phot_bp_mean_flux_error	5.1e+4 s^{-1}
phot_bp_mean_flux_over_error	1.0e+3
phot_bp_mean_mag	6.07
phot_bp_n_blended_transits	1.00
phot_bp_n_contaminated_transits	0
phot_bp_n_obs	42.00
phot_bp_rp_excess_factor	1.16
phot_g_mean_flux	7.0e+7 s^{-1}
phot_g_mean_flux_error	2.3e+4 s^{-1}
phot_g_mean_flux_over_error	3.0e+3
phot_g_n_obs	381.00
phot_proc_mode	0
phot_rp_mean_flux	3.0e+7 s^{-1}
phot_rp_mean_flux_error	2.5e+4 s^{-1}
phot_rp_mean_flux_over_error	1.2e+3
phot_rp_mean_mag	6.07
phot_rp_n_blended_transits	19.00
phot_rp_n_contaminated_transits	0
phot_rp_n_obs	39.00
phot_variable_flag	NOT_AVAILABLE
pm	5.47 mas/yr
pmra_pmdec_corr	-0.14
ra_dec_corr	-0.22
ra_parallax_corr	-0.29
ra_pmdec_corr	0.13

radial_velocity_error	0.39
random_index	389463572
ref_epoch	2016 yr
rv_amplitude_robust	4.90
rv_atm_param_origin	555.00
rv_chisq_pvalue	0.62
rv_expected_sig_to_noise	615.34
rv_method_used	1.00
rv_nb_deblended_transits	0
rv_nb_transits	23.00
rv_renormalised_gof	-0.43
rv_template_fe_h	0.25 dex
rv_template_logg	4.50 log cgs
rv_template_teff	9.5e+3 K
rv_time_duration	886.88
rv_visibility_periods_used	19.00
rvs_spec_sig_to_noise	697.02
solution_id	1636148068921376768
teff_gspphot	1.0e+4 K
teff_gspphot_lower	1.0e+4 K
teff_gspphot_upper	1.0e+4 K
vbroad	137.26
vbroad_error	3.51
vbroad_nb_transits	23.00
visibility_periods_used	26.00

Content of Gaia Data Release 3

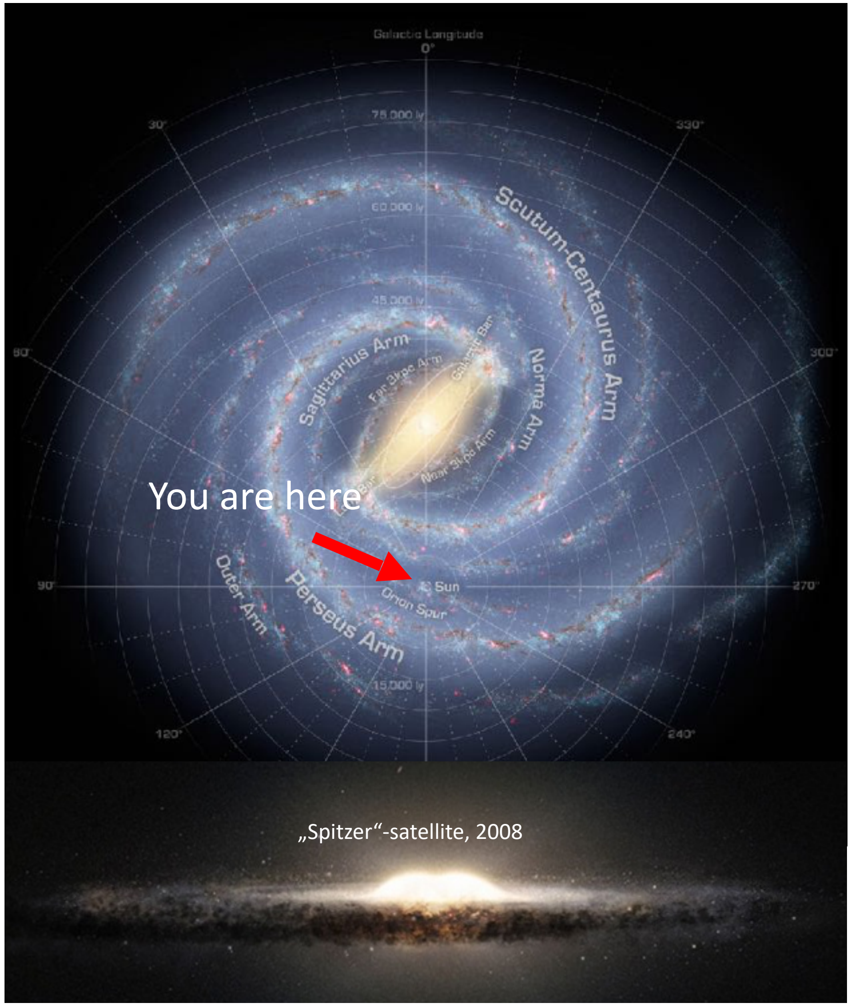


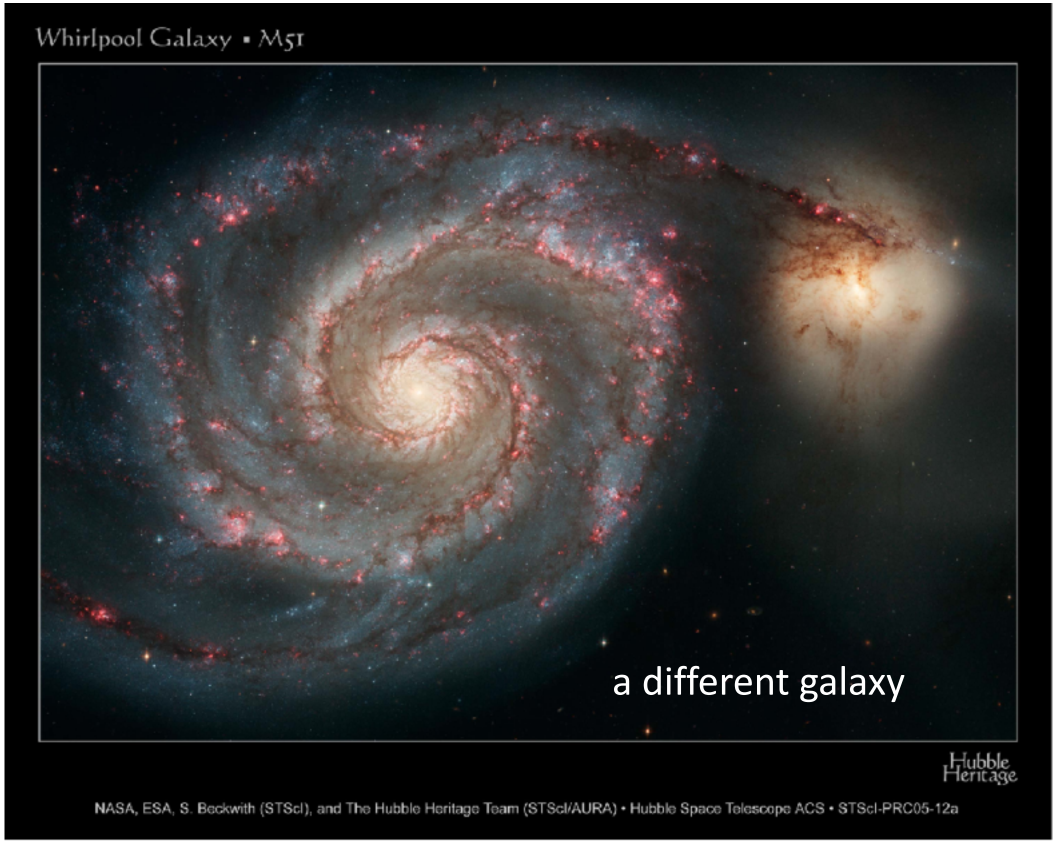
The Milky Way

https://vimeo.com/338373367

Animation: Stefan Payne-Wardenaar

The Milky Way





Our stellar system with 100-300 billion stars

Article in „Sterne und Weltraum“

WELT DER WISSENSCHAFT ASTROMETRIE

Gaias neuer Datenschatz

Dritter Katalog des Weltraumteleskops veröffentlicht

Nach dem ersten Teil von Gaias drittem Sternkatalog Ende 2020 kam nun ein großer Nachschlag dazu: Im Sommer 2022 wurden neue Beobachtungsdaten veröffentlicht, die mit dem ESA-Satelliten Gaia gewonnen wurden. Die hochpräzisen Messwerte sind relevant für alle Bereiche der Astrophysik. Hier erfahren Sie, was Forschende damit anstellen und wo Durchbrüche zu erwarten sind.

Von Stefan Jordan

Der Satellit Gaia wurde im Jahr 2013 von der Europäischen Weltraumbehörde ESA gestartet (siehe SuW 5/2013, S. 36). Das Projekt dient der Astrometrie, um wichtige Messdaten vor allem von Sternen zu sammeln, zum Beispiel ihrer Position, Entfernung, Eigengeschwindigkeit und ihres Spektrums. »Sterne und Weltraum« begleitet die Mission von Anfang an und berichtete jüngst über neue Entdeckungen, die mit dem Projekt gemacht wurden (siehe SuW 1/2021, S. 28, und SuW 4/2022, S. 18). Nach wie vor werden täglich durchschnittlich etwa fünf Forschungsarbeiten publiziert, die von den Gaia-Daten profitieren.

Diese Erfolgsgeschichte geht weiter, denn nun wurde ein großer Datensatz veröffentlicht: der dritte Gaia-Katalog (Gaia Data Release 3, kurz Gaia DR3). Die gemessenen Größen betreffen sehr unterschiedliche astronomische Objekte wie Sterne, Asteroiden, Galaxien und Quasare. Von unschätzbarem Wert ist dabei, dass die beeindruckende Zahl von einer halben Milliarde Sternen in unserer Galaxis klassifiziert werden konnten.

Gaias Stärke liegt im Messen der Positionen von Himmelsobjekten und deren Veränderungen. Aus vielen tausend Einzelmessungen an praktisch jedem Stern bis zur 21. Größenklasse können hochpräzise Standardkoordinaten, Entfernungen und Bewegungen ermittelt werden. Gaia erledigt das milliardenfach an Sternen in unserem Milchstraßensystem. Da diese astrometrischen Daten aus einem Zeitraum von 34 Monaten zusammen mit den Messungen der Sternhelligkeiten und -farben die Grundlage für alle weiteren Daten und Spezialkataloge von Gaia DR3 darstellen, wurden sie bereits im Dezember 2020 veröffentlicht. In diesem Early Data Release 3 (Gaia EDR 3) konnte die ohnehin schon hohe Genauigkeit der Gaia-Entfernungen gegenüber Gaia DR2 noch einmal um 30 Prozent verbessert werden. Bei Sternen 13. Größe beträgt diese etwa 30 millionstel Bogensekunden (Mikrobogensekunden; 1 Bogensekunde = 1/3600 Grad), was einer Verschiebung von 5,5 Zentimetern in der Entfernung des Mondes entspricht. Bei den Eigenbewegungen ergab sich sogar eine Verbesserung der Genauigkeit um einen Faktor zwei.

Am 13. Juni 2022 konnten nun auch die restlichen Teile von Gaia DR3 veröffentlicht werden. Wie facettenreich ihr Charakter ist, demonstrieren einige Kennzahlen in nebenstehender Tabelle.

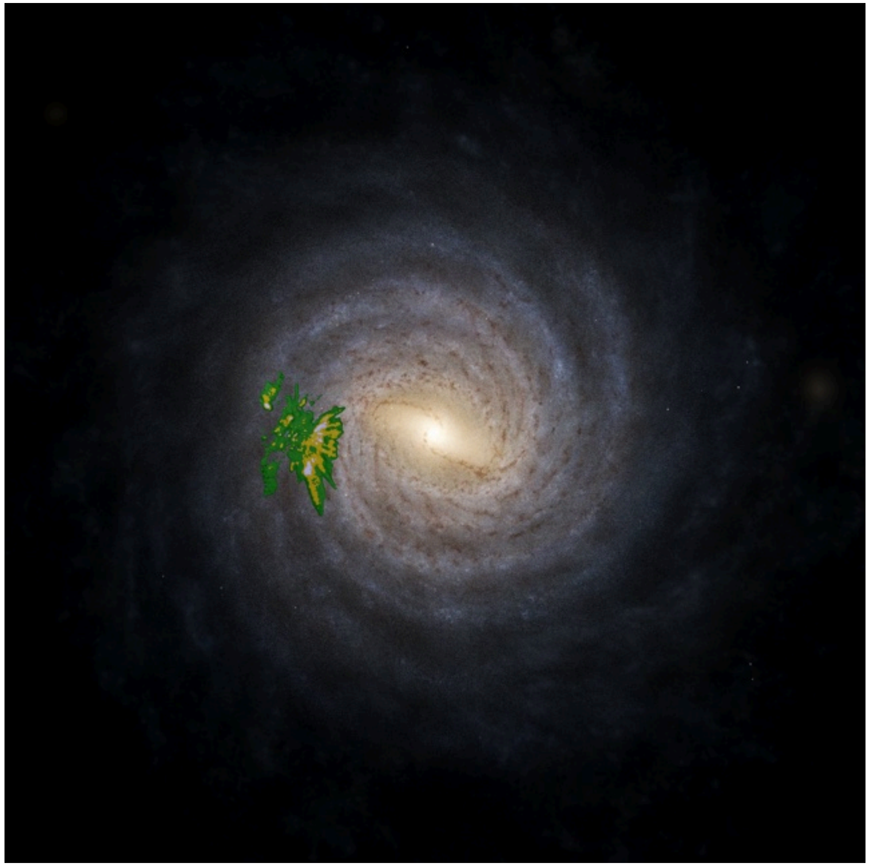
Zusammen mit den Messergebnissen wurden vom Gaia-Team auch neun wissenschaftliche Arbeiten im europäischen Fachjournal »Astronomy and Astrophysics« veröffentlicht. Die Nutzerinnen und Nutzer des Katalogs erfahren darin anhand von Beispielen, welches Poten-

Gesamtzahl der Objekte	1811709771
	Schon im Gaia Early Data Release 3
Eigenbewegungen und Parallaxen	1467744818
Quasare 1)	1614173
Helligkeiten	1806254432
	Neu im Gaia Data Release 3
Radialgeschwindigkeiten	33812183
Helligkeiten 2)	32232187
Rotations-geschwindigkeiten	3524677
Niedrig aufgelöste Photometerspektren	219197643
Hochaufgelöste RVS-Spektren	999645
Analysen variabler Sterne	10509536
Klassifizierte Himmelsobjekte	1590760469
Mehrfachsternsysteme	813687
Quasare 3)	6649162
Galaxien 3)	4842342
Objekte im Sonnensystem 4)	158152

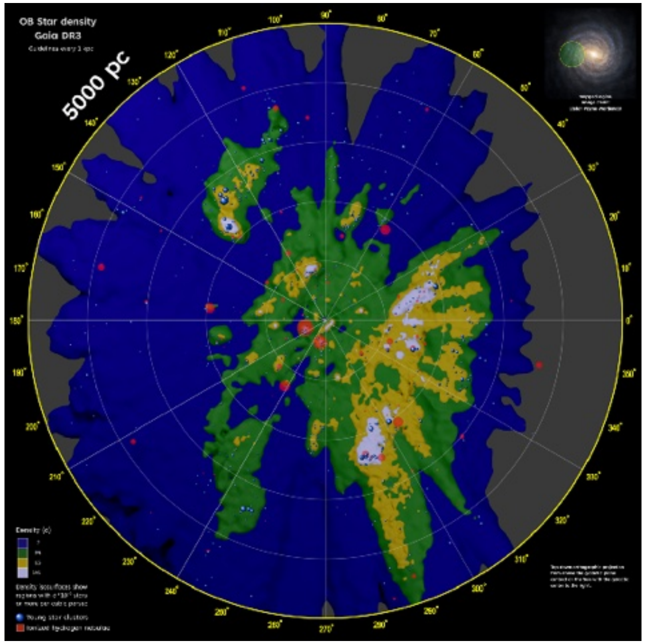
1) zur Definition des Internationalen Himmelsreferenzsystems
2) mit dem Radialgeschwindigkeitsspektrometer (RVS)
3) Kandidaten
4) Asteroiden und Planetenmonde

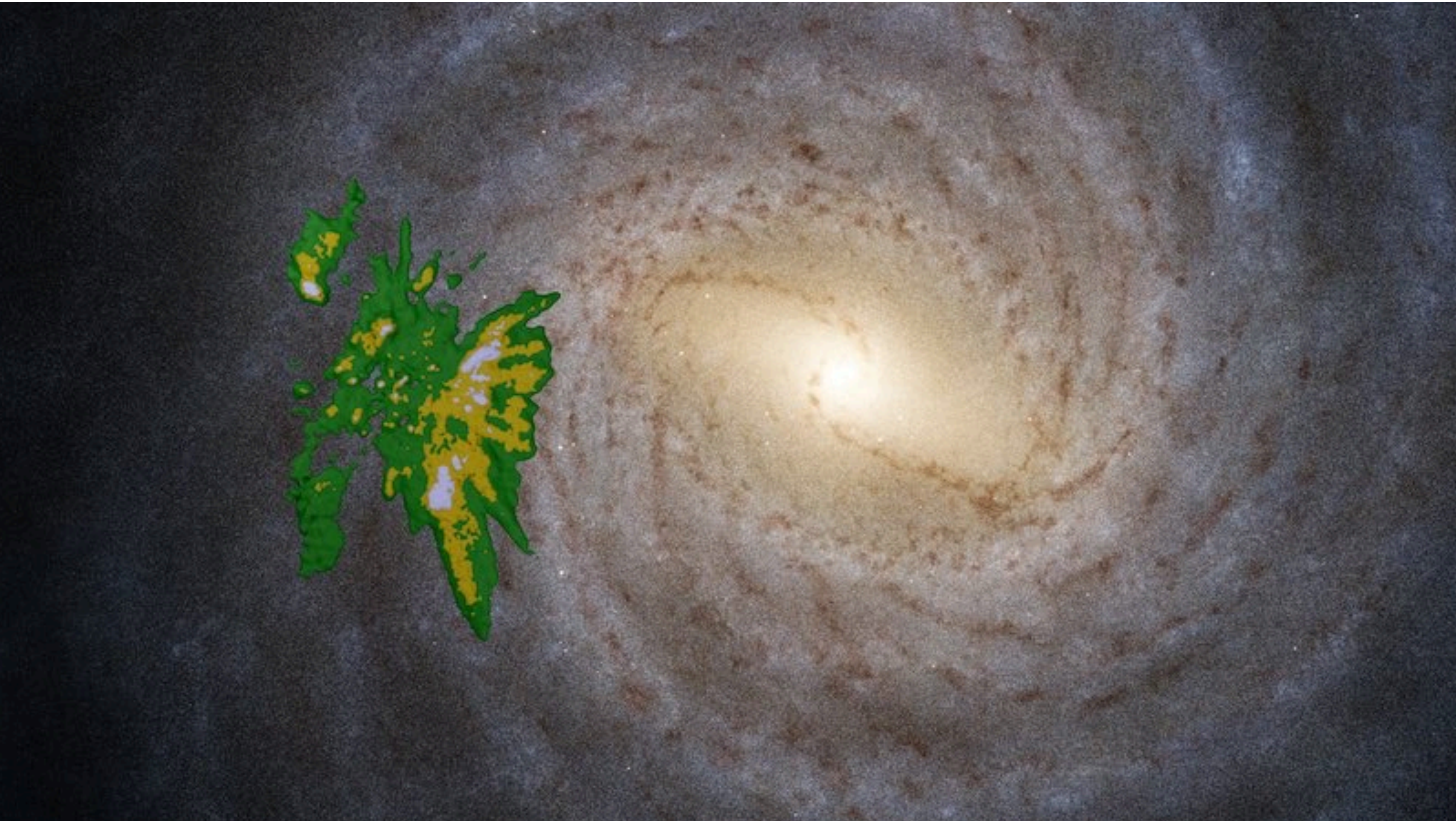
Gaia's new treasure trove of (astronomical) data

The structure of our Milky Way

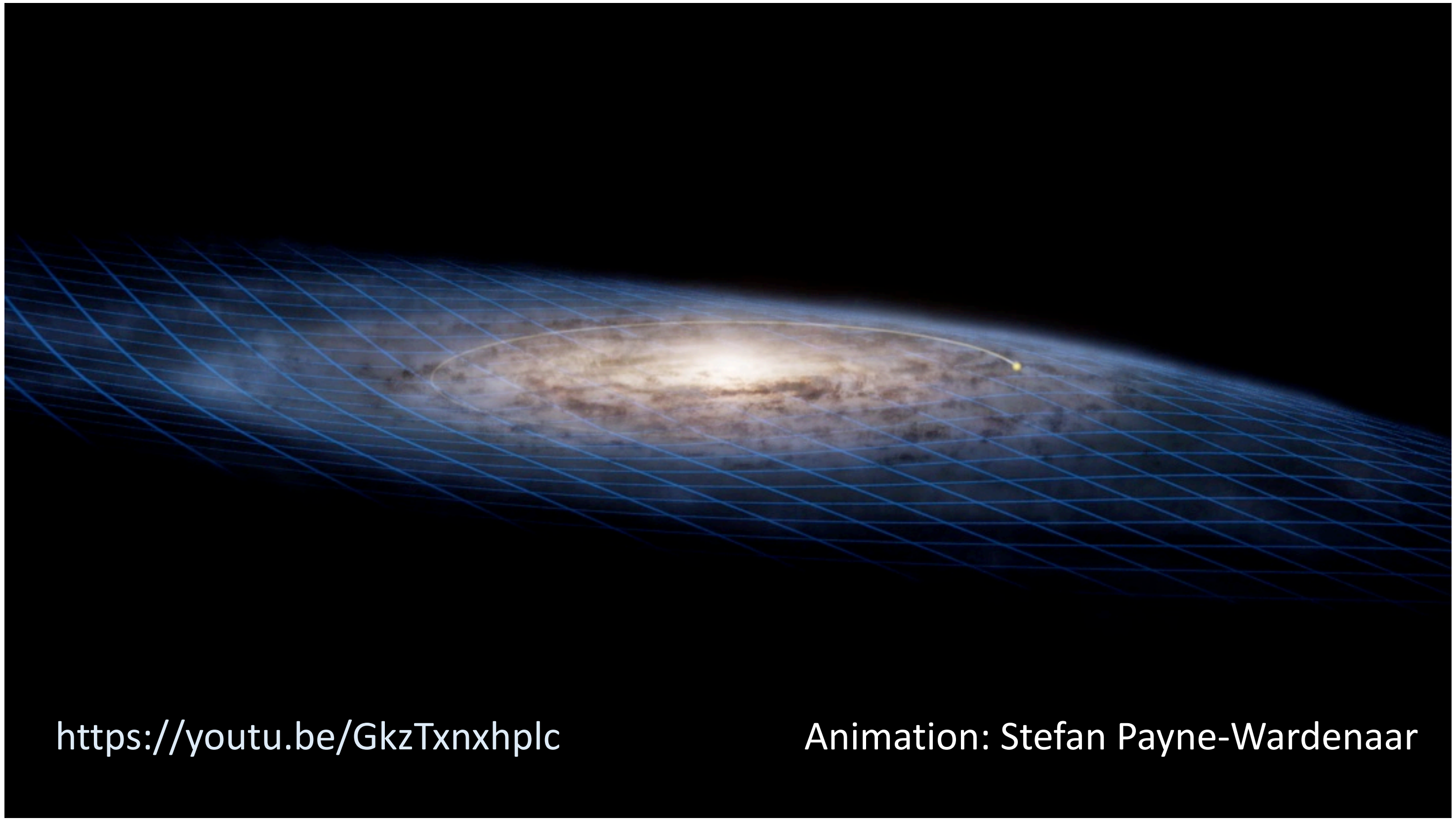


The overlay was created by Kevin Jardine based on Gaia-DR3 data. The artistic impression of the Milky Way in the background was created by Stefan Payne-Wardenaar.

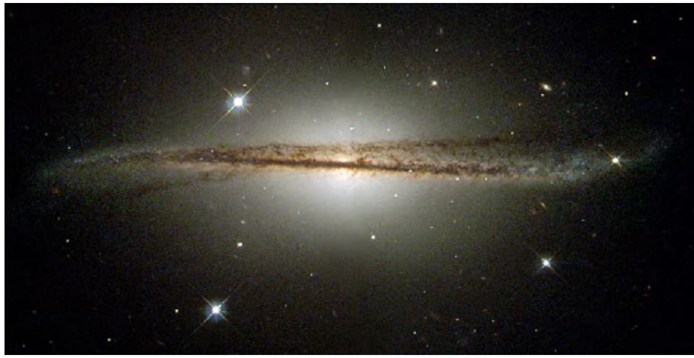




The ‘warped Milky Way’



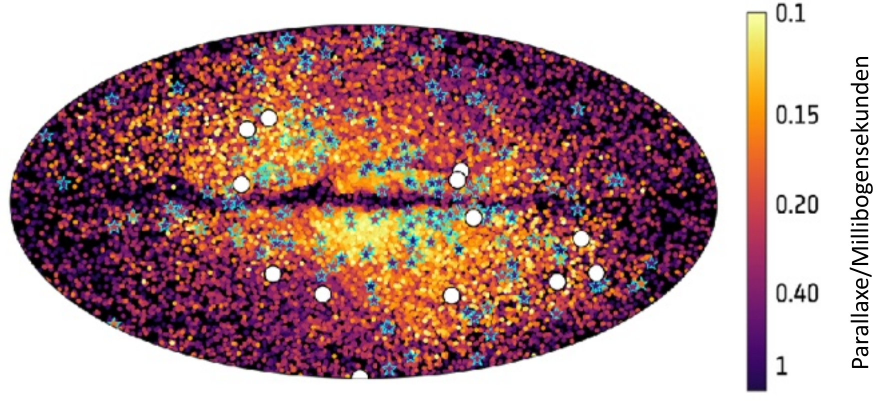
“Evidence of a dynamically evolving Galactic warp”, Eloisa Poggio et al., 2020, *Nature Astronomy*. https://arxiv.org/pdf/1912.10471.pdf



The disc of this spiral galaxy (ESO 510-13) ,150 million light years away, is even more bent than our Milky Way

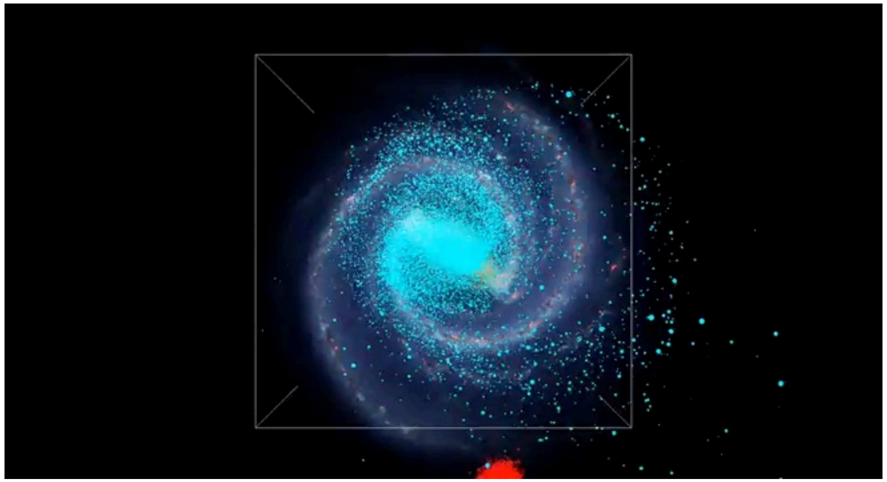
Gaia-Enceladus

- Helmi et al., 2018, Nature, arXiv:1806.06038
  „The merger that led to the formation of
  the Milky Way's inner stellar halo and thick disk“
- 7 million stars with 3D positions +3D speeds
- 30,000 stars with elongated orbits moving in the opposite direction to the majority of stars in our Milky Way
- Different chemical composition than most stars in our galaxy
- Debris from a galaxy that merged with our Milky Way in its early formation phase (about 10 billion years ago)
- Mass approx. 1/10 of the current Milky Way, 1/4 of the mass 10 billion years ago
- „Gaia-Enceladus“



ESA/Gaia/DPAC; A. Helmi et al 2018

White circles show globular clusters with similar orbits

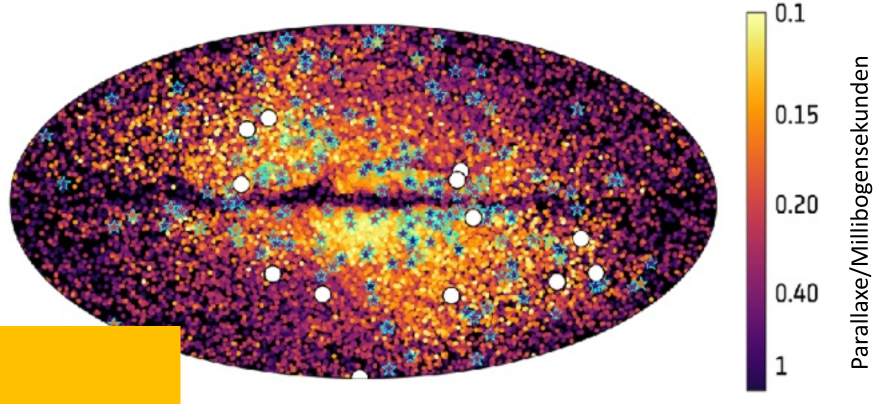


Koppelman, Villalobos & Helmi, Kapteyn Astronomical Institute, University of Groningen, Niederlande

Gaia-Enceladus

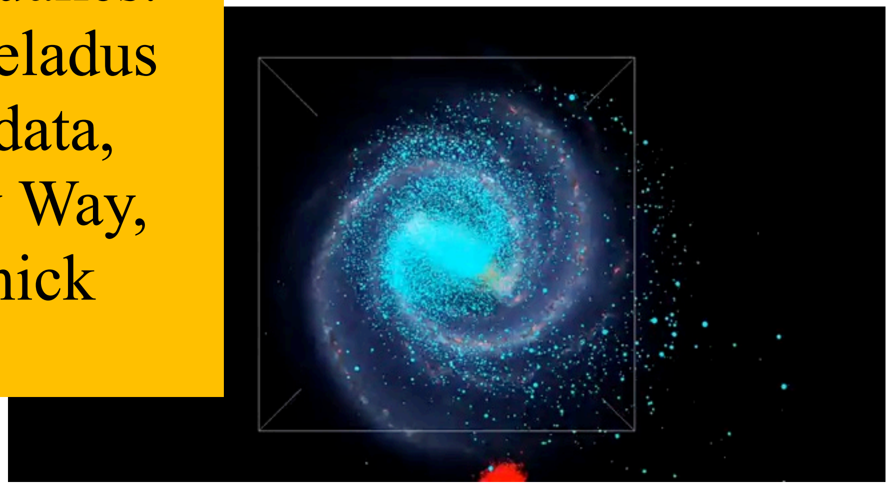
- Helmi et al., 2018, Nature, arXiv:1806.06038
  „The merger that led to the formation of
  the Milky Way's inner stellar halo and thick disk“
- 7 million sta
- 30,000 stars
  opposite dire
  Way
- Different che
  galaxy
- Debris from
  its early form
- Mass approx
  mass 10 billi
- „Gaia-Encela

Amina Helmi:
„According to the legend, Enceladus was buried under Mount Etna, in Sicily, and responsible for local earthquakes. Similarly, the stars of Gaia-Enceladus were deeply buried in the Gaia data, and they have shaken the Milky Way, leading to the formation of its thick disk.“



C; A. Helmi et al 2018

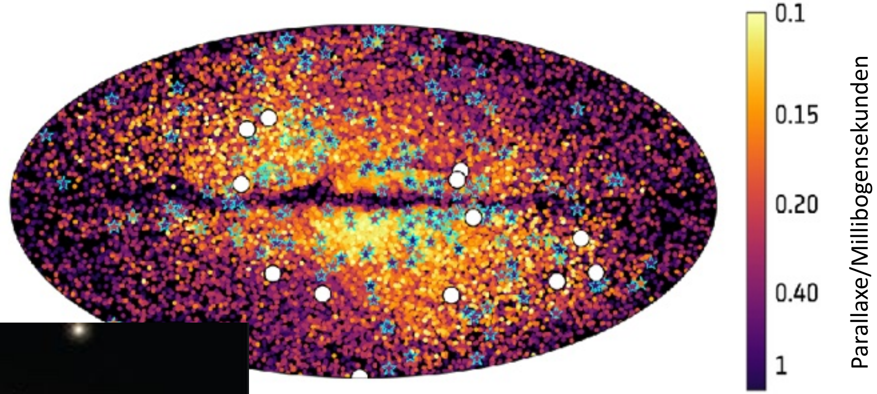
ow globular clusters with similar orbits



Koppelman, Villalobos & Helmi, Kapteyn Astronomical Institute,
University of Groningen, Niederlande

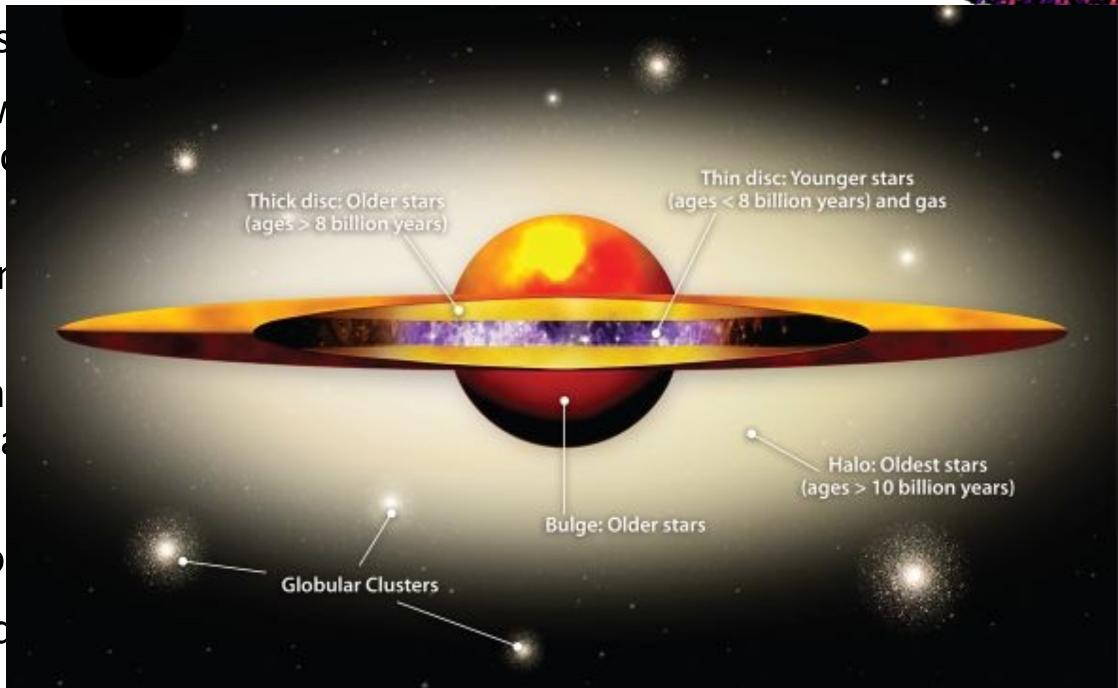
Gaia-Enceladus

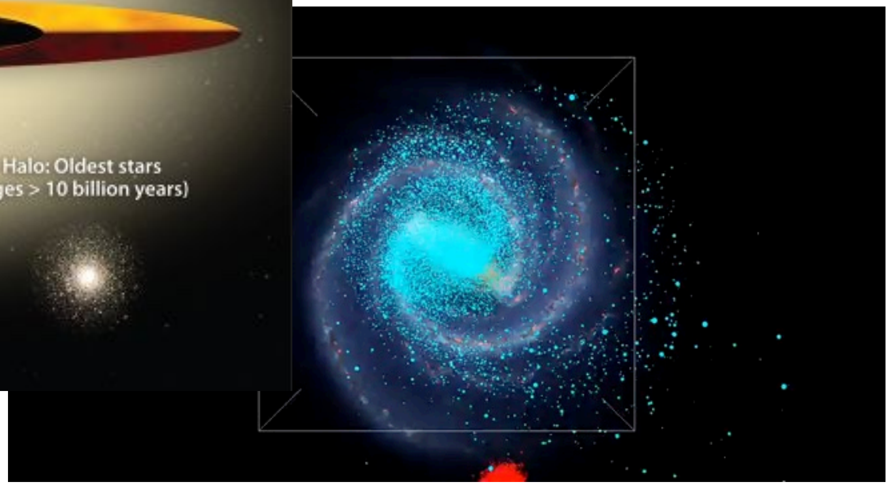
- Helmi et al., 2018, Nature, arXiv:1806.06038
„The merger that led to the formation of
the Milky Way's inner stellar halo and thick disk“
- 7 million stars
- 30,000 stars w
opposite direc
Way
- Different cher
galaxy
- Debris from a
its early forma
- Mass approx.
mass 10 billio
- „Gaia-Encelad



Helmi et al 2018

obular clusters with similar orbits

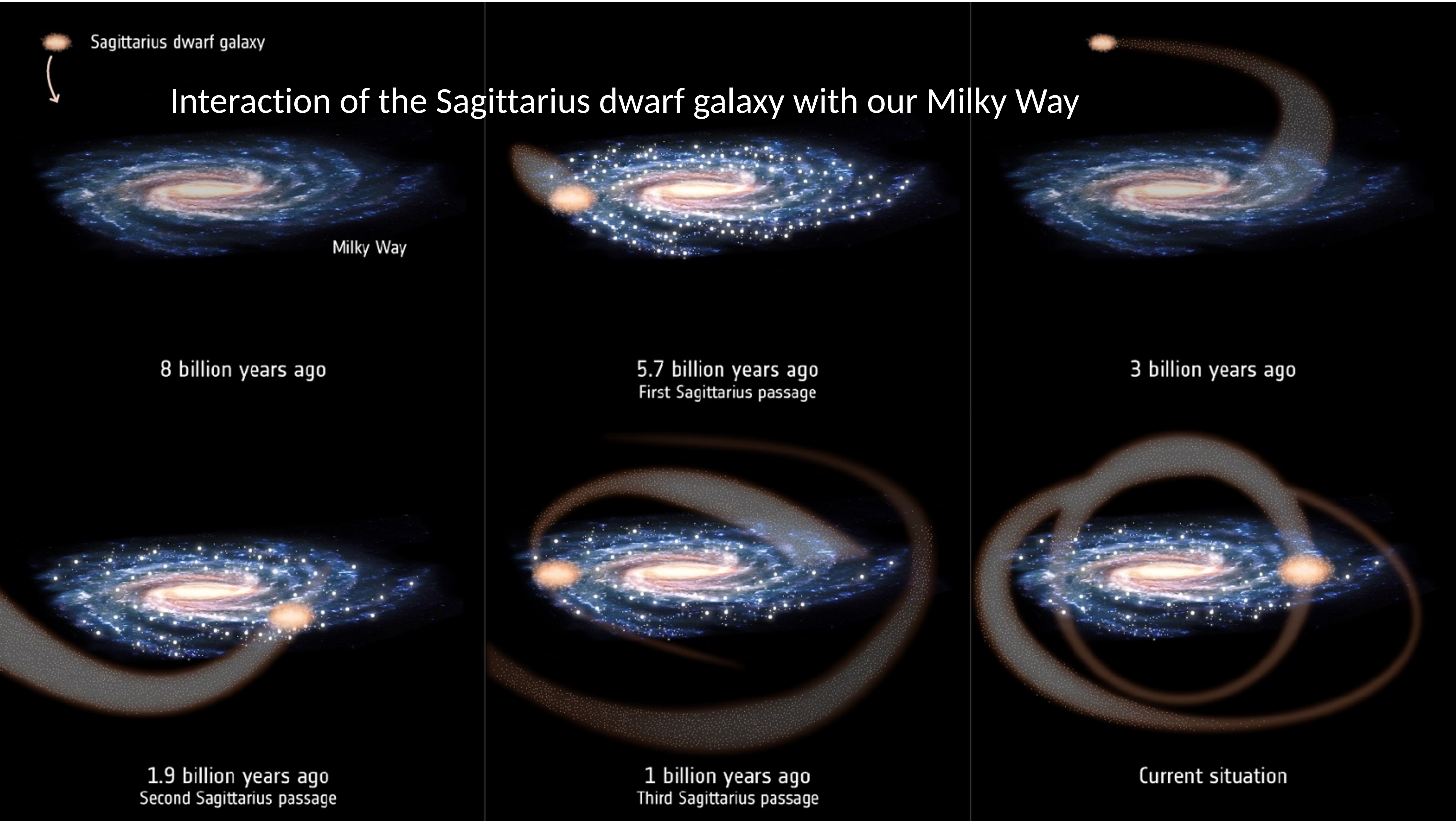




Koppelman, Villalobos & Helmi, Kapteyn Astronomical Institute,
University of Groningen, Niederlande

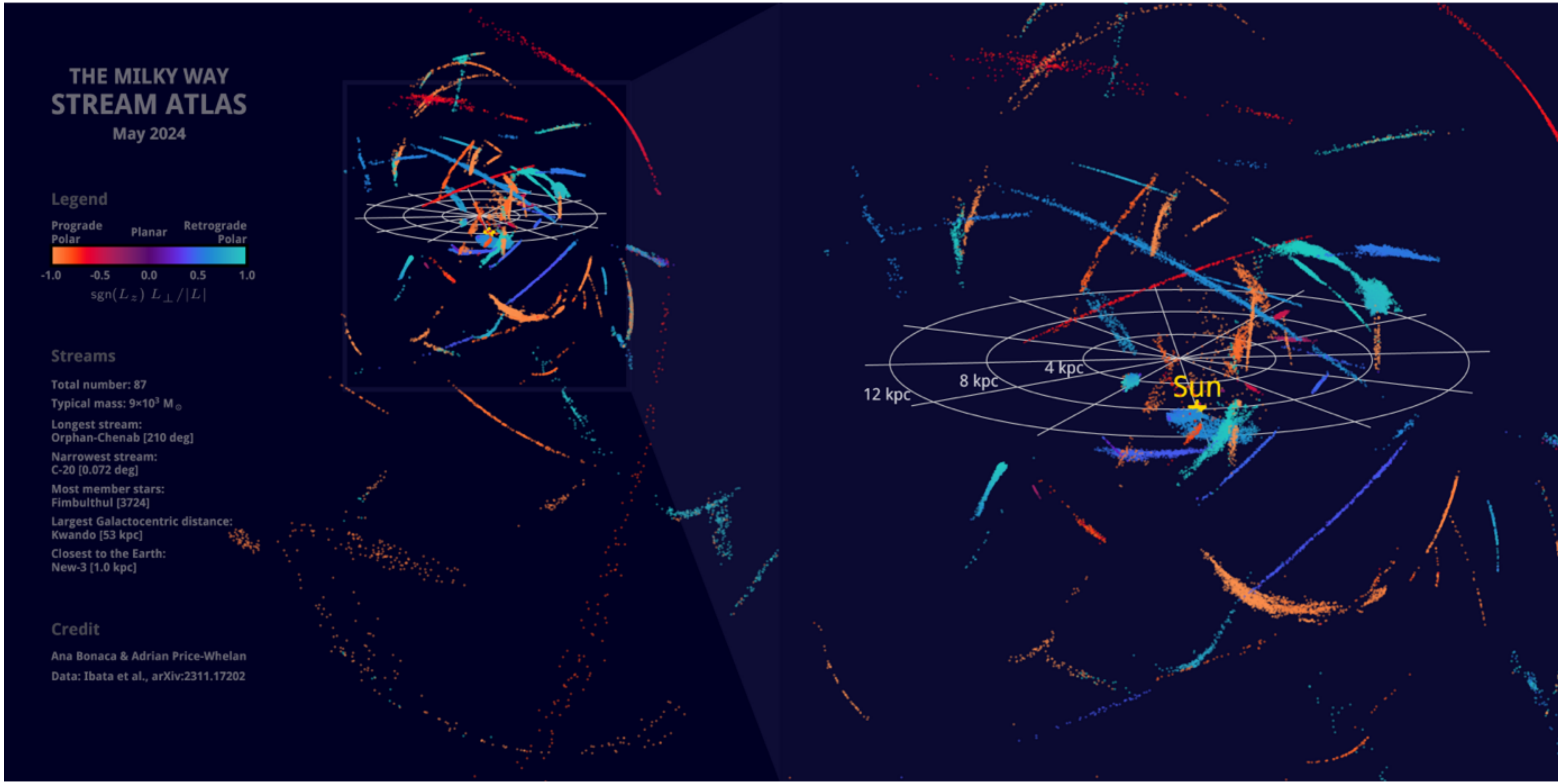
Interaction of the Sagittarius dwarf galaxy with our Milky Way

https://sci.esa.int/web/gaia/-/dwarf-galaxy-collisions-make-stars-from-in-milky-way


Sagittarius dwarf galaxy
Interaction of the Sagittarius dwarf galaxy with our Milky Way
Milky Way
8 billion years ago
5.7 billion years ago
First Sagittarius passage
3 billion years ago
1.9 billion years ago
Second Sagittarius passage
1 billion years ago
Third Sagittarius passage
Current situation

Stellar Streams

More than a hundred stellar streams have been discovered and characterized using Gaia data.



Black Holes

- A black hole is an astronomical object with such strong gravity that nothing, not even light, can escape from it. It is created when a huge mass is compressed into a small amount of space.
- There are supermassive black holes that are located at the centre of galaxies and have millions to billions of times more mass than our sun.
- These are the famous 'pictures' of two of them.

First direct image of a supermassive black hole
found in the galactic core of Messier 87
(2.4 billion solar masses, distance: 50 million light years, Wikipedia)

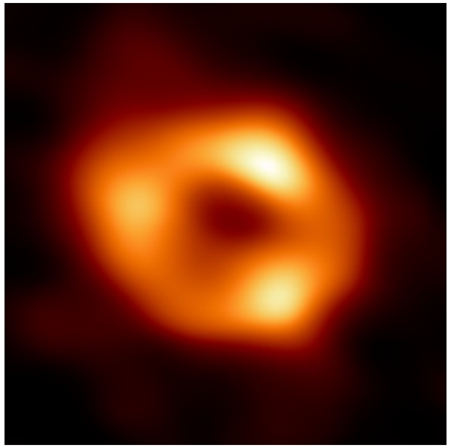


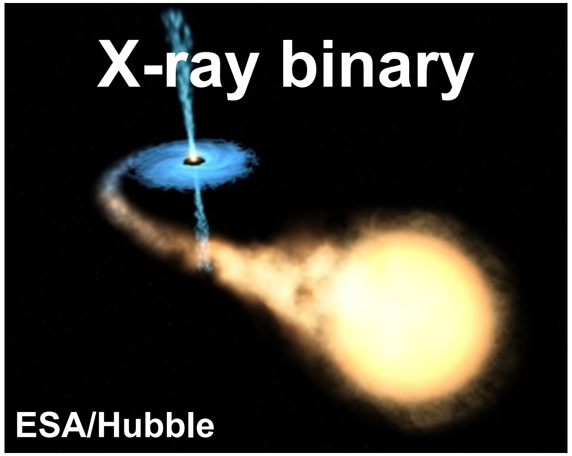
Image of Sgr A*, the supermassive black hole
at the centre of our Milky Way
(4 million solar masses, distance: 27,000 light years, Wikipedia)

Stellar Black Holes

- Stars with masses above approx. 25 solar masses end with a supernova explosion, creating a black hole.
- Their mass can be between 3.5 and about 20 times the mass of our sun.
- Around 50 suspected or confirmed stellar-mass black holes have been discovered in the Milky Way.
- How?

Stellar Black Holes

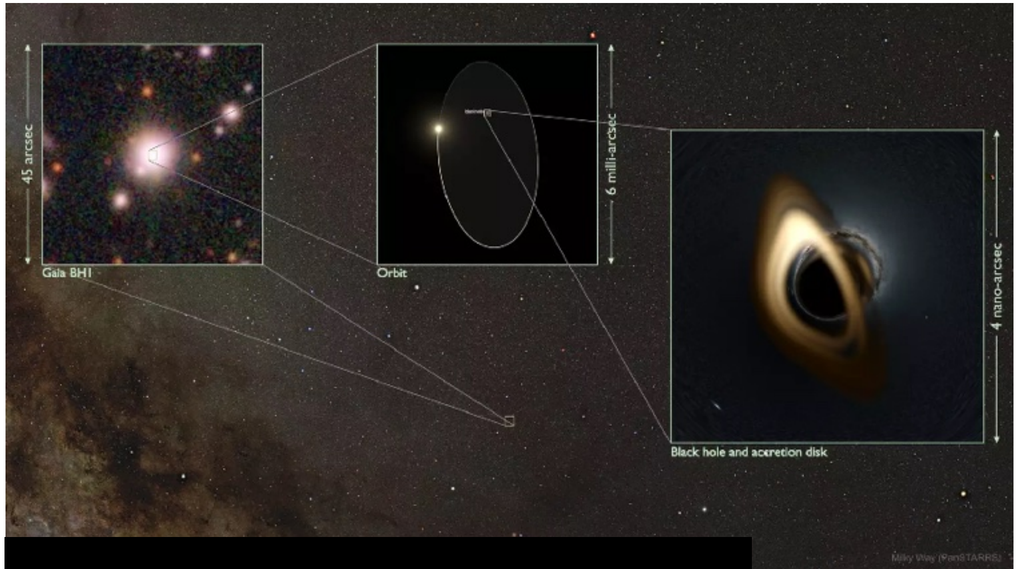
- Stars with masses above approx. 25 solar masses end with a supernova explosion, creating a black hole.
- Their mass can be between 3.5 and about 20 times the mass of our sun.
- Around 50 suspected or confirmed stellar-mass black holes have been discovered in the Milky Way.
- How?
- If the black hole is located in a very close binary star system, a companion star can pull matter towards the black hole.
- In this process, a so-called accretion disc forms around the black hole.
- The impact of the mass and the friction produce X-rays, which can easily detect such systems.

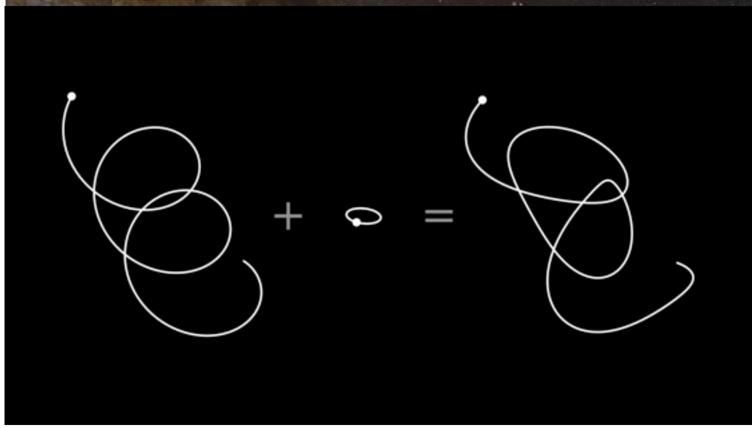


Gaia's first discovery of a black hole

- Discovered as a possible black hole in Gaia DR3
- 1560 light years away
- A sun-like star orbits Gaia BH-1 every 186 days
- Measurement of radial velocity with 6 different instruments
- 10 solar masses
- ‘Dormant’ black hole

El-Badry et al., 2023, “*A Sun-like star orbiting a black hole*”, in the *Monthly Notices of the Royal Astronomical Society*, https://arxiv.org/pdf/2209.06833.pdf





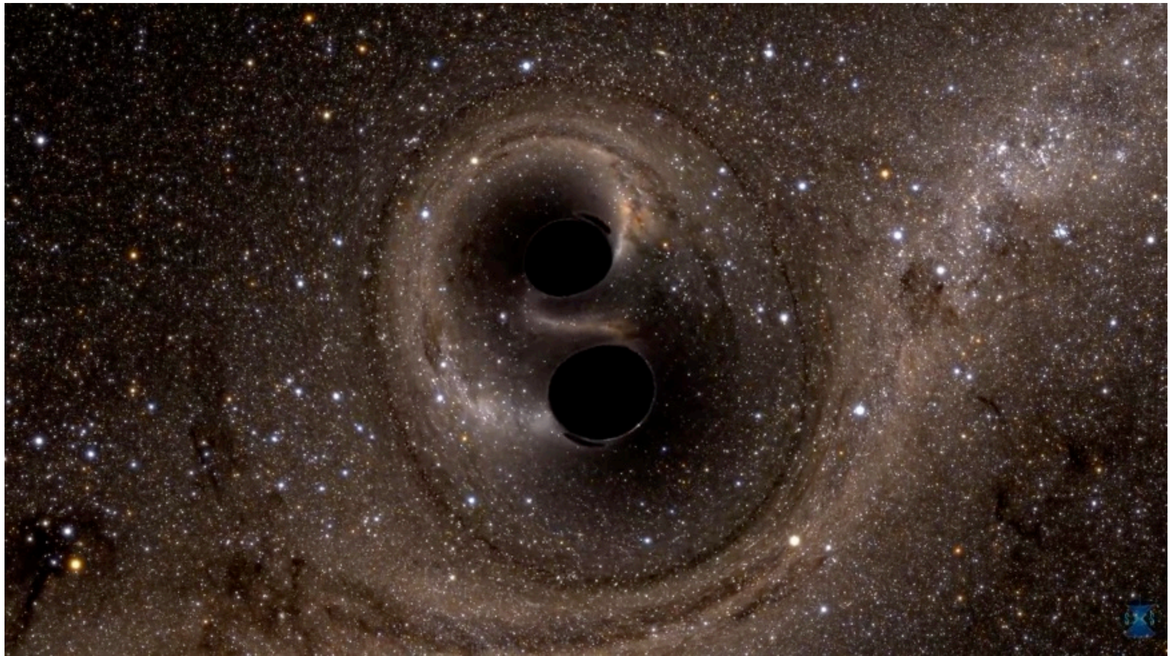
Second black hole discovered by Gaia

- Gaia BH2 (Gaia DR3 5870569352746779008) is a binary star system consisting of a red giant and a stellar black hole
- 3,800 light years (1.16 kpc) away
- The black hole and the red giant orbit the barycentre of the system every 1,276 days
- The mass of the black hole is about 9 solar masses
- Red giant: approx. 1 solar mass, 7 solar radii.

- El-Badry et al., 2023, “*A red giant orbiting a black hole*, in the *Monthly Notices of the Royal Astronomical Society, 512, 4323* , https://ui.adsabs.harvard.edu/link_gateway/2023MNRAS.521.4323E/EPRINT_PDF

Stellar Black Holes

- Stars with masses above approx. 25 solar masses end with a supernova explosion, creating a black hole.
- Their mass can be between 3.5 and about 20 times the mass of our sun.
- However, black holes with larger masses have been discovered!
- When two black holes orbit each other and merge, gravitational waves are generated.
- In February 2016, it was announced for the first time that such a signal could be observed for the first time with two laser interferometers in the USA.
- Distance of these objects: several hundred million to several billion light years!

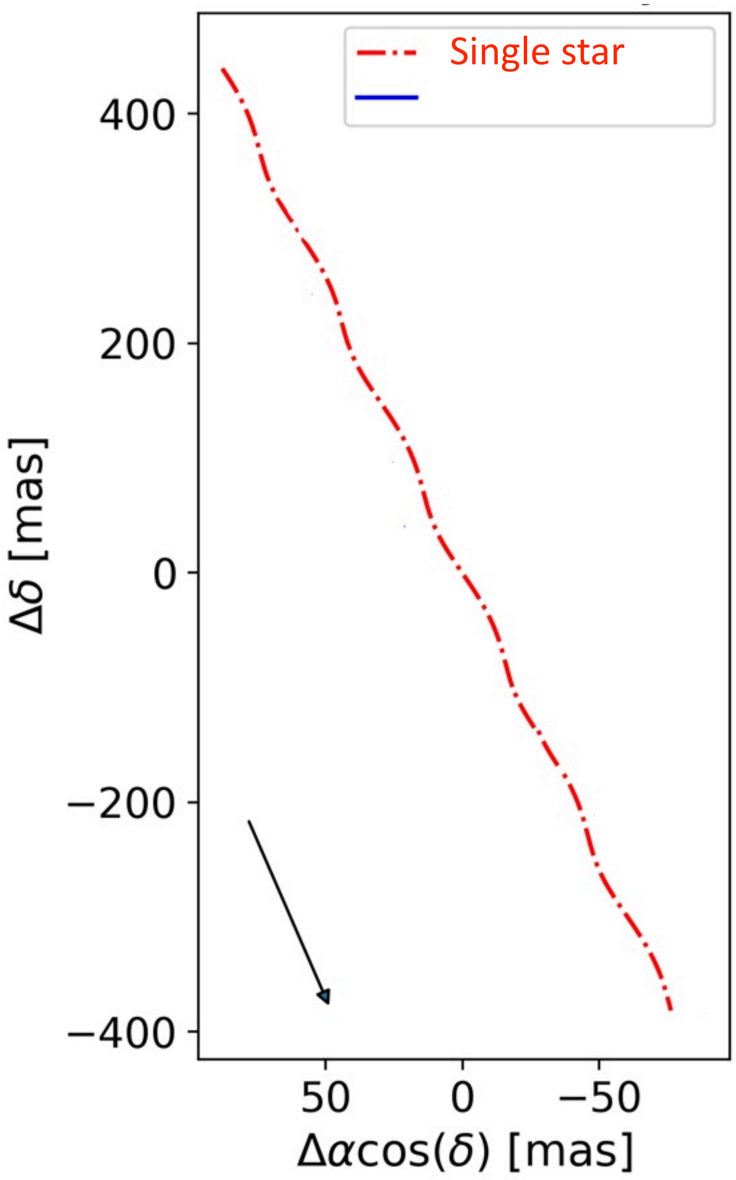


LIGO Lab Caltech: MIT

[redacted]

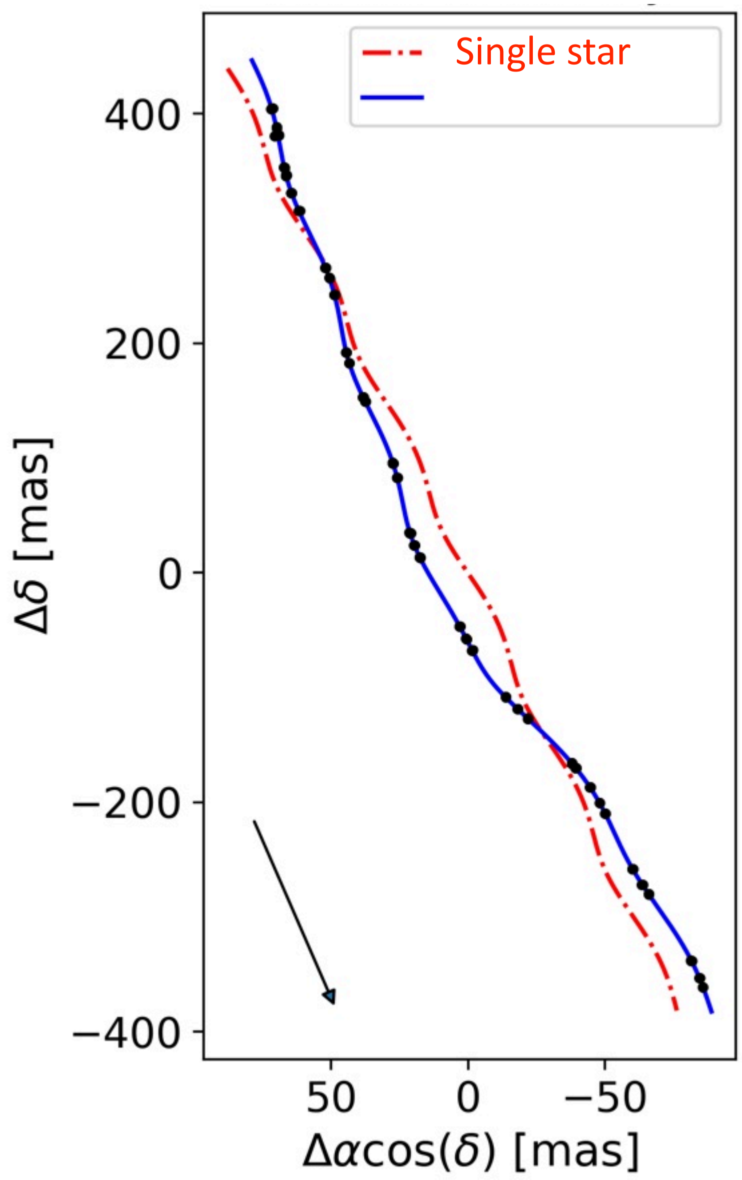
‘Dormant’ black holes

- What if there is no matter far and wide around a black hole that can be ‘ captured’ by it?



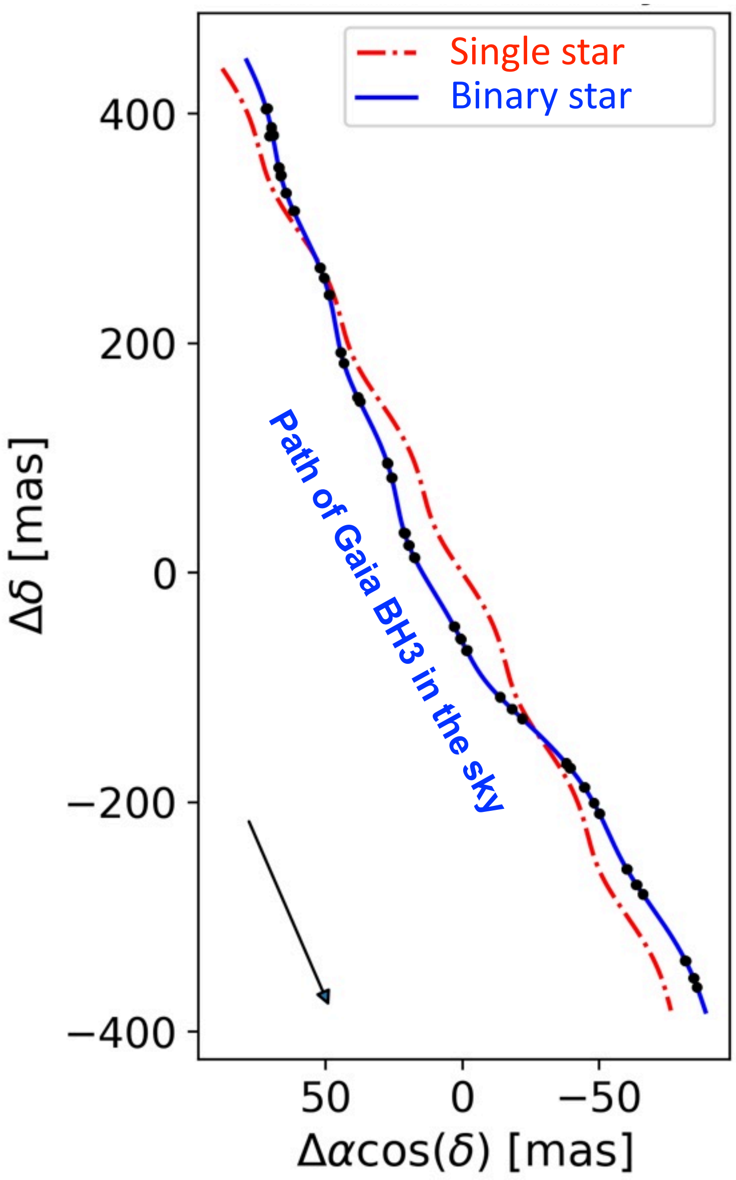
‘Dormant’ black holes

- What if there is no matter far and wide around a black hole that can be ‘ captured’ by it?
- Then it can be discovered even if it is located in a ‘wide’ binary star system.
- This is because both orbit their common centre of gravity.
- The companion star then does not simply fly straight ahead (or on an orbit in our Milky Way.
- In many cases, Gaia is an excellent tool for measuring the motion of a star!
- The black hole causes the companion star to perform an additional wobbling motion.



‘Dormant’ black holes

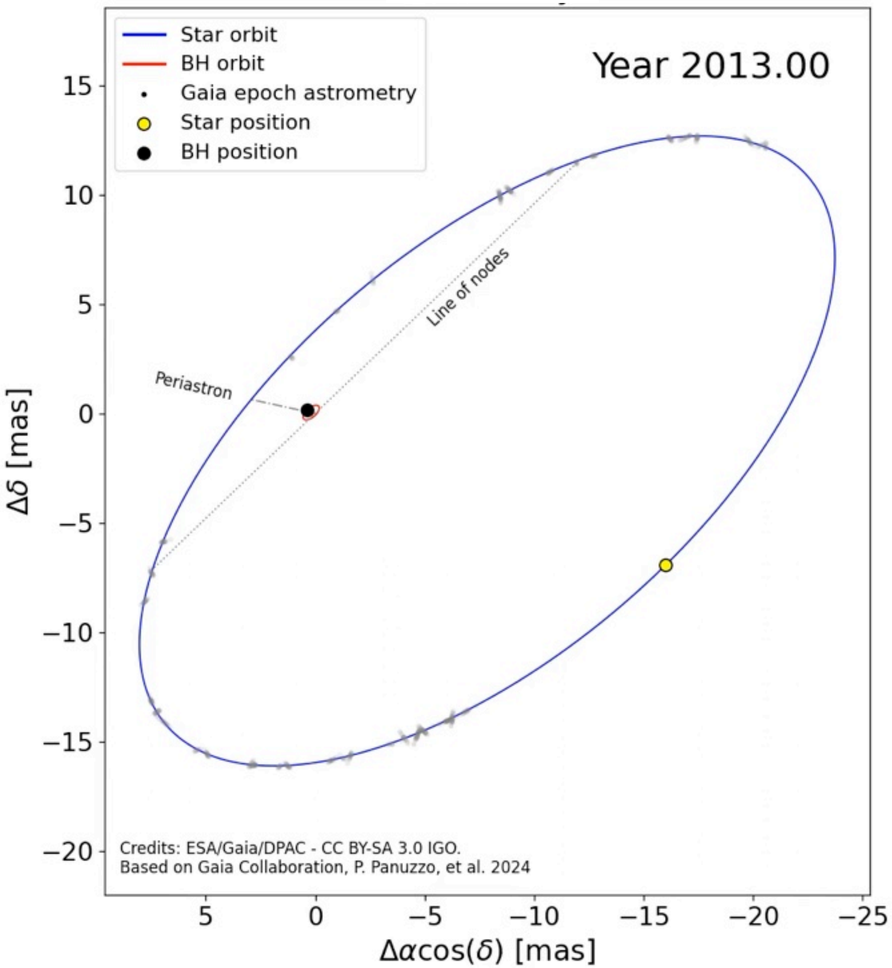
- What if there is no matter far and wide around a black hole that can be ‘ captured’ by it?
- Then it can be discovered even if it is located in a ‘wide’ binary star system.
- This is because both orbit their common centre of gravity.
- The companion star then does not simply fly straight ahead (or on an orbit in our Milky Way.
- In many cases, Gaia is an excellent tool for measuring the motion of a star!
- The black hole causes the companion star to perform an additional wobbling motion.
- The discovery of Gaia BH3 was announced on 16 April 2024!



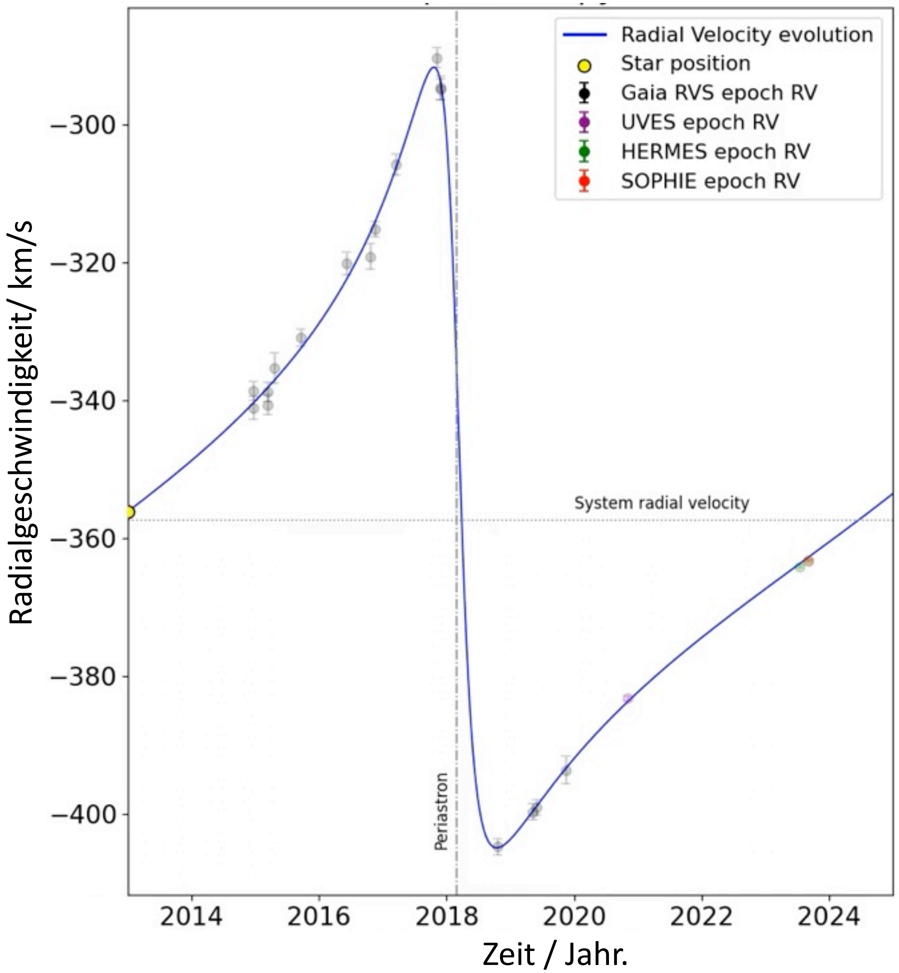
Video on the discovery of Gaia BH3

Gaia BH3

Astrometry



Spectroscopy

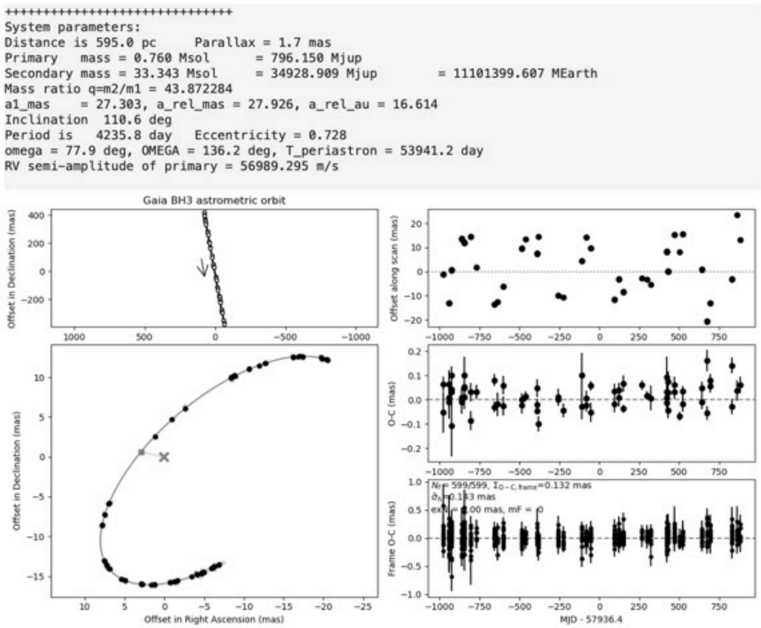


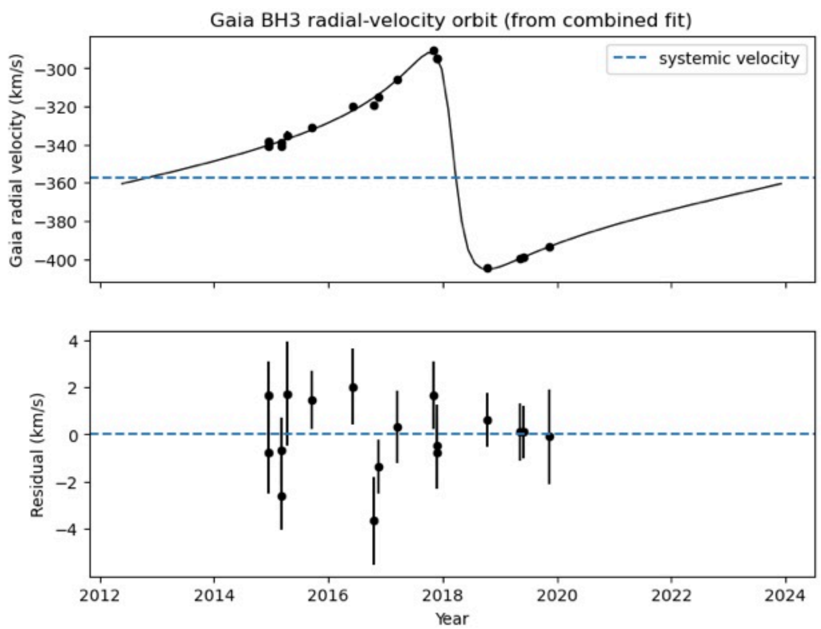
Gaia BH3

- **What is special about the Gaia BH3 system?**
  - With 33 solar masses, it matches the masses of the black holes discovered with gravitational wave detectors perfectly
  - The companion star has a low metallicity (contains only small amounts of heavier elements) and thus presumably also the progenitor star of the black hole
  - This probably meant that the massive progenitor star lost less mass in the course of the star's life than stars with high metallicity
  - It is possibly the remnant of a globular cluster, which also belongs to the galactic halo
  - It is by far the densest black hole in the mass range above 20 solar masses. The nearest one is several million times further away.
  - The companion star is very bright: 100 times fainter than can be seen with the naked eye and 10,000 times brighter than the faintest star that can be recognised with Gaia.
  - ...

Analysis of Gaia measurement time series that led to the discovery of the black hole Gaia BH3

- https://github.com/esa/gaia-bhthree/blob/main/README.md
- Unter Binder laufen lassen: https://mybinder.org/v2/gh/esa/gaia-bhthree/1.0.0?labpath=Gaia_BH3_fit_astrometric_orbit.ipynb





Gaia Papers

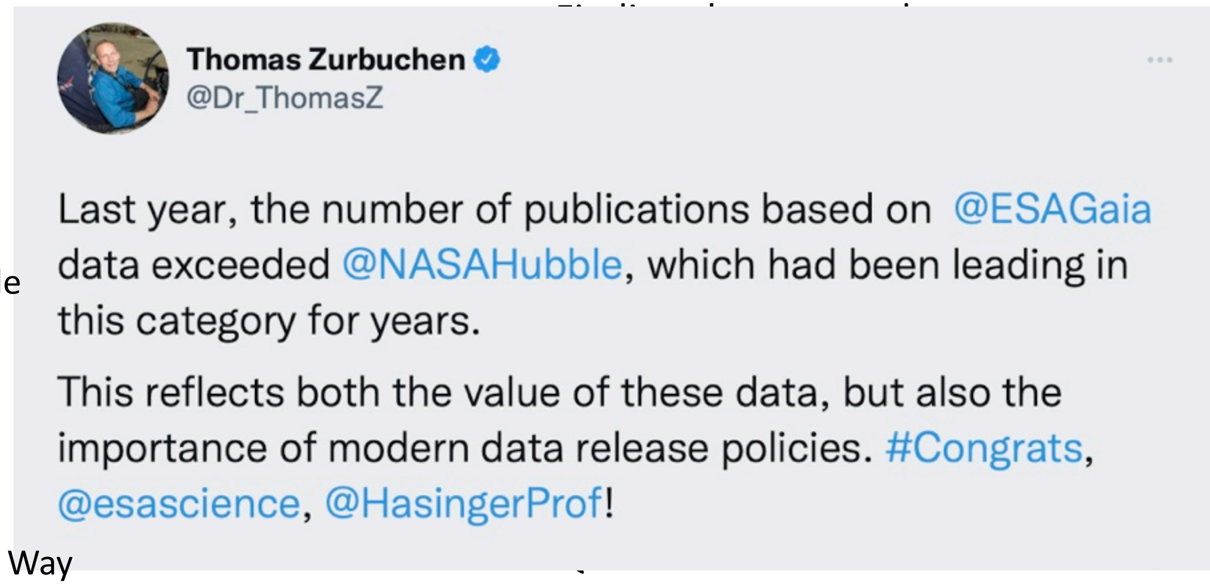
Asteroids
White dwarfs
Cepheids
Cataclysmic variables
Magnetic stars
AGB stars
RR Lyrae Stars
Red Giant Stars
Luminous Blue Variable
Red Clump Stars
High Velocity Stars
Microlensing events
Exoplanet radii
Stellar Dynamics
Structure of the Milky Way
Bolometric corrections
Star-forming regions
Distances and kinematics of pulsars
Double stars for gravitational wave detection (LISA)

Luminosities of exoplanet stars
Discovery of open star clusters
Finding cluster members
Age of stars
Gaia photometry
Stellar distances
Asteroseismology
Kinematics, age, and metallicities of star clusters
Detecting and analysing tidal streams
Galactic disc
Investigating the Milky Way halo
Motion of Milky Way satellites and galaxies in the local group
Quasars
Hubble constant
Reference system
Planetary nebulae
Dark Matter

Gaia Papers

Asteroids
White dwarfs
Cepheids
Cataclysmic variables
Magnetic stars
AGB stars
RR Lyrae Stars
Red Giant Stars
Luminous Blue Variable
Red Clump Stars
High Velocity Stars
Microlensing events
Exoplanet radii
Stellar Dynamics
Structure of the Milky Way
Bolometric corrections
Star-forming regions
Distances and kinematics of pulsars
Double stars for gravitational wave detection (LISA)

Luminosities of exoplanet stars
Discovery of open star clusters
ar clusters
axies in the local group
Hubble constant
Reference system
Planetary nebulae
Dark Matter



Gaia Papers **About five refereed papers per day!**

Asteroids
White dwarfs

Luminosities of exoplanet stars
Discovery of open star clusters

Year	all Gaia publications	Refereed publications
2016	22 = 0.06 per day	17 = 0.05 per day
2017	172 = 0.47	139 = 0.38
2018	871 = 2.39	665 = 1.82
2019	1958 = 5.36	1647 = 4.51
2020	1924 = 5.26	1668 = 4.55
2021	2148 = 5.88	1857 = 5.09
2022	2334 = 6.39	1951 = 5.34
2023	2258 = 6.19	1769 = 4.85
2024	965 = 7.42 (up to 10.5.2024)	631 = 4.85 (up to 10.5.2024)

of star clusters
ams
nd galaxies in the local group

Distances and kinematics of pulsars
Double stars for gravitational wave detection (LISA)

Reference system
Planetary nebulae
Dark Matter

Gaia and Dark Matter

Stellar Streams probe the Galactic potential

- Precise parallaxes and proper motion
- Stellar streams probe the galactic potential also in the halo
- Oblateness of DM halo
- Clumpiness of DM halo

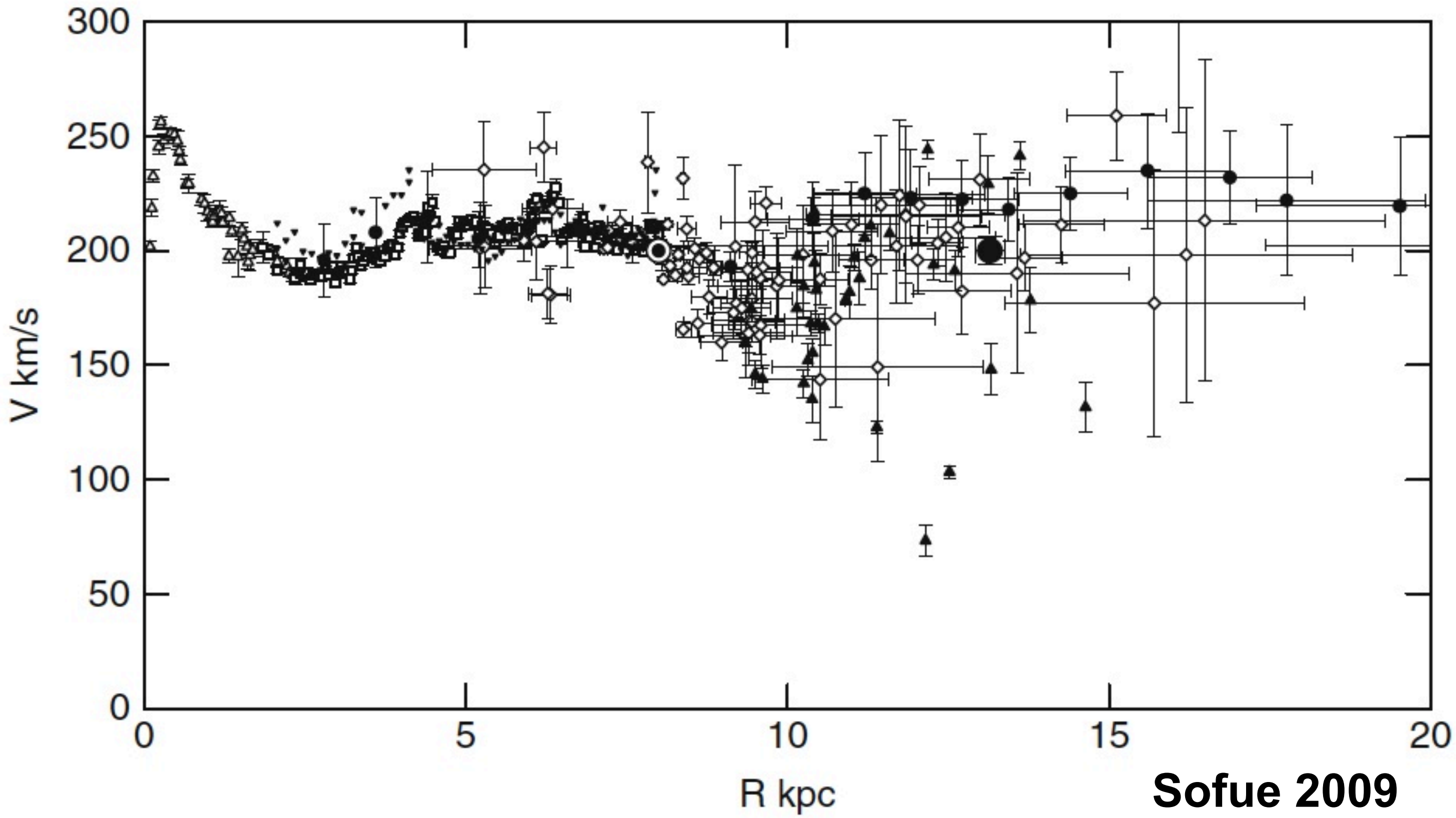
Gaia and Dark Matter

- The only way we've detected dark matter is through it's gravitational effects
- We can find the dark matter density by finding the gravitational potential (and subtracting off the baryonic contribution)

$$\nabla^2\Phi = 4\pi G(\rho_b + \rho_{DM})$$

Gaia and Dark Matter

Rotation curve of our Milky Way

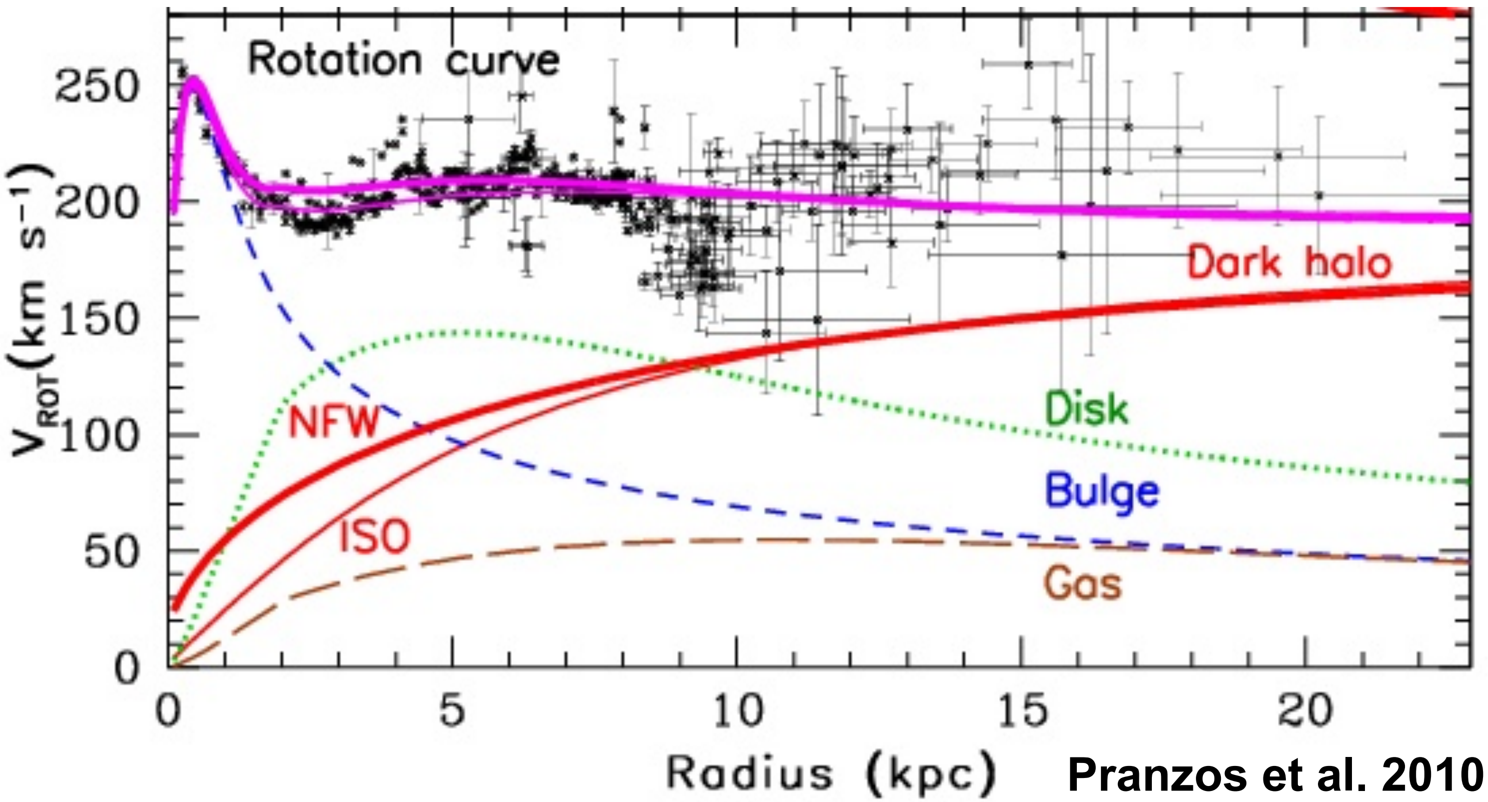


Sofue 2009

Vera Florence Cooper Rubin
(1928 – 2016)

Gaia and Dark Matter

Fit with different components



Pranzos et al. 2010

Mass estimates of the Milky Way with Gaia

THE ASTROPHYSICAL JOURNAL, 945:3 (10pp), 2023 March 1 https://doi.org/10.3847/1538-4357/acb92c

CrossMark

Mass Models of the Milky Way and Estimation of Its Mass from the Gaia DR3 Data Set

Francesco Sylos Labini[1,2], Žofia Chrobáková[3], Roberto Capuzzo-Dolcetta[1,4], and Martín López-Corredoira[5,6]
[1] Centro Ricerche Enrico Fermi, Via Panisperna 89a, I-00184 Rome, Italy; sylos@cref.it
[2] Istituto Nazionale Fisica Nucleare, Unità Roma 1, Dipartimento di Fisica, Universitá di Roma "Sapienza," I-00185 Rome, Italy
[3] Faculty of Mathematics, Physics, and Informatics, Comenius University, Mlynská dolina, 842 48 Bratislava, Slovakia
[4] Dipartimento di Fisica, Universitá di Roma "Sapienza," I-00185 Rome, Italy
[5] Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain
[6] Departamento de Astrofísica, Universidad de La Laguna, E-38206 La Laguna, Tenerife, Spain
Received 2022 December 3; revised 2023 February 2; accepted 2023 February 2; published 2023 March 1

Abstract

We use data from the Gaia DR3 data set to estimate the mass of the Milky Way (MW) by analyzing the rotation curve in the range of distances 5 to 28 kpc. We consider three mass models: The first model adds a spherical dark matter (DM) halo, following the Navarro–Frenk–White (NFW) profile, to the known stellar components. The second model assumes that DM is confined to the Galactic disk, following the idea that the observed density of gas in the Galaxy is related to the presence of a more massive DM disk (DMD), similar to the observed correlation between DM and gas in other galaxies. The third model only uses the known stellar-mass components and is based on the Modified Newton Dynamics (MOND) theory. Our results indicate that the DMD model is comparable in accuracy to the NFW and MOND models and fits the data better at large radii where the rotation curve declines but has the largest errors. For the NFW model, we obtain a virial mass $M_{vir} = (6.5 \pm 0.3) \times 10^{11} M_{\odot}$ with concentration parameter $c = 14.5$, which is lower than what is typically reported. In the DMD case, we find that the MW mass is $M_d = (1.6 \pm 0.5) \times 10^{11} M_{\odot}$ with a disk's characteristic radius of $R_d = 17$ kpc.

Unified Astronomy Thesaurus concepts: Milky Way Galaxy (1054)

1. Introduction

Determining the Milky Way's (MW's) mass pr

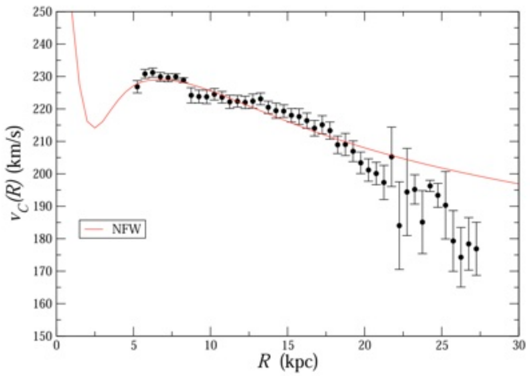


Figure 2. Best fit of the NFW mass model to the rotation curve given in Table 1 (DR3+ determination of the rotation curve).

- The paper uses data from the Gaia DR3 data set to estimate the mass of the Milky Way by analysing the rotation curve in the range of distances 5 to 28 kpc.
- Three mass models are considered:
    - The first model adds a **spherical dark matter (DM) halo**, following the Navarro–Frenk–White (NFW) profile, to the known stellar components.
    - The second model assumes that **DM is confined to the Galactic disk**, following the idea that the observed density of gas in the Galaxy is related to the presence of a more massive DM disk (DMD), similar to the observed correlation between DM and gas in other galaxies.
    - The third model only uses the known stellar-mass components and is based on the Modified Newton Dynamics **(MOND) theory**.
- The results indicate that the DMD model is comparable in accuracy to the NFW and MOND models and fits the data better at large radii where the rotation curve declines but has the largest errors.
- For the NFW model, a virial mass of $M_{vir} = (6.5 \pm 0.3) \times 10^{11}$ solar masses with a concentration parameter of c = 14.5 is obtained, which is lower than what is typically reported.
- In the DMD case, the Milky Way mass is Md = $(1.6 \pm 0.5) \times 10^{11}$ solar masses with a disk's characteristic radius of R_d = 17 kpc.
- The paper combines the determination of the rotation curve derived by Eilers et al. in the range of Galactocentric radii 5–25 kpc, with that by Wang et al. (2023), in the range 8–28 kpc, to make an estimation of the mass of the Milky Way under the three different theoretical mass models.
- The total mass of the stellar components, with these approximations, is $M_{stellar} \approx 8 \times 10^{10}$ solar masses

Dark matter or modified law of gravity

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **527,** 4573–4615 (2024) https://doi.org/10.1093/mnras/stad3393
Advance Access publication 2023 November 3

Strong constraints on the gravitational law from *Gaia* DR3 wide binaries

Indranil Banik ,[1★] Charalambos Pittordis,[2] Will Sutherland,[2★] Benoit Famaey ,[3] Rodrigo Ibata,[3] Steffen Mieske[4] and Hongsheng Zhao[1]

[1] *Scottish Universities Physics Alliance, University of Saint Andrews, North Haugh, Saint Andrews, Fife KY16 9SS, UK*
[2] *The School of Physical and Chemical Sciences, Queen Mary University of London, Mile End Road, London E1 4NS, UK*
[3] *Université de Strasbourg, CNRS UMR 7550, Observatoire astronomique de Strasbourg, 11 rue de l'Université, 67000 Strasbourg, France*
[4] *European Southern Observatory, Alonso de Cordova 3107, Vitacura, Santiago, Chile*

Accepted 2023 November 1. Received 2023 October 28; in original form 2023 March 14

ABSTRACT

We test Milgromian dynamics (MOND) using wide binary stars (WBs) with separations of 2–30 kAU. Locally, the WB orbital velocity in MOND should exceed the Newtonian prediction by ≈ 20 per cent at asymptotically large separations given the Galactic external field effect (EFE). We investigate this with a detailed statistical analysis of *Gaia* DR3 data on 8611 WBs within 250 pc of the Sun. Orbits are integrated in a rigorously calculated gravitational field that directly includes the EFE. We also allow line-of-sight contamination and undetected close binary companions to the stars in each WB. We interpolate between the Newtonian and Milgromian predictions using the parameter $\alpha_{\rm grav}$, with 0 indicating Newtonian gravity and 1 indicating MOND. Directly comparing the best Newtonian and Milgromian models reveals that Newtonian dynamics is preferred at 19σ confidence. Using a complementary Markov Chain Monte Carlo analysis, we find that $\alpha_{\rm grav} = -0.021^{+0.065}_{-0.045}$, which is fully consistent with Newtonian gravity but excludes MOND at 16σ confidence. This is in line with the similar result of Pittordis and Sutherland using a somewhat different sample selection and less thoroughly explored population model. We show that although our best-fitting model does not fully reproduce the observations, an overwhelmingly strong preference for Newtonian gravity remains in a considerable range of variations to our analysis. Adapting the MOND interpolating function to explain this result would cause tension with rotation curve constraints. We discuss the broader implications of our results in light of other works, concluding that MOND must be substantially modified on small scales to account for local WBs.

Key words: gravitation – methods: statistical – celestial mechanics – binaries: general – stars: kinematics and dynamics – galaxies: kinematics and dynamics.

1 INTRODUCTION

Our current best understanding of gravity is encapsulated by the theory of General Relativity (GR; Einstein 1915). This reduces

Several explanations have been put forward for this missing gravity problem, which is also apparent in a number of other ways like dwarf galaxy velocity dispersions (fig. 11 of McConnachie 2012) and weak gravitational lensing (Brouwer et al.

- 8611 wide binary stars (2 - 30 kAU) are used to study gravity at low accelerations
- Wide binary stars with distances of thousands of AU experience gravitational accelerations below the critical MOND acceleration scale of $a_0 = 1.2 \times 10^{-10} \mathrm{m/s}^2$ According to MOND, their orbital velocities at large distances will be about 20 % above Newtonian expectations.
- Contributions from undiscovered close binary companions and unrelated stars were included.
- Their orbital velocities are in agreement with Newtonian expectations
- Milgrom dynamics (MOND) is excluded at high significance.
- A detailed model includes close binaries and objects in the line of sight
- The results are robust to variations in the modelling assumptions.

Mass and Shape of the MW dark matter halo

A&A 621, A56 (2019)
https://doi.org/10.1051/0004-6361/201833355

Astronomy & Astrophysics

Mass and shape of the Milky Way's dark matter halo with globular clusters from *Gaia* and *Hubble*

Lorenzo Posti and Amina Helmi

Kapteyn Astronomical Institute, University of Groningen, PO Box 800, 9700 AV Groningen, The Netherlands
e-mail: posti@astro.rug.nl

Received 3 May 2018 / Accepted 5 November 2018

ABSTRACT

Aims. We estimate the mass of the inner (<20 kpc) Milky Way and the axis ratio of its inner dark matter halo using globular clusters as tracers. At the same time, we constrain the distribution in phase-space of the globular cluster system around the Galaxy.

Methods. We use the *Gaia* Data Release 2 catalogue of 75 globular clusters' proper motions and recent measurements of the proper motions of another 20 distant clusters obtained with the *Hubble* Space Telescope. We describe the globular cluster system with a distribution function (DF) with two components: a flat, rotating disc-like one and a rounder, more extended halo-like one. While fixing the Milky Way's disc and bulge, we let the mass and shape of the dark matter halo and we fit these two parameters, together with six others describing the DF, with a Bayesian method.

Results. We find the mass of the Galaxy within 20 kpc to be $M(<20\,\mathrm{kpc}) = 1.91^{+0.18}_{-0.17} \times 10^{11} M_{\odot}$, of which $M_{\mathrm{DM}}(<20\,\mathrm{kpc}) = 1.37^{+0.18}_{-0.17} \times 10^{11} M_{\odot}$ is in dark matter, and the density axis ratio of the dark matter halo to be $q = 1.30 \pm 0.25$. Assuming a concentration-mass relation, this implies a virial mass $M_{\mathrm{vir}} = 1.3 \pm 0.3 \times 10^{12} M_{\odot}$. Our analysis rules out oblate ($q < 0.8$) and strongly prolate halos ($q > 1.9$) with 99% probability. Our preferred model reproduces well the observed phase-space distribution of globular clusters and has a disc component that closely resembles that of the Galactic thick disc. The halo component follows a power-law density profile $\rho \propto r^{-3.3}$, has a mean rotational velocity of $V_{\mathrm{rot}} \simeq -14\,\mathrm{km\,s^{-1}}$ at 20 kpc, and has a mildly radially biased velocity distribution ($\beta \simeq 0.2 \pm 0.07$, which varies significantly with radius only within the inner 15 kpc). We also find that our distinction between disc and halo clusters resembles, although not fully, the observed distinction in metal-rich ([Fe/H] > −0.8) and metal-poor ([Fe/H] ≤ −0.8) cluster populations.

Key words. Galaxy: kinematics and dynamics – Galaxy: structure – Galaxy: halo – globular clusters: general

1. Introduction

Giant leaps in the physical understanding of our Universe are often made when new superb datasets that peer into previously

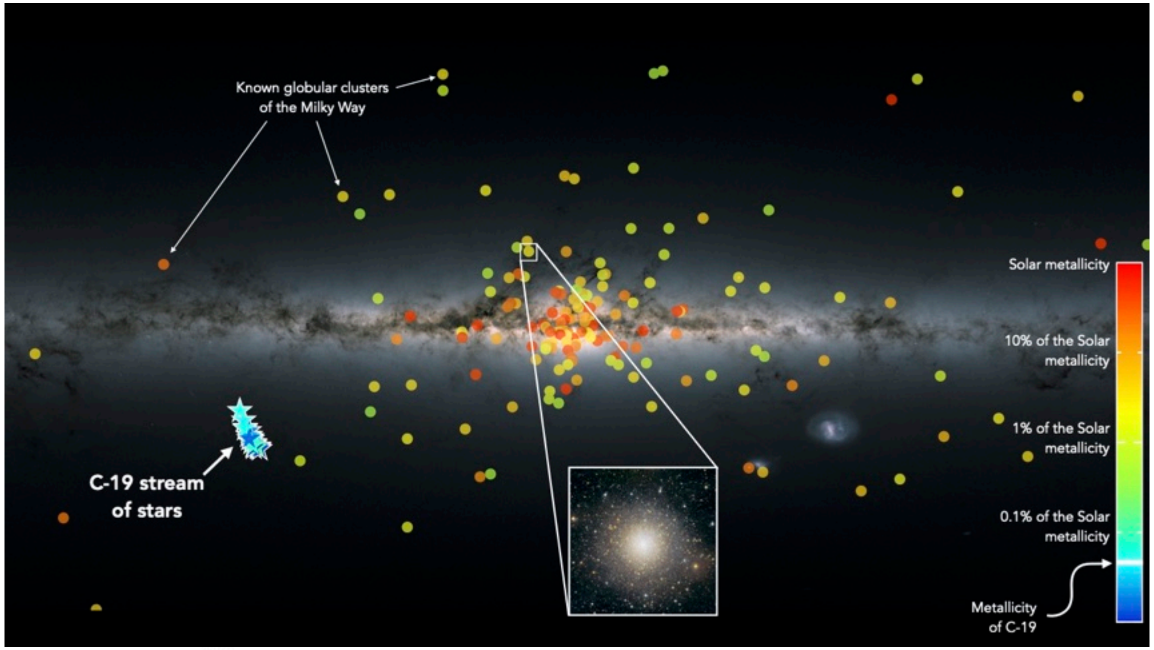
also recently released by Sohn et al. (2018) using the *Hubble* Space Telescope (HST). These authors estimated proper motions of 20 clusters at large Galactocentric distances (>10 kpc), using two HST epochs at least ~6 yr apart

- Gaia DR2: proper motions of 75 globular clusters
- Hubble: proper motions of 20 distant globular clusters
- The mass of the Milky Way within 20 kpc is (1.91+0.18 −0.17) × 10^{11} solar masses, of which (1.37+0.18 −0.17) × 10^{11} solar masses are in dark matter.
- $M_{vir} = (1.3 \pm 0.3) \times 10^{12}\ M_{\odot}$
- The density axis ratio of the dark matter halo is q = 1.30 ± 0.25.
- Oblate (q < 0.8) and strongly prolate halos (q > 1.9) are ruled out with 99% probability.
- The preferred model reproduces the observed phase-space distribution of globular clusters and has a disc component that resembles the Galactic thick disc.

Mass and Shape of the MW dark matter halo

A&A 621, A56 (2019)
https://doi.org/10.1051/0004-6361/201833355

Astronomy & Astrophysics



Key words. Galaxy: kinematics and dynamics – Galaxy: structure – Galaxy: halo – globular clusters: general

https://www.cosmos.esa.int/web/gaia/iow_20220105

1. Introduction

Giant leaps in the physical understanding of our Universe are often made when new superb datasets that peer into previously

also recently released by Sohn et al. (2018) using the *Hubble* Space Telescope (HST). These authors estimated proper motions of 20 clusters at large Galactocentric distances (>10 kpc), using two HST epochs at least ~6 yr apart

- Gaia DR2: proper motions of 75 globular clusters
- Hubble: proper motions of 20 distant globular clusters
- The mass of the Milky Way within 20 kpc is $(1.91{+0.18}\ {-0.17}) \times 10^{11}$ solar masses, of which $(1.37{+0.18}\ {-0.17}) \times 10^{11}$ solar masses are in dark matter.
- $M_{vir} = (1.3 \pm 0.3) \times 10^{12}\ M_{\odot}$
- The density axis ratio of the dark matter halo is $q = 1.30 \pm 0.25$.
- Oblate ($q < 0.8$) and strongly prolate halos ($q > 1.9$) are ruled out with 99% probability.
- The preferred model reproduces the observed phase-space distribution of globular clusters and has a disc component that resembles the Galactic thick disc.

Mass of the Milky Way

THE ASTROPHYSICAL JOURNAL, 873:118 (13pp), 2019 March 10
https://doi.org/10.3847/1538-4357/ab089f

CrossMark

Evidence for an Intermediate-mass Milky Way from *Gaia* DR2 Halo Globular Cluster Motions

Laura L. Watkins[1], Roeland P. van der Marel[1,2], Sangmo Tony Sohn[1], and N. Wyn Evans[3]
[1] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA; lwatkins@stsci.edu
[2] Center for Astrophysical Sciences, Department of Physics & Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA
[3] Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
Received 2018 April 30; revised 2019 January 28; accepted 2019 February 2; published 2019 March 12

Abstract

We estimate the mass of the Milky Way (MW) within 21.1 kpc using the kinematics of halo globular clusters (GCs) determined by *Gaia*. The second *Gaia* data release (DR2) contained a catalog of absolute proper motions (PMs) for a set of Galactic GCs and satellite galaxies. We select from the catalog only halo GCs, identifying a total of 34 GCs spanning $2.0 \leqslant r \leqslant 21.1$ kpc, and use their 3D kinematics to estimate the anisotropy over this range to be $\beta = 0.46^{+0.15}_{-0.19}$, in good agreement with, though slightly lower than, a recent estimate for a sample of halo GCs using *Hubble Space Telescope* (*HST*) PM measurements further out in the halo. We then use the *Gaia* kinematics to estimate the mass of the MW inside the outermost GC to be $M(<21.1\ \mathrm{kpc}) = 0.21^{+0.04}_{-0.03} \times 10^{12}\ M_{\odot}$, which corresponds to a circular velocity at r_{max} of $v_{circ}(21.1\ \mathrm{kpc}) = 206^{+19}_{-16}\ \mathrm{km\ s^{-1}}$. The implied virial mass is $M_{virial} = 1.28^{+0.97}_{-0.48} \times 10^{12}\ M_{\odot}$. The error bars encompass the uncertainties on the anisotropy and on the density profile of the MW dark halo, and the scatter inherent in the mass estimator we use. We get improved estimates when we combine the *Gaia* and *HST* samples to provide kinematics for 46 GCs out to 39.5 kpc: $\beta = 0.52^{+0.11}_{-0.14}$, $M(<39.5\ \mathrm{kpc}) = 0.42^{+0.07}_{-0.06} \times 10^{12}\ M_{\odot}$, and $M_{virial} = 1.54^{+0.75}_{-0.44} \times 10^{12}\ M_{\odot}$. We show that these results are robust to potential substructure in the halo GC distribution. While a wide range of MW virial masses have been advocated in the literature, from below $10^{12}\ M_{\odot}$ to above $2 \times 10^{12}\ M_{\odot}$, these new data imply that an intermediate mass is most likely.

Key words: dark matter – Galaxy: fundamental parameters – Galaxy: halo – Galaxy: kinematics and dynamics – Galaxy: structure – globular clusters: general

Supporting material: machine-readable table

1. Introduction

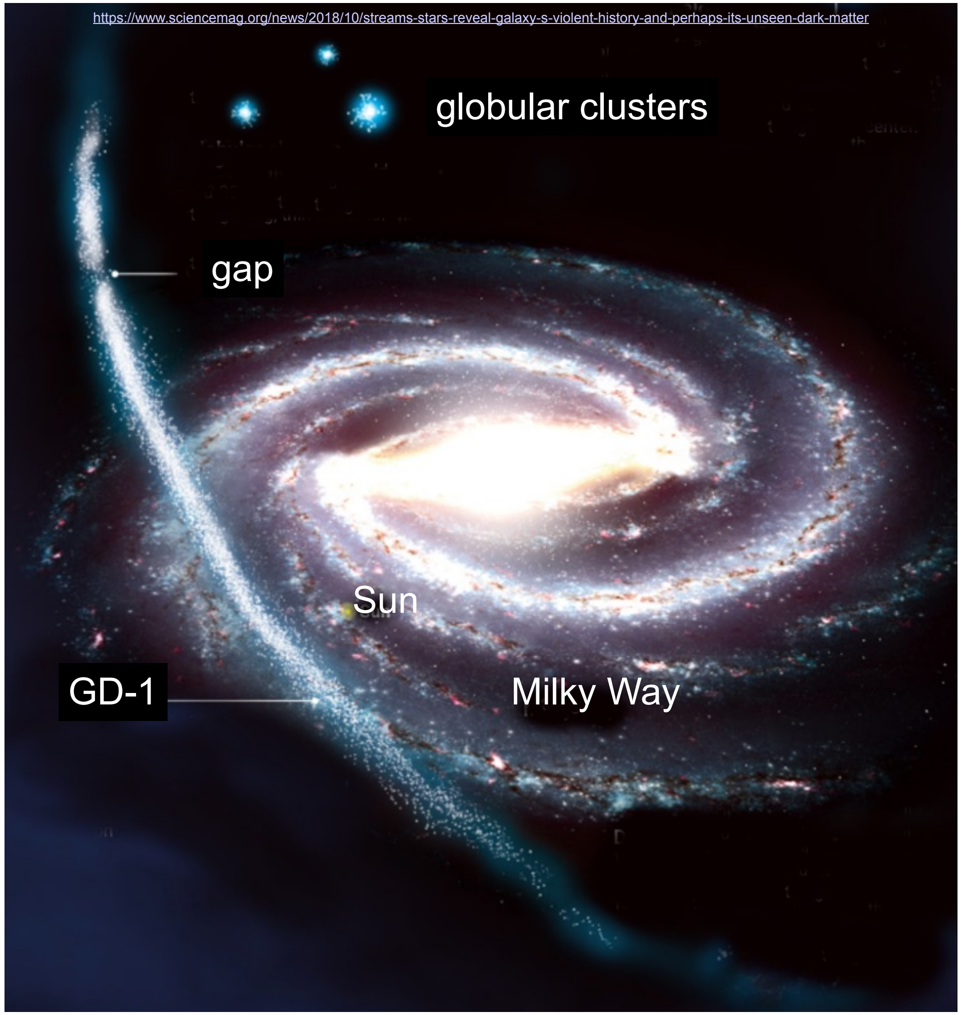
The mass of the Milky Way (MW) is one of its most fundamental parameters, and yet, despite decades of intense structure in the universe (Conselice 2014), so accurately determining these parameters for the MW will give us a clearer understanding of where our Galaxy sits in a

- The same sample as Posti & Helmi (2019): 75 globular clusters from Gaia DR2 and 20 distant globular clusters from Hubble.
- Using only the Gaia GCs, they find $M_{vir}=(1.28_{-0.48}^{+0.97}) \times 10^{12}\ M_{\odot}$ and, using the extended sample: $M_{vir}=(1.54_{-0.44}^{+0.7}) \times 10^{12}\ M_{\odot}$

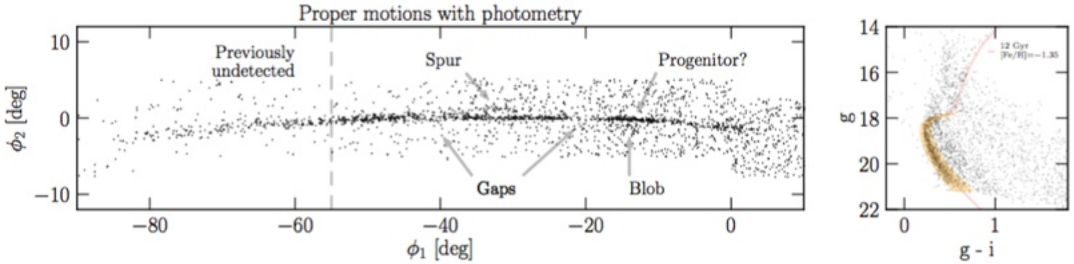
Mass estimates of the Milky Way with Gaia

- Despite all the intensive work over the years, estimates of the Milky Way's mass still vary significantly.
- These estimates are very sensitive to the assumptions made in the modelling, especially the shape of the halo surrounding the galaxy.
- Most mass estimators are limited to the regions explored by the available tracer population, whose spatial distribution and movement are used to estimate the enclosed mass.
- Estimates of the Milky Way's mass have been obtained based on the movement of halo stars, satellite galaxies and globular clusters, the evaluation of the local escape velocity, and the modelling of satellite galaxy tidal streams.
- Estimates typically range from 0.5×10^{12} to 4×10^{12} solar masses.
- These estimates assume that dark matter (DM) is in a quasi-spherical virialised halo around the galaxy.

Stellar Stream GD-1

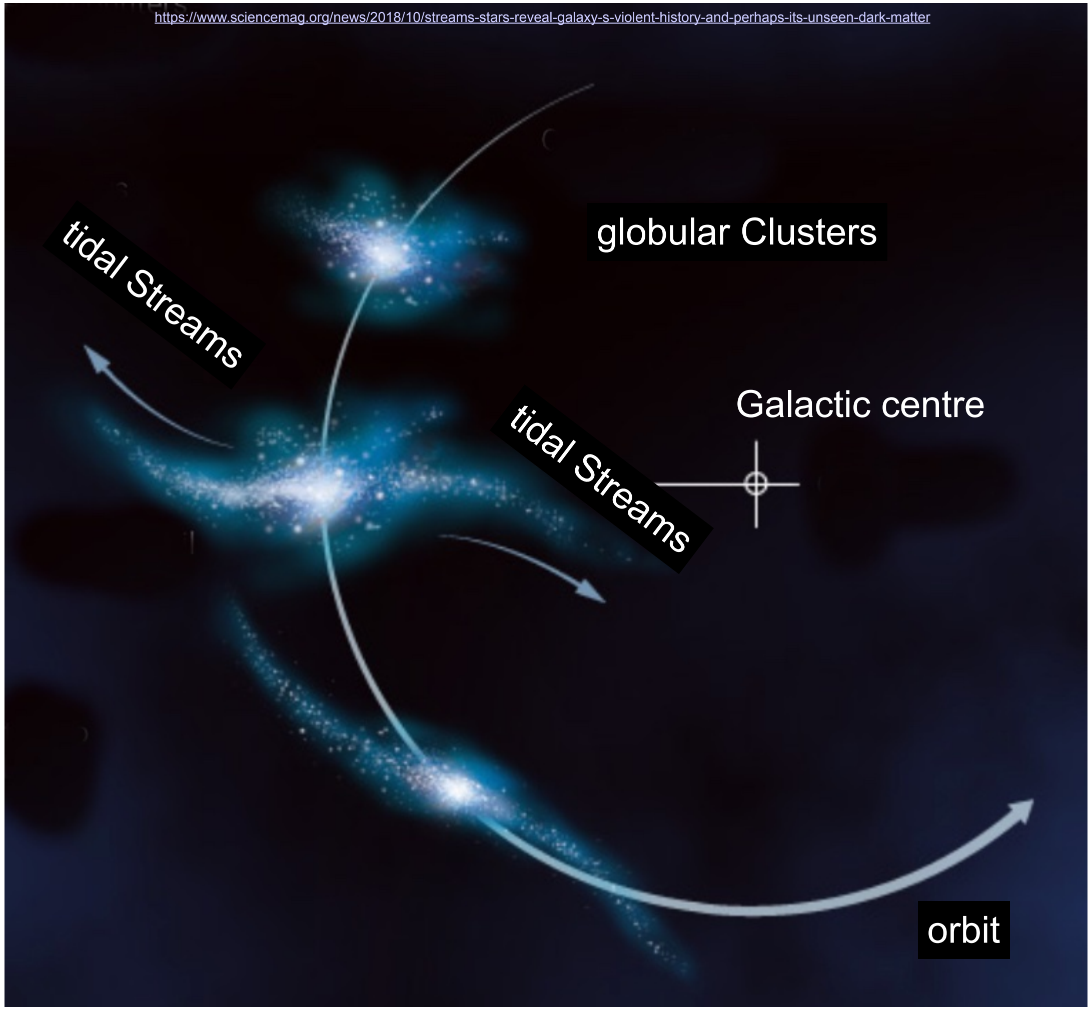


Price-Whelan & Bonaca 2018

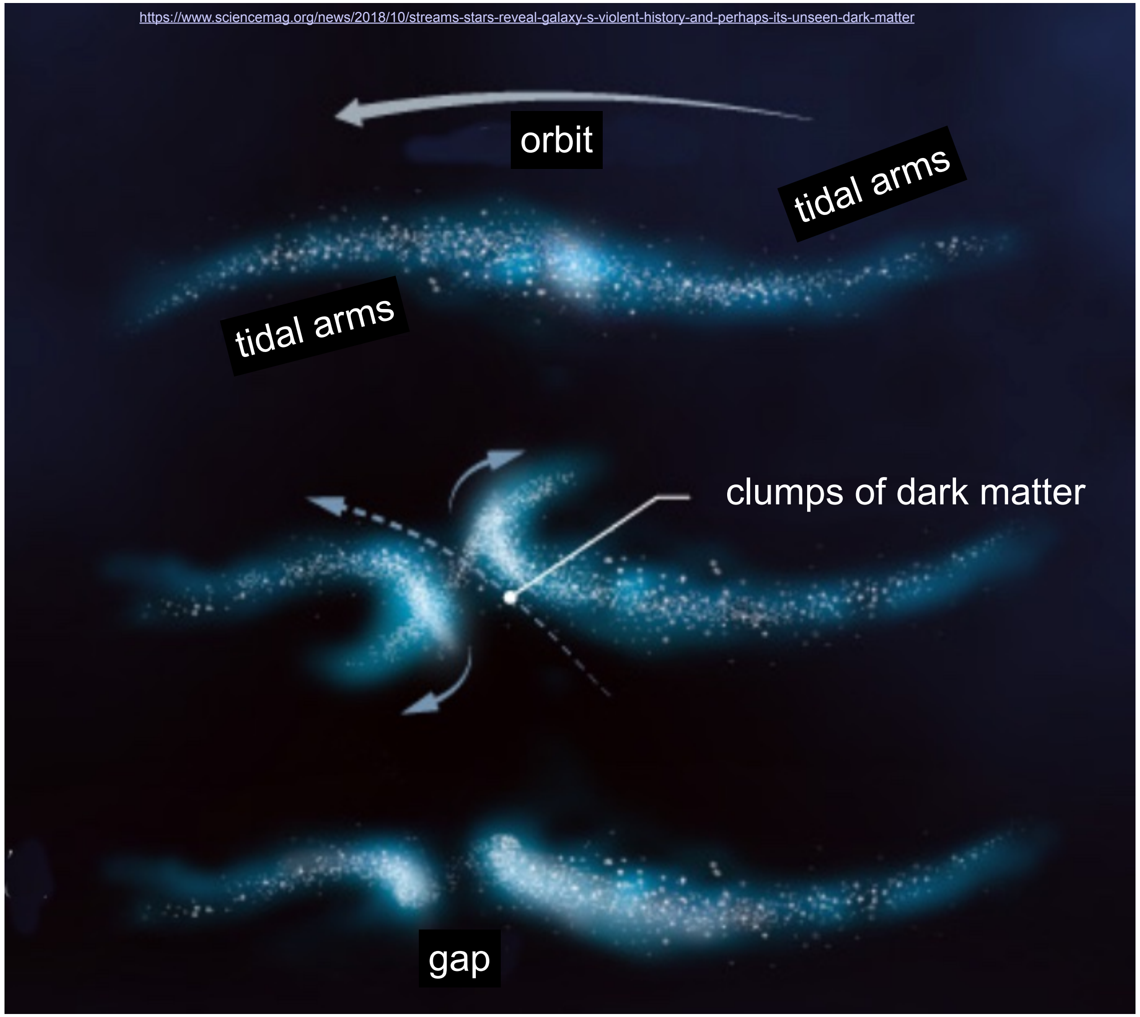


The Milky Way halo contains several thin, dynamically-cold stellar streams that likely formed from the tidal disruption of low-mass stellar systems like globular clusters.

Stellar Streams, Interaction with Clumps of Dark Matter

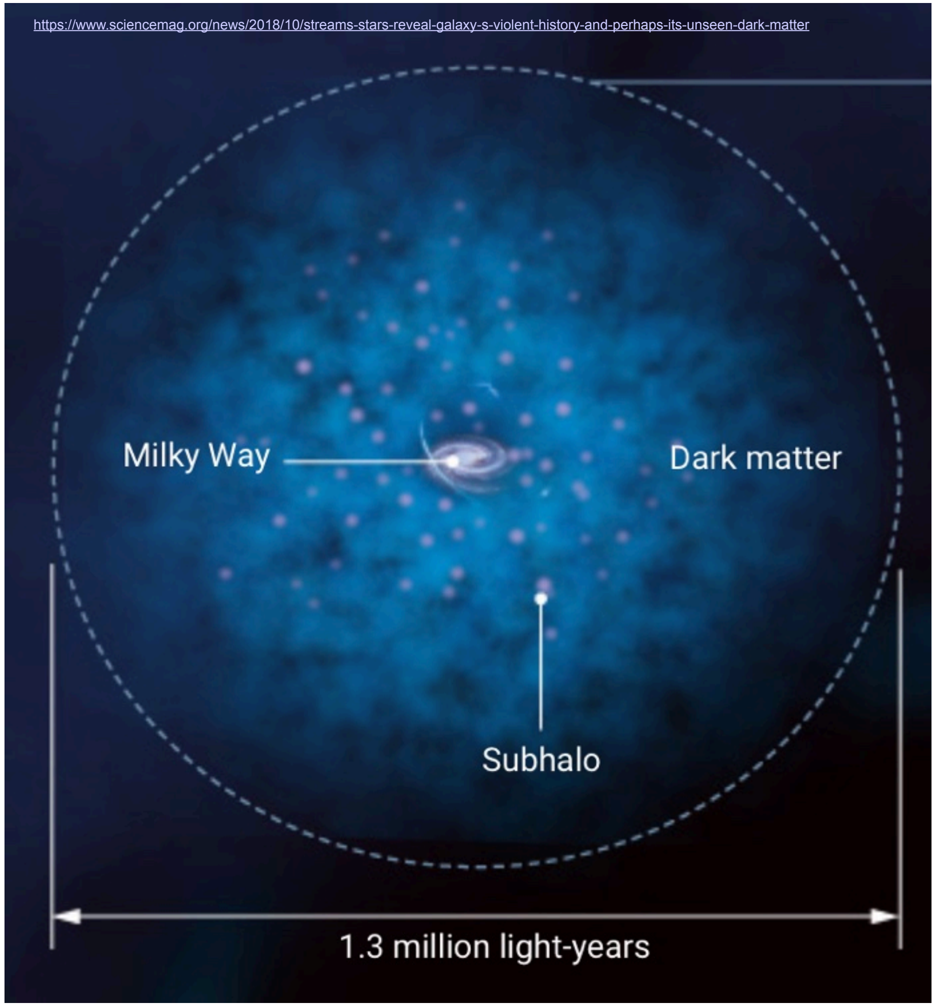


Stellar Streams, Interaction with Clumps of Dark Matter



Encounter with a massive (~10^6-10^8 solar mass) dense perturber

Milky Way with Dark Matter



Mapping the dark Milky Way halo

- Determining the local density of the dark near the Solar system to make predictions for experiments on Earth to detect dark matter particles
- This data allows for a more detailed mapping of the dark matter halo near the Sun's position.
- Gaia provides an unprecedented amount of data, measuring over a billion stars in the Milky Way.
- Understanding the Milky Way's merger history is crucial for dark matter research.
- Gaia helps identify past mergers, like the Gaia Sausage-Enceladus (GSE) event, which significantly contributed to the local dark matter distribution.
- Is the dark matter distribution in equilibrium? The answer depends on the merger history.

Measuring the shape of the (dark) Galactic halo


Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **485**, 3296–3316 (2019) doi:10.1093/mnras/stz572
Advance Access publication 2019 February 26

The gravitational force field of the Galaxy measured from the kinematics of RR Lyrae in *Gaia*

Christopher Wegg,[1,2]★ Ortwin Gerhard[1] and Marie Bieth[3]
[1] *Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstrasse, D-85748 Garching, Germany*
[2] *Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, Bd de l'Observatoire, CS 34229, 06304 Nice cedex 4, France*
[3] *TNG Technology Consulting, Betastr. 13a, D-85774 Unterföhring, Germany*

Accepted 2019 February 13. Received 2019 February 8; in original form 2018 June 25

ABSTRACT
From a sample of 15651 RR Lyrae with accurate proper motions in *Gaia* DR2, we measure the azimuthally averaged kinematics of the inner stellar halo between 1.5 and 20 kpc from the Galactic centre. We find that their kinematics are strongly radially anisotropic, and their velocity ellipsoid nearly spherically aligned over this volume. Only in the inner regions $\lesssim 5$ kpc does the anisotropy significantly fall (but still with $\beta > 0.25$) and the velocity ellipsoid tilt towards cylindrical alignment. In the inner regions, our sample of halo stars rotates at up to $50\,\mathrm{km\,s^{-1}}$, which may reflect the early history of the Milky Way, although there is also a significant angular momentum exchange with the Galactic bar at these radii. We subsequently apply the Jeans equations to these kinematic measurements in order to non-parametrically infer the azimuthally averaged gravitational acceleration field over this volume, and by removing the contribution from baryonic matter, measure the contribution from dark matter. We find that the gravitational potential of the dark matter is nearly spherical with average flattening $q_\Phi = 1.01 \pm 0.06$ between 5 and 20 kpc, and by fitting parametric ellipsoidal density profiles to the acceleration field, we measure the flattening of the dark matter halo over these radii to be $q_\rho = 1.00 \pm 0.09$.

Key words: Galaxy: halo – Galaxy: kinematics and dynamics – dark matter.

1 INTRODUCTION

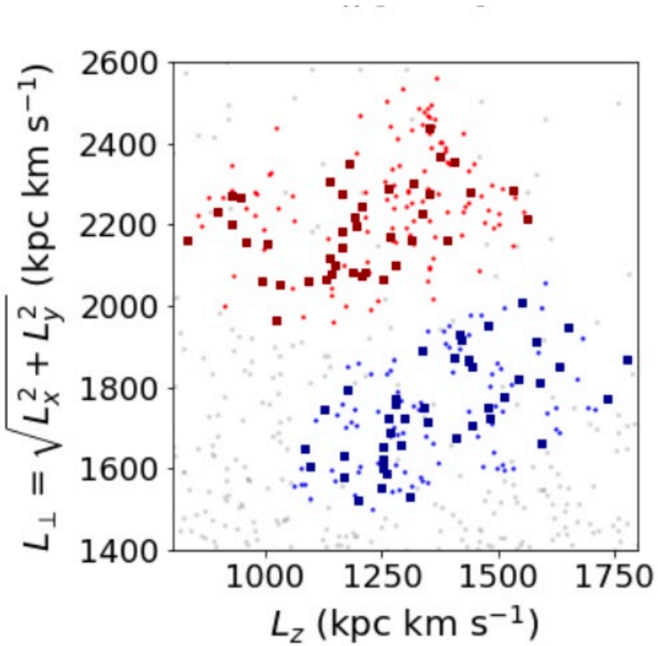
Simulations of structure formation in a ΛCDM universe have

In external galaxies, we are typically only able to measure dark matter halo properties using samples of galaxies (e.g. van Uitert et al. 2012; Martinsson et al. 2013; Aniyan et al. 2015). In the Milky Way

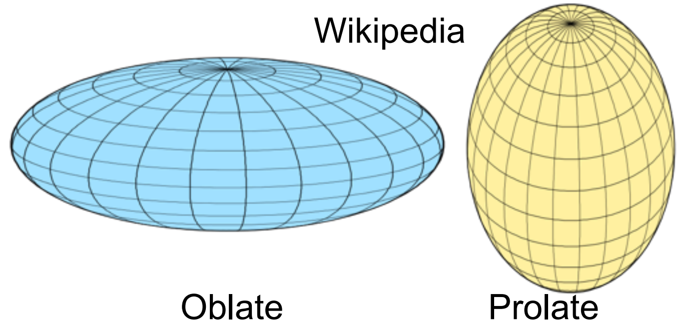
- RR Lyrae stars were used as kinematic tracers to measure the properties of the dark matter halo within 20 kpc of the galactic centre.
- Gaia data are used to measure their proper motions
- The kinematics of the inner stellar halo are strongly radially anisotropic (stars move more radially than perpendicular to the Galactic plane).
- Their velocity ellipsoid is nearly spherically aligned over the volume of 1.5 to 20 kpc from the galactic centre.
- The gravitational potential of the dark matter is nearly spherical with average flattening q = 1.01 ± 0.06 between 5 and 20 kpc.
- Some uncertainty of the study comes from the fact that no radial velocities were available.

Helmi Streams

- The Helmi streams are thought to represent debris from a massive dwarf galaxy that was accreted by the Milky Way approximately 5-8 billion years ago.
- This dwarf galaxy was gravitationally disrupted during the merger, and its stars were stripped and scattered throughout the Milky Way's halo. These stars have since formed the Helmi streams, which are identifiable as clumps in integrals of motion space, such as angular momentum space (Lz - L⊥) and by their chemical composition.
- The fact that the two clumps in the streams share consistent metallicity distributions and stellar populations supports the idea that they originated from the same progenitor, meaning they all come from this single dwarf galaxy merger.



Helmi Streams



- 1:1 Resonance in the Helmi Streams
- In the Helmi streams, many of the stars are on 1:1 resonance orbits. This means that for every full orbit, the star makes around the centre of the Milky Way, it also goes up and down once. So the two motions (up-down and around) happen at the same rate, like synchronized dancers.
- Why Does This Matter?
- Stability: When stars are in resonance like this, their orbits become more stable, and they don't spread out as quickly. That’s why the stars in the Helmi streams still form clumps, even billions of years after their dwarf galaxy was torn apart.
- Clues About the Dark Matter Halo: The fact that this resonance is seen tells us something about the shape of the Milky Way’s dark matter halo. A 1:1 resonance happens because of the gravitational forces at play, and it suggests the dark matter halo has a particular shape (prolate, or elongated).
- These findings offer insights into the shape of the dark matter halo, constraining it to a prolate configuration with a flattening ratio of $q \approx 1.2$.

Stellar Streams and MOND

A&A, 689, A57 (2024)
https://doi.org/10.1051/0004-6361/202348211

Astronomy & Astrophysics

Testing MOND using the dynamics of nearby stellar streams

Orlin Koop* and Amina Helmi

Kapteyn Astronomical Institute, University of Groningen, Landleven 12, 9747 AD Groningen, The Netherlands

Received 9 October 2023 / Accepted 18 June 2024

ABSTRACT

Context. The stellar halo of the Milky Way is built up at least in part from debris from past mergers. The stars from these merger events define substructures in phase space, for example in the form of streams, which are groups of stars that move on similar trajectories. The nearby Helmi streams discovered more than two decades ago are a well-known example. Using 6D phase-space information from the Gaia space mission, recent work showed that the Helmi streams are split into two clumps in angular momentum space. This substructure can be explained and sustained in time if the dark matter halo of the Milky Way takes a prolate shape in the region probed by the orbits of the stars in the streams.
Aims. Here, we explore the behaviour of the two clumps identified in the Helmi streams in a modified Newtonian dynamics (MOND) framework to test this alternative model of gravity.
Methods. We performed orbit integrations of Helmi streams member stars in a simplified MOND model of the Milky Way and using the more sophisticated phantom of RAMSES simulation framework.
Results. We find with both approaches that the two Helmi streams clumps do not retain their identity and dissolve after merely 100 Myr. This extremely short timescale would render the detection of two separate clumps very unlikely in MONDian gravity.
Conclusions. The observational constraints provided by the streams, which MOND fails to reproduce in its current formulation, could potentially also be used to test other alternative gravity models.

Key words. gravitation – Galaxy: kinematics and dynamics – Galaxy: structure

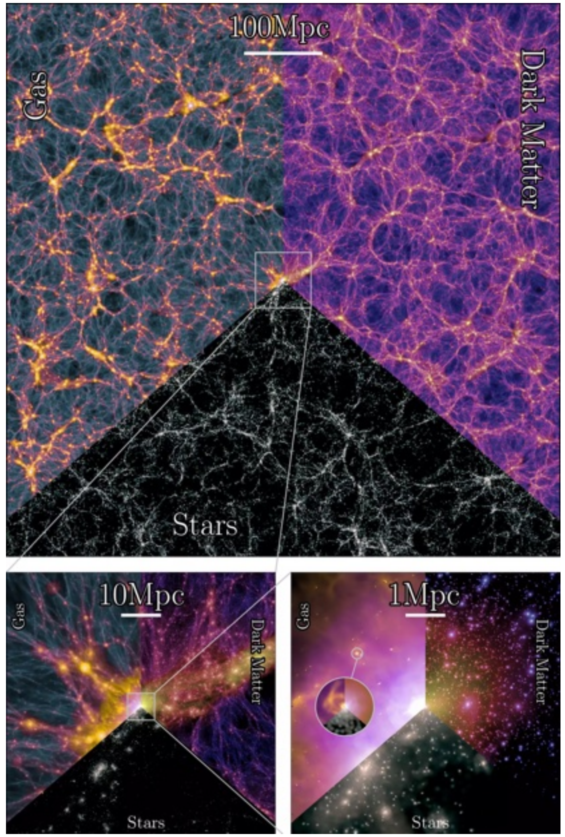
1. Introduction

and possible solutions and outstanding problems on the dwarf galaxy scale). Another challenge is the radial acceleration rela-

- Orbit integration of Helmi stream stars in both MOND and Newtonian frameworks.
- Gaia provided detailed 6-dimensional data (positions and velocities) for millions of stars, including those in the Helmi streams. This high-precision data was critical in identifying and analyzing the motion of these stars in the Milky Way.
- The structure of the Galactic potential leaves a clear imprint on the properties of phase-mixed debris streams.
- Used the AQUAL and phantom of RAMSES frameworks for MOND simulations.
- **MOND Models**: The two distinct clumps observed in angular momentum space (Lz-L⊥) in the streams do not retain their structure over time.
- **Clump Dissolution**: In MOND, the clumps mix and dissolve within 100 Myr, making it unlikely for them to survive in MOND gravity.
- The Newtonian model, with a prolate dark matter halo, preserves the clumps for a longer period (~200 Myr).
- MOND models cannot reproduce the long-term survival of the clumps observed in the Milky Way.
- The rapid mixing in MOND challenges its validity in explaining the Helmi streams.
- Current MOND formulations fail to match the observed structure, hinting at a need to explore alternative models or modifications to MOND

Gaia and cosmological simulations

- Gaia has revolutionised our understanding of stellar evolution, exoplanets, and solar system studies. It has become central to cosmological problems.
- **Cosmological Simulations:** Major N-body simulations, particularly within the ΛCDM paradigm. These include simulations on both large and small cosmological scales.
- **Key Simulations:**
  - **Millennium Simulation**: First large-scale project tracking dark matter structures from the Big Bang to the present. (Springel et al., 2005).
  - **Illustris & IllustrisTNG**: Evolved over 13 billion years and generated galaxy structures, providing insights into galaxy formation, feedback mechanisms, and gas recycling. (Vogelsberger et al., 2014a; Genel et al., 2014, Pillepich et al., 2018).
  - **Other Notable Simulations:** Include Bolshoi, Eris, EAGLE, HESTIA, NewHorizon, and derivatives like Auriga and Thesan.
- - Gaia's Observations can be compared to these simulations
- Gaia data confirms predictions from simulations about stellar streams, local group galaxy dynamics, and satellite interactions.
- Cosmological simulations have helped interpret key events in the Milky Way, such as the Gaia-Sausage-Enceladus (GSE) merger.



Two-dimensional projections of the three-dimensional MillenniumTNG simulation at the present epoch.

https://www.mpg.de/20761326/millennium-tng-cosmology-simulation

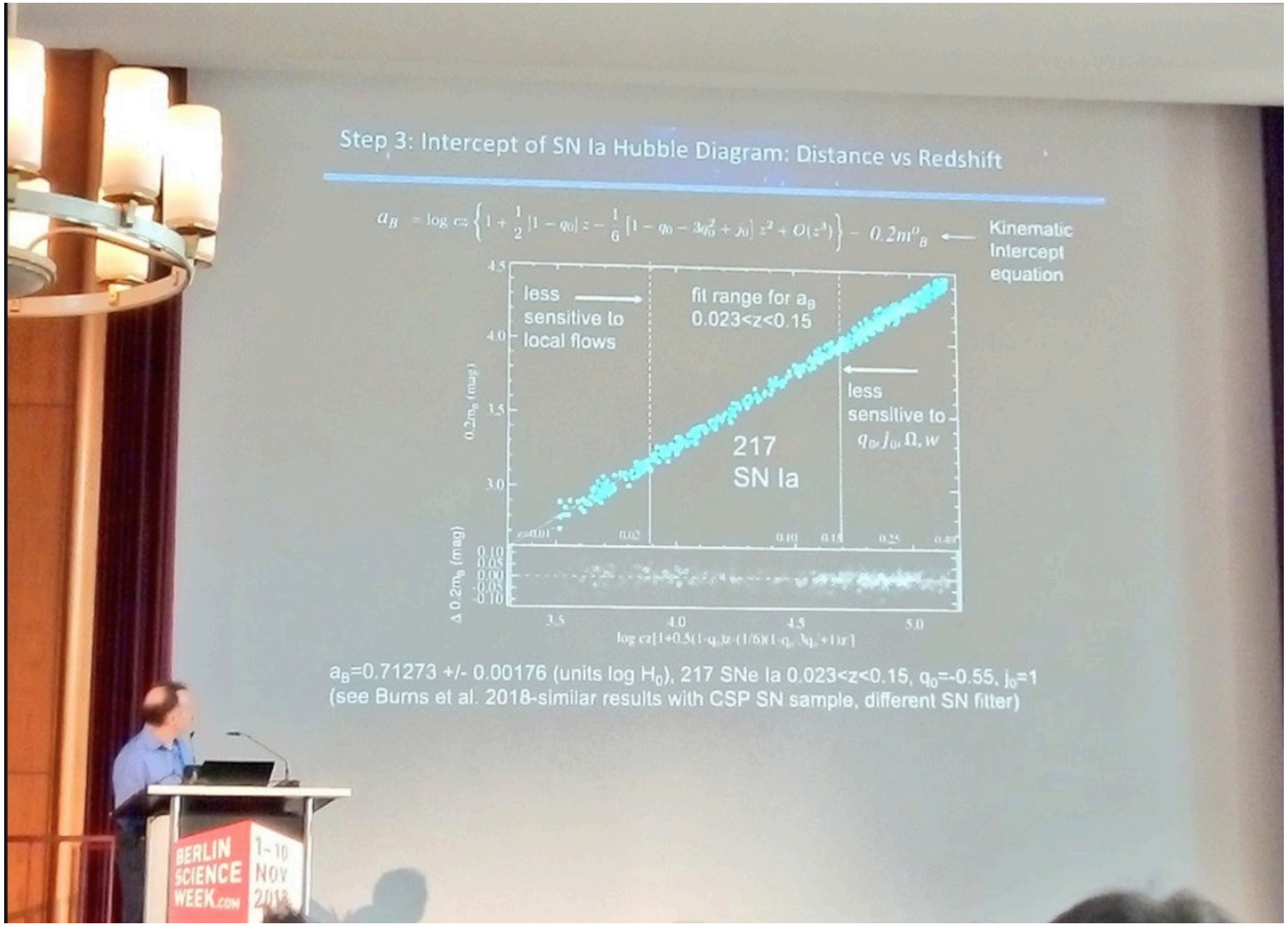
https://www.michaelperryman.co.uk/_files/ugd/6e4321_f376623954e045c78d6b4da43b532e44.pdf

Gaia and cosmological simulations

- **Challenges to the ΛCDM Model:**
  - Missing Satellites Problem: Fewer observed dwarf galaxies than predicted.
  - Core–Cusp Problem: Dark matter simulations show 'cuspy' density profiles, while observed galaxies have flatter density cores.
  - Too-Big-to-Fail Problem: Simulations predict massive sub-halos, but they don't align with the smallest dwarf galaxies should be the densest, while observations show the opposite.

https://www.michaelperryman.co.uk/_files/ugd/6e4321_62ecaa77a88b4ad98ffc57d8f32cf96d.pdf

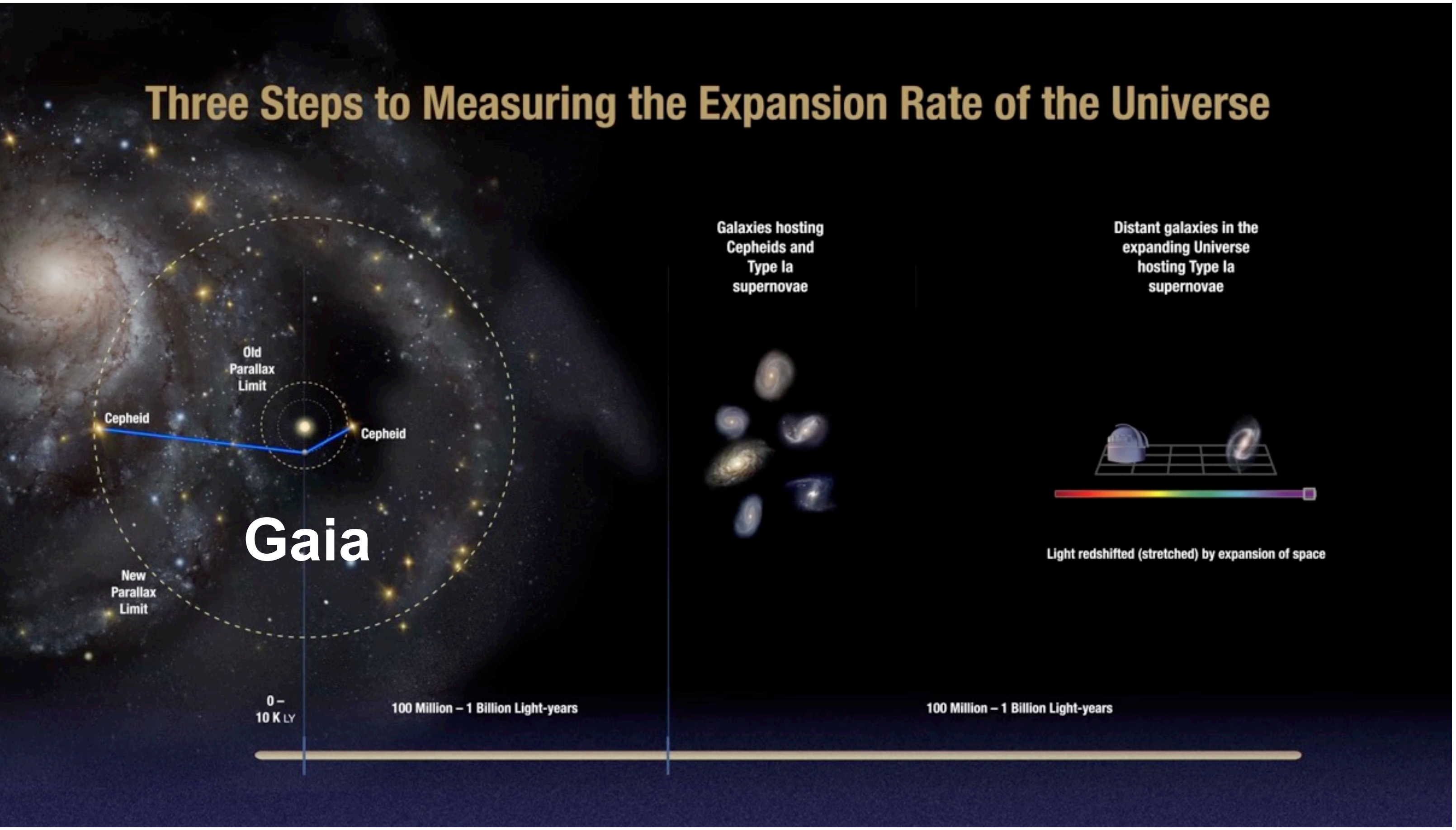
Three steps towards the large-scale measurement of the universe



Adam Riess
Berlin, 10 November 2018
Photo: S. Jordan

https://www.we-heraeus-stiftung.de/veranstaltungen/tagungen/2018/hubble2018/

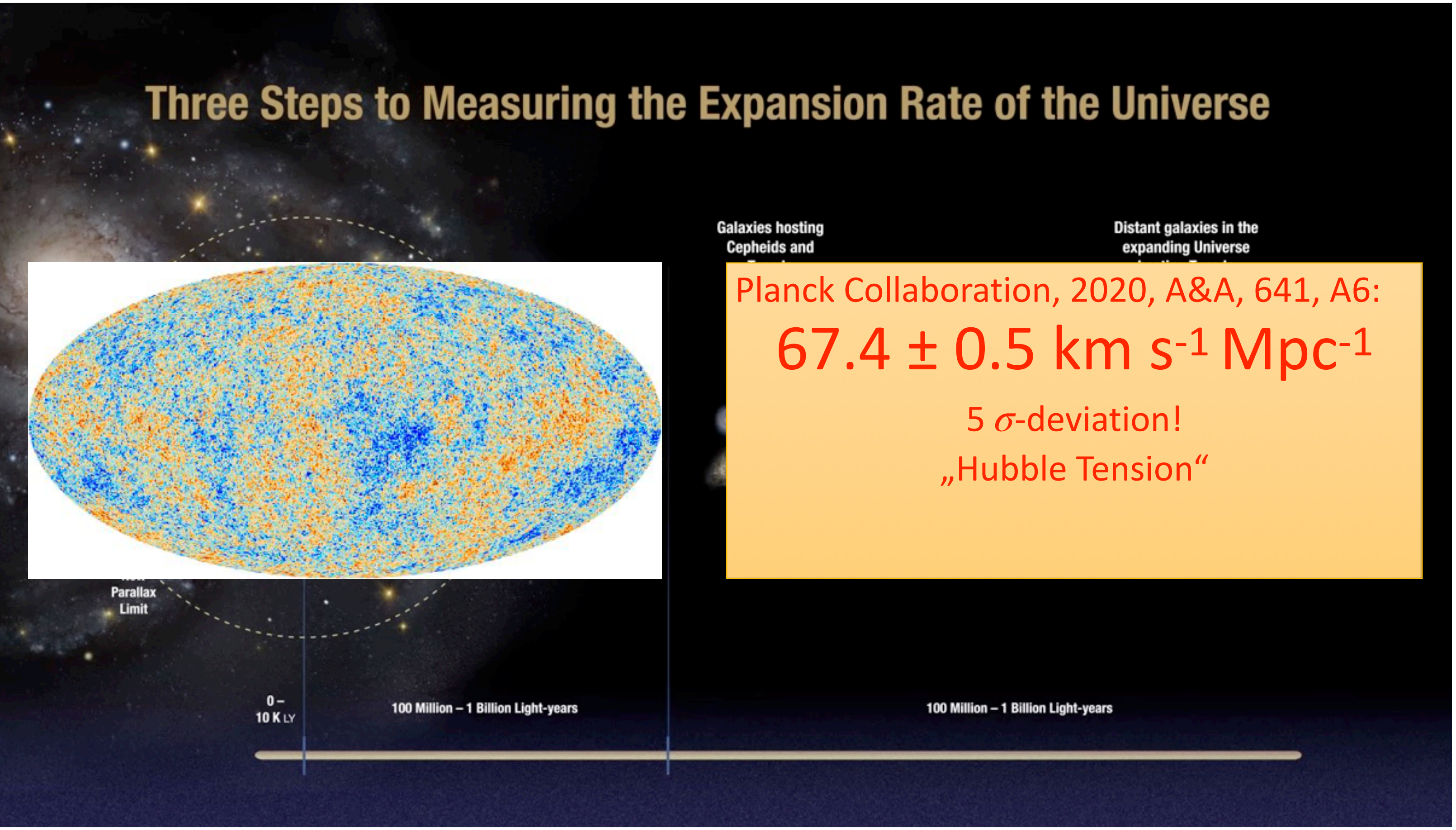
Three steps towards the large-scale measurement of the universe



- Riess et al.: Milky Way Cepheid Standards for Measuring Cosmic Distances and Application to Gaia DR2: Implications for the Hubble Constant, 2018, ApJ, 861, 126
- Riess et al.: A Comprehensive Measurement of the Local Value of the Hubble Constant with 1 km^{-1} Mpc^{-1} Uncertainty from the Hubble Space Telescope and the SH0ES Team, 2022, ApJ, 934, 7
- Riess et al.: Cosmic Distances Calibrated to 1% Precision with Gaia EDR3 Parallaxes and Hubble Space Telescope Photometry of 75 Milky Way Cepheids Confirm Tension with ΛCDM, 2021, ApJ, 908, 6
- Riess et al.: Cluster Cepheids with High Precision Gaia Parallaxes, Low Zeropoint Uncertainties, and Hubble Space Telescope Photometry, 2022, ApJ, 938, 36

Hubble constant measured with Gaia-calibrated Cepheids and type Ia supernovae:
73.01 ± 0.99 km s^{-1} Mpc^{-1}

Three steps towards the large-scale measurement of the universe



Planck Collaboration, 2020, A&A, 641, A6:

67.4 ± 0.5 km s^{-1} Mpc^{-1}

5 σ-deviation!

„Hubble Tension“

- Riess et al.: Milky Way Cepheid Standards for Measuring Cosmic Distances and Application to Gaia DR2: Implications for the Hubble Constant, 2018, ApJ, 861, 126
- Riess et al.: A Comprehensive Measurement of the Local Value of the Hubble Constant with 1 km^{-1} Mpc^{-1} Uncertainty from the Hubble Space Telescope and the SH0ES Team, 2022, ApJ, 934, 7
- Riess et al.: Cosmic Distances Calibrated to 1% Precision with Gaia EDR3 Parallaxes and Hubble Space Telescope Photometry of 75 Milky Way Cepheids Confirm Tension with ΛCDM, 2021, ApJ, 908, 6
- Riess et al.: Cluster Cepheids with High Precision Gaia Parallaxes, Low Zeropoint Uncertainties, and Hubble Space Telescope Photometry, 2022, ApJ, 938, 36

Hubble constant measured with Gaia-calibrated Cepheids and type Ia supernovae:
73.01 ± 0.99 km s^{-1} Mpc^{-1}

Gaia Sky is developed by Toni Sagristà

Download Gaia Sky 3.6.2-3
linux | windows | macos | tgz
release date: 2024-06-07

Gaia Sky is a real-time, 3D, astronomy visualisation software that runs on Windows, Linux and macOS. It is developed in the framework of ESA's Gaia mission to chart about 1 billion stars of our Galaxy in the Gaia group of the Astronomisches Rechen-Institut (ZAH, Universität Heidelberg).

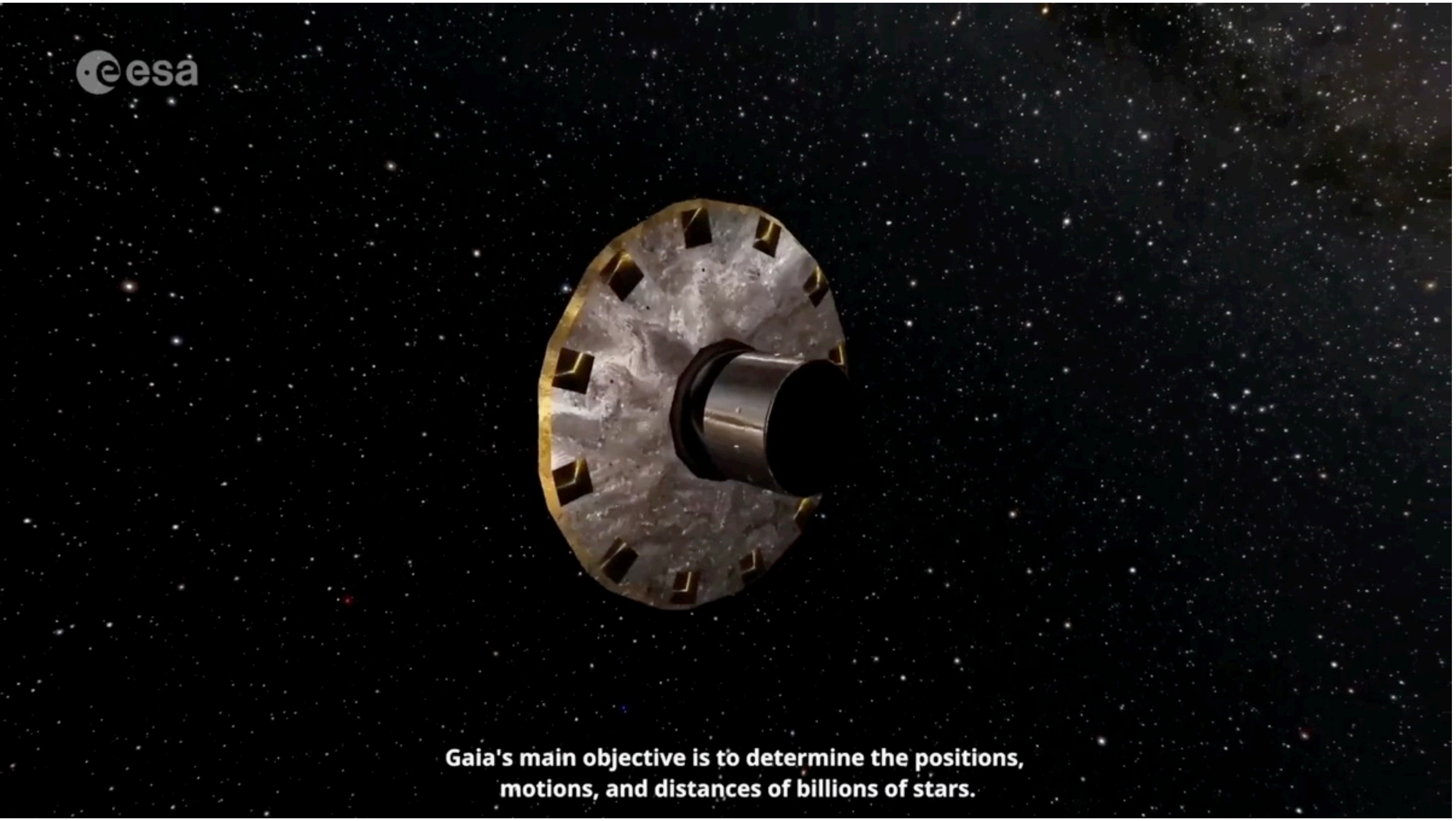
- **Free and open source** - Open source and free, and will stay this way. Contribute to the development and translations.
- **High object count** - The MS-LOD technique enables the real-time exploration of billions of objects.
- **From Gaia to the cosmos** - Explore from high-z galaxies to small asteroids in a seamless manner.
- **Virtual Reality** - Visit the whole Universe in VR!
- **6D exploration** - Observe star positions but also proper motions and radial velocities, if available.
- **Planetary surfaces** - Explore surfaces with elevation maps (using tessellation, if available).
- **Procedural planets** - Procedurally generate planet surfaces, clouds and atmospheres.
- **Advanced graphics** - Virtual textures, screen space reflections, shadows, HDR, ray-marched distance fields, dynamic resolution, etc.
- **Eclipses** - Real-time eclipse representation in all bodies.
- **3D-ready** - 6 stereoscopic modes: Anaglyphic (red-cyan), VR headset, 3DTV (H and V), cross-eye and parallel view.
- **360 mode** - Spherical (equirectangular), cylindrical and Hammer projections available, plus many reprojection modes.
- **Planetarium projection mode** - Azimuthal equidistant (dome master) projection for single-projector setups. MPCDI for real-time usage in multi-projector systems. Ready to produce videos for full domes from the desktop app.
- **Gaia** - Observe Gaia in its orbit and discover its movement in the sky and its attitude.
- **Use your data** - Download pre-packed datasets (Gaia DR3+, NEARGALCAT, SDSS, Open Clusters catalog, etc.) or use your own, in *VOTable*, *FITS*, *CSV* and other formats (*STIL*).
- **Real-time filters** - Filter any dataset by distance, magnitude, galactic, ecliptic, equatorial coordinates, and more.
- **SAMP aware** - Use SAMP to interoperate with SAMP-ready software such as Topcat and Aladin.
- **Navigate the galaxy** - Use your favorite controllers and gamepads to navigate the Galaxy. Piece of cake!
- **Camera paths** - Record and play camera paths off-the-shelf.
- **Scriptable and extensible** - Use Python to script and extend the capabilities of the Gaia Sky.
- **Internationalised** - Translated to English, German, Spanish, French, Catalan, Slovenian and Bulgarian.

http://www.zah.uni-heidelberg.de/gaia/outreach/gaiasky

Nobel laureate George Smoot

ESA astronaut (SpaceX Crew-3) Matthias Maurer

Visualisation of the Gaia mission with Gaia Sky



https://youtu.be/m5JErseISTE


Gaia's main objective is to determine the positions,
motions, and distances of billions of stars.

Gaia's schedule

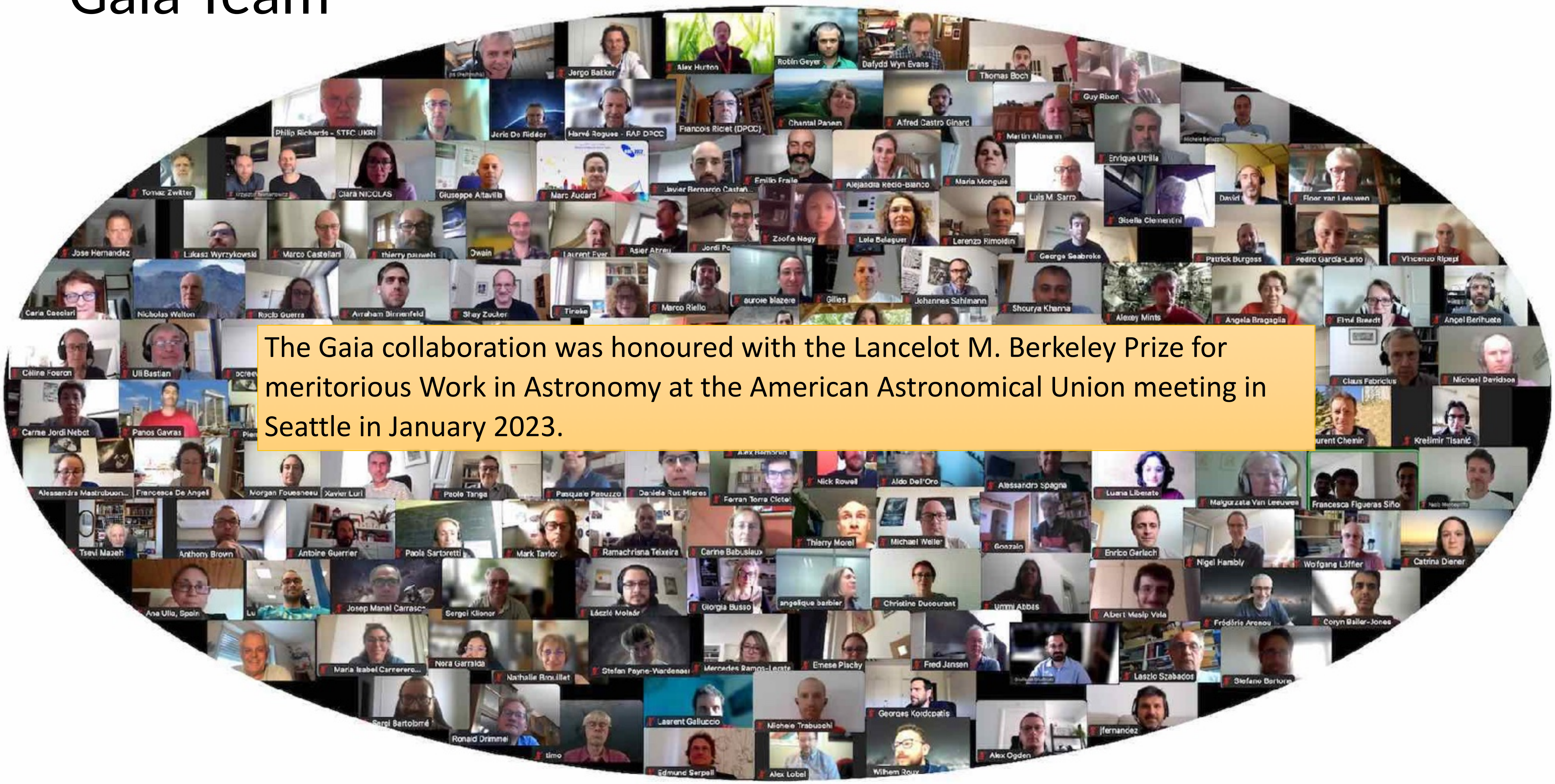
- **May 1993:** First proposal for Gaia to ESA
- **2000**: Accepted as an ESA project, ‘Cornerstone Mission’
- **2006:** Start of the industrial phase
- **2007-2013:** Various reviews
- **19 December 2013:** Launch
- **Until 18 July 2014:** ‘Commissioning’ (test phase)
- **Since 19 July 2014:** Regular measurements
- **14 September 2016:** First Gaia catalogue (DR1)
- **25 April 2018:** Second (first ‘real’) Gaia catalogue (DR2)
- **July 2019:** End of the nominal mission (5 years of measurements), the start of the extended mission
- **3 December 2020:** First part of the third Gaia catalogue (EDR3), 34 months of measurements
- **13 June 2022:** Third Gaia catalogue (DR3), 34 months of measurements
- **10 October 2023:** Gaia Focused Product Release (interim release of some special data)
- **End of 2024:** End of measurements
- **First half of 2026:** Fourth catalogue based on the nominal mission (DR4), 66 months of measurements
- **2030?:** Fifth catalogue based on the extended mission (DR5), more than 10 years of measurements

Improvements of Gaia Data Release

- Each DR contains more stars for which the parallaxes and proper motions could be significantly measured
- Longer data collection:
  - The time period of the observations increased from 14 months (Gaia DR1) to 22 months (DR2), and to 34 months (DR3).
  - Gaia DR4 (first half of 2026) will be based on 66 months (5.5 years) and DR4 (2030?) will contain data from the whole mission of 125 months (10.4 years)
- This will lead to smaller random errors for parallaxes ($\propto t^{1/2}$) and proper motions ($\propto t^{3/2}$)
- Due to an increasingly better understanding of the instruments, the systematic errors are also reduced from DR to DR
- Additional data products are coming up:
  - In DR4 epoch data will be published for astrometry, photometry, and spectroscopy
- We are just at the beginning of exploiting the treasure produced by Gaia

Gaia Team

Gaia Team



The Gaia collaboration was honoured with the Lancelot M. Berkeley Prize for meritorious Work in Astronomy at the American Astronomical Union meeting in Seattle in January 2023.

Gaia only works with teamwork

- About a third of those working on Gaia
- Meeting of the DPAC consortium in Heidelberg (13-17 March 2023)
- DPAC = Data Processing and Analysis Consortium

Gaia Team

Gaia-Sky

- Gaia Sky is a program for visualising Gaia data (positions, motions and distances of stars in the Gaia catalogue)
- The programme is public domain and open source
- http://www.zah.uni-heidelberg.de/gaia/outreach/gaiasky
- Software developer: Toni Sagristá from the Astronomischen Rechen-Institut in Heidelberg

If you want to view the newest Gaia videos, subscribe to our YouTube channels

Stefan Jordan: https://www.youtube.com/channel/UCaQGWvf5PvJ-AMJtrTpXLMw

Gaia Sky/Toni Sagristà: https://www.youtube.com/user/toninoni

Follow Stefan Jordan on Twitter: https://twitter.com/StefanJordanARI

Links to all Gaia DR3 videos

- The chemistry of our Milky Way: https://youtu.be/L7WnIJEJXFo
- Chemistry of asteroids as seen by Gaia: https://youtu.be/ObskcpB6JDA
- Asteroid populations: https://youtu.be/XYir3bQMfgQ
- Gaia Sky video on Non Single Stars, fly to a few specific cases: https://youtu.be/JUnGS27xIL4
- Gaia sees starquakes: https://youtu.be/hMaiTLVFpEw
- Milky Way in motion: https://youtu.be/S9ipbsdxwvA
- Social stars: https://youtu.be/TPkjhXmW8k8
- How Gaia detects binary stars: https://youtu.be/BTzifJxi7wE
- Asteroid populations: https://youtu.be/XYir3bQMfgQ
- Parallaxes and proper motions explained (based on Gaia DR2): https://www.youtube.com/watch?v=KynOQRd5oLs
- Animated infographic on the wavy pattern seen in Gaia data (Gaia Data Release 3): https://youtu.be/5b-eDLVHwrg
- Full details seen on Gaia's velocity map (Gaia Data Release 3): https://youtu.be/EjAUqRwGlaQ
- Gaia DR3 extinction map (based on GSPPhot) - video from MPIA: https://youtu.be/aOevXQqLRgE
- Infographic on Gaia's non-single star catalogue (Gaia Data Release 3) - Science version: https://youtu.be/c_nFgolEO5w
- Gaia's detection of non-single stars with spectroscopy - Science version: https://youtu.be/PcN5pvggcbw
- Gaia's detection of eclipsing binaries: https://youtu.be/lGogR6F_oi4
- Gaia's astrometric detection of non-single stars: https://youtu.be/jWFAmhLHvfg
- Sky-projected motion of a binary star: https://youtu.be/oGqSgBIJtZ0
- From Gaia observations to astrophysical parameters, the life of a star: https://youtu.be/Nf6kYYtkZpA
- Gaia CU8 explained: https://youtu.be/fAYbpOUFWX0
- The many dimensions of Gaia Data Release 3 (with titles): https://youtu.be/jKWQmbB5EQE
- The many dimensions of Gaia Data Release 3 (no titles, 1 sec slides): https://youtu.be/Th_O9YVfO20
- The many dimensions of Gaia Data Release 3 (no titles, 2 sec slides): https://youtu.be/AtEA3-itCSM
- The Gaia DR3 Golden Sample of Astrophysical Parameters (the selection of the FGKM stars): https://youtu.be/7uVRdRx5_Ko
- Microlensing events in Gaia DR3 captured in 30 seconds: https://youtu.be/o17MoMTbwy0
- Microlensing events in Gaia DR3 captured in 90 seconds: https://youtu.be/ciKteY7QVOE
- Gaia Sky video on Non Single Stars, fly to a few specific cases: https://youtu.be/JUnGS27xIL4
- Gaia DR3 - Composite QSO spectrum: https://youtu.be/ZsmyVwKUHC0

Links to all Gaia FPR videos

(FPR = Gaia Focused Product Release, released on Tuesday 10 October 2023)

- omega Centauri: Unveiling half a million undetected Gaia stars: https://youtu.be/AAGk0BxCu40
- Service Interface Function (SIF) image of the globular cluster ω Centauri (Gaia FPR): https://youtu.be/DYINZG1KxHA
- Spatial distribution of two diffuse interstellar bands: https://youtu.be/6mUs9aKoSlk
- Search for gravitational lenses with Gaia: https://youtu.be/_XYr2MmjLZo
- Gravitational lensing explained: https://youtu.be/YECc5IFecoE
- Gaia spectacularly improves asteroid orbits: https://youtu.be/-l42TIevzWg
- Gaia Observations of Mira Long Period Variables: https://youtu.be/kHrqNojDN6k

Gaia ESA

https://www.cosmos.esa.int/web/gaia/dr3-stories