

Big datasets in astronomy

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What do astronomers measure?

$$f_\lambda(\theta, \varphi, \lambda, t)$$

Brightness,
as a function of

Sky location

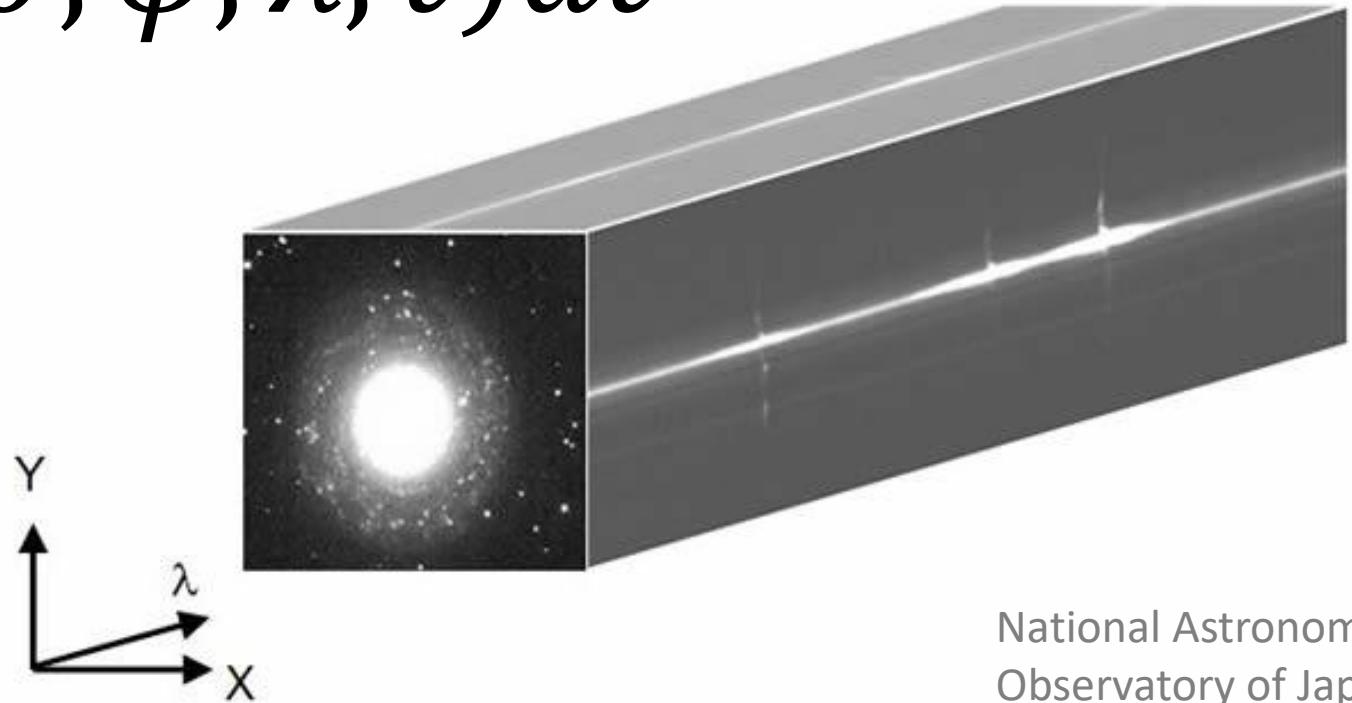
Wavelength or
frequency of light

time

The diagram illustrates the function $f_\lambda(\theta, \varphi, \lambda, t)$ as a brightness measurement. The variables are labeled as follows: θ and φ represent the sky location; λ represents the wavelength or frequency of light; and t represents time. Arrows point from each label to its corresponding variable in the function.

Data cube

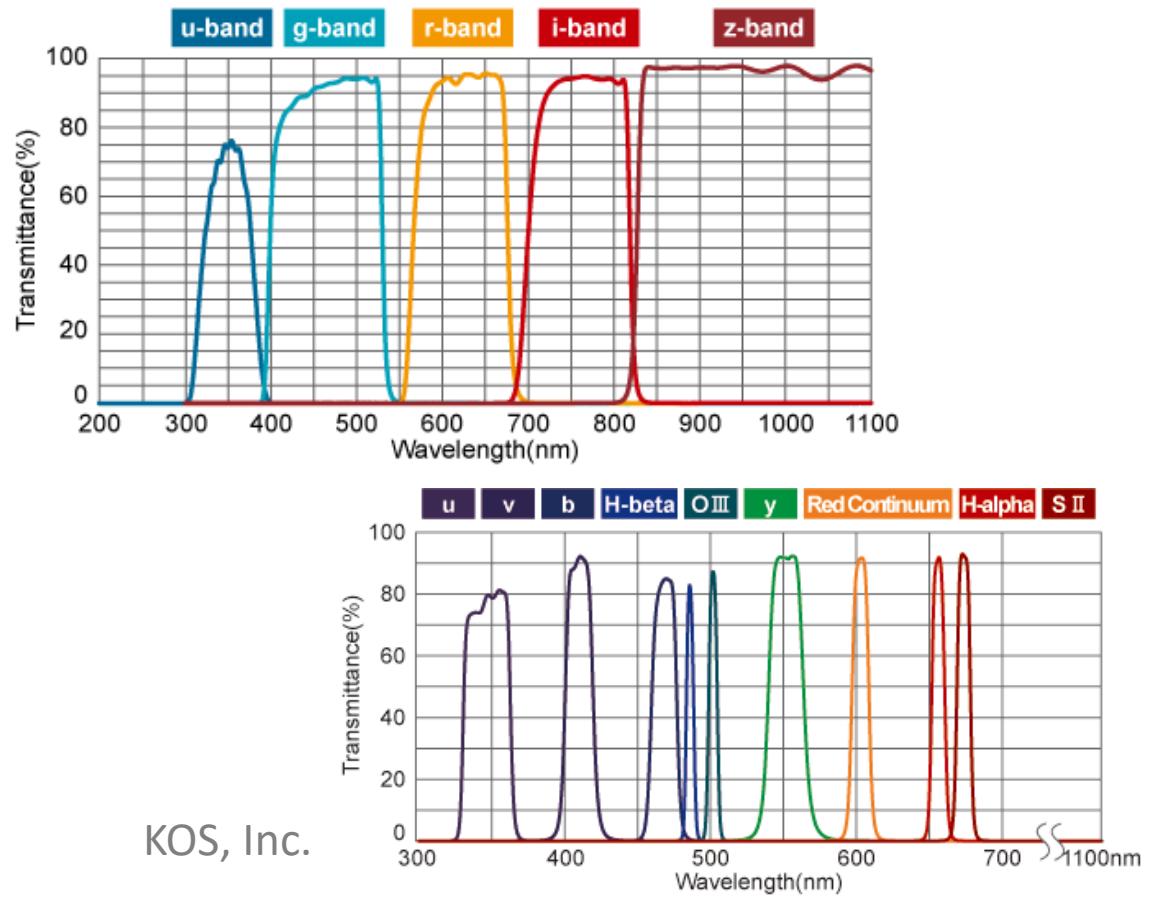
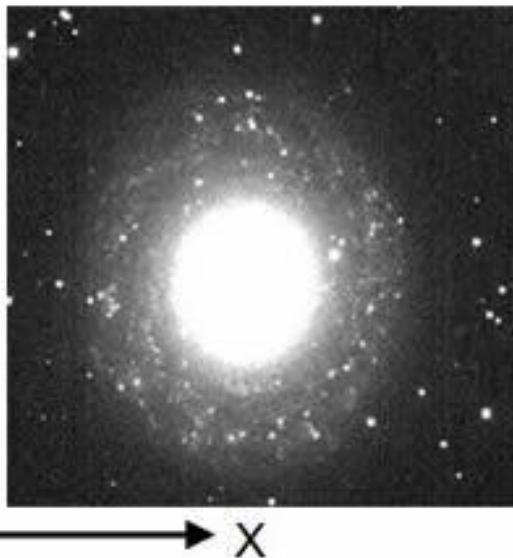
$$\int f_{\lambda}(\theta, \varphi, \lambda, t) dt$$



National Astronomical
Observatory of Japan

Image

$$\int f_{\lambda}(\theta, \varphi, \lambda, t) dt d\lambda$$



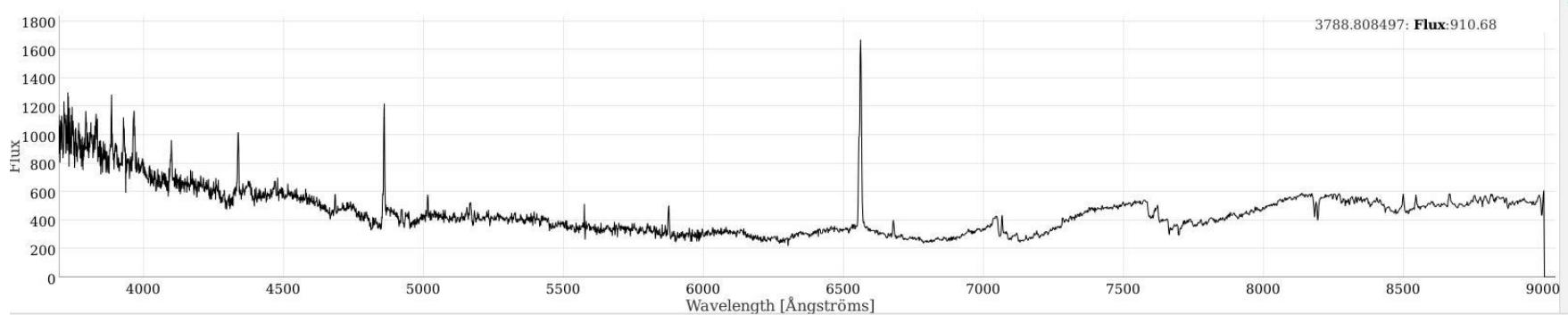
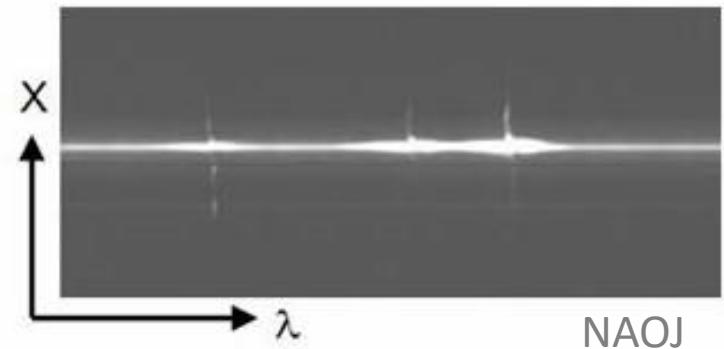
National Astronomical
Observatory of Japan

KOS, Inc.

Western  Science

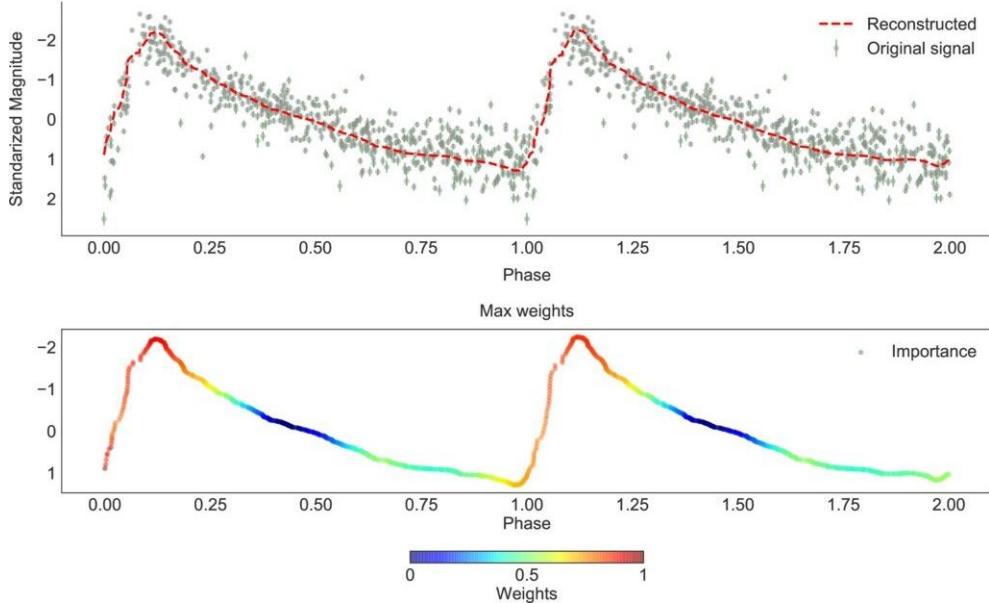
Spectrum

$$\int f_{\lambda}(\theta, \varphi, \lambda, t) dt d\Omega$$

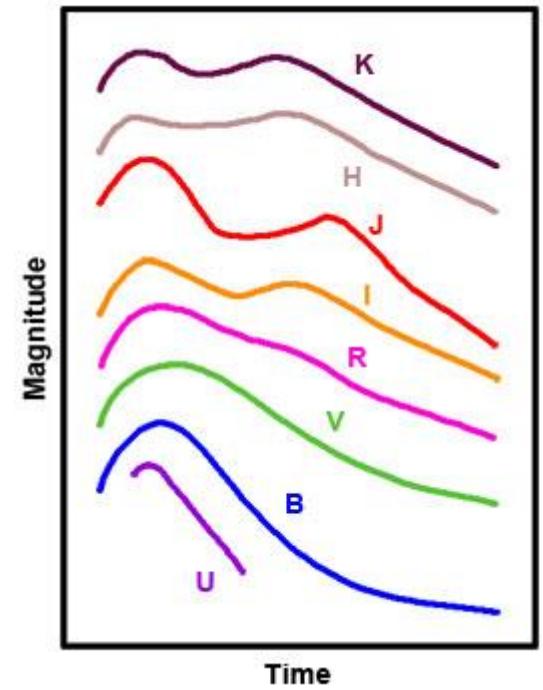


Time series photometry

$$\int f_{\lambda}(\theta, \varphi, \lambda, t) d\lambda d\Omega$$

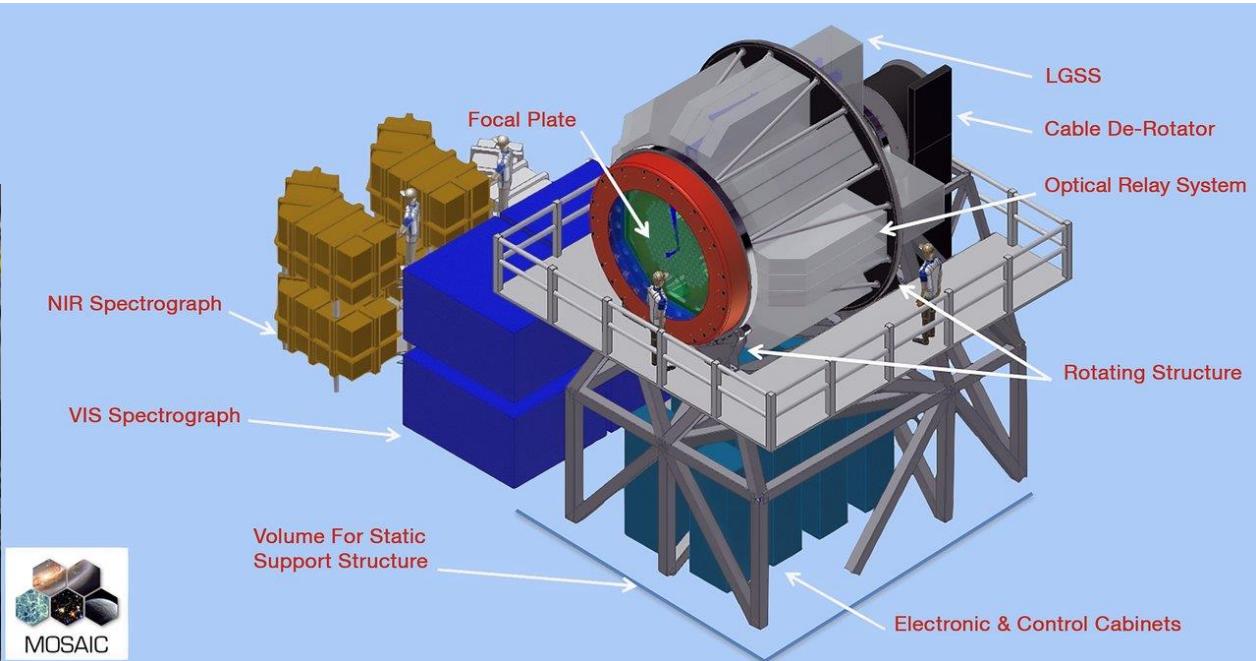


Pieringer et al 2019

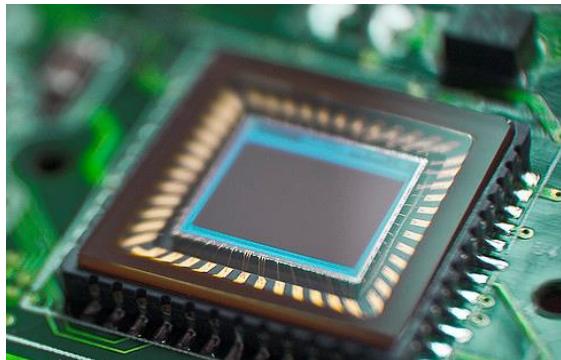


Swinburne Astronomy Online

Capturing the light

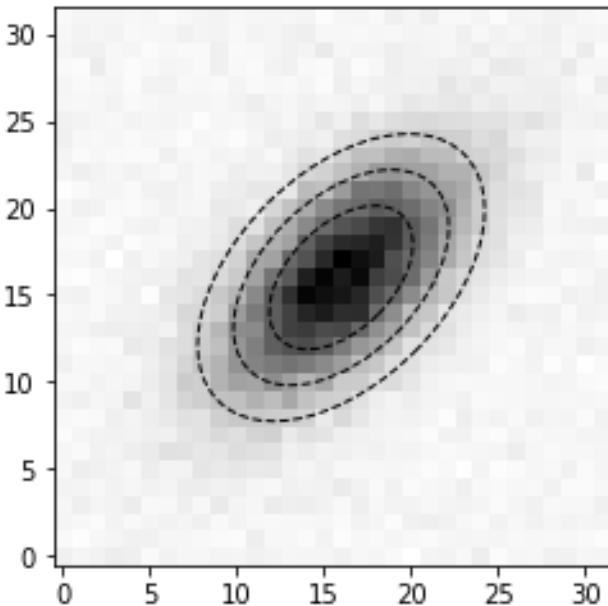


ESO

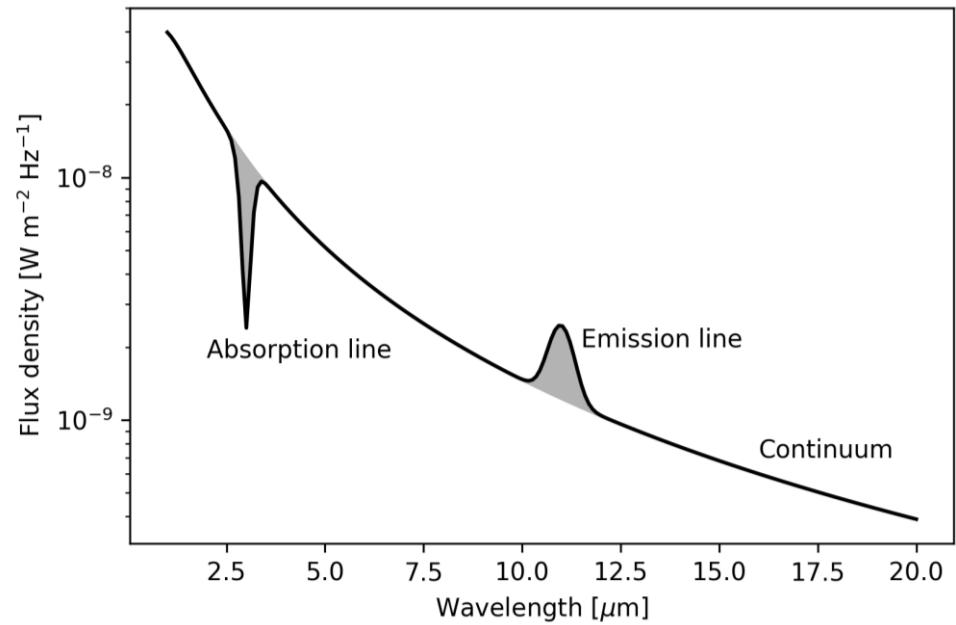


M. Laskowski via Flickr

Measurements (and uncertainties!) from data



Location, structure,
luminosity



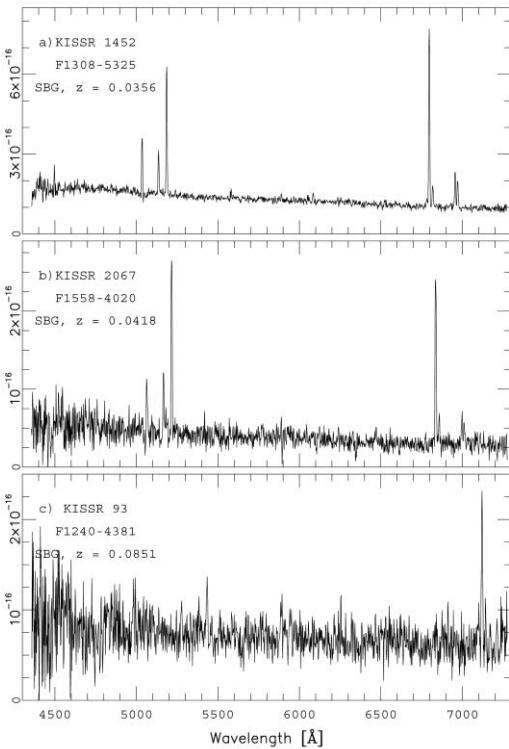
Motion, composition,
physical conditions

Measurements are compiled into catalogues

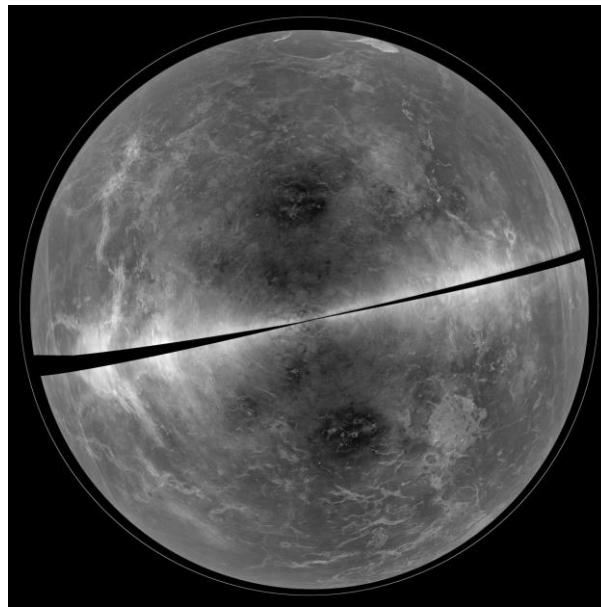
MESSIER NUMBER	OTHER DESIGNATION	RIGHT ASCENSION	DECLINATION	CONSTELLATION	TYPE	MAGNITUDE	SIZE	MESSIER NUMBER	OTHER DESIGNATION	RIGHT ASCENSION	DECLINATION	CONSTELLATION	TYPE	MAGNITUDE	SIZE
M1	NGC 1952	5h35m	22°01'	Taurus	Supernova remnant	8.0	6' by 4'	M45	The Pleiades	3h47m	24°07'	Taurus	Open cluster	1.5	110'
M2	NGC 7089	21h33m	-0°49'	Aquarius	Globular cluster	6.3	16'	M46	NGC 2437	7h42m	-14°49'	Puppis	Open cluster	6.1	27'
M3	NGC 5272	13h32m	28°23'	Canes Venatici	Globular cluster	5.9	18'	M47	NGC 2422	7h32m	-14°30'	Puppis	Open cluster	4.4	30'
M4	NGC 2171	16h24m	-26°31'	Scorpius	Globular cluster	5.4	36'	M48	NGC 2548	8h14m	-5°48'	Hydra	Open cluster	5.8	54'
M5	NGC 5904	15h19m	2°05'	Serpens	Globular cluster	5.7	23'	M49	NGC 4472	12h30m	8°00'	Virgo	Galaxy	8.4	9' by 7.5'
M6	NGC 6405	17h40m	32°16'	Scorpius	Open cluster	4.2	25'	M50	NGC 2323	7h03m	-8°20'	Monoceros	Open cluster	5.9	16'
M7	NGC 6475	17h54m	-34°47'	Scorpius	Open cluster	2.8	75'	M51	NGC 5194	13h30m	47°12'	Canes Venatici	Galaxy	8.4	11' by 7'
M8	NGC 6523	18h04m	-24°23'	Sagittarius	Nebula	6.0	90' by 40'	M52	NGC 7623	23h24m	61°35'	Cassiopeia	Open Cluster	6.9	13'
M9	NGC 6333	17h19m	-18°31'	Ophiuchus	Globular cluster	7.8	12'	M53	NGC 5024	13h13m	18°10'	Coma Berenices	Globular cluster	7.7	13'
M10	NGC 6254	16h57m	-4°06'	Ophiuchus	Globular cluster	6.6	20'	M54	NGC 6715	18h55m	-30°29'	Sagittarius	Globular cluster	7.2	12'
M11	NGC 6705	18h51m	-6°16'	Scutum	Open cluster	5.3	14'	M55	NGC 6809	19h40m	-30°58'	Sagittarius	Globular cluster	6.3	19'
M12	NGC 6218	16h47m	-1°57'	Ophiuchus	Globular cluster	6.8	16'	M56	NGC 6779	19h17m	30°11'	Lyra	Globular cluster	8.4	8.8'
M13	NGC 6205	16h42m	36°28'	Hercules	Globular cluster	5.3	20'	M57	NGC 6720	18h54m	33°02'	Lyra	Planetary nebula	8.8	1.4' by 1'
M14	NGC 6402	17h38m	-3°15'	Ophiuchus	Globular cluster	7.6	11'	M58	NGC 4579	12h38m	11°49'	Virgo	Galaxy	9.6	5.5' by 4.5'
M15	NGC 7078	21h30m	12°10'	Pegasus	Globular cluster	6.0	18'	M59	NGC 4621	12h42m	11°39'	Virgo	Galaxy	9.6	5' by 3.5'
M16	NGC 6611	18h19m	-13°47'	Serpens	Open cluster	6.0	7'	M60	NGC 4649	12h44m	11°33'	Virgo	Galaxy	8.8	7' by 6'
M17	NGC 6618	18h21m	-16°11'	Sagittarius	Nebula	7.0	11'	M61	NGC 4303	12h22m	4°28'	Virgo	Galaxy	9.6	6' by 5.5'
M18	NGC 6613	18h20m	-17°08'	Sagittarius	Open cluster	6.9	9'	M62	NGC 6266	17h01m	-30°07'	Ophiuchus	Globular cluster	6.7	15'
M19	NGC 6273	17h03m	-26°16'	Ophiuchus	Globular cluster	6.8	17'	M63	NGC 5053	13h16m	42°02'	Canes Venatici	Galaxy	8.6	10' by 6'
M20	NGC 6514	18h03m	-23°02'	Sagittarius	Nebula	9.0	28'	M64	NGC 4826	12h57m	21°41'	Coma Berenices	Galaxy	8.5	9.3' by 5.4'
M21	NGC 6531	18h05m	-22°30'	Sagittarius	Open cluster	5.9	13'	M65	NGC 3623	11h19m	13°05'	Leo	Galaxy	8.8	8' by 1.5'
M22	NGC 6656	18h36m	-23°54'	Sagittarius	Globular cluster	5.2	32'	M66	NGC 3627	11h20m	12°59'	Leo	Galaxy	9.0	8' by 2.5'
M23	NGC 6494	17h57m	-19°01'	Sagittarius	Open cluster	5.5	27'	M67	NGC 2682	0h50m	11°49'	Cancer	Open cluster	6.0	30'
M24	NGC 6603	18h17m	-18°29'	Sagittarius	Star cloud	2.5	90'	M68	NGC 4590	12h40m	-26°45'	Hydra	Globular cluster	7.6	11'
M25	IC 4725	18h32m	-19°15'	Sagittarius	Open cluster	4.6	32'	M69	NGC 6637	18h31m	-32°21'	Sagittarius	Globular cluster	7.4	9.8'
M26	NGC 6694	18h45m	-9°24'	Scutum	Open cluster	8.0	15'	M70	NGC 6681	18h43m	-32°18'	Sagittarius	Globular cluster	7.8	8'
M27	NGC 6853	20h00m	22°43'	Vulpecula	Planetary nebula	7.3	8' by 5.7'	M71	NGC 6838	19h45m	18°47'	Sagitta	Globular cluster	8.0	7.2'
M28	NGC 6626	18h25m	-24°52'	Sagittarius	Globular cluster	6.9	11'	M72	NGC 6981	20h54m	-12°52'	Aquarius	Globular cluster	9.2	6.6'
M29	NGC 6913	20h24m	38°32'	Cygnus	Open cluster	6.6	7'	M73	NGC 6994	20h59m	-12°38'	Aquarius	Open cluster	8.9	2.8'
M30	NGC 7099	21h40m	-23°11'	Capricornus	Globular cluster	6.9	12'	M74	NGC 6206	1h37m	15°47'	Pisces	Galaxy	8.5	10.2' by 9.5'
M31	NGC 234	0h43m	41°16'	Andromeda	Galaxy	3.4	178' by 63'	M75	NGC 6864	20h06m	-21°55'	Sagittarius	Globular cluster	8.6	6.8'
M32	NGC 221	0h43m	40°52'	Andromeda	Galaxy	8.2	8' by 6'	M76	NGC 6550	1h42m	51°34'	Perseus	Planetary nebula	10.1	2.7' by 1.8'
M33	NGC 598	1h34m	30°39'	Triangulum	Galaxy	5.7	73' by 45'	M77	NGC 1068	2h43m	-0°01'	Cetus	Galaxy	8.9	7' by 6'
M34	NGC 1039	2h42m	42°47'	Perseus	Open cluster	5.2	35'	M78	NGC 2068	5h47m	0°03'	Orion	Nebula	8.0	8' by 6'
M35	NGC 2168	6h09m	24°20'	Gemini	Open cluster	5.1	28'	M79	NGC 1904	5h25m	-24°33'	Lepus	Globular cluster	7.7	9.6'
M36	NGC 1960	5h36m	34°08'	Auriga	Open cluster	6.0	12'	M80	NGC 6993	16h17m	-22°59'	Scorpius	Globular cluster	7.3	10'
M37	NGC 2099	5h15m	32°33'	Auriga	Open cluster	5.6	24'	M81	NGC 3931	9h56m	69°04'	Ursa Major	Galaxy	6.9	21' by 10'
M38	NGC 1922	5h28m	35°50'	Auriga	Open cluster	6.4	21'	M82	NGC 3954	9h56m	69°41'	Ursa Major	Galaxy	8.4	9' by 4'
M39	NGC 7092	21h32m	48°26'	Cygnus	Open cluster	4.6	32'	M83	NGC 5236	13h13m	-29°52'	Hydra	Galaxy	7.5	11' by 10'
M40	Winnecke 4	12h22m	58°05'	Ursa Major	Double star	9.0/9.6	0.8'	M84	NGC 4374	12h25m	12°53'	Virgo	Galaxy	9.1	5'
M41	NGC 2287	6h46m	-20°44'	Canis Major	Open cluster	4.5	38'	M85	NGC 4382	12h25m	18h11'	Coma Berenices	Galaxy	9.1	7.1' by 5.2'
M42	NGC 1976	5h15m	-5°27'	Orion	Nebula	3.7	85' by 60'	M86	NGC 4406	12h26m	12°57'	Virgo	Galaxy	8.9	7.5' by 5.5'
M43	NGC 1982	5h36m	-5°16'	Orion	Nebula	6.8	20' by 15'	M87	NGC 4486	12h31m	12°24'	Virgo	Galaxy	8.6	7'
M44	NGC 2632	8h40m	19°59'	Cancer	Open cluster	3.1	95'	M88	NGC 4501	12h32m	14°25'	Coma Berenices	Galaxy	9.6	7' by 4'
M89	NGC 4552	12h36m	12°33'	Virgo	Galaxy	9.7	4'	M90	NGC 4569	12h37m	13°10'	Virgo	Galaxy	9.5	9.5' by 4.5'
M91	NGC 4548	12h35m	14°30'	Coma Berenices	Galaxy	10.1	5.4' by 4.4'	M92	NGC 6341	17h17m	45°08'	Hercules	Globular cluster	6.5	14'
M93	NGC 2447	7h43m	-23°52'	Puppis	Open cluster	6.2	22'	M94	NGC 4736	12h51m	41°07'	Canes Venatici	Galaxy	8.2	7' by 3'
M95	NGC 3351	10h44m	11h42'	Leo	Galaxy	9.7	4.4' by 3.3'	M96	NGC 3368	10h47m	11h49'	Leo	Galaxy	9.2	6' by 4'
M97	NGC 3587	11h15m	55°01'	Ursa Major	Planetary nebula	9.9	3.4' by 3.3'	M98	NGC 4192	12h14m	14°54'	Coma Berenices	Galaxy	10.1	9.5' by 4.5'
M99	NGC 4254	12h19m	14°25'	Coma Berenices	Galaxy	9.9	5.4' by 4.8'	M100	NGC 4321	12h23m	15°49'	Coma Berenices	Galaxy	9.3	7' by 6'
M101	NGC 5457	14h03m	54°21'	Ursa Major	Galaxy	7.9	22'	M102	NGC 5866	15h07m	55°46'	Draco	Galaxy	10.0	5.2' by 2.3'
M103	NGC 581	1h33m	60°42'	Cassiopeia	Open cluster	7.4	6'	M104	NGC 4594	12h40m	-11°37'	Virgo	Galaxy	8.0	9' by 4'
M105	NGC 3379	10h48m	12°35'	Leo	Galaxy	9.3	2'	M106	NGC 4258	12h19m	47°18'	Canes Venatici	Galaxy	8.3	19' by 8'
M107	NGC 6171	16h33m	-13°03'	Ophiuchus	Globular cluster	7.8	13'	M108	NGC 3556	11h12m	55°40'	Ursa Major	Galaxy	10.0	8' by 1'
M109	NGC 3992	11h58m	53°23'	Ursa Major	Galaxy	9.8	7' by 4'								



Astro-data can differ from other big data



B. Campbell/NRAO



Performance level	Database DTUs	Storage included	Storage limit
Standard S0 – S2	10 – 50	250 GB	250 GB
Standard S3	100	250 GB	1 TB new
Standard S4 new	200	250 GB	1 TB new
Standard S6 new	400	250 GB	1 TB new
Standard S7 new	800	250 GB	1 TB new
Standard S9 new	1600	250 GB	1 TB new
Standard S12 new	3000	250 GB	1 TB new
Premium P1	125	500 GB	1 TB new
Premium P2	250	500 GB	1 TB new
Premium P4	500	500 GB	1 TB new
Premium P6	1000	500 GB	1 TB new
Premium P11 – P15	1750 – 4000	4 TB	4 TB
Premium RS PRS1	125	500 GB	1 TB new
Premium RS PRS2	250	500 GB	1 TB new
Premium RS PRS4	500	500 GB	1 TB new
Premium RS PRS6	1000	500 GB	1 TB new

Doesn't always fit into a database model

Incomplete/truncated

Noisy

Astro-data is very often public!

Canada
Canadian Astronomy Data Centre
CADC Home

Search for data by target
Search
[Advanced Search](#)

Telescope Data Products

Gemini CFHT
JCMT HST
BLAST

Advanced Data Products

MegaPipe
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IRIS

Services

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Select a collection... and enter target:
All MAST Observations Enter object name or RA and Dec Search
[About Collections...](#) [Show Examples...](#) [Random Search](#)

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MAST: Barbara A. Mikulski Archive for Space Telescopes

The MAST Portal lets you search multiple collections of astronomical datasets all in one place. Use this tool to find astronomical data, publications, and images.

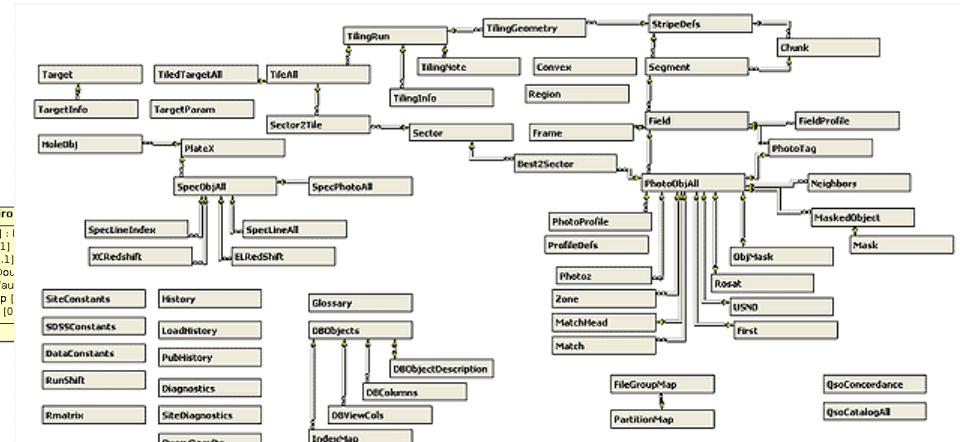
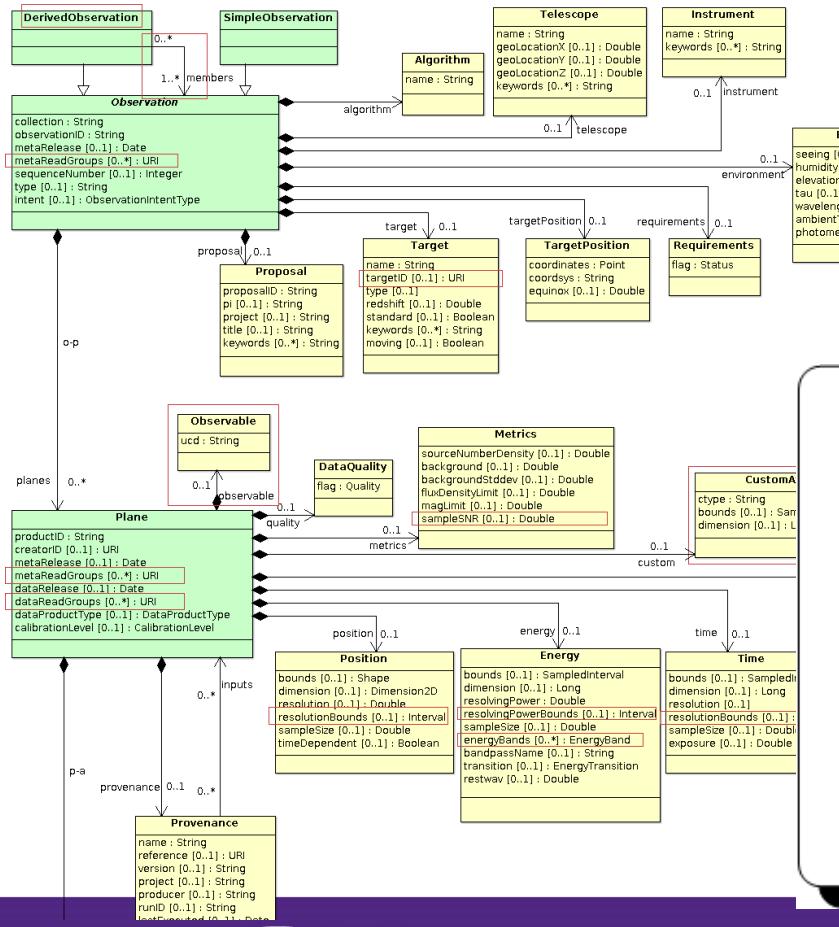
Currently available data collections:

- MAST Observations: Millions of observations from Hubble, Kepler, G. IUE, FUSE, and more.
- Virtual Observatory: Search thousands of astronomical data archives around the world for images, spectra, and catalogs.
- Hubble Source Catalog: A master catalog with a hundred million measurements of objects in Hubble images.

Quick Start:

1. Select a collection and enter a new search target OR upload an existing list

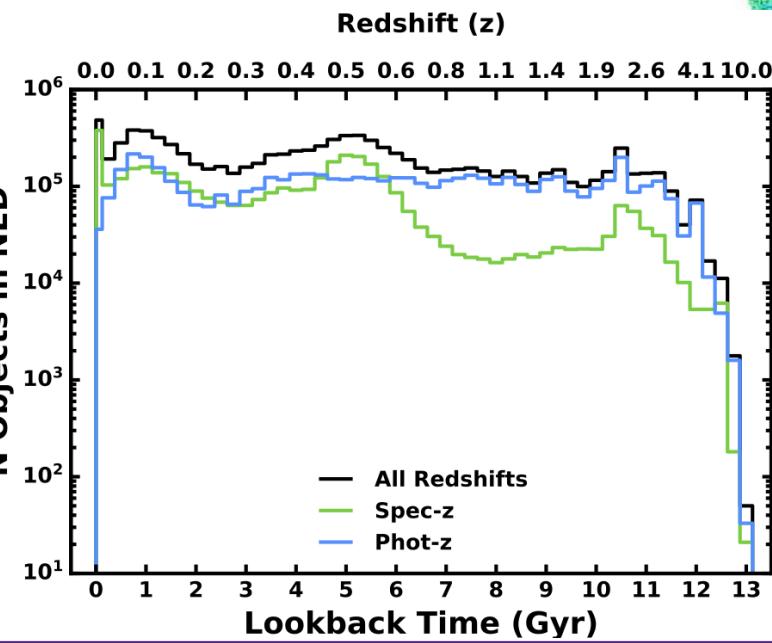
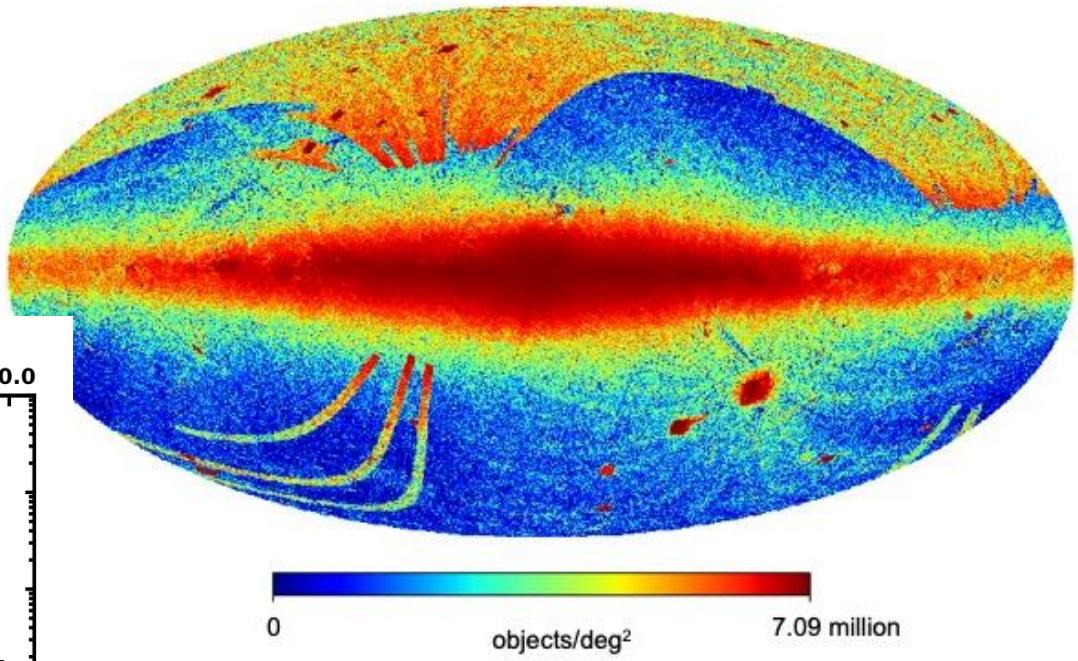
Data(base) practices are still evolving



Astronomical Data Query Language

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SELECT * FROM gaia
JOIN tycho2
ON 1=CONTAINS (POINT('ICRS',gaia.ra, gaia.dec),
CIRCLE('ICRS', tycho2.ra, tycho2.dec, 2/3600))
```

Meta-databases: SIMBAD, NED, etc



Gaia: a billion stars, many database columns

→ EUROPEAN SPACE AGENCY  ABOUT ESAC 

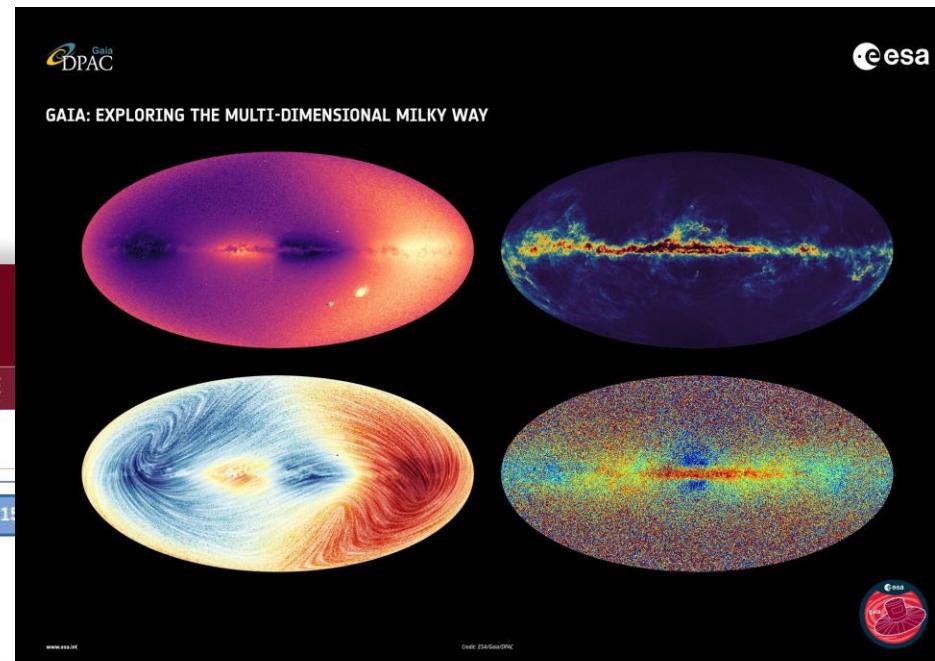
gaia archive

HOME SEARCH STATISTICS VISUALIZATION HELP DOCUMENTATION VOSPACE SHARE

Simple Form ADQL Form Query Results

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	deg	Angle[mas]	deg				
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ESA, M. Richmond

Gaia mission: numbers

- 2×10^9 objects in Milky Way & beyond, first distance for 99.9%
- About 1% of Milky Way stars
- Faintest stars: 10^{-6} x human eye detection limit
- Positional accuracy: $24 \mu\text{arcsec} = 0.11 \text{ nanoradian}$
- Nearest stars: distances measured to 0.001%
- Stars near Galactic Centre (30k lt-yr): distances to 20%
- 400+ people in Gaia Data Processing and Analysis Consortium

https://www.esa.int/Science_Exploration/Space_Science/Gaia/Gaia_factsheet

Digital telescopes: CHIME & CHORD (Canada)

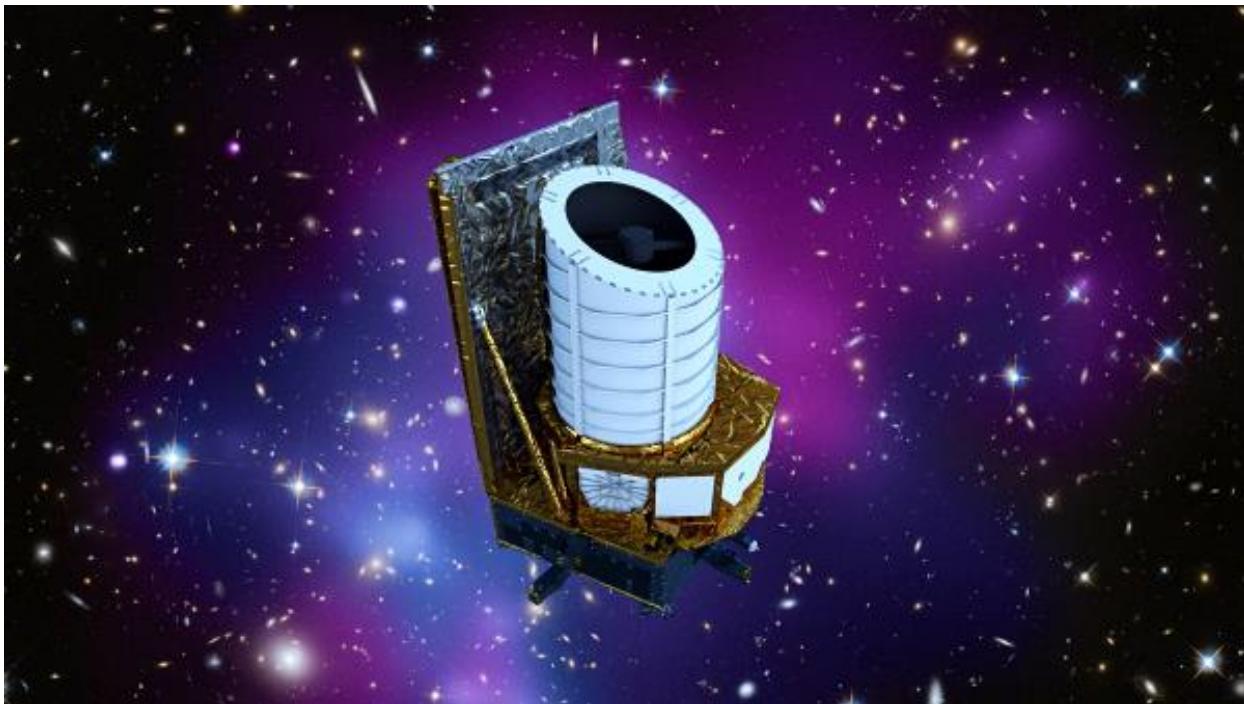
13 Tb/sec



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Euclid mission (ESA)



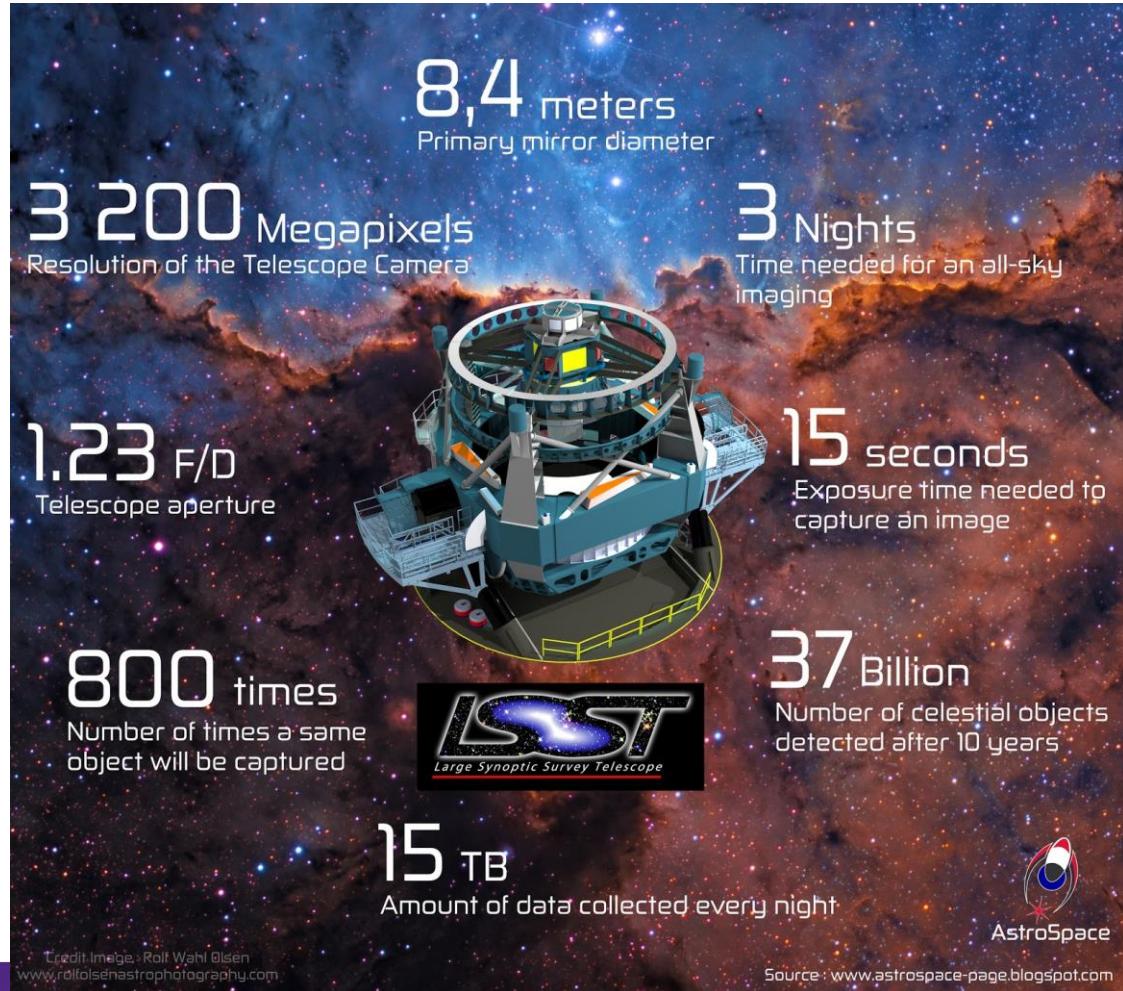
- 1.2-m diameter visible/near-infrared telescope designed for surveys; imaging and spectroscopy
- launched July 2023, first public data 2025

ESA/ATG medialab; NASA, ESA, CXC, C.
Ma, H. Ebeling and E. Barrett al., STScI

Rubin/Legacy Survey of Space & Time (Chile)

Under construction in Chile, operations to begin 2025

Will survey entire southern sky once/week over 10 years

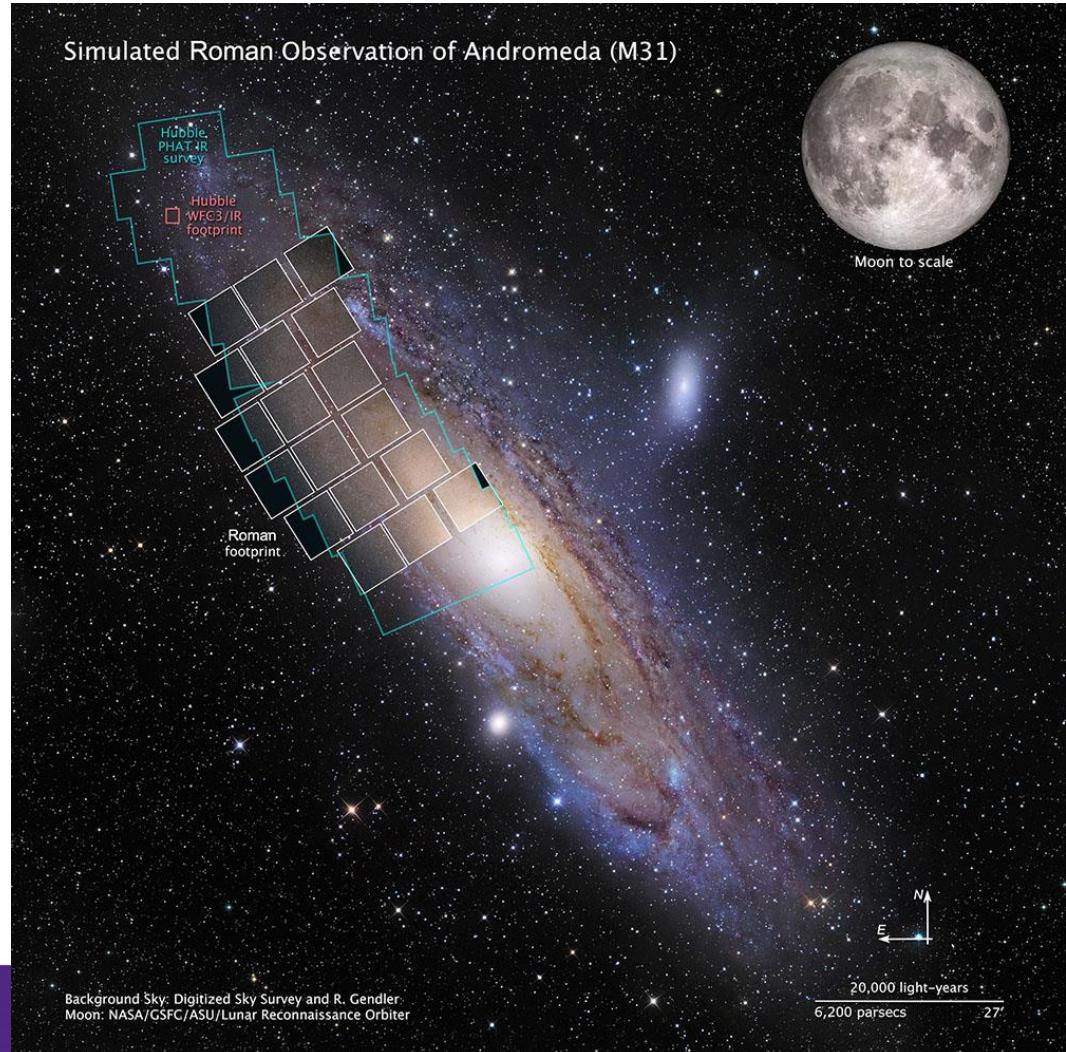


Nancy Grace Roman Space Telescope (NASA)

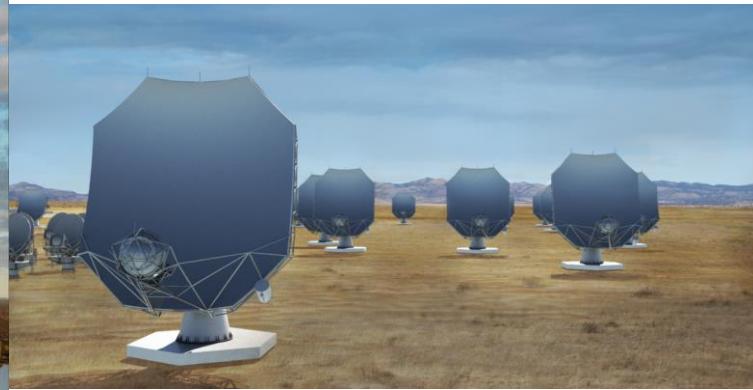
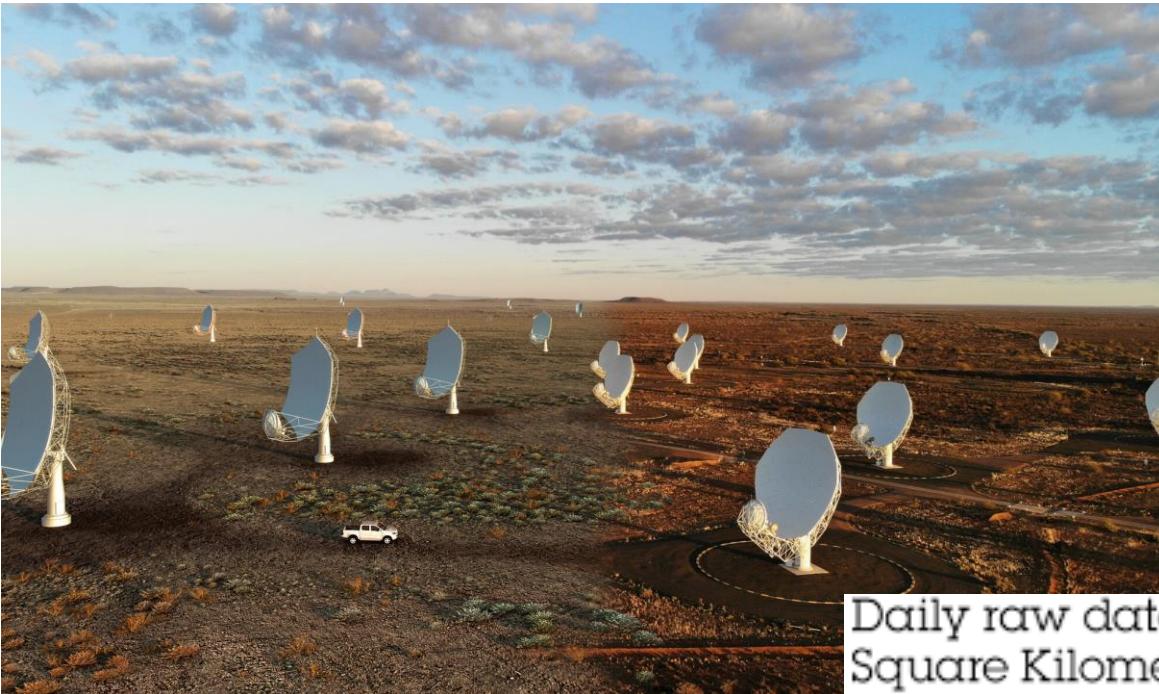
Hubble-sized telescope, but with 100x larger field of view

Visible and infrared imaging surveys and coronagraph

Launch 202?



SKA Observatory (S. Africa, Australia, NZ)



300 PB/year,
operations begin 2027

Daily raw data generated by the
Square Kilometer Array:

15 million
64GB iPods



2X
daily global internet traffic

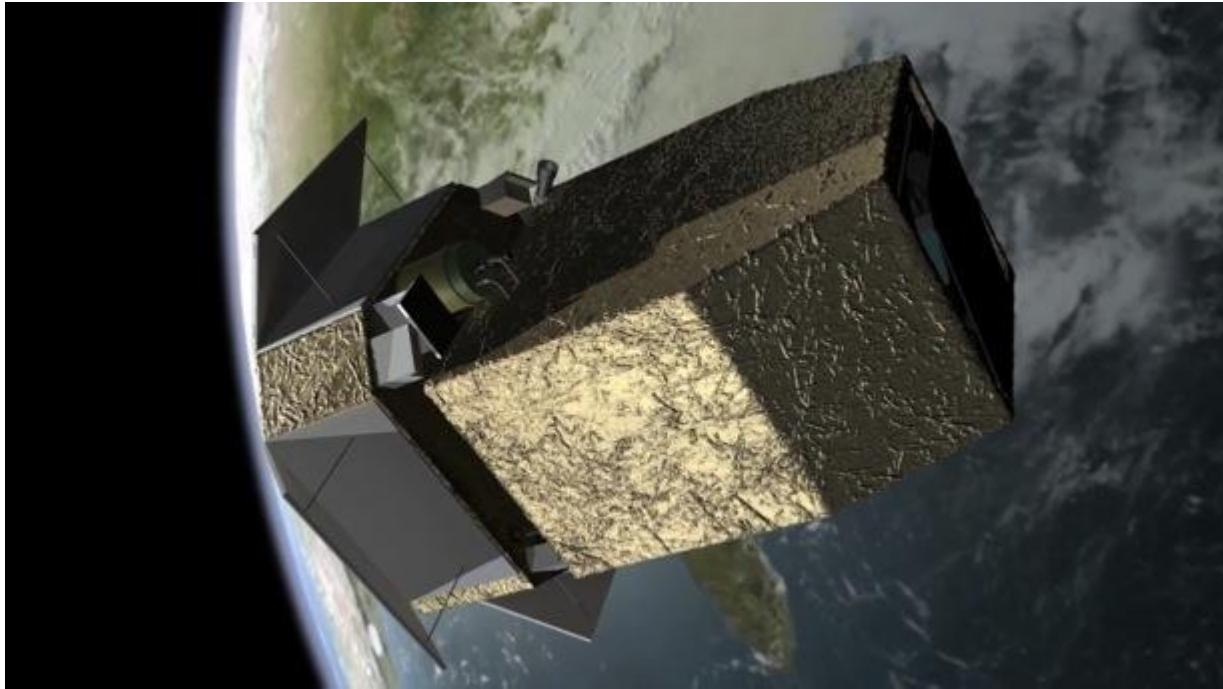


SKAO, NAOJ

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ibm.com

CASTOR (CSA)

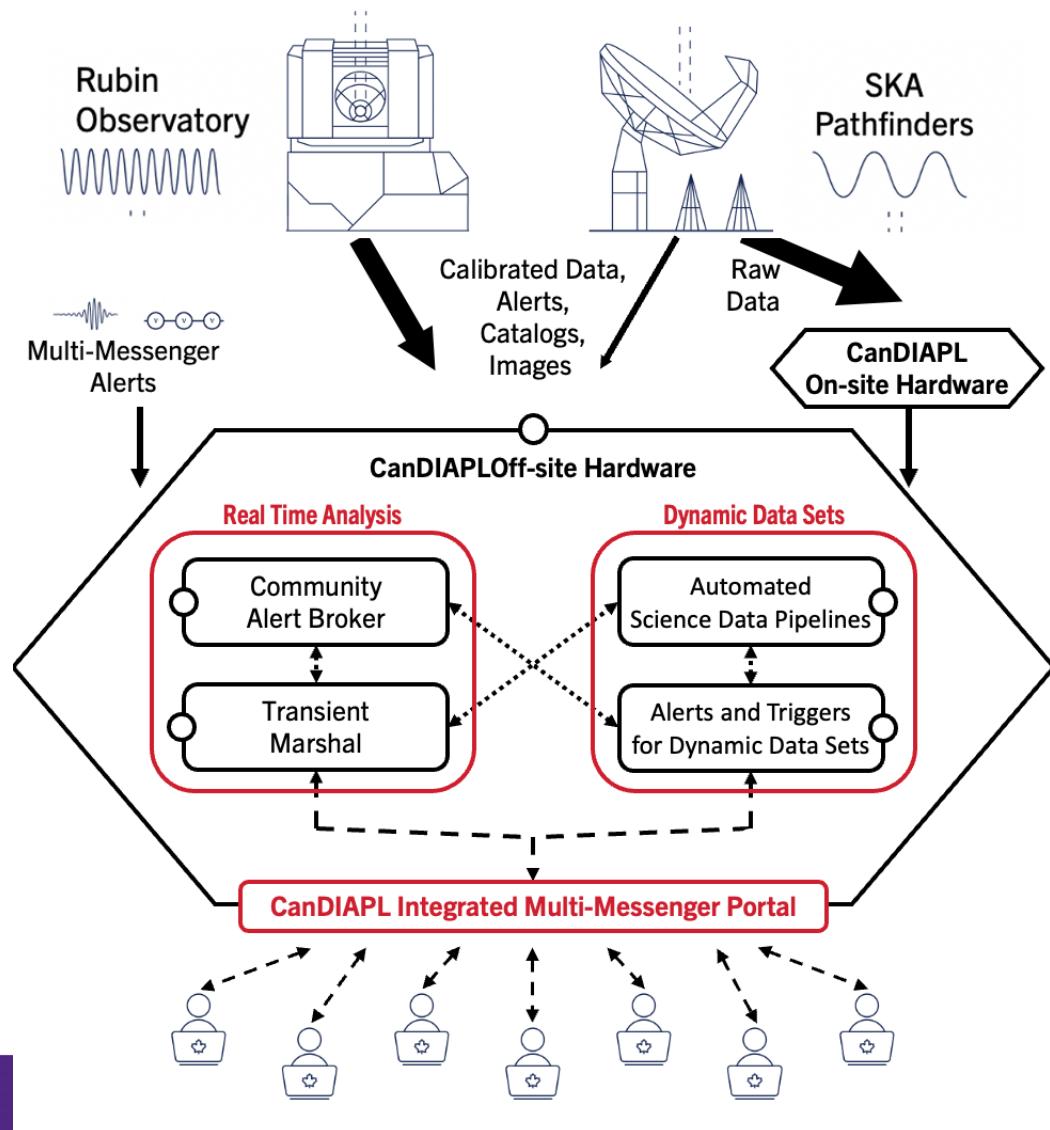
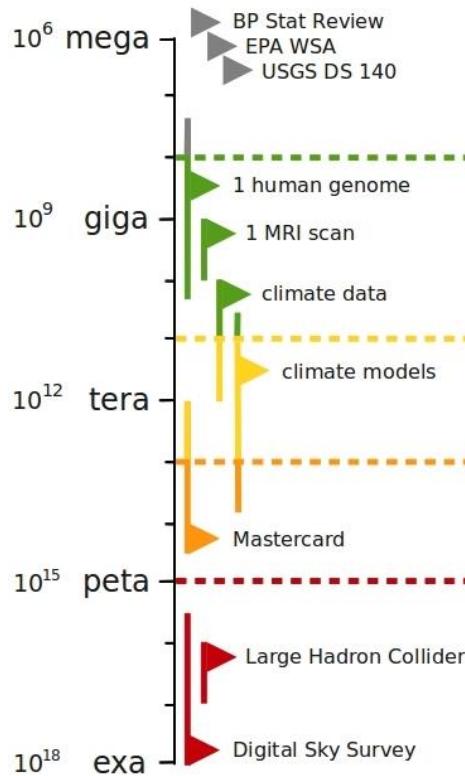


- 1-m diameter visible/ultraviolet telescope with large field of view; imaging and spectroscopy
- CSA-led with Japan, India, US: funding advocacy in progress

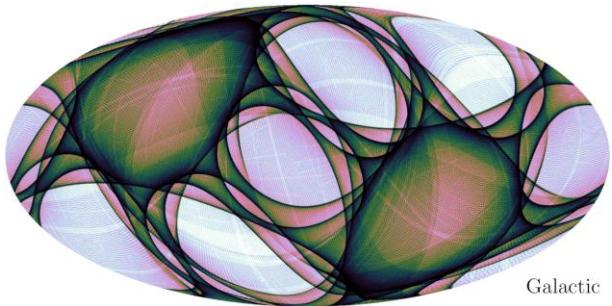
CSA & CASTOR team

Putting it all together: CanDIAPL

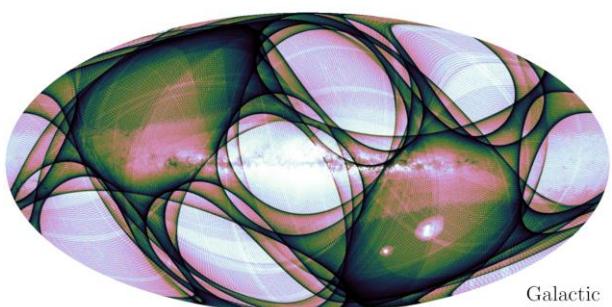
Mazamascience.com



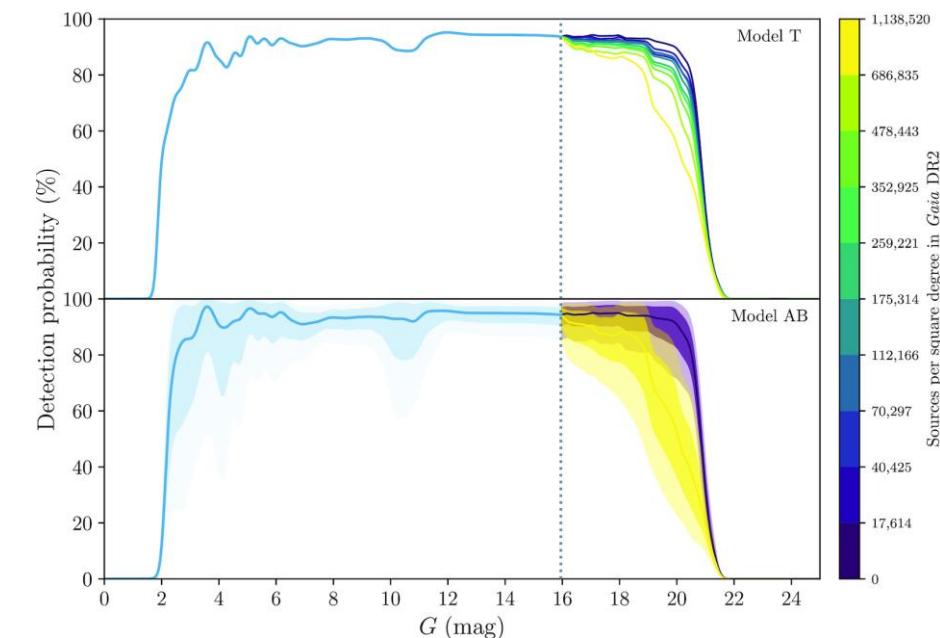
Gaia science: what did *Gaia* miss?



(a) *Gaia* DR2 completeness map based on our 1st-order selection function that only depends on the source magnitude and number of observations.

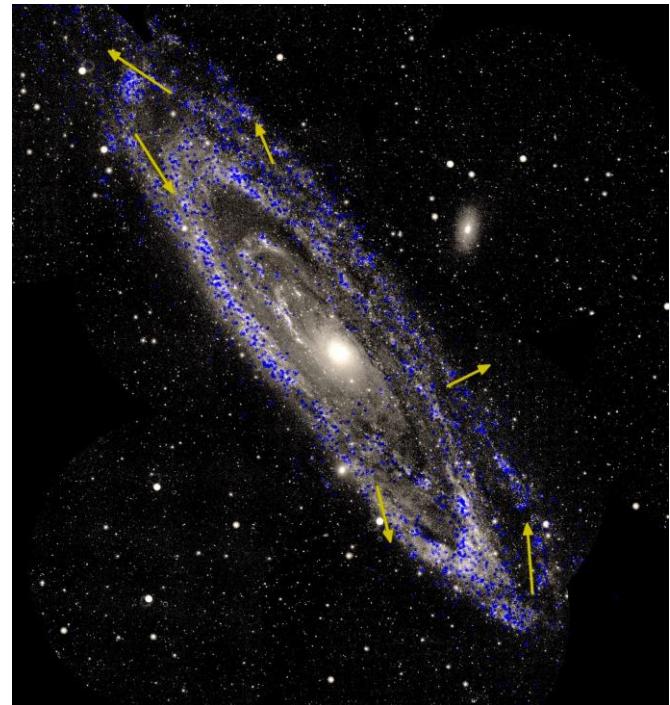
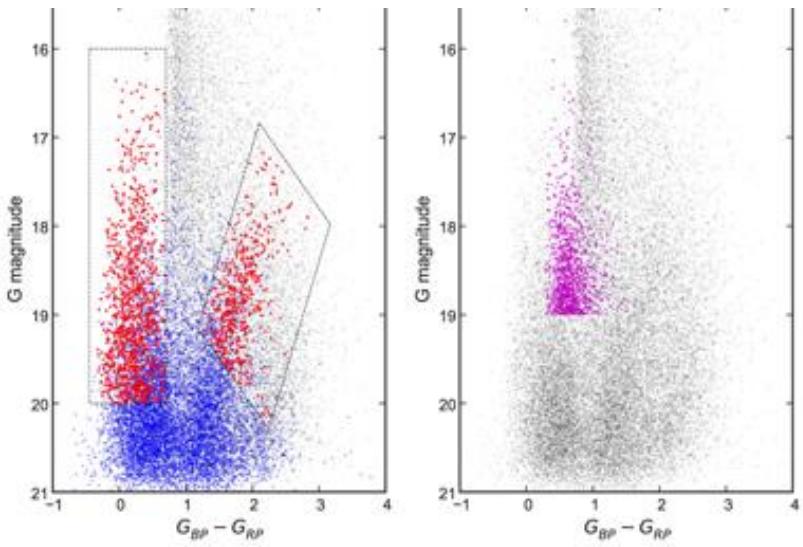


(b) *Gaia* DR2 completeness map based on our 2nd-order selection function that additionally depends on the nearby source density.



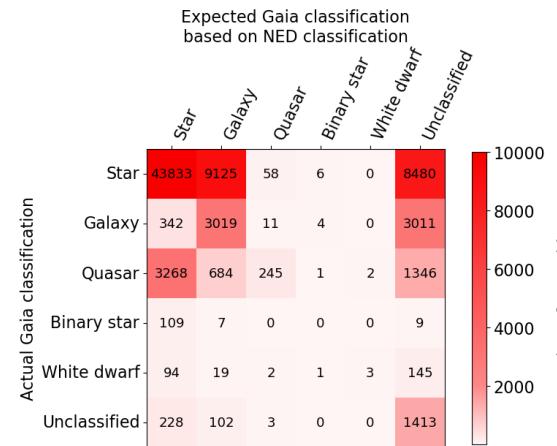
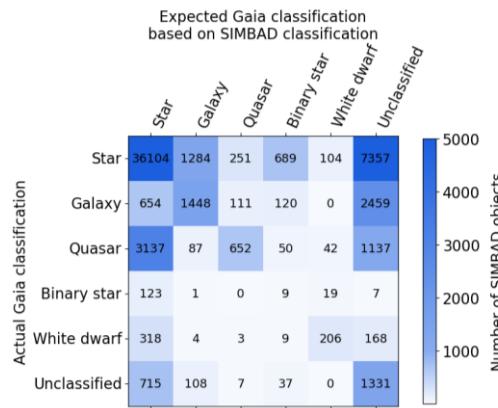
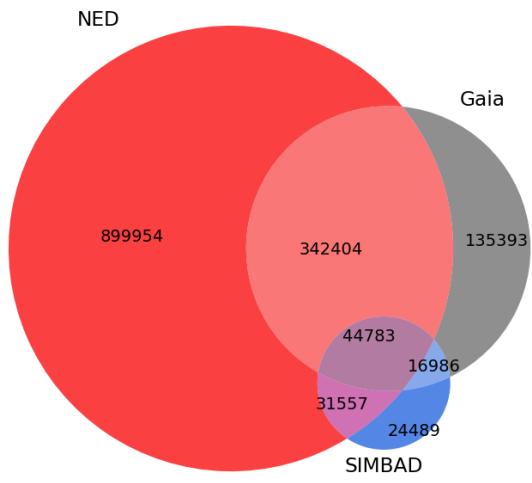
Boubert & Everall et al 2020, MNRAS, 497, 4246–426 DOI [10.1093/mnras/staa2305](https://doi.org/10.1093/mnras/staa2305)

Gaia science: nearby galaxy rotation



van der Marel et al 2019 ApJ 872 24 DOI [10.3847/1538-4357/ab001b](https://doi.org/10.3847/1538-4357/ab001b)

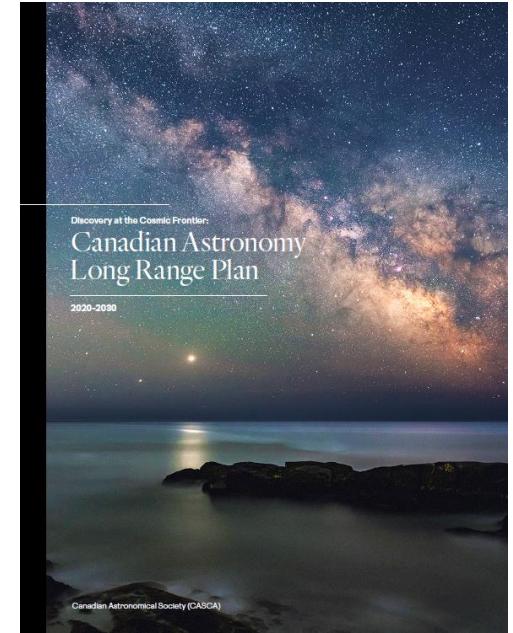
Gaia science: classifying nearby galaxy contents



Hales & Barmby 2023 MNRAS, submitted

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- [Astronomical observations: a guide for allied researchers](#)
- [Data in observational astronomy](#)
- [Gaia archive](#)
- [casca.ca/lrp2020](#) & US counterpart [Astro2020](#)



Boubert & Evarull 2020, ESA

