

From historical records to modern time-domain surveys

The Variable Universe – Lecture 01
Fall Semester 2021

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Sauverny Observatory #265



A few introductory words

- Standard Candles and Distances Group @ IPHYS (GR-ANDERSON)
- We combine stellar physics with cosmological application: measure accurate distances to determine Hubble constant
- TP4b / Master projects available!
- www.epfl.ch/labs/scd
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- 022 379 24 25



**Swiss National
Science Foundation**



European Research Council
Established by the European Commission

Course Overview

L01 : from historical records to large time-domain surveys

L02 : Variability across the Solar system

L03 : Extrinsic stellar variability

L04 & L05 : Intrinsic stellar variability (eruptive & pulsations)

L06 : Exoplanets

L07 : Transients

L08 : Degenerate objects (white dwarfs, neutron stars)

L09 : Active galaxies

L10 & L11: Multi-messenger astronomy (neutrinos, grav. waves)

L12 : Cosmic distances & expansion

L13 & L14 : Applications for fundamental physics and cosmology

Course Goals

- Develop a "time-domain mindset"
- Get inspired by variability applications in astrophysics & cosmology
- Understand basics of time-domain data analysis techniques
- Become familiar with the growing landscape of time-domain surveys, strategies & instrumentation
- Practice synthesizing info from articles outside your specialization
- Foster your presentation skills
- Have fun engaging with research close to the bleeding edge!

Course mentality / setup

- Do interrupt!
- Do take notes!
- Streaming is offered, but presence is better
- Online = video ON!
- Exercises (1h) after lectures
- Feedback wanted (good & bad)
- Moodle page: <https://moodle.epfl.ch/course/view.php?id=16823>

Exercises

- Please show up & participate!
- 1h after lecture
- Important to process course material
- Main idea:
 - All read same article during week after lecture
 - Next exercise: Informal 15 min presentation & guided group discussion
- This means
 - Two (journal club-style) paper presentations per student
 - Little preparation needed for exam
- Please sign up via link on Moodle page (PHYS-643)

Exam modalities

- Oral 30-min exam during regular exam session:
 - Between 23 Jan 23 and 3 Feb 23
 - Counts 100%
- Composition of grade:
 - 50% : 10-minute presentation of a paper discussed during exercises
 - 50% : Q&A following presentation & discussion of course content

Any questions?



**Why do
time-domain
astronomy?**

Questions

- Who among you works with time-domain data?
- What kinds of objects are you studying?
- What kind of variability timescales?
- What kind of data do we use?
- Outside of your field: where is time-domain important?

What defines time-domain astronomy?

- Distinction between "classical" variability studies and transient astronomy (transition: periodic phenomena -> any changes with time)
- All objects change on some timescale: variations & changes ubiquitous
- Today: a limited overview of astronomical surveys with time-domain connections
- Following lectures: different types of astrophysical applications, and then we will end with applications for fundamental physics and cosmology

Time domain is sexy & essential!



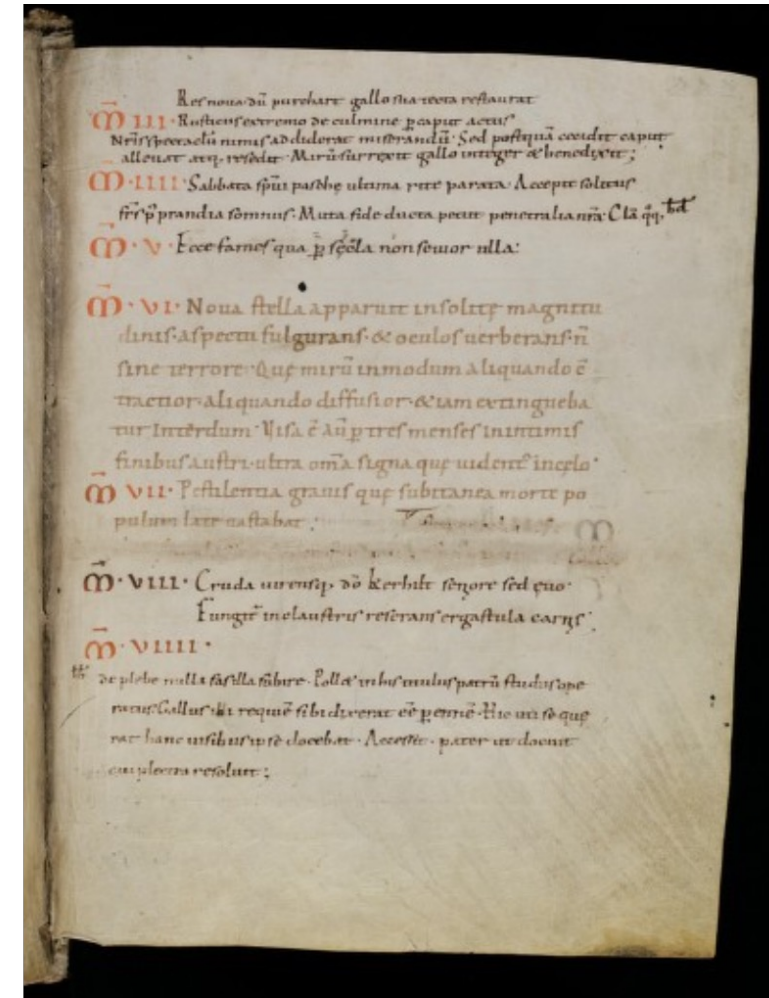
- All 5 astro-related physics Nobel prizes in past decade (2011 - 2020) directly employed time domain observations!
Accelerated Universe, Neutrino Oscillations, Gravitational Waves, Exoplanets, Black Holes
- 2002: X-ray astronomy & neutrino detections [Sun & SN1987A]
- 2006: CMB anisotropy; no direct time-domain connection

The time-domain partially makes up for the passivity of astronomy as an observational science: it allows us to see the same surface of a rotating star at different times, or to gain statistical insights into rare phenomena, such as stellar explosions

A (too short) history of time-domain astrophysics

A brief history of variability

- "Guest stars" possibly as early as 4500 BCE in Kashmir
- Algol may have been known to early Egyptians
- Earliest record of supernova in China 185 CE
- Earliest Swiss record in St Gall (SN1006), peak -7.5mag
- Tycho's star (SN1572) & Kepler's Star (1604) within a generation, no Galactic SN observed since!
- Mira [o Ceti] : the first variable star
Fabricius (1596) : Nova, Holwarda (1638) : 11 months
- Edward Pigott & John Goodricke (1784)
<https://wonderdome.co.uk/goodricke-pigott-algol-cepheids/>



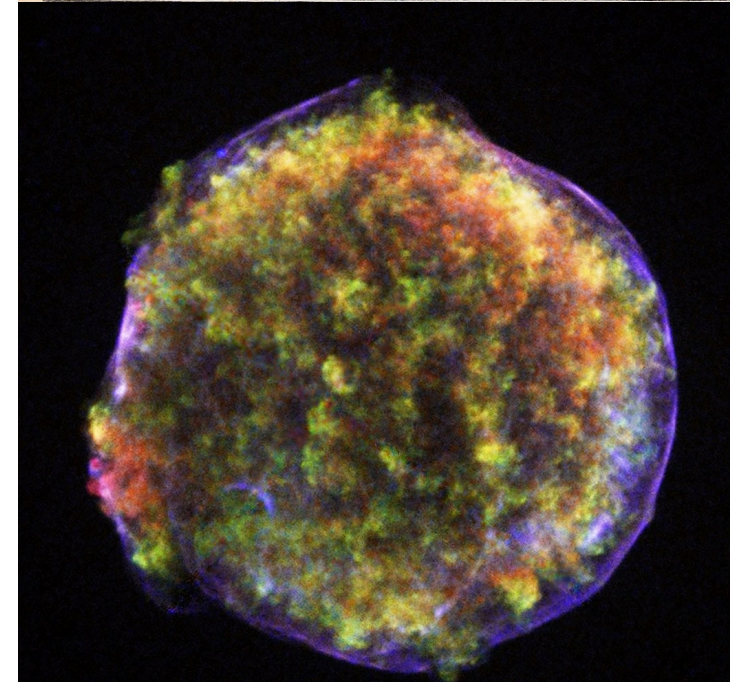
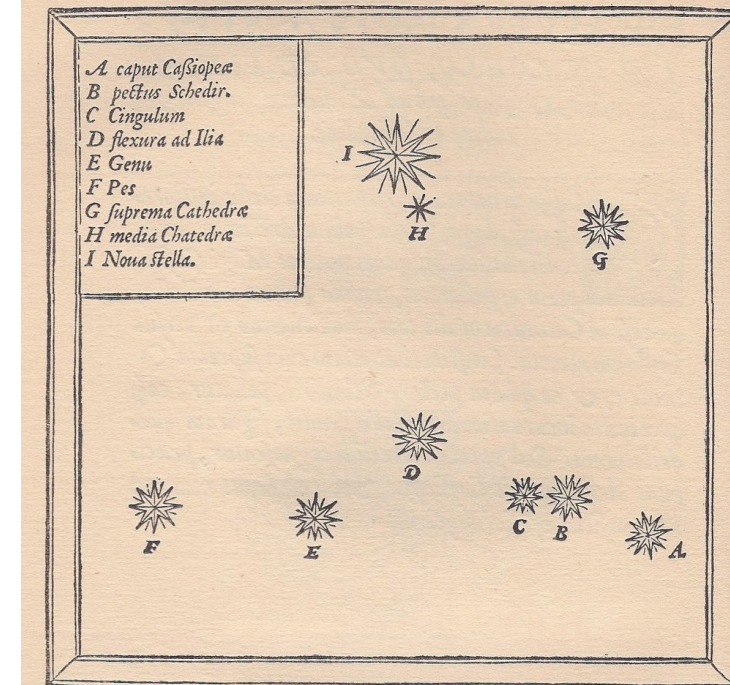
[i]n a wonderful manner this was sometimes contracted, sometimes diffused, and moreover sometimes extinguished ... It was seen likewise for three months in the inmost limits of the south, beyond all the constellations which are seen in the sky

19th Century: variable stars!

- Friedrich Wilhelm Argelander (1799 – 1875):
astrometry, variable star systematic studies,
Bonner Durchmusterung (last w/out photography)
- Charles Pickering (1846 – 1919):
photographic spectroscopy: binaries,
coordinated follow-up

Table 4. Variables discovered by 1796.

<i>Name</i>	<i>Year</i>	<i>Type</i>	<i>Period</i>	<i>Spectrum</i>	<i>Discoverer</i>
α Ceti	1596	Mira	372	M5e-M9e	Fabritius
β Persei	1667	EA	2.87	B8V	Montanari
χ Cygni	1686	M	408	S6.2e-S10.4e	Kirch
R Hydrae	1704	M	384	M6e-M9e	Maraldi
R Leonis	1782	M	310	M6e-M9.5IIIe	Koch
β Lyrae	1784	EB	12.9	B8II-IIIep	Goodricke
η Aquilae	1784	δ Cep	7.18	F6Ib	Pigott
δ Cephei	1784	δ Cep	5.37	F5-G1Ib	Goodricke
R CrB	1795	RCB	—	G0Iep	Pigott
α Herculis	1795	SRc	—	M5Ib-II	W. Herschel
R Scuti	1795	RVa	147	G0Iae-K2pIbe	Pigott

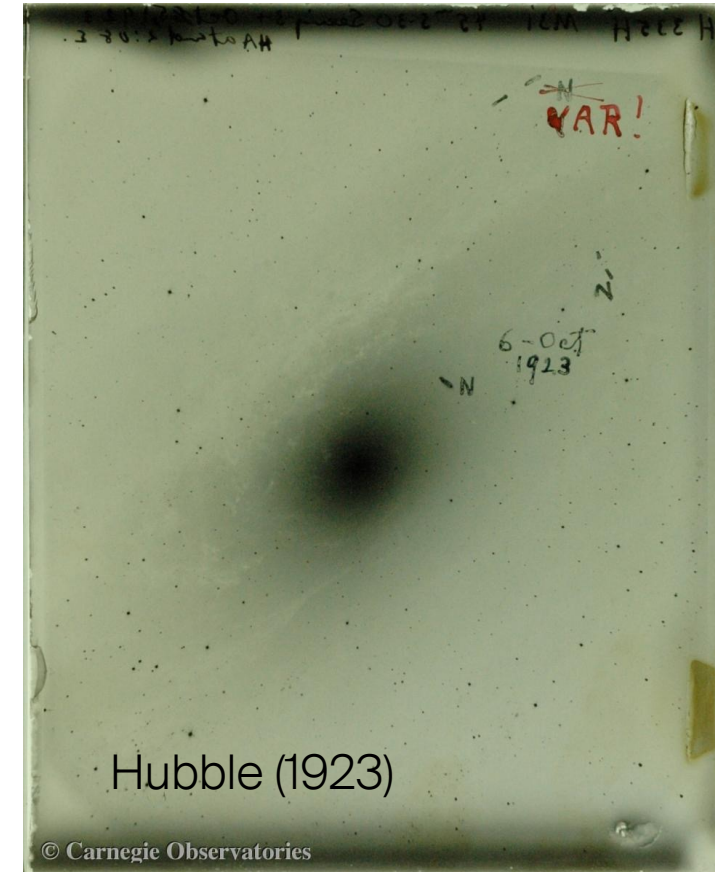


20th Century: categorizing

- Harvard "computers"
 - Henrietta Leavitt; Harvard Variables: <https://library.cfa.harvard.edu/variable-stars>
 - Williamina Paton Fleming; <https://library.cfa.harvard.edu/fleming-work>
 - Dorrit Hoffleit: bright star catalog, very important mentor for female astro PhDs; <https://www.cwhf.org/inductees/dorrit-hoffleit>
 - Henrietta Hill Swope: 275 Cepheids in M31 (Baade & Swope 1964)
- Leavitt, then Hubble: extragalactic variables!
- American Association of Variable Star Observers (AAVSO) founded 1912
- Rapid progress with invention of CCDs
- Extensions beyond visible EM

H.	Max.	Min.	Epoch.	Period.	Res. M.	Res. m.	H.	Max.	Min.	Epoch.	Period.	Res. M.	Res. m.
1505	14.8	16.1	0.02	1.25336	-0.6	-0.5	1400	14.1	14.8	4.0	6.650	+0.2	-0.3
1436	14.8	16.4	0.02	1.6637	-0.3	+0.1	1355	14.0	14.8	4.8	7.483	+0.2	-0.2
1446	14.8	16.4	1.38	1.7620	-0.3	+0.1	1374	13.9	15.2	6.0	8.397	+0.2	-0.3
1506	15.1	16.3	1.08	1.87502	+0.1	+0.1	818	13.6	14.7	4.0	10.336	0.0	0.0
1413	14.7	15.6	0.35	2.17352	-0.2	-0.5	1610	13.4	14.6	11.0	11.645	0.0	0.0
1460	14.4	15.7	0.00	2.913	-0.3	-0.1	1365	13.8	14.8	9.6	12.417	+0.4	+0.2
1422	14.7	15.9	0.6	3.501	+0.2	+0.2	1351	13.4	14.4	4.0	13.08	+0.1	-0.1
842	14.6	16.1	2.61	4.2897	+0.3	+0.6	827	13.4	14.3	11.6	13.47	+0.1	-0.2
1425	14.3	15.3	2.8	4.547	0.0	-0.1	822	13.6	14.6	13.0	16.75	-0.1	+0.3
1742	14.3	15.5	0.95	4.9866	+0.1	+0.2	823	12.2	14.1	2.9	31.94	-0.3	+0.4
1646	14.4	15.4	4.30	5.311	+0.3	+0.1	824	11.4	12.8	4.	65.8	-0.4	-0.2
1649	14.3	15.2	5.05	5.323	+0.2	-0.1	821	11.2	12.1	97.	127.0	-0.1	-0.4
1492	13.8	14.8	0.6	6.2926	-0.2	-0.4							

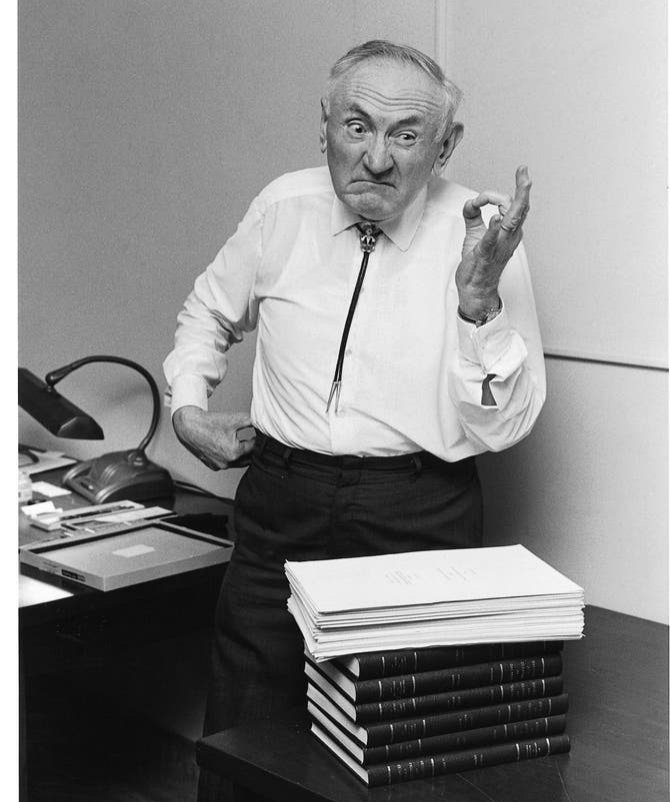
Leavitt & Pickering (1912)



Hubble (1923)

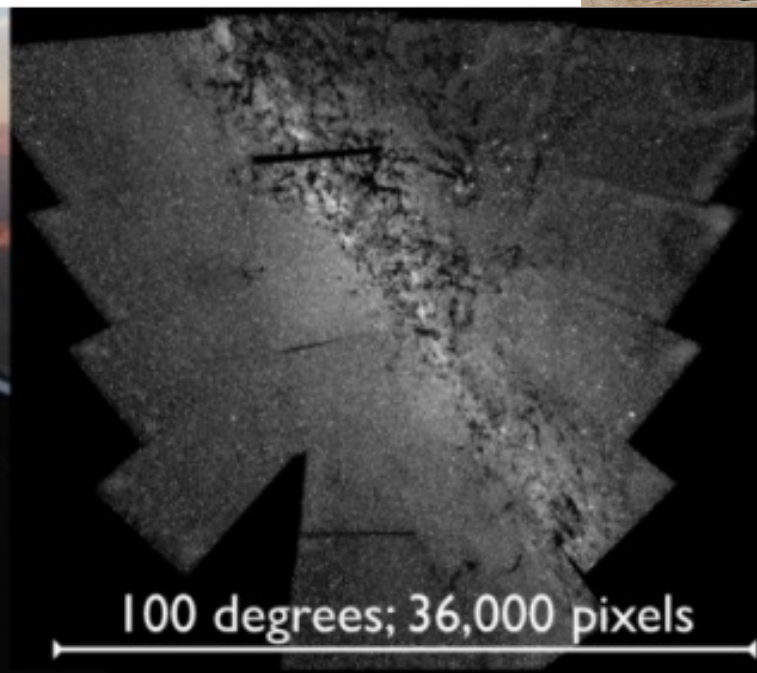
Towards the first sky surveys

- 1950s: Palomar Observatory Sky Surveys, POSS I & II
- DPOSS -> 3TB digitized version of POSSII (>50 million galaxies & 1 billion stars)
- Sloan Digital Sky Survey (SDSS): CCD-based survey
- 2MASS : first all-sky NIR survey
- Ever wider, deeper, more colors
- Identify interesting objects, follow them up later with larger infrastructure
- Statistical studies (large scale structure, MW structure, etc.)



Variability surveys across the electromagnetic spectrum

Ground-based photometric

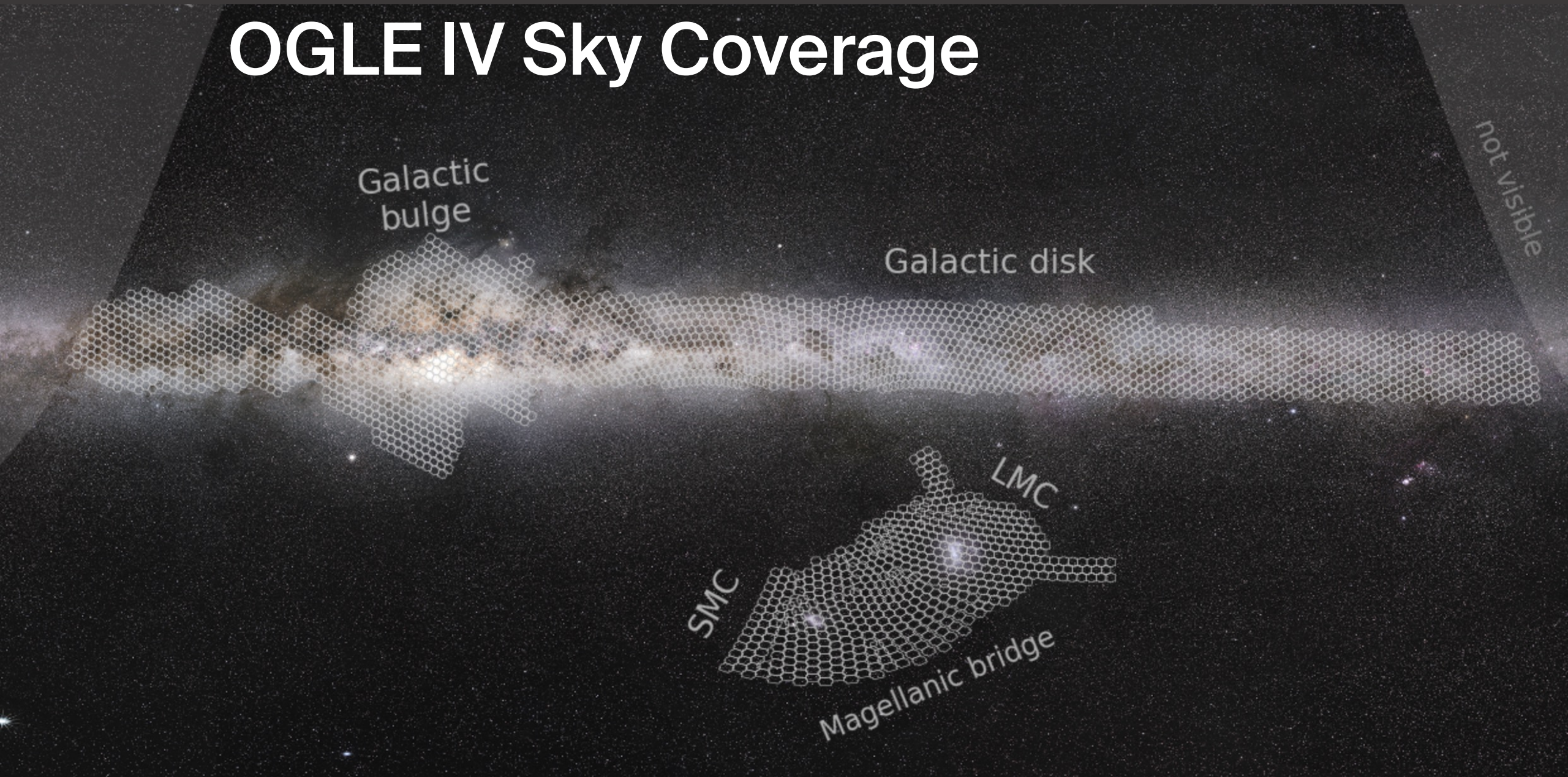


First-generation microlensing surveys of the 90s: MACHO, EROS, OGLE

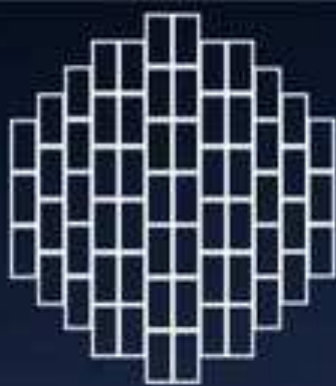
- 1m class telescopes with fast CCD cameras pointed at Magellanic Clouds
- MACHO (US & AUS):
 - Biggest camera of the 90s: 16 Mpix, 42x42' FoV, simultaneous color (dichroic)
 - First strong detection of microlensing of star, 1993
 - First real-time alert of ongoing microlensing, 1994
 - First observation of parallax in microlensing, 1995
- [EROS](#) (FR) – Experience pour la Recherche d'Objets Sombres
- [OGLE](#) (PL) – Optical Gravitational Lensing Experiment
 - Most succesful of them, ongoing: OGLE-IV
 - hugely important for stellar astrophysics and Magellanic clouds



OGLE IV Sky Coverage



DES,
 2.5 deg^2

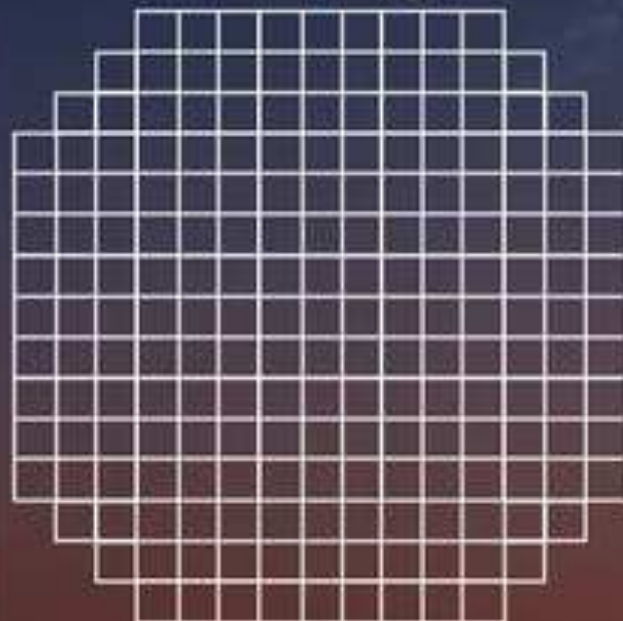
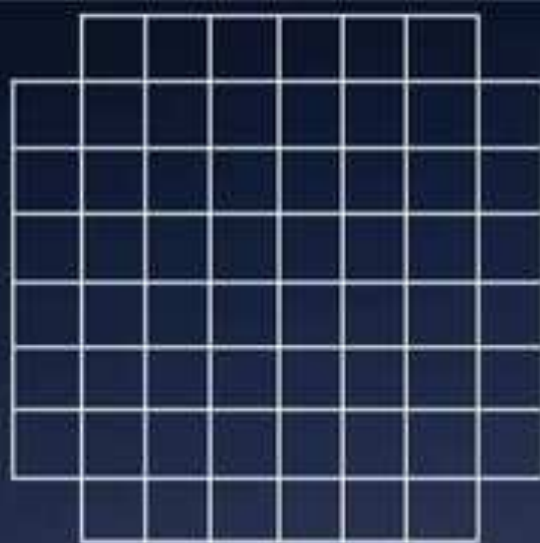


SDSS,
 3 deg^2

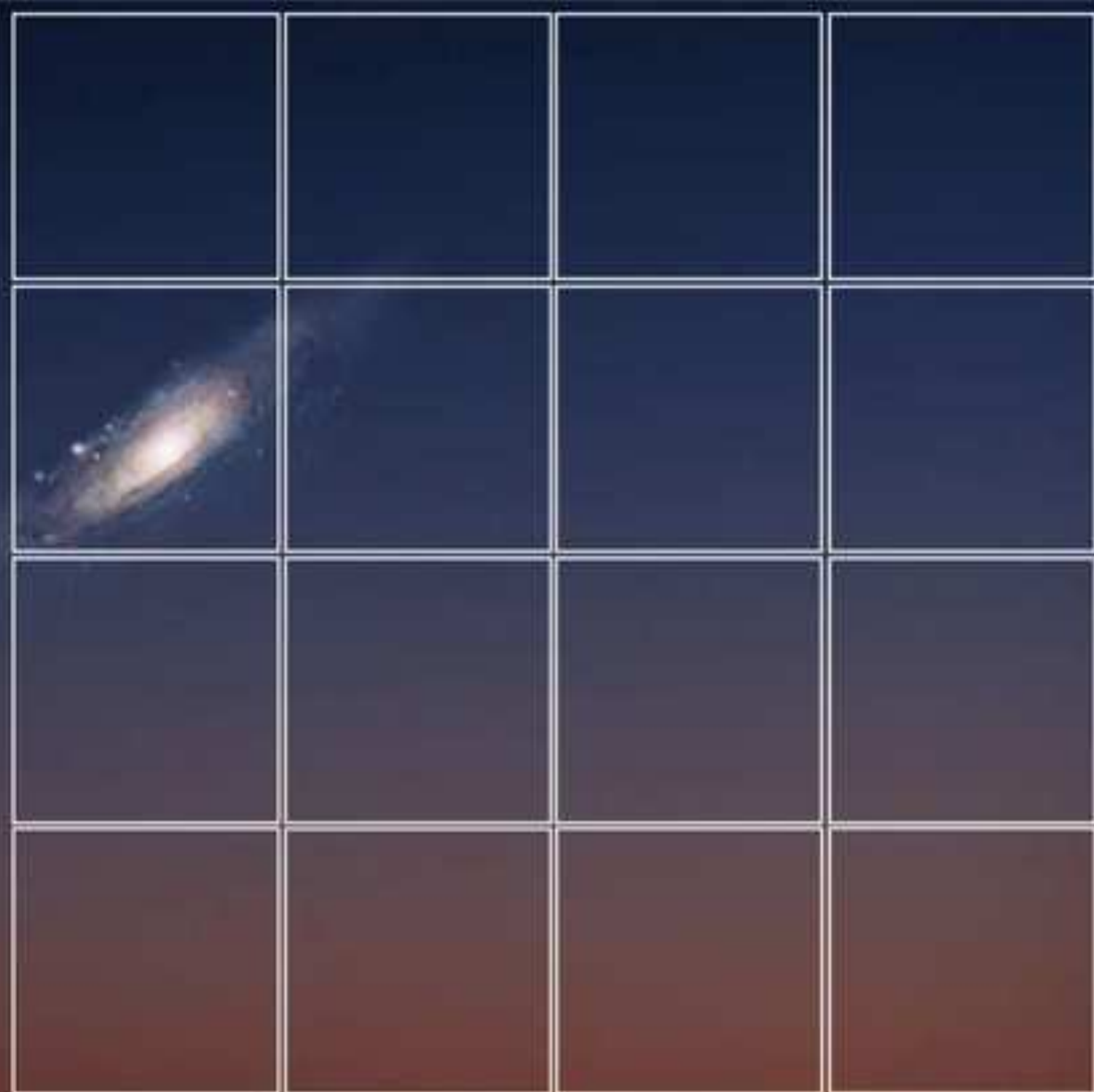


PTF/IPTF, 7.3 deg^2

PS1, 7 deg^2



LSST, 9.6 deg^2

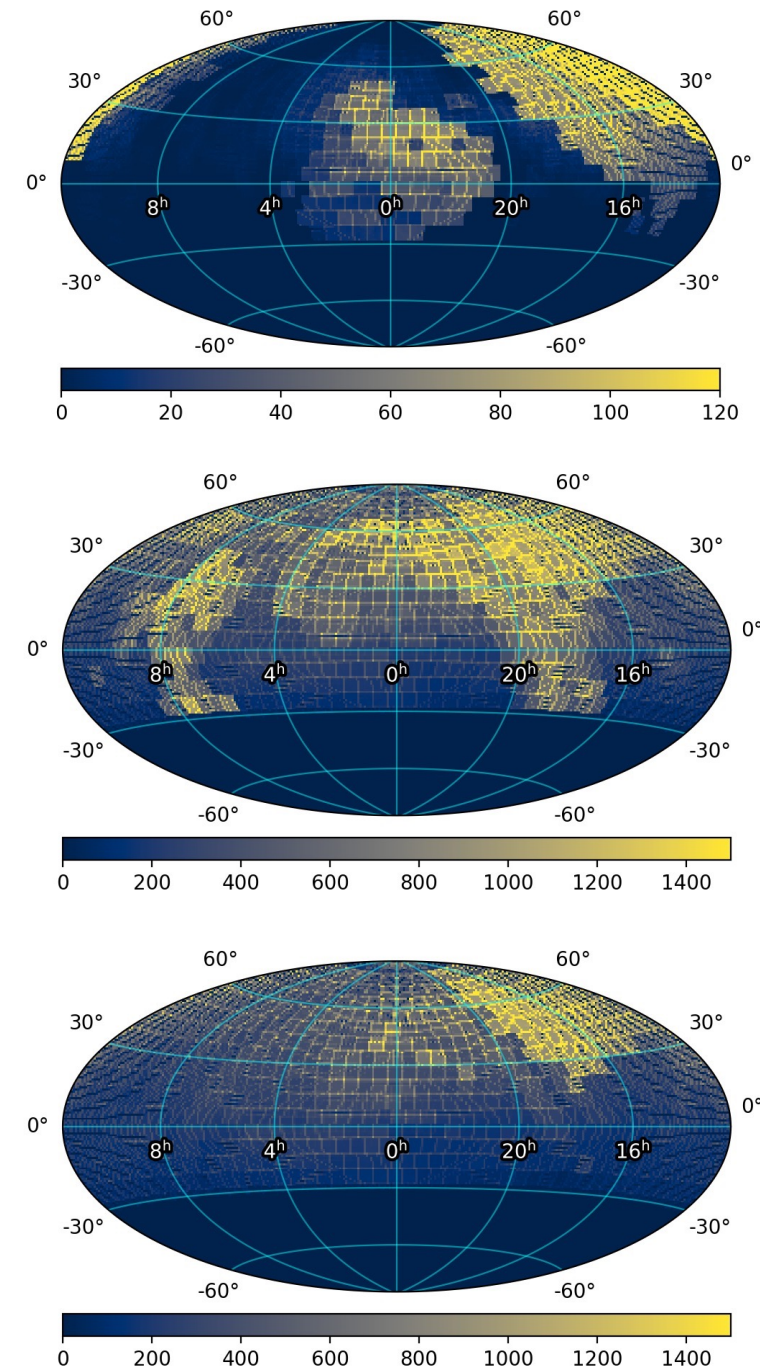


ZTF, 47 deg^2

1 deg

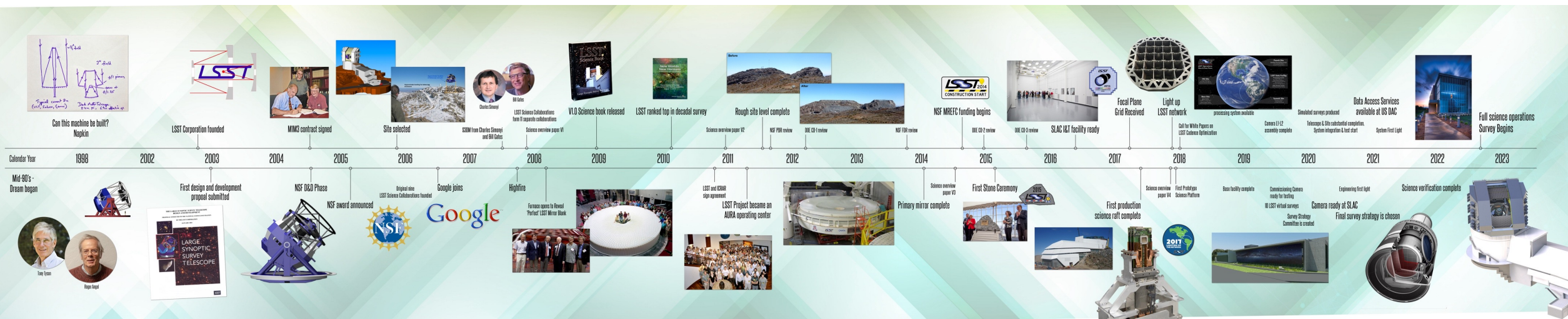
The Zwicky Transient Facility

- 48in (1.2m) Schmidt telescope @ Mt Palomar
- Full Northern sky every 2 nights (1"/pix)
- 47 deg^2 ; 1"/pix; 20.4 mag limit
- 4 x 4 array of 6k x 6k CCD = 600 Mpix
- ZTF g, r, i filters
- Bi-monthly data releases
- Sep 2022: 41.7 M exposures, 4.37 bn light curves
- www.ztf.caltech.edu/page/dr7



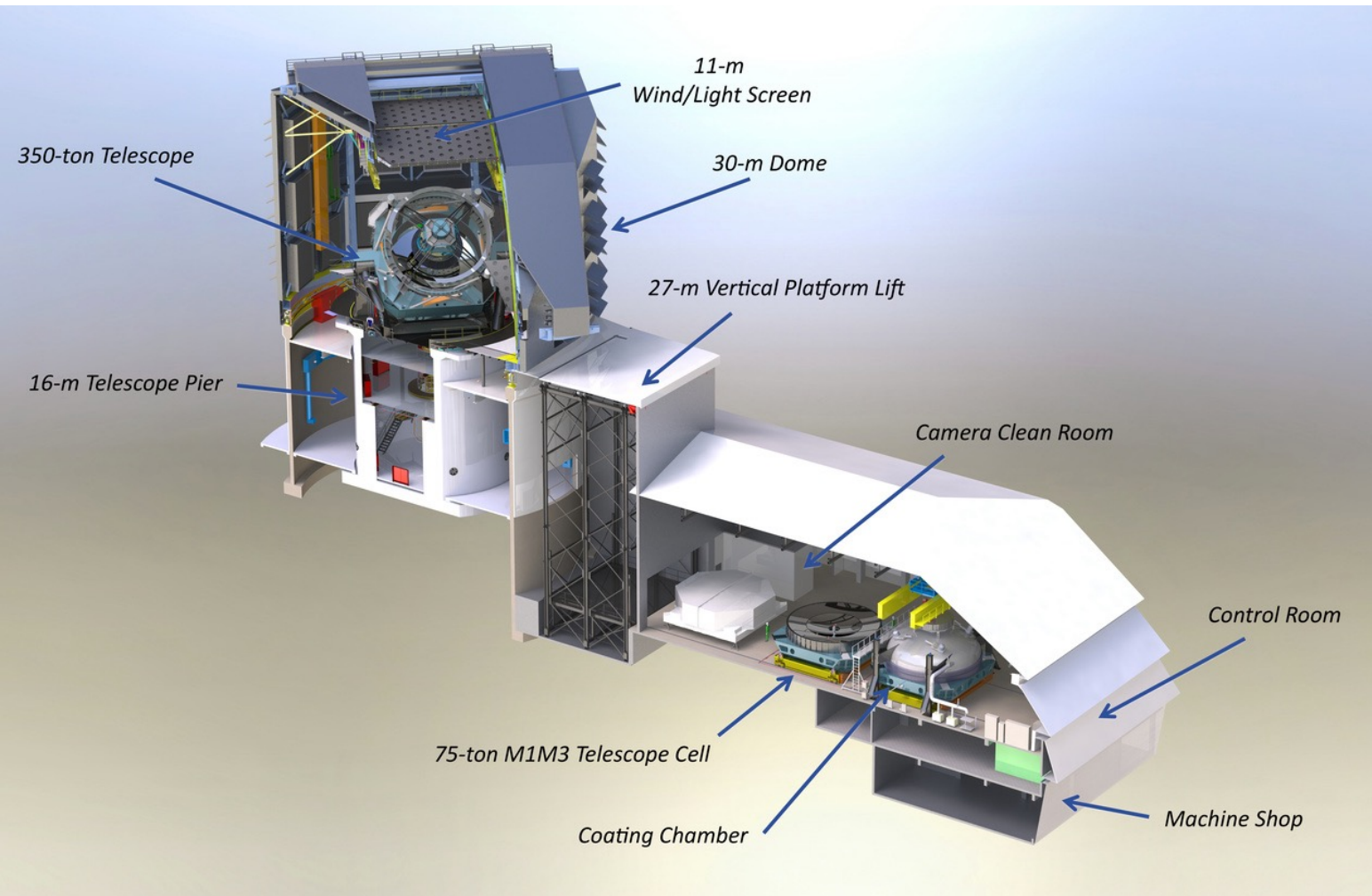
Vera C. Rubin Observatory / LSST

- 8.4m telescope in Chile dedicated to survey
- 3.2 Gpix camera, FoV 3.5deg (9.6 sq deg) = 40* full moon FoV; full sky every few nights
- 0.2"/pixel, standard texp 2x15sec
- 10 year survey, 37 bn stars & galaxies
- Each night: 20 TB of data, 10 M alerts, 1000 exposure pairs
- Final dataset: 500 PB (images & data products); 11 data releases
- <https://www.lsst.org/scientists>



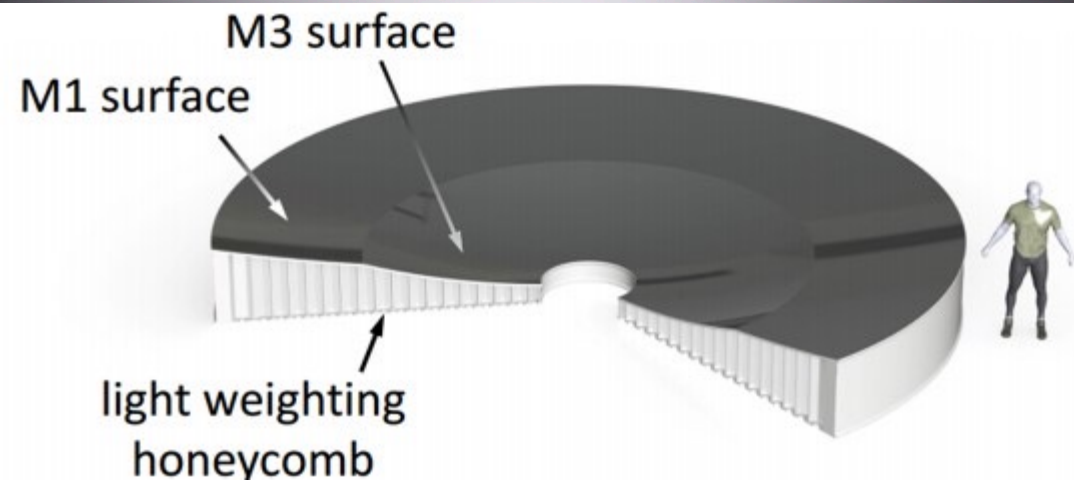
Rubin's Legacy Survey of Space and Time

<https://lsst.slac.stanford.edu/>

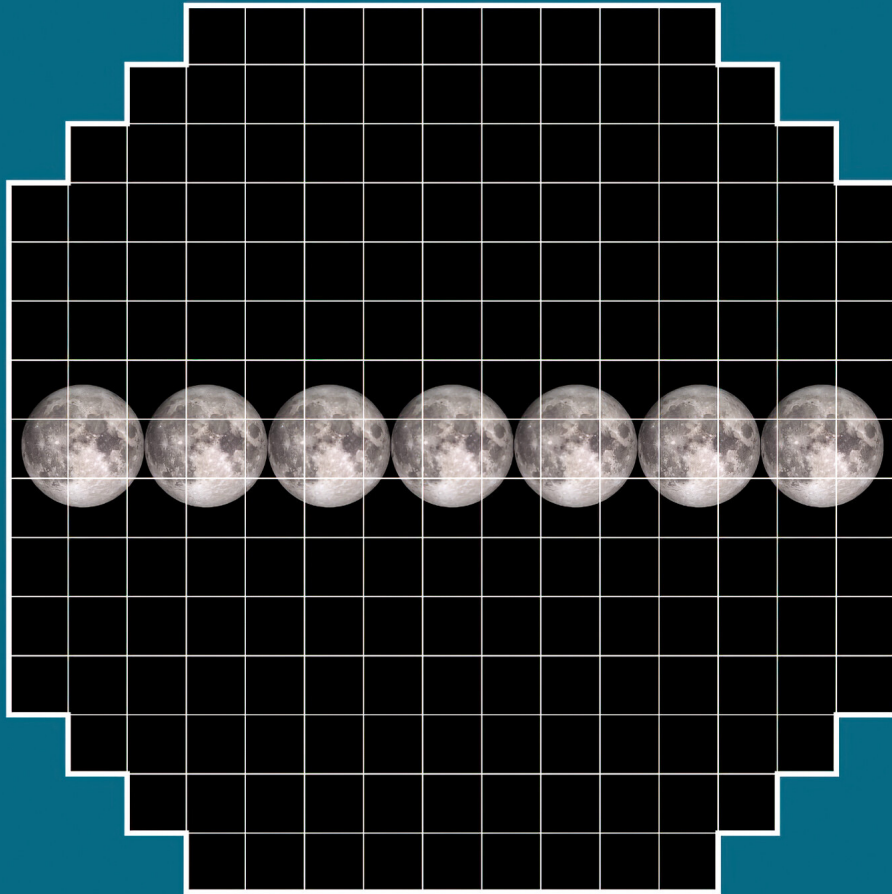


- Dark energy & matter
- Solar System Inventory
- Transient optical sky
- Mapping Milky Way





Field of View



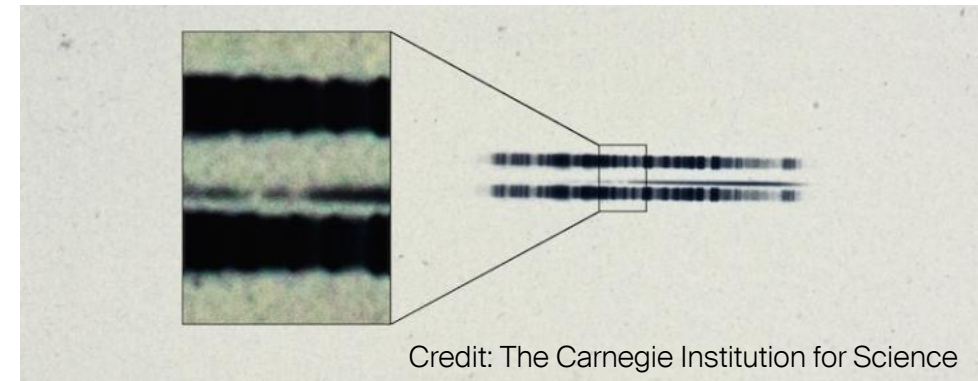
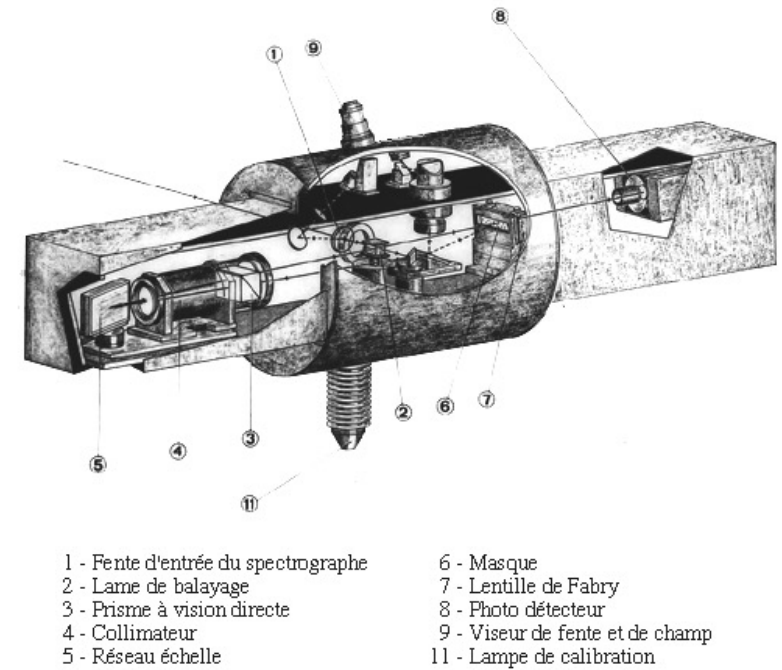
Resolution



**Spectroscopic surveys are
entering the time-domain**

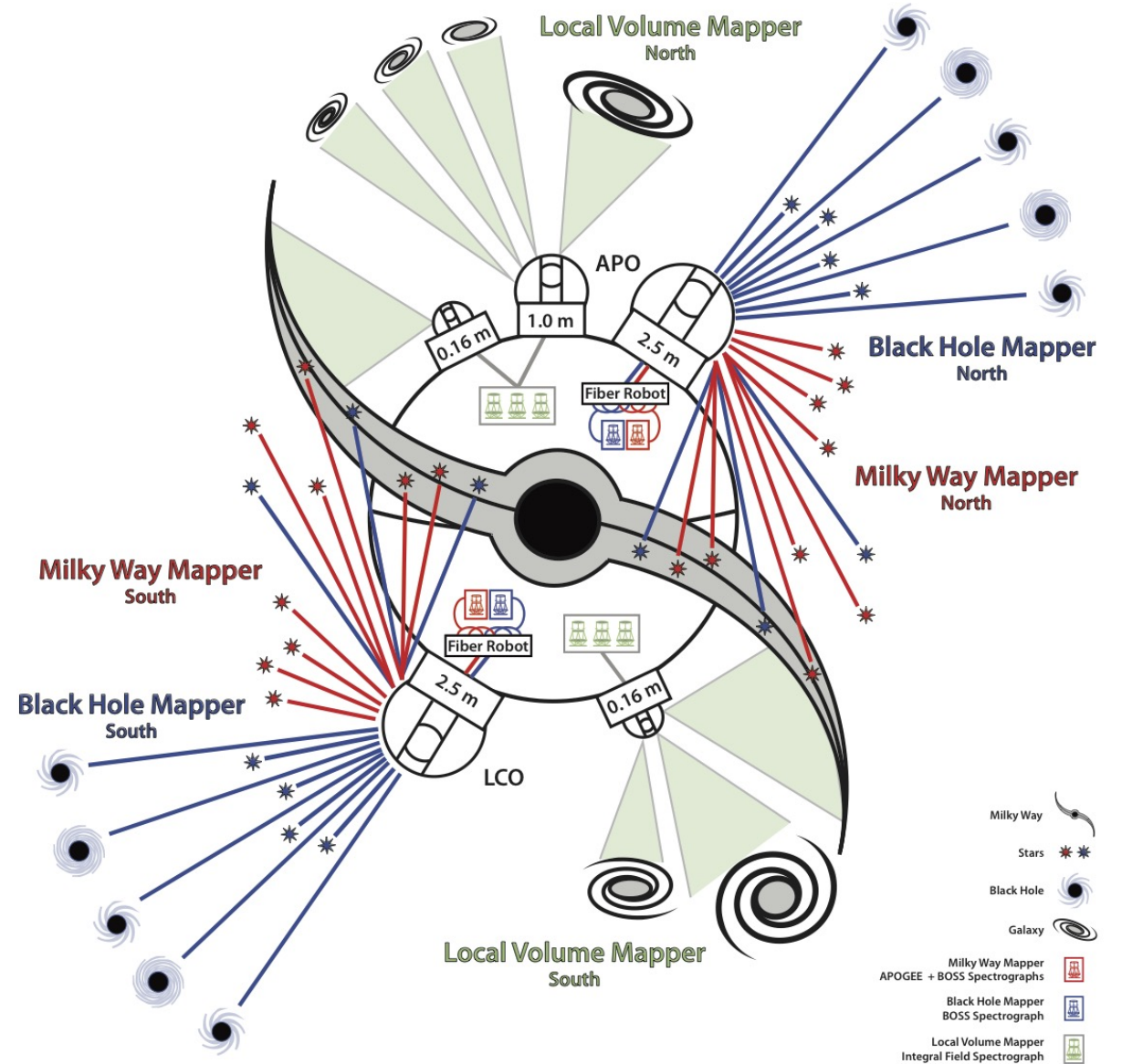
From photographic slit spectra to robotic fiber surveys

- Initially slit spectroscopy on photographic plates
- Line of sight velocities by comparing individual line positions
- 1970s: physical correlation instrument
- 1990s: fiber optics revolutionize spectroscopy
- 1997: 2dFGRS with fiber positioning system
- 2000: Sloan Digital Sky Survey (SDSS)
- LAMOST (since 2010s)
- Most not optimized for time-domain (yet)



<https://www.eurekalert.org/multimedia/669108>

Ground-based spectroscopic



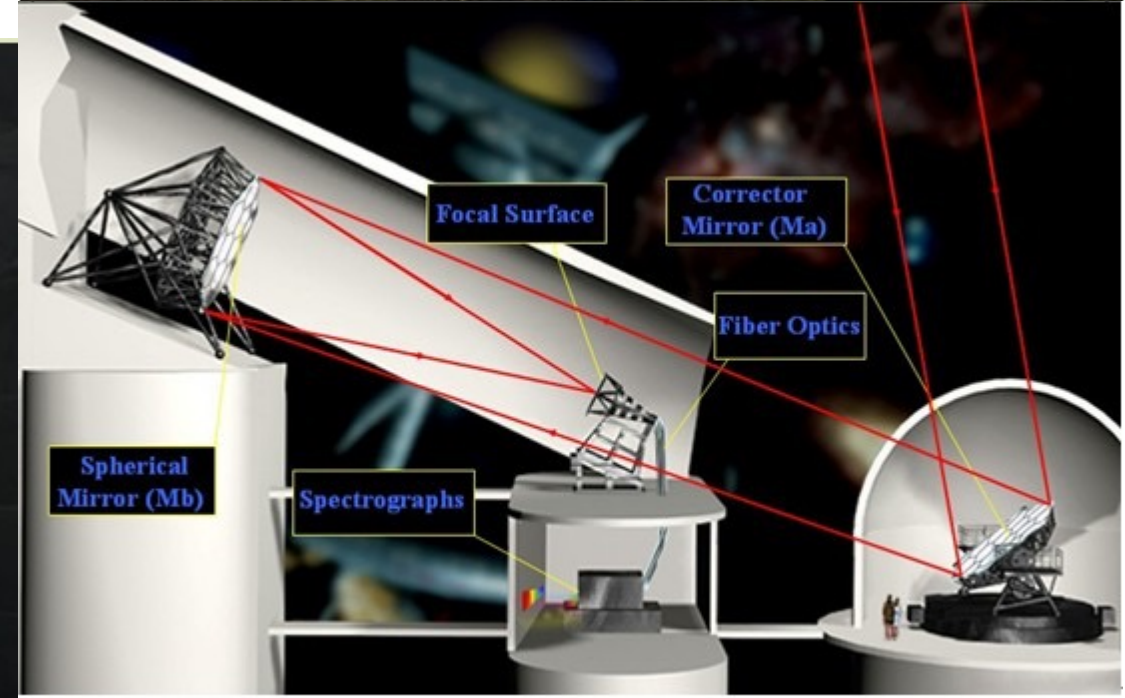
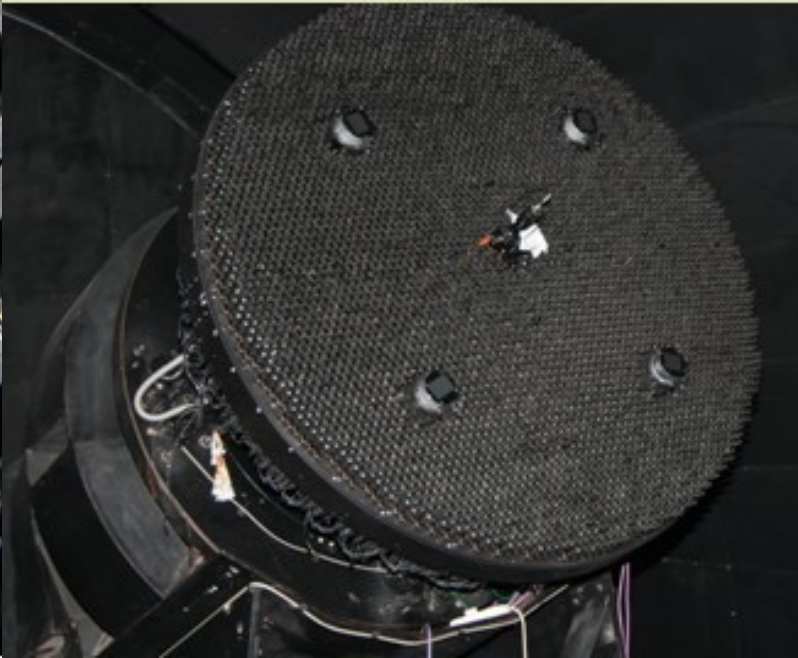
Fast focal plane sampling w/ robotic fiber positioners

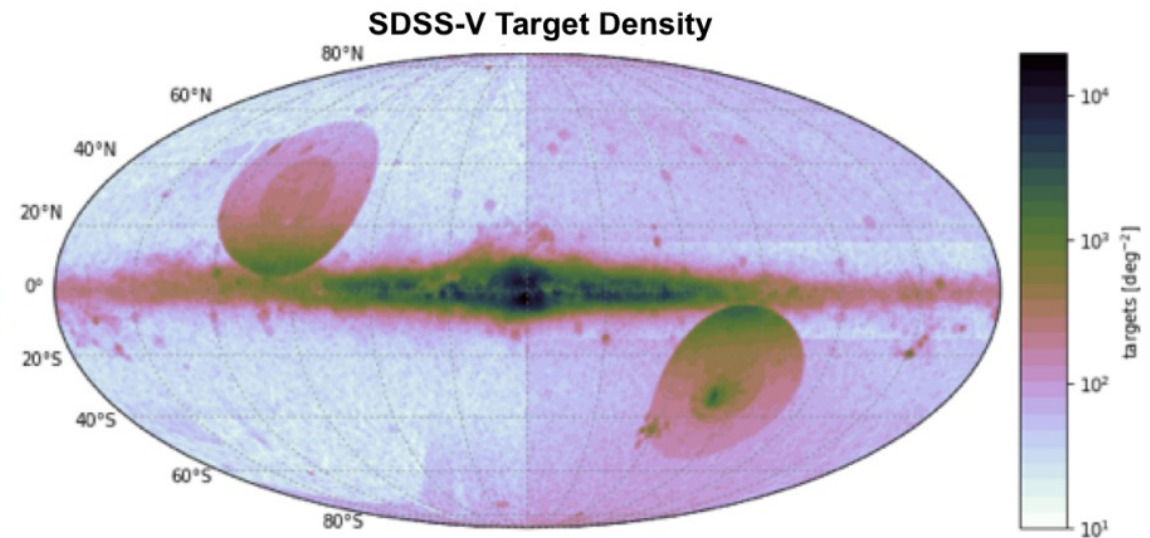
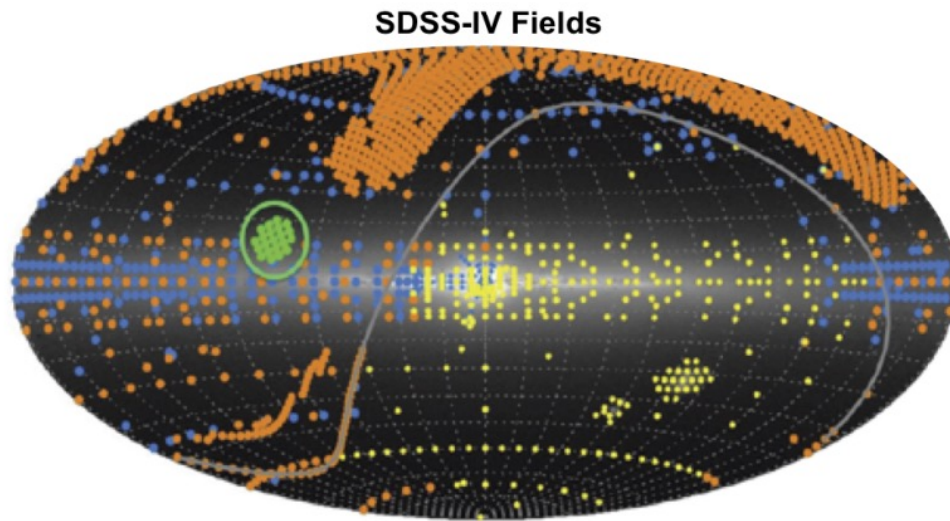
EPFL contribution to SDSS-V:

<https://player.vimeo.com/video/519959391>

LAMOST

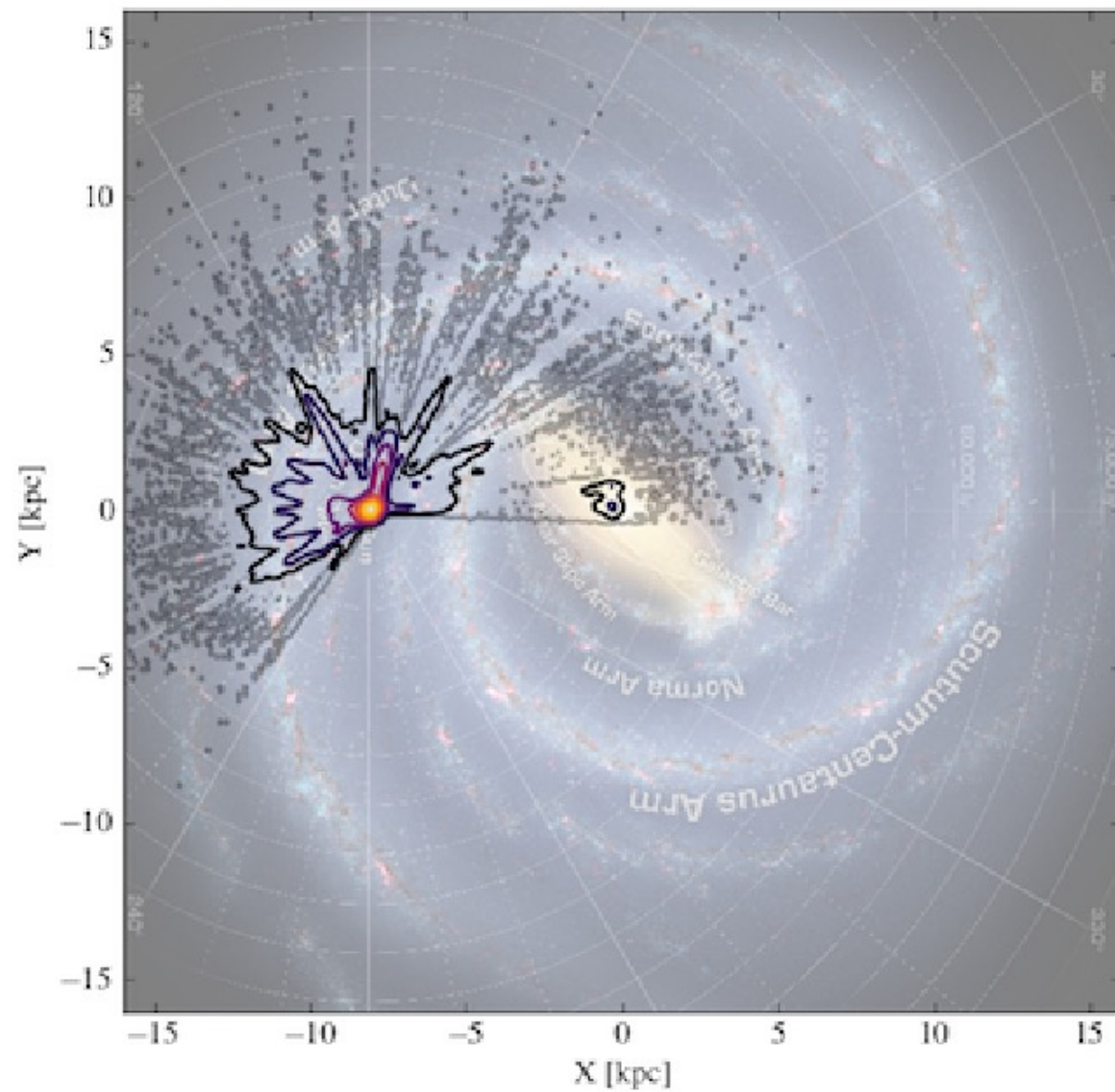
Large Sky Area Multi-Object Fibre
Spectroscopic Telescope



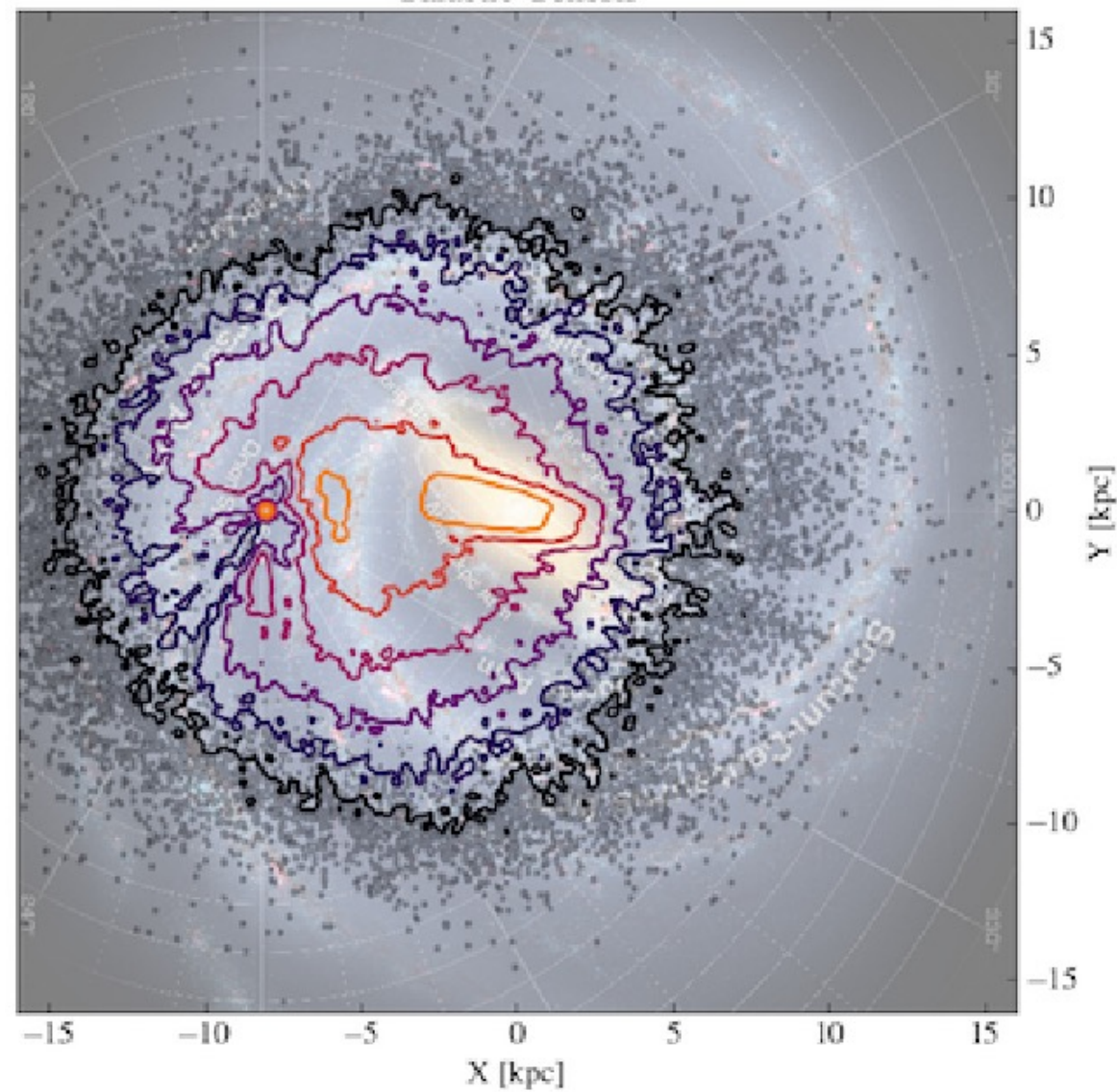


Program	Science Targets	N_{Objects} and/or Sky Area	Primary Spectral Range and Hardware	Primary Science Goals
Milky Way Mapper (MWM)	Stars across the Milky Way	$>6\text{M}$ stars; all-sky	IR; APOGEE ($R \sim 22,000$) with fiber-positioning system	Understanding the formation of the Milky Way and the physics of its stars
Black Hole Mapper (BHM)	Primarily supermassive black holes	$>400,000$ sources; all-sky	Optical; e.g., BOSS ($R \sim 2000$) with fiber-positioning system	Probing black hole growth and mapping the X-ray sky
Local Volume Mapper (LVM)	ISM & stellar populations in the MW, Local Group, and nearby galaxies	$>25\text{M}$ contiguous spectra over $3,000 \text{ deg}^2$	Optical; new integral field spectrographs covering $3600\text{-}10000\text{\AA}$ at $R \sim 4000$	Exploring galaxy formation and regulation by star formation; feedback, enrichment, & ISM physics

SDSS IV : APOGEE



SDSS V : MWM Galactic Genesis Survey



Kollmeier+2017
arxiv: 1711.03234

Ongoing or upcoming spectroscopic surveys

- **DESI** – Dark Energy Spectroscopic Instrument
(5000 fibers, medium res 360 – 980nm)
- **4MOST** – 4-meter Multi-Object Spectroscopic Telescope
(2435 fibers, 2.5 deg diameter FoV, medium/high res, ESO VISTA)
- **MOONS** – Multi-Object Optical and Near-infrared Spectrograph
(1000 fibers, 500 arcmin², moderate & high res, ESO UT1)
- **WEAVE** – WHT Enhanced Area Velocity Explorer
(1000 fibers, medium/high res, 2 deg diameter FoV, La Palma)
- **MSE** – Mauna Kea Spectroscopic Explorer (proposed 11m replacement of CFHT)
- And several other proposed projects for LSST follow-up

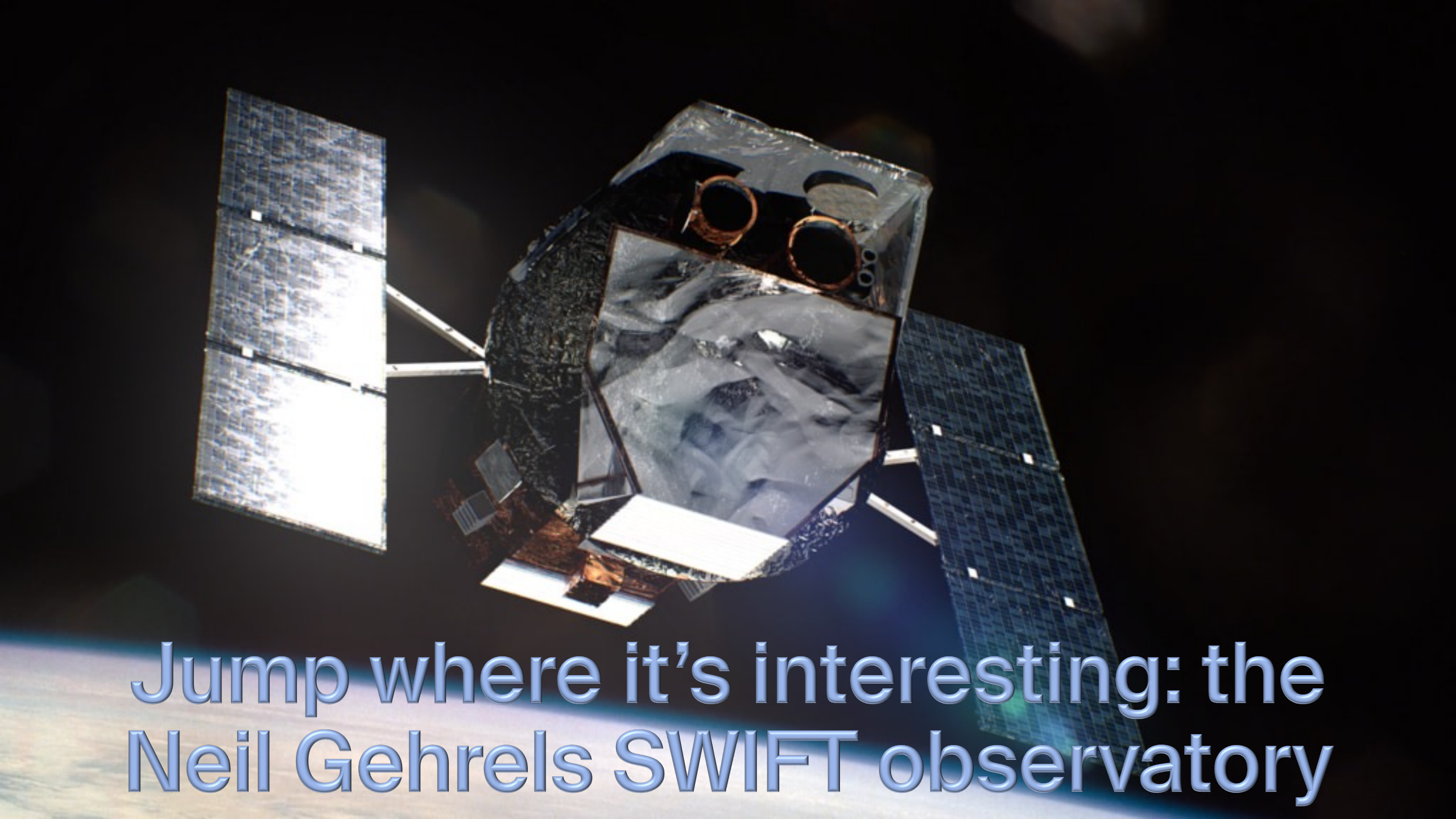
Space-borne facilities

The benefits of leaving the atmosphere

INTEGRAL : ESA's INTERnational Gamma Ray Astrophysics Laboratory

- Targets's gamma ray sources since Oct 2002
- 15 keV – 10 MeV spectroscopy ($E/dE = 500$) and imaging (12' FWHM)
- 4 – 35 keV X-ray monitoring & V-band (550nm) monitoring
- Switzerland hosts center for scientific data at ISDC, part of UniGE astro department
- Most sensitive gamma-ray instrument before FERMI
- Heaviest payload launched by ESA (2019): 5m tall, 4 tons heavy
- Weekly scans of galactic plane
- www.cosmos.esa.int/web/integral/pom-archive

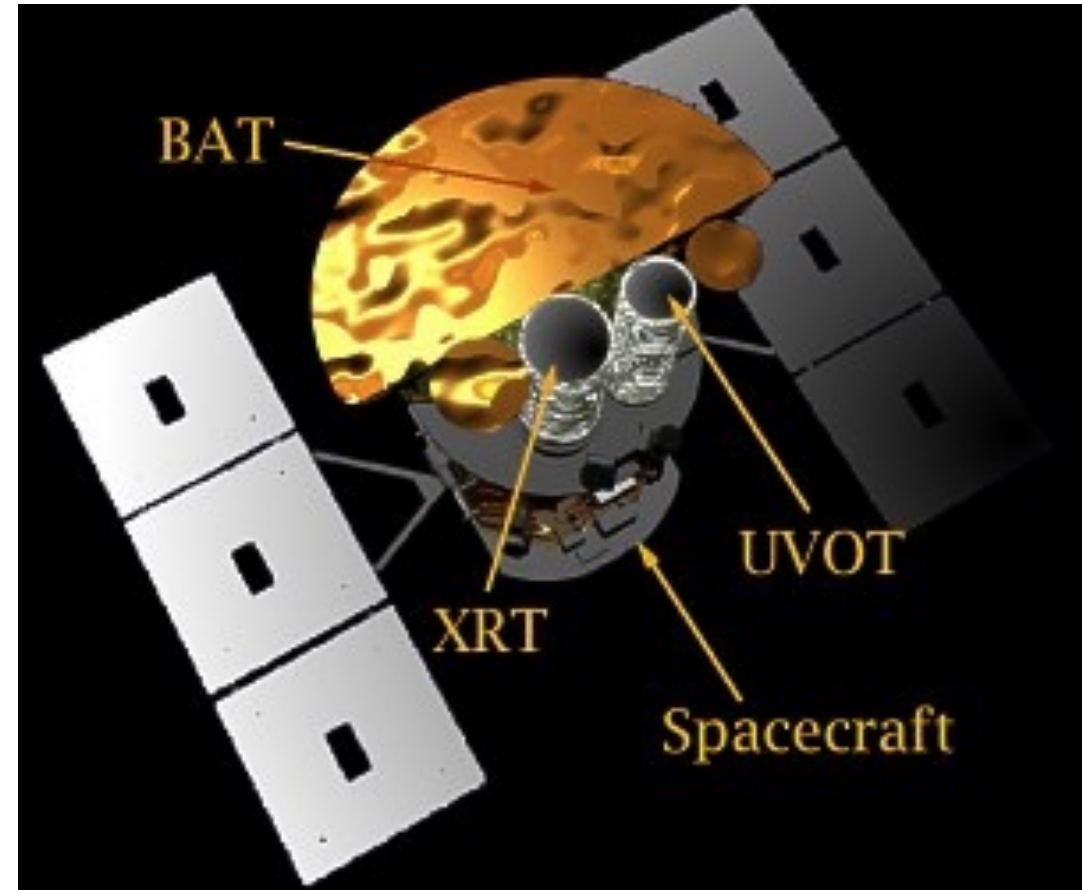




Jump where it's interesting: the
Neil Gehrels SWIFT observatory

Neil Gehrels Swift Observatory

- Launch: 2004
- 2 yr mission but still active!
- 100 GRBs / yr -> currently almost 1500
- Very fast slewing capability: 20-70s to target
- Gamma-ray (BAT), X-ray (XRT), UV & optical (UVOT) imaging
- BAT wide angle burst alert
- Then follow-up with X-rays & UV + optical
- Immediate image downlink for follow-up
- Astronomerstelegram.org



Ground-based follow-up

[[Previous](#) | [Next](#) | [ADS](#)]

A Neil Gehrels Swift Observatory Snapshot of the Black Hole Candidate XTE J1908+094

ATel #12632; *J. M. Miller, M. Reynolds, B. Tetarenko, S. Ali, M. Balakrishnan, J. Chen, D. Voza (University of Michigan)*

on 5 Apr 2019; 21:53 UT

Credential Certification: Jon Miller (jonmm@umich.edu)

Subjects: X-ray, Black Hole, Transient

Referred to by ATel #: 12652, 14912

[Tweet](#)

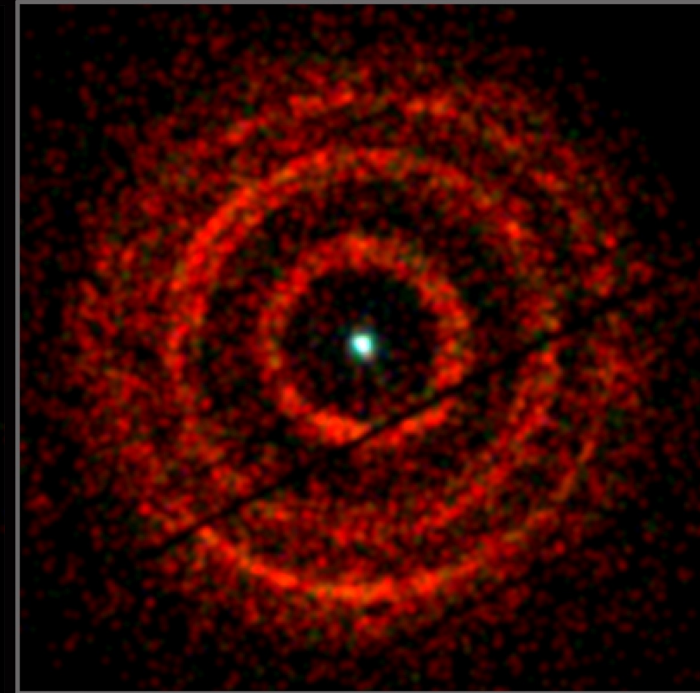
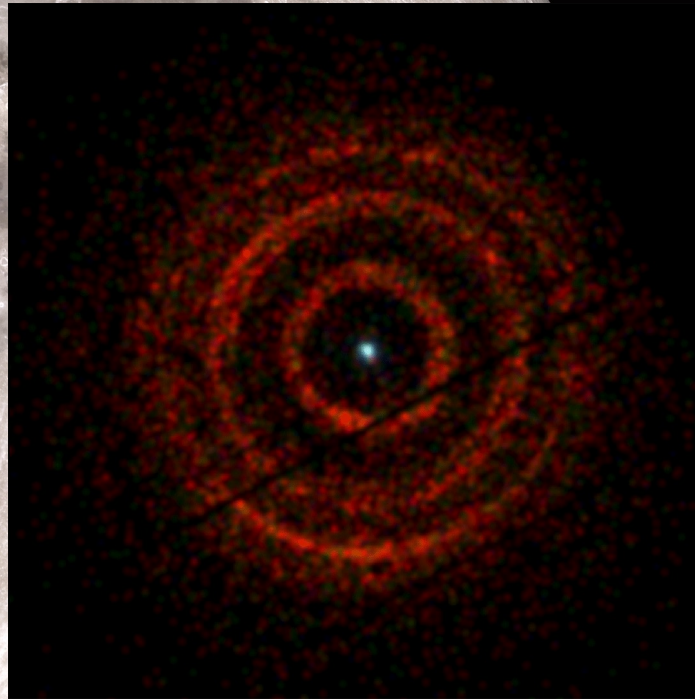
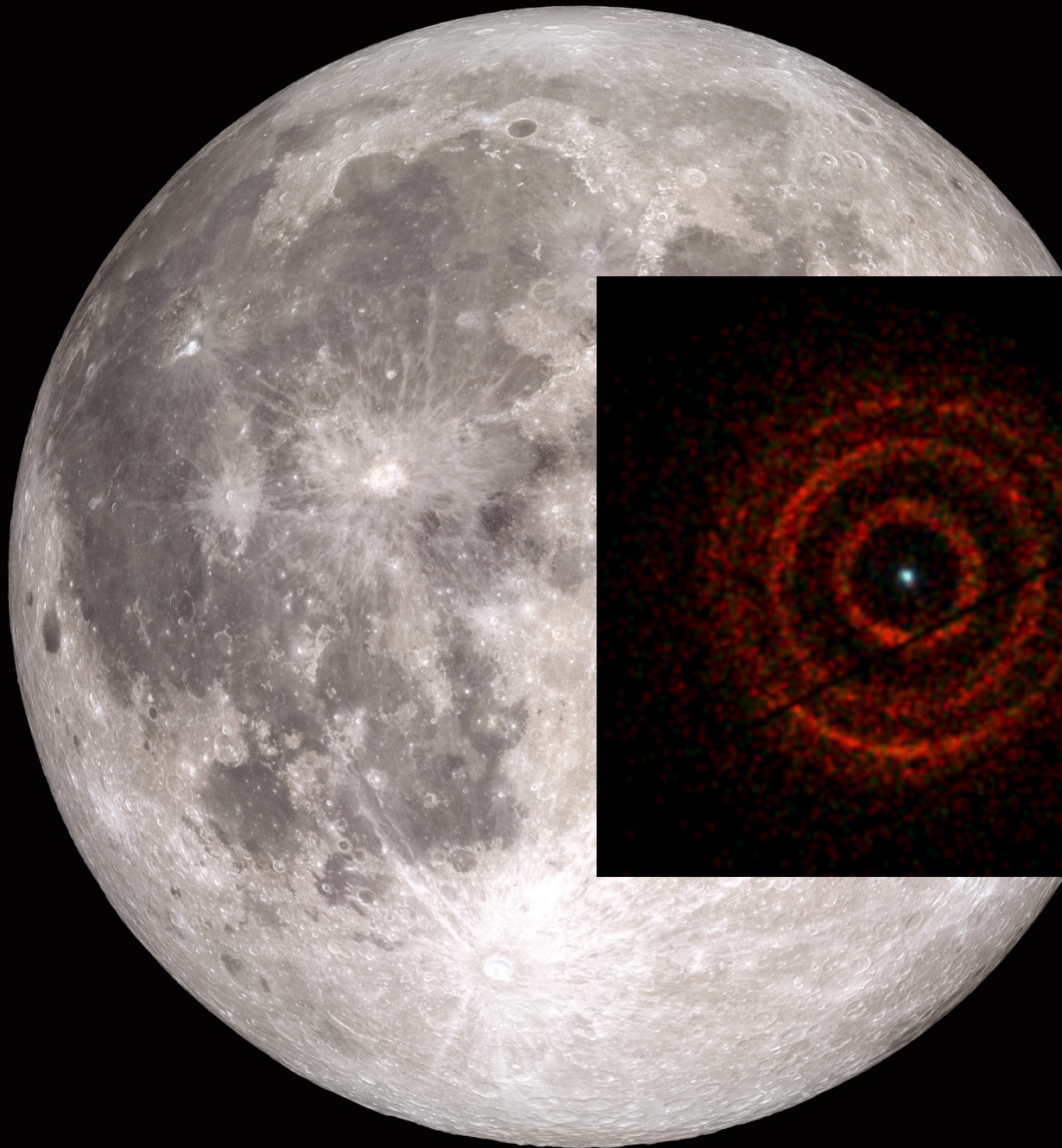
XTE J1908+094 is a black hole candidate and recurrent transient. During its 2013 outburst, complex, relativistic radio jets were resolved with the VLBA and EVN (Rushton et al. 2017). A preliminary black hole spin measurement of $a = 0.75 \pm 0.09$ was obtained based on modeling of BeppoSAX spectra (Miller et al. 2009; also see in't Zand et al. 2002); subsequent studies during the 2013 outburst did not achieve the sensitivity required to update this measurement (Tao et al. 2015, Zhang et al. 2015).

Related

- 14920 [Swift observations identified the X-ray transient MAXI J1909+094 as 4U 1907+09](#)
- 14912 [MAXI/GSC detection of renewed activity from XTE J1908+094/MAXI J1909+094](#)
- 12652 [NICER Observations of the new outburst from XTE J1908+094](#)
- 12632 [A Neil Gehrels Swift Observatory Snapshot of the Black Hole Candidate XTE J1908+094](#)
- 12630 [AMI-LA 15.5 GHz observation of the Black Hole candidate XTE J1908+094](#)
- 12628 [INTEGRAL detects renewed activity from the microquasar XTE J1908+094](#)
- 5575 [Optically thin synchrotron emission from XTE J1908+094 observed by the ATCA](#)
- 5551 [AMI detection of a flare from BHC XTE1908+094 at 2cm](#)
- 5549 [MAXI/GSC detection of a hard-to-soft state transition of XTE J1908+094](#)
- 5532 [AMI detection of 2 cm radio emission from the XRB BHC J1908+094](#)
- 5530 [VLA detection of radio emission from the new outburst of XTE J1908+094](#)
- 5529 [Swift Observations of the current outburst of XTE J1908+094](#)
- 5523 [Swift/BAT detects a new outburst from the HXMB/BHC XTE J1908+094](#)



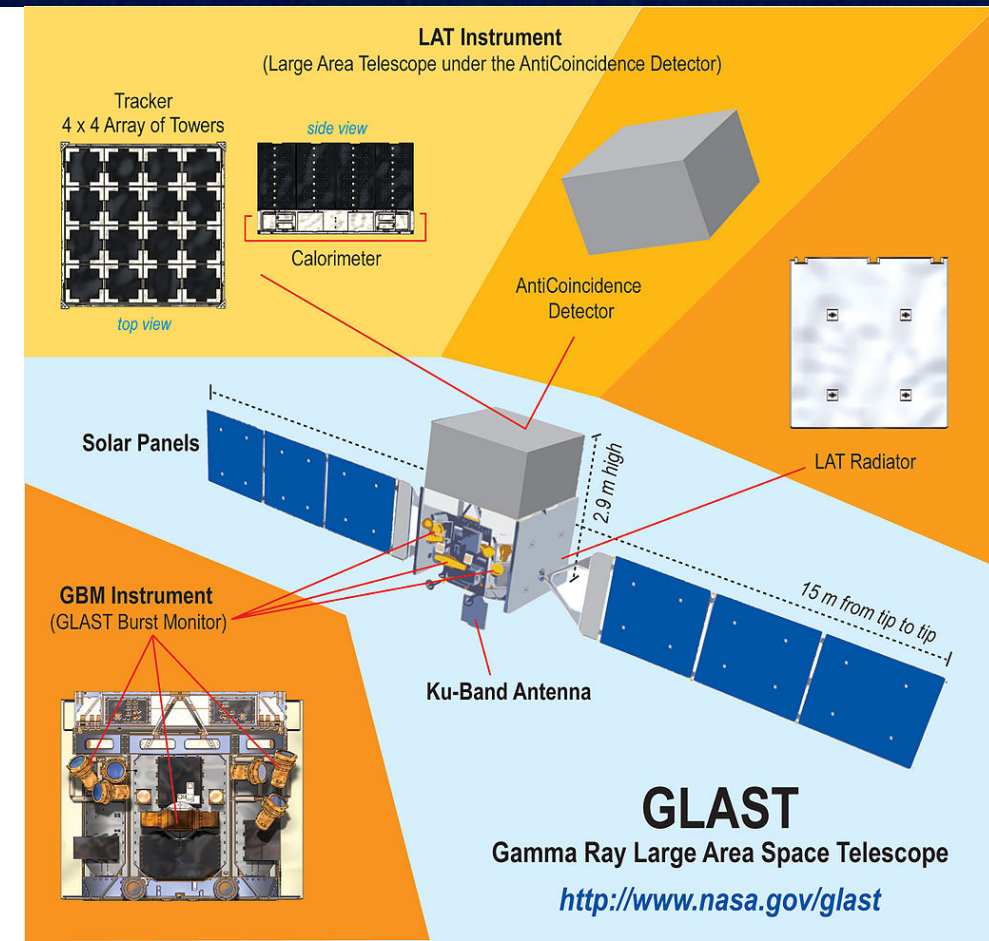
SWIFT/BAT X-ray Echoes of V404 Cyg



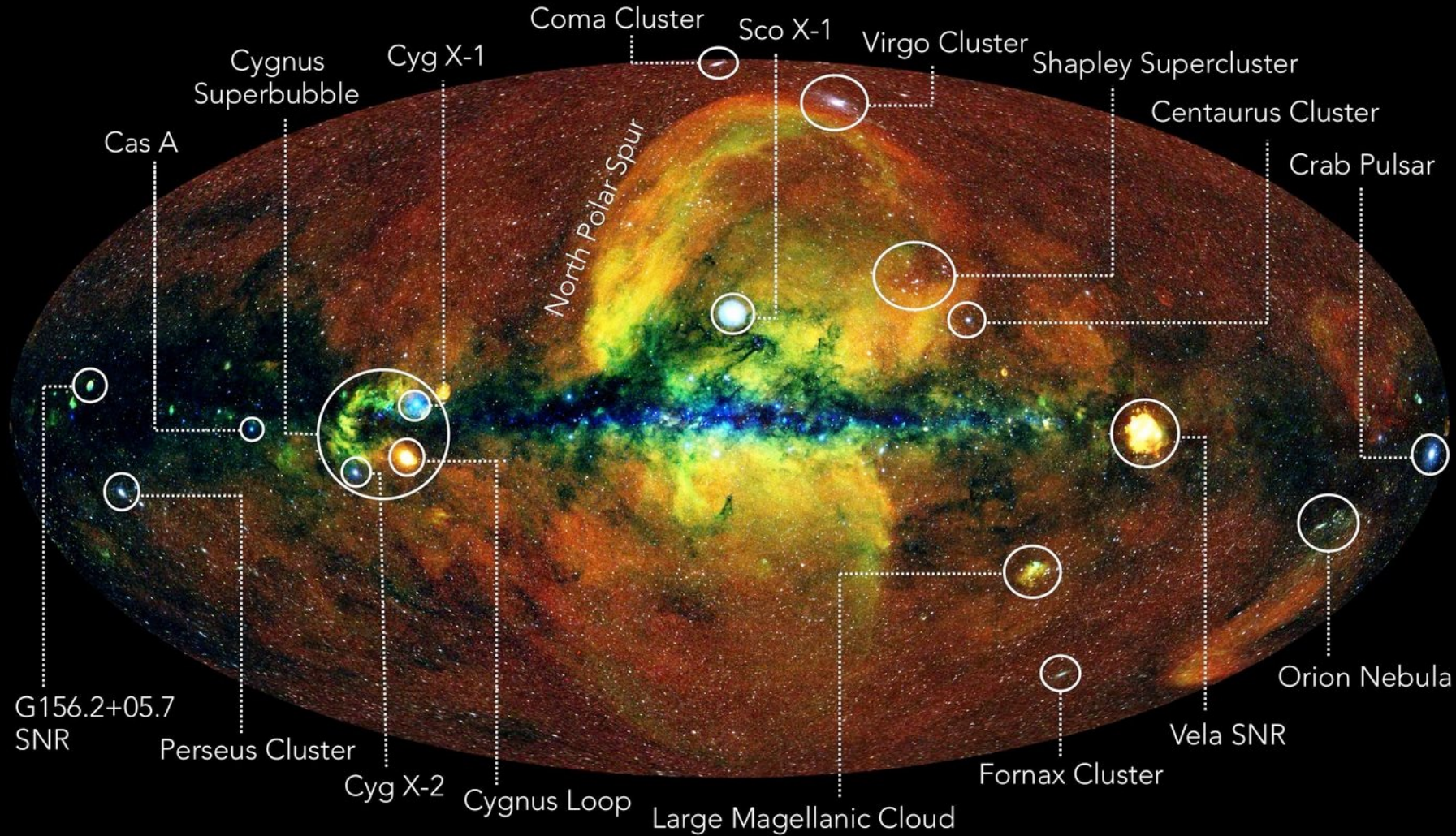
5 arcminutes



- INTEGRAL successor, launched in 2008
- Most sensitive gamma-ray instrument
- 8 keV to 300 GeV (VHE gamma rays)
- Fermi bubbles in MW
- GW170817 GRB counterpart to gravitational waves



SRG/eROSITA – the new kid on the block

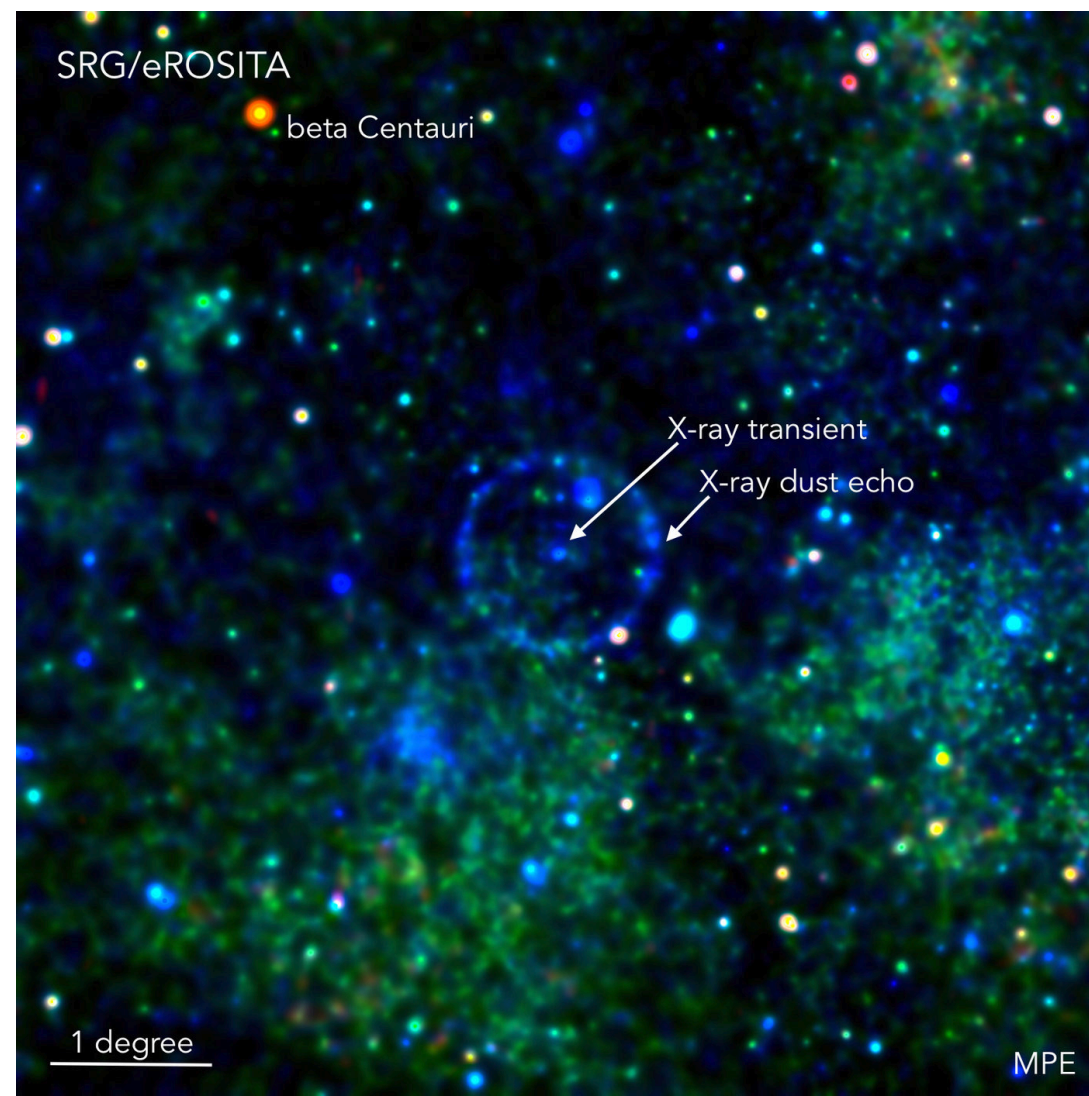
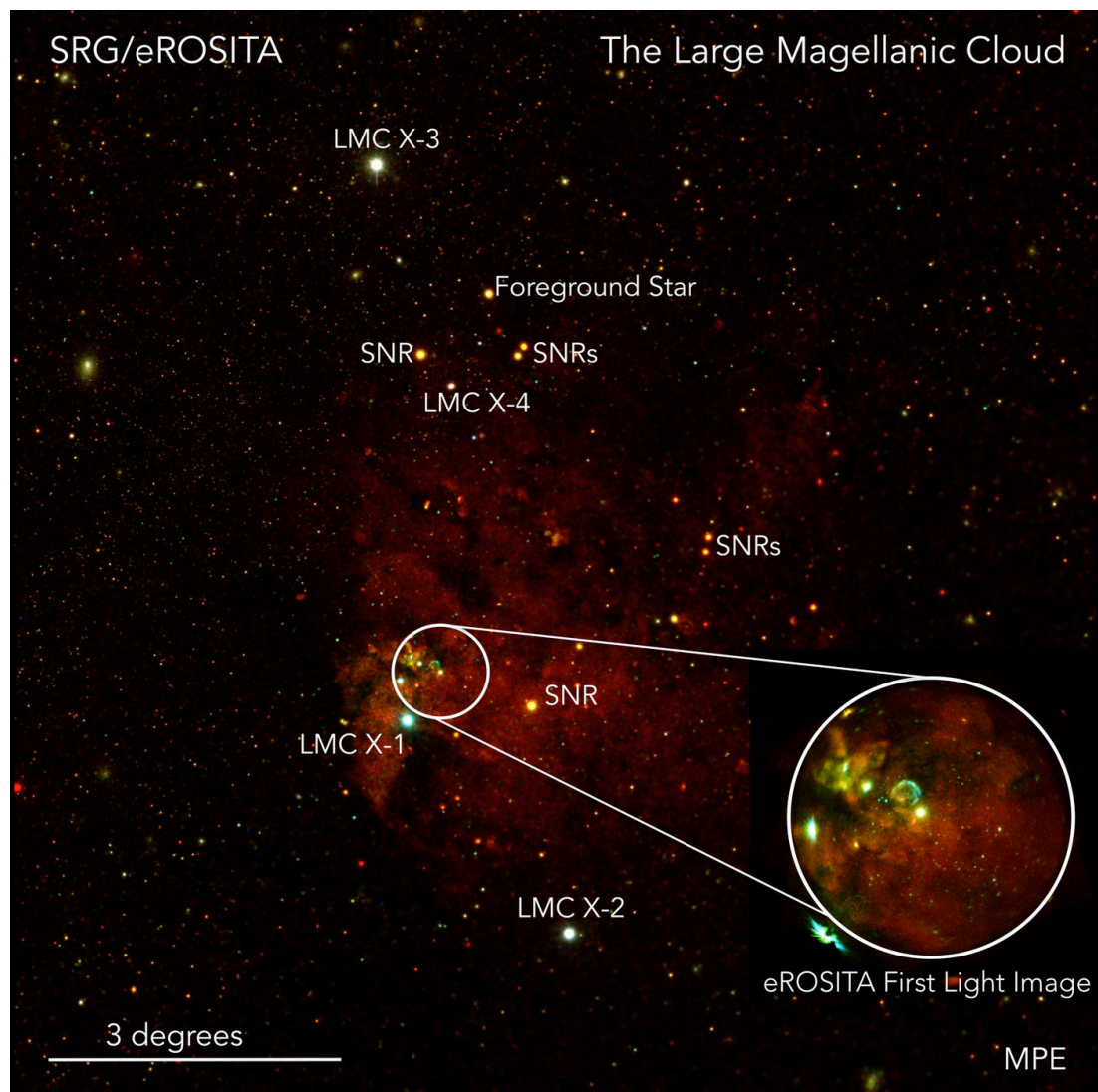


IKI

SRG/eROSITA 0.3-2.3 keV - RGB Map

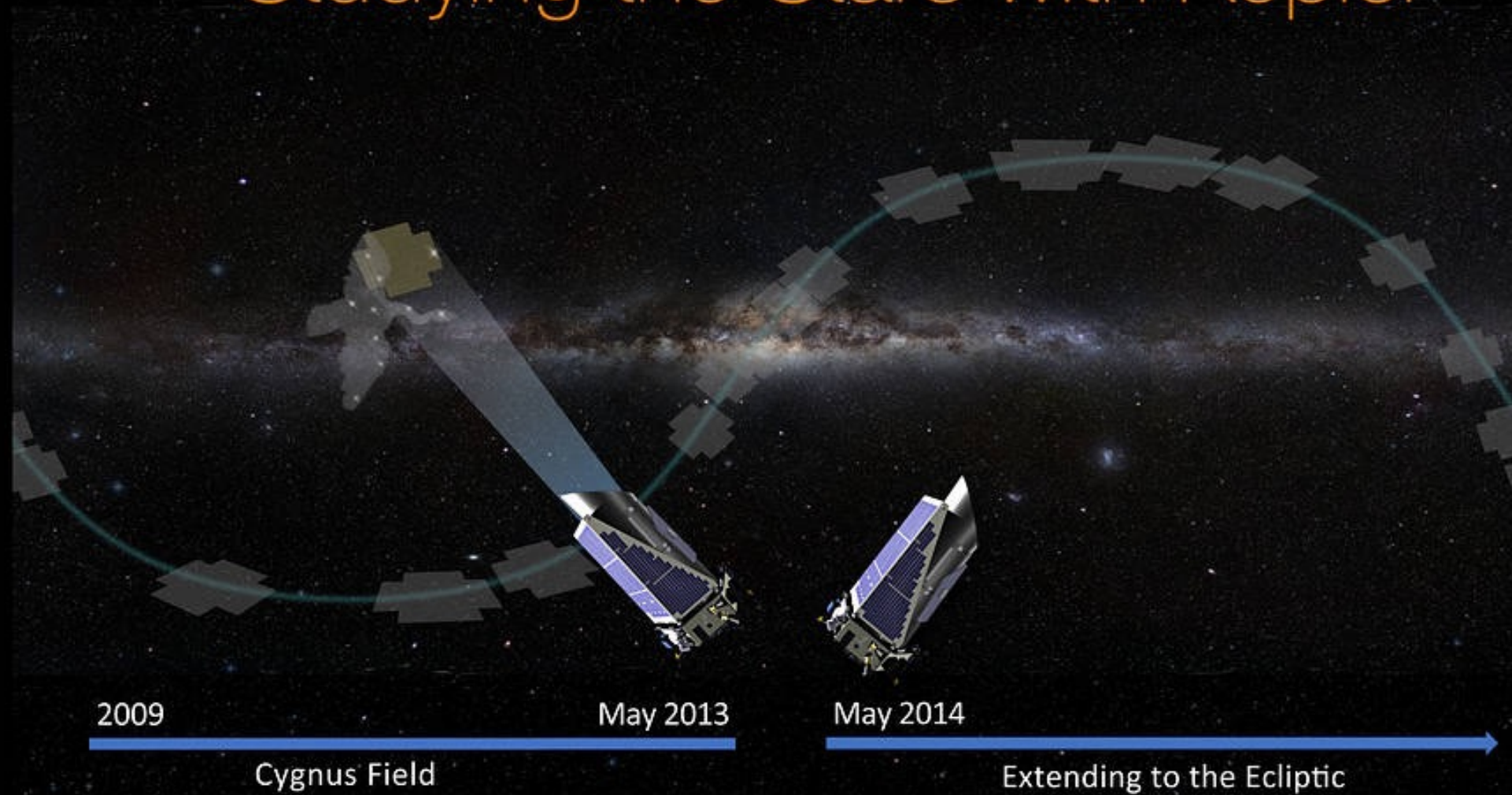
MPE

SRG/eROSITA – all sky & high resolution



Optical time-series photometry from space

Studying the Stars with Kepler

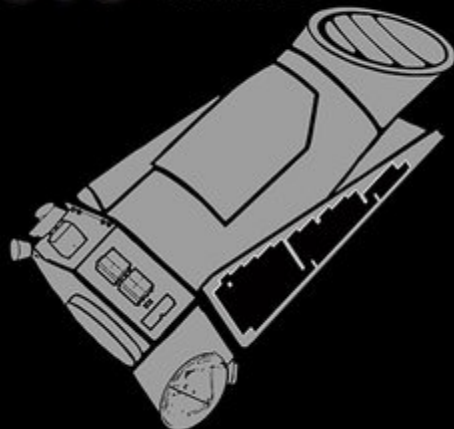


Kepler

BY THE NUMBERS



9.6 YEARS IN SPACE



530,506
STARS OBSERVED



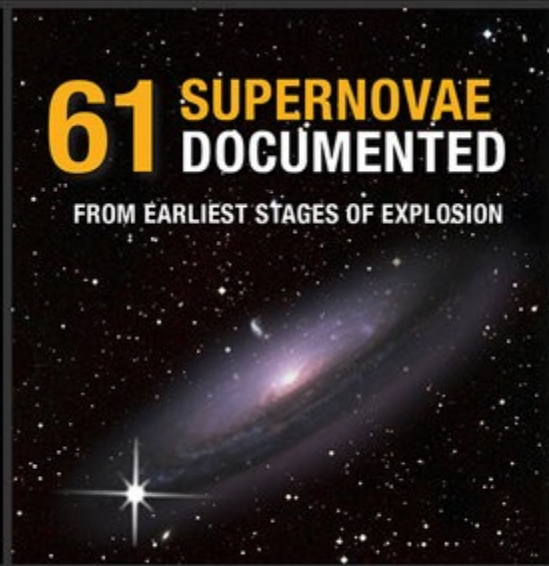
2,662

PLANETS CONFIRMED



61 SUPERNOVAE DOCUMENTED

FROM EARLIEST STAGES OF EXPLOSION



2 MISSIONS COMPLETED

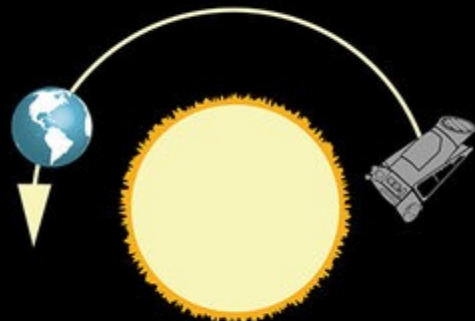
678 GB SCIENCE DATA COLLECTED



2,946 SCIENTIFIC PAPERS PUBLISHED

732,128
COMMANDS EXECUTED

94 MILLION MILES AWAY



3.12 GALLONS FUEL USED

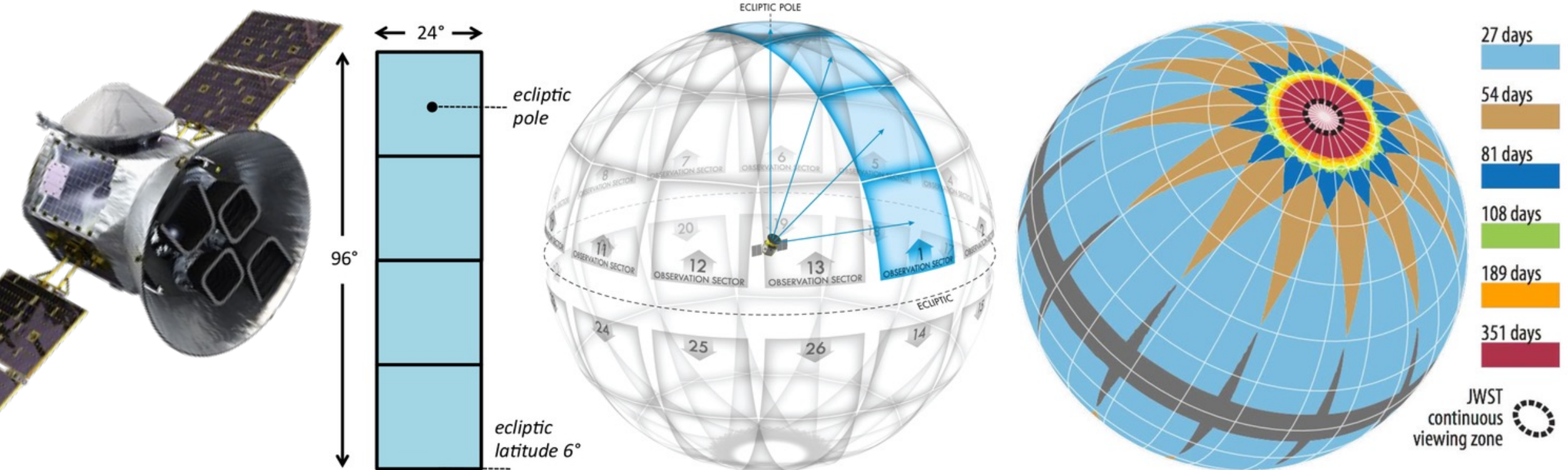


www.nasa.gov/kepler

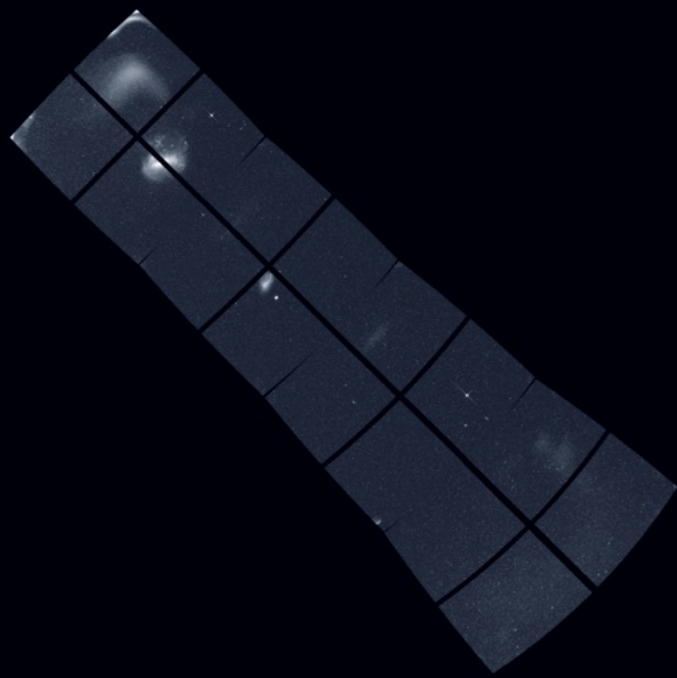
As of October 24, 2018

@NASAKepler

TESS – Transiting Exoplanet Survey Satellite

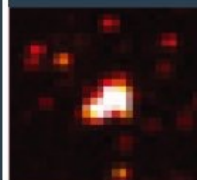


TESS



Ground Based Follow-Up

High-Resolution Imaging



Deep
Image of
Target Field

High SNR
Transit
Observation

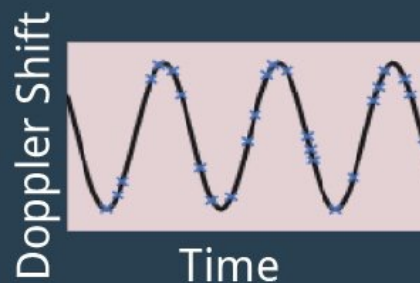


Reconnnaissance Spectroscopy



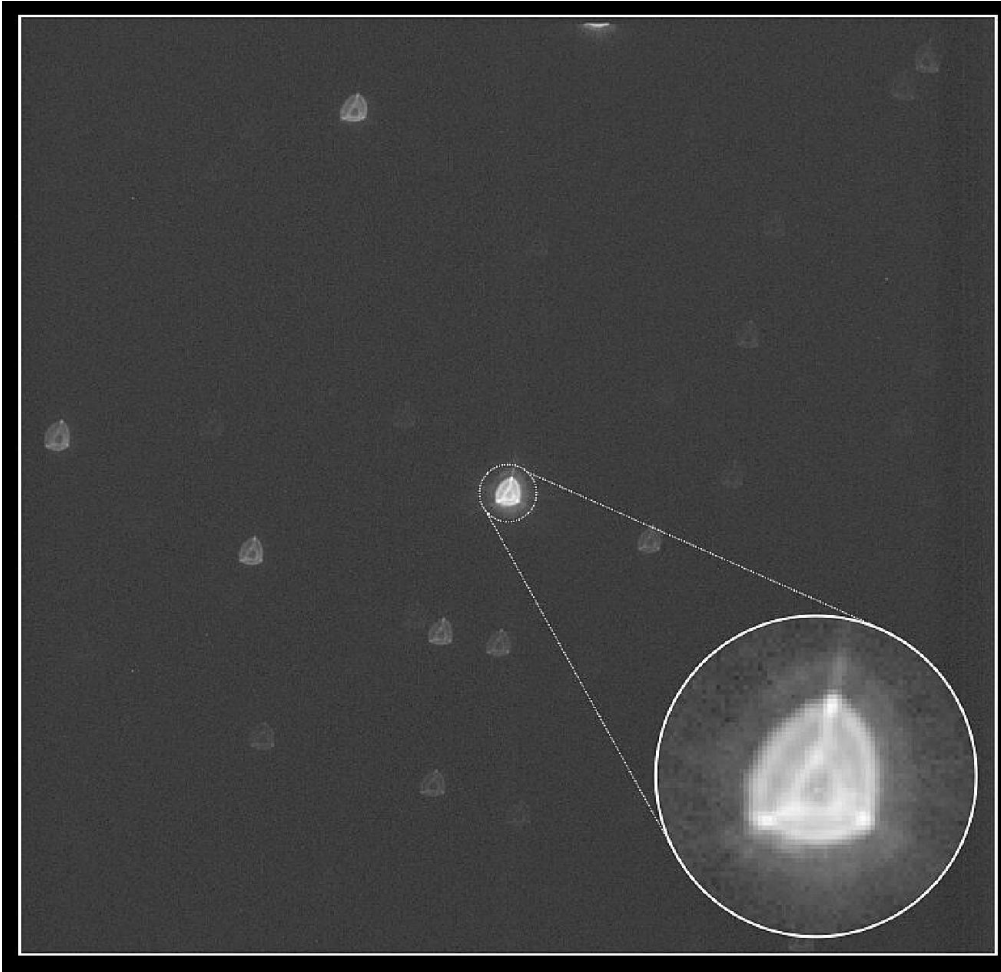
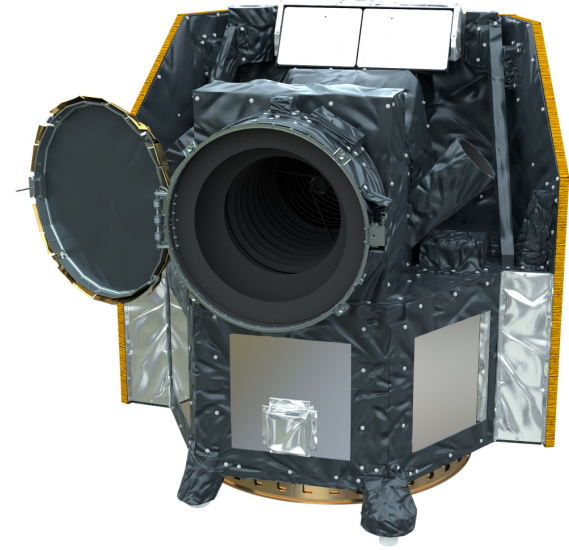
Improve Stellar Parameters (T_{eff} , $\log g$, $[m/H]$)

Precise Doppler Spectroscopy

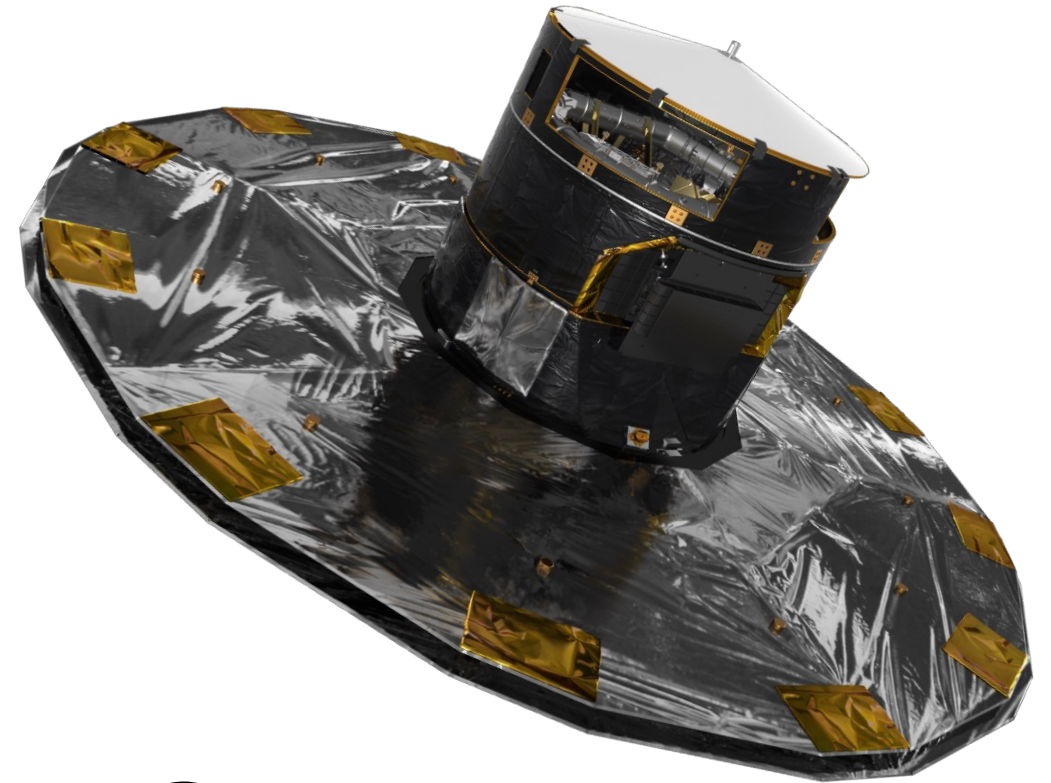


Planet Mass
Measurement

CHEOPS – first Swiss-led ESA Satellite



- Selected 2012
launched 2019
- Ultraprecise photometry (150ppm)
- Strategy:
 - pointed observations
 - Individual target stare down
- Orbit:
 - 700 km elevation
 - Sun-synchronous (dusk/dawn)
 - Typical observation: 48 hours

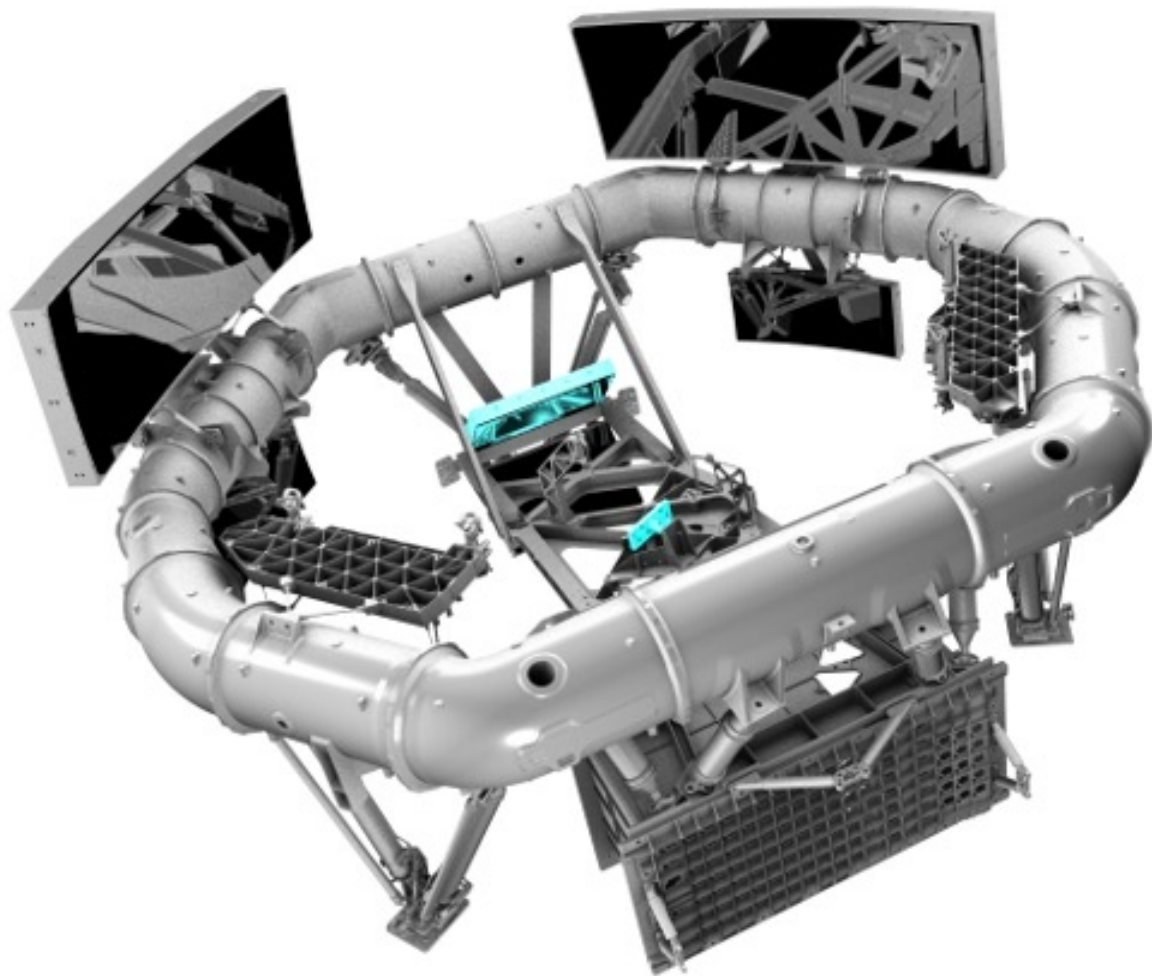


The ESA mission Gaia

Exploiting positional and electromagnetic variability



Gaia's Payload Design



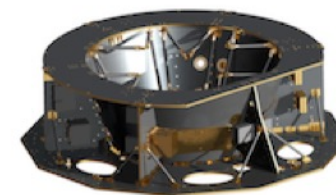
(a)



(b)



(c)



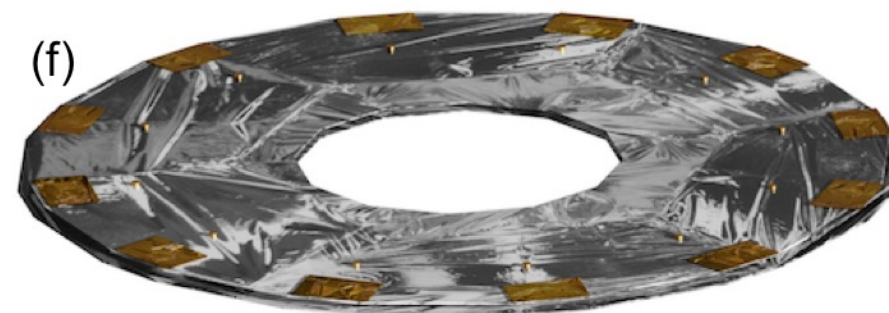
(d)

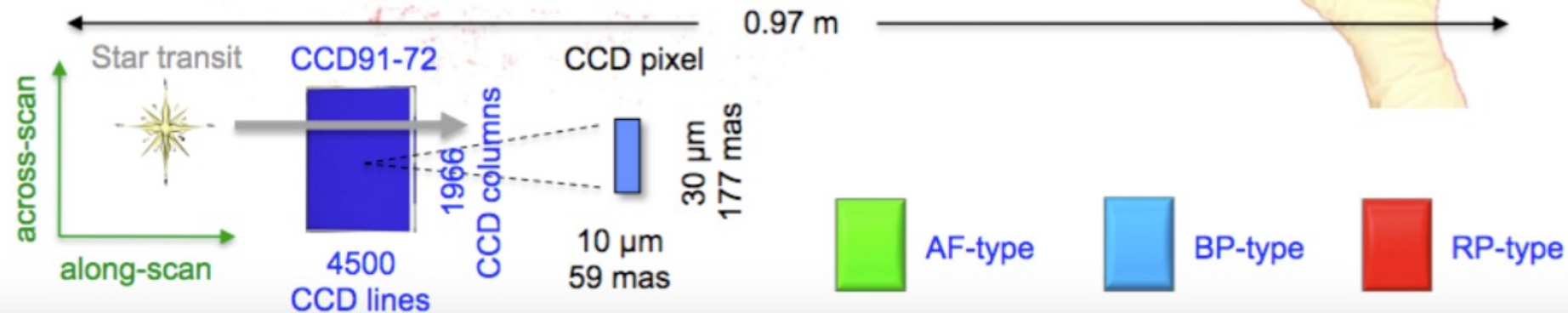


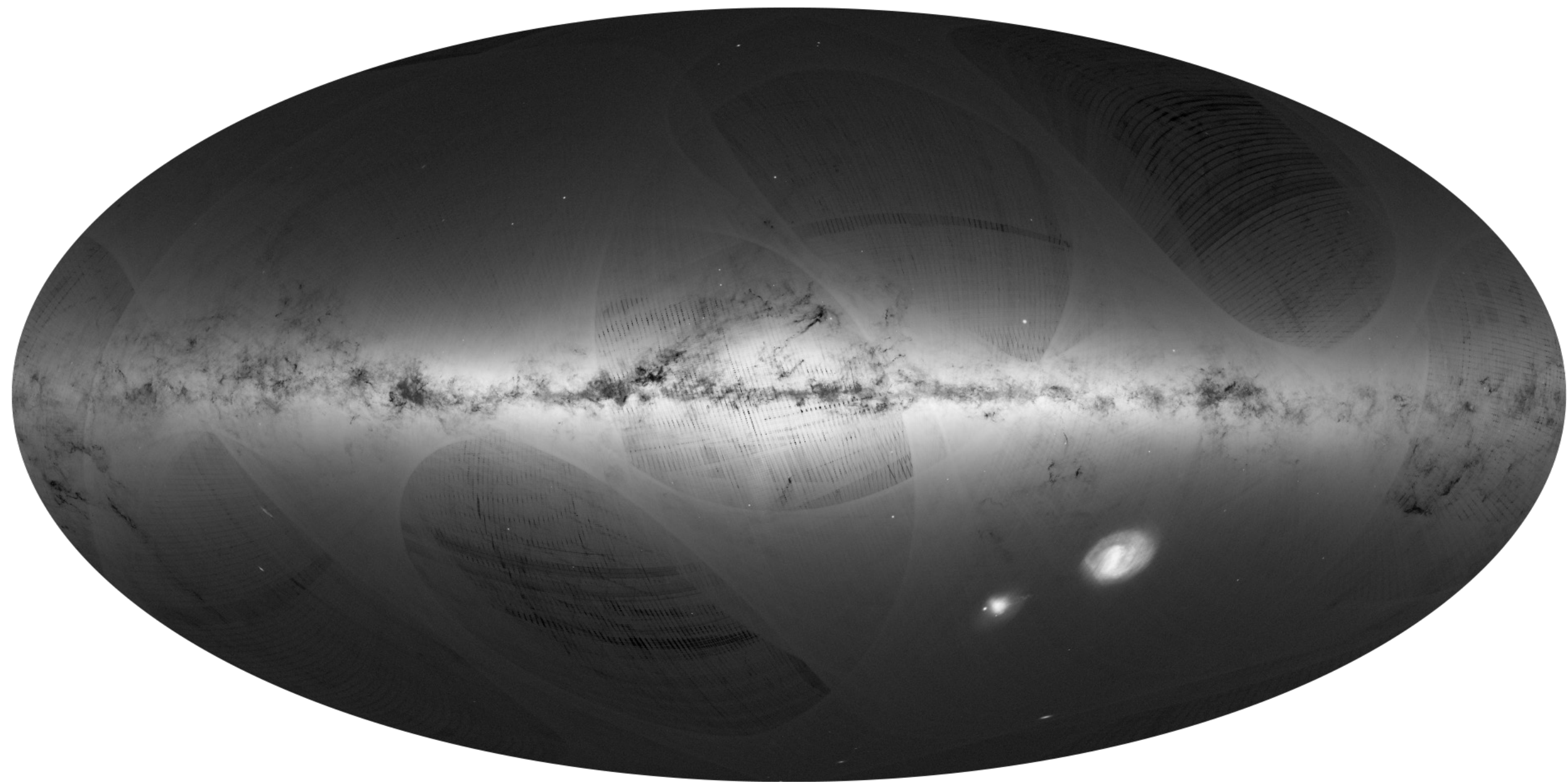
(e)



(f)

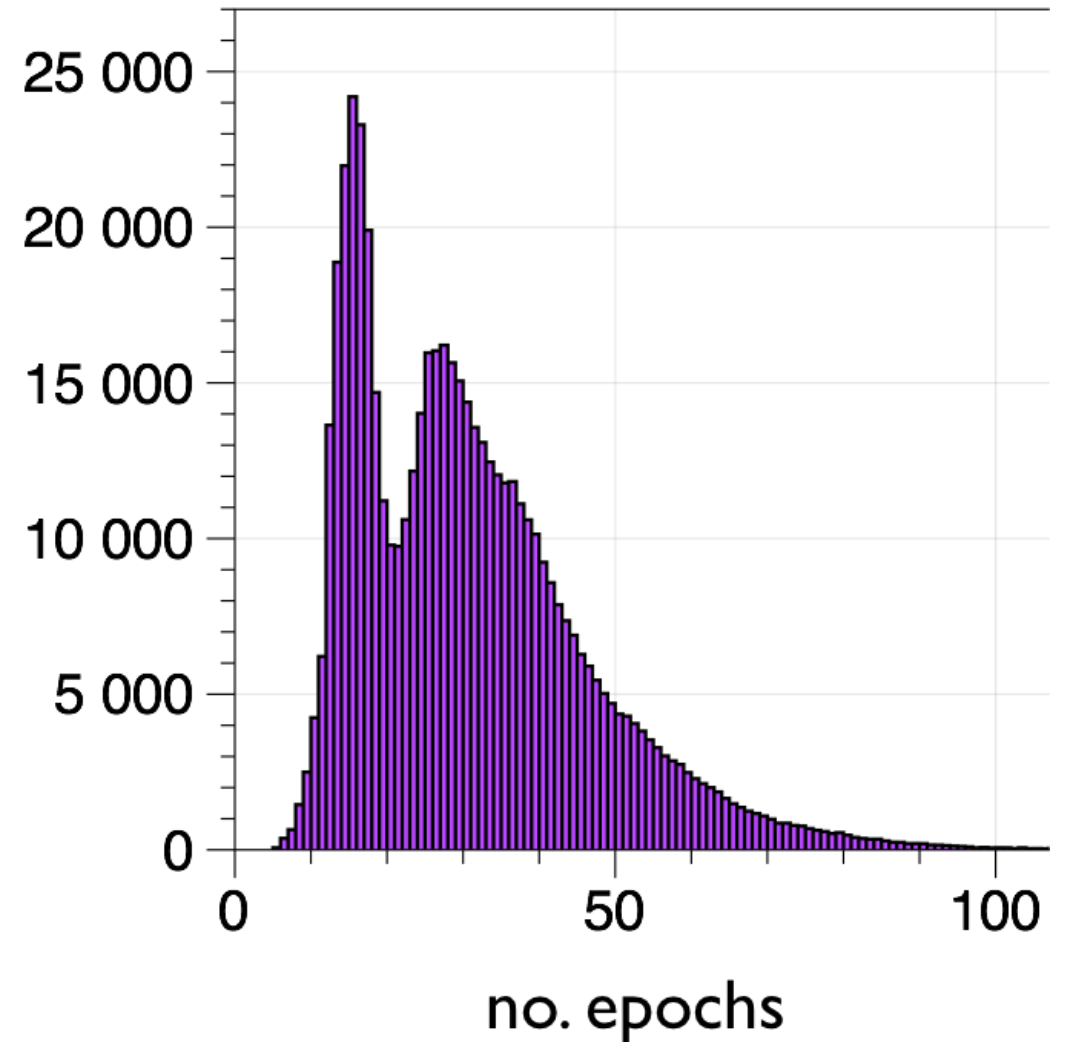


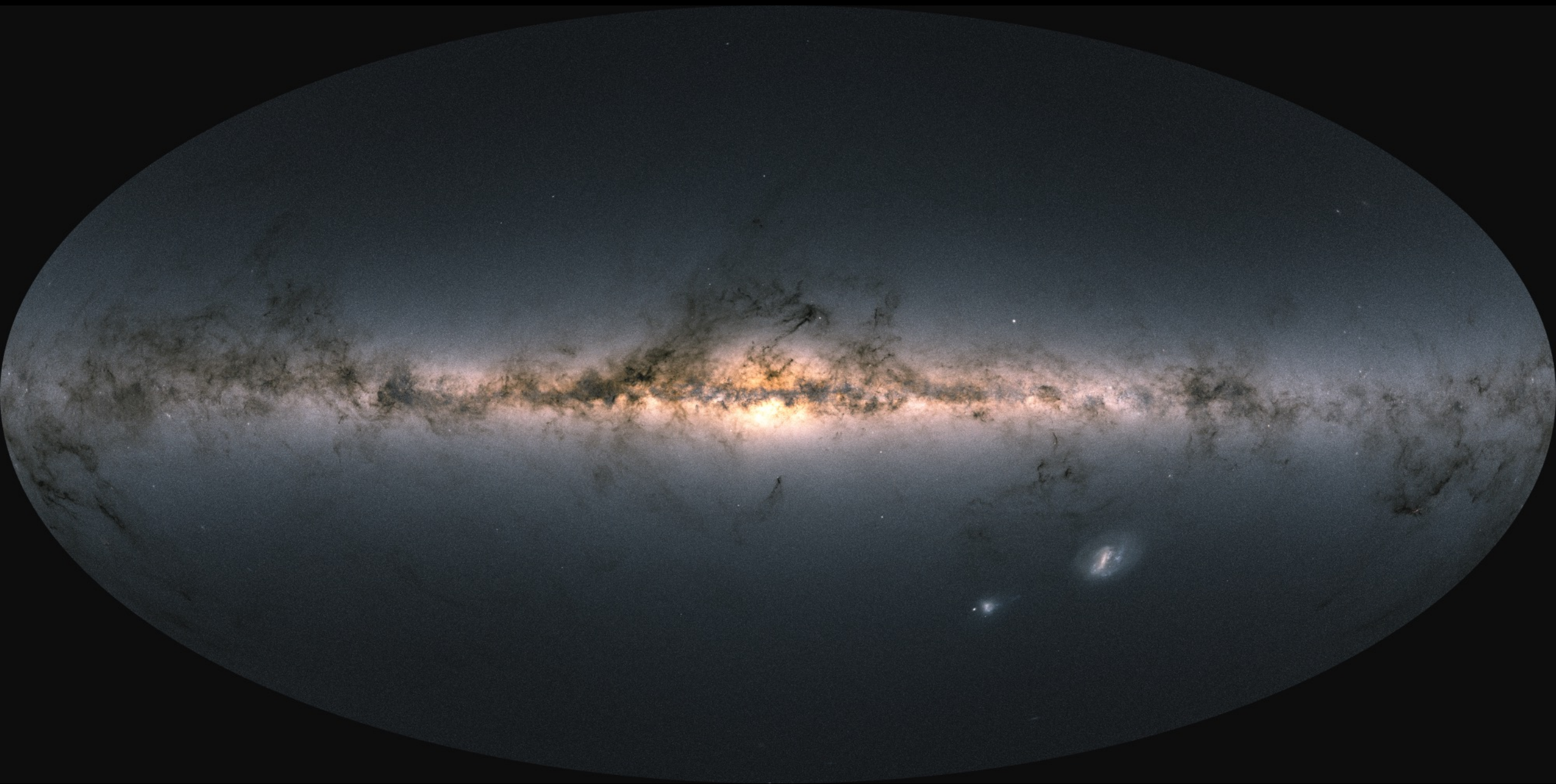




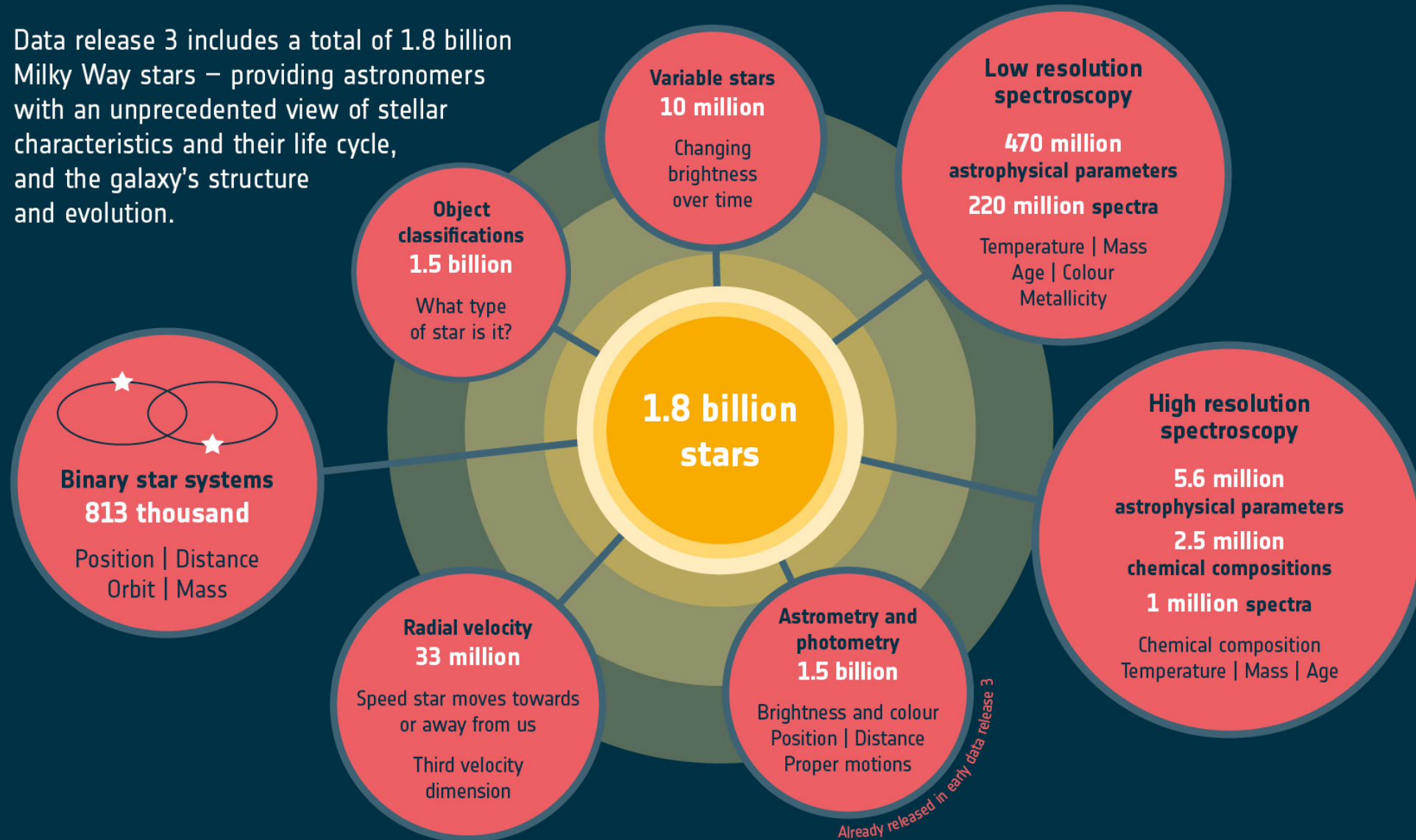
Light intensity variability in Gaia DR2

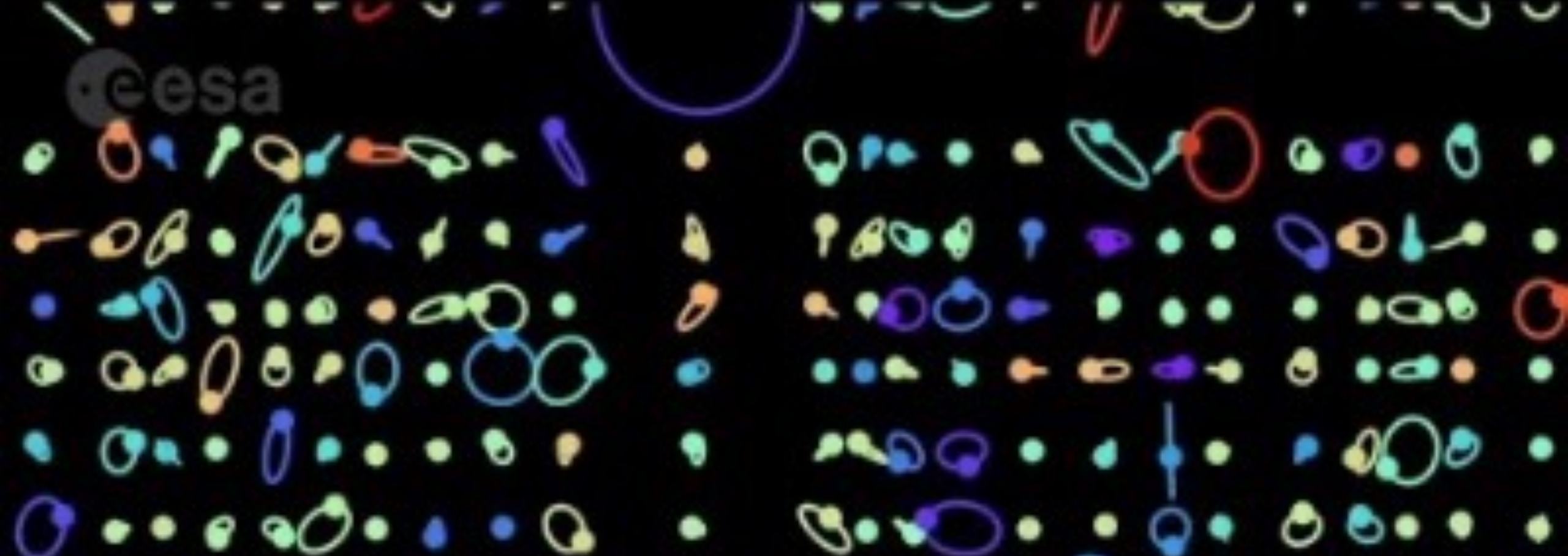
- 550 000 variable stars identified (min. 5 transits)
- 3-band light curves for all
- 70% with more than 20 epochs in G
- 360 000 objects classified
- High-amplitude variable stars, short-timescale variables





Data release 3 includes a total of 1.8 billion Milky Way stars – providing astronomers with an unprecedented view of stellar characteristics and their life cycle, and the galaxy's structure and evolution.

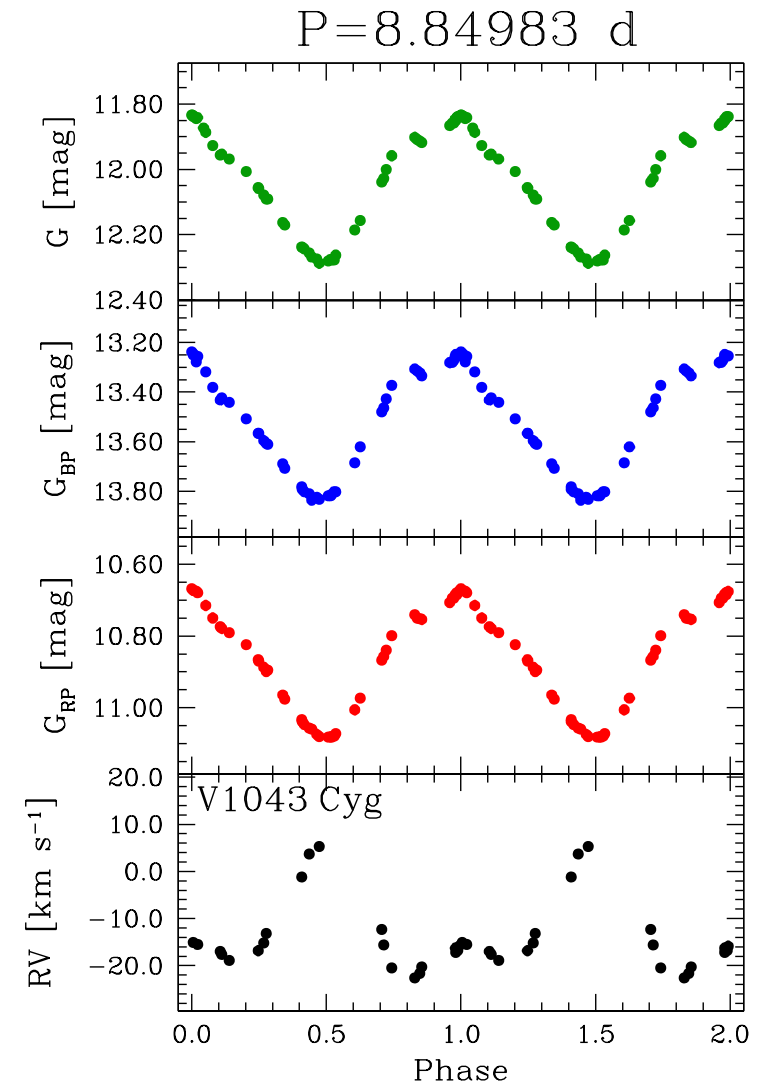
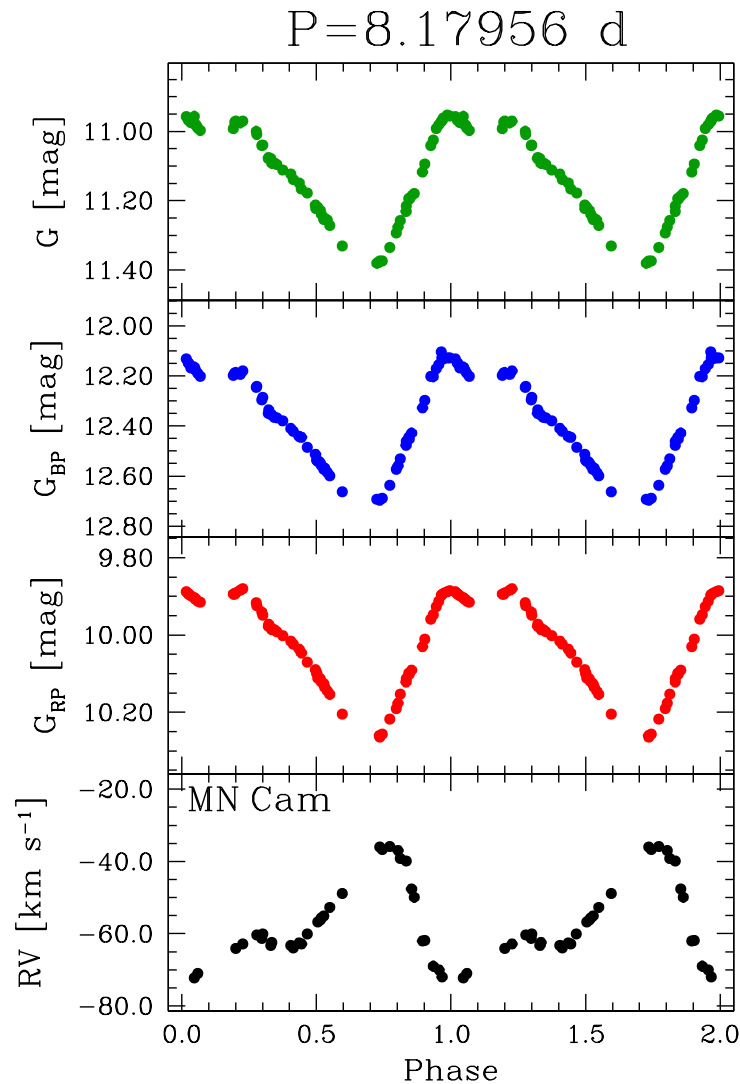
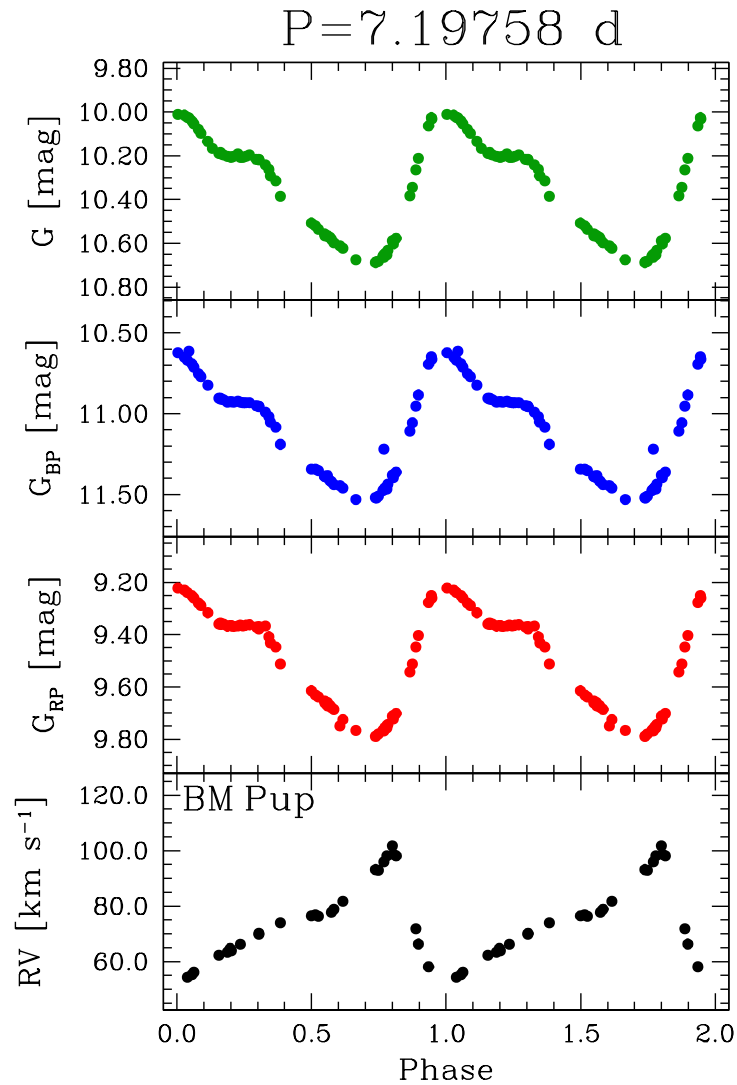




SOCIAL STARS

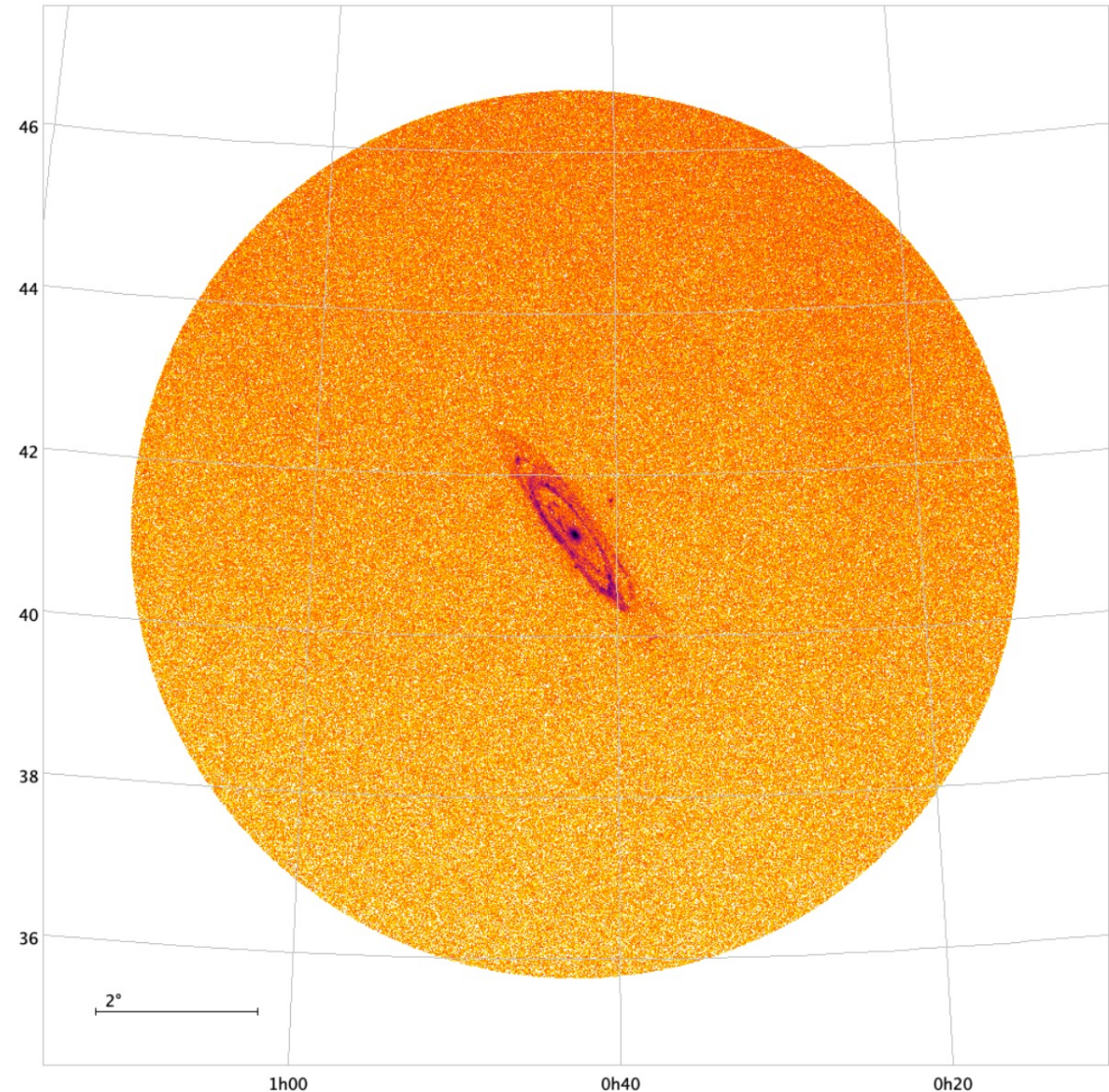


3-band & radial velocity time series



Gaia Andromeda Photometric Survey

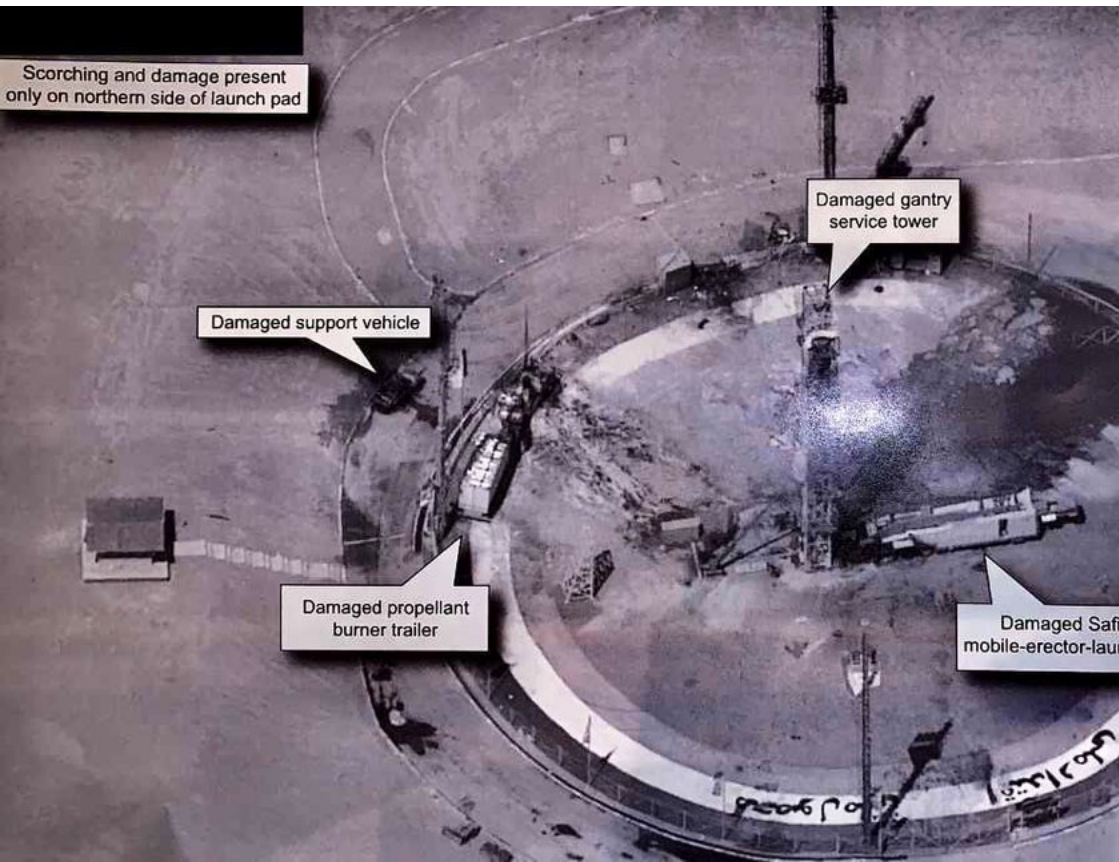
- 5.5deg cone centered on M31
- All time series observations available in Gaia DR3
- Preview of what Gaia will deliver in DR4 and 5
- Chromatic light curves of Cepheids at 1 Mpc!



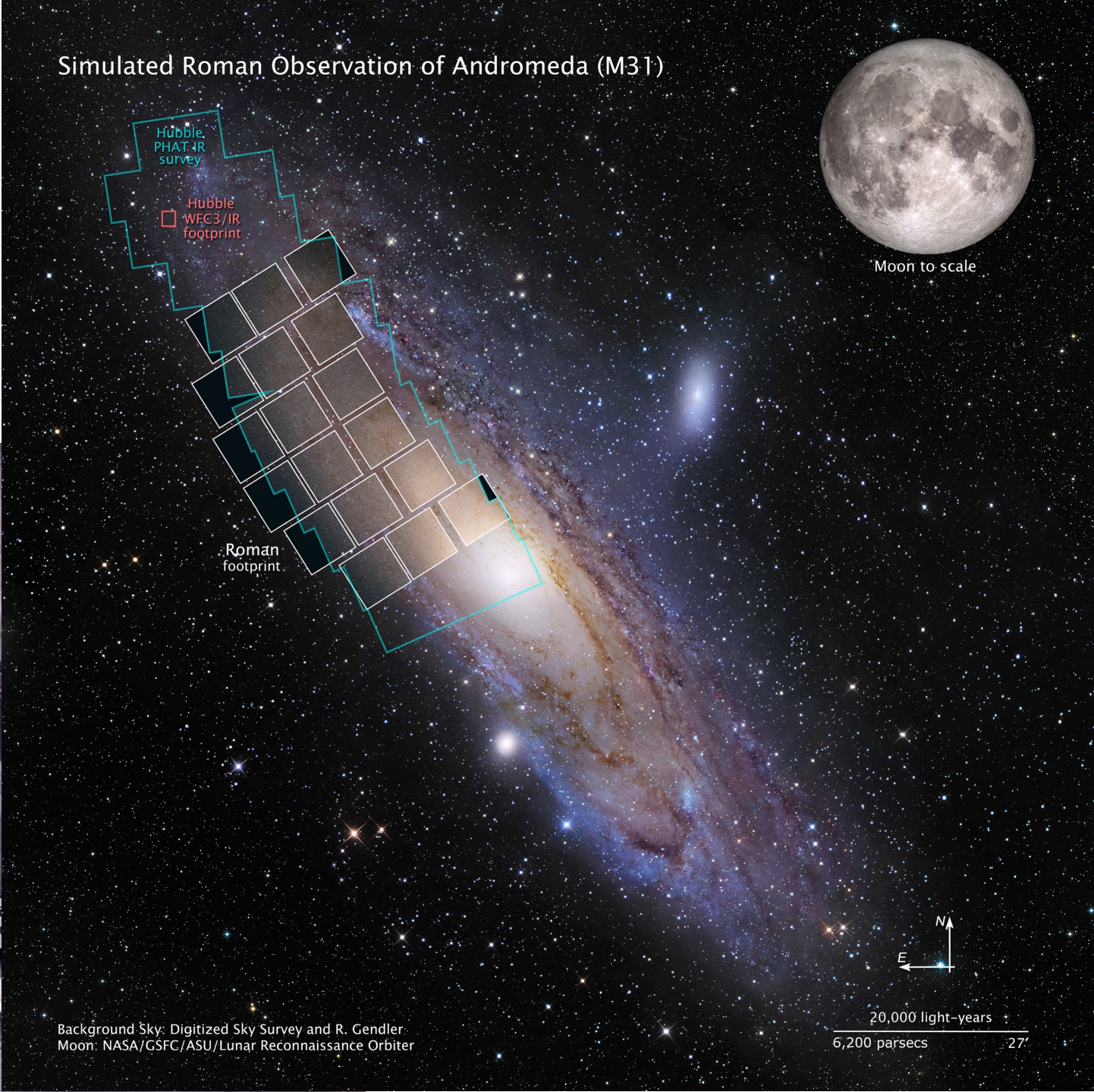
Nancy Grace Roman Space Telescope (WFIRST)

Nancy Roman Grace Space Telescope

- Decommissioned 2.4m wide-field spy telescope



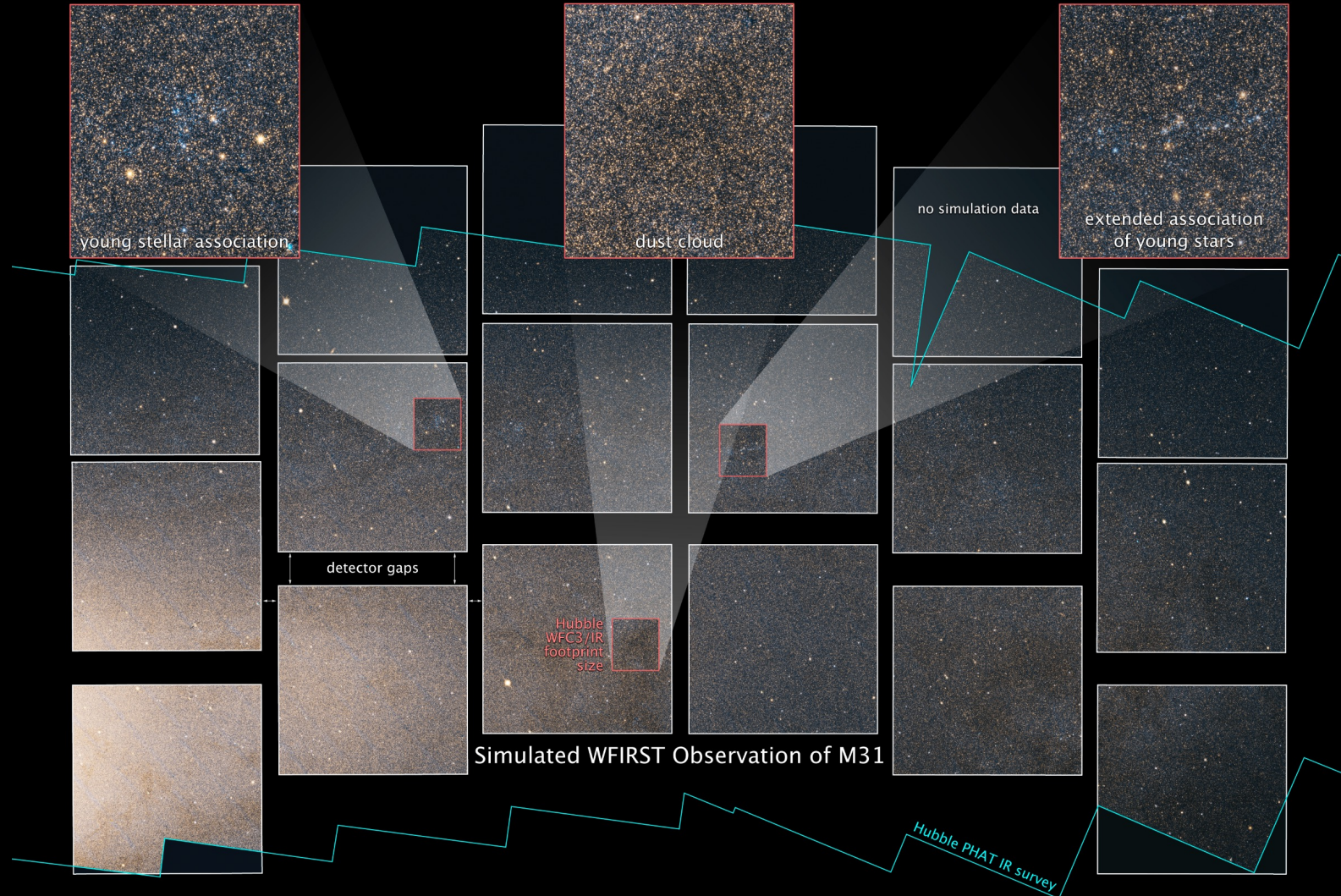
Simulated Roman Observation of Andromeda (M31)



Roman Quick Facts

- 45' x 23' FoV (0.28sq deg)
- 0.5 – 2.3 micron
- 0.11"/pix ~ WFC3/IR
- Imaging
- Spectroscopy
- Coronagraphy
- 2/3 core surveys on time-domain: High lat & Galactic bulge

<https://roman.gsfc.nasa.gov>



BIG DATA

The Nancy Grace Roman Space Telescope will transmit an unprecedented amount of data from its orbit a million miles away from Earth. Scientists expect it to average almost 1.4 terabytes each day, and after just five years of observations, it should total 20,000 terabytes on MAST, the Mikulski Archive for Space Telescopes. The Hubble Space Telescope sends less than three gigabytes a day, while in the same time even the James Webb Space Telescope will send less than 60 gigabytes.

Hubble

| 2.7

Webb

58

Roman

1,375

Gigabytes per day sent to Earth



172 terabytes

Hubble's data archive
1990-2020



1,000 terabytes

Webb's data archive
after five-year primary
mission (projected)



20,000 terabytes (20 petabytes)

Roman's data archive
after five-year primary
mission (projected)

Take aways

- We live in the era of survey astronomy
- Most surveys now have time resolution
- LSST et al. push the full-sky time-resolution multi-band frontier
- Spectroscopic surveys: increasing time-domain applications
- There are Peta-byte scale data avalanches everywhere
- Astrostatistics is a booming field (and a course of its own)
- Check out lecture series: <https://www.samsi.info/astro-time-series-methods-astronomy/>

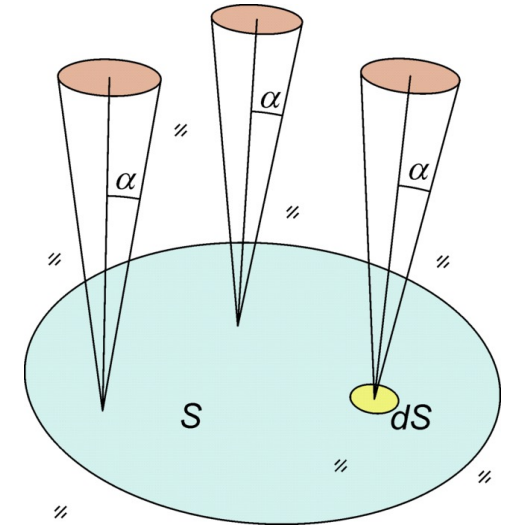
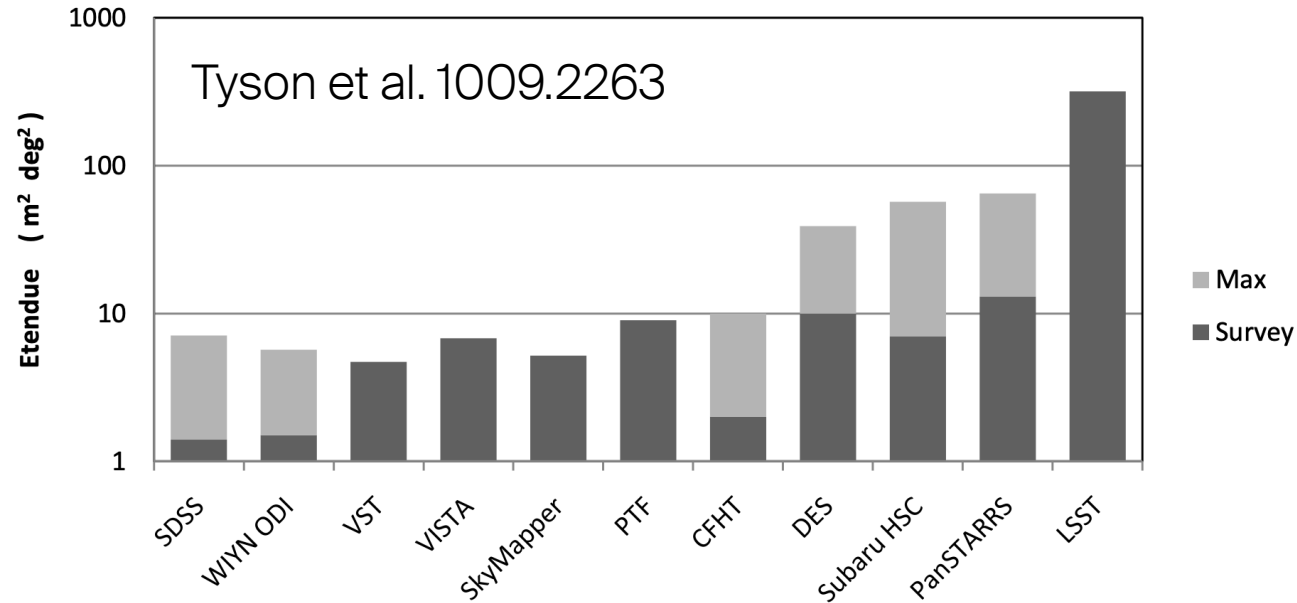
Quantifying surveys

Figures of merit – quantifying system performance to achieve science goals

- Cadence, duty cycle & duration
- Sky coverage: location, Field-of-View (FoV), area
- Sky quality
- Depth
- Resolution
- Synergies (e.g. photometry + spectroscopy)
- Tonry 2011, PASP 123, 58
Bellm 2016, PASP 128, 084501

Etendue

e.g. Tyson et al. 2010



$$G = \int dS \cos \theta \, d\Omega = A\Omega$$

- Etendue = effective area m^2 * FoV deg^2
- Extensions possible: seeing, QE of detector, etc.
- Combines optical speed (solid angle of pupil) with sensor size
- Rate at which a facility can survey area of sky in single exposure
- Higher etendue = more photons = better S/N!

Instantaneous volumetric survey speed

Bellm (2016), PASP 128, 084501

$$\dot{V}_M = \frac{\Omega_{\text{fov}}}{4\pi} \frac{V_c(z_{\text{lim}}(M, t_{\text{exp}}))}{t_{\text{exp}} + t_{\text{OH}}}$$

In Euclidean space:

$$\dot{V}_M \propto \frac{\Omega_{\text{fov}}}{t_{\text{exp}} + t_{\text{OH}}} d^3$$

$$\text{areal survey speed } \dot{\Omega} = \frac{\Omega_{\text{fov}}}{t_{\text{exp}} + t_{\text{OH}}}$$

Instantaneous volumetric survey speed =
comoving spatial volume in which object of fiducial abs mag M
is detected in single exposure with specified SNR,
divided by total time per exposure

Ω_{fov} : camera field of view

$t_{\text{exp}}, t_{\text{OH}}$: exposure time + overhead

z_{lim} : redshift of object at detection limit

$V_c(z_{\text{lim}})$: comoving volume out to z_{lim}

Modern wide-field surveys run out of fresh sky to observe in
a given night!

Trade offs depending on survey interests, etc. Figures of merit useful to understand how
survey instruments can be built to most effectively deliver desired results!

XII – Selection functions

Selection functions

- S is a multiplication of probabilities for a type of object to be seen by the survey
- Critical to understand survey content

$$\lambda_c(y|\theta) = S_c(y) \int p(y|z) \lambda_0(z|\theta) dz = S_c(y) \lambda_0(y|\theta)$$

S_c : selection function
 y : object properties
 z : true quantities
 θ : model parameters
 λ : phys/math model

- Fraction of stars observed:
 - Of all stars in area
 - Of observable stars in area
 - Of observable stars in current footprint (e.g. Gaia ESO: likely members)
- Quantification requires input distribution, but where to get that?
 - Photometry usually available deeper than spectroscopy
- Design (desired cadence) vs actuality (interruptions, etc.)
- Fraction of stars passing quality cuts after observation

Gaia selection function

- Gaia selection function not studied (and difficult to know) ahead of survey
- Roughly 1% of stars in MW (2 billion): what is that representative of?
- Magnitude-limited survey; different instrument have different limits
- All-sky
- Crowded areas can be a problem: blending & data quantity
- Scanning law: completeness can depend on scan direction
- Time-dependent scanning law: not all objects observed on each pass/visit
- Different instruments
- Complex processing steps

Selection functions

- Usually: unknown
- Frequently: determined post-factum
- Almost always: importance underestimated!
- Ignore it at your own peril
- Arbitrarily complicated: is S constant in time?
- Strauss et al. 1991, PASP 103, 1012
Mints & Hekker 2018, A&A, 621, A17
Wojno et al. 2017, MNRAS 468, 3368