Charting the Universe: the next generation of cosmological surveys

Part 2

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Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

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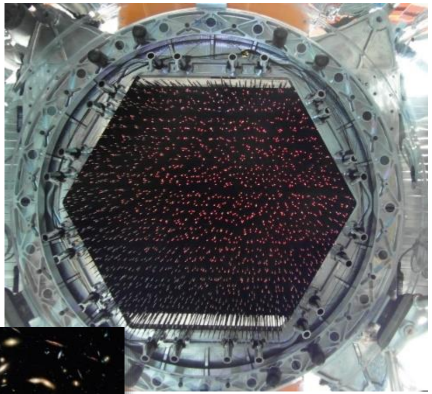
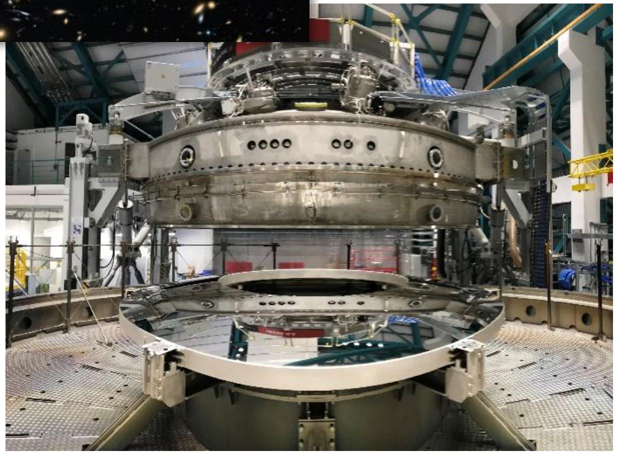




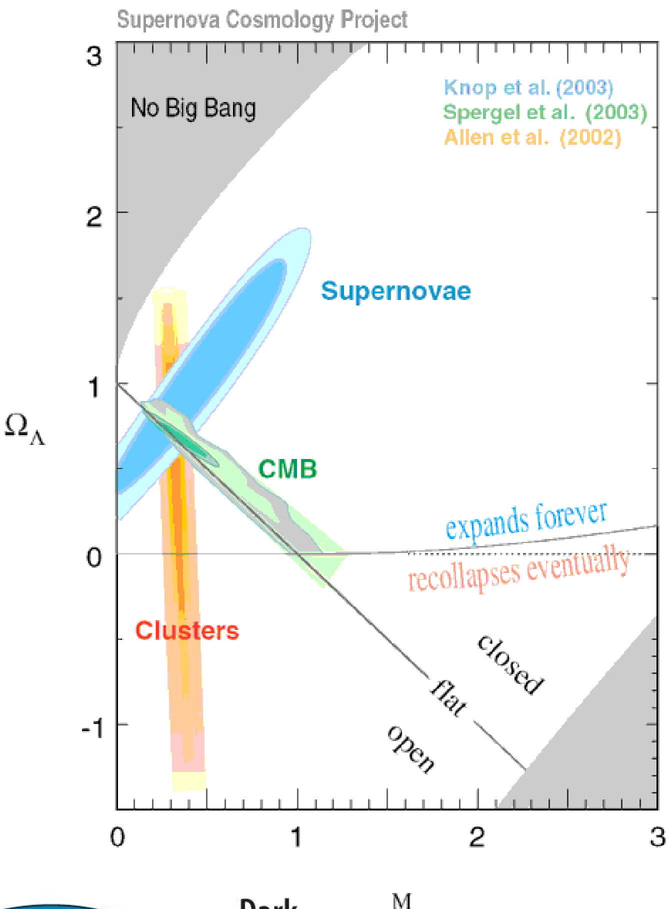
The ΛCDM standard model of cosmology

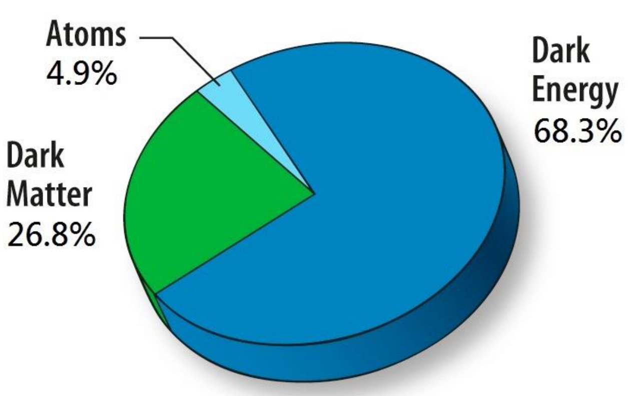
Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046	0.1202 ± 0.0014	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04077 ± 0.00047	1.04139 ± 0.00049	1.03999 ± 0.00089	1.04090 ± 0.00031	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.040 ± 0.016	$3.018^{+0.020}_{-0.018}$	3.052 ± 0.022	3.045 ± 0.016	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9626 ± 0.0057	0.967 ± 0.011	0.980 ± 0.015	0.9649 ± 0.0044	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0 [$\mathrm{km\,s^{-1}\,Mpc^{-1}}$] . .	66.88 ± 0.92	68.44 ± 0.91	69.9 ± 2.7	67.27 ± 0.60	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.679 ± 0.013	0.699 ± 0.012	$0.711^{+0.033}_{-0.026}$	0.6834 ± 0.0084	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.321 ± 0.013	0.301 ± 0.012	$0.289^{+0.026}_{-0.033}$	0.3166 ± 0.0084	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1434 ± 0.0020	0.1408 ± 0.0019	$0.1404^{+0.0034}_{-0.0039}$	0.1432 ± 0.0013	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09589 ± 0.00046	0.09635 ± 0.00051	$0.0981^{+0.0016}_{-0.0018}$	0.09633 ± 0.00029	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8118 ± 0.0089	0.793 ± 0.011	0.796 ± 0.018	0.8120 ± 0.0073	0.8111 ± 0.0060	0.8102 ± 0.0060
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$.	0.840 ± 0.024	0.794 ± 0.024	$0.781^{+0.052}_{-0.060}$	0.834 ± 0.016	0.832 ± 0.013	0.825 ± 0.011
$\sigma_8 \Omega_m^{0.25}$	0.611 ± 0.012	0.587 ± 0.012	0.583 ± 0.027	0.6090 ± 0.0081	0.6078 ± 0.0064	0.6051 ± 0.0058
z_{re}	7.50 ± 0.82	$7.11^{+0.91}_{-0.75}$	$7.10^{+0.87}_{-0.73}$	7.68 ± 0.79	7.67 ± 0.73	7.82 ± 0.71
$10^9 A_s$	2.092 ± 0.034	2.045 ± 0.041	2.116 ± 0.047	$2.101^{+0.031}_{-0.034}$	2.100 ± 0.030	2.105 ± 0.030
$10^9 A_s e^{-2\tau}$	1.884 ± 0.014	1.851 ± 0.018	1.904 ± 0.024	1.884 ± 0.012	1.883 ± 0.011	1.881 ± 0.010
Age [Gyr]	13.830 ± 0.037	13.761 ± 0.038	$13.64^{+0.16}_{-0.14}$	13.800 ± 0.024	13.797 ± 0.023	13.787 ± 0.020
z_*	1090.30 ± 0.41	1089.57 ± 0.42	$1087.8^{+1.6}_{-1.7}$	1089.95 ± 0.27	1089.92 ± 0.25	1089.80 ± 0.21
r_* [Mpc]	144.46 ± 0.48	144.95 ± 0.48	144.29 ± 0.64	144.39 ± 0.30	144.43 ± 0.26	144.57 ± 0.22
$100\theta_*$	1.04097 ± 0.00046	1.04156 ± 0.00049	1.04001 ± 0.00086	1.04109 ± 0.00030	1.04110 ± 0.00031	1.04119 ± 0.00029
z_{drag}	1059.39 ± 0.46	1060.03 ± 0.54	1063.2 ± 2.4	1059.93 ± 0.30	1059.94 ± 0.30	1060.01 ± 0.29
r_{drag} [Mpc]	147.21 ± 0.48	147.59 ± 0.49	146.46 ± 0.70	147.05 ± 0.30	147.09 ± 0.26	147.21 ± 0.23
k_D [$\mathrm{Mpc^{-1}}$]	0.14054 ± 0.00052	0.14043 ± 0.00057	0.1426 ± 0.0012	0.14090 ± 0.00032	0.14087 ± 0.00030	0.14078 ± 0.00028
z_{eq}	3411 ± 48	3349 ± 46	3340^{+81}_{-92}	3407 ± 31	3402 ± 26	3387 ± 21
k_{eq} [$\mathrm{Mpc^{-1}}$]	0.01041 ± 0.00014	0.01022 ± 0.00014	$0.01019^{+0.00025}_{-0.00028}$	0.010398 ± 0.000094	0.010384 ± 0.000081	0.010339 ± 0.000063
$100\theta_{s,eq}$	0.4483 ± 0.0046	0.4547 ± 0.0045	0.4562 ± 0.0092	0.4490 ± 0.0030	0.4494 ± 0.0026	0.4509 ± 0.0020

Planck collaboration (2021)

Our Universe

- Best measurements:
  $\Omega_\Lambda \approx 0.68$
  $\Omega_M \approx 0.32$ ($\Omega_b \approx 0.05$)
  $\Omega_{rad} \approx 10^{-5}$
  $H_0 \approx 70$ km/s/Mpc
- The Universe
  - is flat
  - is infinite
  - accelerates!
  - expands for ever
  - is 13.8×10^9 yr old
  - consists of unknown mass/energy components at the 95% level!



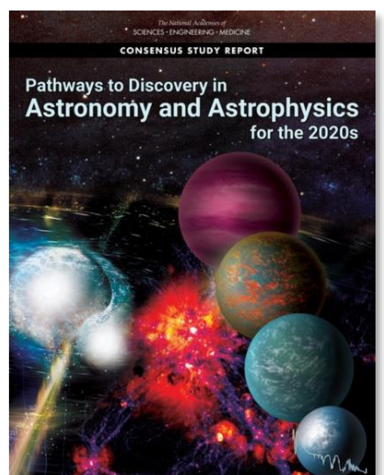


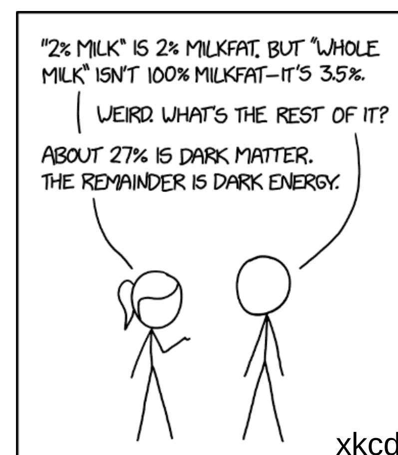
So what is there left to do (for surveys)?

Two elephants in the room:

COSMOLOGY IN THE 2020S AND BEYOND

With both compelling mysteries and extensive observational means by which to explore them, this will be an amazing decade for cosmology. In this report, the panel identifies four major science questions for the upcoming decade: (1) What set the Hot Big Bang in motion? (2) What are the properties of dark matter and the dark sector? (3) What physics drives the cosmic expansion and large-scale evolution of the universe? (4) How will measurements of gravitational waves reshape our cosmological view? The panel also identified a discovery area: The Dark Ages as a cosmological probe.

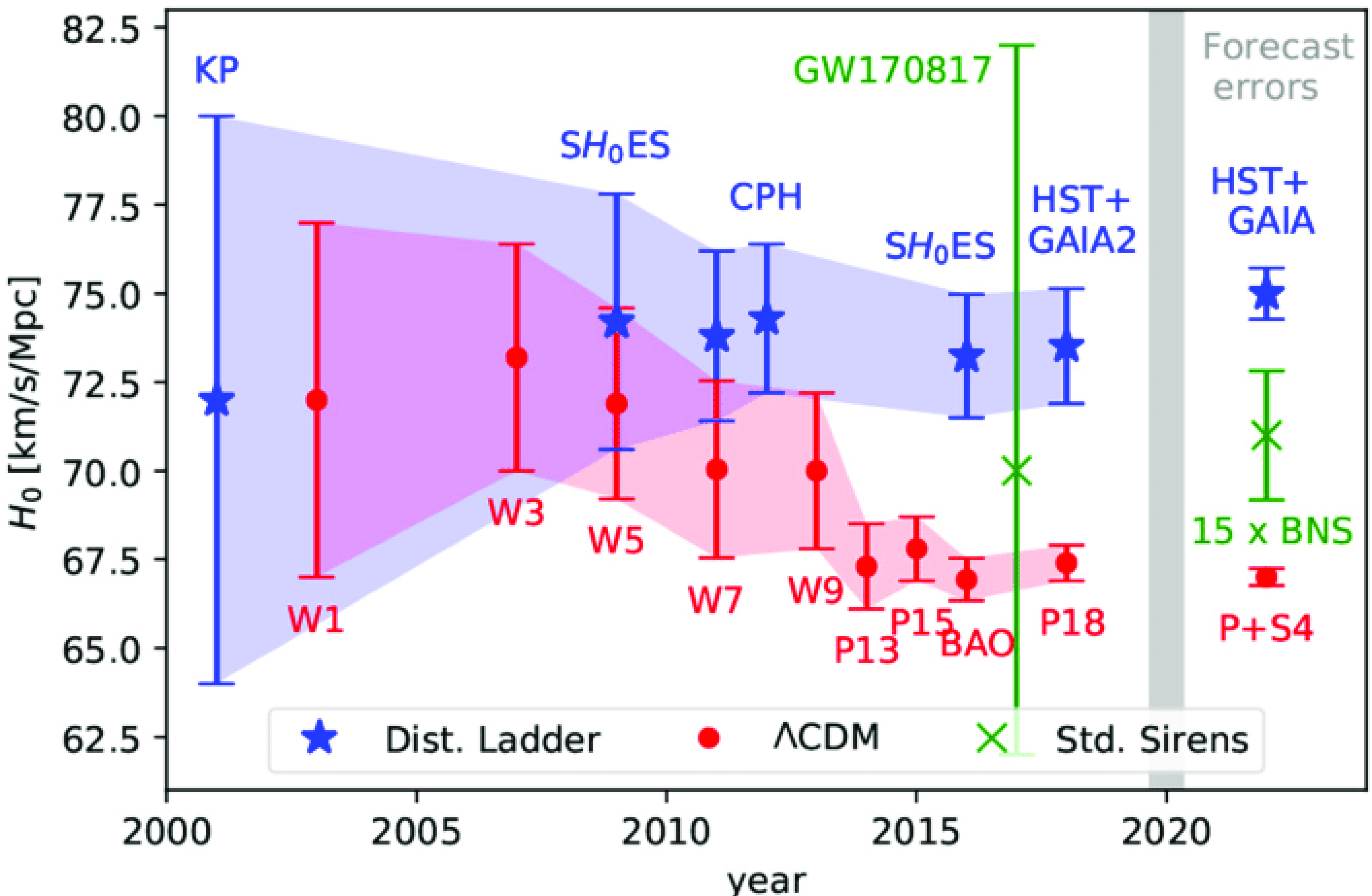




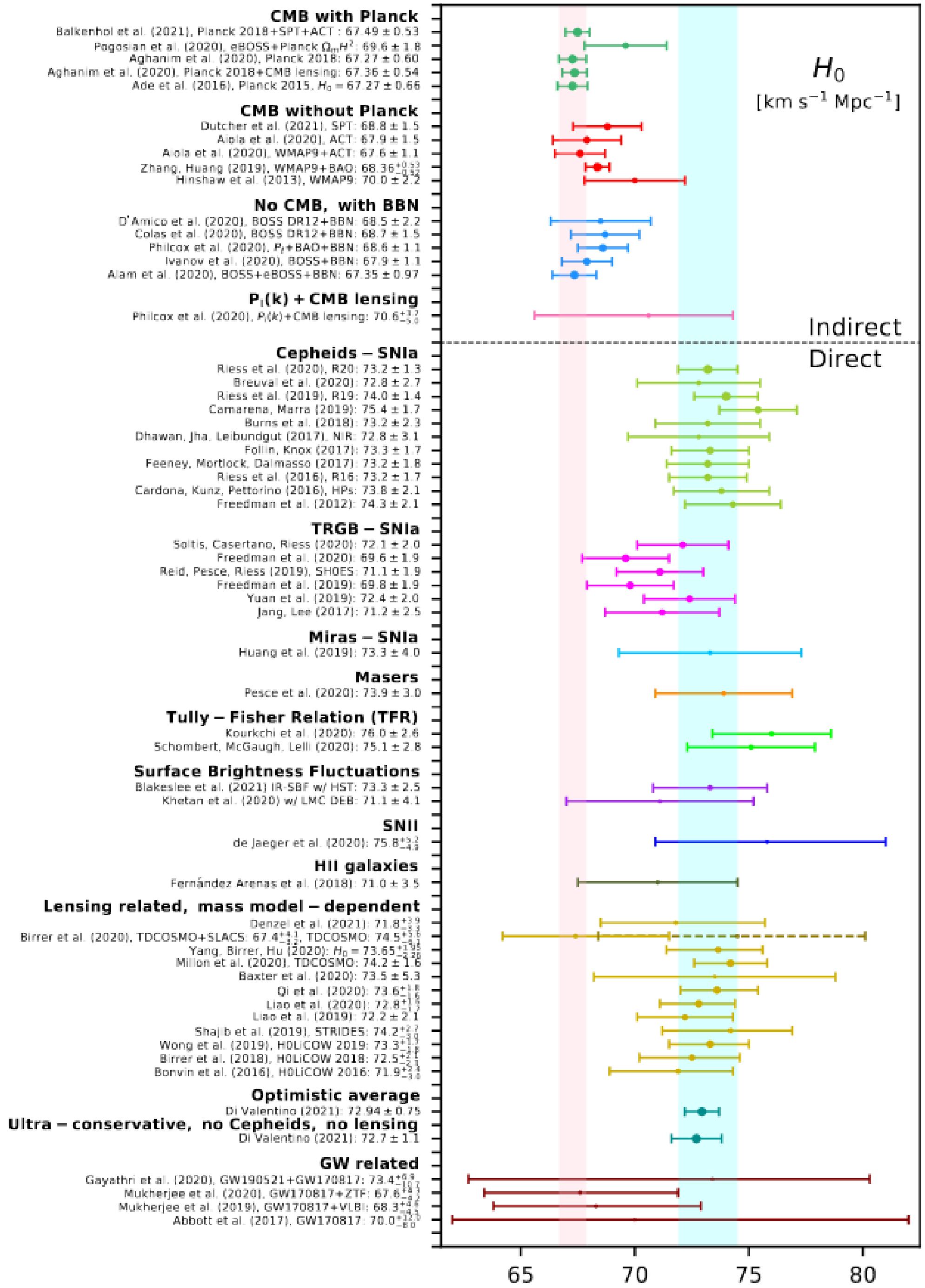
So what is there left to do (for surveys)?

Is the model beginning to crack?

- Hubble tension



Ezquiaga et al. (2018)



Di Valentino et al. (2021)

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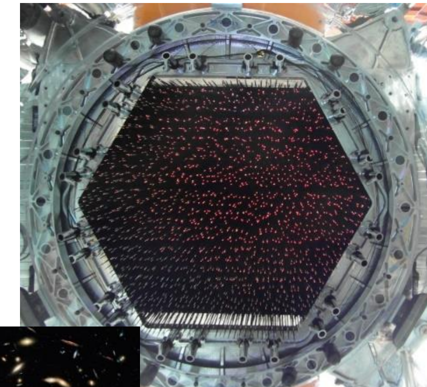
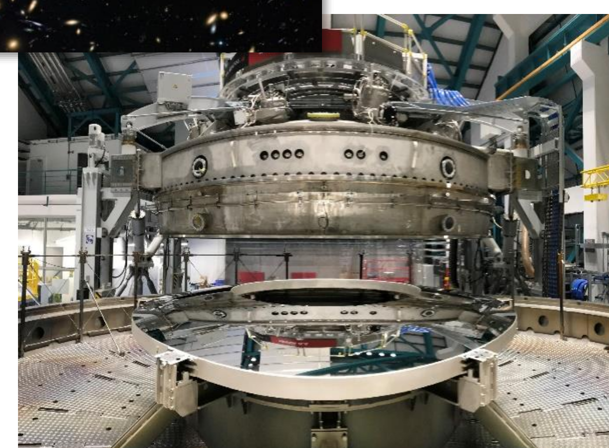
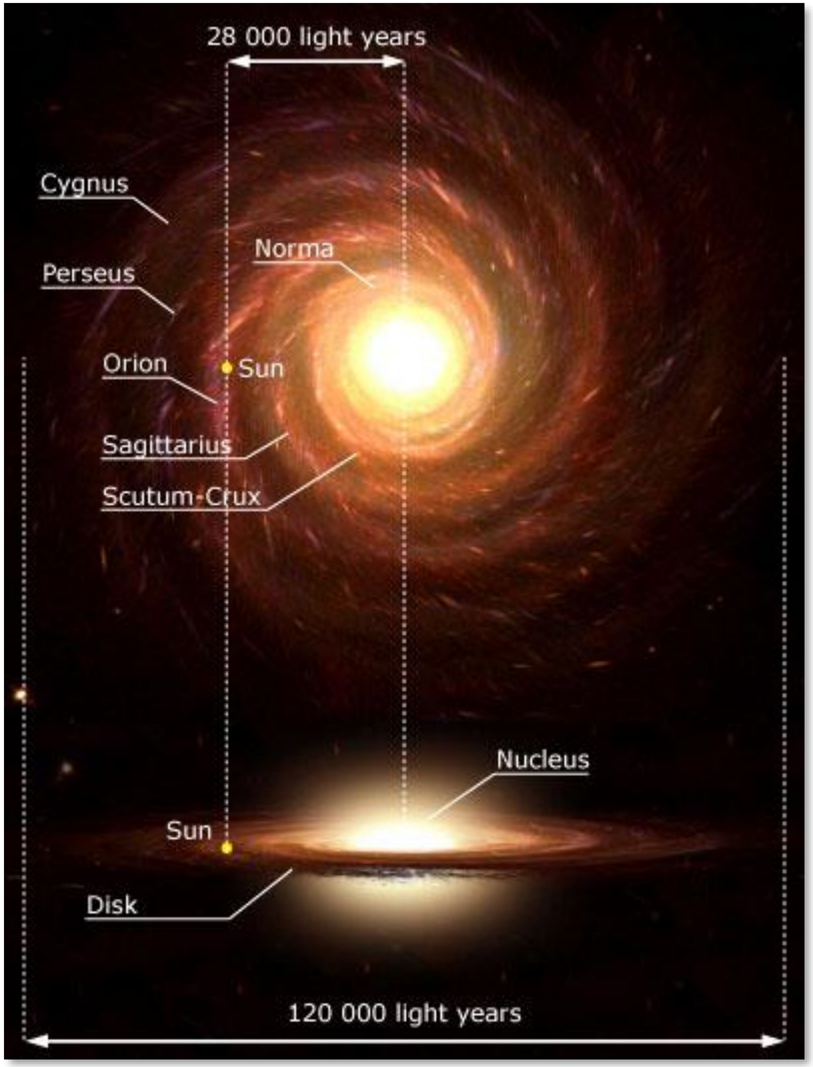


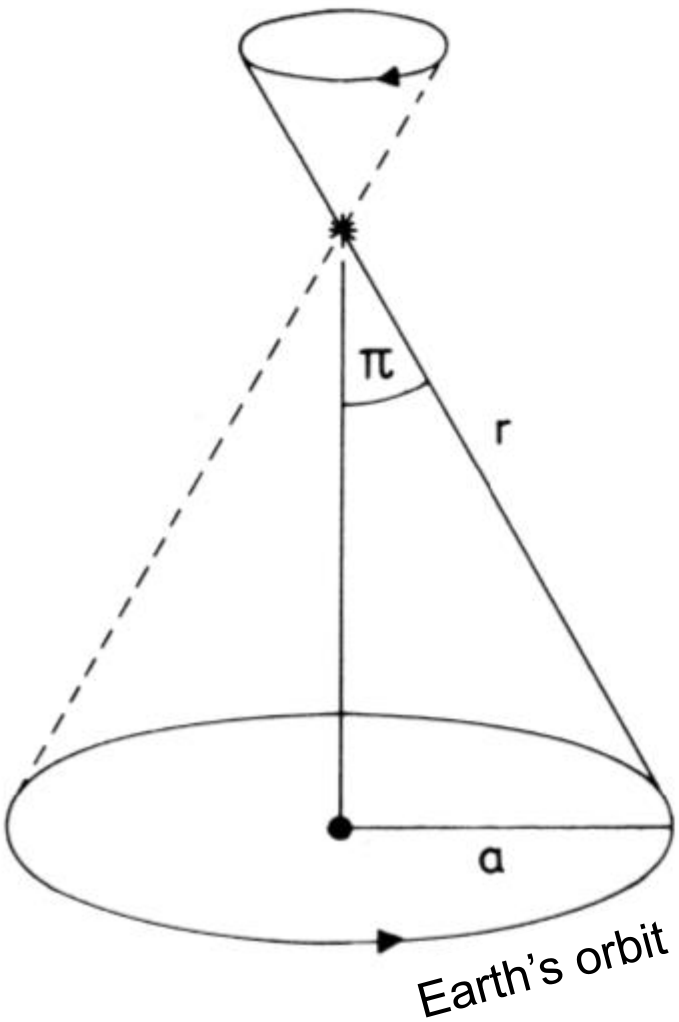


Gaia and the Dark Mater halo of the Milky Way

- A complete description of the dynamical structure of the Milky Way requires a survey of the 6D phase space of its stars
- 3D position in space
  - Position on sky
  - Distance
- 3D velocity
  - Tangential velocity (i.e. in the plane of the sky)
  - Radial velocity



Distance determination by parallax



Trigonometric parallax

- Direct distance determination
- Parallax angle π: $\sin(\pi) \approx \pi = a/r$ (for $r \gg a$)
- Definition of the unit of length parallax second = parsec = pc:

  $a = 1$ AU ($\approx 150 \times 10^6$ km)

  $\pi = 1''$

➢ $r \equiv 1$ pc $= 3.26$ Lj $= 30.9 \times 10^{12}$ km

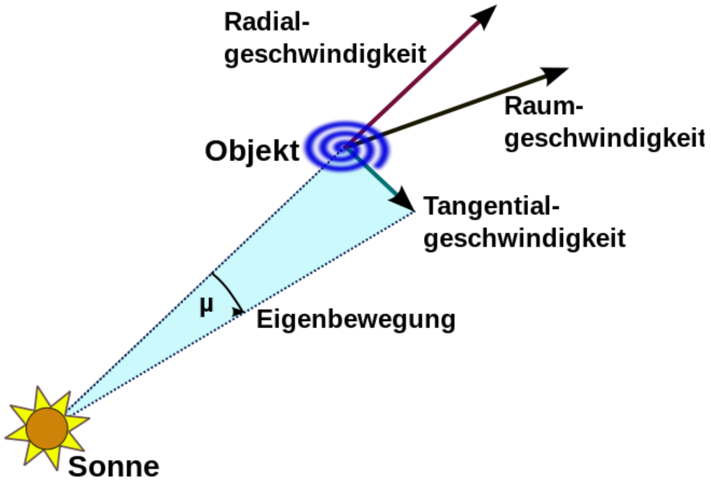
- Works only for very nearby stars
- Except when you can measure positions with extreme precision
- Gaia: 26 μas (G = 15 mag)!

Velocities

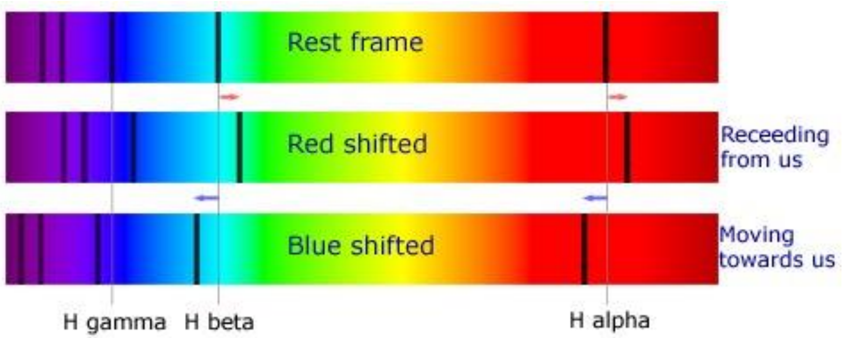
- Tangential velocity v_t
  - Causes proper motion μ = change of position in the sky (angular velocity)

$$\frac{\mu}{1'' \, a^{-1}} = \frac{v_{\mathrm{t}}}{4.74 \, \mathrm{km \ sec}^{-1}} \left(\frac{d}{1 \, \mathrm{pc}} \right)^{-1}$$

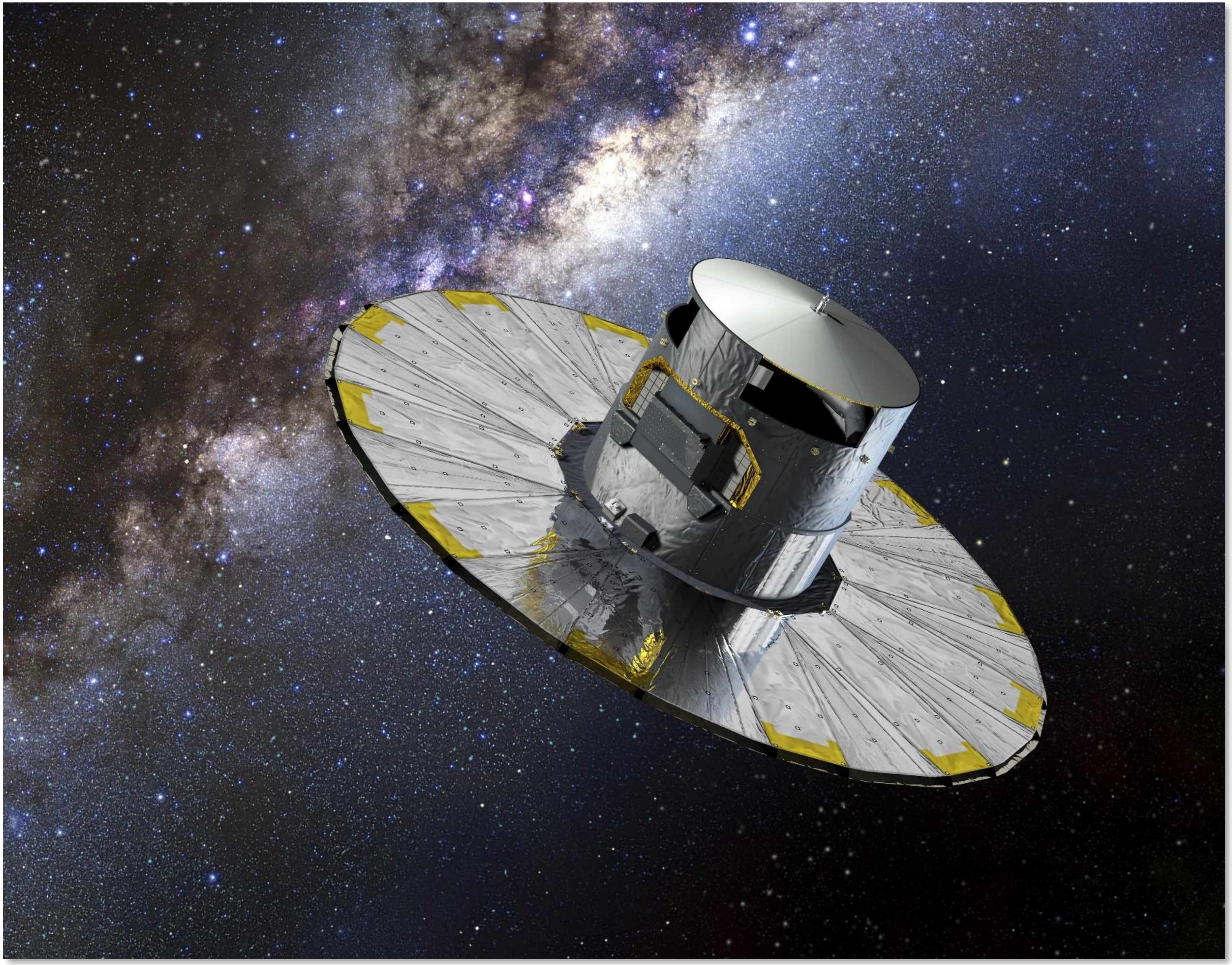
  - Measure from repeated astrometric observations



- Radial velocity v_r
  - Spectroscopy → Doppler effect



Gaia: a 6D survey of the Milky Way



Gaia

Credit: ESA

Gaia in numbers

First astrometry space mission
(ESA, 1989 – 1993)

	Hipparcos	**Gaia**
Magnitude limit	12 mag	20 mag
Completeness	7.3 – 9.0 mag	20 mag
Bright limit	0 mag	3 mag (assessment for brighter stars ongoing)
Number of objects	120,000	47 million to G = 15 mag 360 million to G = 18 mag 1192 million to G = 20 mag
Effective distance limit	1 kpc	50 kpc
Quasars	1 (3C 273)	500,000
Galaxies	None	1,000,000
Accuracy	1 milliarcsec	7 μarcsec at G = 10 mag 26 μarcsec at G = 15 mag 600 μarcsec at G = 20 mag
Photometry	2-colour (B and V)	Low-res. spectra to G = 20 mag
Radial velocity	None	15 km s^{-1} to G_{RVS} = 16 mag
Observing	Pre-selected	Complete and unbiased

Gaia in numbers

- Originally planned as 5-yr mission, now extended to 10 yr

- Astrometry (G < 20 mag):
  - Complete to 20 mag (on-board detection) → 10^9 stars!!!
  - Precision: 26 μas at G=15 mag (Hipparcos: 1 mas at 9 mag)
  - Scanning satellite, two viewing directions

    ⇒ global accuracy, with optimal use of observing time
  - Principle: global astrometric reduction (as for Hipparcos)

- Photometry (G < 20 mag):
  - Astrophysical diagnostics (low-dispersion photometry) + chromaticity → ΔT_{eff} ~ 100 K, log g, [Fe/H] to 0.2 dex, extinction (at G=15 mag)

- Radial velocity (G_{RVS} < 16 mag):
  - Precision: 15 km/s at G_{RVS}=16 mag
  - Principle: slitless spectroscopy of Ca triplet (845 – 872 nm) at R = 10,800

Payload and telescope

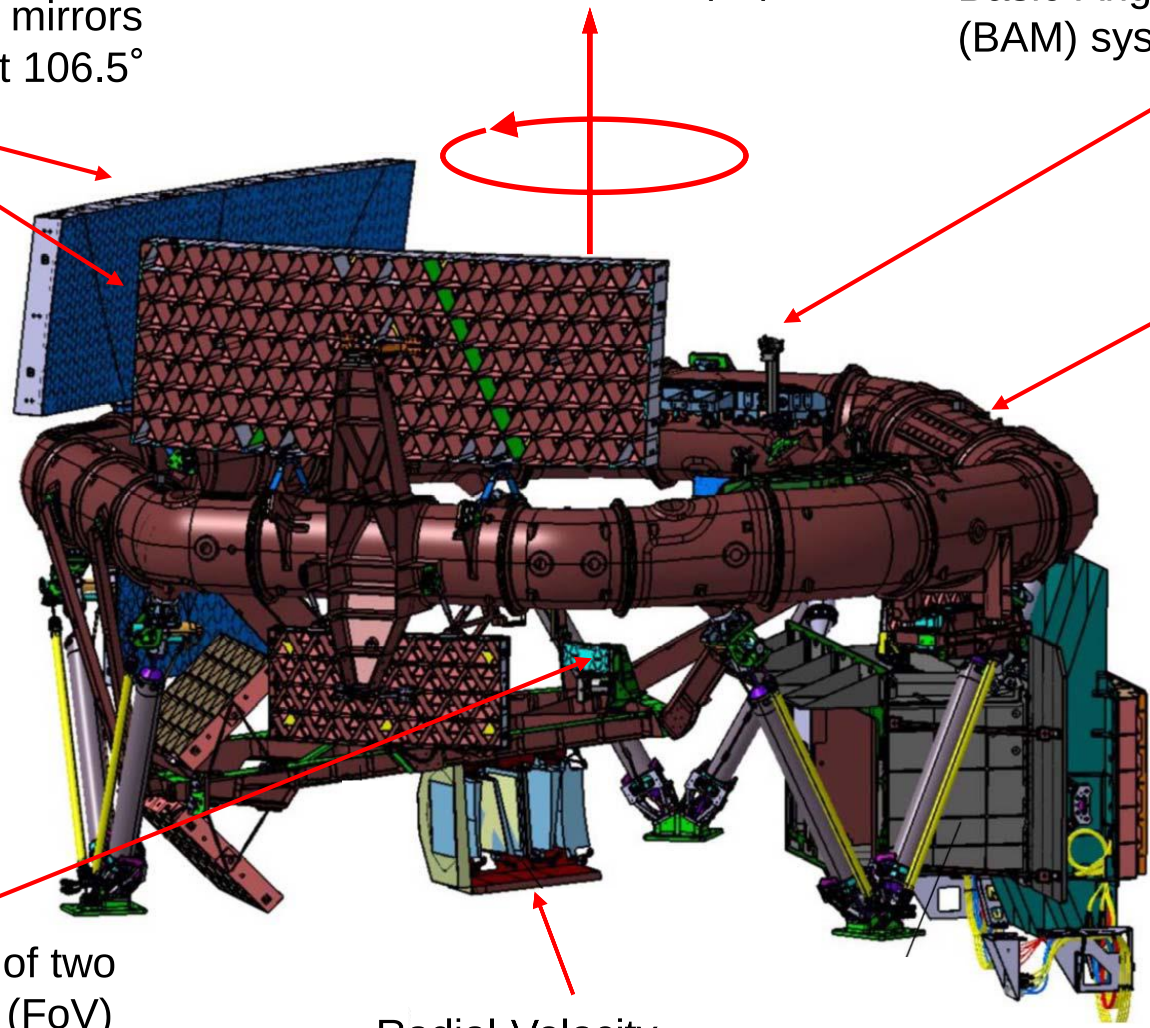
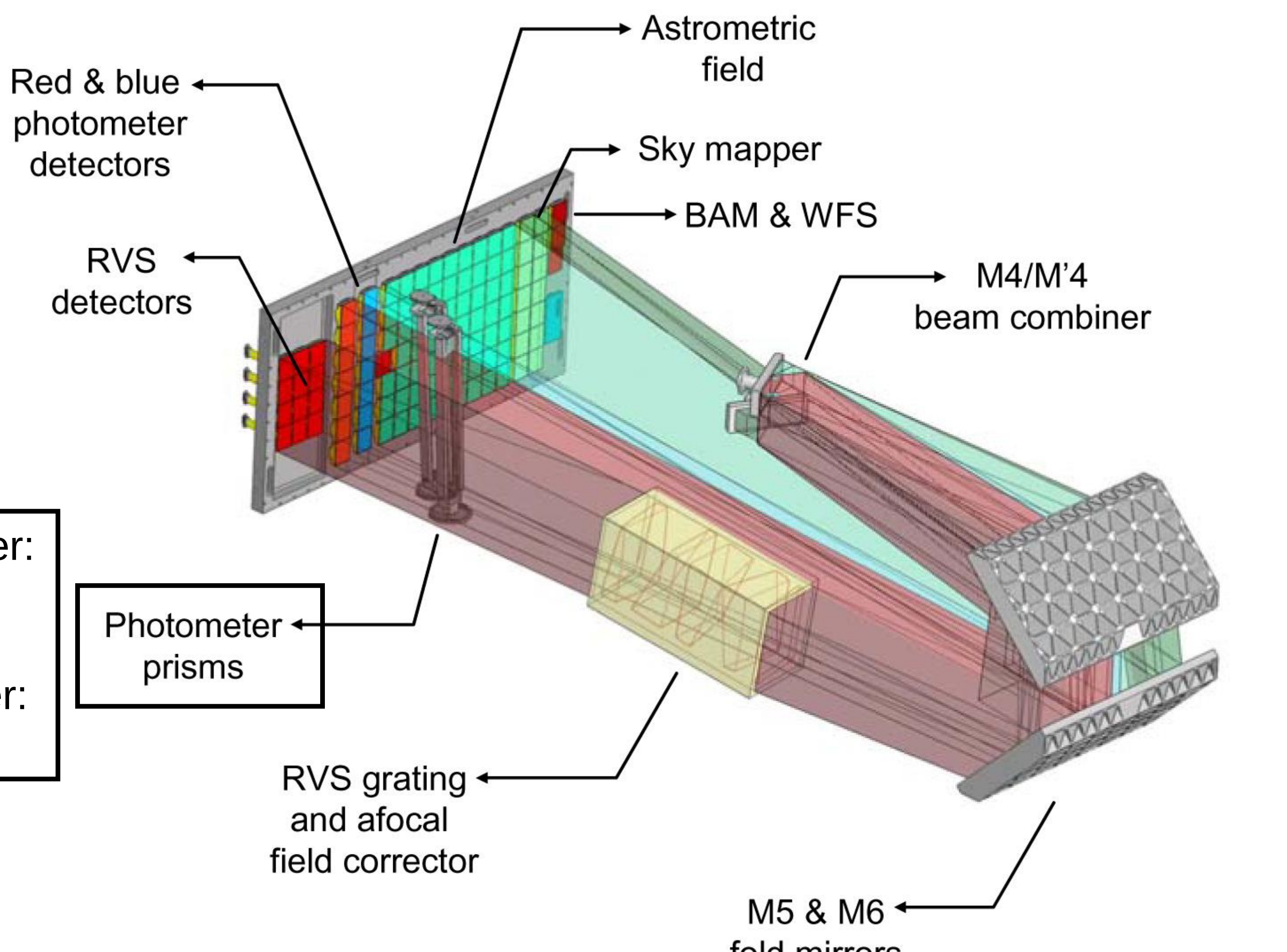


Figure courtesy EADS-Astrium

Inside Gaia



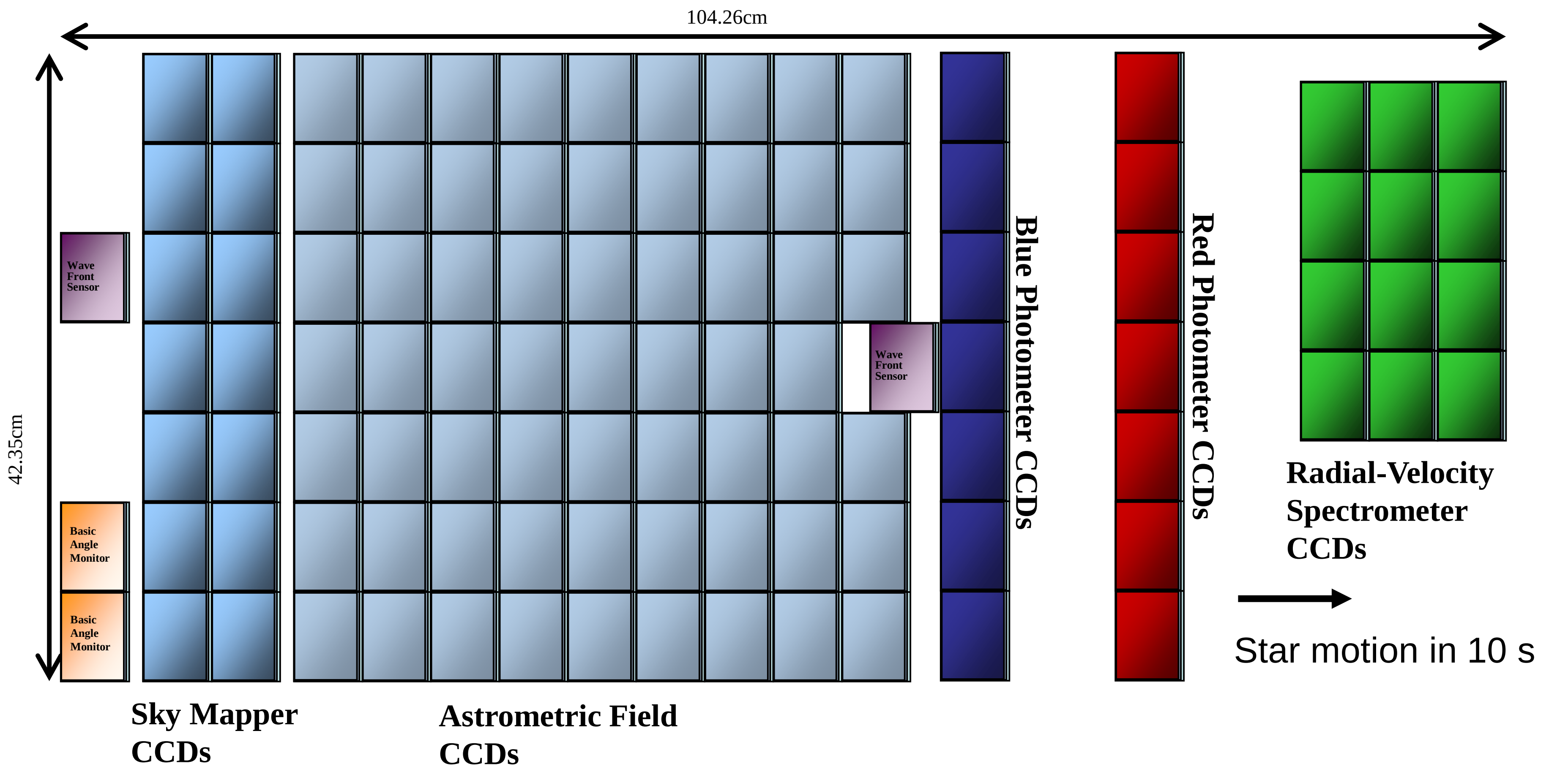
Blue photometer: 330 – 680 nm

Red photometer: 640 – 1050 nm

Figure courtesy EADS-Astrium

Figure courtesy Alex Short

Gaia focal plane



Total field:
- active area: 0.75 deg^2
- CCDs: 14 + 62 + 14 + 12 (+ 4)
- 4500 x 1966 pixels (TDI)
- pixel size = 10 µm × 30 µm = 59 mas × 177 mas

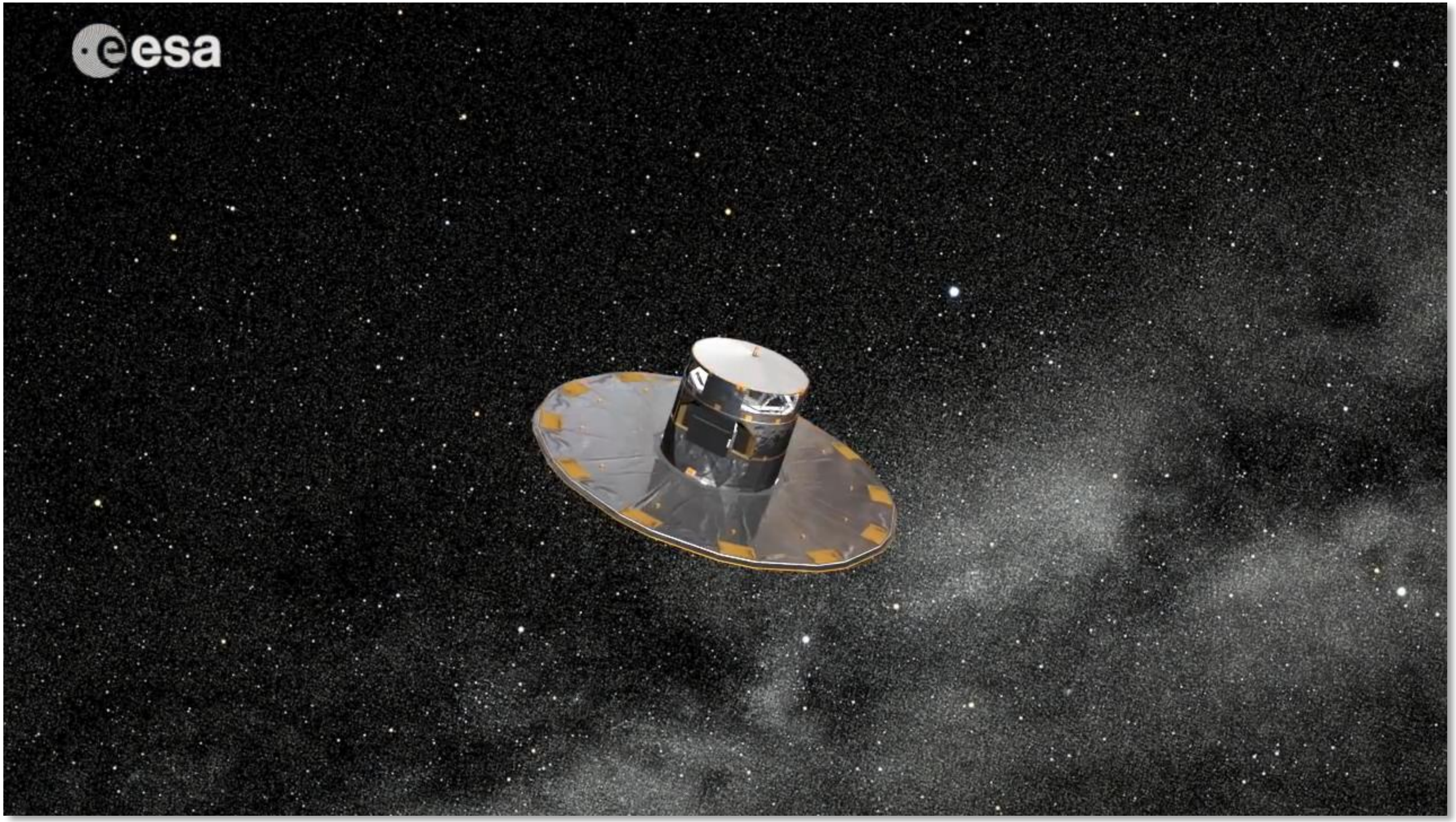
Sky mapper:
- detects all objects to G=20 mag
- rejects cosmic-ray events
- field-of-view discrimination

Astrometry:
- total detection noise ~4 e$^-$

Photometry:
- spectro-photometer
- blue and red CCDs

Spectroscopy:
- high-resolution spectra
- red CCDs

Gaia

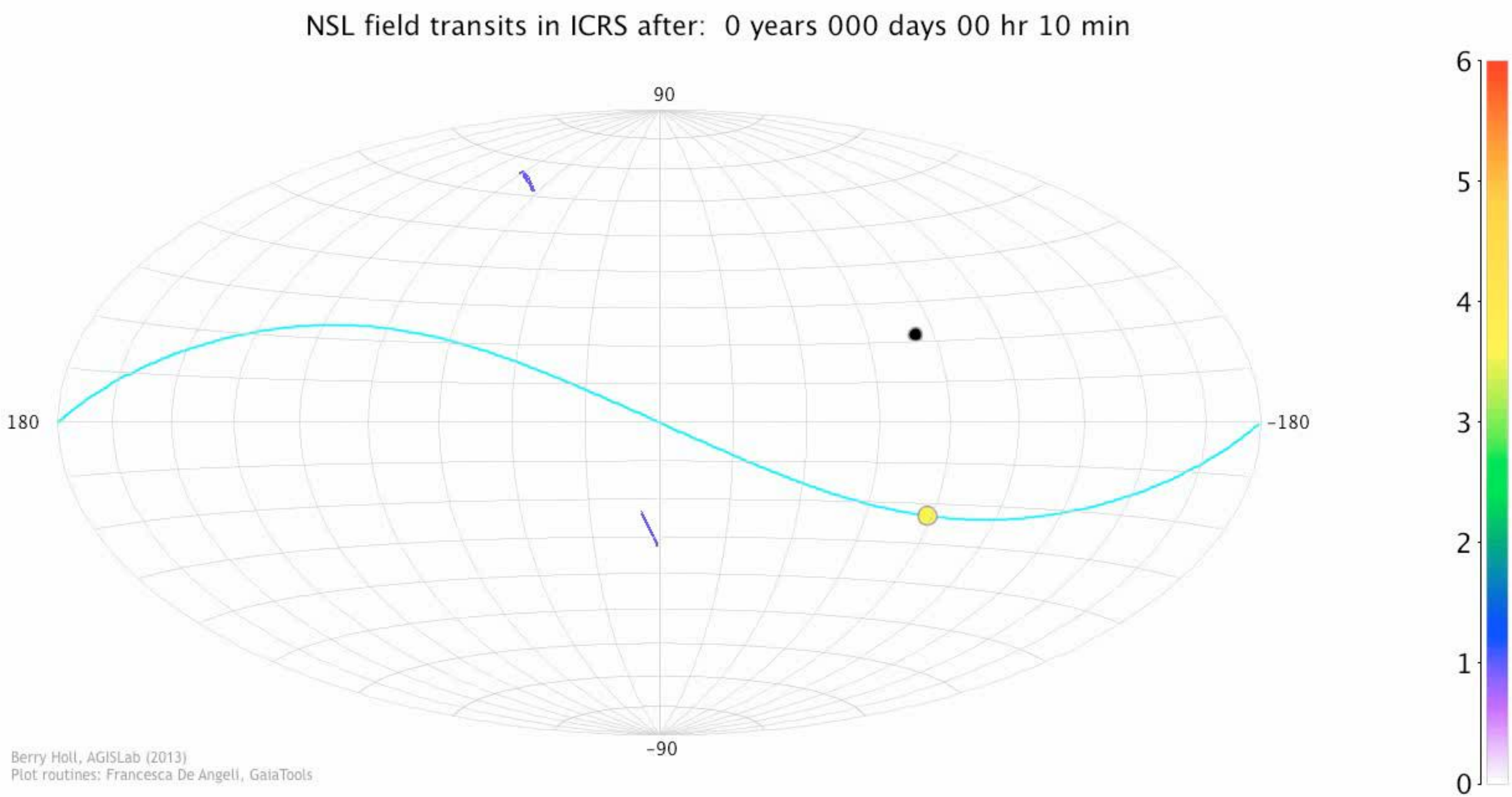


Credit: ESA

Gaia

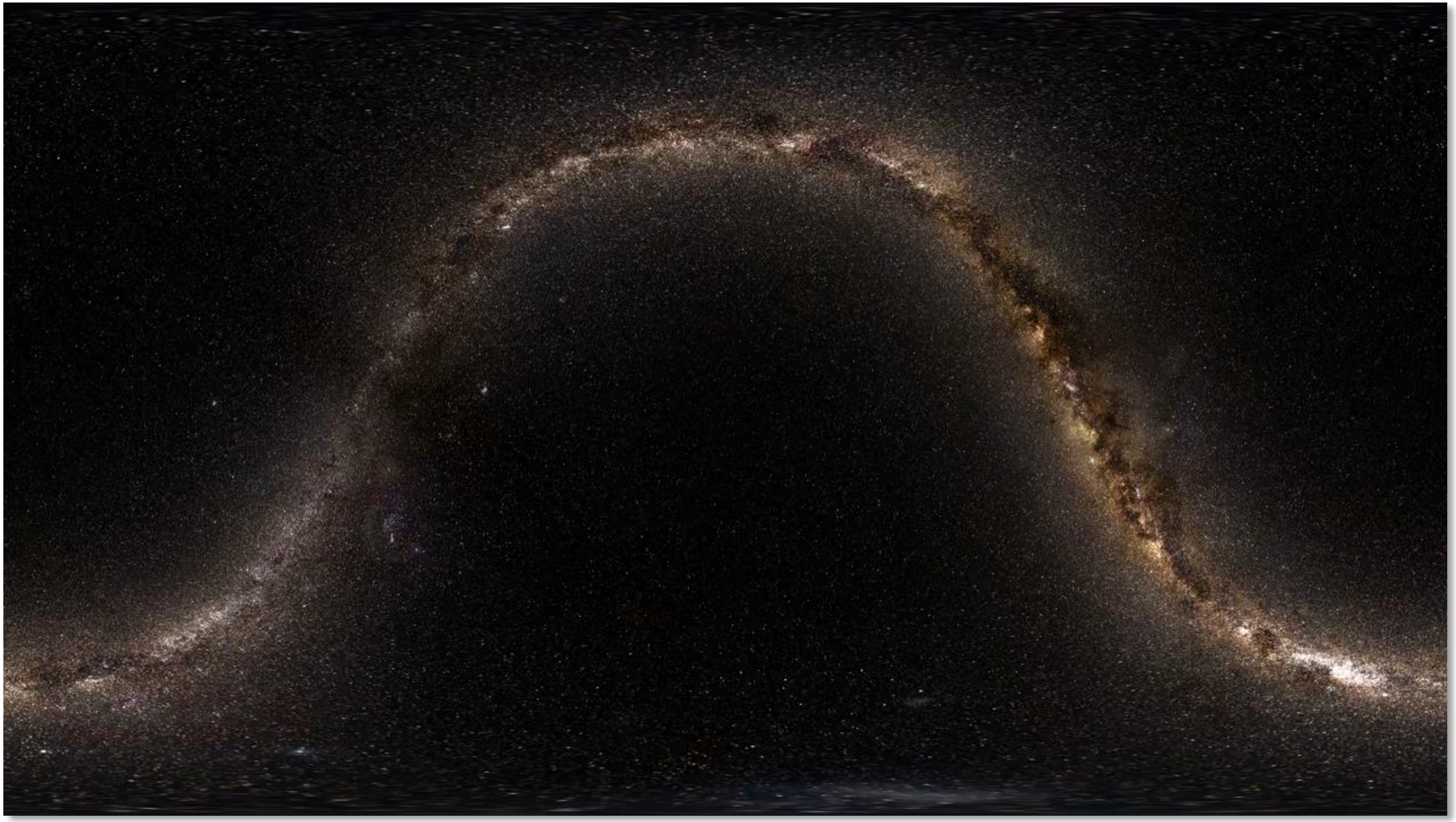
Credit: [ESA]

Gaia



NSL field transits in ICRS after: 0 years 000 days 00 hr 10 min
90
180
-180
-90
Berry Holl, AGISLab (2013)
Plot routines: Francesca De Angeli, GaiaTools
6
5
4
3
2
1
0

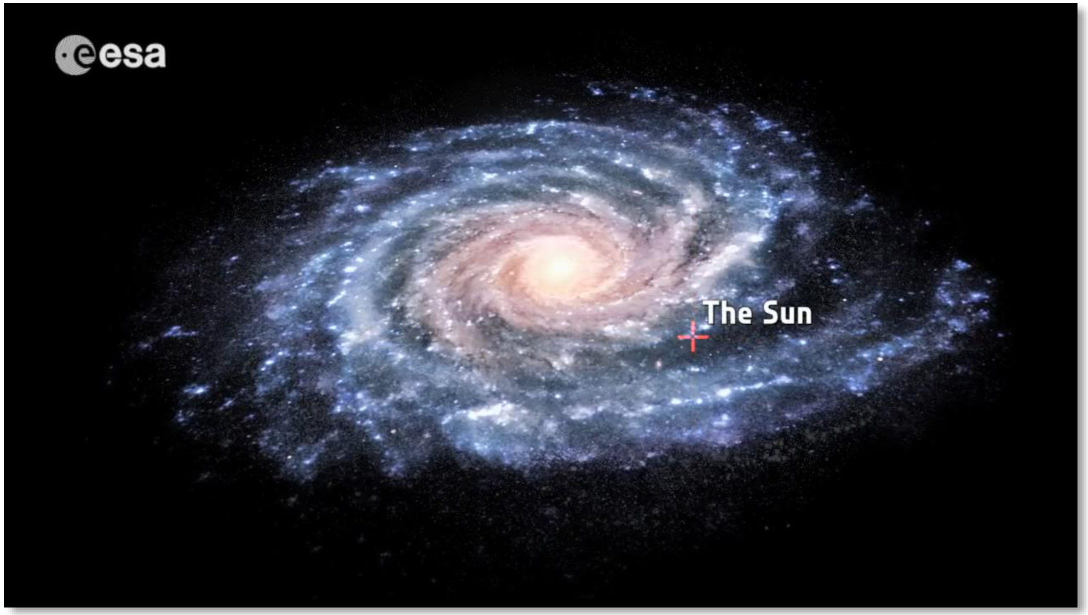
Gaia: Parallax and proper motion



Credit: ESA

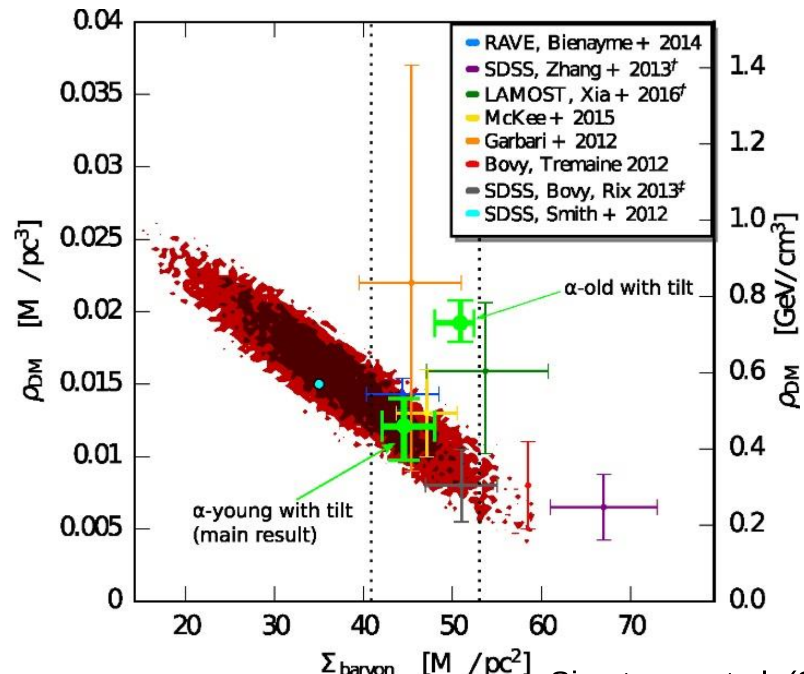
Gaia: 10^9 stars in 6D

- Will provide in our Galaxy:
  - Distance and velocity distributions of all stellar populations
  - Spatial and dynamical structure of the disk and halo
  - Formation history
  - Detailed mapping of the Galactic Dark Matter distribution
    - Extent and shape of the halo
    - $\rho_{DM}(r)$
    - Towards full 6D distribution function of DM

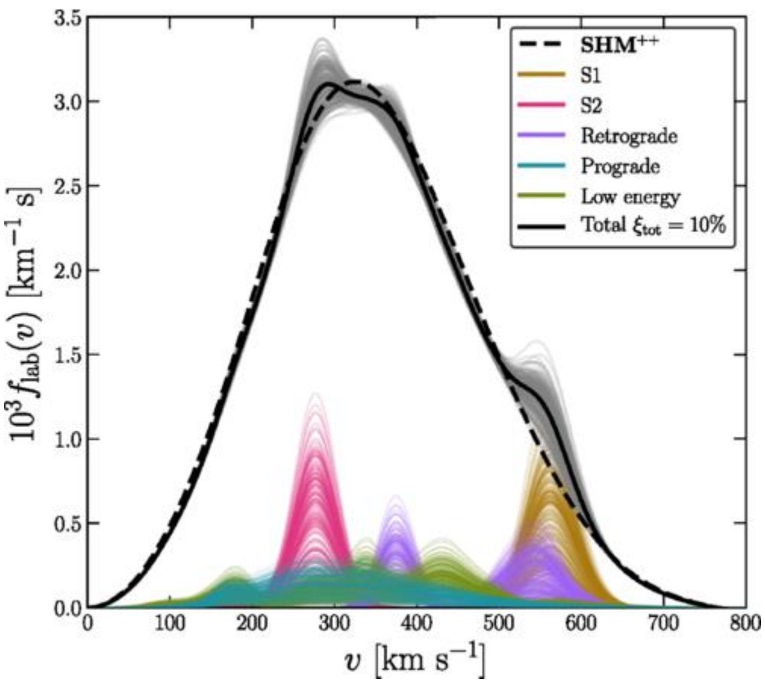


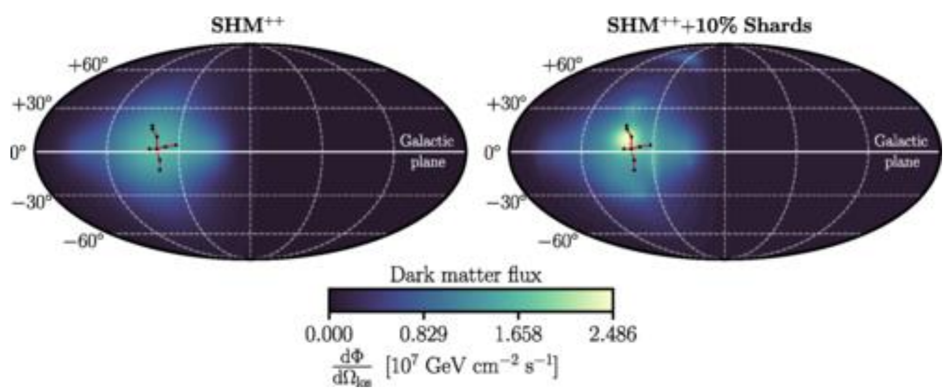
Gaia: early results

- Density and velocity distribution of DM at the Sun's location in the MW
- Essential for the interpretation of DM direct detection experiments
  - DM flux distribution on sky



Sivertsson et al. (2018)

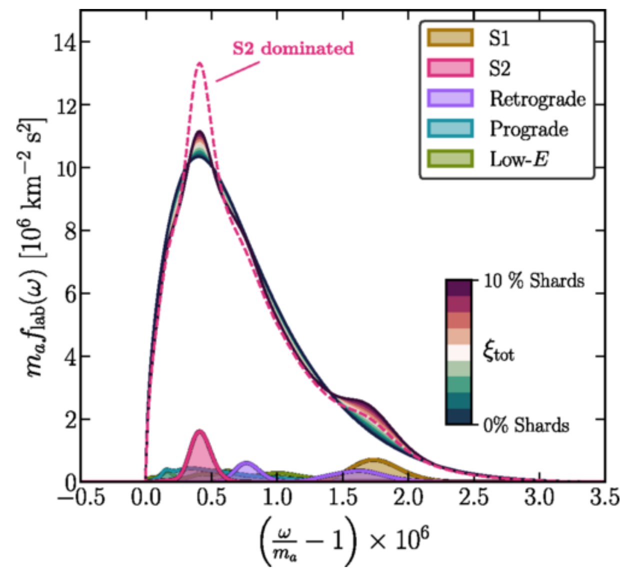


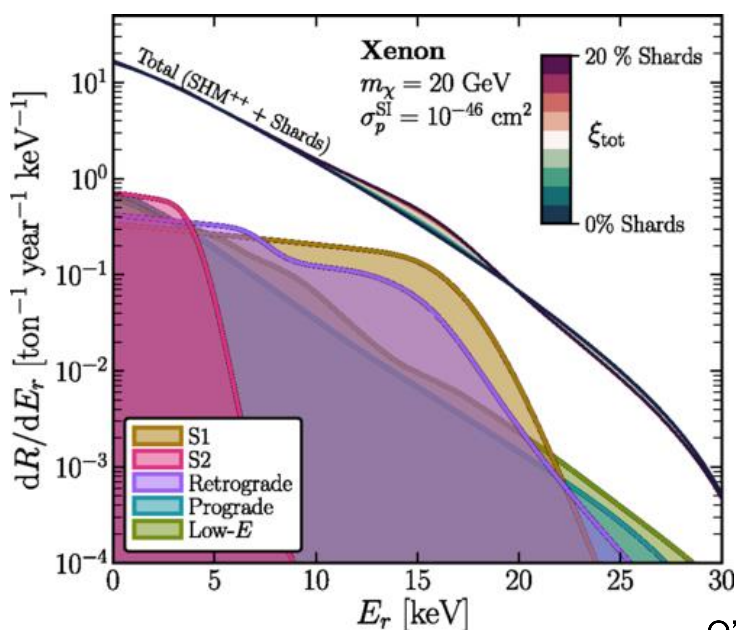


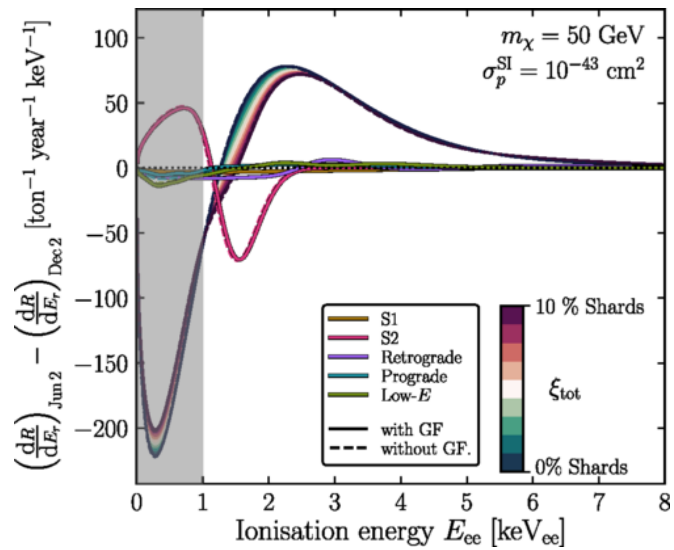
O'Hare et al. (2020)

Gaia: early results

- Density and velocity distribution of DM at the Sun's location in the MW
- Essential for the interpretation of DM direct detection experiments
  - DM flux distribution on sky
  - Spectral line shape in axion haloscope
  - WIMP interaction event rates



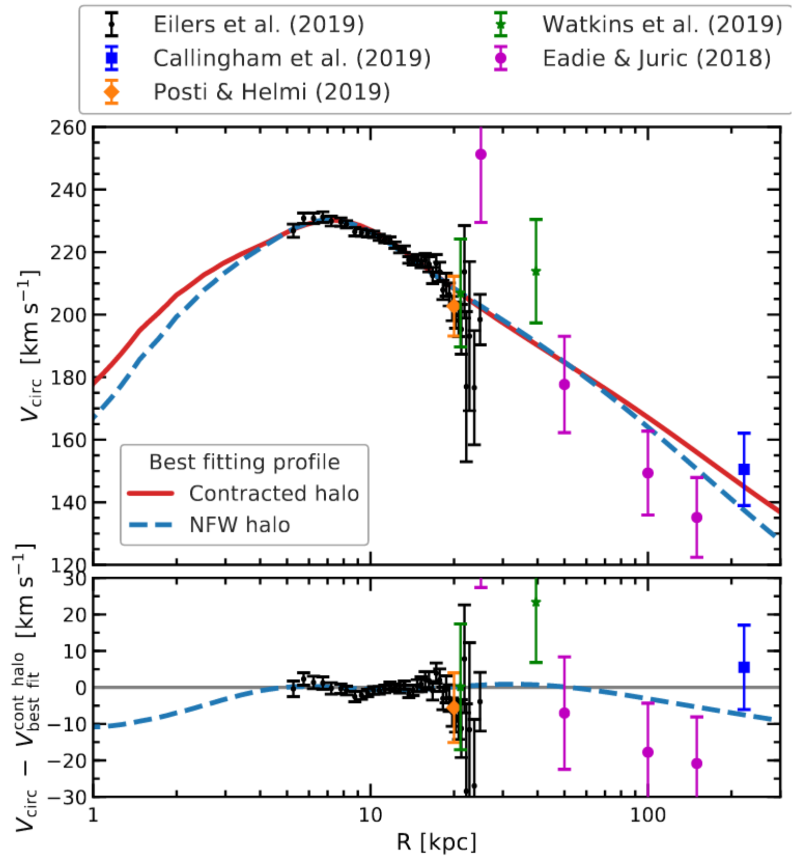




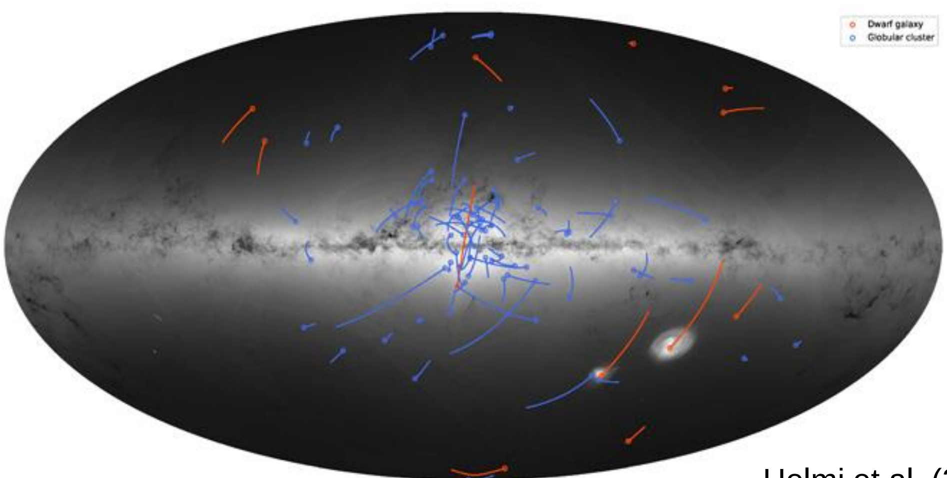
O'Hare et al. (2020)

Gaia: early results

- Rotation curve → mass profile and total mass of the MW
  - Stars
  - Stellar streams
  - Globular cluster
  - MW dwarf satellites (Which are bound to MW? Orbits? Effect of LMC?)
  - $M_{tot} = 1.1 \times 10^{12}\ M_{\odot}$



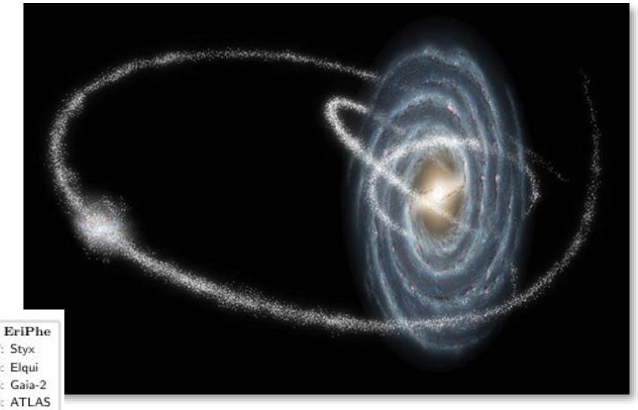
Cautun et al. (2020)

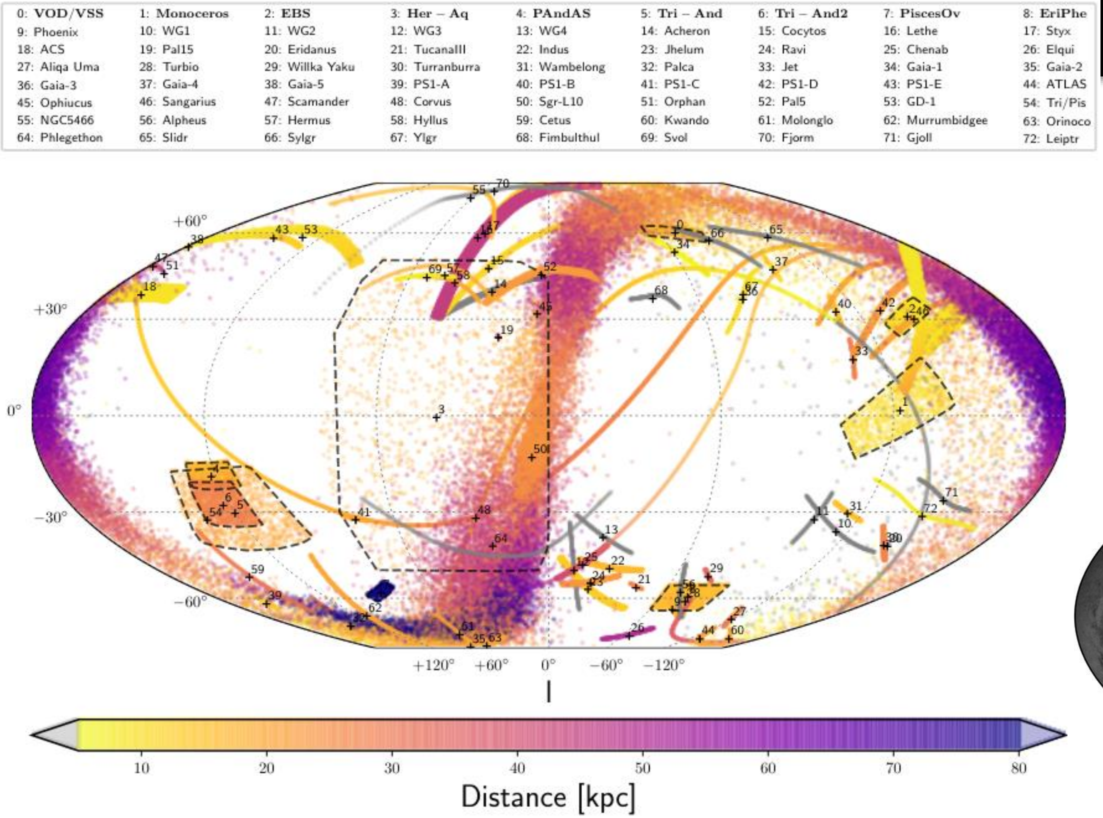


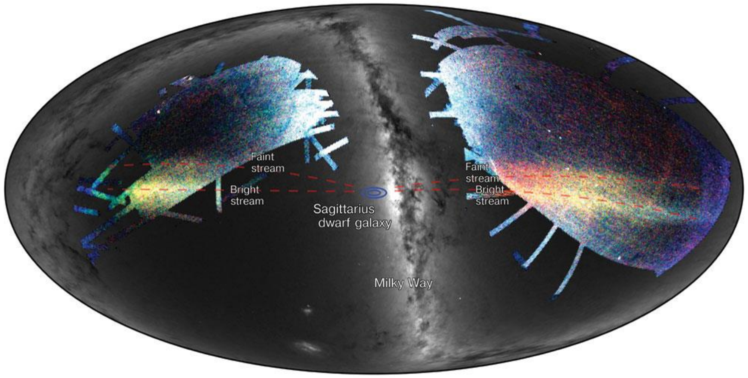
Helmi et al. (2018), Maarten Breddels

Gaia: early results

- DM substructure from
  - Substructure in stellar streams





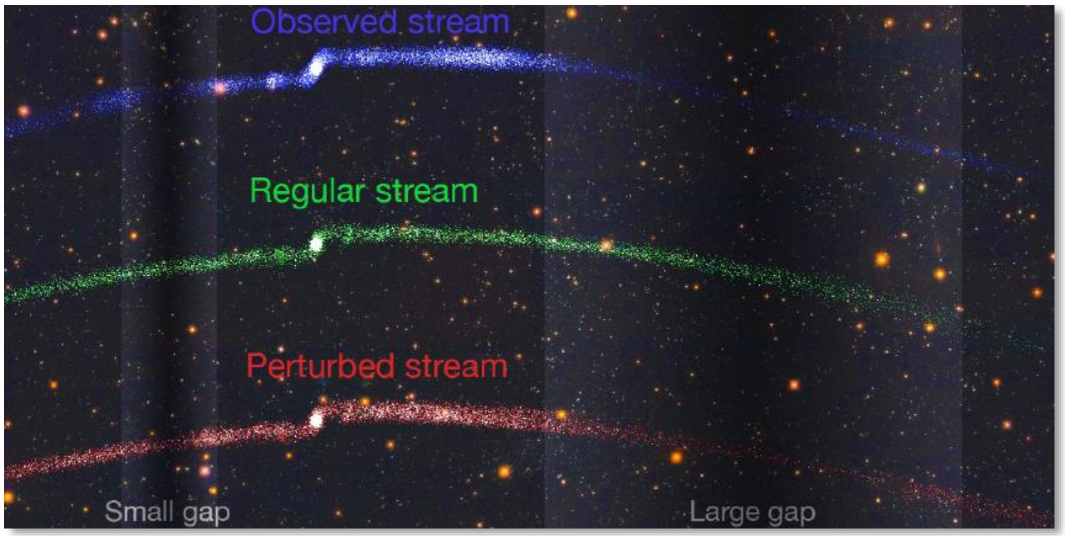


Helmi et al. (2020)

SDSS / Koposov et al. (2017)

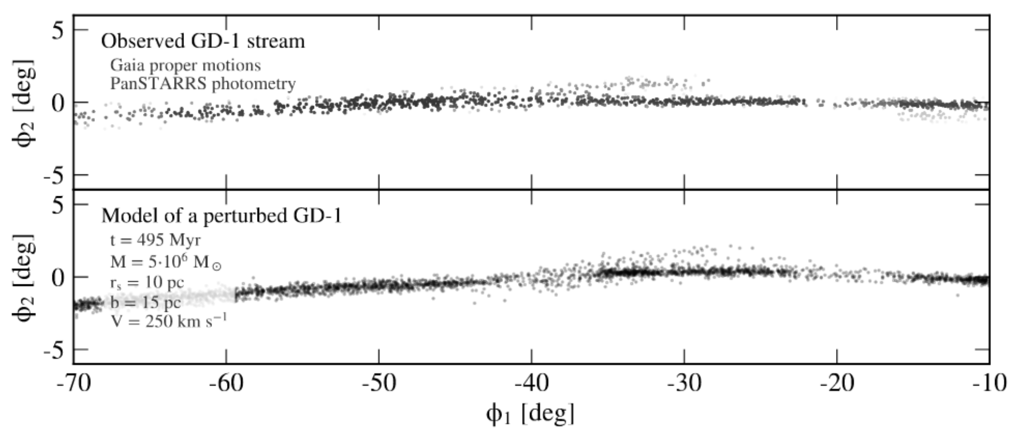
Gaia: early results

- DM substructure from
  - Substructure in stellar streams



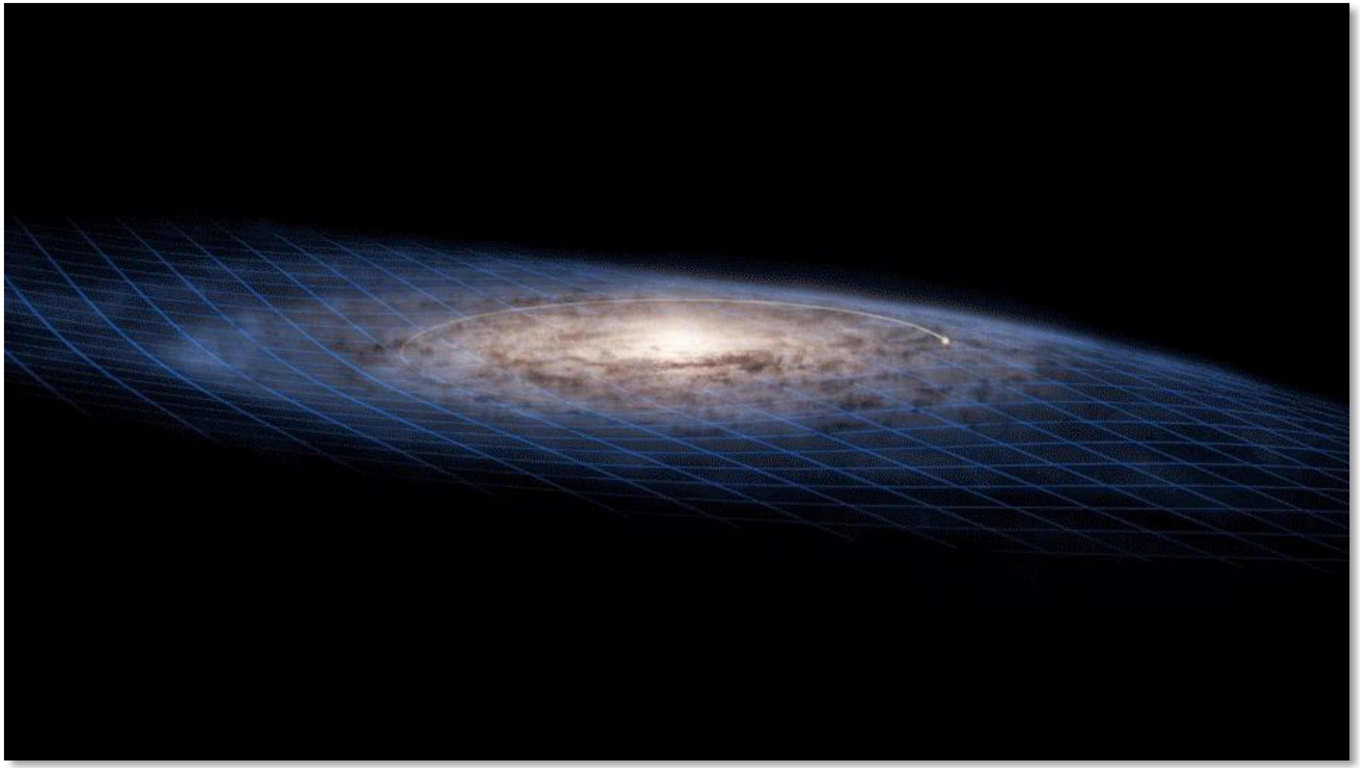
Erkal et al. (2017)

Bonaca et al. (2019)



Gaia: early results

- DM substructure from
  - Substructure in stellar streams
  - Warp and ripples in disk



Poggio et al. (2020), S. Payne-Wardenaar

Questions?

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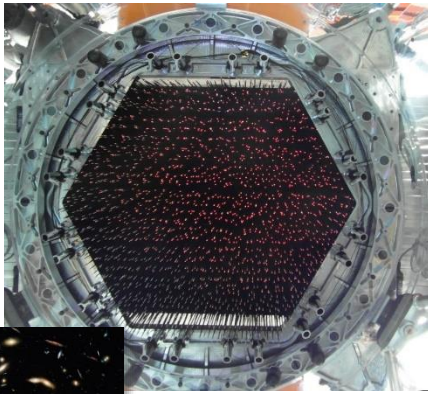
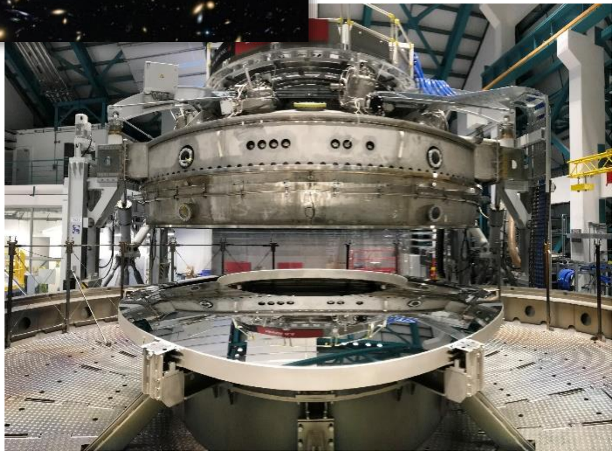
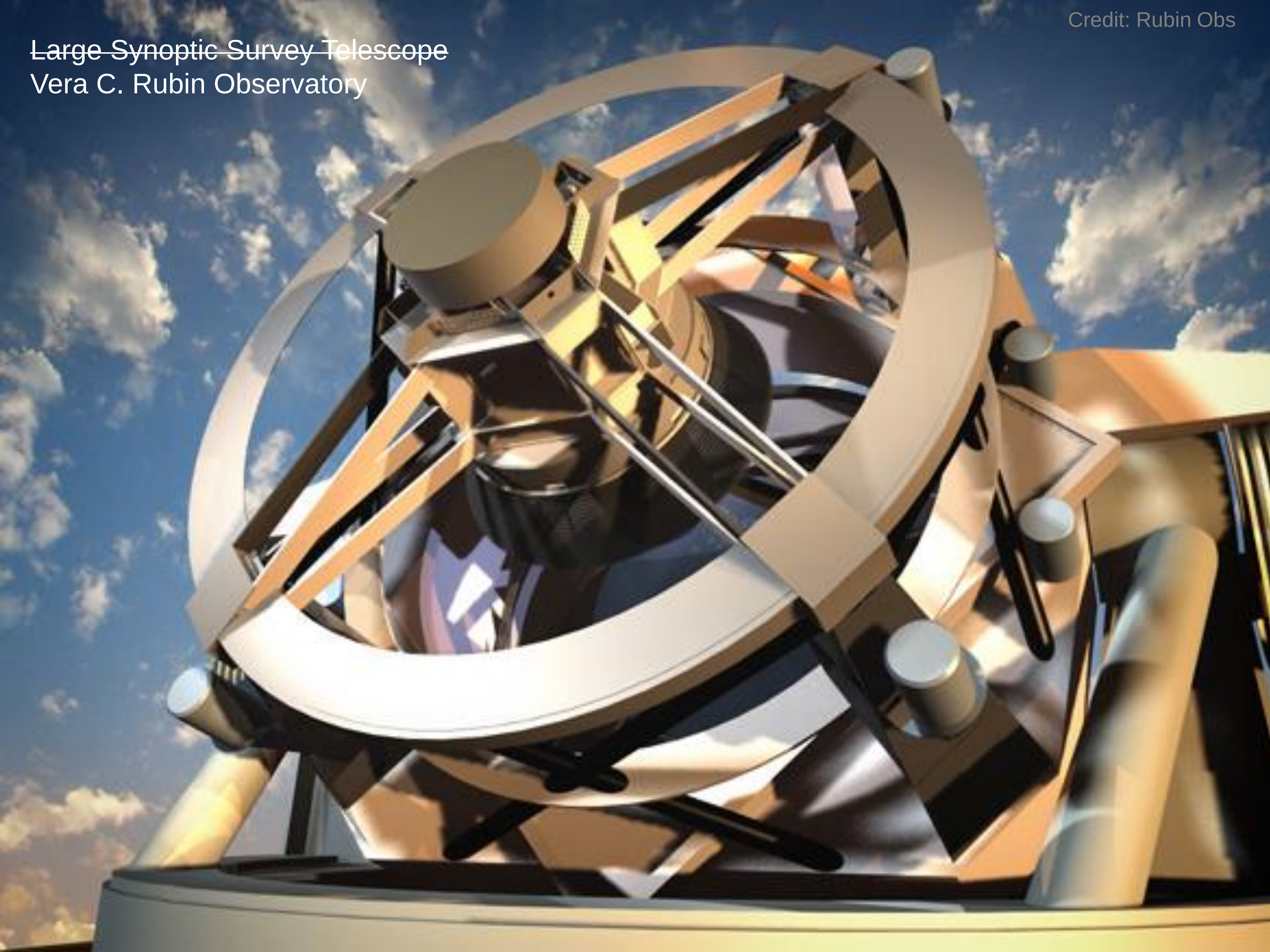




~~Large Synoptic Survey Telescope~~
Vera C. Rubin Observatory

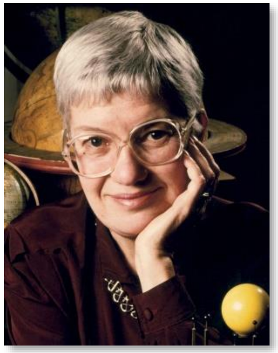


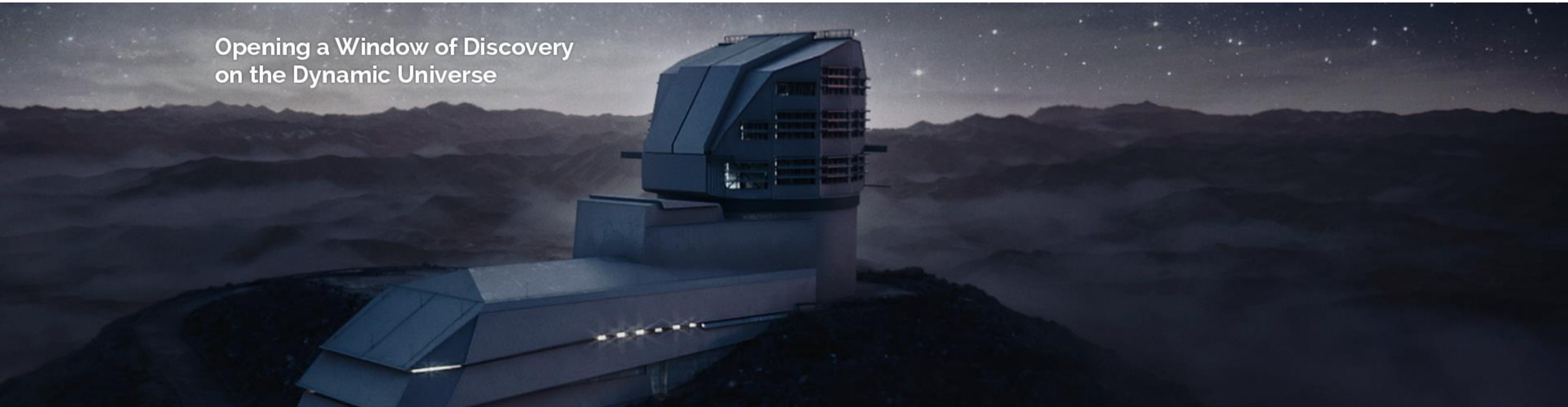
Credit: Rubin Obs

LSST

- The Vera C. Rubin Observatory will deliver the Legacy Survey of Space and Time (LSST)
- LSST = An optical/near-IR survey of half the sky in ugrizy bands to r $\approx$ 27.5 mag based on ~1000 visits over a 10-year period
- 90% of time will be spent on a uniform survey: every 3-4 nights, the whole observable sky will be scanned twice per night
- A catalogue of 20 billion stars and 20 billion galaxies with exquisite photometry, astrometry and image quality!
- ~1 billion 16 Mpix images → ~100 PB of data
- Digital colour movie of the Universe

VERA C. RUBIN
OBSERVATORY





Telescope System:

- Etendue (AΩ) : 319 meter²degrees²
- Field of View : 3.5 degrees (9.6 square degrees)
- Primary mirror diameter : 8.4 m
- Mean effective aperture : 6.423 m (area weighted over FOV)
- Final f-ratio : f/1.234
- Camera weight : 6,746 lbs (3,060 kg)
- Mirror (M1+M3 glass mirror only) weight : 35,900 pounds (16,284 kg)

Imaging System:

- Pixel count : 3.2 Gpixels
- Focal plane : 189 4kx4k science CCD chips
- Pixel pitch : 0.2 arcsec/pixel
- Pixel size : 10 microns
- Filling factor : >90%
- Minimum exposure time : 1 sec

Throughput:

- 5-sigma point source depth: Single exposure and idealized for stationary sources after 10 years,
  - u : 23.9, 26.1
  - g : 25.0, 27.4
  - r : 24.7, 27.5
  - i : 24.0 , 26.8
  - z : 23.3, 26.1
  - y : 22.1, 24.9

Start of ops: Oct 2022

(https://smtn-002.lsst.io : Calculating Rubin Observatory limiting magnitudes and SNR)

Site Stats:

- Median Atmospheric PSF with outer scale of 30m: 0.67" (Tokovinin)
- Site: El Penon, Cerro Pachon, Chile
- Site coordinates: latitude -30:14:40.68 longitude -70:44:57.90
- Altitude: 2647m
- Site observatory code: TBD
- Photometric time: 53% of night time (estimated)

Observation Properties:

- Standard visit exposures (expected) : 2 x 15 sec.
- Median (Mean) visit time : 39s (42.2s)
- Photometric accuracy : 10 mmag
- Astrometric accuracy : 50 mas
- Astrometric precision : 10 mas

Dataset properties:

- Nightly data size: 20TB/night
- Final database size (DR11) : 15 PB
- Real-time alert latency : 60 seconds

Data Releases:

- Survey duration : 10 years
- Number of Data Releases : 11
- Number of objects (full survey, DR11):
  - 20B galaxies
  - 17B resolved stars
  - 6M orbits of solar system bodies
  - Average number of alerts per night: about 10 million

Credit: Rubin Obs

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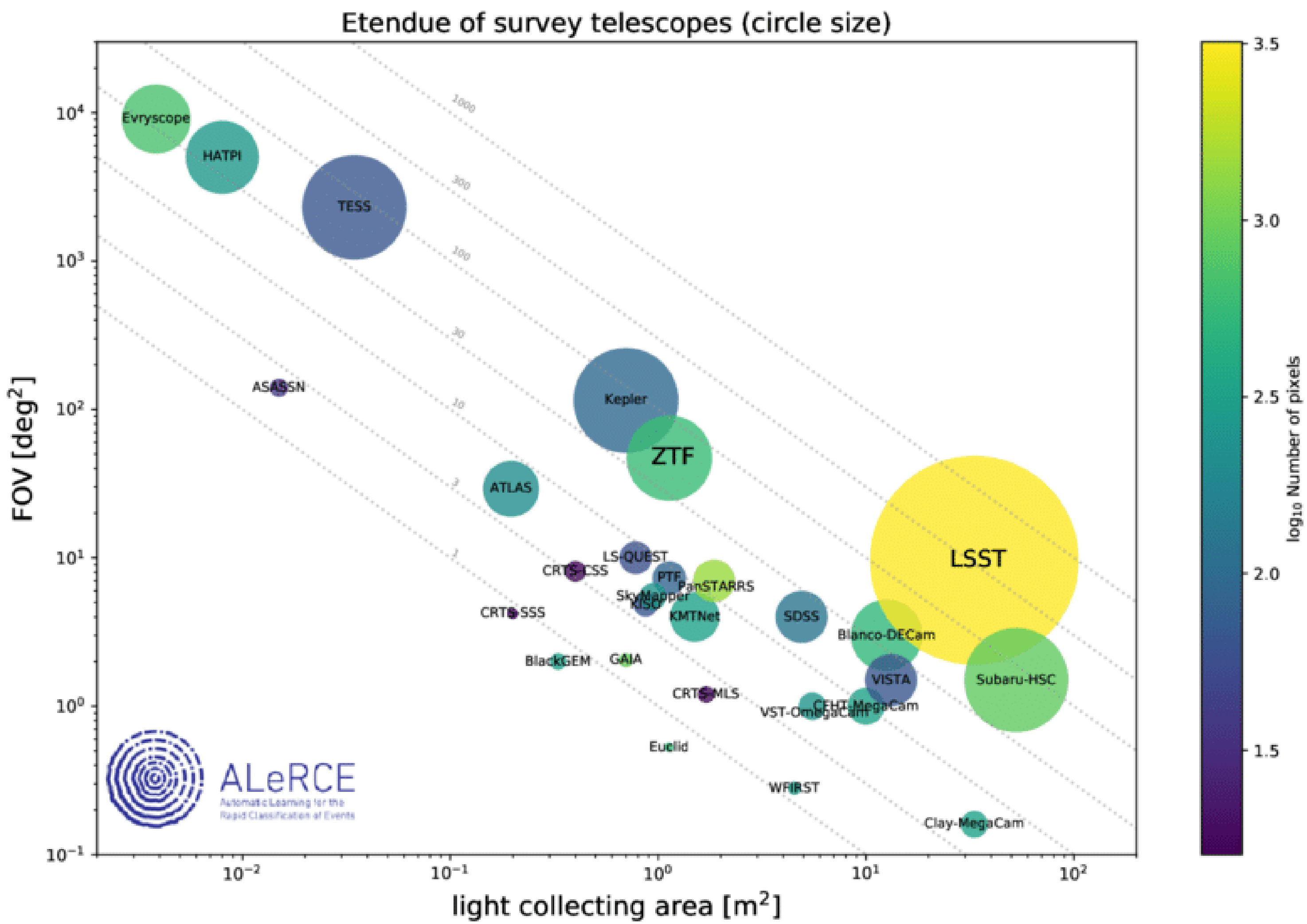
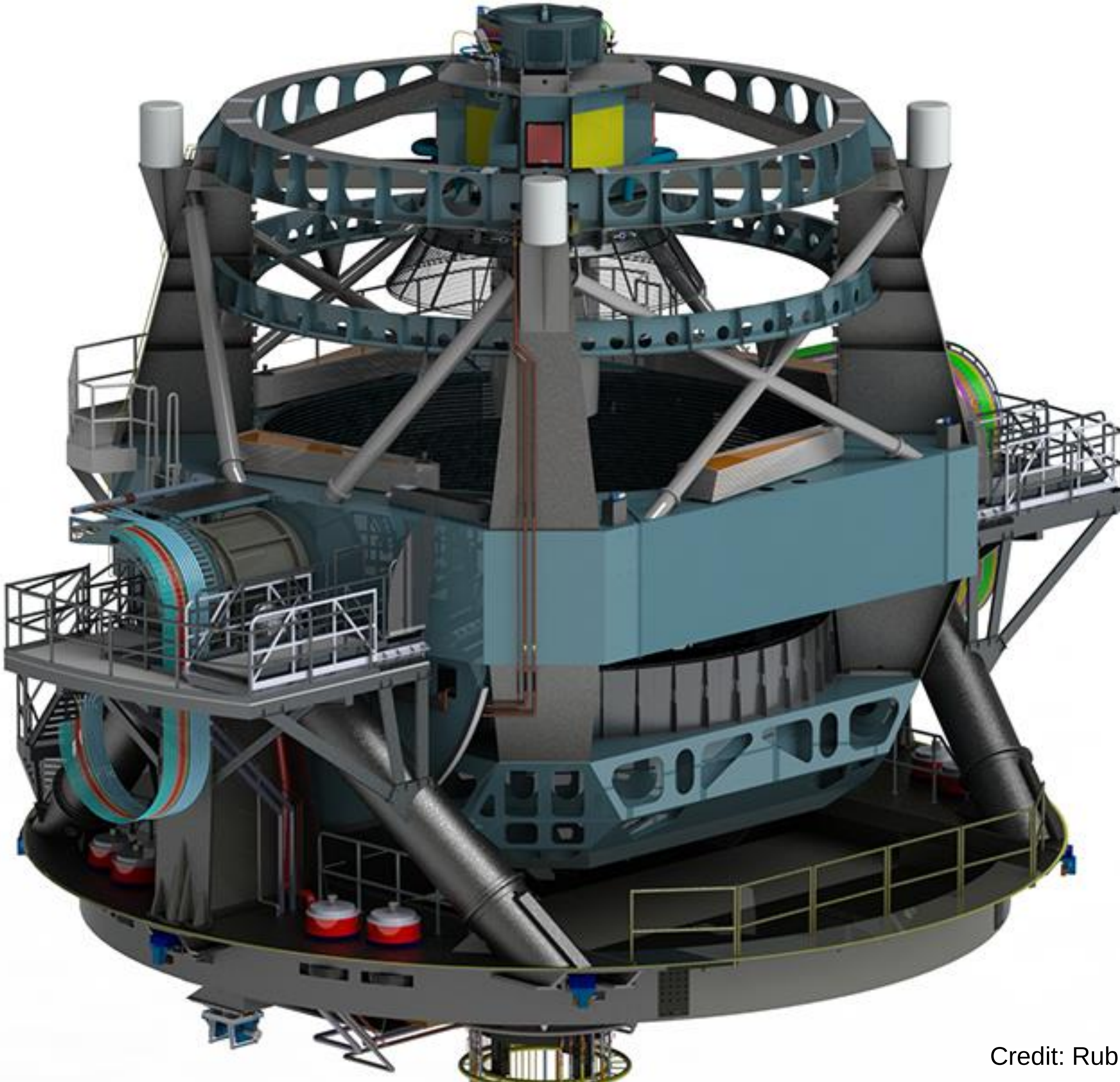


Förster et al. (2020)



Credit: Rubin Obs

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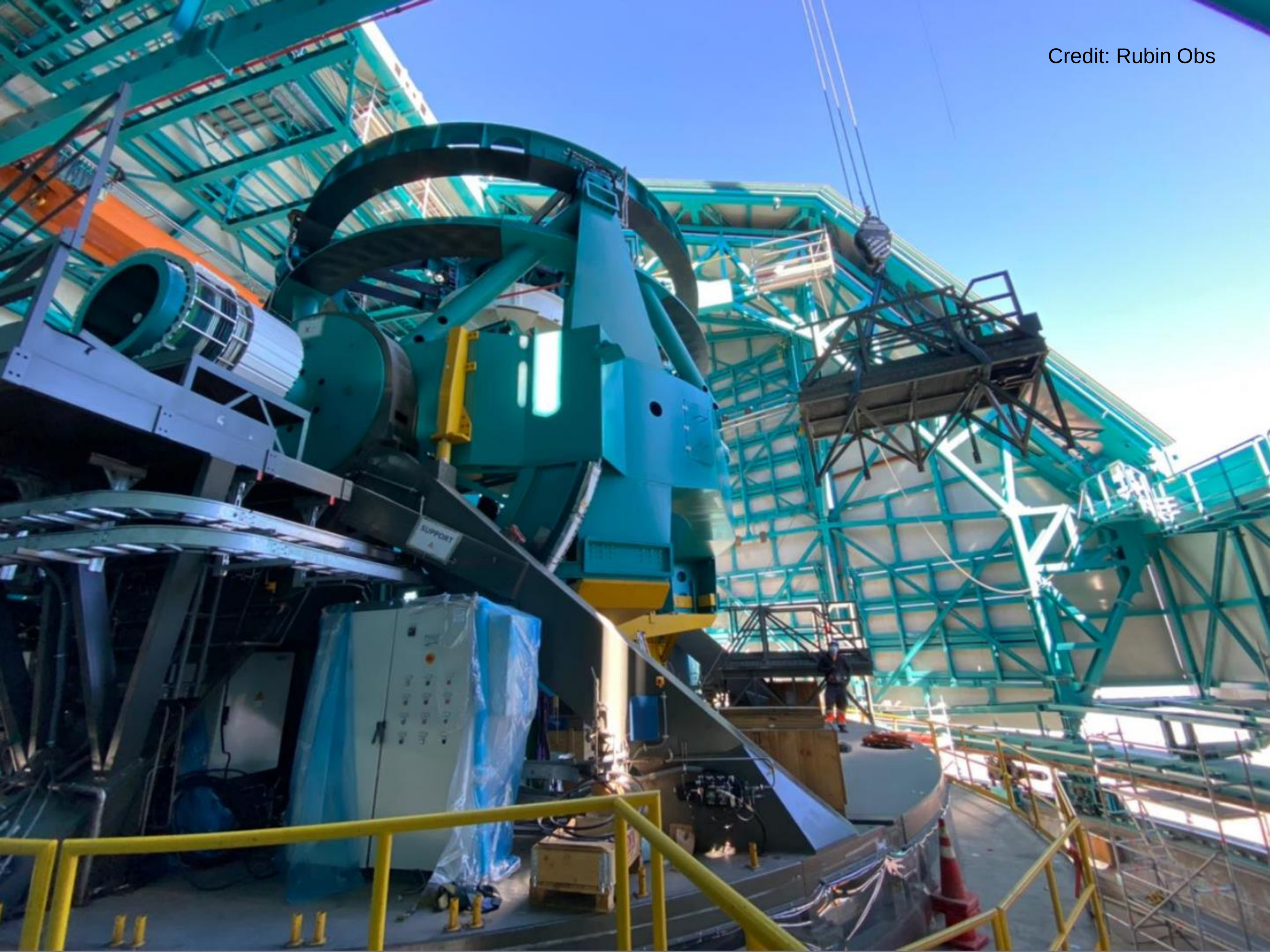
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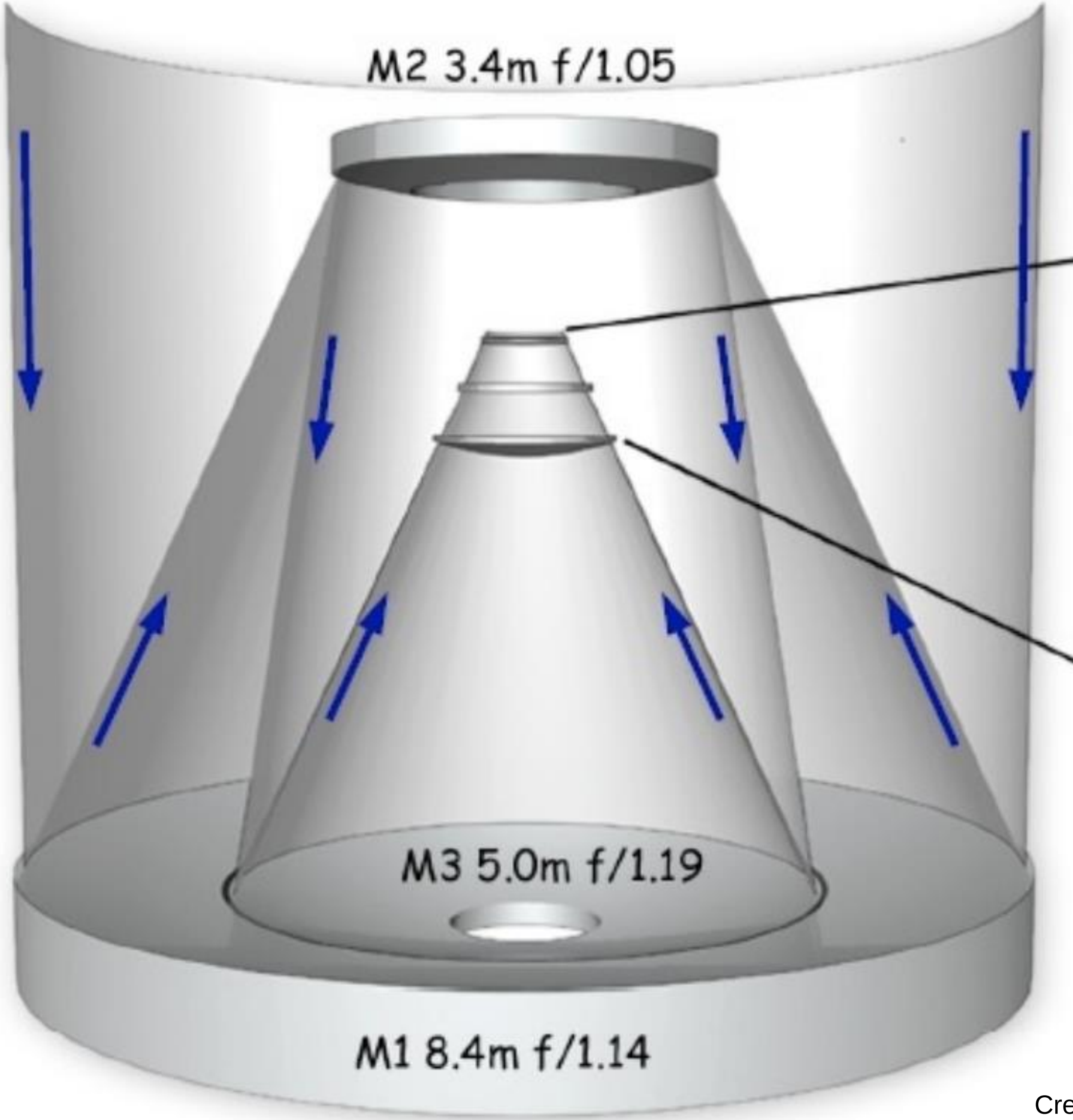

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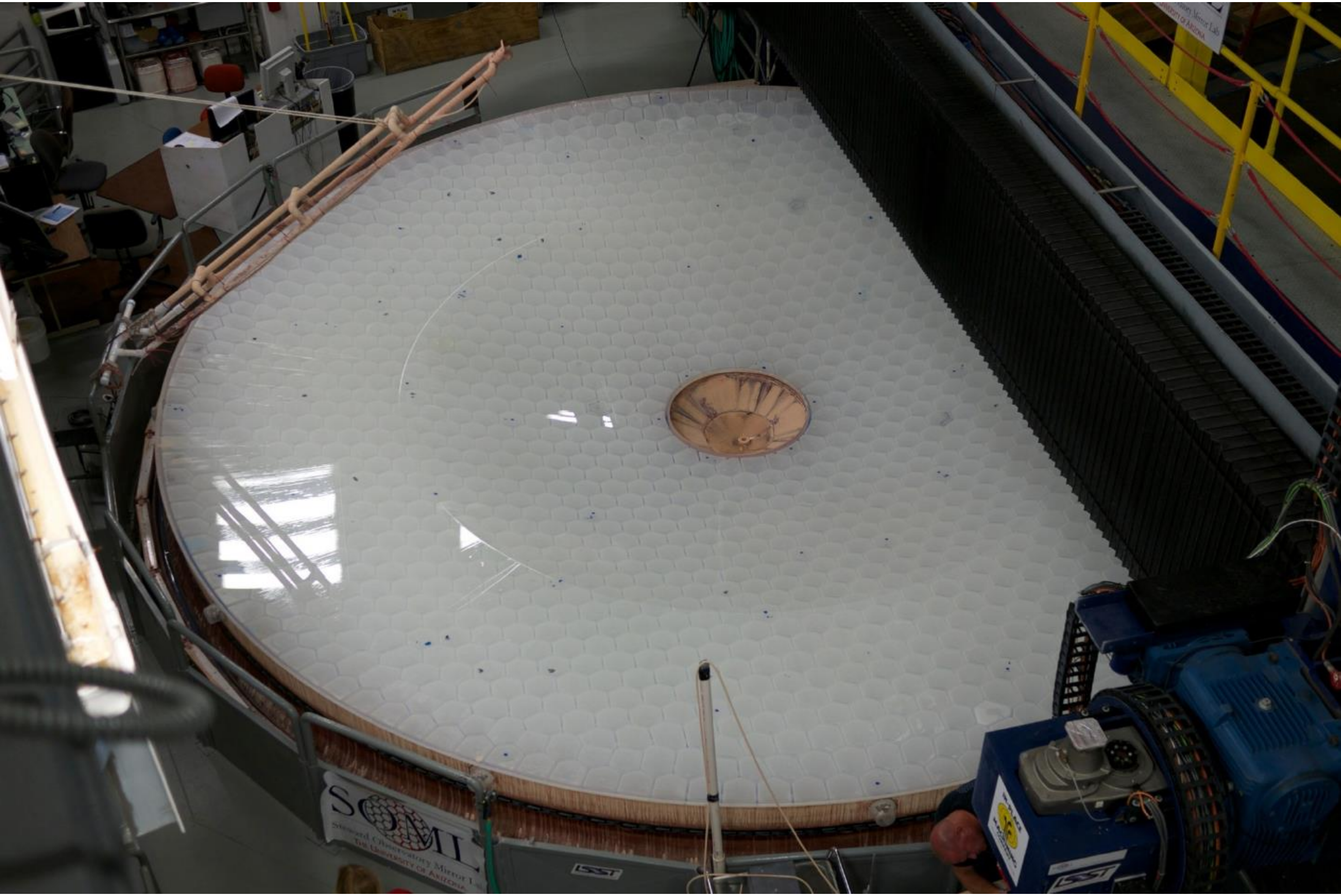

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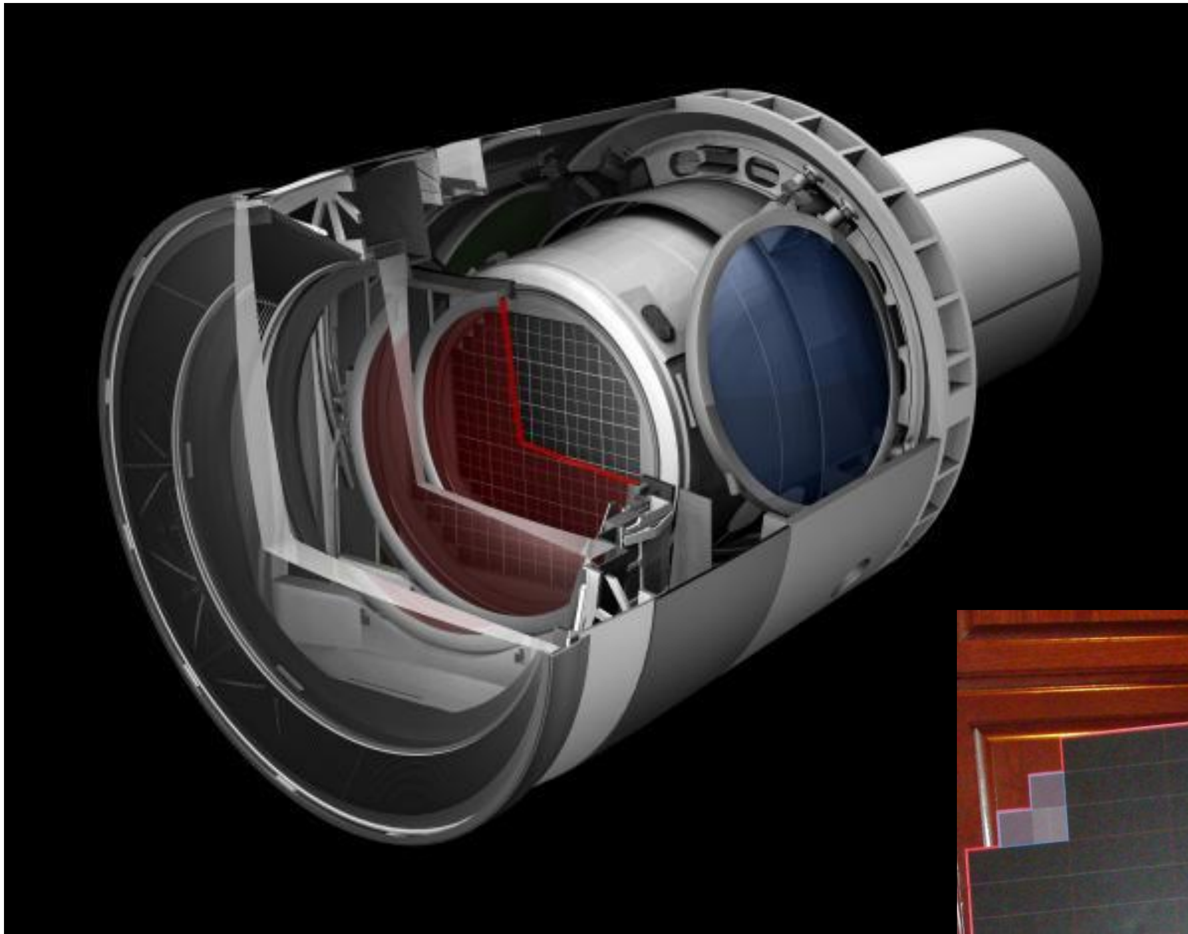
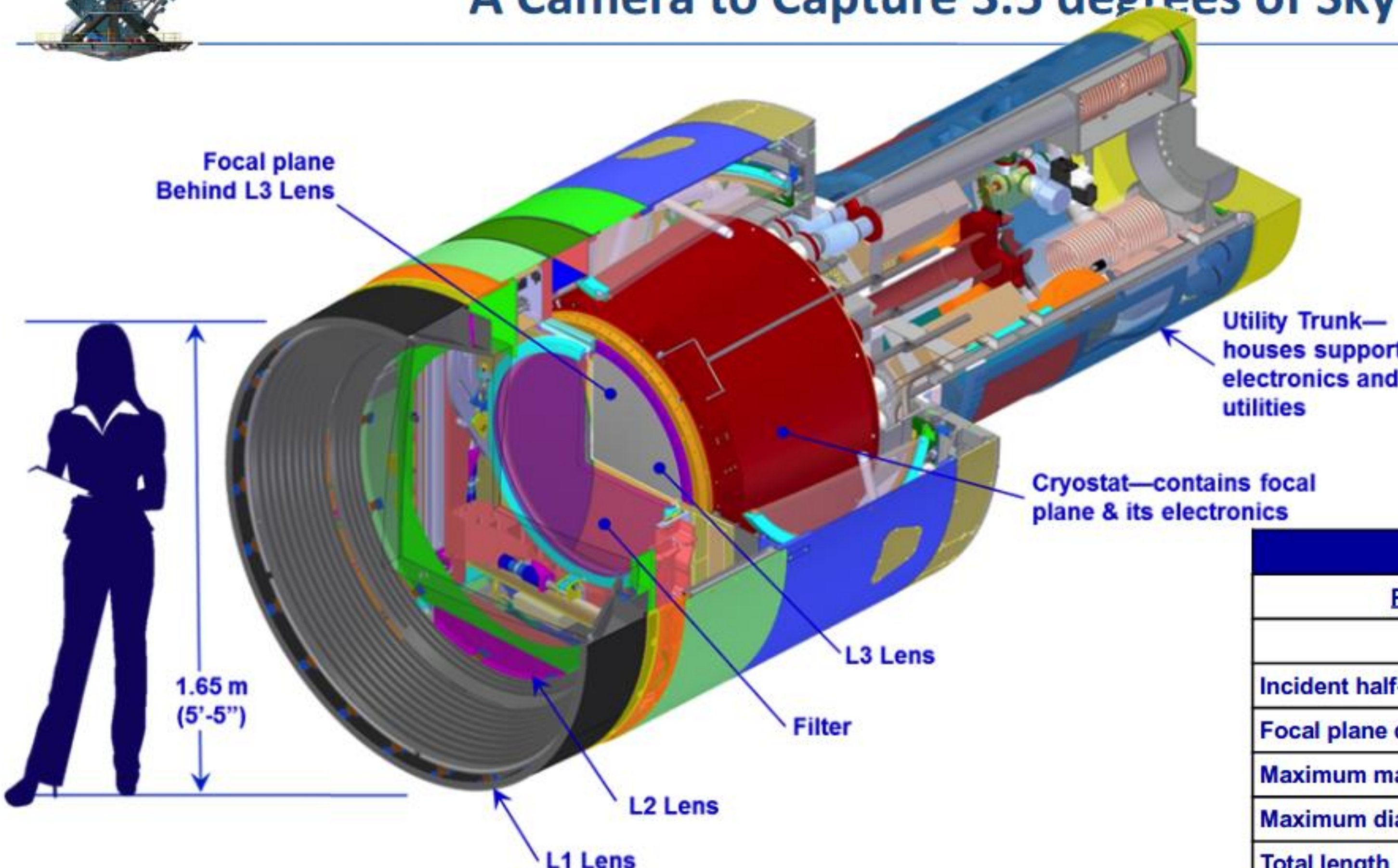


Credit: Rubin Obs

A Camera to Capture 3.5 degrees of Sky

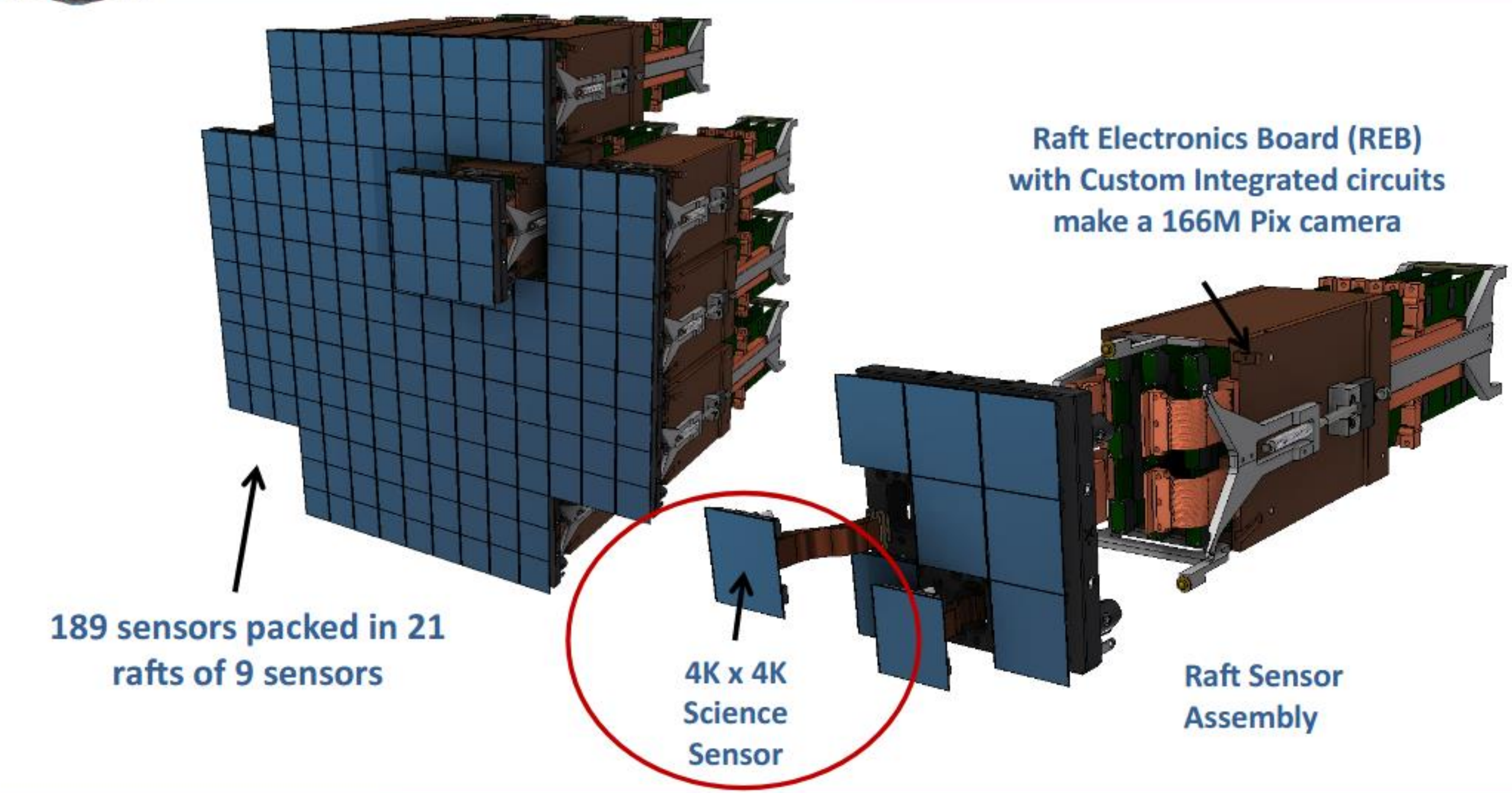


Camera ¾ Section

Camera Parameters	
Property	Value
	15 years
Incident half-angle in air	14.2°-23.6°
Focal plane diameter	634 mm
Maximum mass	3060 kg
Maximum diameter	1650 mm
Total length	3732 mm

Credit: Rubin Obs

63 CM Diameter Focal Plane with 3.2 GigaPixels



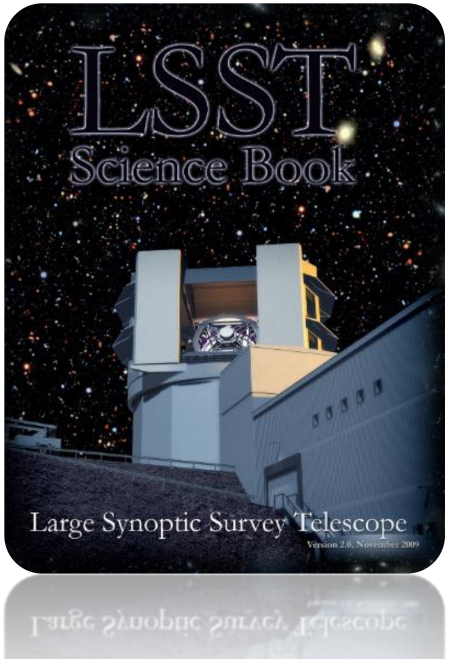
Credit: Rubin Obs

Credit: Rubin Obs

Legacy Survey of Space and Time (LSST)

- Covers over half of the entire sky
- Six photometric bands
- Each visit: 2 × 15 s exposure
- ~1000 visits of every patch of sky
  - Colour movie of the Universe
  - Enormous depth when stacked
- Exact cadence still being worked out
- Deep Drill Fields

- Headline science goals:
  - Probing dark energy and dark matter
  - Taking an inventory of the solar system
  - Exploring the transient optical sky
  - Mapping the Milky Way



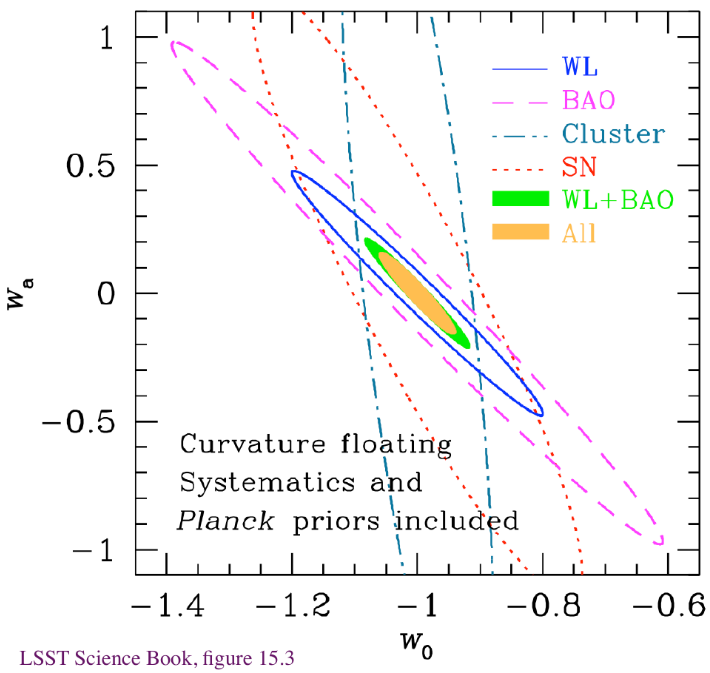
arXiv:0912.0201

LSST and dark energy

How will LSST constrain dark energy?

- Cosmic shear (growth of structure + cosmic geometry)
- Counts of massive structures vs redshift (growth of structure)
- Baryon acoustic oscillations (angular diameter distance)
- Measurements of type Ia SNe (luminosity distance)
- Mass power spectrum on very large scales tests CDM paradigm

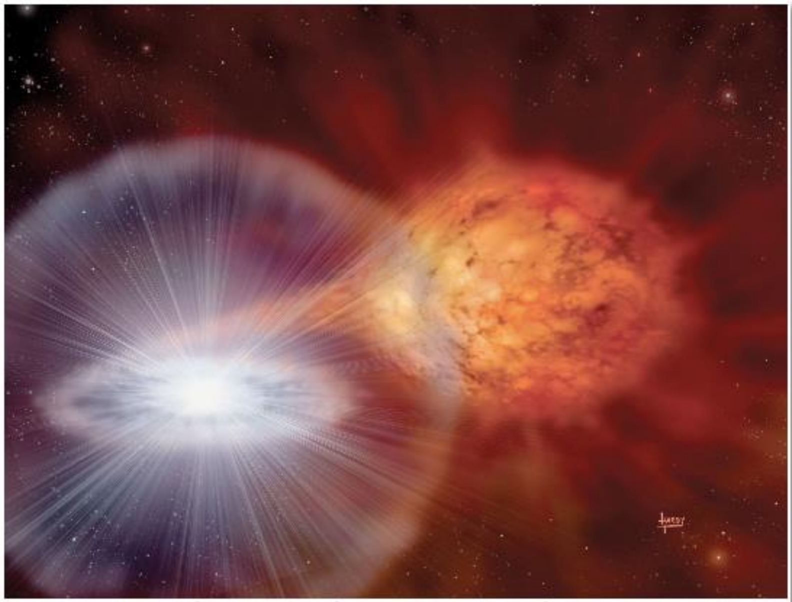
➢ Multiple probes are the key!



LSST Science Book, figure 15.3

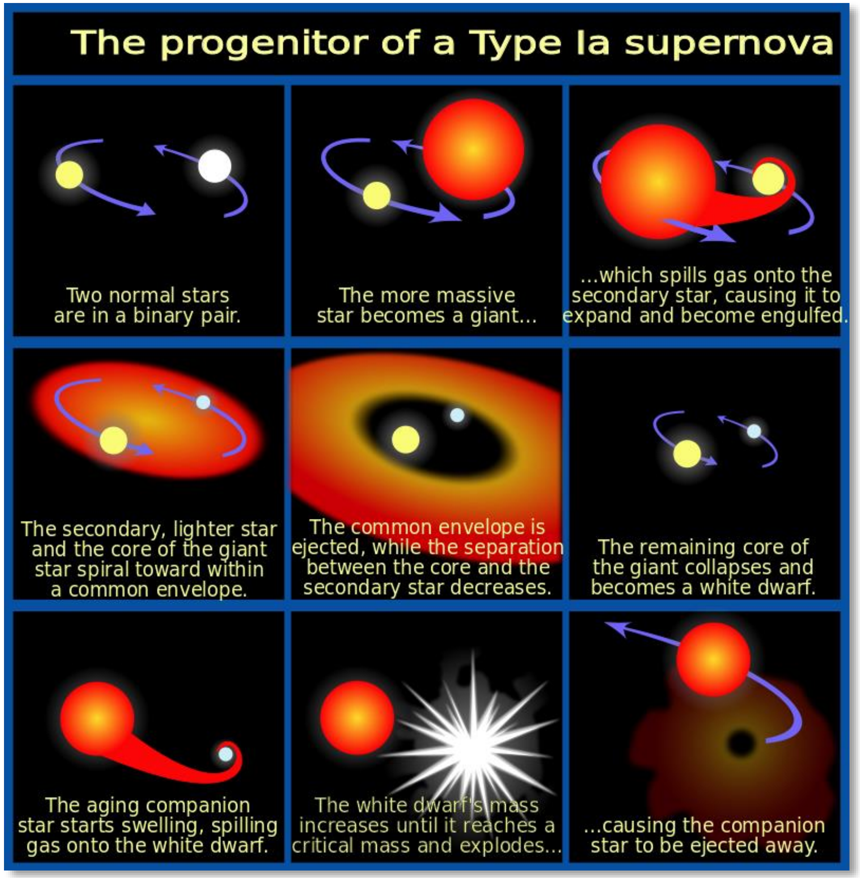
Type Ia Supernovae

- White Dwarf in binary system with mass transfer:
- M_{WD} → critical mass → core reaches T needed for C-fusion
- Type Ia Supernova = thermonuclear explosion



Artist's rendition of a white dwarf accumulating mass from a nearby companion star. This type of progenitor system would be considered singly-degenerate.

Image courtesy of David A. Hardy, © David A. Hardy/www.astroart.org.



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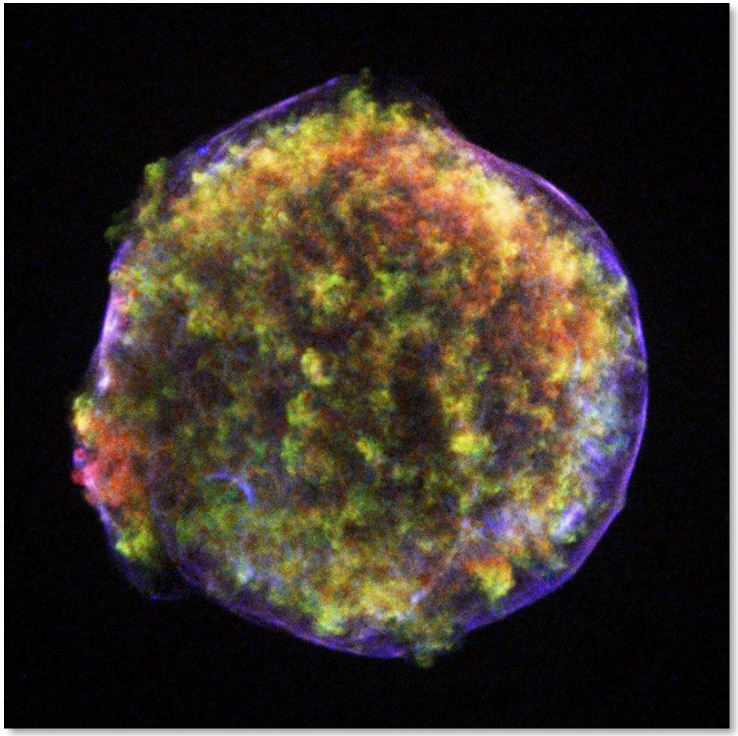
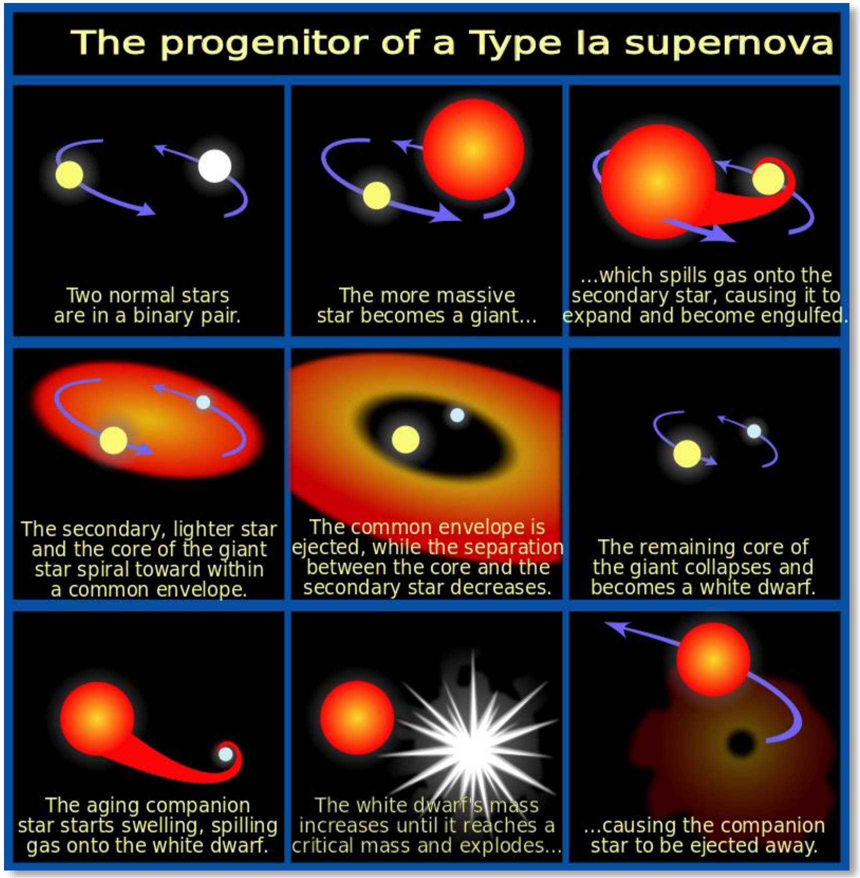




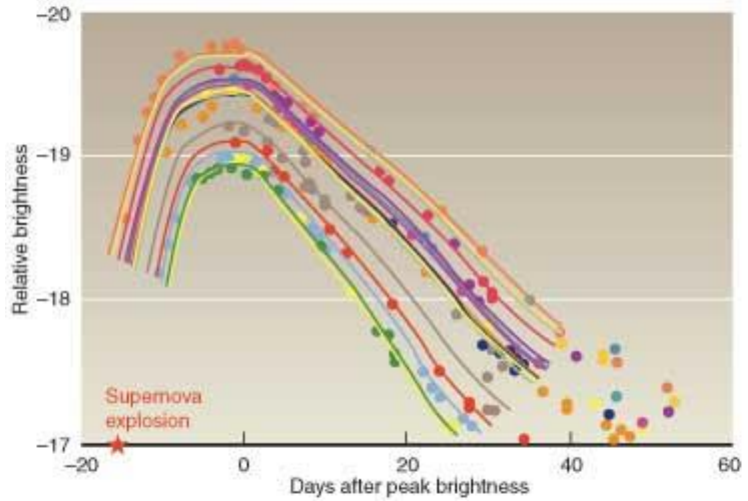
Type Ia Supernovae

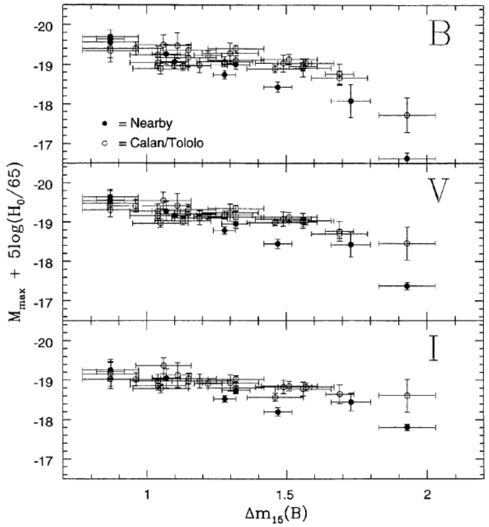
- White Dwarf in binary system with mass transfer:
- M_{WD} → critical mass → core reaches T needed for C-fusion
- Type Ia Supernova = thermonuclear explosion
- Extremely bright → observable over cosmological distances

NASA/ESA, The Hubble Key Project Team and The High-Z Supernova Search Team

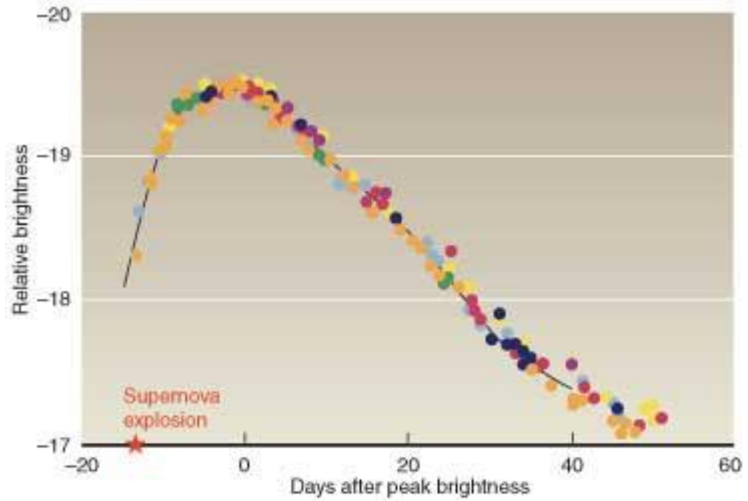
Type Ia Supernovae

- Every SNIa explosion proceeds very similarly because the initial conditions are always the same
- Maximum luminosity of a SNIa is correlated with the width of its lightcurve
- SNIa are “standardisable”, but need to calibrate the width-luminosity relation





Hamuy et al. (1996)



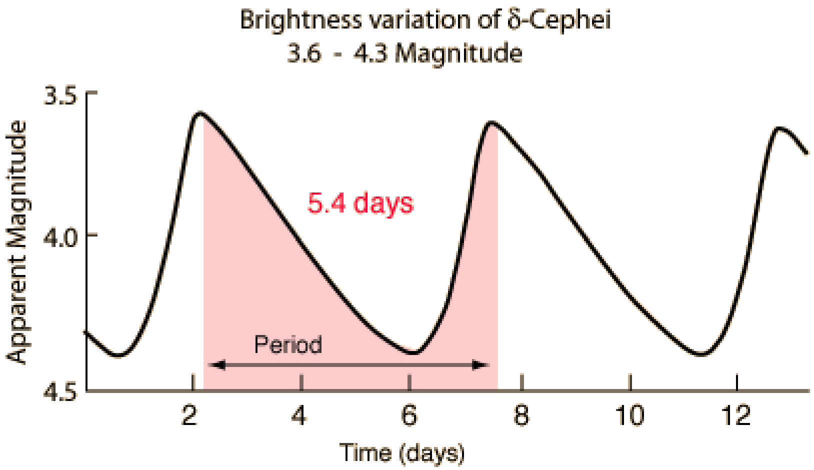
Cepheids

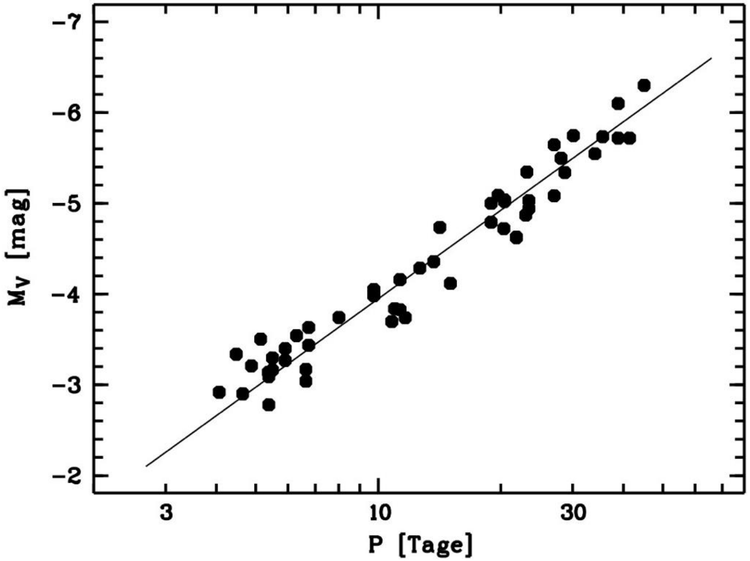
- Cepheids = periodic pulsating variable stars
- Giant stars, extremely bright → observable over large distances (Local Group)
- Amplitudes < 2 mag, Periods: 1 − 130 d
- Empirical relationship between period and luminosity: $L \propto P^n$, $n \approx 1.1$

➢ Cepheids are “standardisable”, but need to calibrate the period-luminosity relation

➢ Gaia!

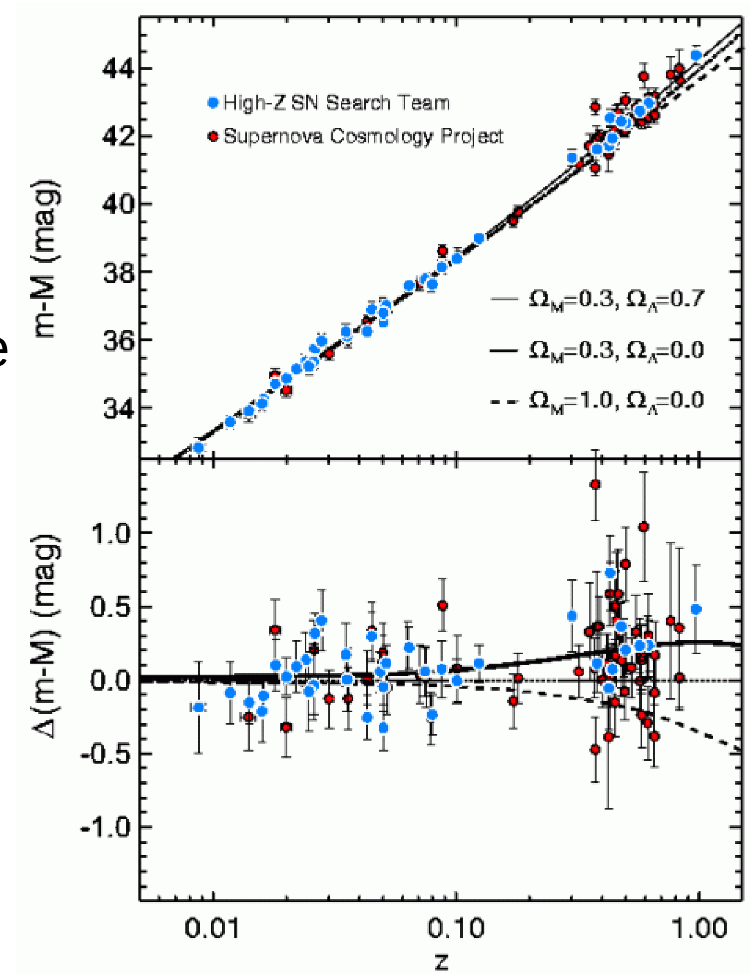
Henrietta Swan Leavitt (1868 – 1921)





Type Ia Supernovae

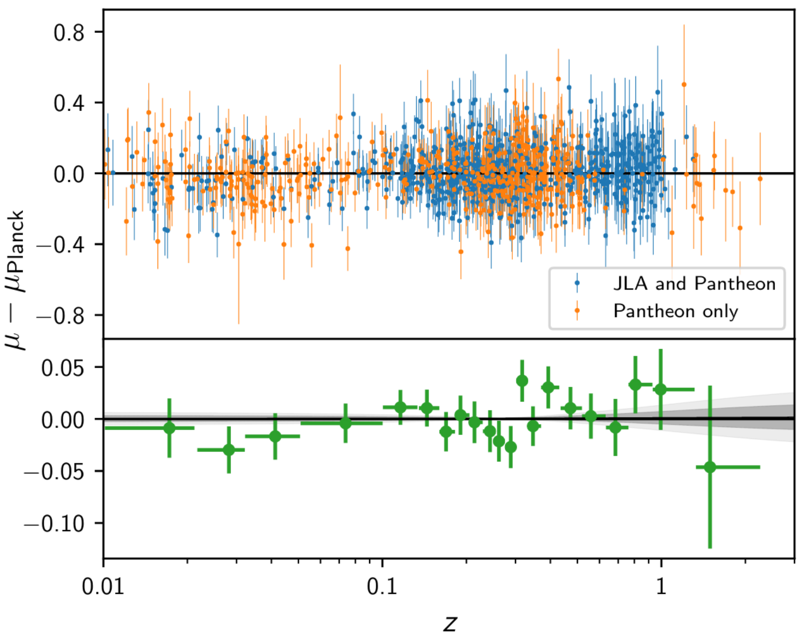
- Every SNIa explosion proceeds very similarly because the initial conditions are always the same
- Maximum luminosity of a SNIa is correlated with the width of its lightcurve
- SNIa are “standardisable”, but need to calibrate the width-luminosity relation
- Comparison of derived luminosity with observed brightness → luminosity distance
- Measurement of luminosity distance as function of redshift: $D_L(z) \propto \int 1/H(z)$



Riess et al. (1998)

Type Ia SNe

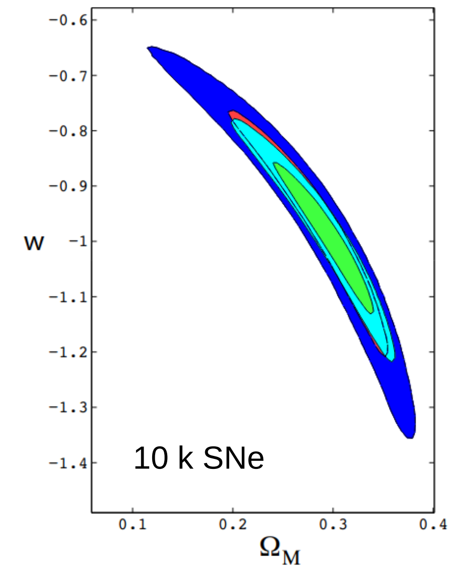
- Measurement of luminosity distance as function of redshift: $D_L(z) \propto \int 1/H(z)$
- Largest current sample: JLA + Pantheon ≈ 1000 SNIa

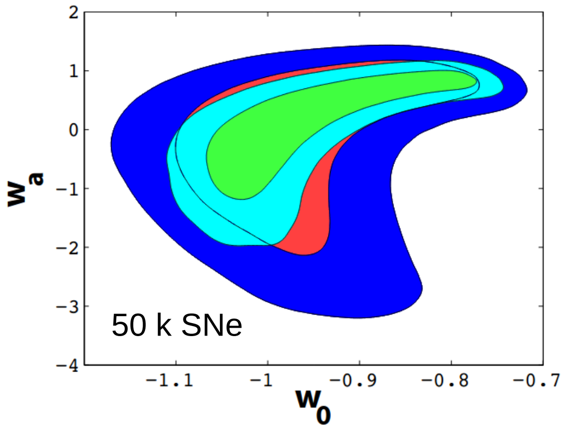


Betoule et al. (2014), Scolnic et al. (2018), Planck Collaboration (2021)

Type Ia SNe

- Measurement of luminosity distance as function of redshift: $D_L(z) \propto \int 1/H(z)$
- Largest current sample: JLA + Pantheon ≈ 1000 SNIa
- As a transient detection machine, LSST is perfect for detecting large samples of SNIa
  - Expected sample: a few × 10^5!
  - Need identifications and redshifts → spectroscopy
  - Will need to rely on photo-z for some (large) fraction
- Interesting constraints on dark energy equation of state parameters from SNe alone



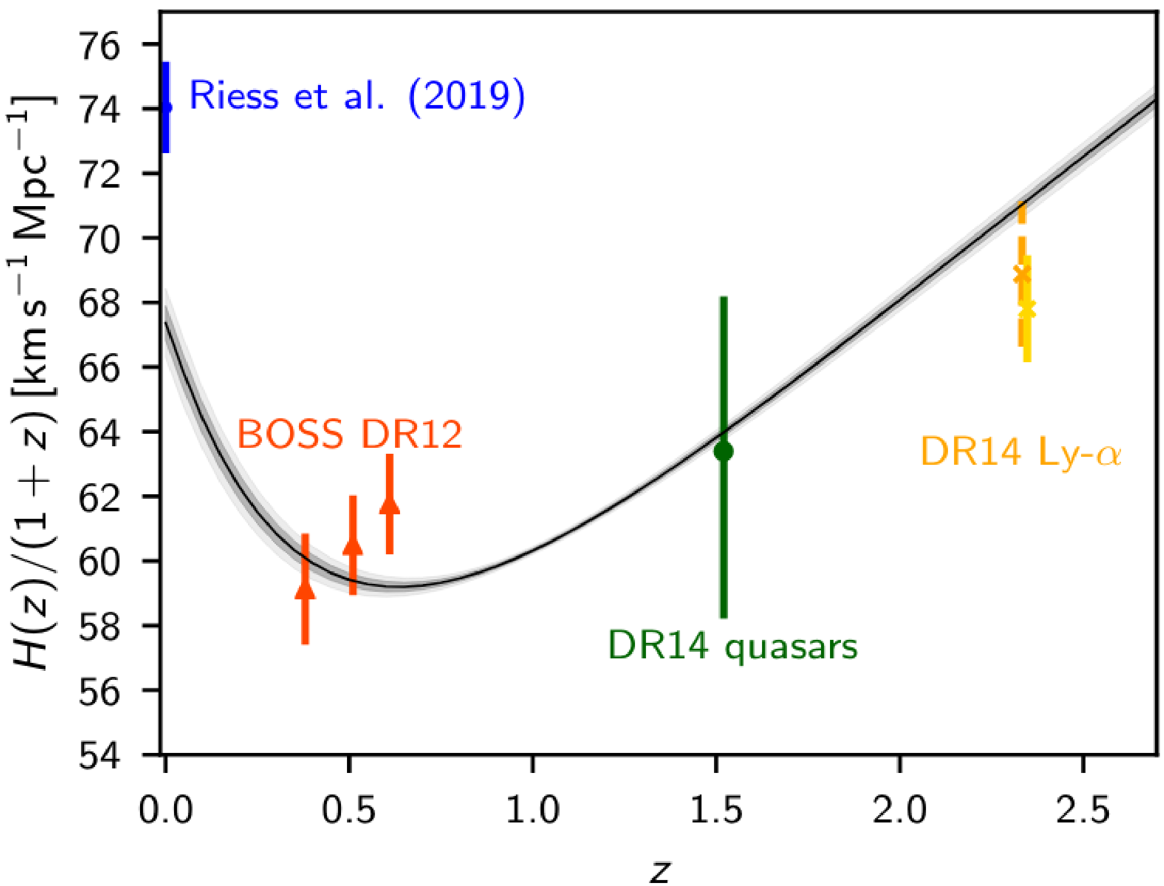


LSST Science Book (2009)

So what is there left to do (for surveys)?

Is the model beginning to crack?

- Hubble tension



Planck Collaboration (2021)

Questions?