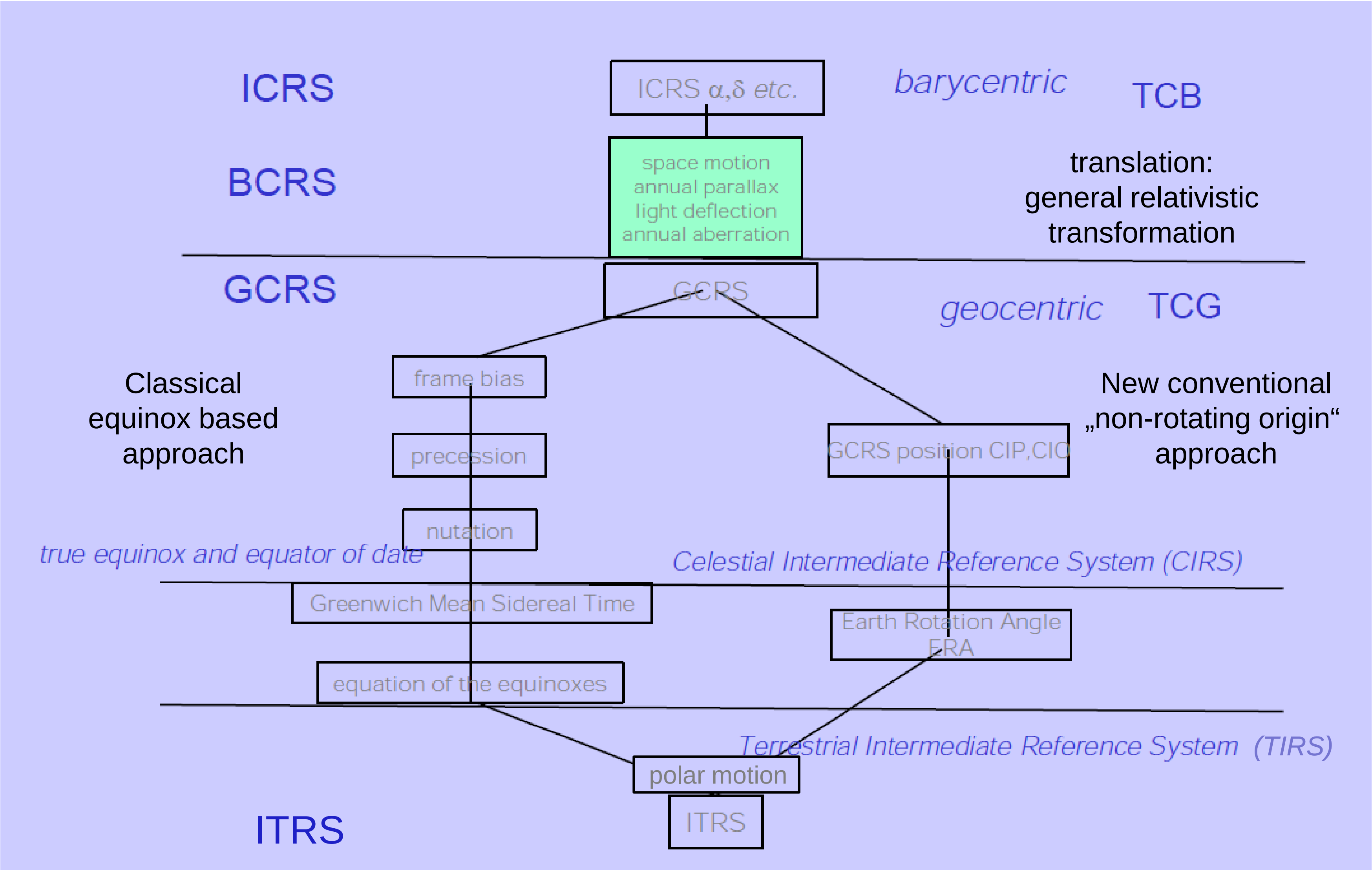
Assignment 4:
Earth orientation

Introduction

Dr. Robert Heinkelmann

GFZ
Helmholtz Centre
POTSDAM

Earth orientation ITRS←→GCRS



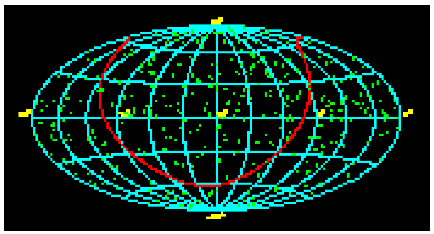
Celestial reference systems - overview

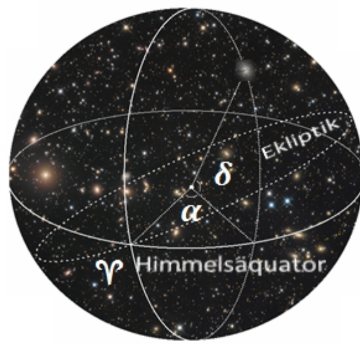
derived

Barycentric celestial

Geocentric celestial

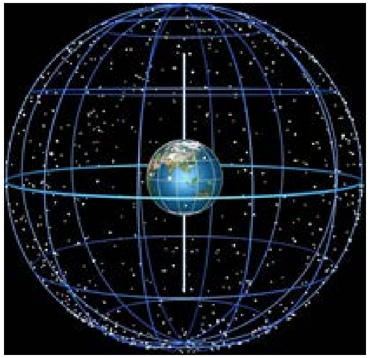
J2000.0 / FK5 system
Identical to ICRS,
but in optical wavelength



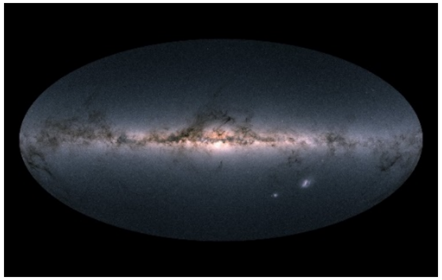


ICRS
Radio wavelength reference frame

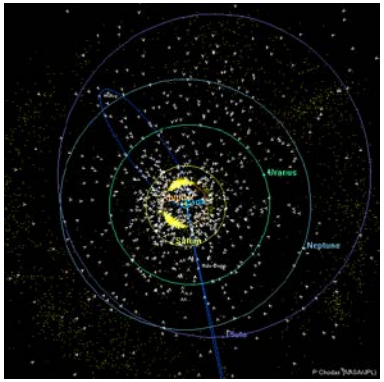
Defining element: celestial equator



Gaia (ESA mission) system
orientation and spin w.r.t. ICRS, optical wavelength, typically in galactic coordinate system
$(\alpha_0 = 17^h 45^m 40^s, \delta_0 = -29^\circ 00' 28'')$

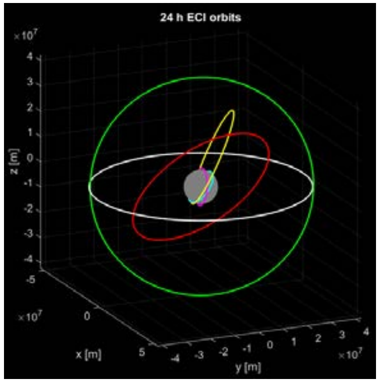


Planetary + Lunar ephemerides
orientation w.r.t. ICRS
a) inner planets: VLBI observations
b) outer planets: optical observations
+ transformation



Defining elements: SSB, dynamical ecliptic

Earth satellite orbits (ECI)
longitude of ascending node Ω, argument of periapsis ω, inclination i



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Realization of the CRS

- All **objects are moving** in space and
  space itself **is expanding**
  There is no fix point

- The **universe has no center**
  There is no preferred point

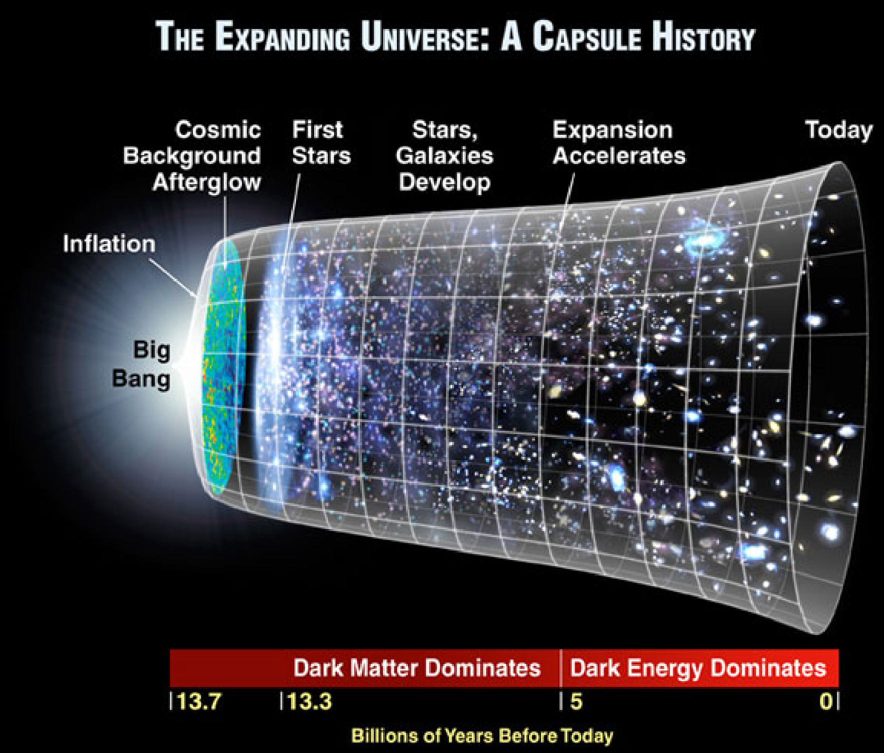
- Since there is no **absolute** measureable motion
  in the universe, only the **relative** motion
  between observer and observed object **is relevant**

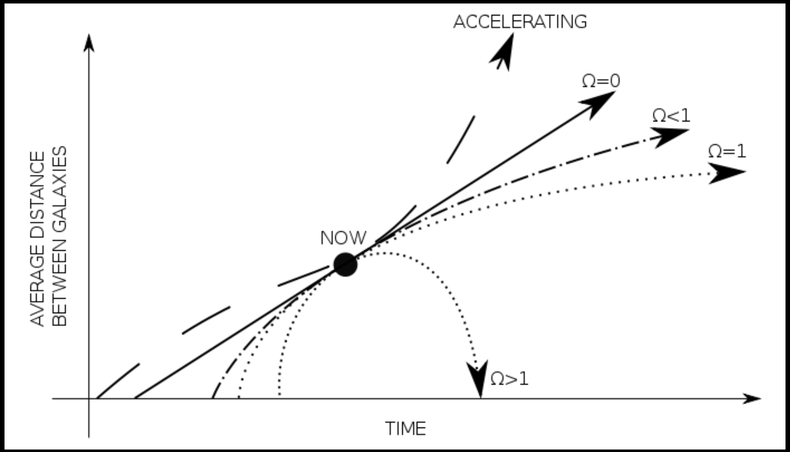
  - The relative motion perpendicular to the line of sight depends on the **distance of the observer and the observed object**

  - Preferred objects for the realization of a celestial reference system are therefore **the most distant observable objects → quasars**

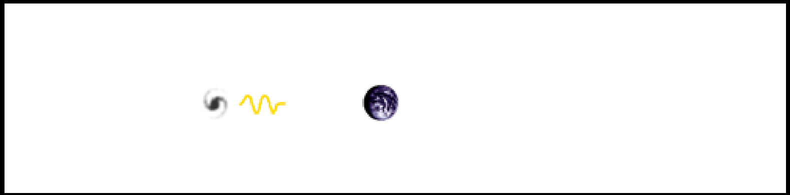
Metric expansion of space

- Space has a **history** (and consequently a future): In **cosmological theories** space is expanding or inflating at a certain rate following a big bang





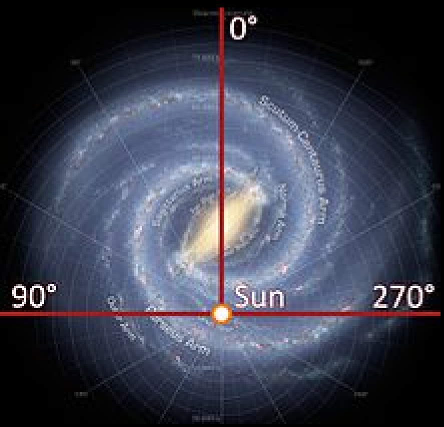
Note: the question about the **size** of the universe is the question about the **age** of the universe



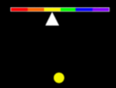
Cosmological redshift

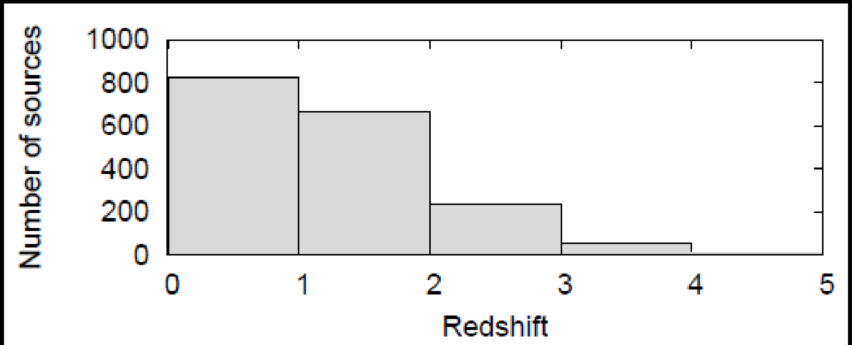
Redshift

- Cosmological (far-field) redshift z is dominated by the metric expansion of the universe
  - Redshift is known for ≈45.7% of ICRF objects
- Near-field redshift is dominated by the relative velocity in line-of-sight



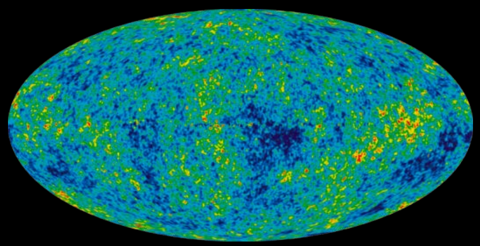
Redshift of near objects (z < 0.1) is mainly caused by line-of-sight velocity





Nearest quasar
M87, z = 0.004

Most distant quasar
J1120+0641, z = 7.085



Cosmic microwave background (CMB), z = 1090

Calculation of redshift, z

Based on wavelength	Based on frequency
$z = \frac{\lambda_{\mathrm{obsv}} - \lambda_{\mathrm{emit}}}{\lambda_{\mathrm{emit}}}$	$z = \frac{f_{\mathrm{emit}} - f_{\mathrm{obsv}}}{f_{\mathrm{obsv}}}$
$1 + z = \frac{\lambda_{\mathrm{obsv}}}{\lambda_{\mathrm{emit}}}$	$1 + z = \frac{f_{\mathrm{emit}}}{f_{\mathrm{obsv}}}$

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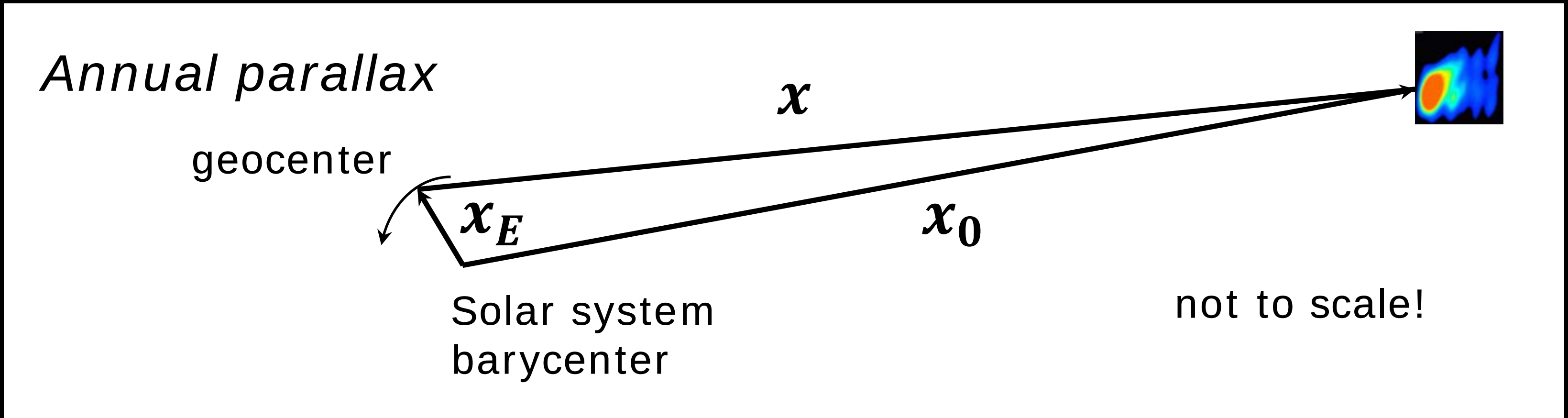
Relative motion: parallax

An Earth-based observer moves

- during one day due to Earth rotation: maximal shift at equator by one Earth diameter $2\,R \approx 12{,}756.2$ km (topocenter vs. geocenter) → diurnal parallax
- during one year due to Earth orbital motion: maximal shift $2\,AU \approx 299{,}195{,}741.4$ km (geocenter vs. SSB) → annual parallax



where

$\boldsymbol{x}_E$ barycentric position vector of the geocenter

$\boldsymbol{x}_0$ barycentric position vector of the celestial object

$\boldsymbol{x}$ position vector of the celestial object as seen from the geocenter in barycentric-compatible coordinates

Relative motion effect: parallax

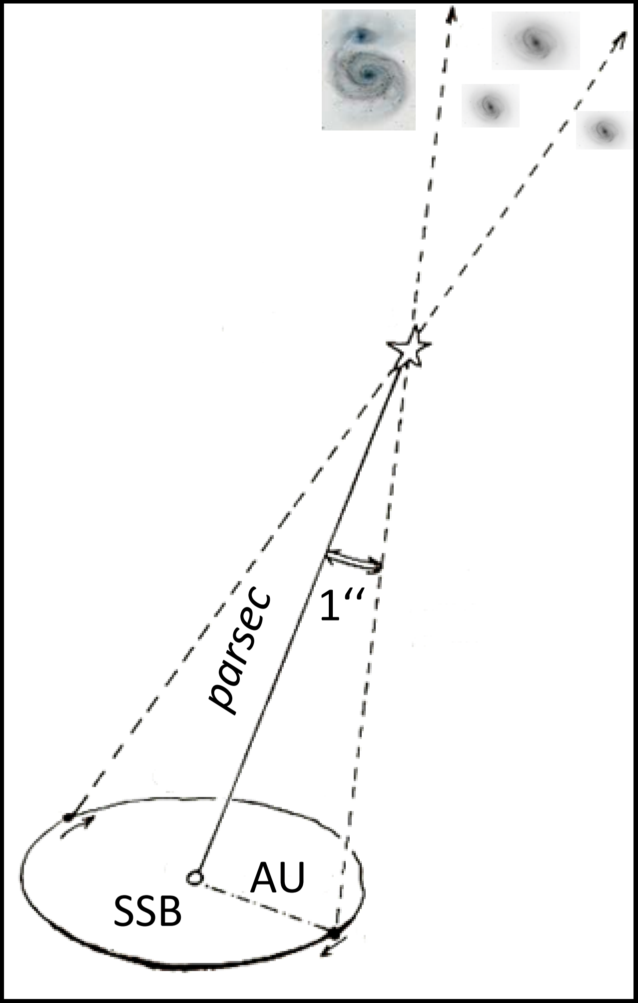
The **apparent position** of an object relative to more distant objects viewed from an **observer on Earth** can change.

Annual parallax is used to determine the distance to a celestial object most of all to stars.

There is a unit for distance called **parsec**.
A parsec (≈3.26 light years) is defined as the distance at which the annual parallax is 1 arc second.

$$1\,parsec = \frac{360 \times 60 \times 60}{2\pi} AU \approx 206264.8 AU$$

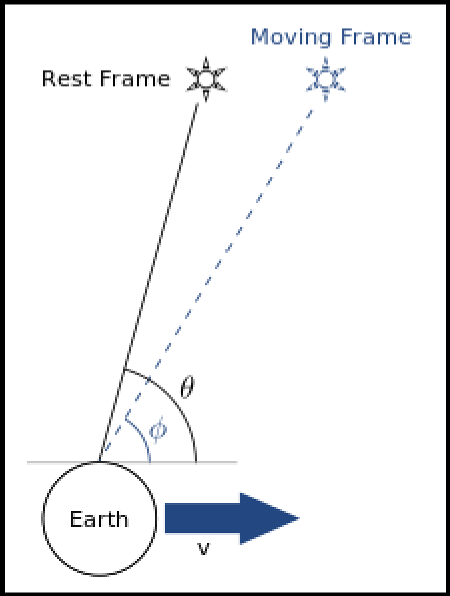
Definition of a parsec



Annual parallax

Relative motion effect: aberration

The apparent position of an object viewed from an observer depends on the **velocity of the observer**. E.g. an Earth-bound observer experiences annual and diurnal ***aberration***. Annual aberration is caused by the Earth's orbital motion around the solar system barycenter along the ecliptic during the year. Diurnal aberration is caused by the changing position of the observer on Earth due to Earth rotation: 1 cycle/d. Aberration is due to the finite speed of light. The SSB is affected by galactic aberration due to the rotation of our galaxy.



Annual aberration

Galactic aberration

Relative motion effect: proper motion

The ***proper motion*** is the angular change of the position over time.
It is perpendicular to the line of sight. (The line of sight or radial velocity is the change in the distance between the object and the observer.)
The ***true proper motion*** is entirely caused by the motion of the object itself (intrinsic).
Whatever effect interferes with the intrinsic ones is called ***apparent proper motion***, e.g. structure variations of radio sources, anisotropy of space, effects through gravitational lensing or gravitational waves or aberration and parallax.

$$\mu_\alpha = \alpha_1 - \alpha$$
$$\mu_\delta = \delta_1 - \delta \ .$$

$$\mu^2 = \mu_\delta{}^2 + \mu_\alpha{}^2 \cdot \cos^2 \delta$$

Proper motion of Barnard‘s star

Realization of the CRS

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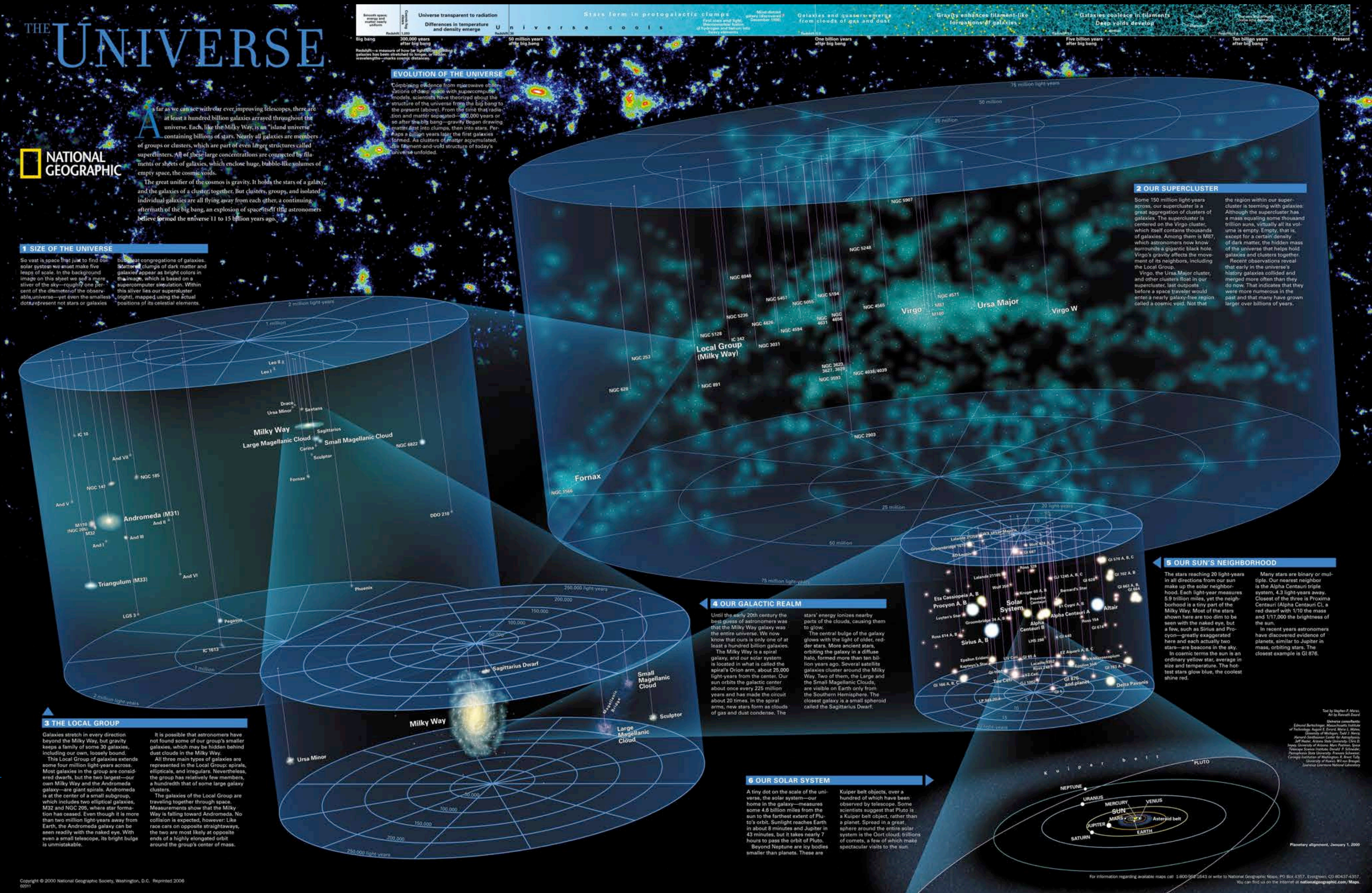
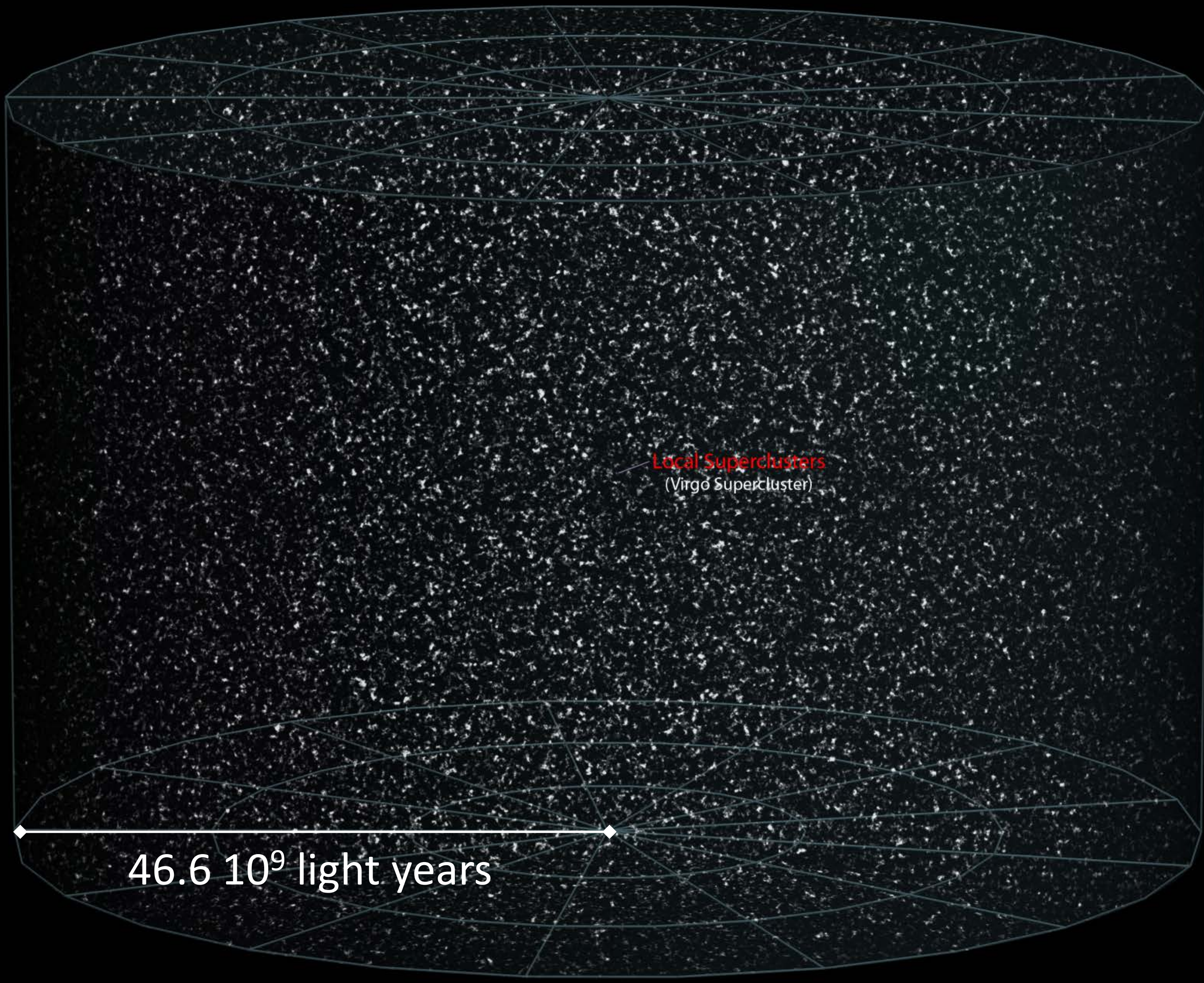
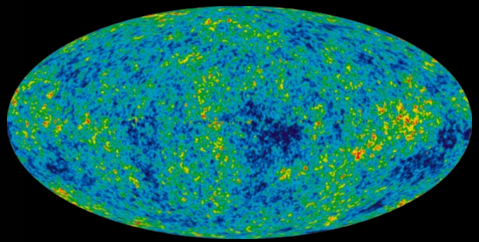
Structures in the universe



Observable Universe





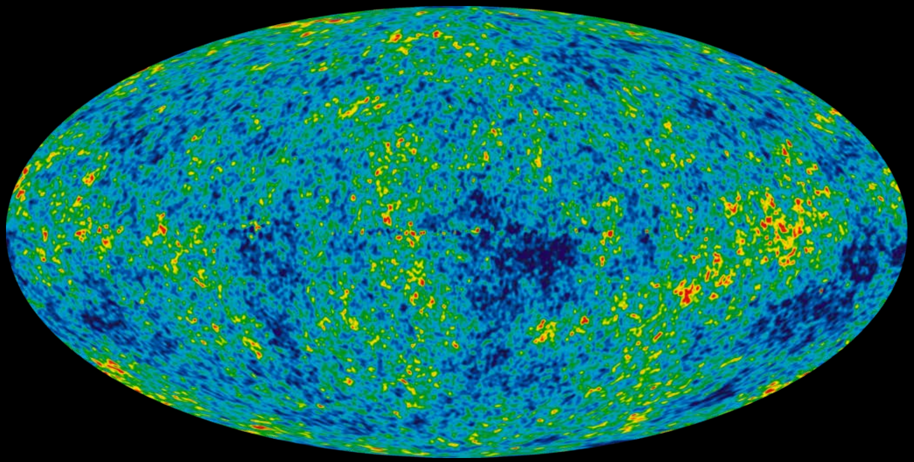
Cosmic microwave background (CMB)

Observable universe contains

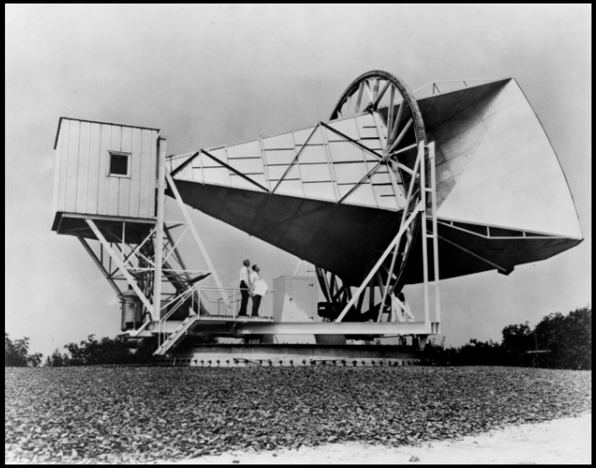
- 10 10^6 superclusters

Cosmic microwave background (CMB)

- CMB characteristics:
  - **Radio telescopes** show a faint background glow, almost isotropic, that is not associated with any star, galaxy, or other (foreground) object
  - Thermal radiation, strongest at microwave wavelengths, "black" in optical, black body spectrum at a temperature of 2.72548±0.00057 K
  - Oldest information of the universe (≈380,000 years after Big Bang)

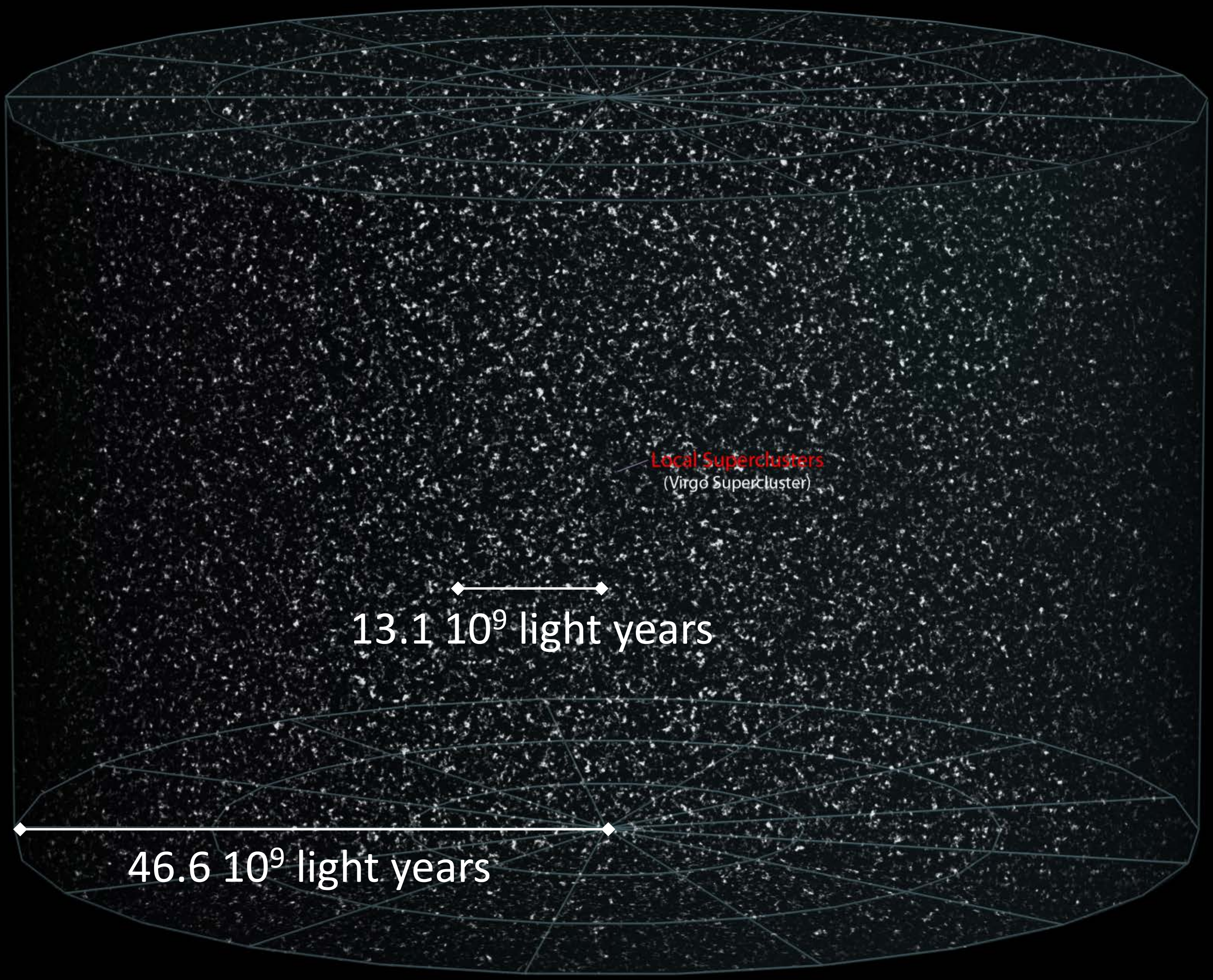


– Main anisotropy: dipole anisotropy from the Doppler shift of the background radiation caused by the peculiar velocity of the Earth relative to the cosmic rest frame



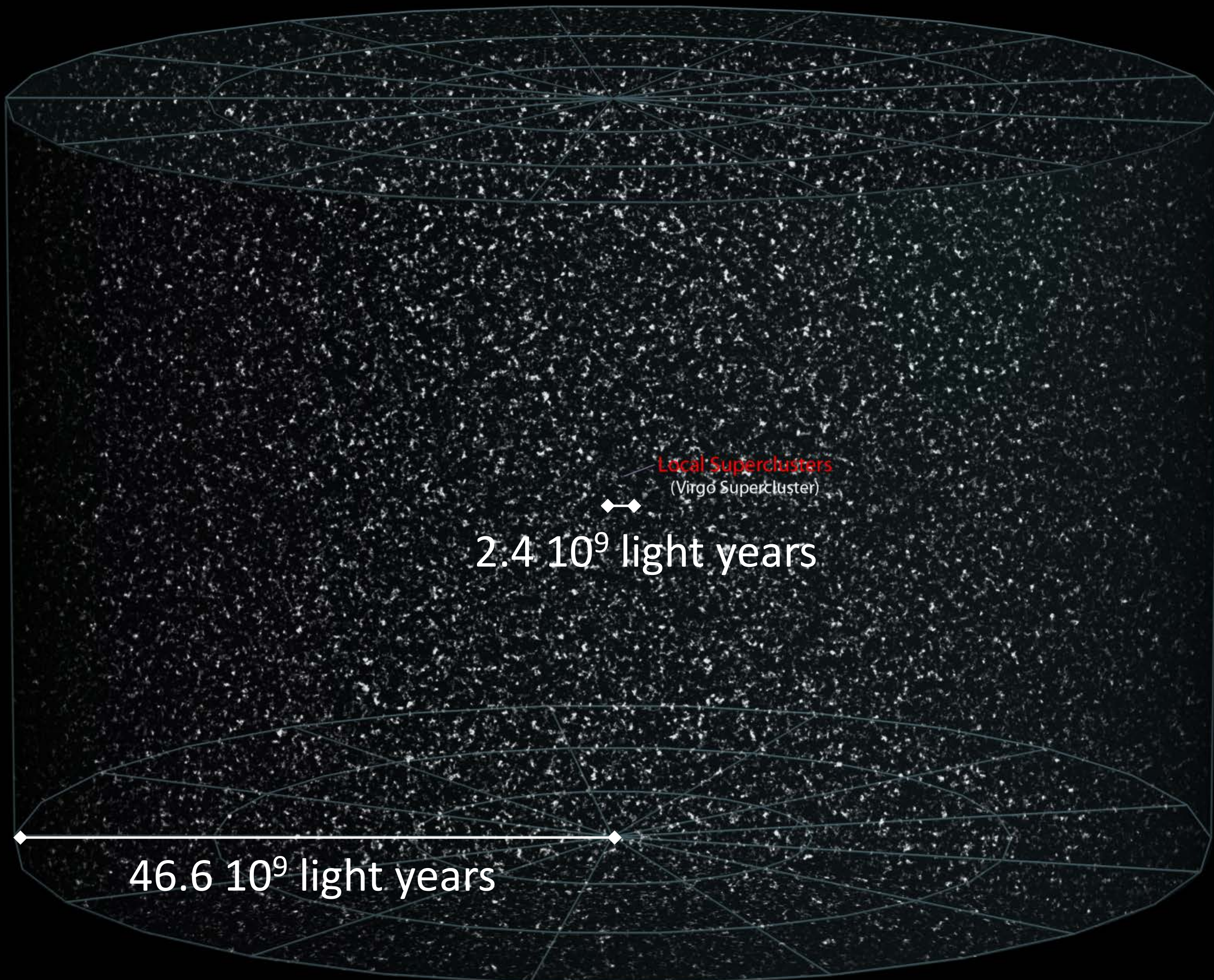
– Accidental discovery of CMB in 1964 by radio astronomers Arno Penzias and Robert Wilson

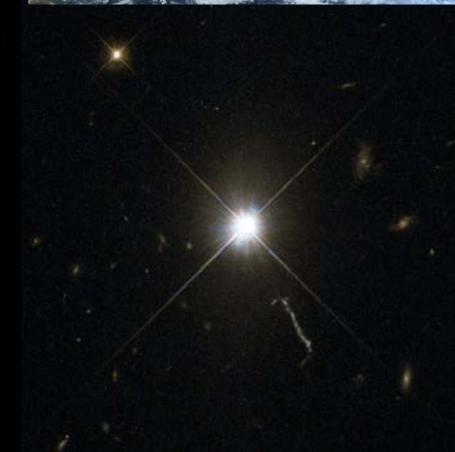
Observable Universe



J1120+0641
most distant
observed quasar
(Mortlock et al.,
Nature, 2011)

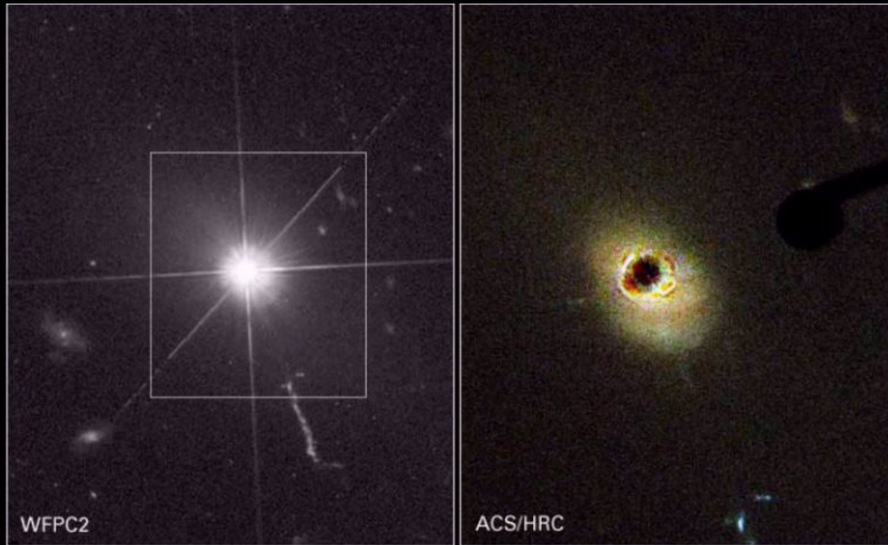
Observable Universe



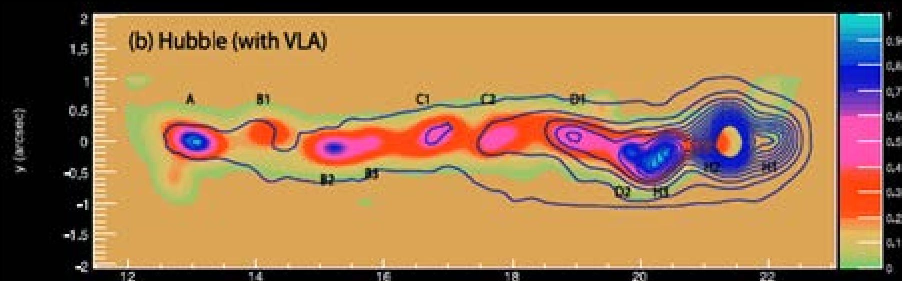


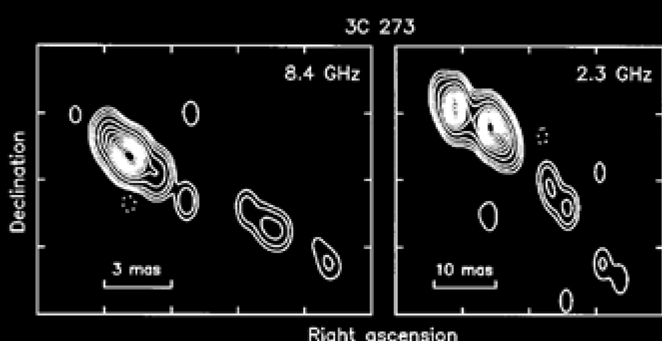
3C 273
brightest observed
quasar
(Hubble ST
NASA/ESA)

3C 273: brightest and first identified quasar



NASA, A. Martel (JHU), the ACS Science Team, J. Bahcall (IAS) and ESA STScI-PRC03-03





2.4 billion light years, direction: Virgo

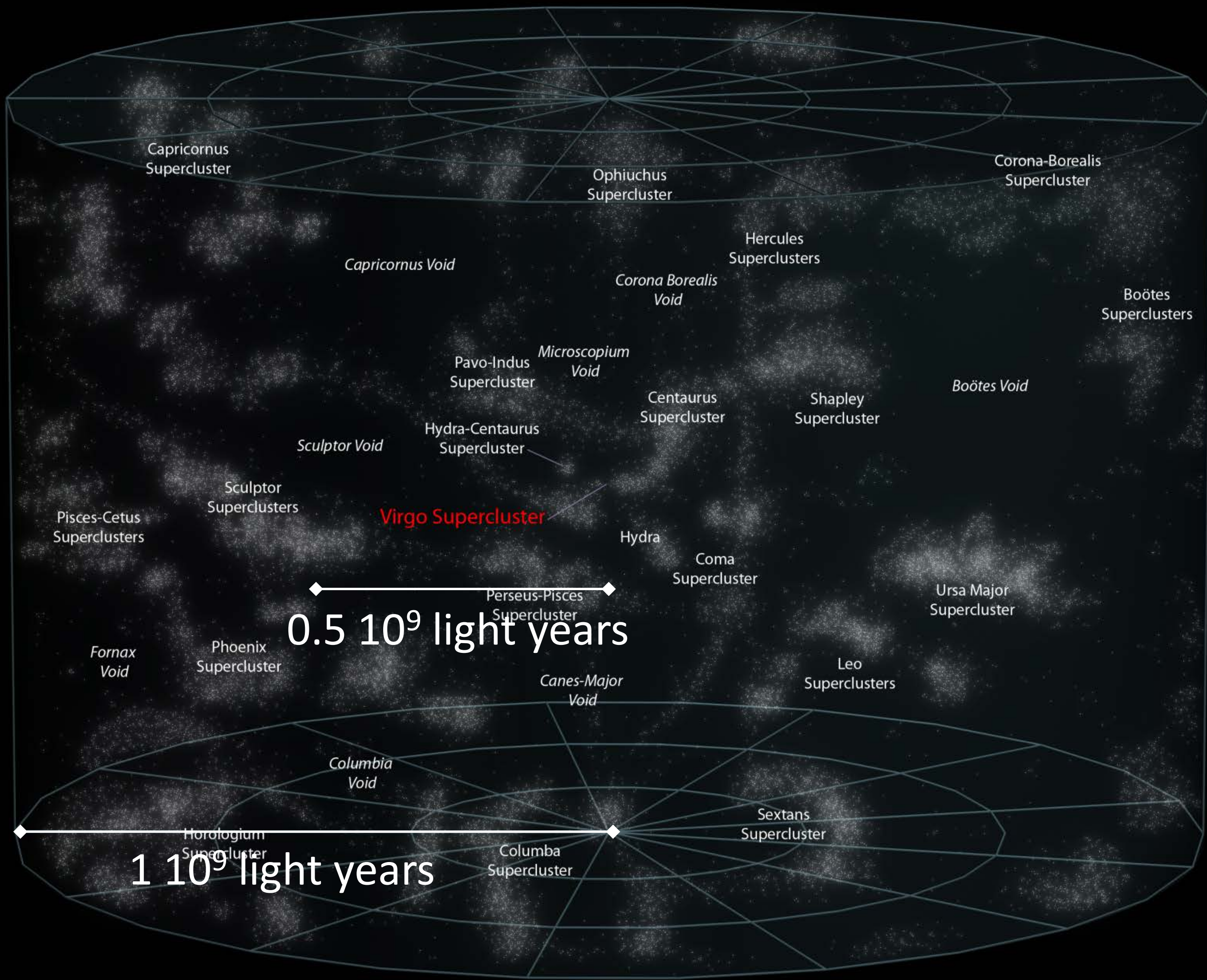
Hubble:

- WFPC2: Wide field and planetary camera 2
- ACS: Advanced camera for surveys
- HRC: High resolution channel

Overlay of optical (620 nm) and radio (VLA 2.0 cm) images of the 3C 273 jet
Uchiyama et al. (2006)

Geodetic VLBI image in X- and S-bands
Radio contour plot
Sovers et al. (1998)

Local Superclusters

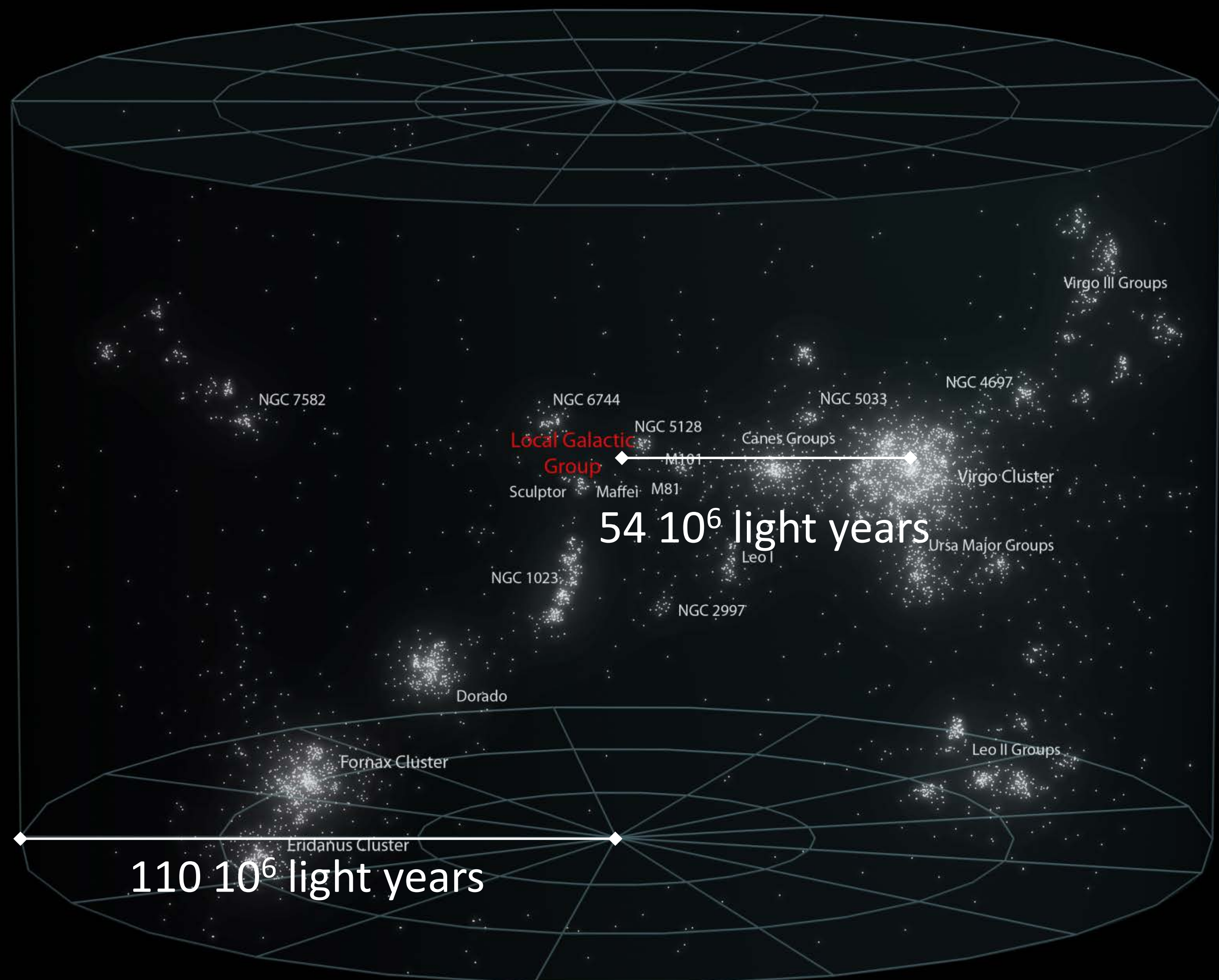


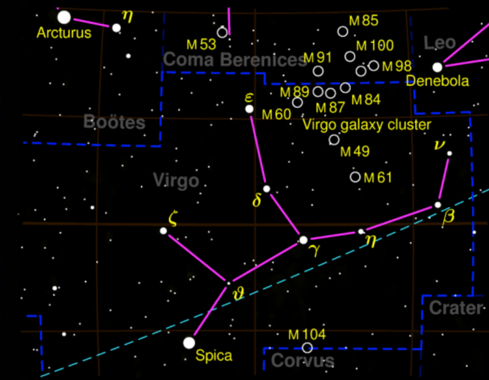
Largest clumps of **matter** in the observable universe group into so-called **superclusters** that are separated by **voids**.

Laniakea supercluster contains

- Virgo supercluster
- 100,000 galaxies

Virgo Supercluster

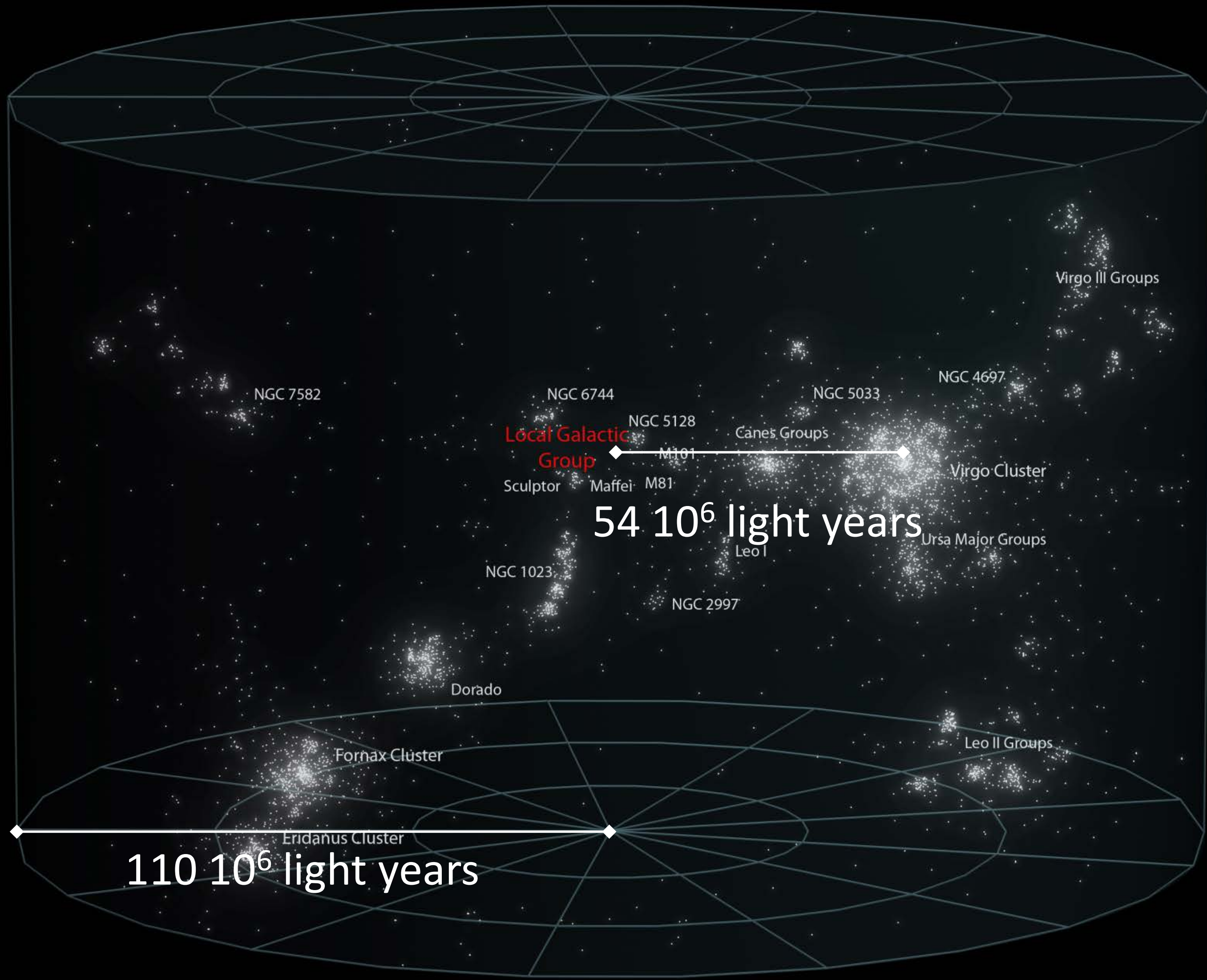


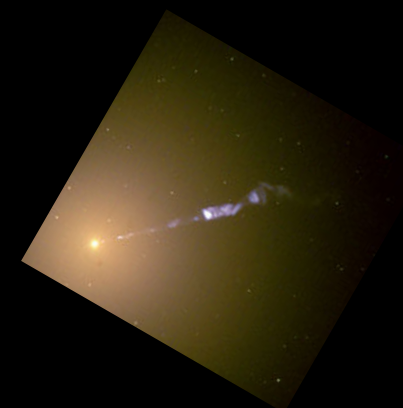


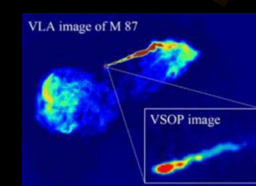
Virgo or local supercluster contains

- Virgo Cluster
- local group (our galactic neighborhood)

Virgo Supercluster

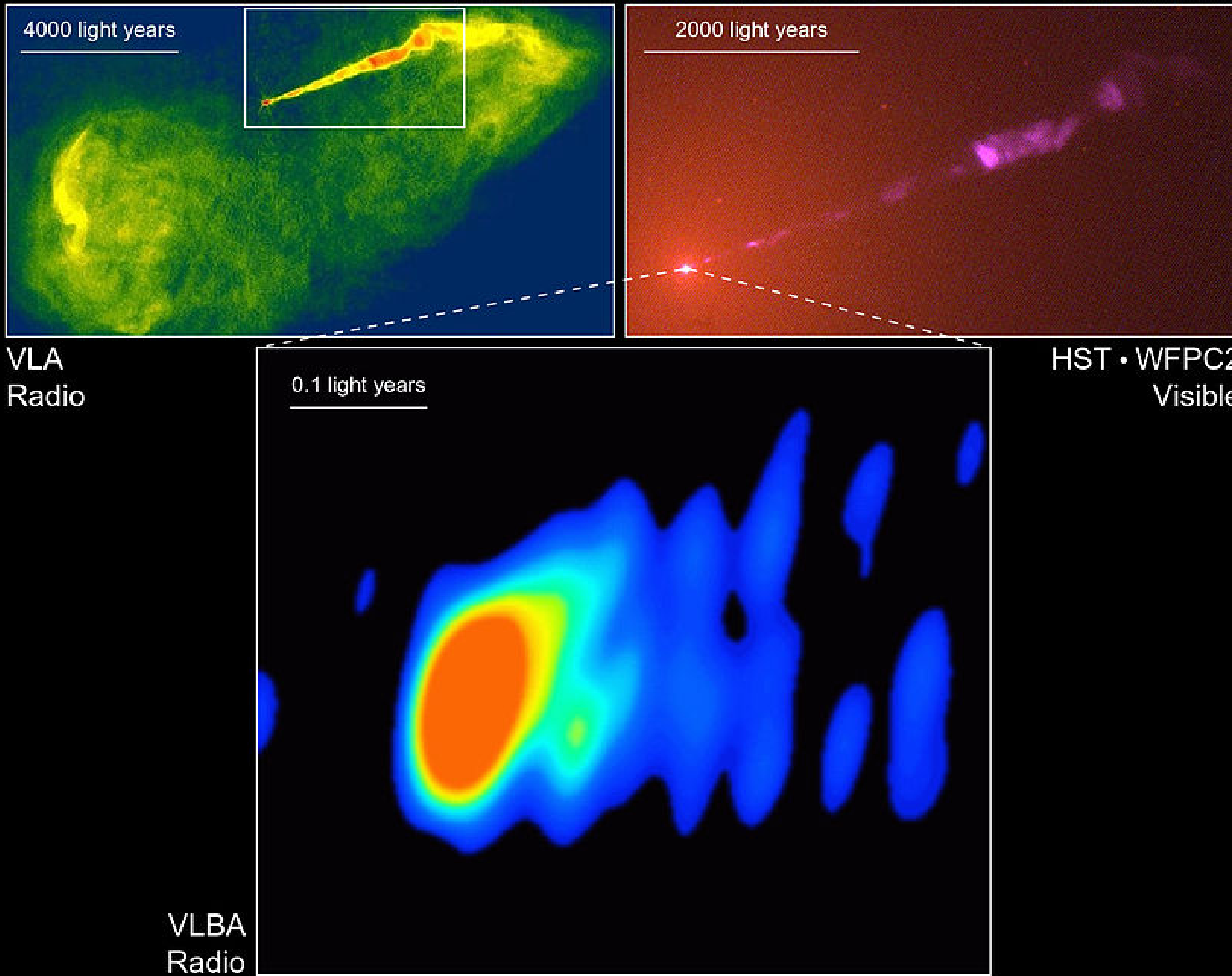






Messier 87 – Virgo-A
a very close quasar

M87: giant elliptical galaxy



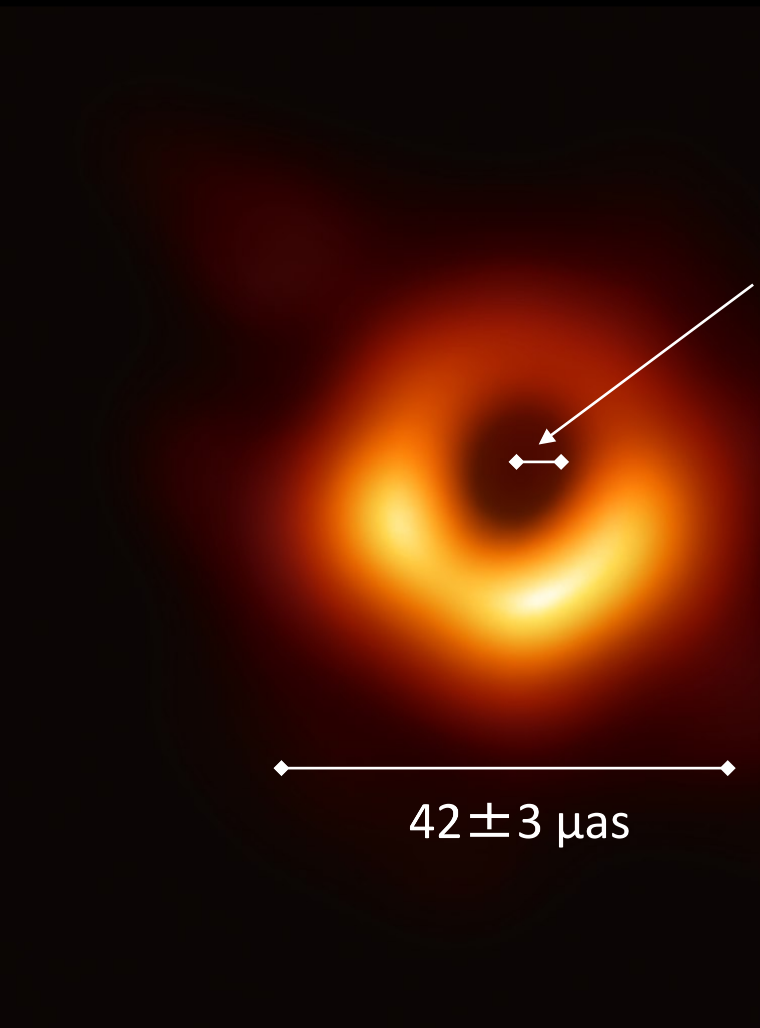
NASA, NRAO and J. Biretta (STScI) • STScI-PRC99-43

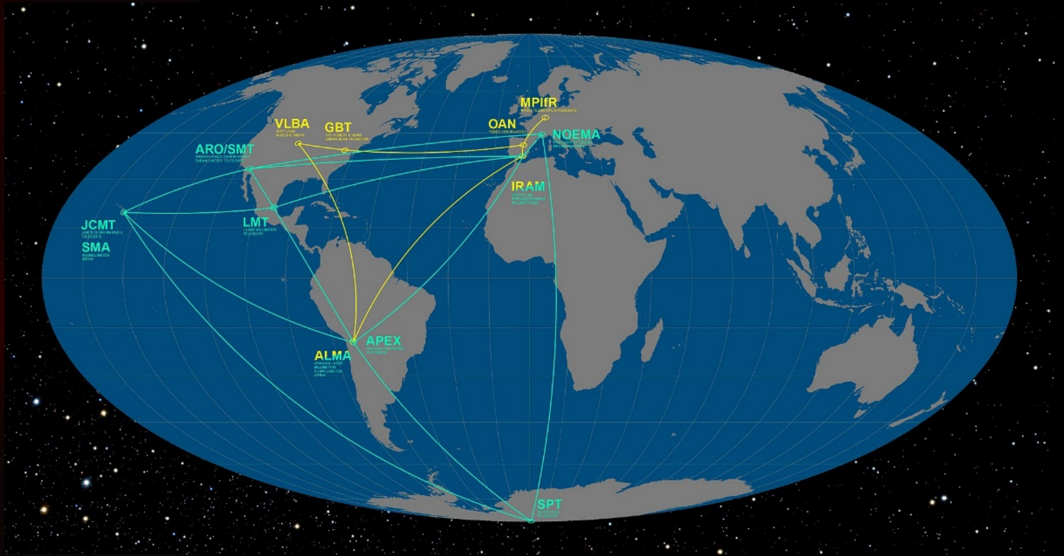
M87: giant elliptical galaxy

2019-04-10: image of active nucleus of M87

M87 core: 6.6 10^9 solar masses super massive black hole surrounded by accretion flow of matter

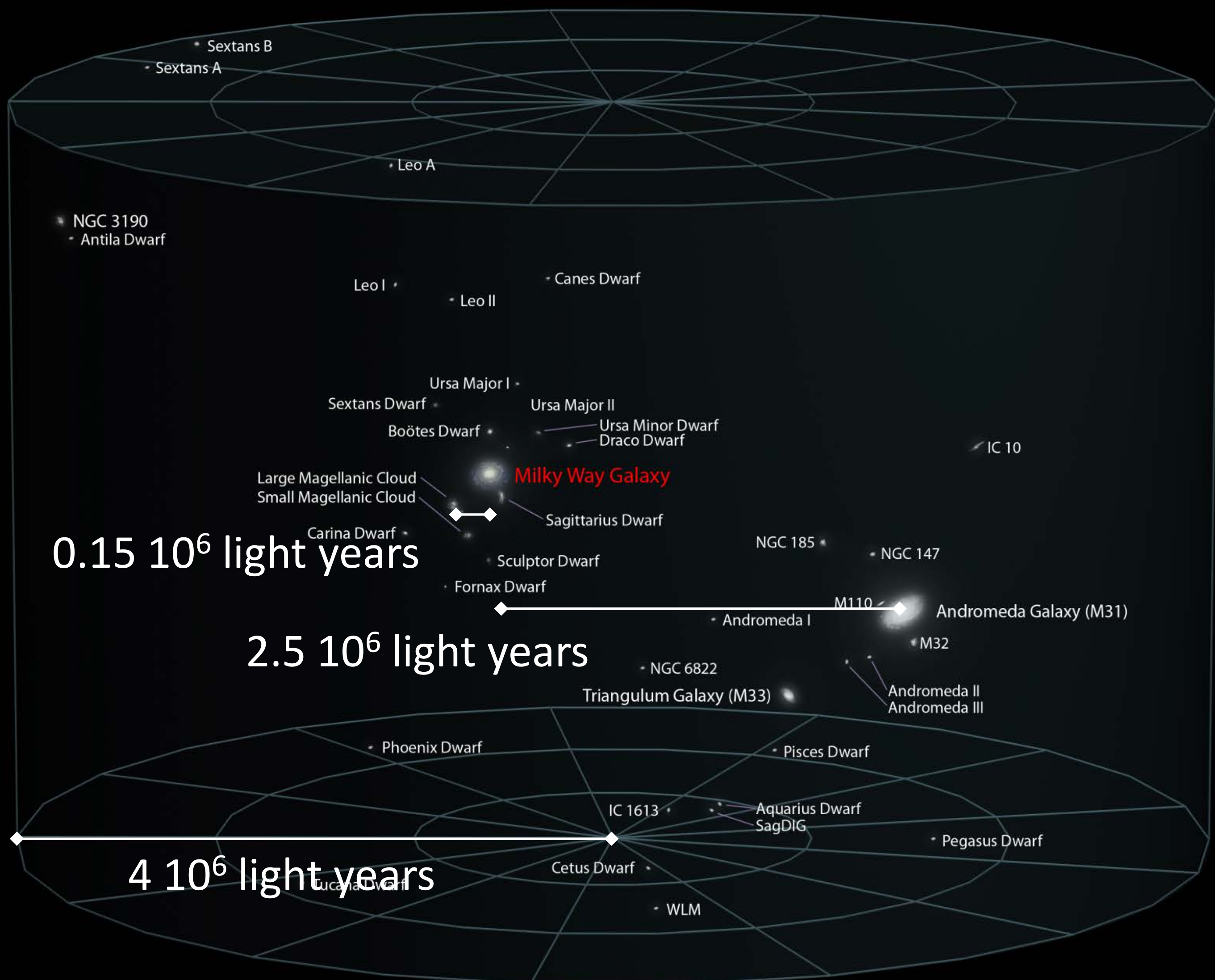
estimated Schwartzschild radius



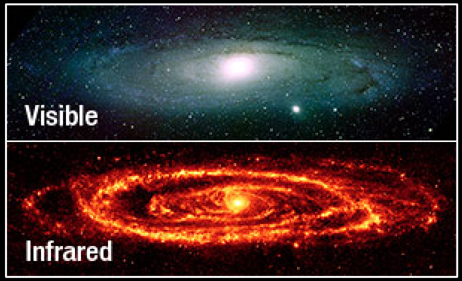


as seen by the VLBI array
Event Horizon Telescope

Local Galactic Group



Magellanic clouds



M31 Andromeda
„crash“ in 4 10^9 yrs

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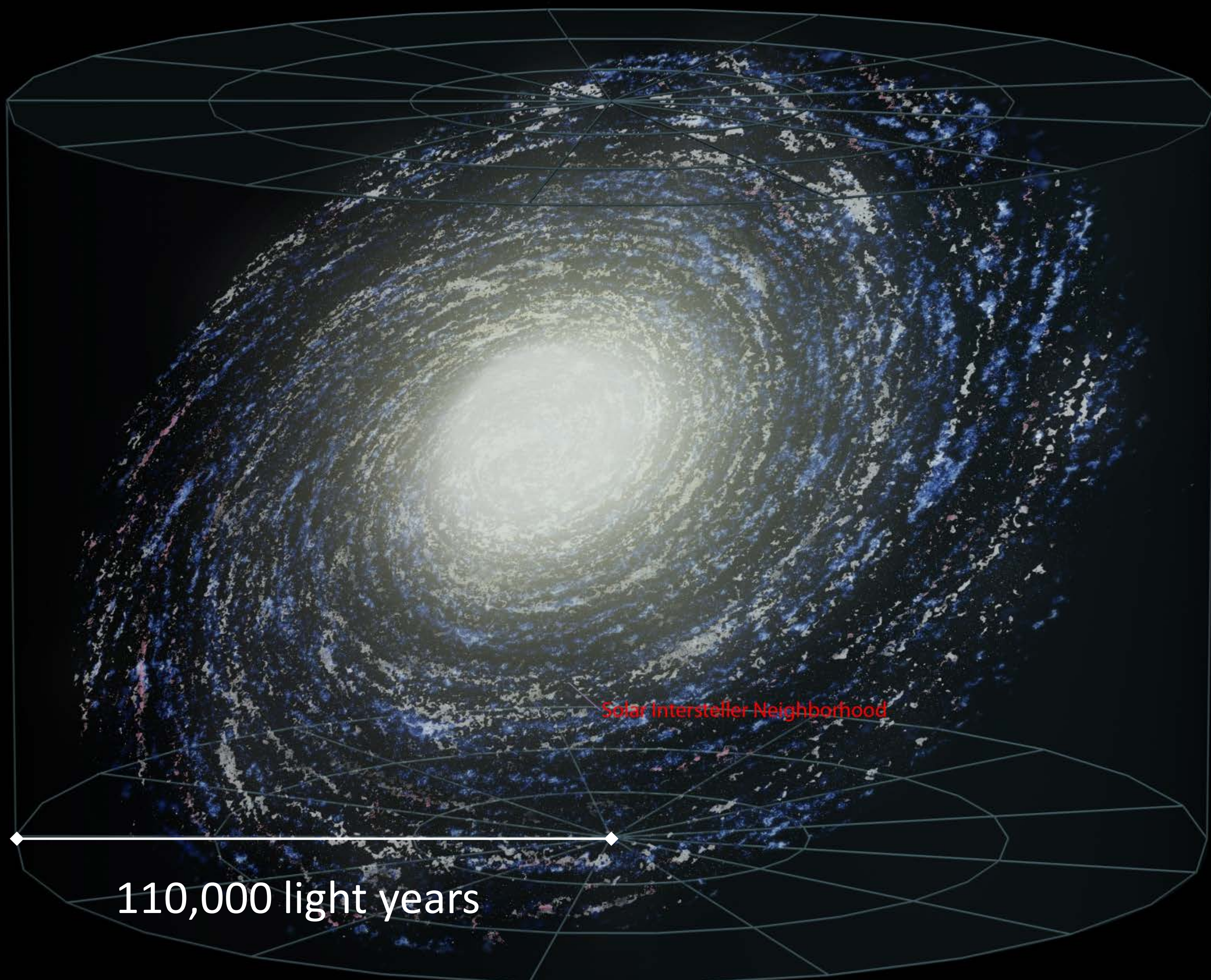
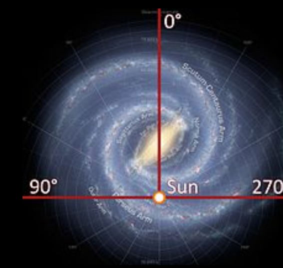
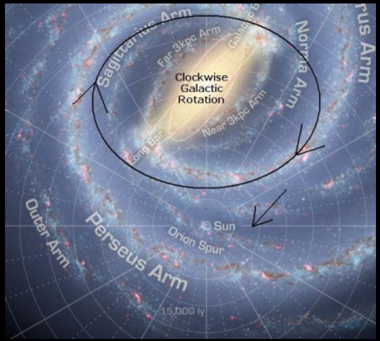
Milky Way Galaxy





Galactic Coordinate System



Galactic rotation

The Milky Way: home of the observable stars

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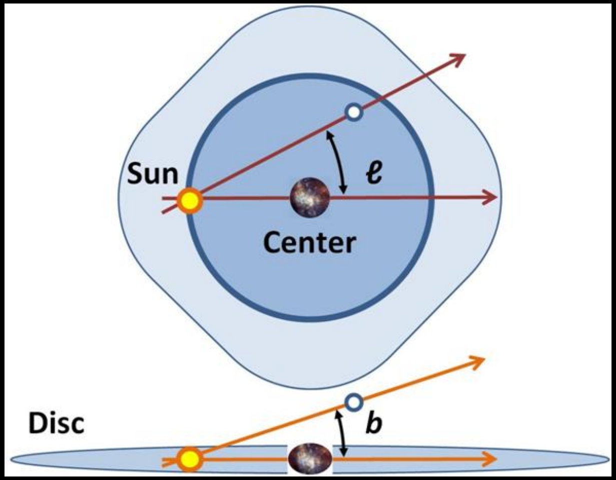
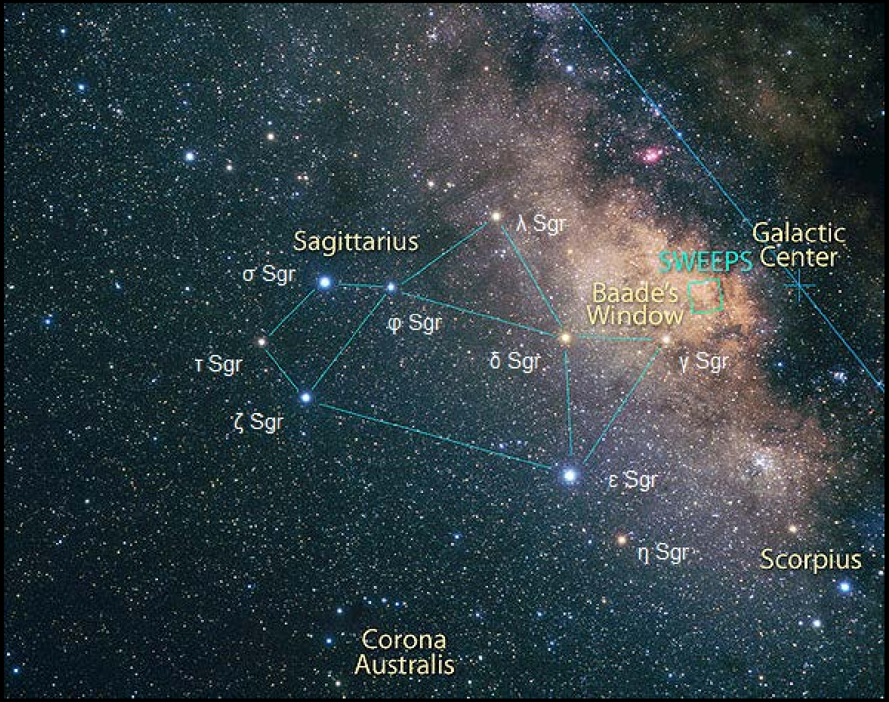
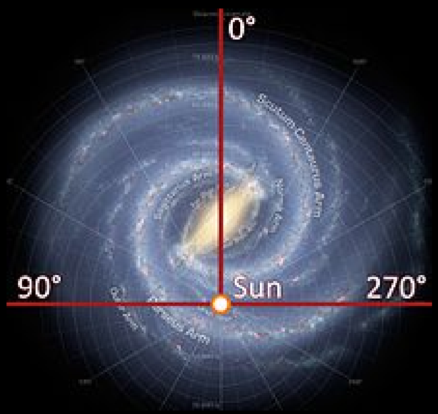
Galactic reference system (GalRS)





Origin
Heliocenter or SSB (ambiguous)
Orientation
Principal plain (***b*** = 0): galactic plain (plain disc model)
Galactic latitude (***b***) is the angle above/below the galactic plain
Reference direction (***l*** = 0) points towards the galactic center
(realized through observations of Sagittarius A)
Galactic longitude (***l***) counted counter-clockwise
Purpose
Kinematics and dynamics of the galaxy, galactic observational astronomy



Stars, neutron stars, pulsars

A stellar catalogue is the numerical result of astrometry of stellar objects, i.e. stars

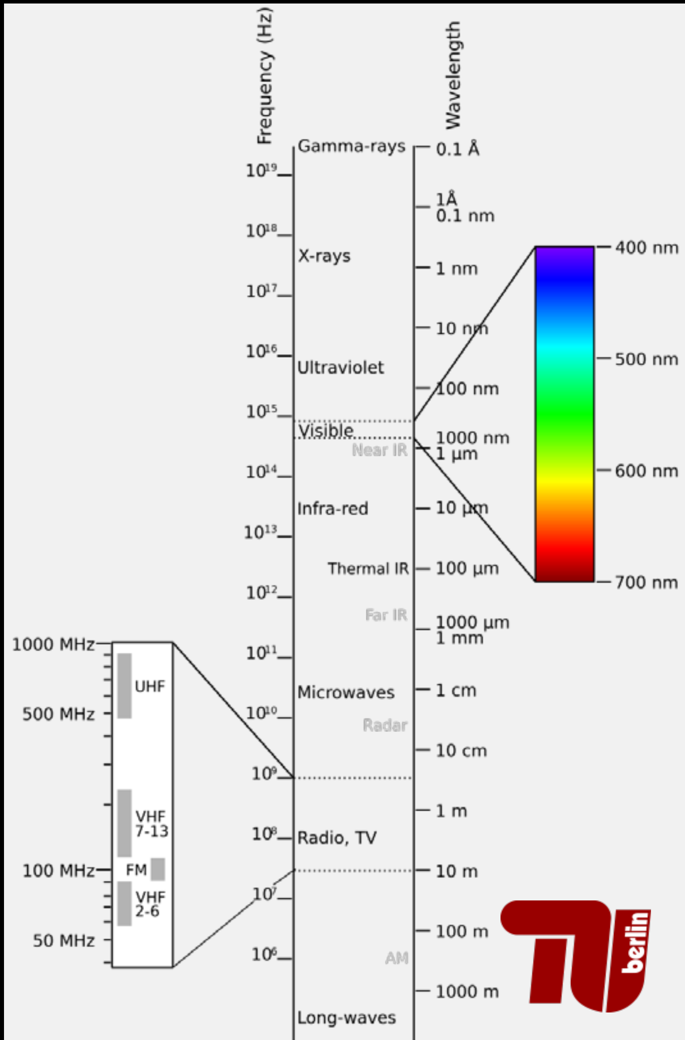
- The stars predominantly emit at optical wavelength

„Pleiades" star formation in the Taurus constellation

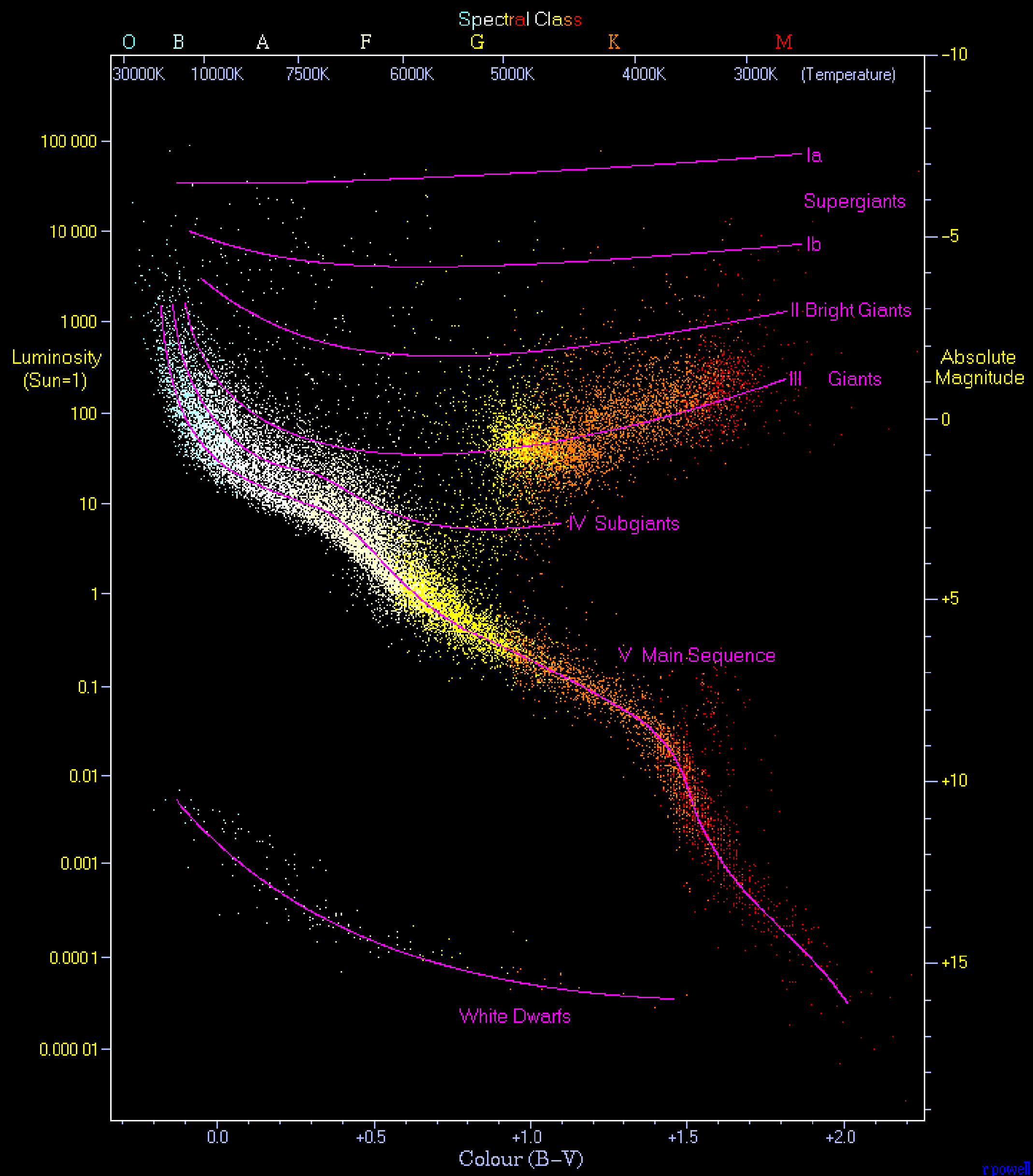
Besides: there are also radio stars, which emit significant amounts of radio waves, e.g. neutron stars or pulsars

Neutron star in the crab nebula

Gamma-ray pulsar „Vela"



Galactic population – what kind of stars do we observe?



The **Hertzsprung-Russell diagram** shows luminosity / magnitude vs. spectral class / eff. temperature

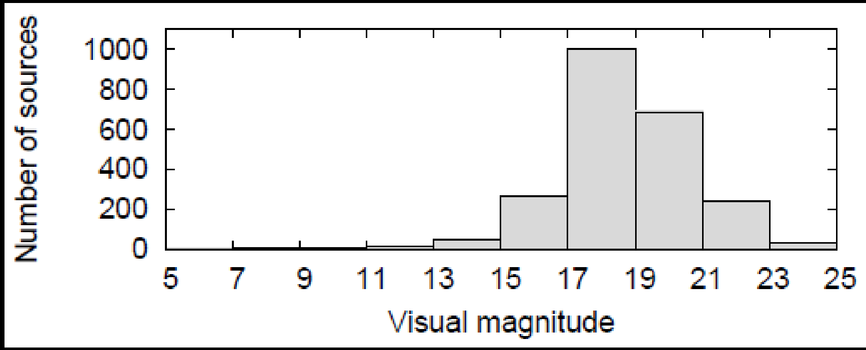
The stars appear to fall into certain categories:

- **Main** sequence stars
- **Giants** and Supergiants
- White **dwarfs**

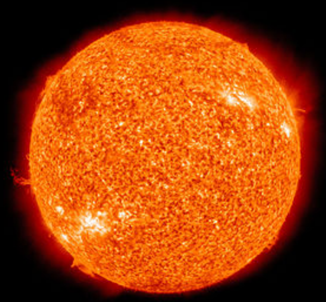
- The categories are depending on the **mass** and the **life cycle (age)** of the stars

Visual or apparent magnitude

– Visual magnitude: Vmag or mag known for ≈58.8% of ICRF sources



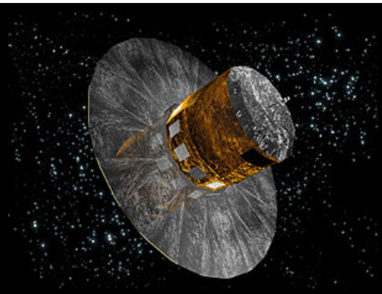
Visible to typical human eye[1]	Apparent magnitude	Brightness relative to Vega	Number of stars brighter than apparent magnitude[2]
Yes	−1.0	250%	1
	0.0	100%	4
	1.0	40%	15
	2.0	16%	48
	3.0	6.3%	171
	4.0	2.5%	513
	5.0	1.0%	1 602
	6.0	0.40%	4 800
No	7.0	0.16%	14 000
	8.0	0.063%	42 000
	9.0	0.025%	121 000
	10.0	0.010%	340 000



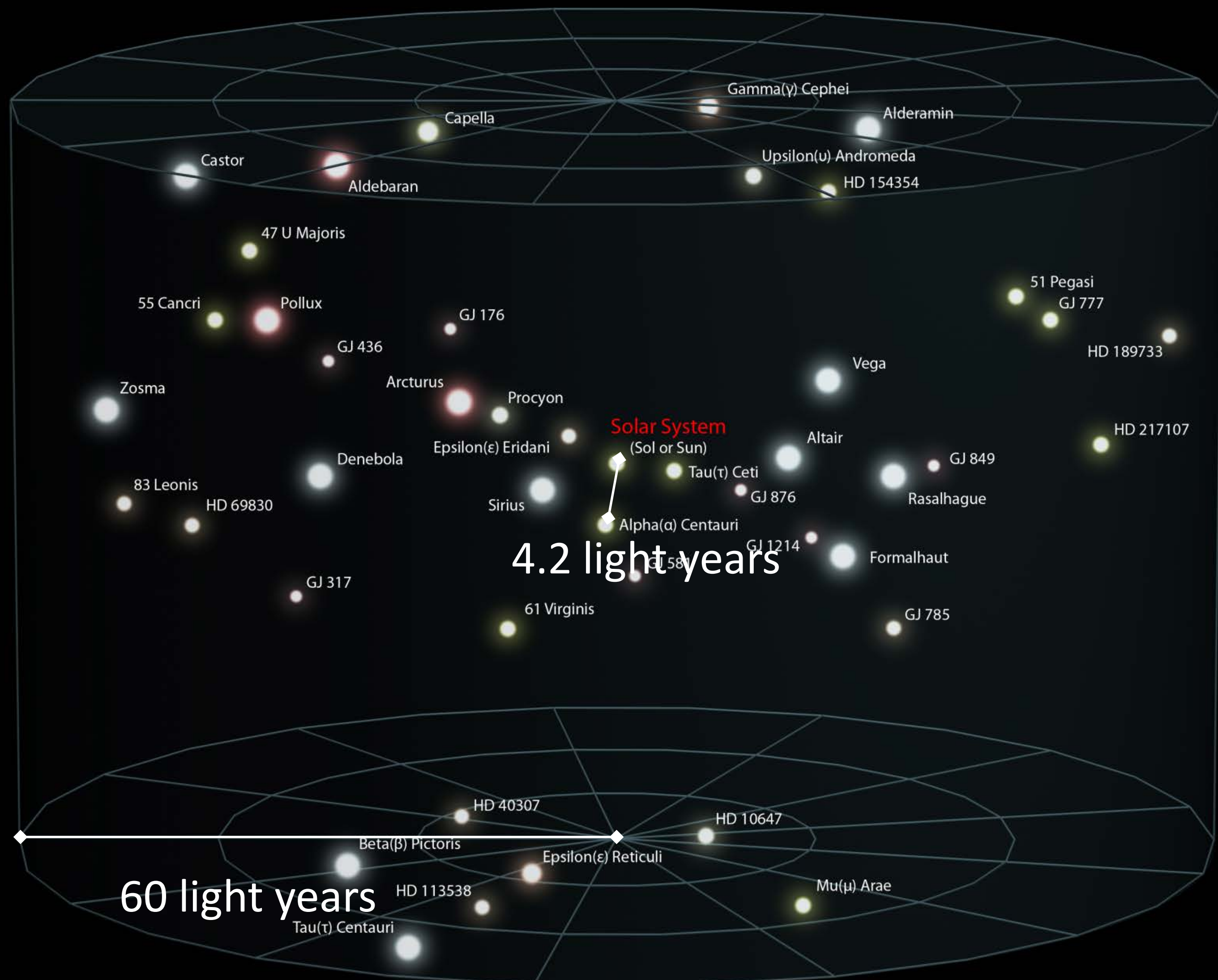
Sun: -26.74

Moon: -12.74

Gaia precision:
7 µas @ 10 mag
26 µas @ 15 mag
600 µas @ 20 mag



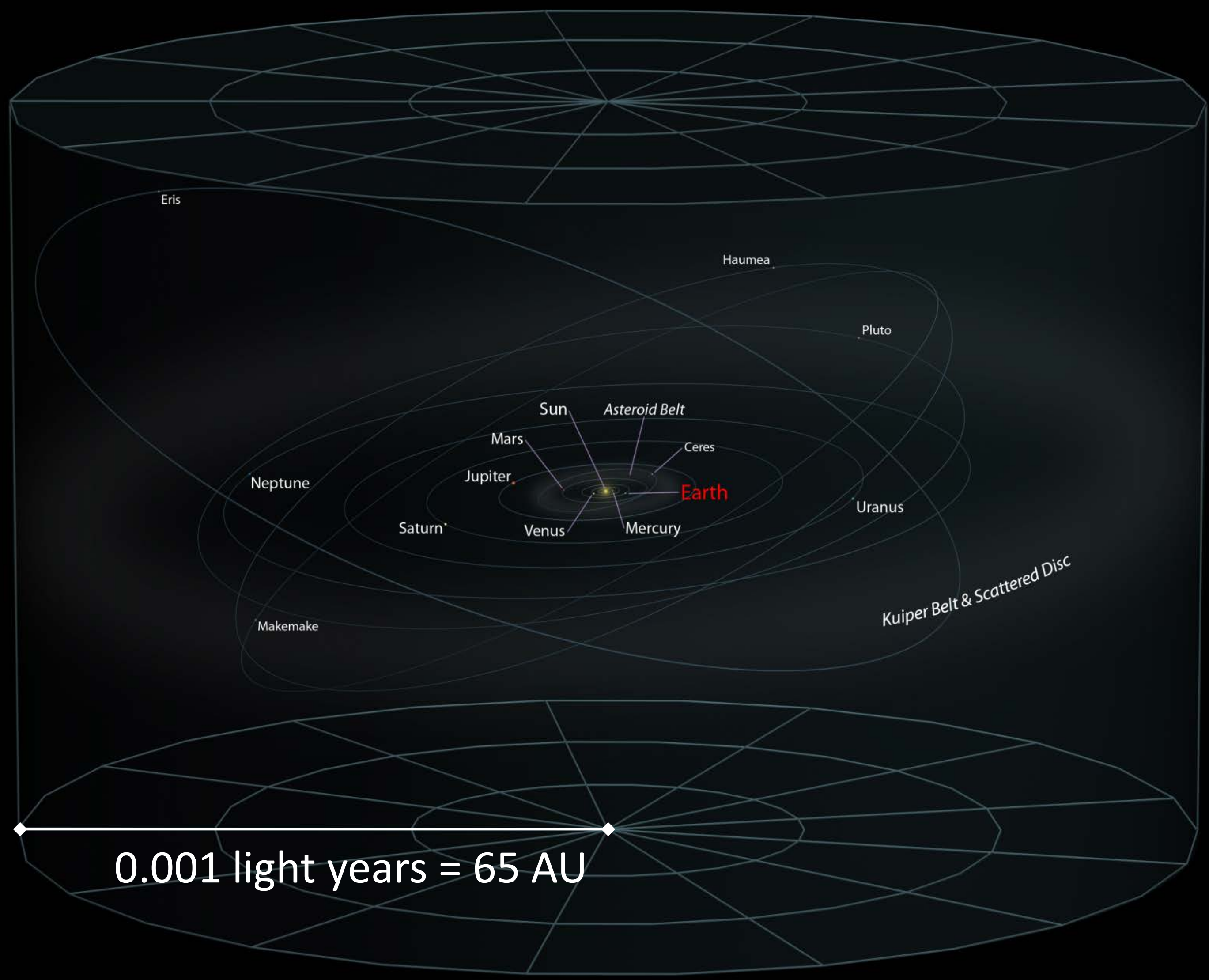
Solar Interstellar Neighborhood

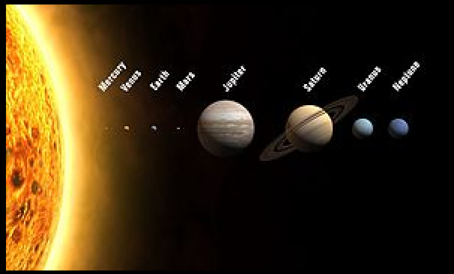


Closest star:
α-Centauri

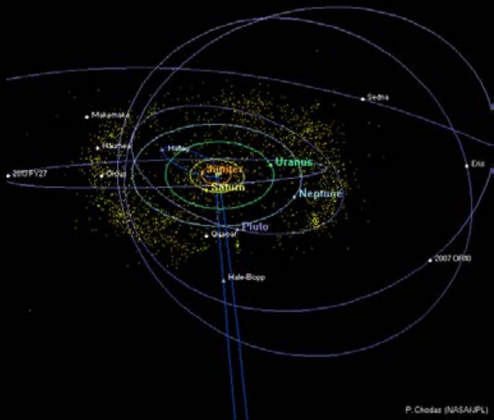
Together with β-/γ-Centauri a triple star system in the constellation: Centaurus

Solar System





Radii to scale



Planets, asteroids and comets of solar system

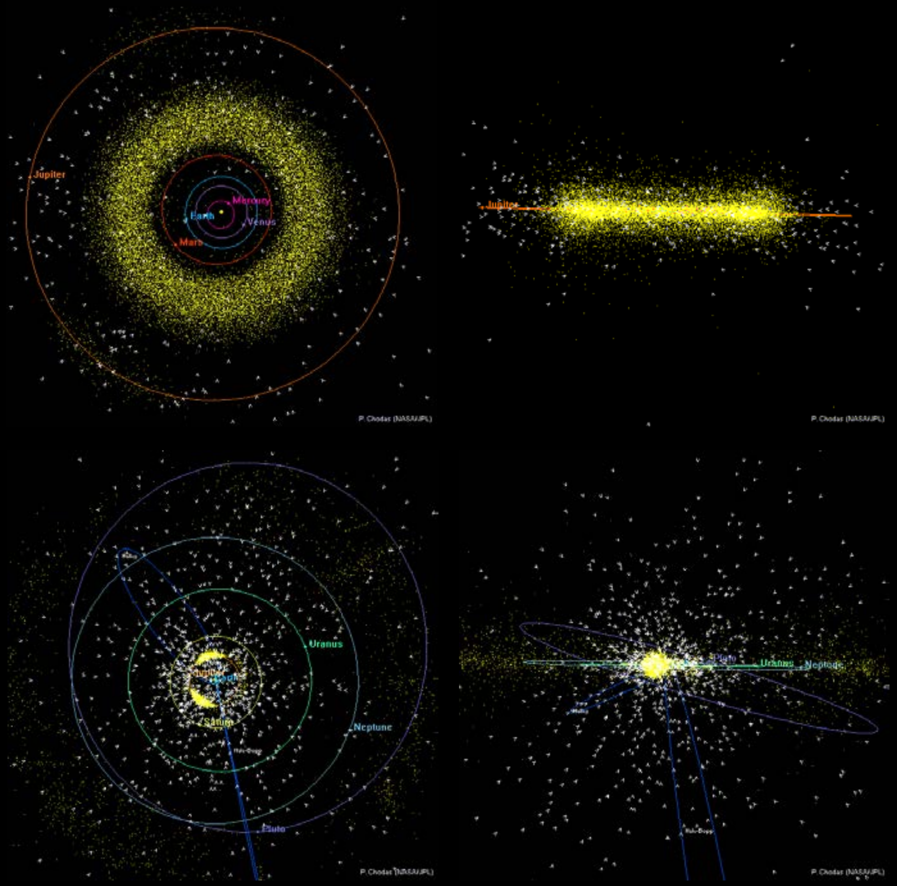
Solar System Ephemerides

Origin (defining)
Solar System Barycenter (SSB)

Orientation
Principal plain: ecliptic (defining)
Oriented w.r.t. ICRF (by convention)
Coordinates: spacetime coordinates of objects, e.g. positions, velocities, accelerations as a result of the integration of the system of differential equations (n-body problem)

Purpose
Dynamics of the solar system bodies, Sun, planets, Moon, other planets' moons, asteroids, comets, inter-planetary spacecraft navigation, deep space probes

De facto standard
JPL Planetary and Lunar Ephemerides
Version DE440 DE441 now refer to ICRF3 [1]
http://ssd.jpl.nasa.gov/?ephemerides#planets



1) Park, R.S., et al. (2021) *Astron. J.* 161:105, doi:10.3847/1538-3881/abd414

Kinematic celestial reference frames

Realization of the CRS

- All **objects are moving** in space and
  space itself **is expanding**
  There is no fix point

- The **universe has no center**
  There is no preferred point

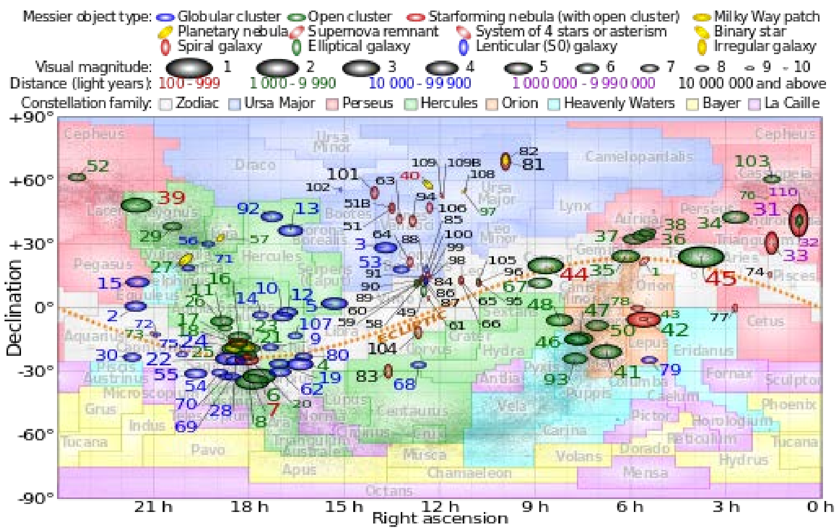
- Since there is no **absolute** measureable motion in the universe, only the **relative** motion between observer and observed object **is relevant**
  - The relative motion perpendicular to the line of sight depends on the **distance of the observer and the observed object**
  - Preferred objects for the realization of a celestial reference system are therefore **the most distant observable objects → distant galaxies (extra galactic radio sources)**

Stellar catalogues

A huge number (> 2,500) of different catalogues exists, most prominent examples

- **Messier** catalogue 1782 (M1 – M110)
- 3rd and 4th **Cambridge** catalogues, e.g. 3C 31, 4C
- **New General Catalogue** of nebulae and clusters of stars (NGC) 7840 objects by Dreyer, e.g. NGC 2841
- USNO: United States Naval Observatory, a variety of catalogues
- HD: Henry-Draper-Catalogue (brightness, spectral types)
- …

Useful archive: http://simbad.u-strasbg.fr/simbad/sim-fid



Objects of the Messier catalogue

3C 31

NGC 2841

Fundamental star catalogues

name	# stars	publ. date	Positional observations	Proper motion observations
FK für Zonenbeobachtungen am nördlichen Himmel	539	1879	∅ 1860 δ down to -10°	1850 - 1870
Neuer FK Berliner Astron. Jahrbuch nach den Grundlagen von Auwers	925	1907	∅ 1880 δ down to -89°	1745 - 1900
FK3	873	1937	1912 - 1915	
FK4	1535	1963	∅ 1950	
FK5 (CCRF 1988 - 1997)	1535	1988	∅ 1975	
FK6 (FK5 + Hipparcos)	4150	2000	∅ 1992	

Fundamental catalogues examples

Veröffentlichungen
des Astronomischen Rechen-Instituts
Heidelberg
Nr. 10

FOURTH FUNDAMENTAL CATALOGUE
(FK 4)

Resulting from the revision of the
Third Fundamental Catalogue (FK 3)

carried out under the supervision of
W. FRICKE, A. KOPFF †

in collaboration with
W. GLIESE, F. GONDOLATSCH, T. LEDERLE,
H. NOWACKI, W. STROBEL, P. STUMPFF

1963
Verlag G. Braun · Karlsruhe

http://adsabs.harvard.edu/abs/1963VeARI..10....1F

Veröffentlichungen
Astronomisches Rechen-Institut
Heidelberg

No.35

Sixth Catalogue of Fundamental Stars
(FK6)

Part I
Basic Fundamental Stars with Direct Solutions

R. Wielen, H. Schwan, C. Dettbarn,
H. Lenhardt, H. Jahreiß, R. Jährling

Kommissions-Verlag G. Braun Karlsruhe 1999

http://wwwadd.zah.uni-heidelberg.de/publikationen/vhd/vhd035/fulltext/vhd035.pdf

Radio Reference Frames

< 1977 More than 50 different radio source catalogues with about 30,000 objects [1]

1991 The IERS extragalactic Celestial Reference Frame and its tie to HIPPARCOS [2]

1997 Definition and realization of the ICRS by VLBI astrometry of extragalactic objects [3]

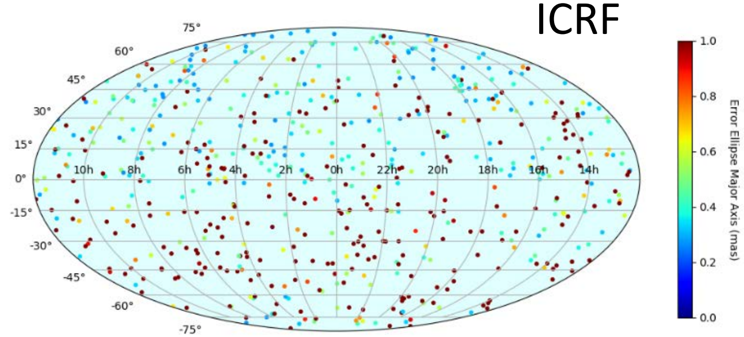
1998 ICRF [4]
212 defining
294 candidate
102 others

1999 ICRF-Ext.1 [5] 59 new

2004 ICRF-Ext.2 [6] 50 new

717 total

ICRF

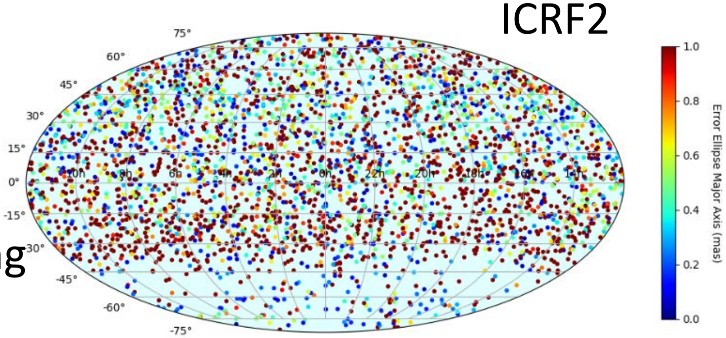


Adopted re-definition of the CCRS

2010 ICRF2 [7]
295 defining
1114 candidate
1966 survey
39 special handling

3414 total

ICRF2



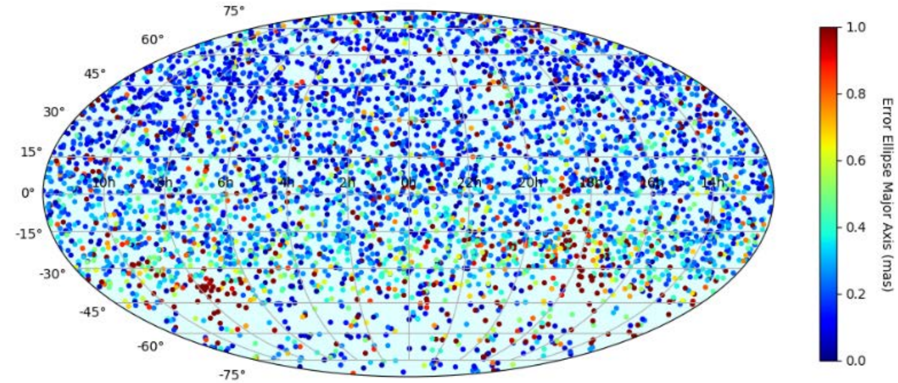
1: Kesteven & Bridle (1977), 1977JRASC..71...21K 2: IERS TN 7 (1991) 3: IERS TN 23 (1997)
4: Ma et al. (1998), 1998AJ....116..516M 5: IERS AR 1999 6: Fey et al. (2004) 7: Fey et al (2015)

Radio Reference Frames (contd.)

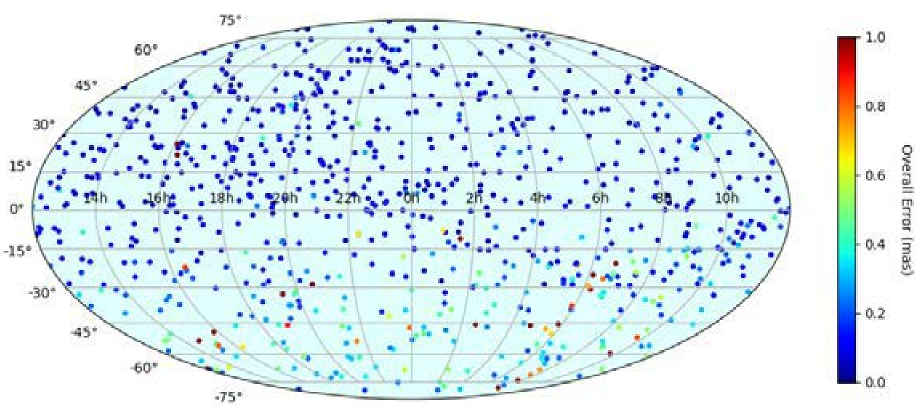
2019 ICRF3 [1]

303 defining
4233 candidates
4536 total

ICRF3 – X/S

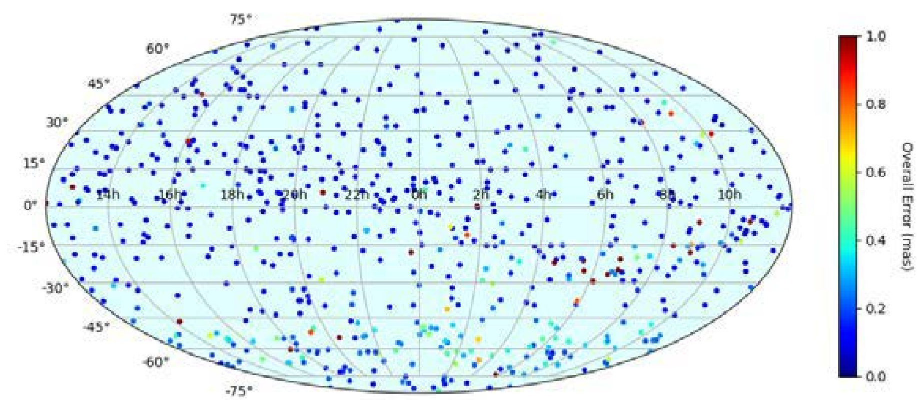


ICRF3 - K



824 total

ICRF3 – Ka/X

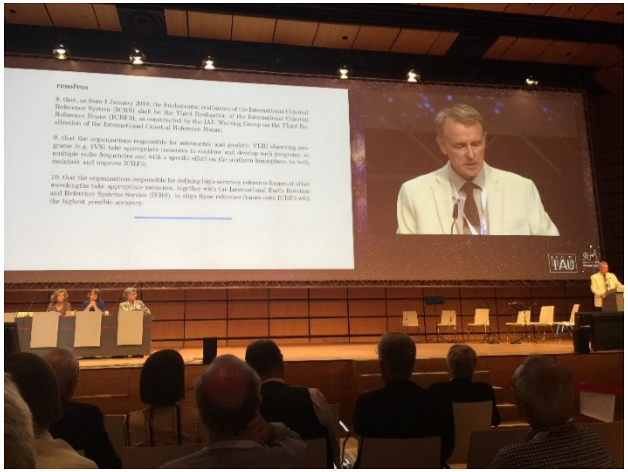


678 total

1: Charlot et al. (2020), *Astron. & Astrophys.*

Current Celestial Reference Frame: ICRF3

- The current conventional International Celestial Reference Frame ICRF3 [1] was adopted at the IAU General Assembly 2018 in Vienna, Austria



- ICRF3 was determined by an IAU Div. A WG "Third realization of the International Celestial Reference System: ICRF3" since 2012 [2]

- ICRF3 incorporates independent X/S-band, K-band and Ka/X-band solutions

- ICRF3 provides a more uniform positional error distribution (revisited ICRF2 survey sources)

- Includes about 30% more sources (≈4536) and about twice as many observations ($\approx 12 \cdot 10^6$) vs. ICRF2

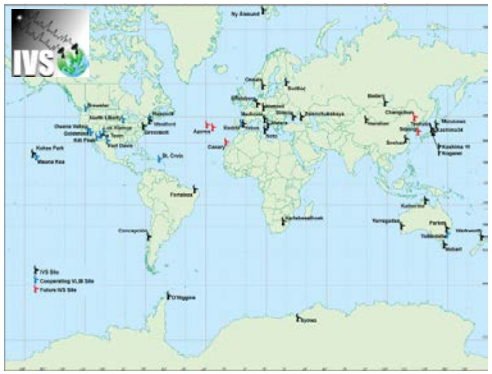
1: IAU Resolution 2018 B2 (https://www.iau.org/static/resolutions/IAU2018_ResolB2_English.pdf)

2: IAU Div. A Working Group „Third realization of the ICRF“ https://www.iau.org/science/scientific_bodies/working_groups/192/

Data sets used for ICRF3

- ICRF3 is a three-frequency frame: X/S band, K band and Ka/X band

IVS

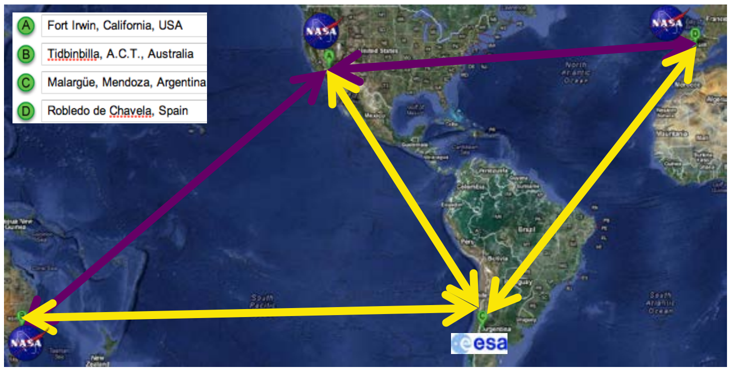


X/S band

VLBA

X/S band and K band

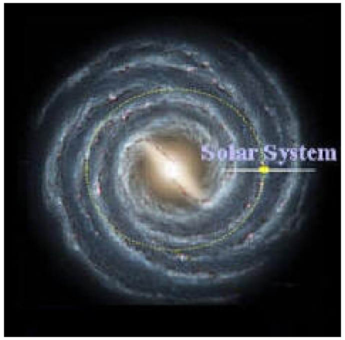
DSN + ESA



Ka/X band

Band	Frequency (GHz)	Nb of obs. (millions)	Fraction of observations (%)					Data span
			IVS	VLBA	Ht-Ho	DSN	ESA	
X/S	8.4 / 2.3	13.2	74	26				1979-2018
K	24	0.5		99	1			2002-2018
Ka/X	32 / 8.4	0.07				87	13	2005-2018

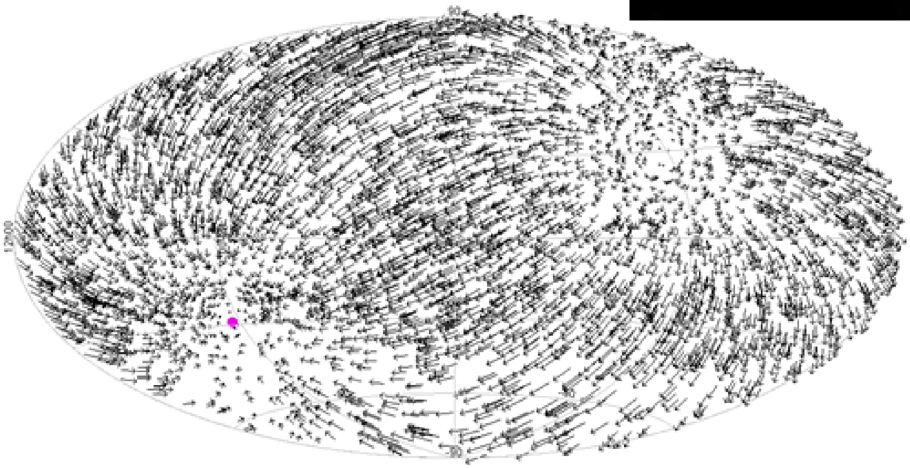
ICRF3 – galactic aberration



- ICRF3 coordinates are corrected for galactic aberration
- The linear motion of the SSB (≈220 km s^{-1}) is irrelevant (it is part of the coordinates)

- De-Sitter precession is negligible: 0.0085 μas yr^{-1} (1)

- Aberration is not negligible: ICRF3 uses VLBI value: 5.8 μas yr^{-1} while fixing the position of the galactic center to IAU values:
- $\alpha = 17^h 45^m 40^s$
  $\delta = -29° \, 00' \, 28''$



The aberration causes a dipole proper motion field towards the GC

- ICRF3 considers the aberration due to rotation of the solar system (SSB) around the galactic center (GC) on the observation level (2) → coordinates refer to epoch 2015.0 (close to Gaia)

1: Kovalevsky (2003) *Astron. Astrophys.* 404, 743

2: Titov (2011) *Astron. Rep.* 55 (1), 91

Gaia Celestial Reference Frame

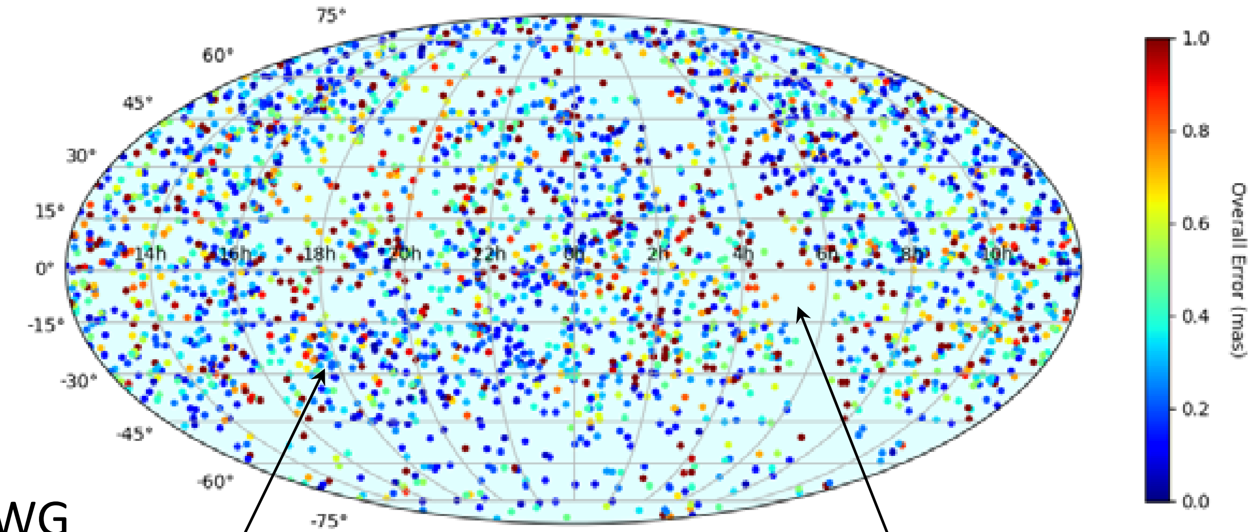
- The comparison of ICRF3 with Gaia (ESA) optical catalogue states a unique historical chance of detecting systematic errors of the VLBI and of the Gaia catalogues

- Gaia DR1 2014-07-25 – 2015-09-15

- Gaia DR2 available since 2018-04-25 [1] provides much more observations

- ICRF3 prototype solution was delivered by the IAU WG to the Gaia community for fixation of the absolute orientation and spin

Gaia DR2



Galactic center

Galactic plain

Astrometric satellite missions

Hipparcos - astrometry mission

HIPPARCOS (High Precision Parallax Collecting Satellite)

esa **1989-1993**

The Hipparcos Catalogue as a realisation of the extragalactic reference system (1)

Hipparcos-catalogue (non-inertial)
120,000 star positions (< 9 mag)
relative precision
coordinates ~1 mas @ 9 mag
Optical realization of ICRS (1)

Tycho-catalogue (non-inertial)
> 1,000,000 star positions (12.4 mag)
relative precision
coordinates ~30 mas

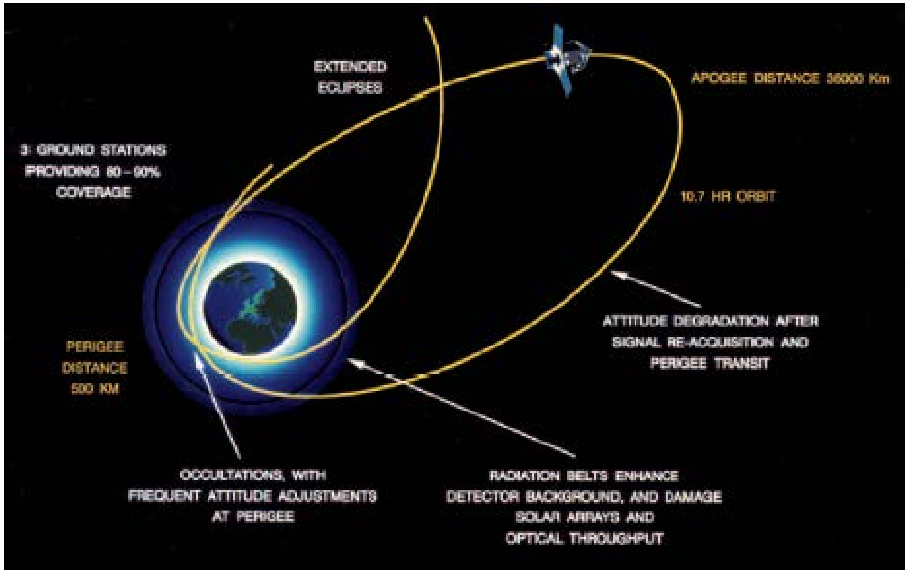
1 Kovalevsky et al. (1997) + IAU Resolution B1.2 (2000)

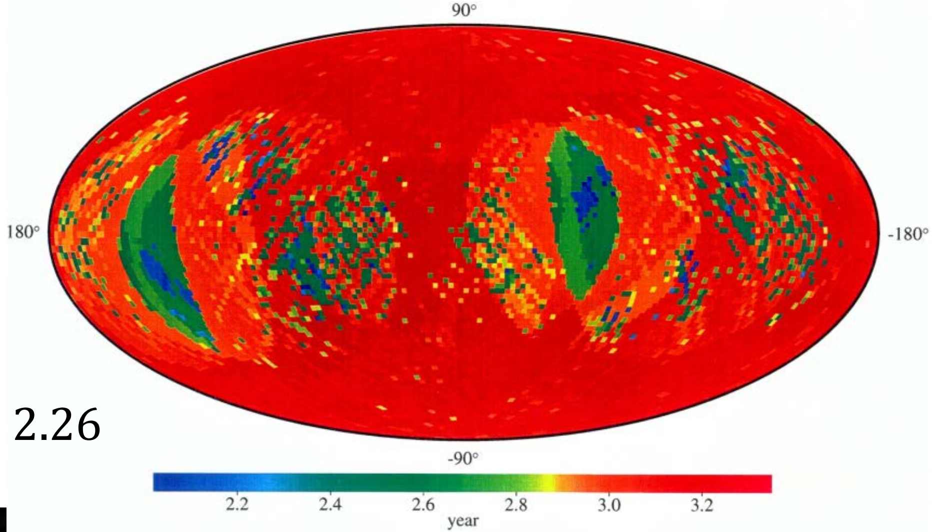
Hipparcos precision and orbit

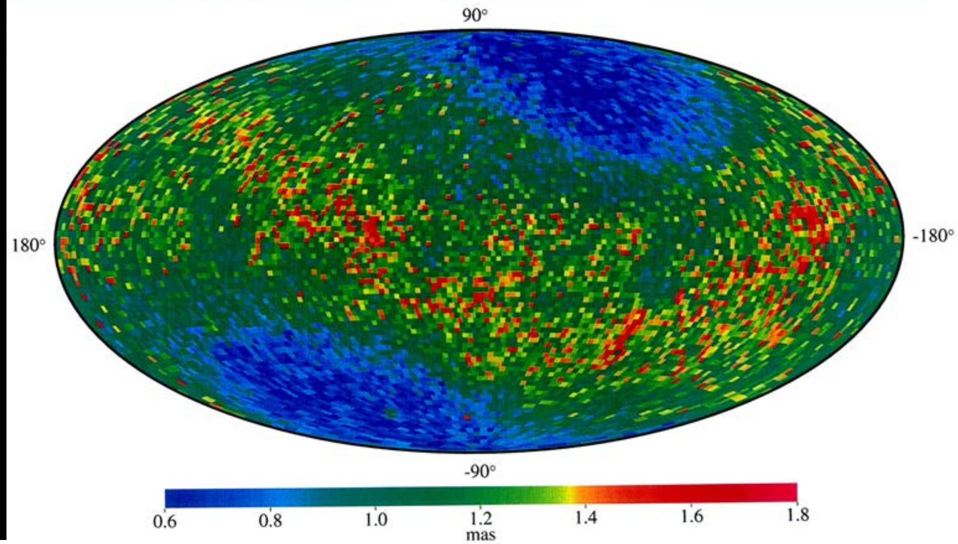
HIPPARCOS

Highly elliptical orbit
(following a failure to reach its
nominal geostationary orbit)

$$e = 0.72, i = 6.8, \Omega = 84.4, \omega = 116.5, n = 2.26$$



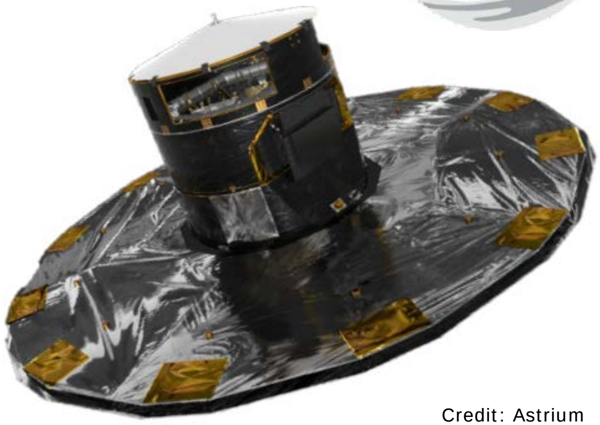




Gaia - astrometry mission

Gaia (Global Astrometric Interferometer for Astrophysics)

esa **since DEC 2013 for ~ 5 yr**



Credit: Astrium

Gaia-catalogue (non-inertial)
> 1,000,000,000 star positions
relative precision

astrometry-grid	7 μas @ 10 mag
	26 μas @ 15 mag
	600 μas @ 20 mag

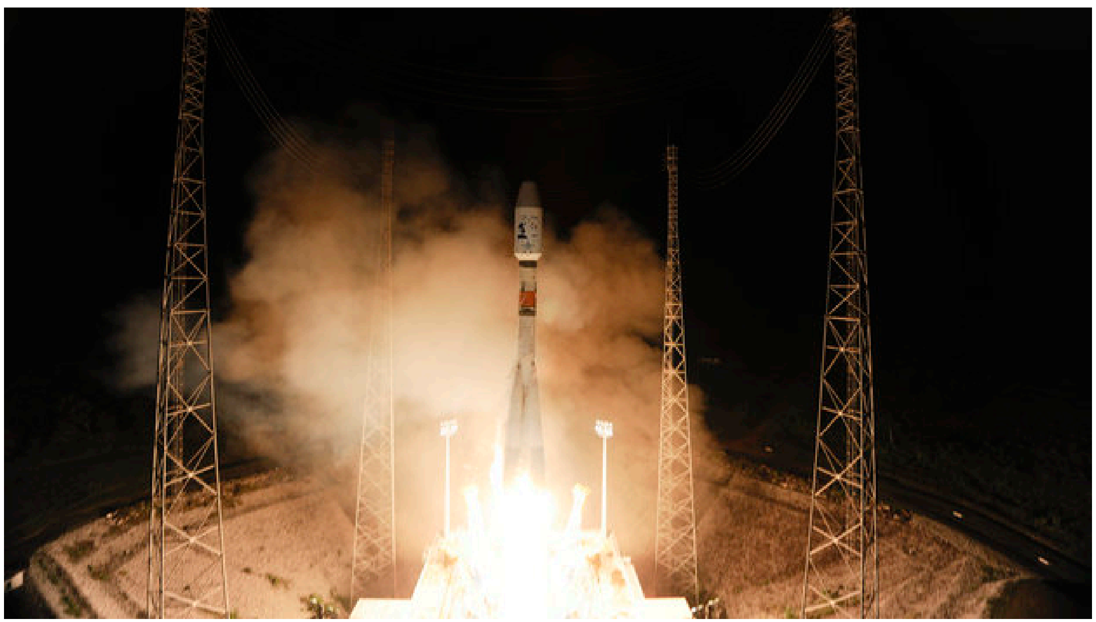
Besides optical objects, 600,000 radio sources will be observed as well!

Gaia launch

Gaia

19 DEC 2013

from Kourou (France)



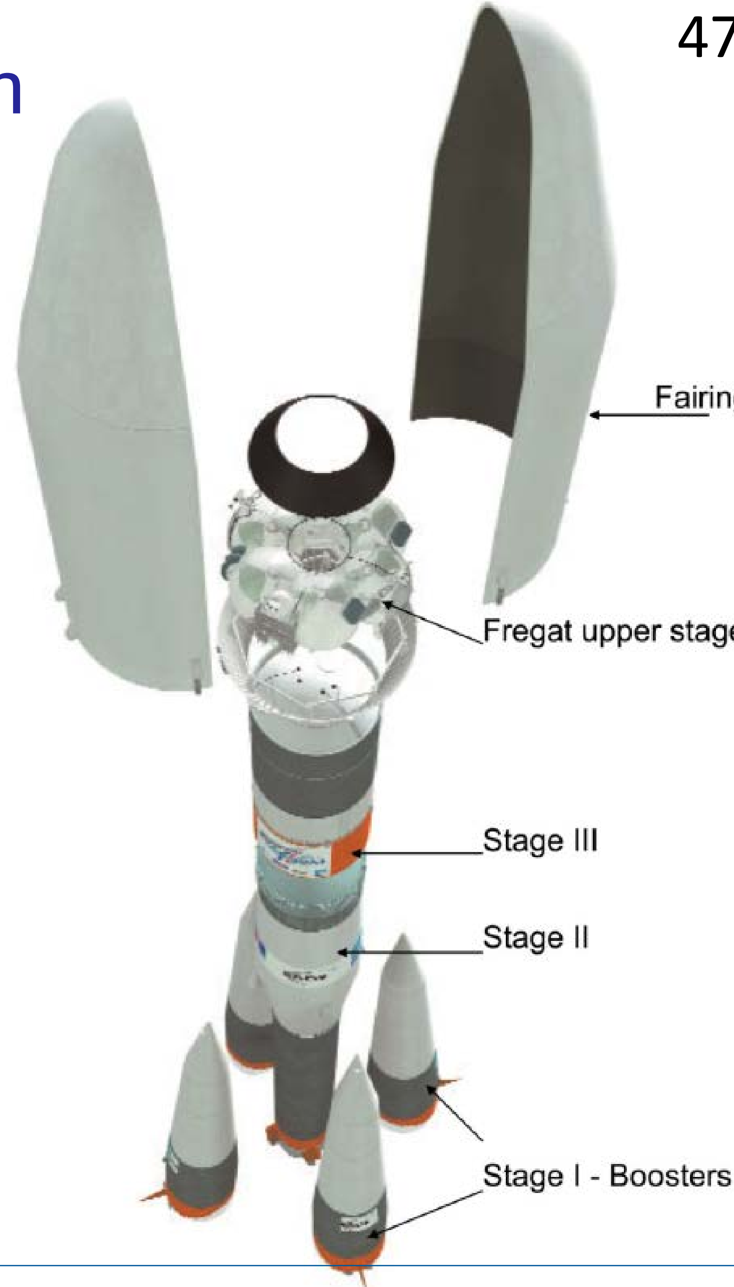
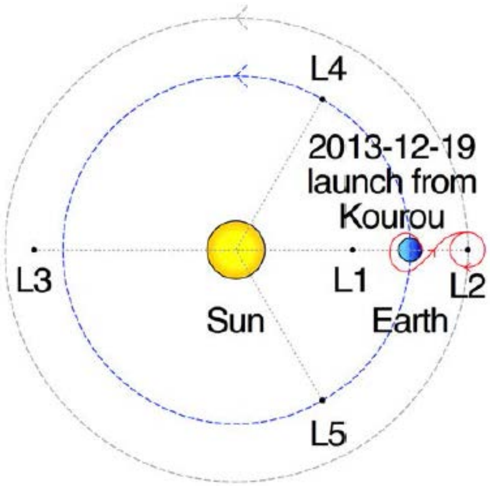
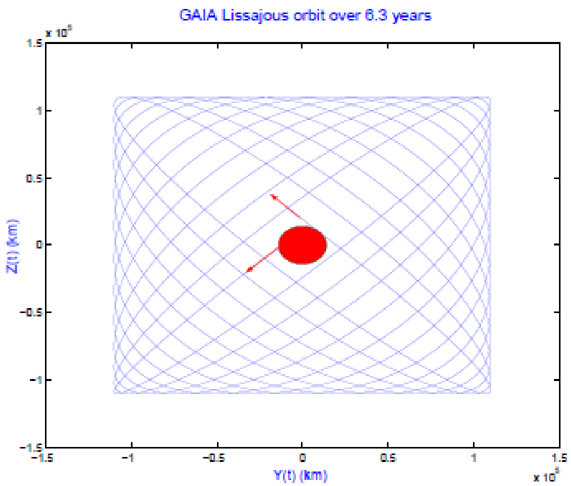


Figure Soyuz: Arianespace; figure Gaia: ESA - C. Carreau

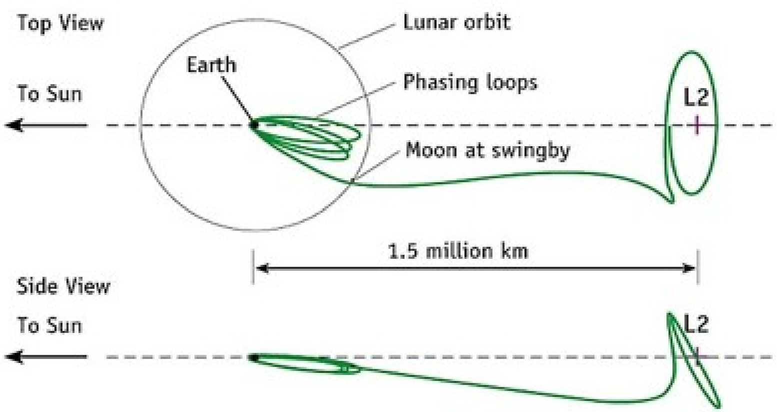
Gaia orbit



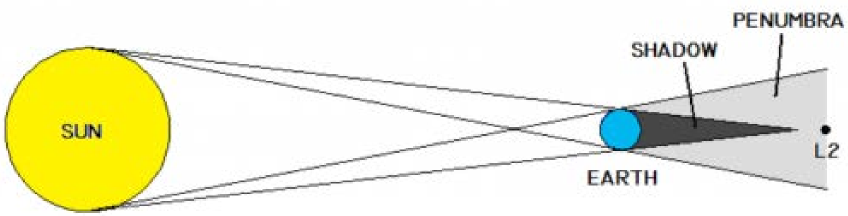
L2 Lagrangian Point



Lissajous orbit around L2



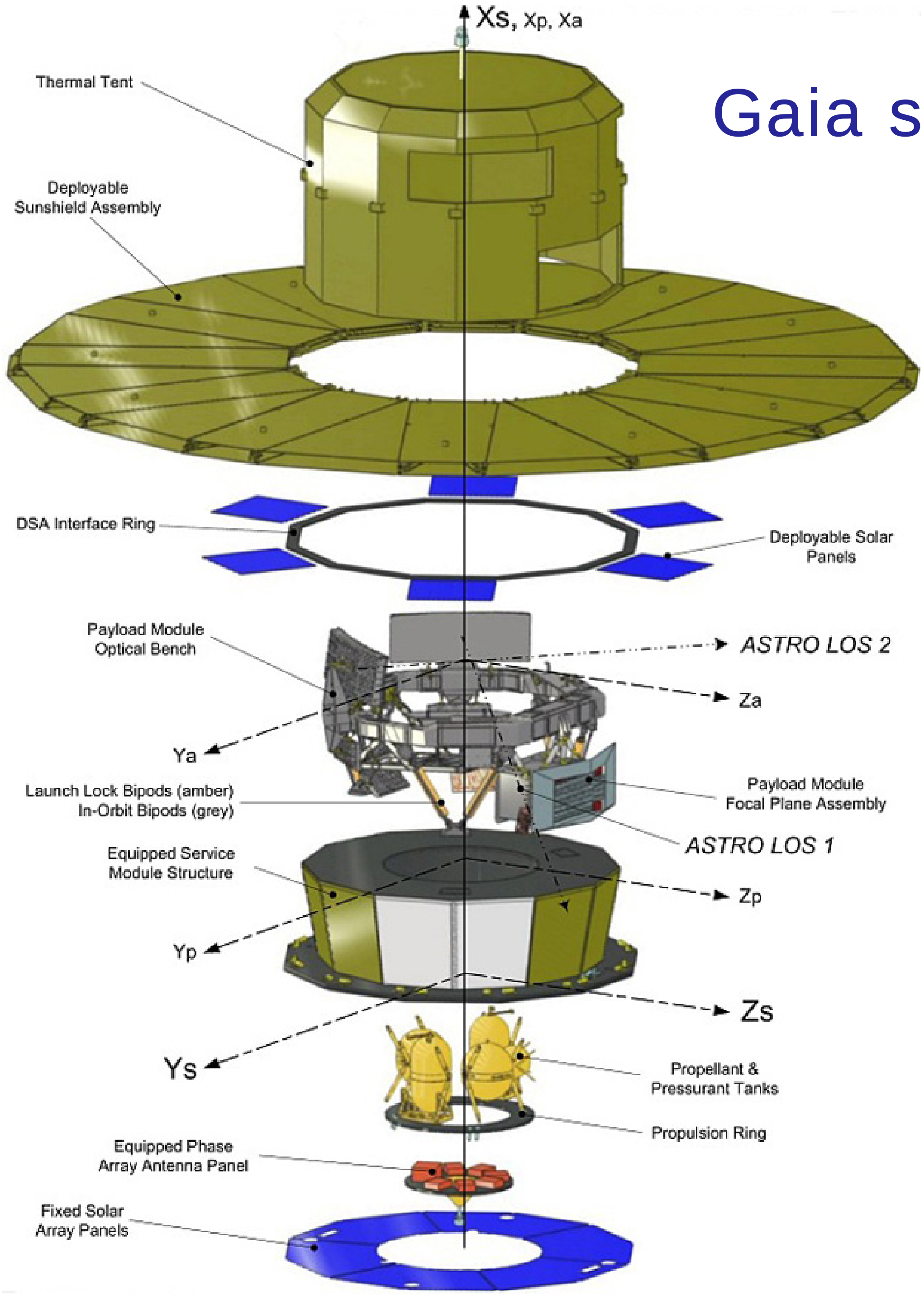
Orbit and orbit insertion



Sun light situation at L2 point

ESA Gaia technology video

Gaia satellite design



GFZ Helmholtz Centre Potsdam

Gaia payload

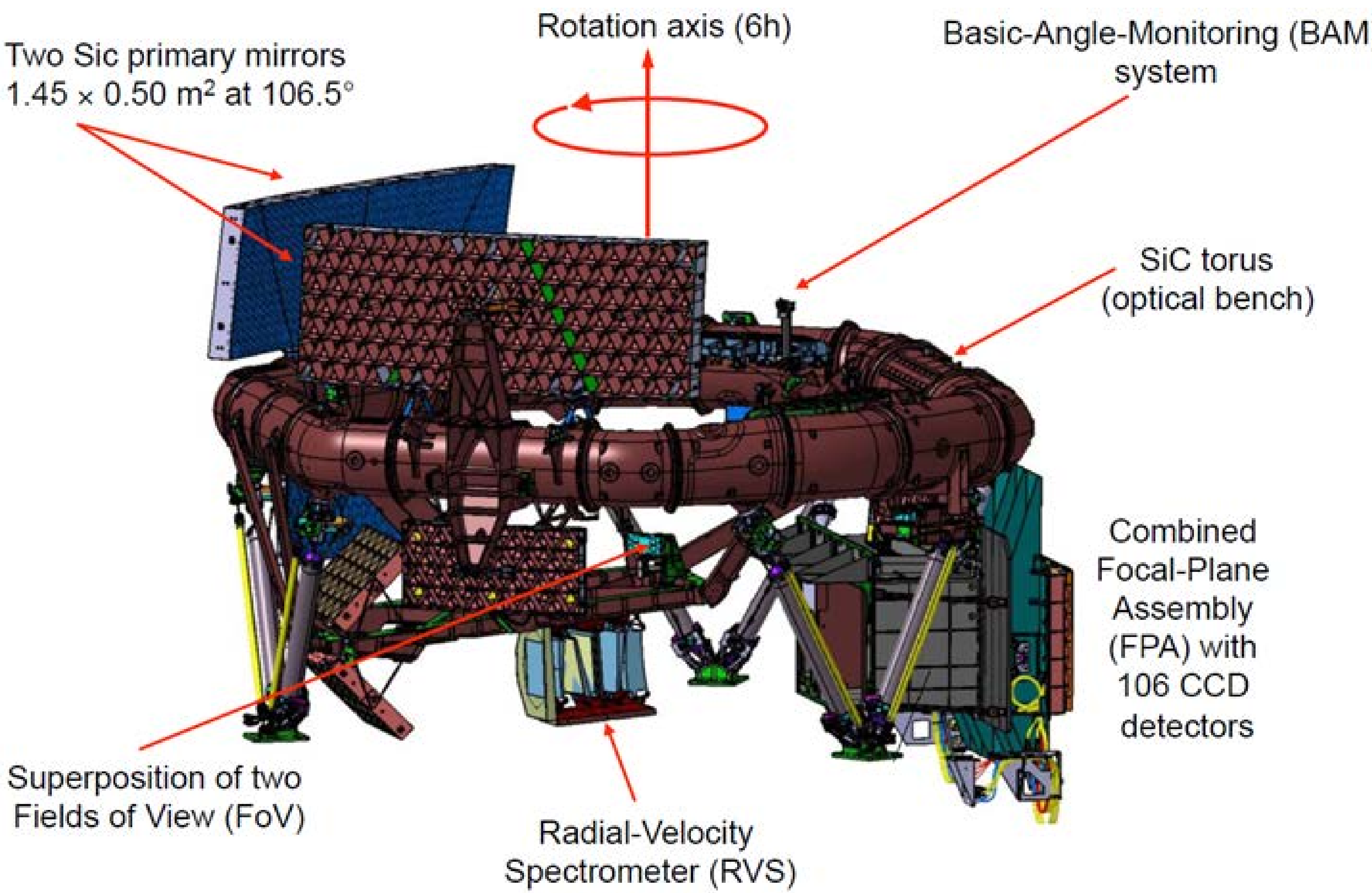
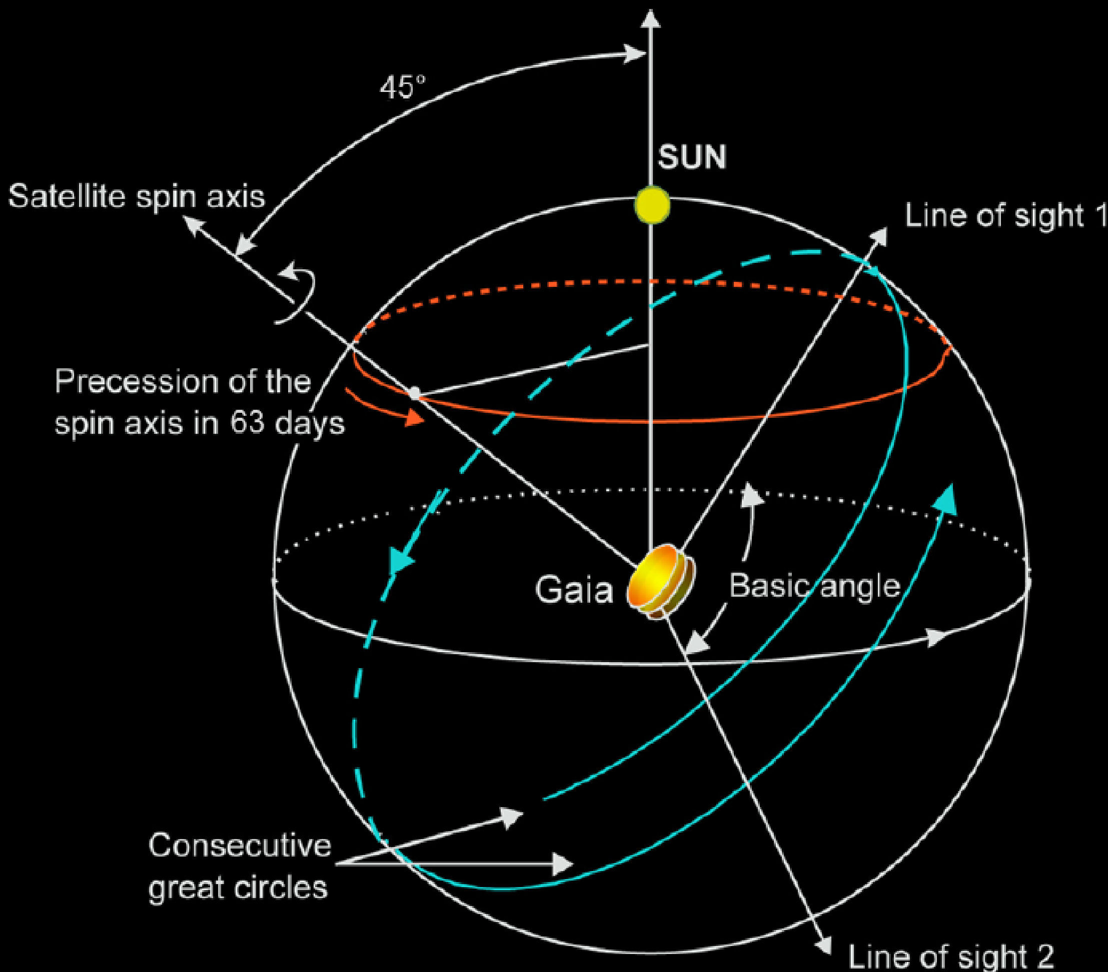


Figure courtesy EADS-Astrium

GFZ
Helmholtz Centre
POTSDAM

Inside Gaia’s billion-pixel camera

Gaia observing principle

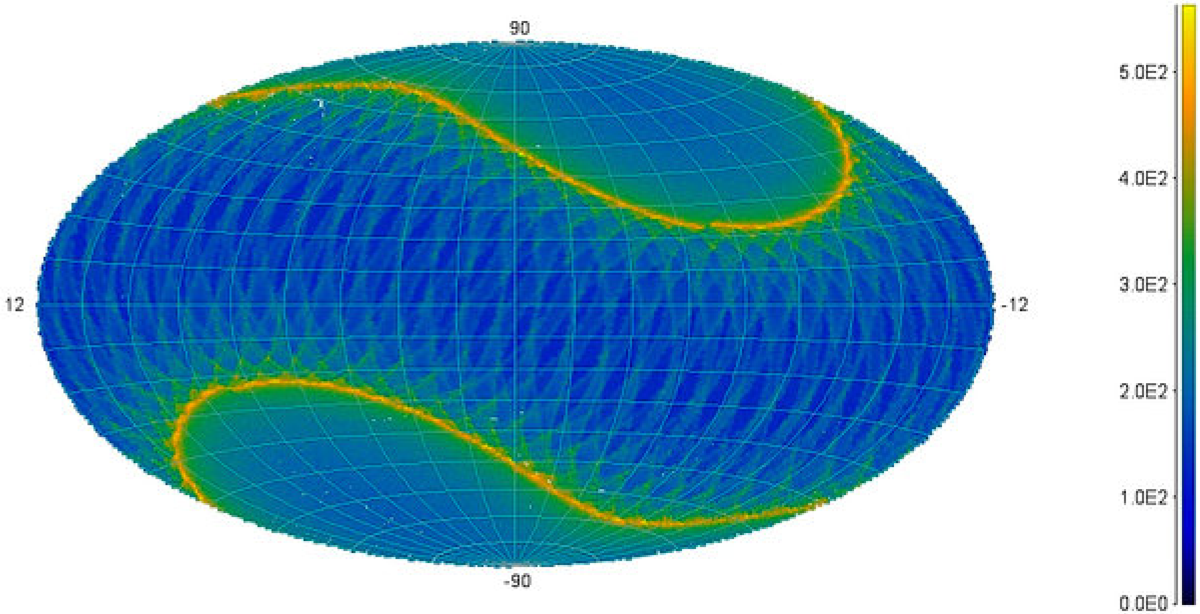


Spin axis	45° to Sun
Scan rate:	60 arcsec s^{-1}
Spin period:	6 hours

Gaia scanning law

Gaia is a scanning mission → no pointing, no change in the schedule

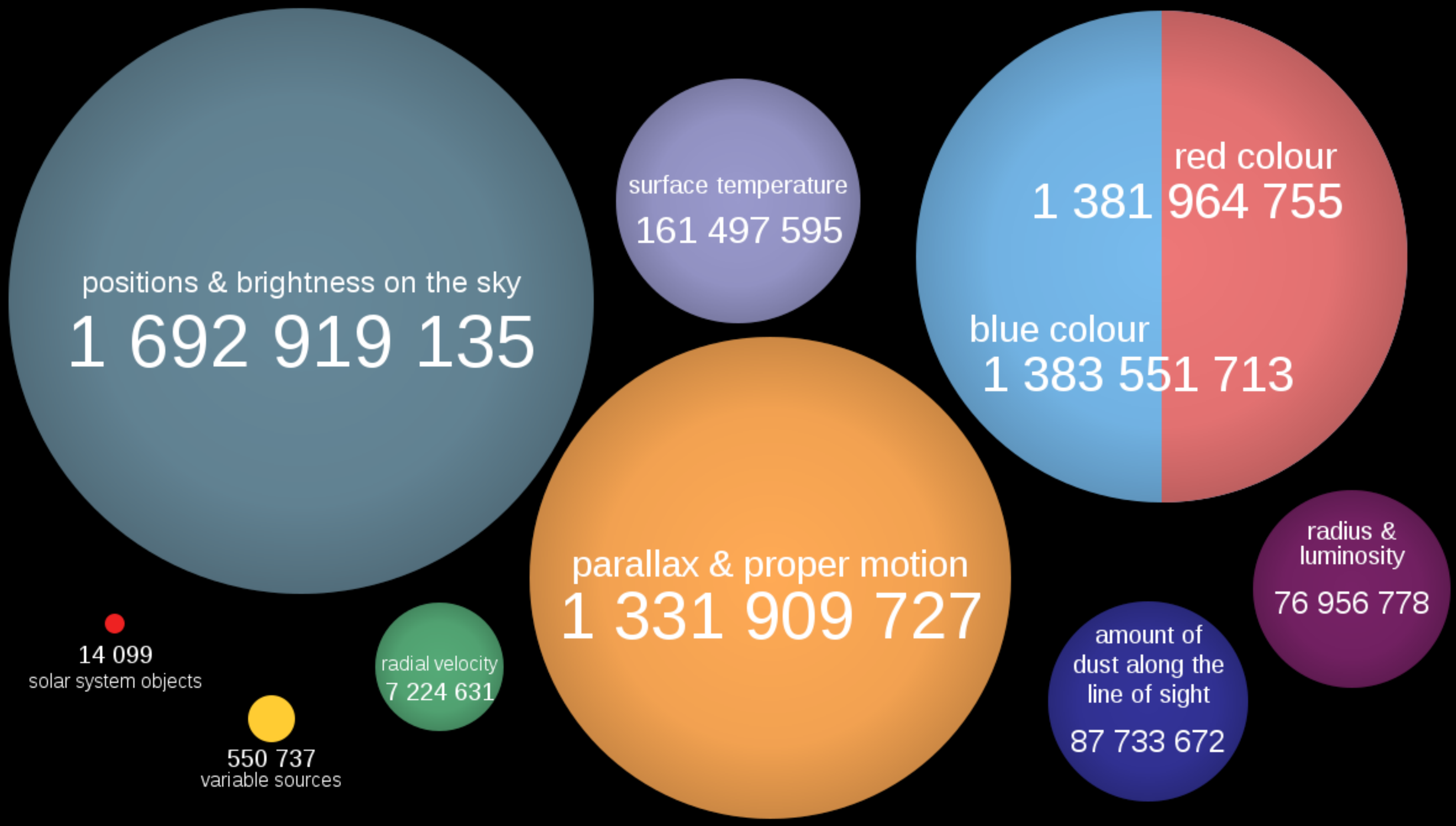
Gaia scanning law



Gaia gathers astrometric, photometric, and spectroscopic data →
each object is observed ~ 75 times in astrometric and photometric and
~ 50 times in spectroscopic mode during the mission duration ~ 5 y

Gaia data release 2 (DR2)

How many stars will there be in the second Gaia data release?



Gaia data release scenario

Gaia

esa

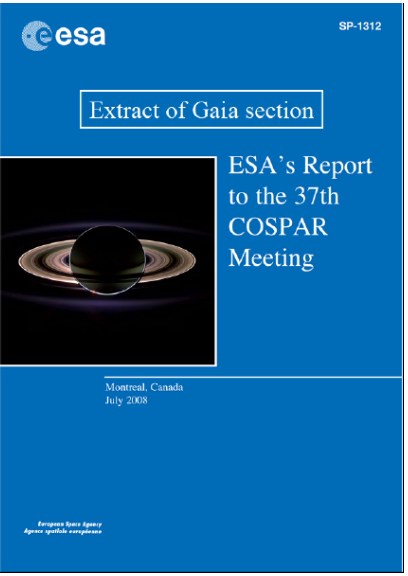
- Gaia DR1 2014-07-25 – 2015-09-15
- Gaia DR2 2014-07-25 – 2016-05-23 available since 2018-04-25 [1] provides much more observations
  - astrometry (positions, start of proper motions, parallaxes)
  - radial velocities
- Gaia DR3 split into EDR3 (Early Data Release) since 2020-12-03 [2] and DR3, date TBD, currently delayed due to SARS-CoV-2 pandemic
  - improved astrometry (proper motions)
- Gaia full release for the nominal mission

GFZ Helmholtz Centre POTSDAM

1) https://www.cosmos.esa.int/web/gaia/release
2) https://www.cosmos.esa.int/web/gaia/earlydr3

TU berlin

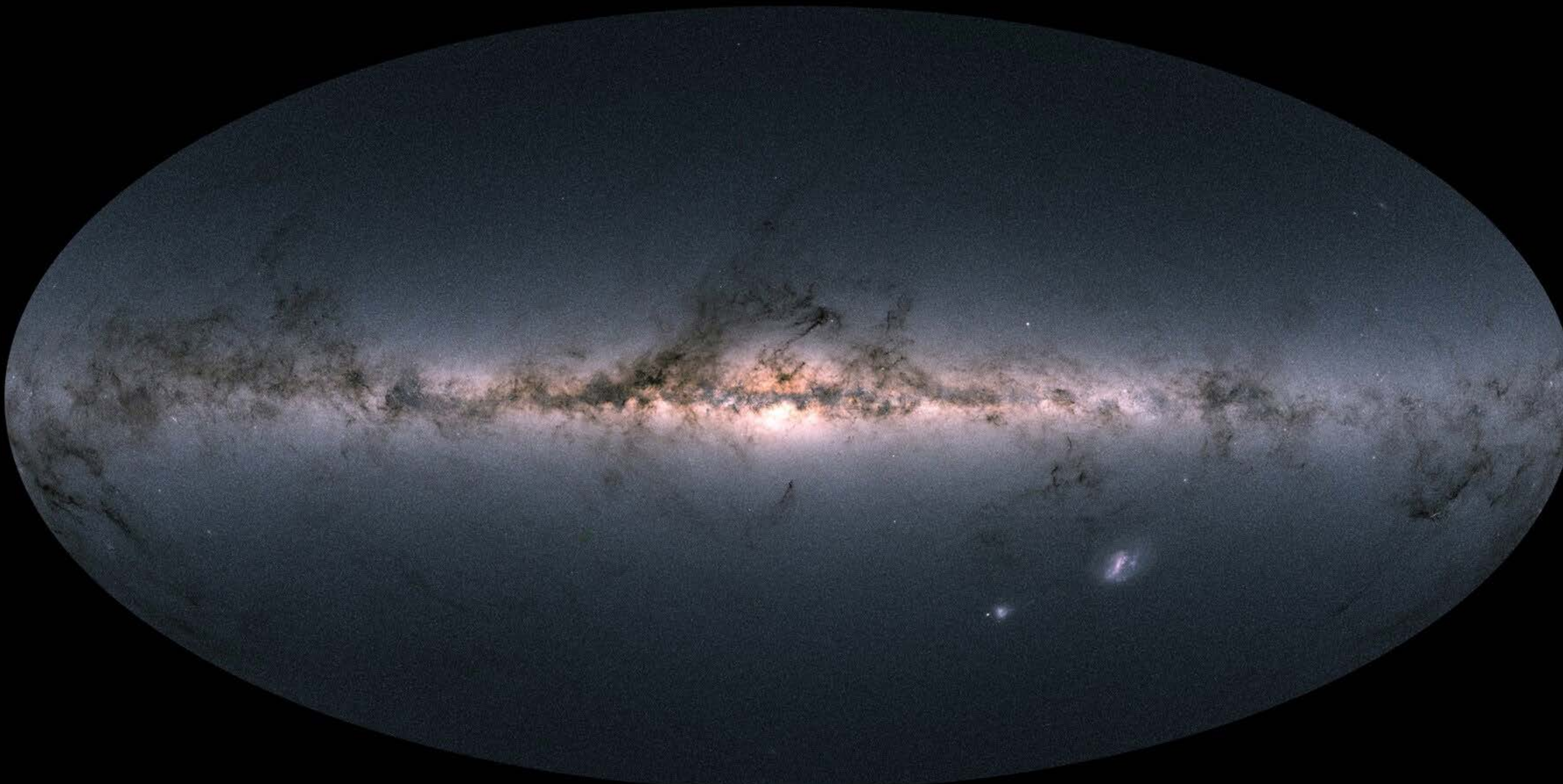
Gaia – Hipparcos comparison

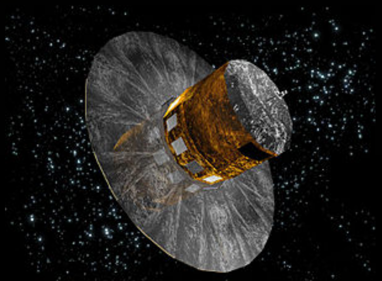


	Hipparcos	Gaia *
Magnitude limit	12 mag	20 mag
Completeness	7.3 – 9.0 mag	20 mag
Bright limit	0 mag	3 mag (assessment for brighter stars ongoing)
Number of objects	120,000	47 million to G = 15 mag 360 million to G = 18 mag 1192 million to G = 20 mag
Effective distance limit	1 kpc	50 kpc
Quasars	1 (3C 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

* However, Gaia is already exceeding its nominal life time

Local Galactic Group





as seen by Gaia

GFZ Helmholtz Centre POTSDAM

berlin

References

References

Antonucci, R., Nature, 495, 7440, 165-167, 2013
Fey, A., et al., Astron J, 127, 3587—3608, 2004
Fey, A., et al., Astron J, 150, 2, 58, 16, 2015
Kesteven M.J.L., Bridle A.H. 1977, J. Roy. Astron. Soc. Canada 71, 21, 1977
Kovalevsky, J., et al., Astron Astrophys, 323, 620—633, 1997
Le Bail, K., et al., Astron J 151, 79, DOI: 10.3847/0004-6256/151/3/79, 2016
Lieske, J.H., et al., Astron. Astrophy, 58, 1—16, 1977
Ma, C., et al., Astron J, 116, 516—546, 1998
Mortlock, D.J., et al., Nature, 474, 7353, 616-619, 2011
Seidelmann, P.K., Celestial Mechanics, 27, 79—106, 1982
Sovers, O.J., et al., Reviews of Modern Physics, 70, 4, 1393-1454, 1998
Uchiyama, Y., et al., Astrophys. J., 648 (2), DOI: 10.1086/505964, 2006
Wilkins, G.A. & I.I. Mueller, http://adsabs.harvard.edu/full/1986HiA.....7..771W, 1986

Web resources:
IAU 1991: https://www.iau.org/static/resolutions/IAU1991_French.pdf
IAU 1997: https://www.iau.org/static/resolutions/IAU1997_French.pdf
IAU 2000: https://www.iau.org/static/resolutions/IAU2000_French.pdf
IERS, Annual Report 1999:
http://www.iers.org/IERS/EN/Publications/AnnualReports/AnnualReport1999.html
IERS TN 7, 1991: http://www.iers.org/IERS/EN/Publications/TechnicalNotes/tn07.html
IERS TN 23, 1997: http://www.iers.org/IERS/EN/Publications/TechnicalNotes/tn23.html

http://sci.esa.int/hipparcos/
http://sci.esa.int/gaia/
https://www.cosmos.esa.int/web/gaia/

The end