



Astronomija i astrofizika I

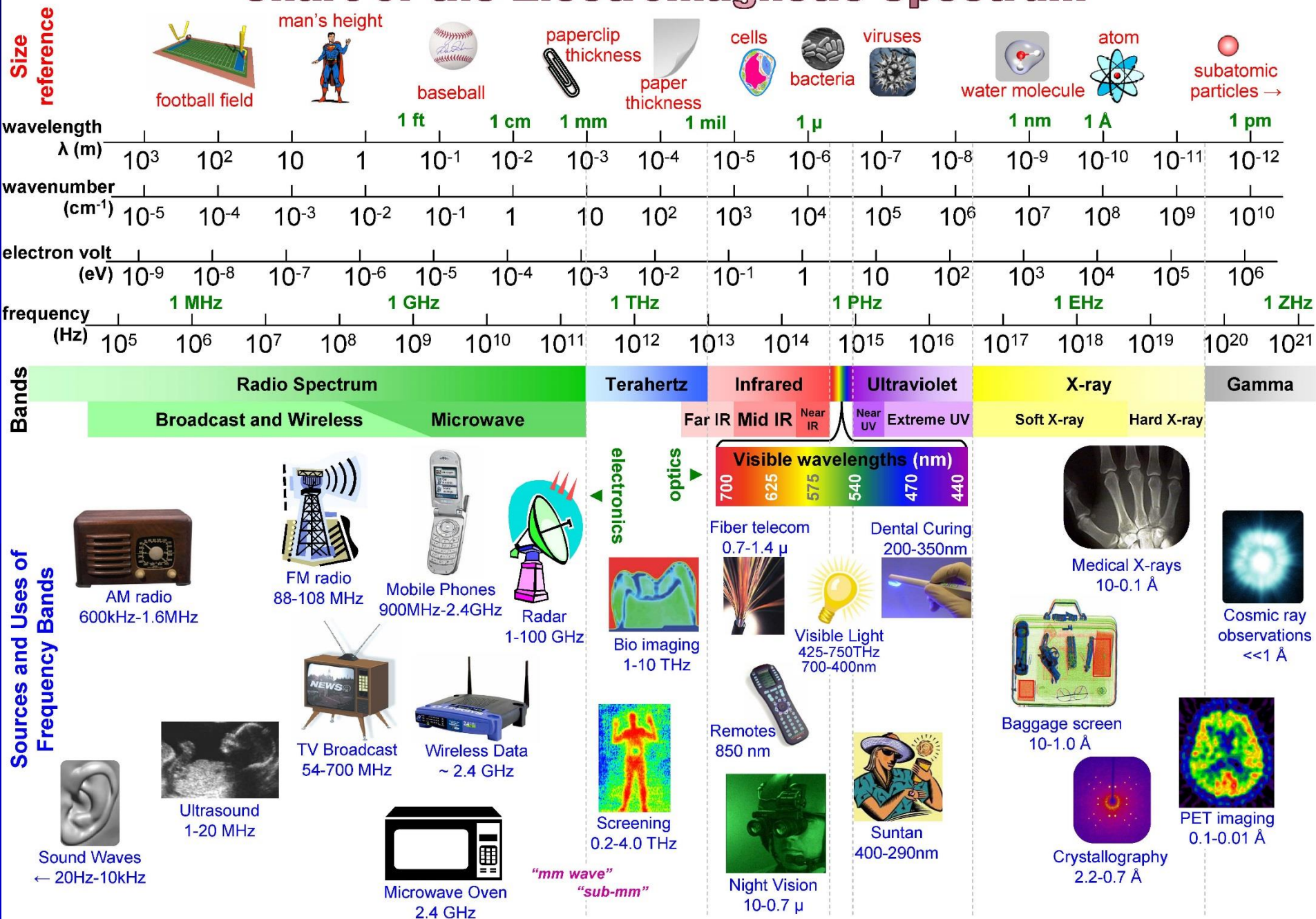
Teleskopi i detektori

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Chart of the Electromagnetic Spectrum



$$\lambda = 3 \times 10^8 / \text{freq} = 1 / (\text{wn} \times 100) = 1.24 \times 10^{-6} / \text{eV}$$

THE ELECTROMAGNETIC SPECTRUM

THESE WAVES TRAVEL THROUGH THE ELECTROMAGNETIC FIELD. THEY WERE FORMERLY CARRIED BY THE AETHER, WHICH WAS DECOMMISSIONED IN 1897 DUE TO BUDGET CUTS.

ABSORPTION SPECTRA:

HYDROGEN:



HELIUM:



DEPENDS®:



TAMPAX®:



RED ORANGE YELLOW GREEN BLUE VIOLET



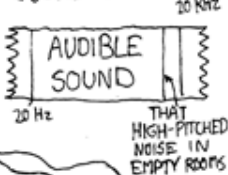
VISIBLE LIGHT

OTHER WAVES:

SLINKY WAVES



SOUND WAVES



THE WAVE



SHOUTING CAR DEALERSHIP COMMERCIALS

CIA (SECRET)

HAM RADIO

KOSHER RADIO

SPACE RAYS CONTROLLING STEVE BALLMER

99.3 "THE FOX"

101.5 "THE BADGER"

106.3 "THE FRIGHTENED SQUIRREL"

24/7 NPR PLEDGE DRIVES

AM (US)

VHF

UHF

FHF

CELL PHONE CANCER RAYS

ALIENS SETI

WIFI

BRAIN WAVES

SULAWESI

GRAVITY

SUPERMAN'S HEAT VISION

JACK BLACK'S HEAT VISION

SUNLIGHT

MAIN DEATH STAR LASER

POTATO

BLOGORAYS

MAIL-ORDER X-RAY GLASSES

SINISTER GOOGLE PROJECTS

CENSORED UNDER PATRIOT ACT

POWER & TELEPHONE

RADIO & TV

MICROWAVES

TOASTERS

IR

VISIBLE LIGHT

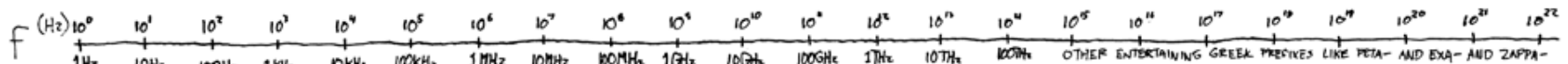
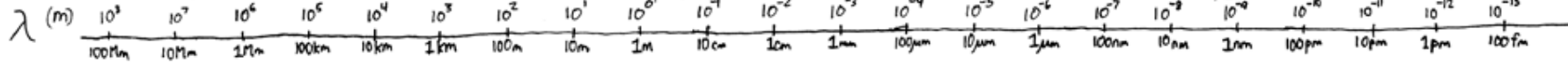
UV

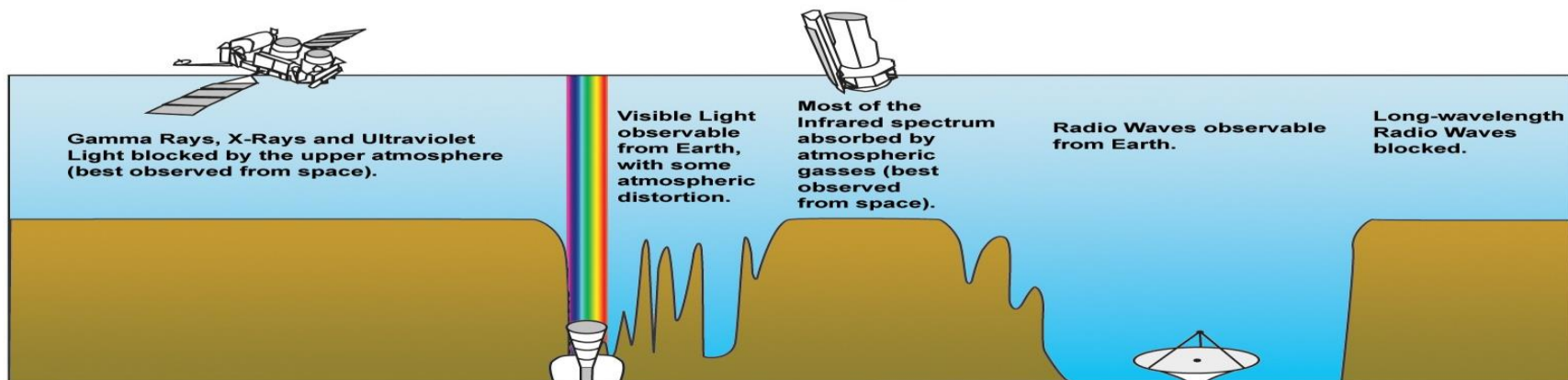
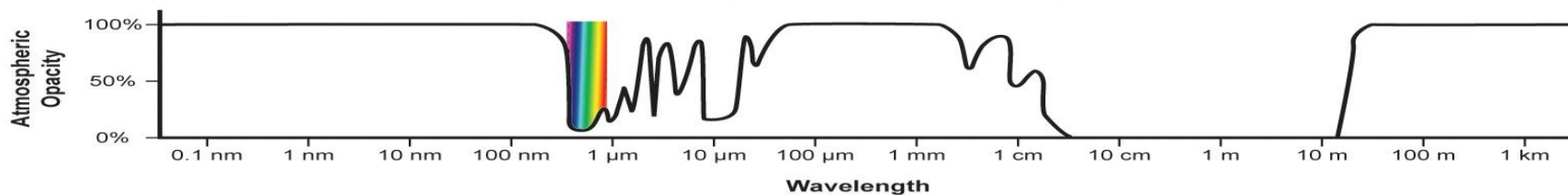
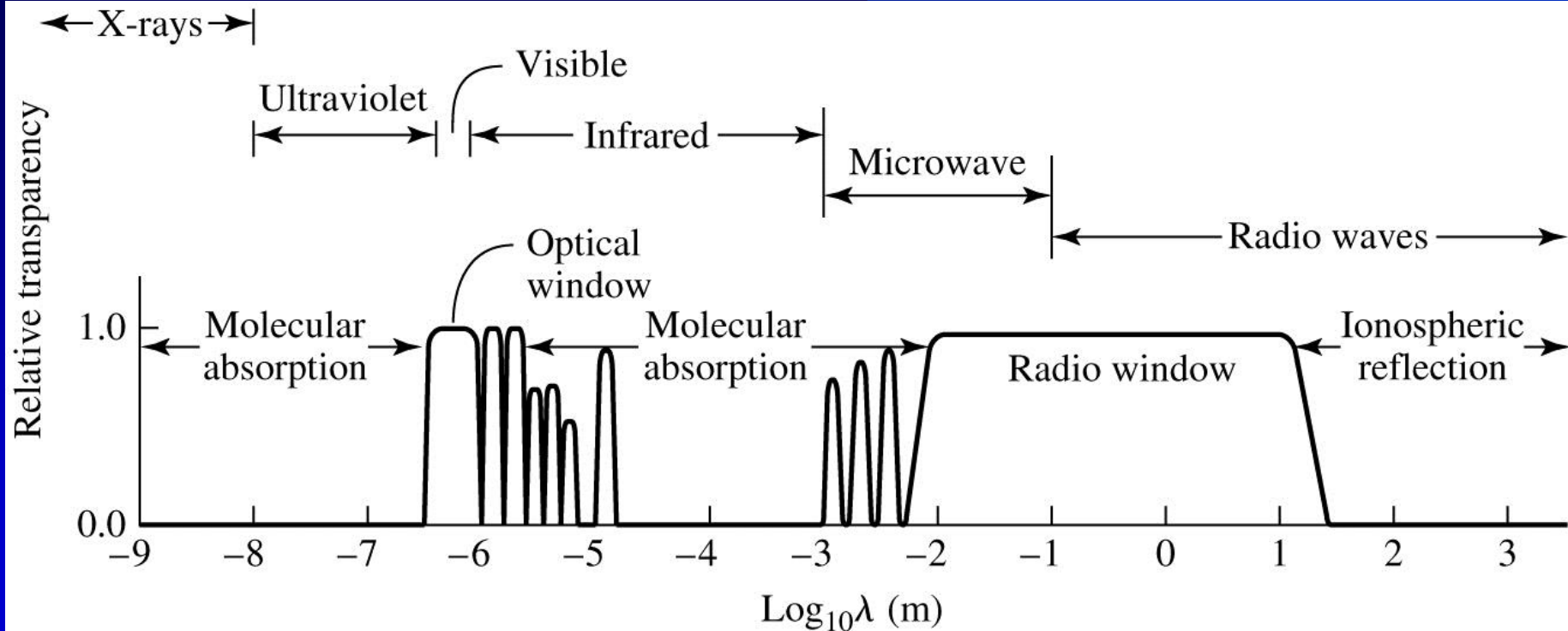
VISIBLE DARK

MILLER LIGHT

X-RAYS

GAMMA/COSMIC RAYS





Teleskopi

1. Refraktori (objektiv je leća)
2. Reflektori (objektiv je ogledalo)
3. Katadioptri (kombinacija leća i ogledala)

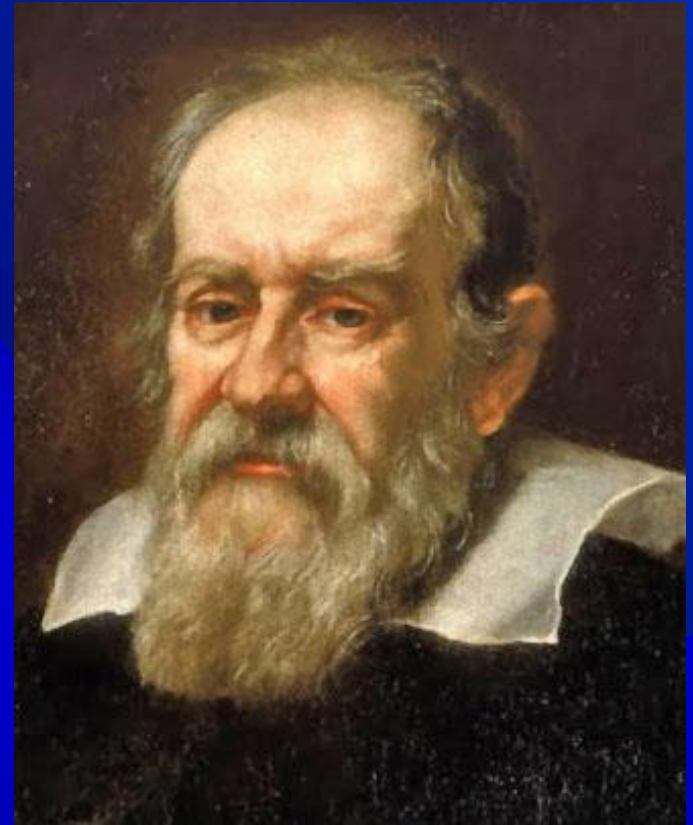
1608. Nizozemska – Hans Lippershey & Zacharias Janssen (Middelburg), Jacob Metius (Alkmaar) – refraktor



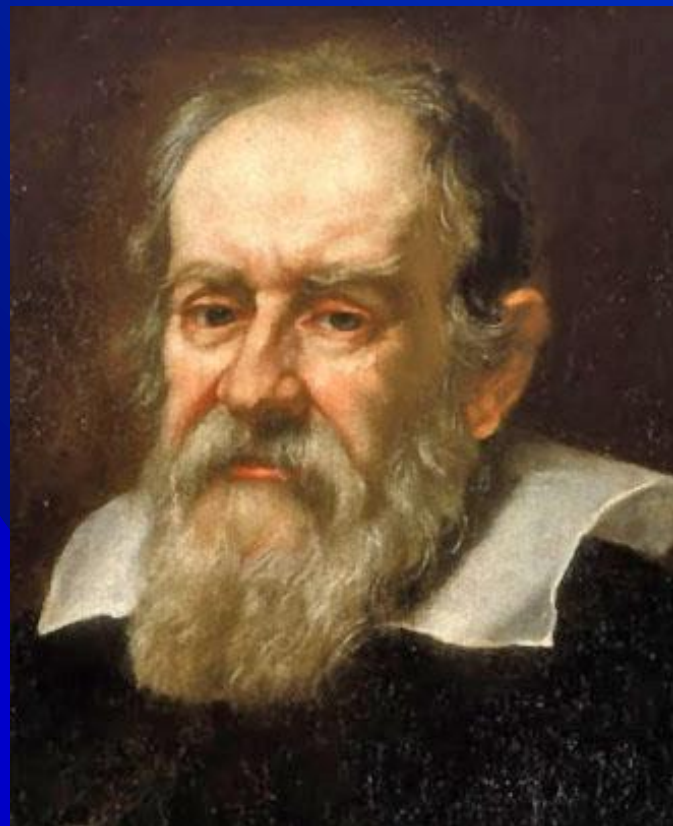
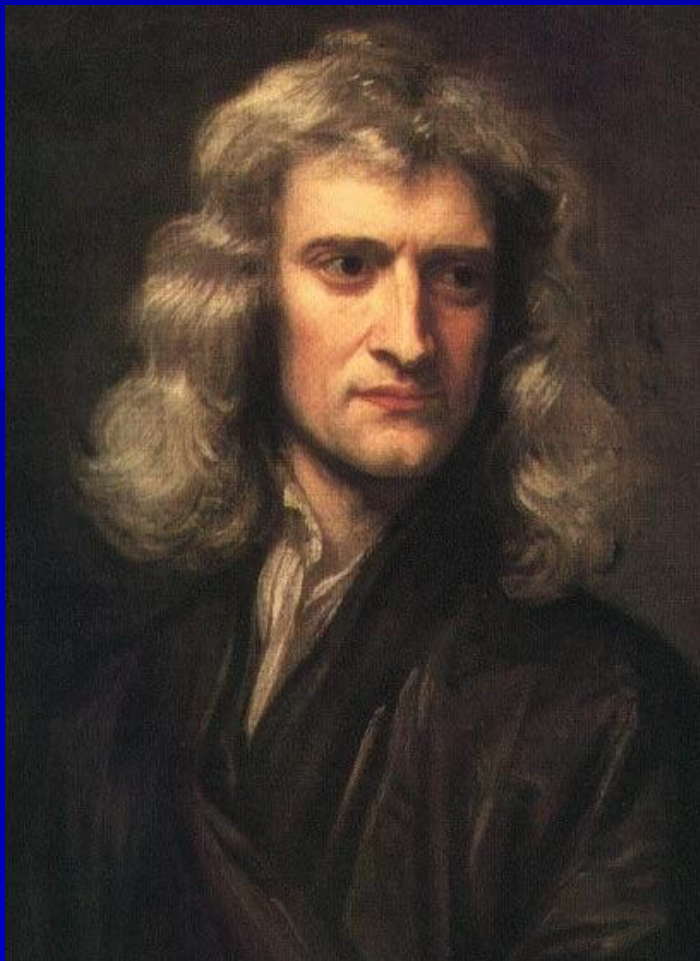
Teleskop, grč., 'tele' – daleko,
'skopein' – vidjeti -> Giovanni
Demisiani 1611.

Galileo Galilei:

- Heliocentrički sustav
- Krateri na Mjesecu
- Mliječni put
- Faze Venere
- Sunčeve pjege
- Jupiterovi sateliti



Teleskop, grč., 'tele' – daleko,
'skopein' – vidjeti -> Giovanni
Demisiani 1611.



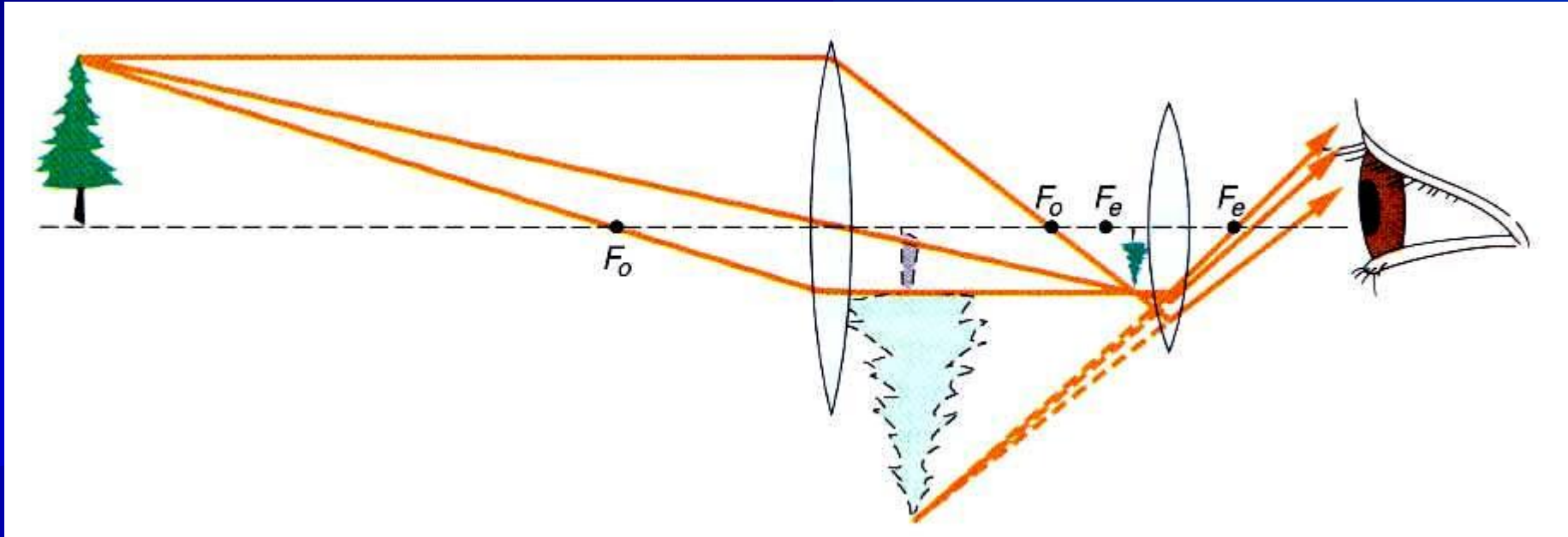
1668. V. Britanija – Isaac Newton –
reflektor

1733. – akromatska leća

1857. – posrebrivanje ogledala

1937. – aluminizacija ogledala

KEPLEROV (ASTRONOMSKI) TELESKOP



Objektiv – konveksna leća

Okular – konveksna leća

Obrnuta slika

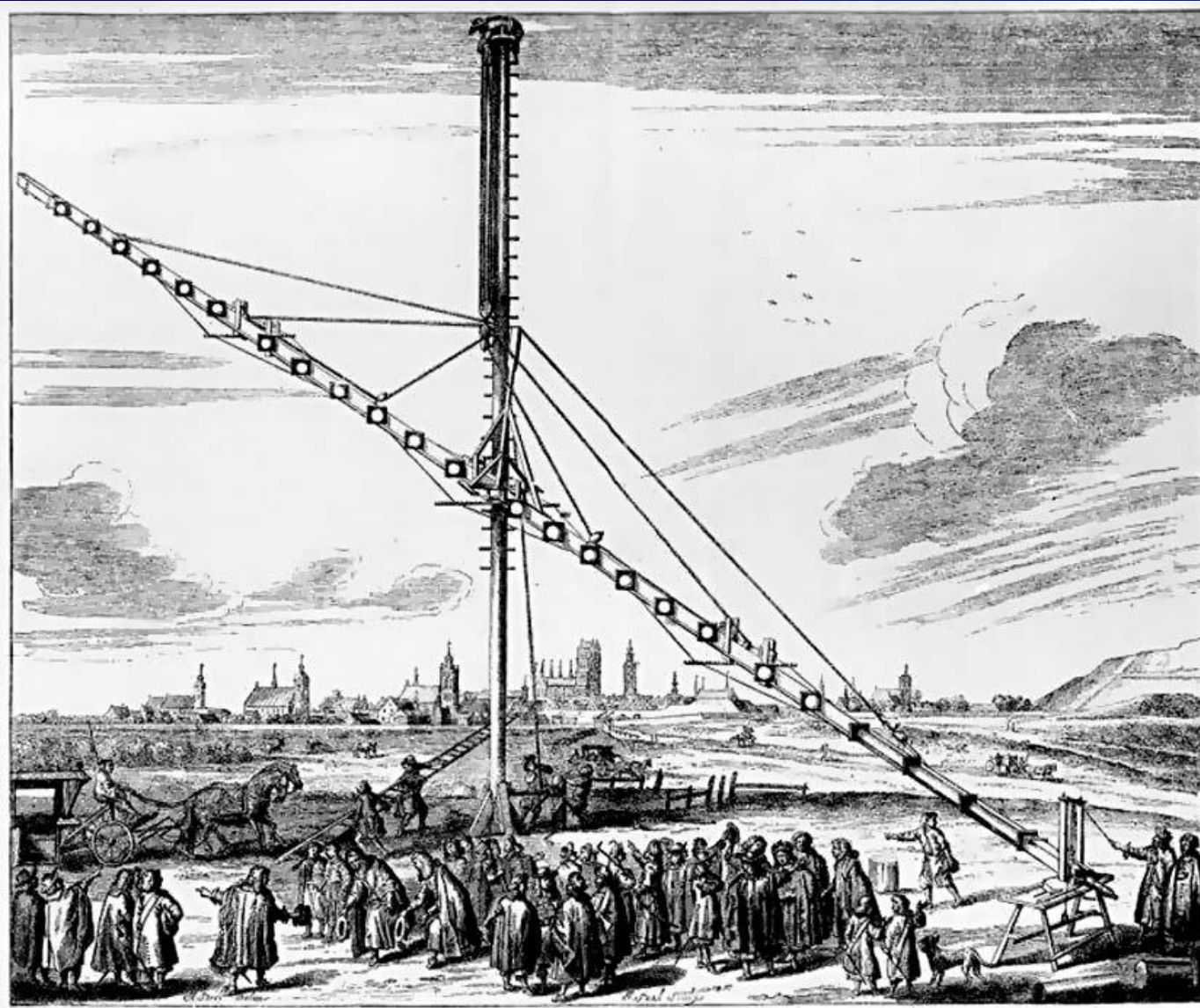
Veliko vidno polje

Dobar kontrast

Kromatska i sferna aberacija – zahtjeva veliki f-omjer

$$l = f_o + f_e$$

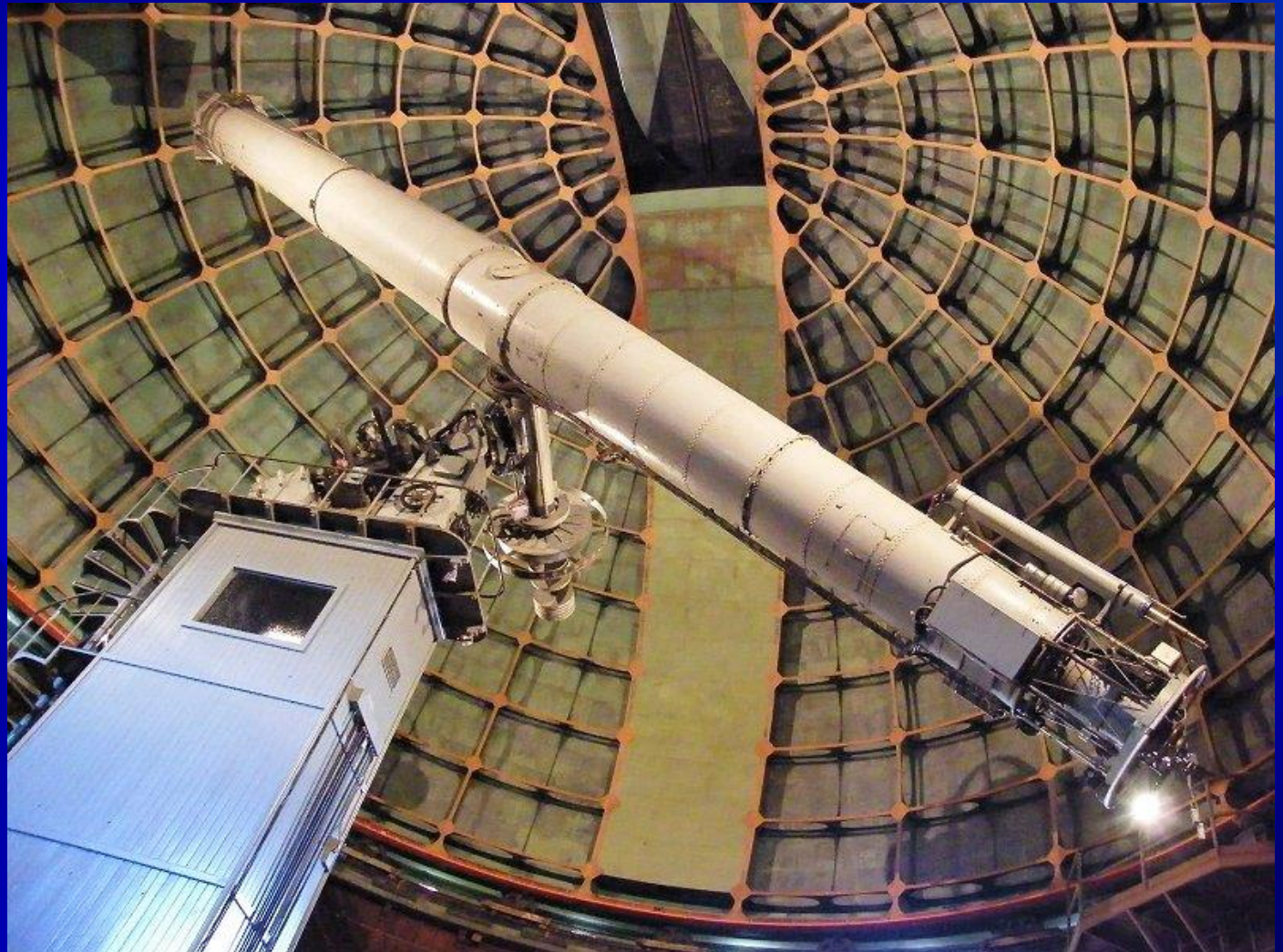
KEPLEROV (ASTRONOMSKI) TELESKOP



YERKES (102 cm)



LICK Obs. (91 cm)



GALILEJEV TELESKOP

Objektiv – konveksna leća

Okular – konkavna leća

Uspravna slika

Malo vidno polje

Slab kontrast

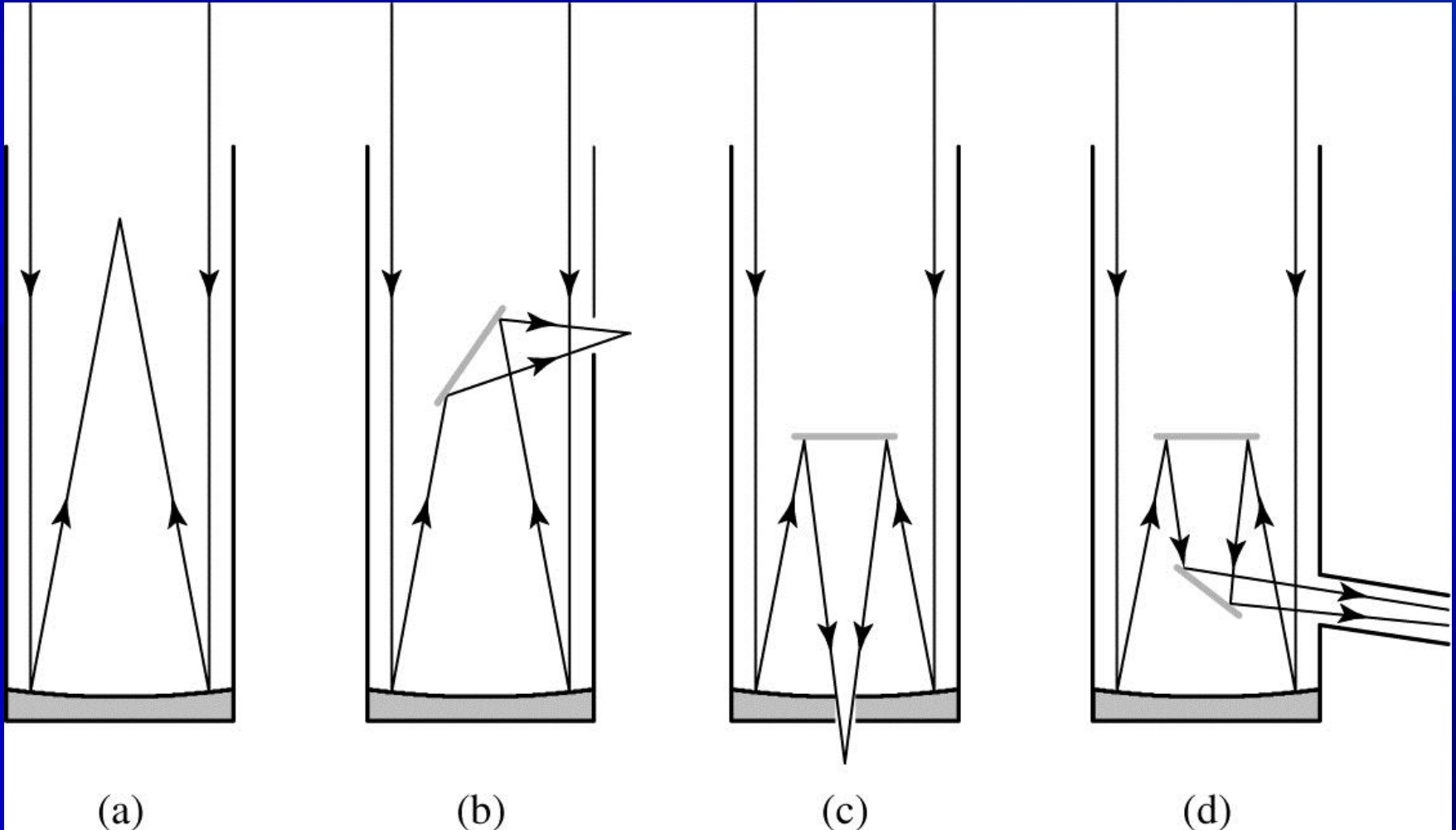
Kromatska i sferna aberacija – zahtjeva veliki f-omjer

$$l = f_o - f_e$$

Reflektor

Objektiv je OGLEDALO, a okular je LEĆA

NEWTONOV TELESKOP



Reflektor

NEWTONOV TELESKOP

Nema kromatske aberacije (nema leća)

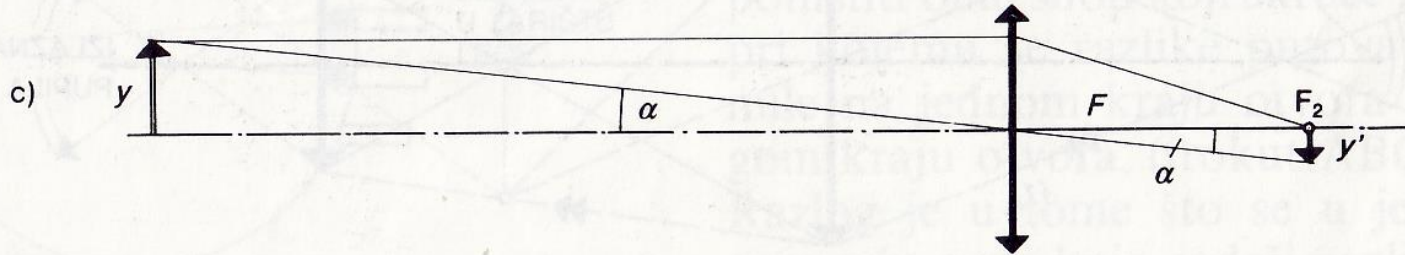
Sferna aberacija – parabolično zrcalo

Mali f-omjer – kompaktan, kratki teleskop

Veliko vidno polje

Objektiv je OGLEDALO, a okular je LEĆA

Kutno povećanje

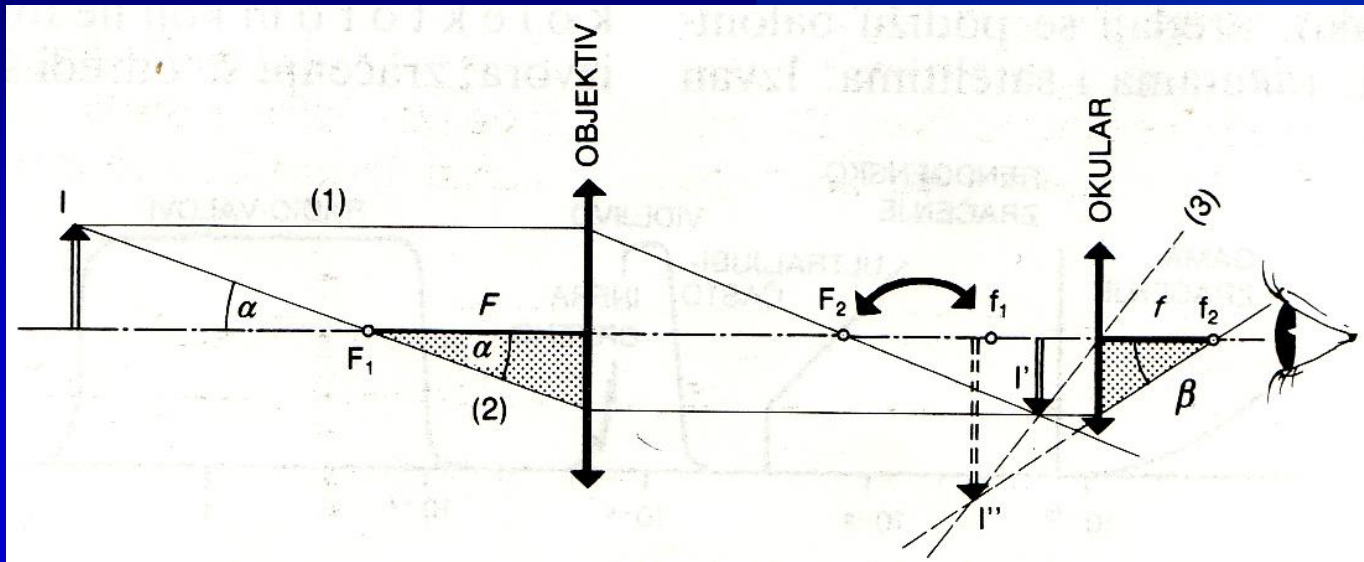


$$y' = F \tan \alpha$$

$$y' = F \alpha$$

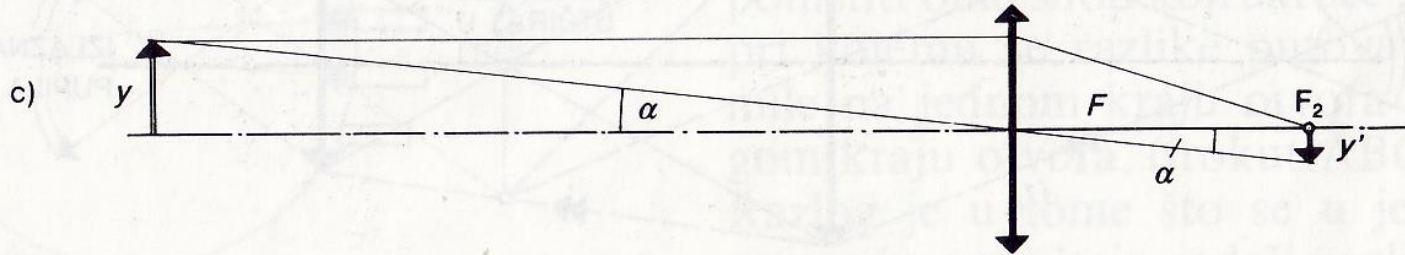
- Veličina slike y' je konačna za mali kut α ako je F objektiva dovoljno velik
- Slika je veća ukoliko je F objektiva veći – ograničenje na povećanje i razlučivanje

Kutno povećanje refraktora



- Povećanje vidnog kuta $M = \alpha/\beta = f_{\text{objektiv}}/f_{\text{okular}}$
- M od 200-300 je maksimalan, više nema smisla zbog seeinga
- Povećanje ima smisla samo za proširene, razlučene objekte
- Povećanje raste kada raste žarišna duljina objektiva f_{objektiv}
- Povećanjem žarišne duljina f_{objektiv} smanjuje se svjetlosna moć J teleskopa, što se kompenzira povećanjem otvora objektiva D
- Povećanje otvora objektiva je ograničeno tehničkim problemima (deformacija leće uslijed težine, leća mora biti savršeno brušena s preciznošću reda $\lambda/20$)

Kutno povećanje

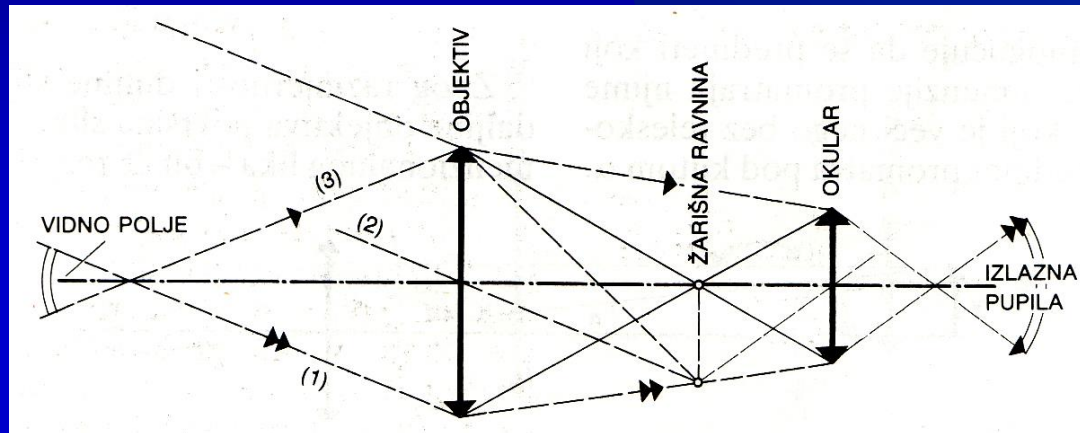


$$y' = F \tan \alpha$$

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- Veličina slike y' je konačna za mali kut α ako je F objektiva dovoljno velik
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Vidno polje



- Vidno polje – određeno promjerom objektiva i žarišnom duljinom
- Izlazna pupila je veličine zenice oka (7-8 mm)

Svjetlosna moć teleskopa

- Svjetlosna moć teleskopa – iluminacija J (mjera za prihvaćenu zračenu energiju) $\rightarrow$ količina svjetlosne energije u sekundi koja je fokusirana na jediničnu površinu slike
- veći promjer objektiva (D) $\rightarrow$ veće razlučivanje, veća iluminacija (svjetlosna moć)
- veća žarišna duljina f $\rightarrow$ veća slika, manja svjetlosna moć (iluminacija)
- za $F = \text{const.}$ porastom otvora objektiva (D) pada žarišna udaljenost $f \rightarrow J = \text{const.}$

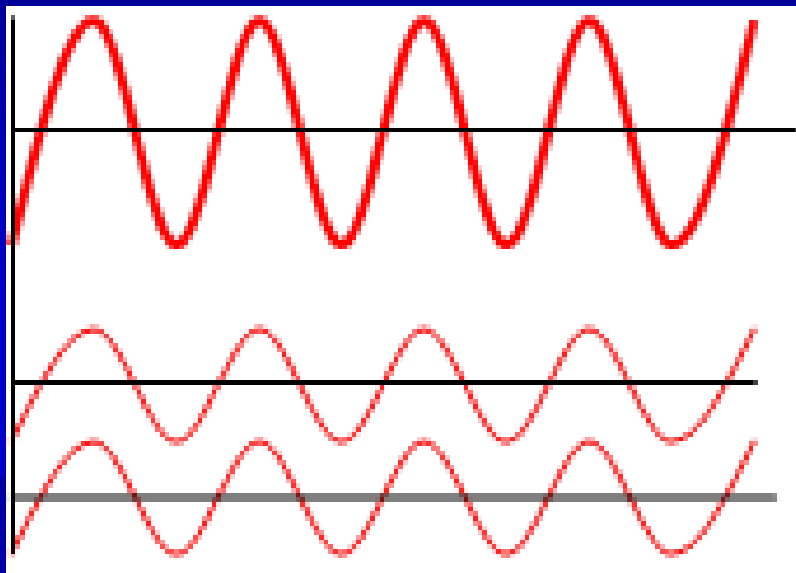
Ozračenost detektora

- $J_D \rightarrow$ ozračenost detektora
- $\Phi \rightarrow$ količina svjetlosne energije koja u sekundi upadne na površinu detektora
- $A_{\text{detektor}} \rightarrow$ površina detektora (okomito postavljena na optičku os)
- J_D karakterističan za zvijezdu i isti svuda na Zemlji
- Mijenja se $\Phi = A_{\text{detektor}} J_D$, količina svjetlosne energije Φ raste ako površina detektora A_{detektor} raste

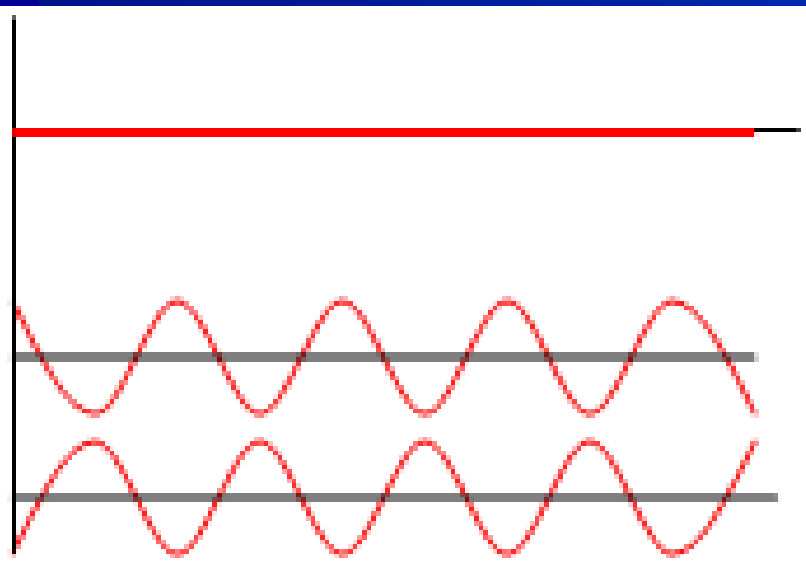
Radijancija (ozračenost) slike

- $A_{\text{slike}} \rightarrow$ površina slike
- $d\Omega \rightarrow$ prostorni kut protegnut od slike prema objektivu

Moć razlučivanja



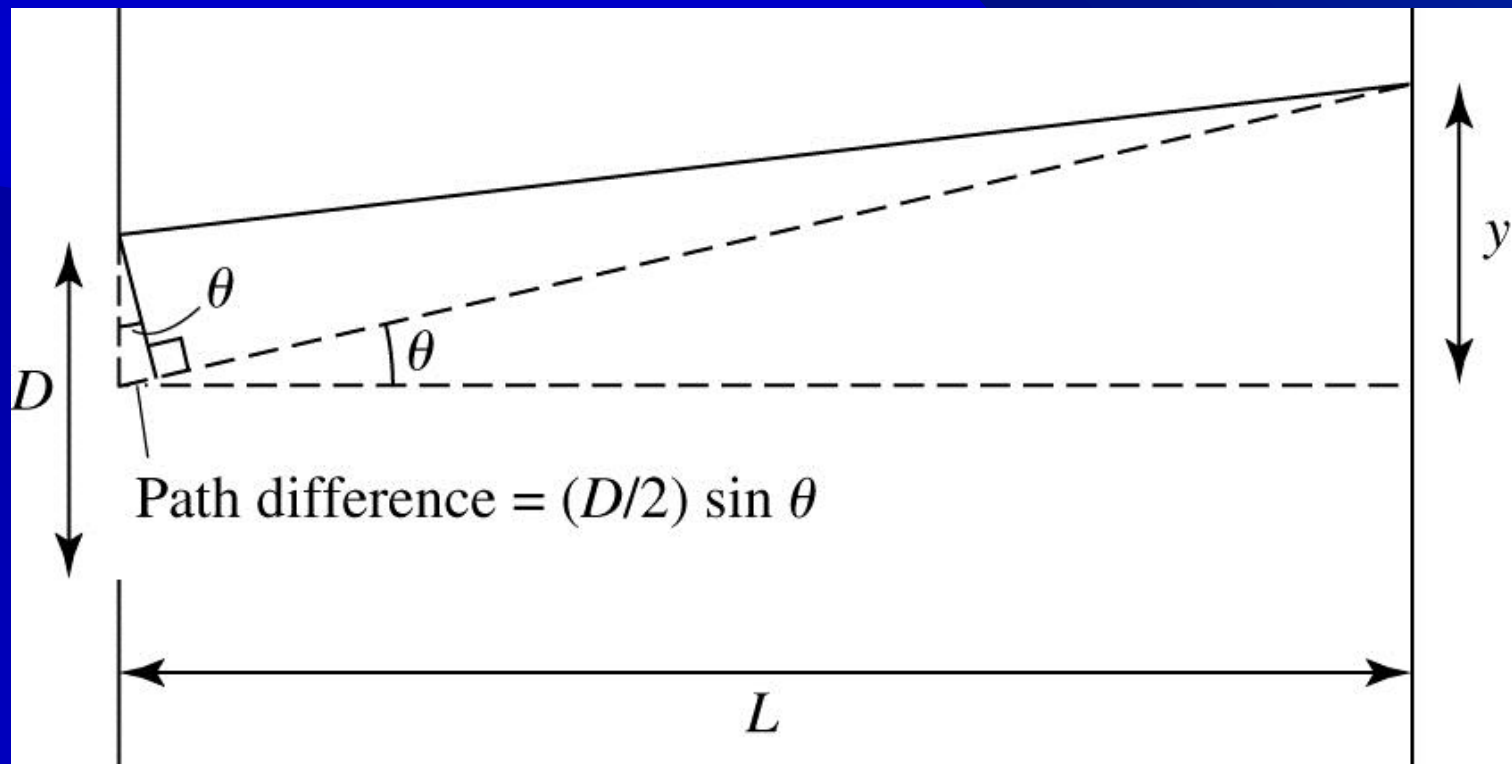
KONSTRUKTIVNA
INTERFERENCIJA



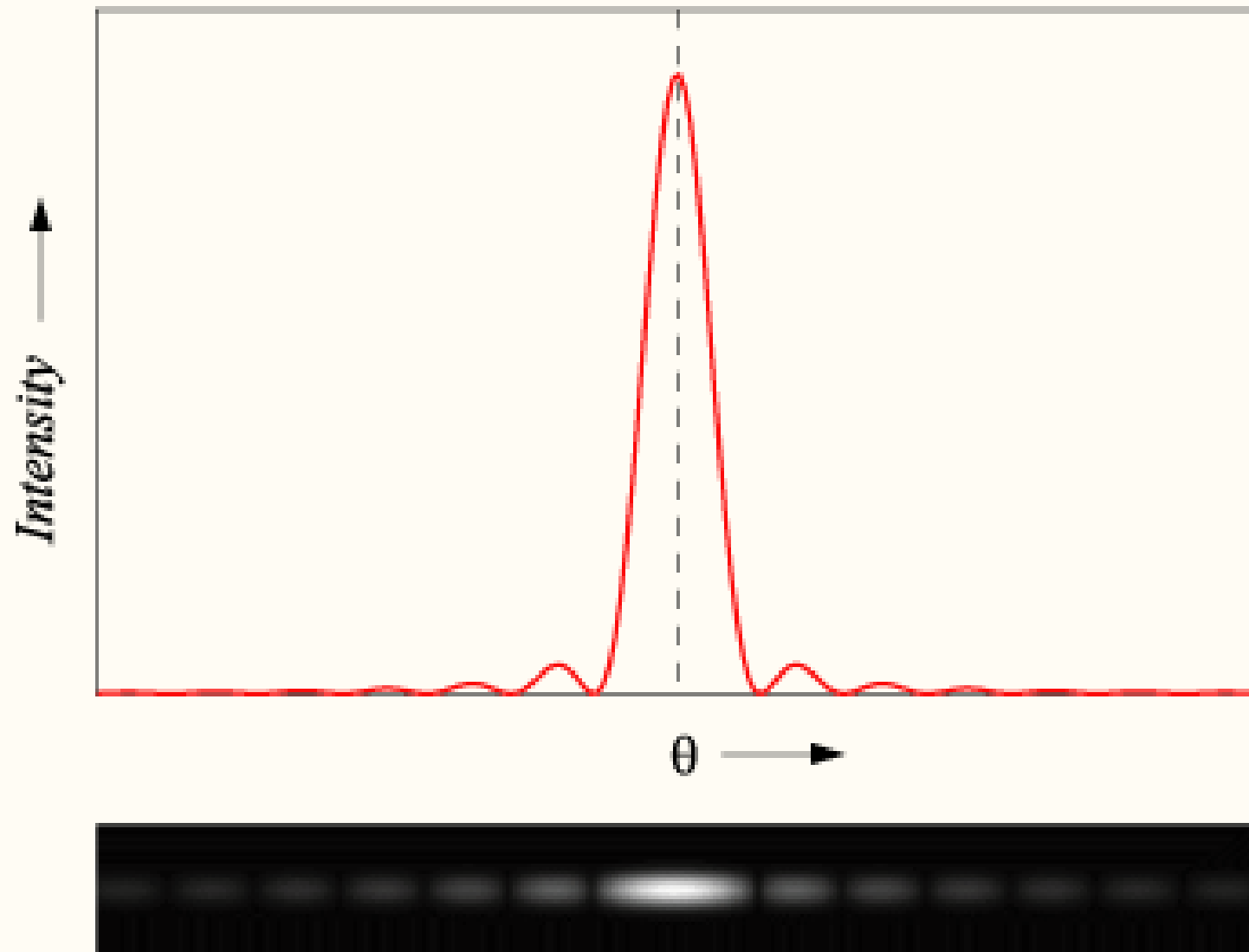
DESTRUKTIVNA
INTERFERENCIJA

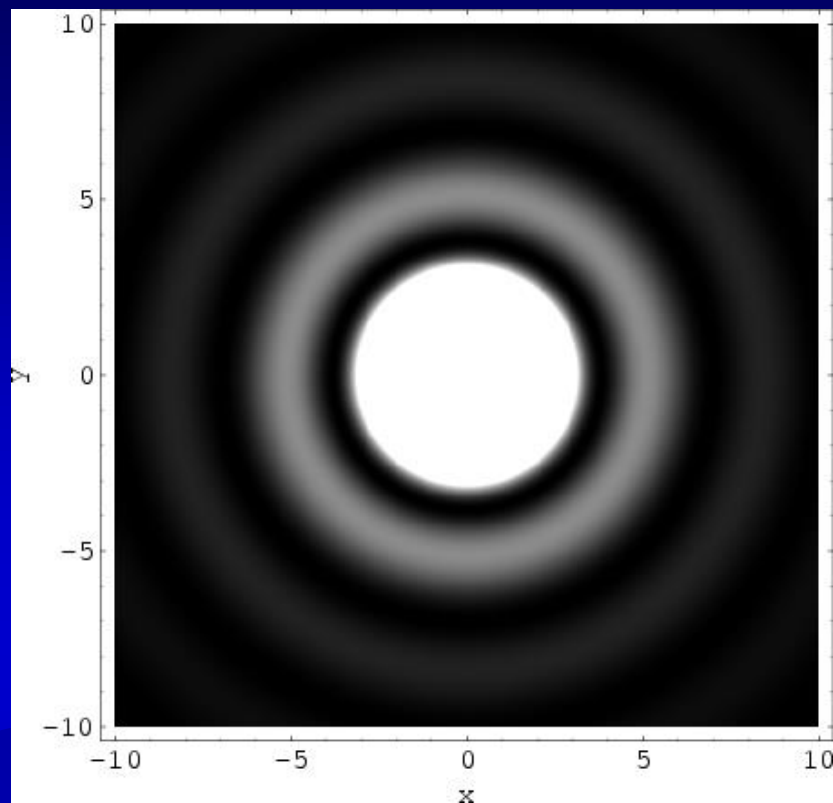
Moć razlučivanja

- Razlučivanje ne ovisi isključivo o povećanju – veličini slike, odnosno žarišnoj duljini objektiva F
- Razlučivanje je ograničeno ogibom zraka svjetlosti na objektivu teleskopa

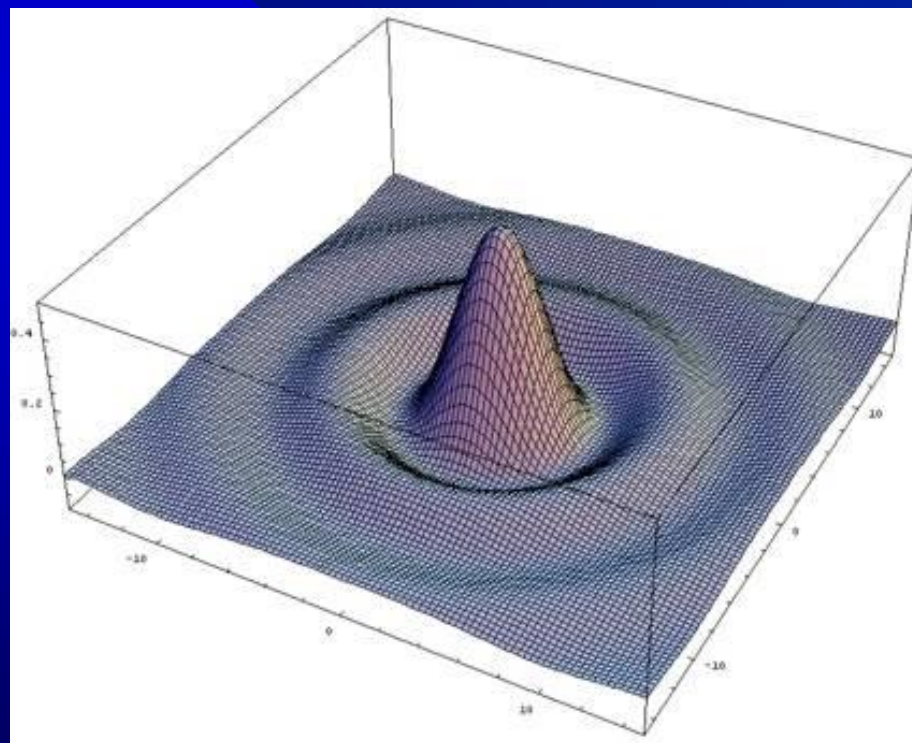


Single-slit diffraction pattern



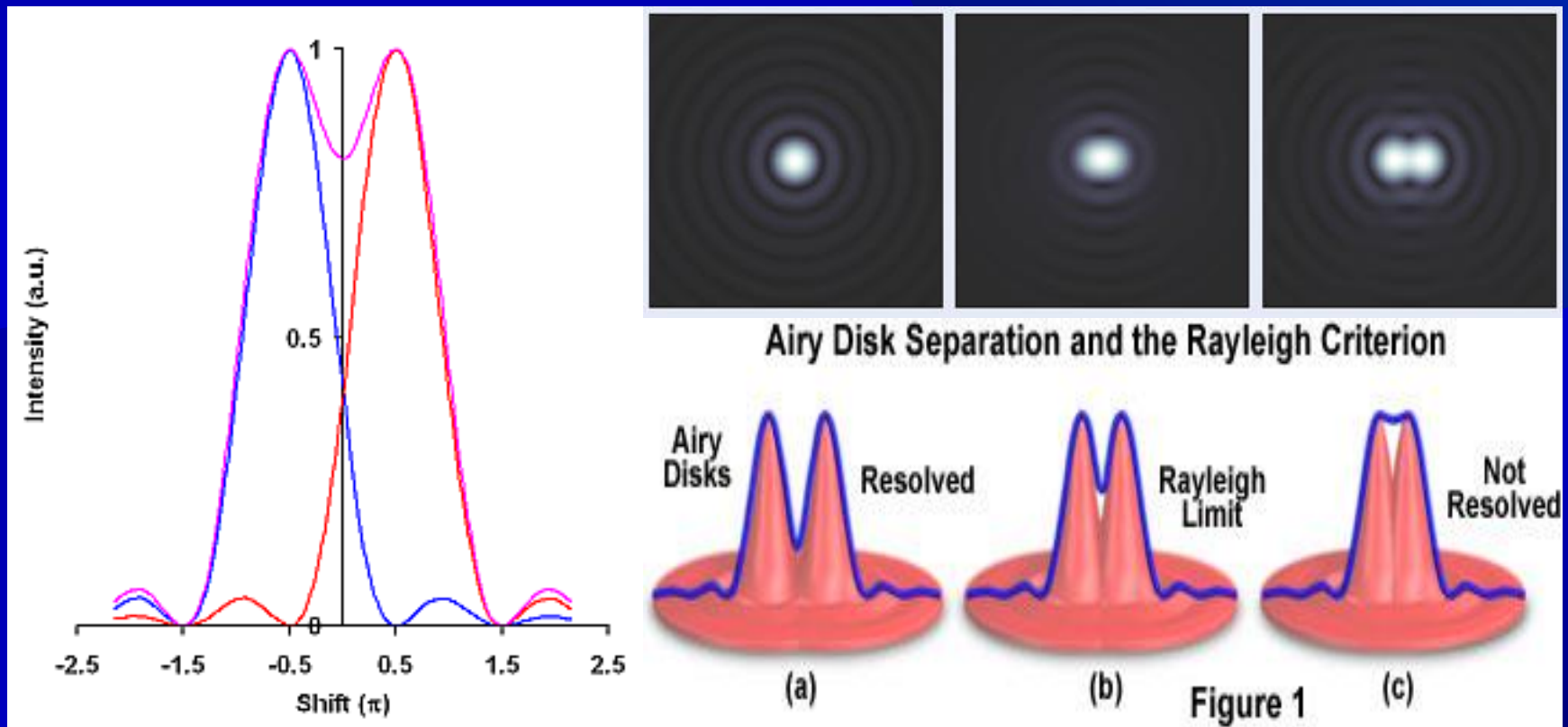


Difrakcija na kružnom otvoru
teleskopa
Airyjev disk – George Airy
(1835.)



Moć razlučivanja

Rayleighev kriterij



Seeing

Ograničenje na kutno razlučivanje:

1. Promjer otvora objektiva $\rightarrow$ veći otvor objektiva D , veće razlučivanje

2. Seeing

➤ Turbulentna gibanja u Zemljinoj atmosferi – lokalne promjene u temperaturi različitih slojeva atmosfere uzrokuju promjene gustoće, gibanje masa različitih temperatura također mijenja gustoću

➤ Promjena gustoće slojeva u atmosferi djeluje poput leće s različitim indeksima loma

➤ Promjene gustoće su nasumične, pa tako i promjene indeksa loma $\rightarrow$ rezultat je razmazana, nejasna slika

Seeing

Turbulentna priroda atmosfere uzrokuje slabije razlučivanje i lošiju sliku bez obzira na veličinu i kvalitetu teleskopa

Seeing – kvaliteta slike zvjezdanog točkastog izvora na određenoj lokaciji u određeno vrijeme

Najbolje lokacije – suha klima, bez vlage u zraku, velika visina

1. Havaji (5000 m n.v.) – Mauna Kea – razlučivanje reda 0.5'' do 0.6'' u 50% vremena, maksimalno 0.25''
2. Čile – VLT, Cerro Tololo Inter-American Observatory
3. Arizona – Kitt Peak National OBservatory

Seeing

Havaji (5000 m n.v.) – Mauna Kea – razlučivanje reda 0.5'' do 0.6'' u 50% vremena, maksimalno 0.25''



Seeing

Čile – VLT, Cerro Tololo Inter-American Observatory



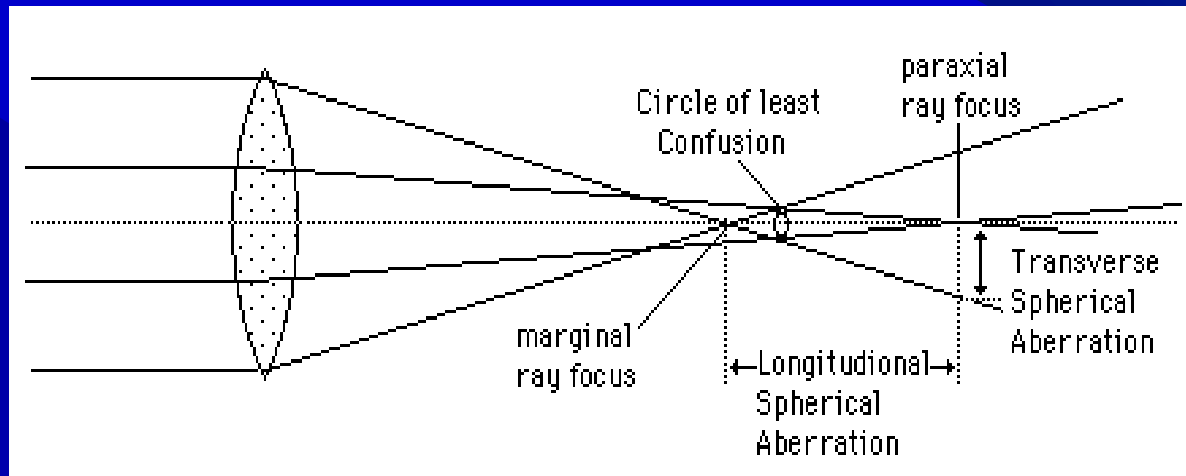
Seeing

Arizona – Kitt Peak National OBservatory

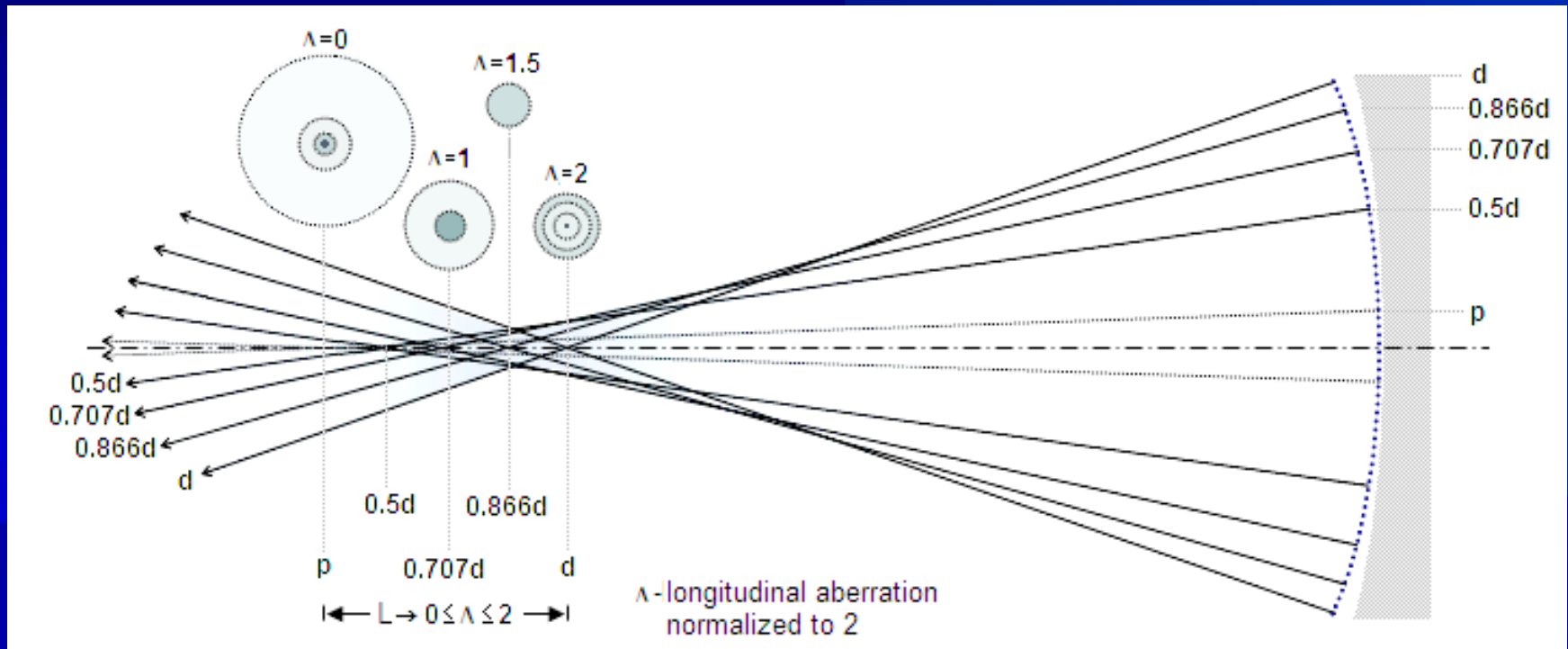


Sferna aberacija

- Sferne površine: i ogledala i leće!
- Monokromatski karakter
- Zrake paralelne s optičkom osi ali na različitim udaljenostima od nje različito se lome/reflektiraju i nemaju zajednički fokus!
- Slika je замуćena



Sferna aberacija

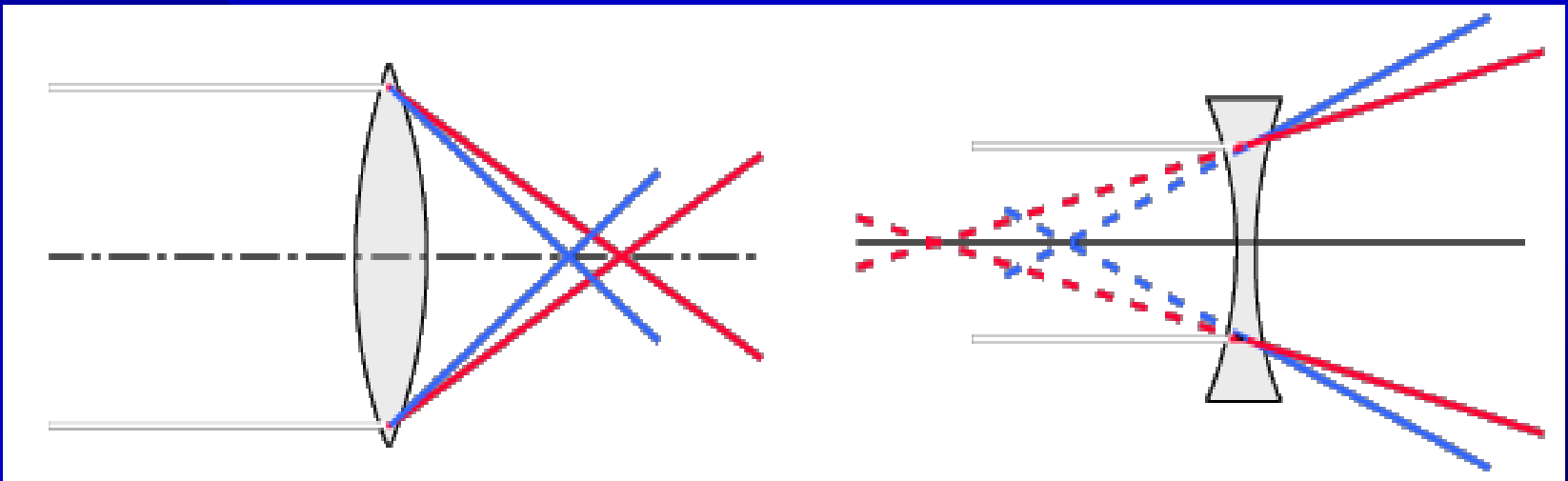


Korekcija:

- Sferni dublet – korištenje dviju leća (bikonveksna + plankonkavna leća) izrađene od različitih materijala
- Sferne leće – minimizacija aberacije odabirom najpovoljnije zakrivljenosti sferne površine

Kromatska aberacija

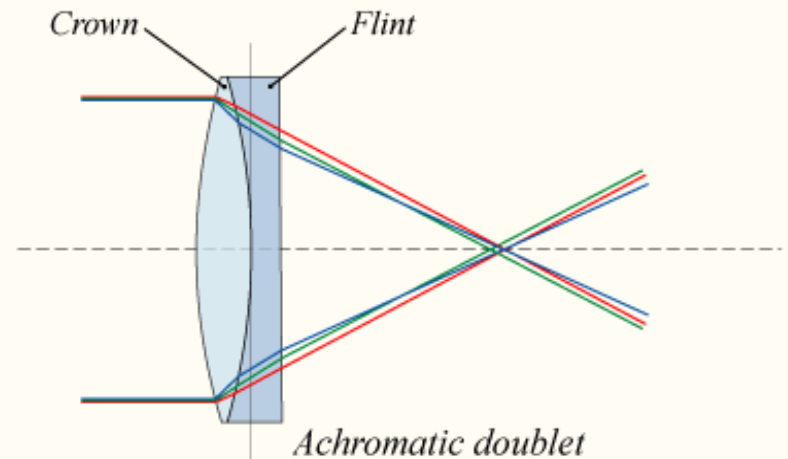
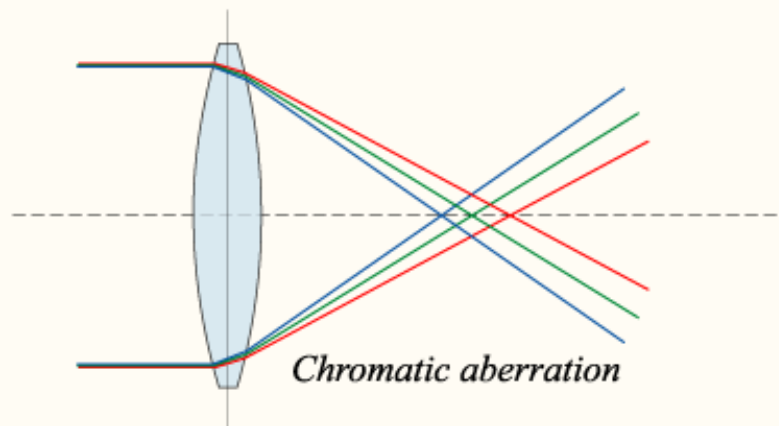
- Indeks loma stakla funkcija je valne duljine: $n = f(\lambda)$
- Svjetlost različitih valnih duljina ima različite indekse loma, pa se stoga i različito lomi kroz staklo
- Svjetlost različitih valnih duljina zbog ovisnosti indeksa loma o valnoj duljini fokusirat će se u različitim točkama
- Kromatska aberacija ovisit će o disperziji stakla – vrsta stakla je važna!
- Kromatska aberacija je prisutna samo kod leća, ne i kod zrcala!



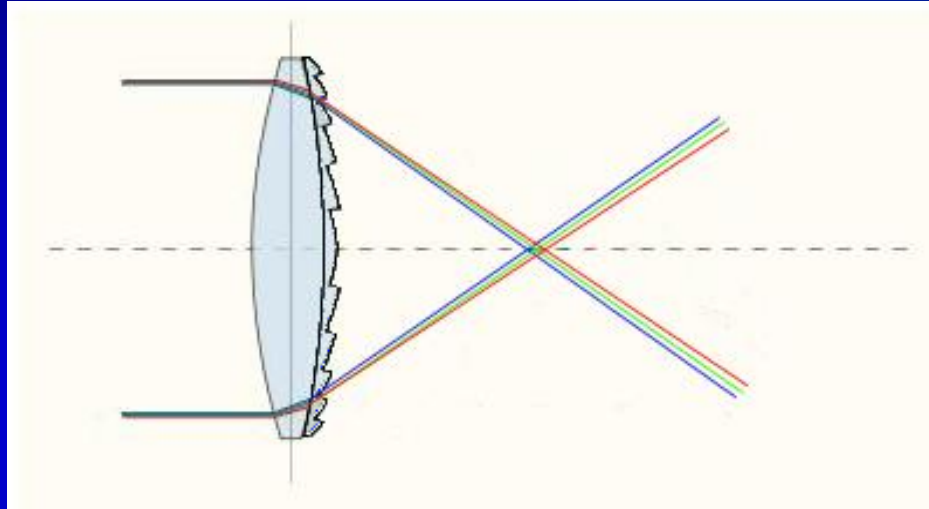
Kromatska aberacija

Korekcija:

- Koristi se teleskop reflektor umjesto refraktor
- Akromatski dublet leća – dvije leće različitih indeksa loma ‘spojene’ u dublet
- Apokromatske leće – složen sustav od više akromatskih leća
- Difrakcijski optički elementi – komplementarne disperzijske karakteristike lećama

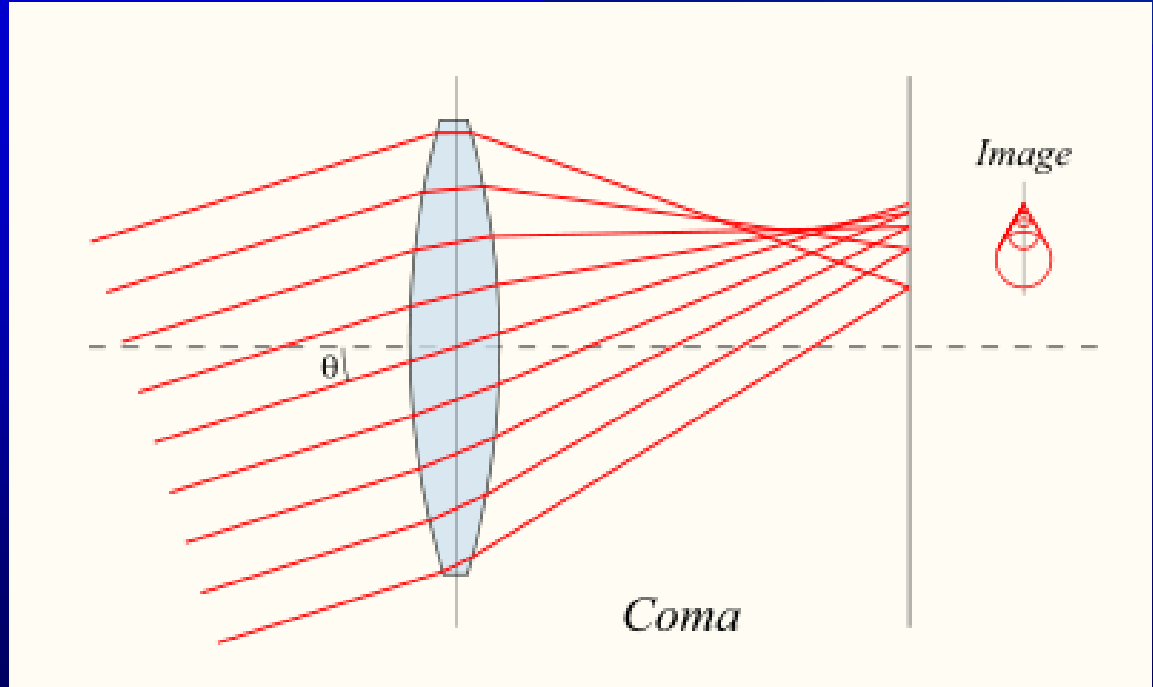


Kromatska aberacija

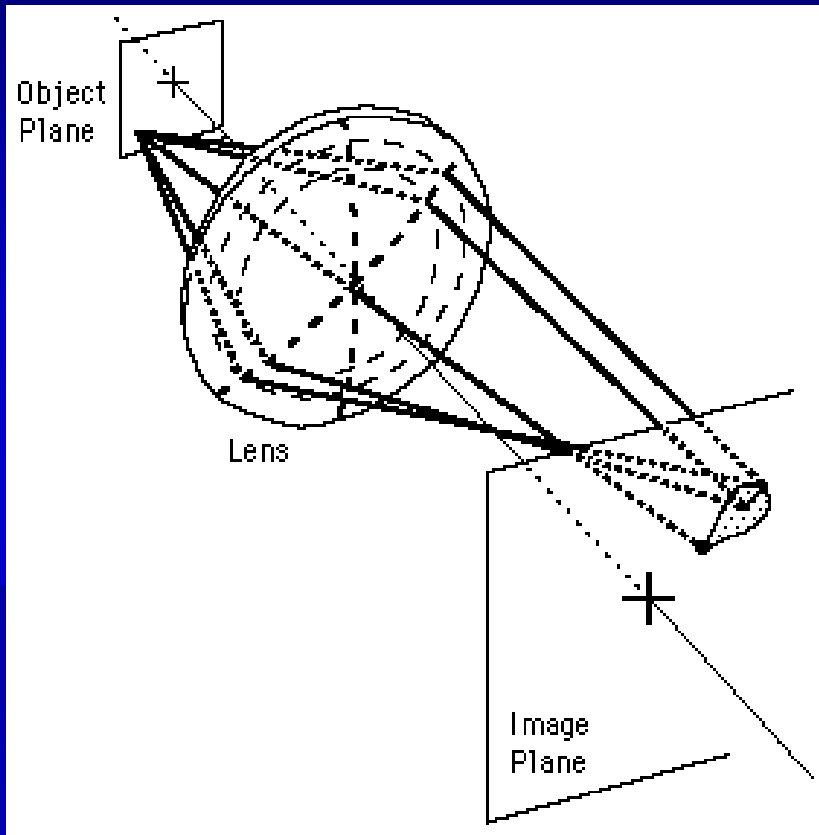


Koma

- Vrsta aberacije uzrokovana nesavršenošću leća i/ili optičkog sustava
- Javlja se kod paraboličnih zrcala
- Kada je zrake svjetlosti s izvora padaju na leću/zrcalo pod nekim kutem (van optičke osi), različiti dijelovi leće/zrcala imaju različit fokus te fokusiraju predmet u različitim točkama
- Javlja se distorzija slike predmeta u obliku kome
- Što je izvor više van osi, efekt je izraženiji iako je fokus u optičkoj osi savršen

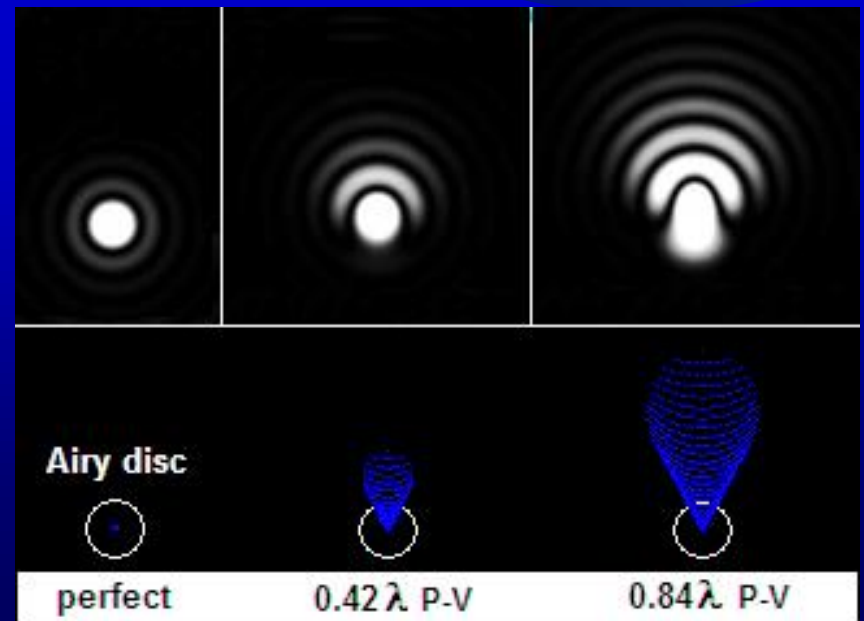


Koma



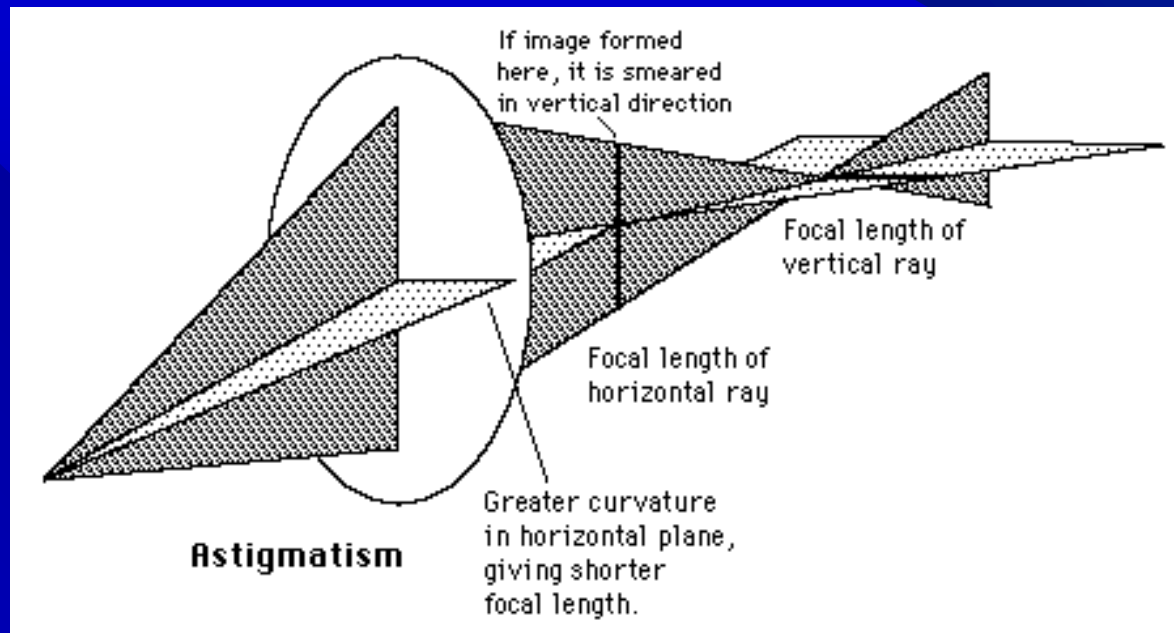
Korekcija:

- Korektivne ploče – Schmidt optički sustav
- Površina leća se tako oblikuje da korigira komu
- Aplanatske leće/zrcala – eliminatorana koma i sferna aberacija

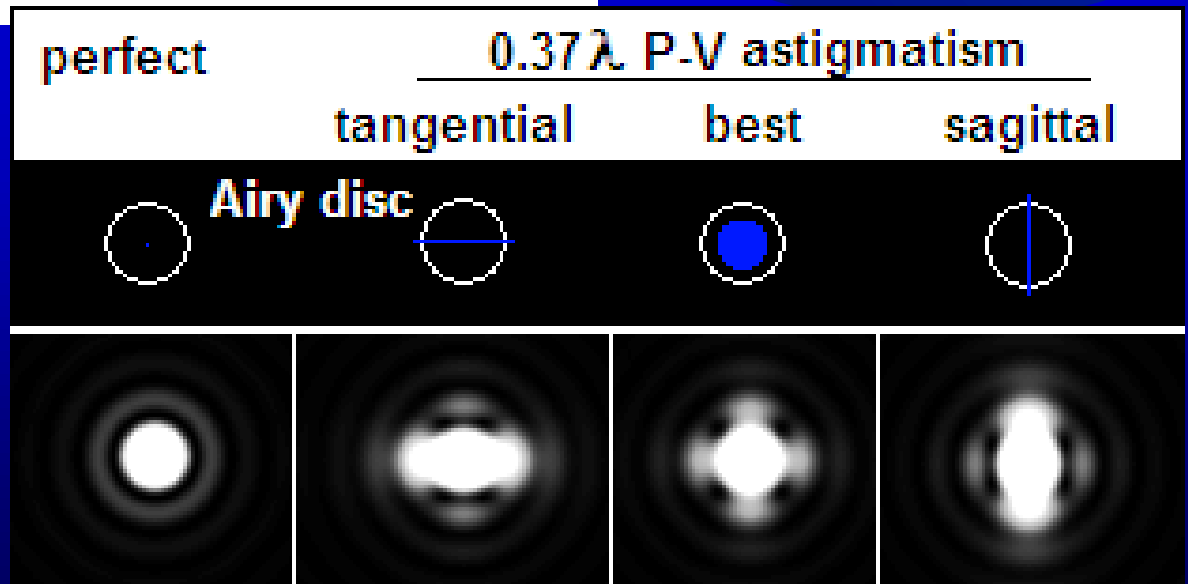
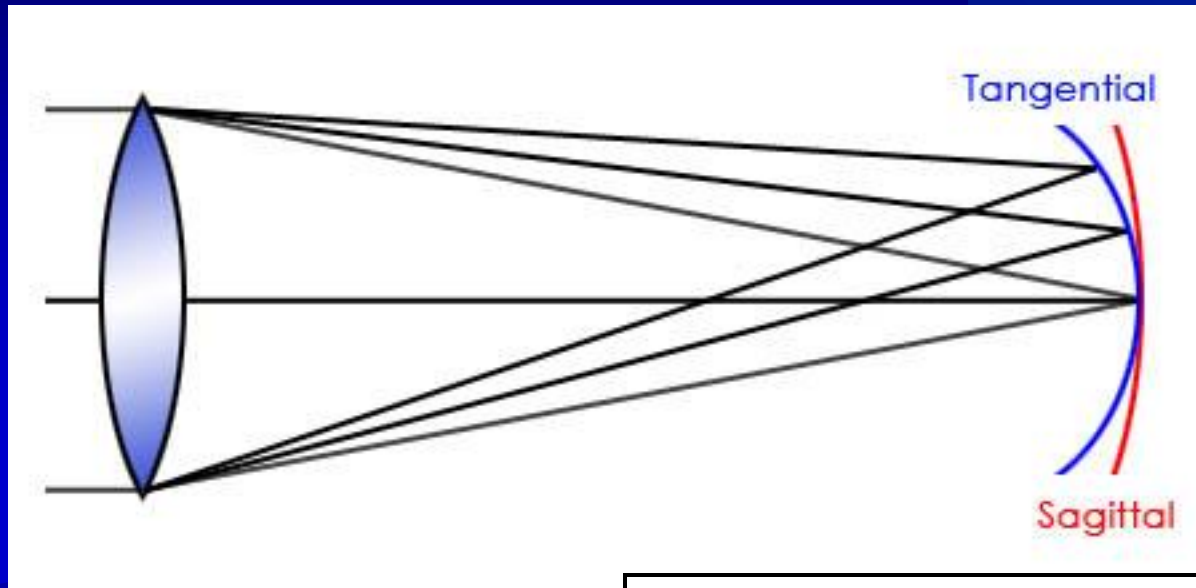


Astigmatizam

- Optički sustav ima dvije međusobno okomite ravnine – tangencijalnu i radijalnu
- Realne leće imaju različitu zakrivljenost u različitim smjerovima-optičkim ravninama
- Položaj fokusa u tangencijalnoj i radijalnoj optičkoj ravnini je različit-slika je deformirana



Astigmatizam

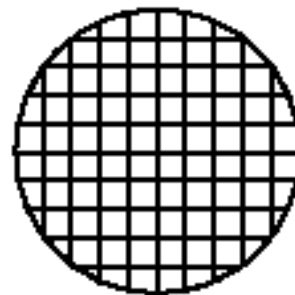
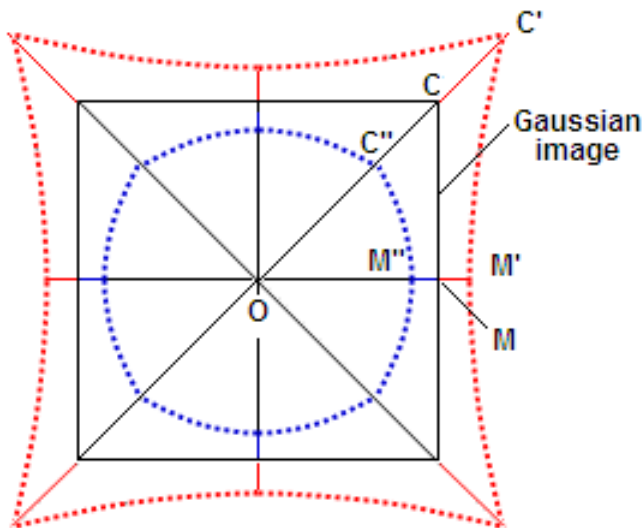


Distorzija

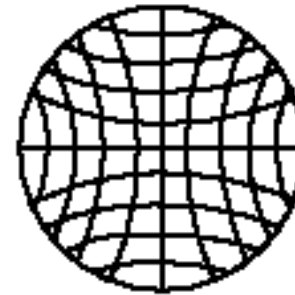
- Nije uzrokovana nesavršenošću leće, već konačnim dimenzijama/debljinom i geometrijom leće
- debela bikonveksna leća zbog geometrije površine uzrokuje distorziju slike

Korekcija:

- Simetrični dubleti (ortoskopski dublet)



Undistorted
Image

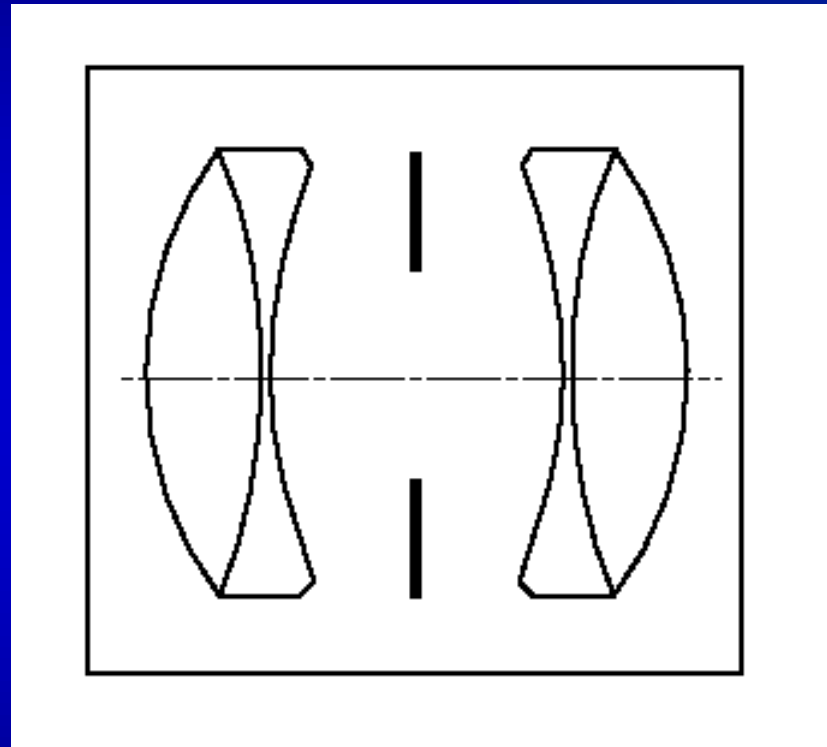


Pincushion
Distortion



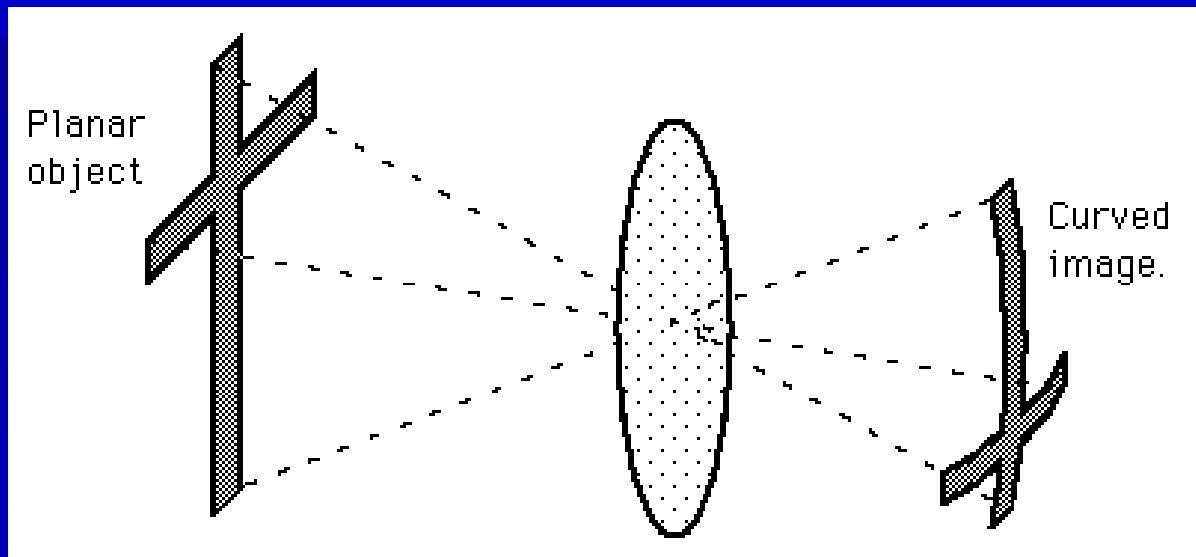
Barrel
Distortion

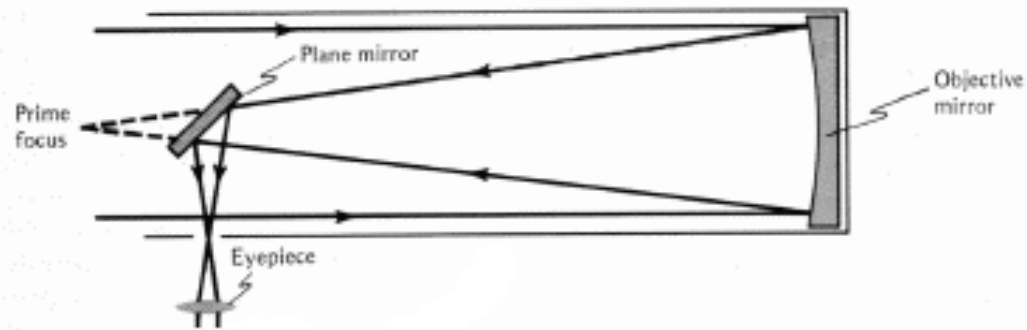
Distorzija



Zakrivljenost polja

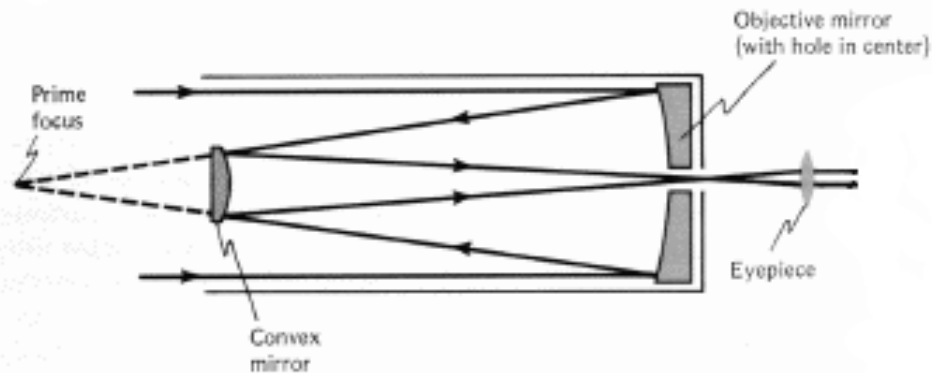
- Zakrivljenost polja uzrokuje da slika planarnog objekta postane zakrivljena
- Uzrok je u većoj svjetlosnoj moći za zrake koje padaju na leću pod velikim kutem žarišne duljine
- Takve zrake koje padaju pod većim kutem vide leću manjeg promjera i veće svjetlosne snage, zbog čega slika nastaje van osi bliže leći



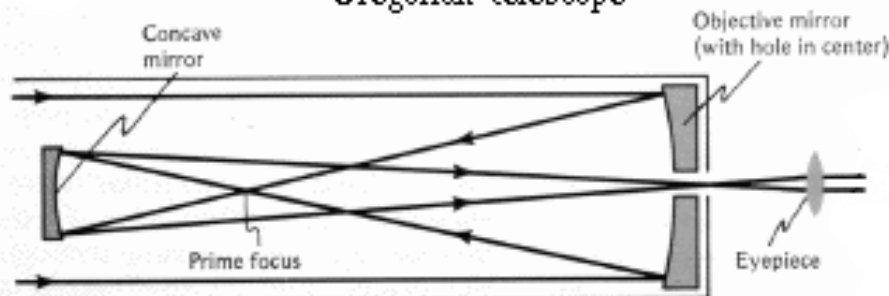


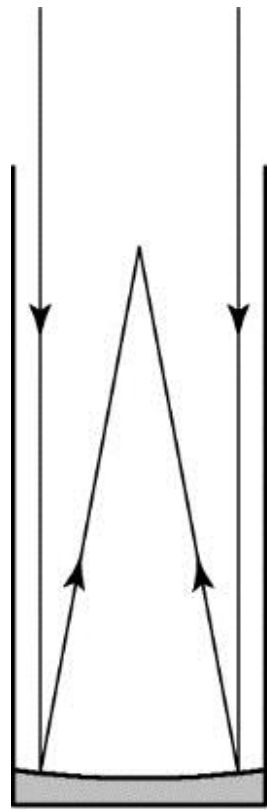
Newtonian telescopes

Cassegrain telescope



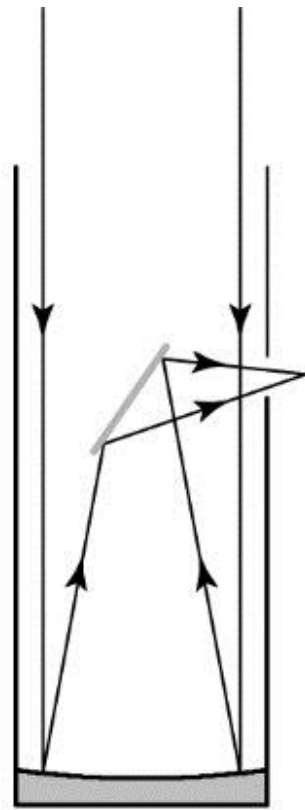
Gregorian telescope





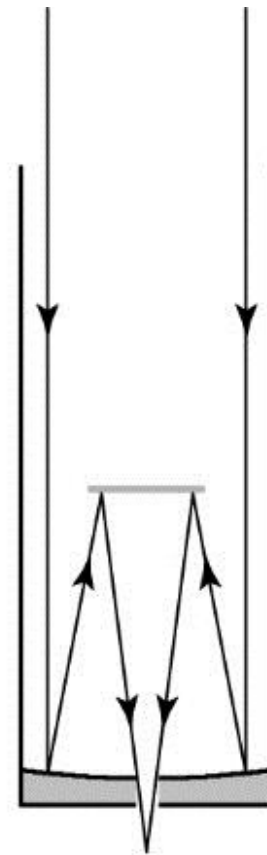
(a)

PRIMARNI
FOKUS



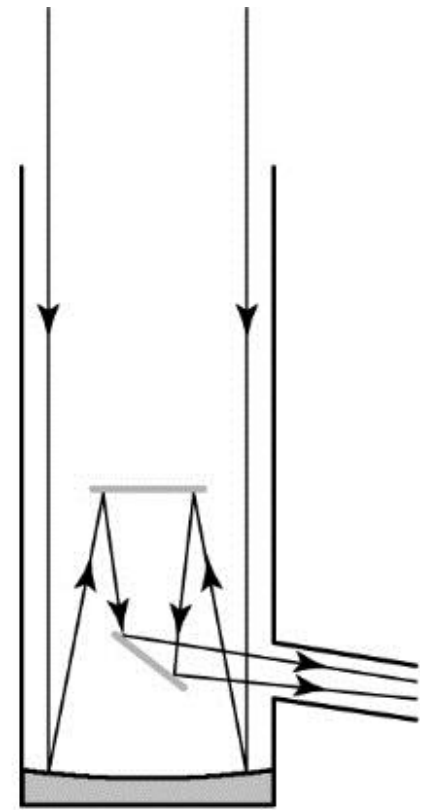
(b)

NEWTON



(c)

CASSEGRAIN

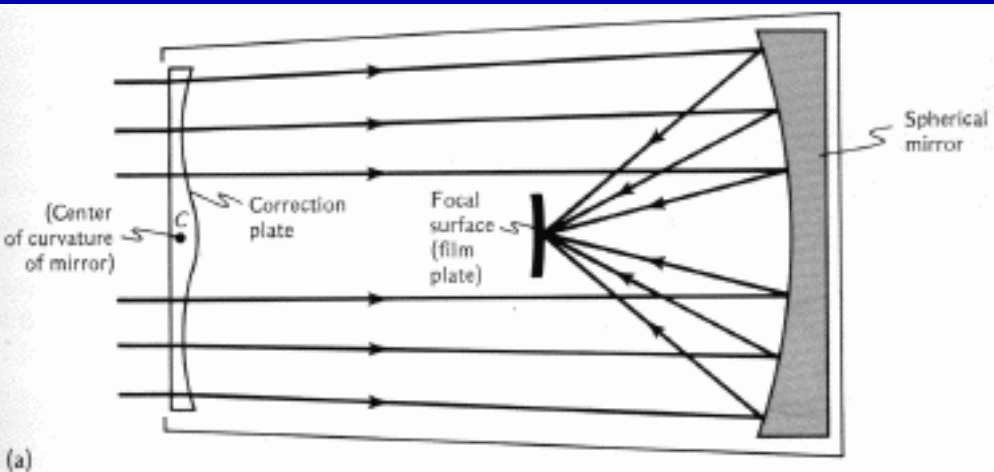


(d)

COUDE

Katadioptri

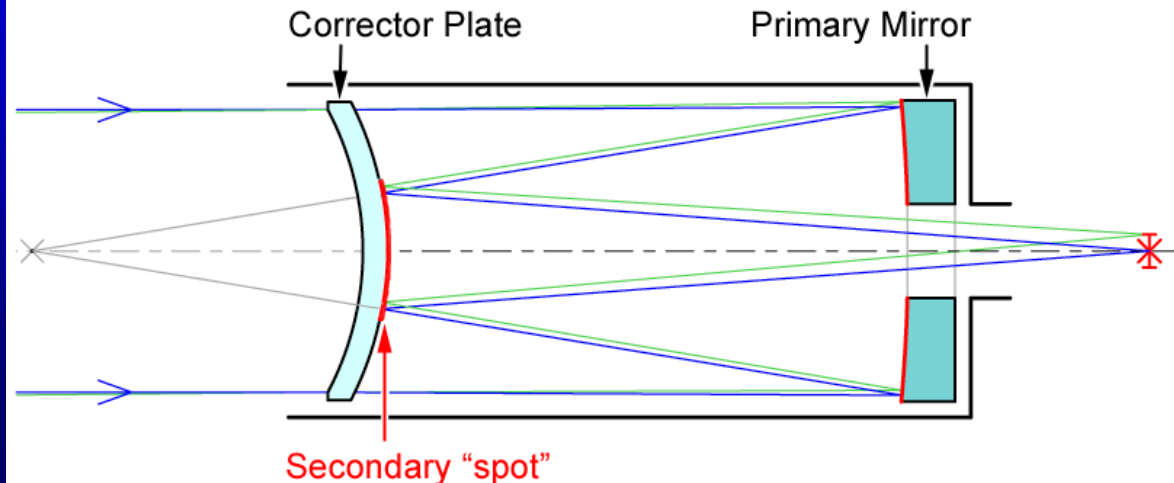
OGLEDALO + LEĆE



Sferne površine
Veliki fokusi i f-omjeri,
kompaktni dizajn
Kontrola aberacije (koma,
sferna aberacija i
astigmatizam)

MAKSUTOV-CASSEGRAIN

SCHMIDT- CASSEGRAIN



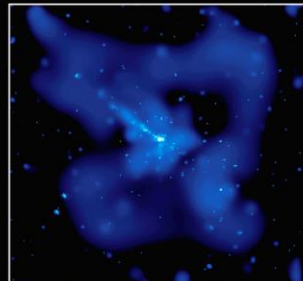
Radio astronomija

Arecibo Observatory – Puerto Rico

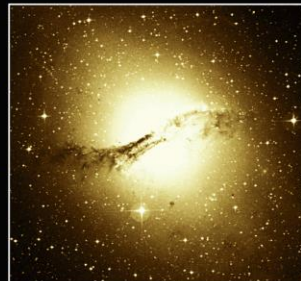


Radio astronomija

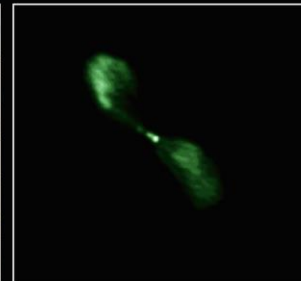
Centaurus A



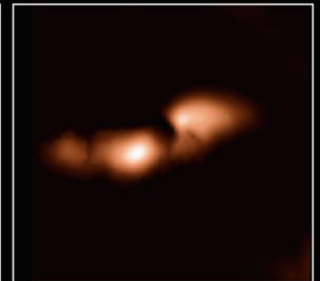
CHANDRA X-RAY



DSS OPTICAL



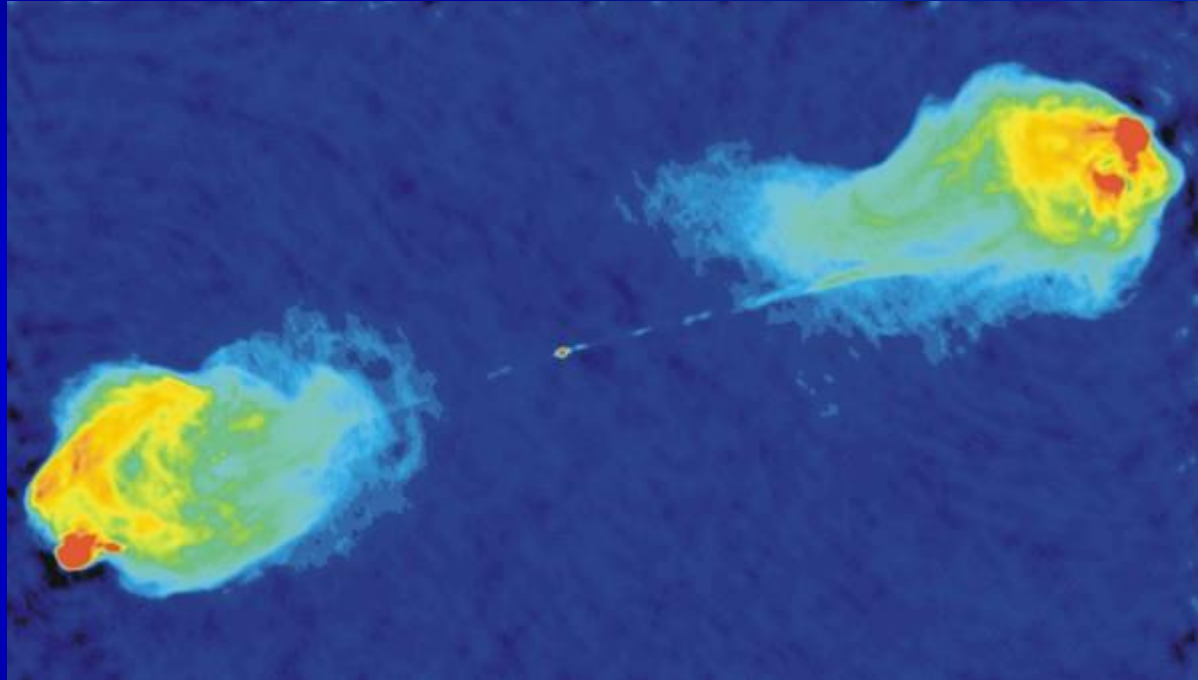
NRAO RADIO
CONTINUUM



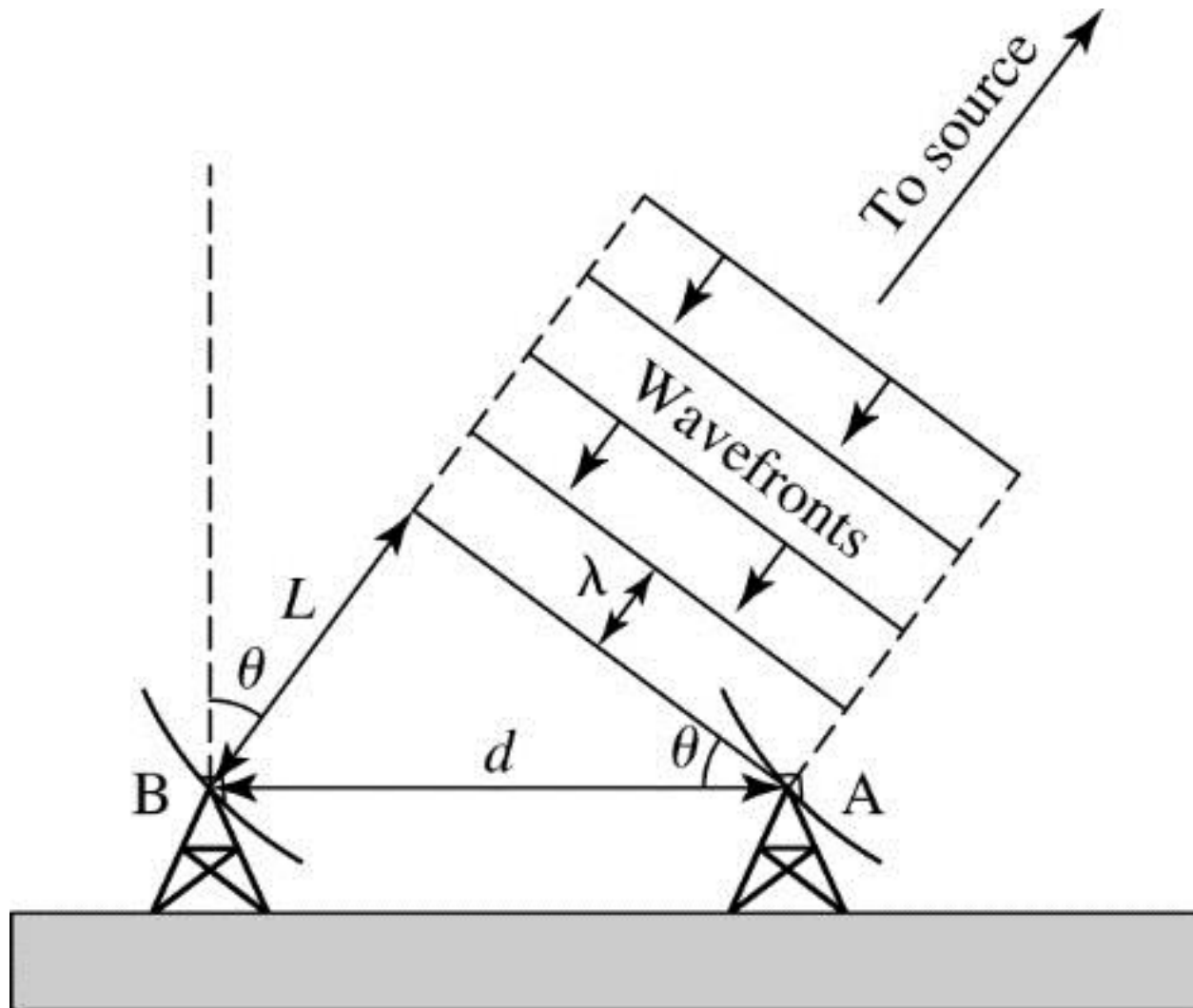
NRAO RADIO
(21-CM)

Radio astronomija

Cygnus A



Radio interferometrija



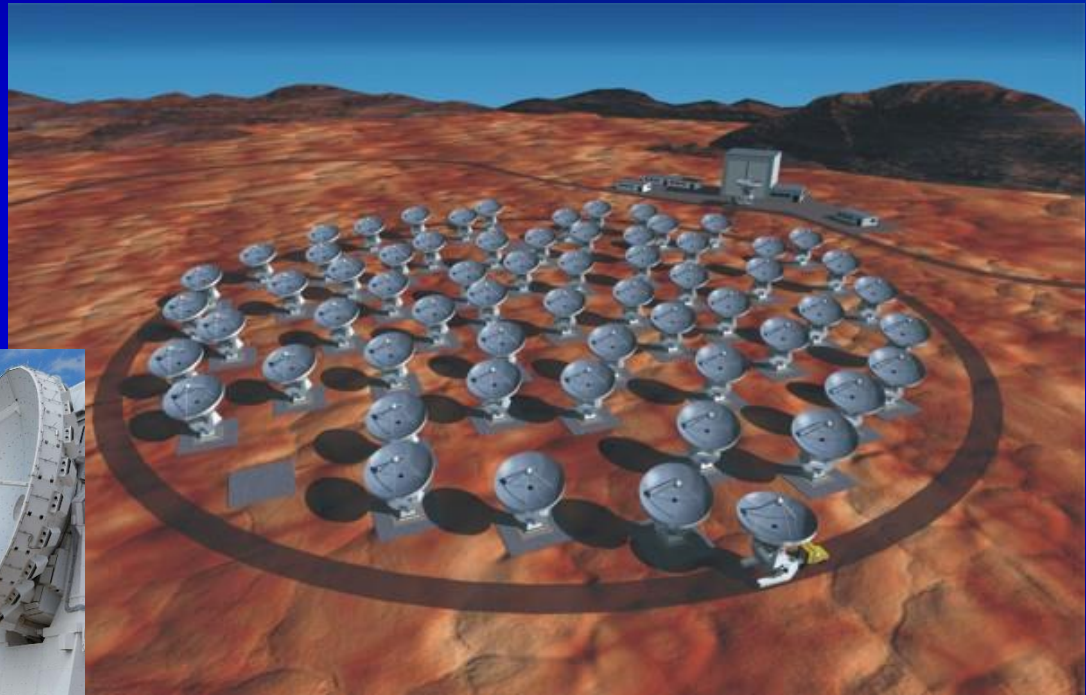
Radio astronomija

VLA – Very Large Array – New Mexico, USA



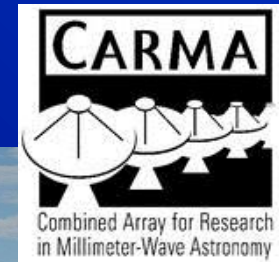
Radio astronomija

ALMA – Atacama Large Milimeter/Submillimeter Array – pustinja Atacama, Chile



Radio astronomija

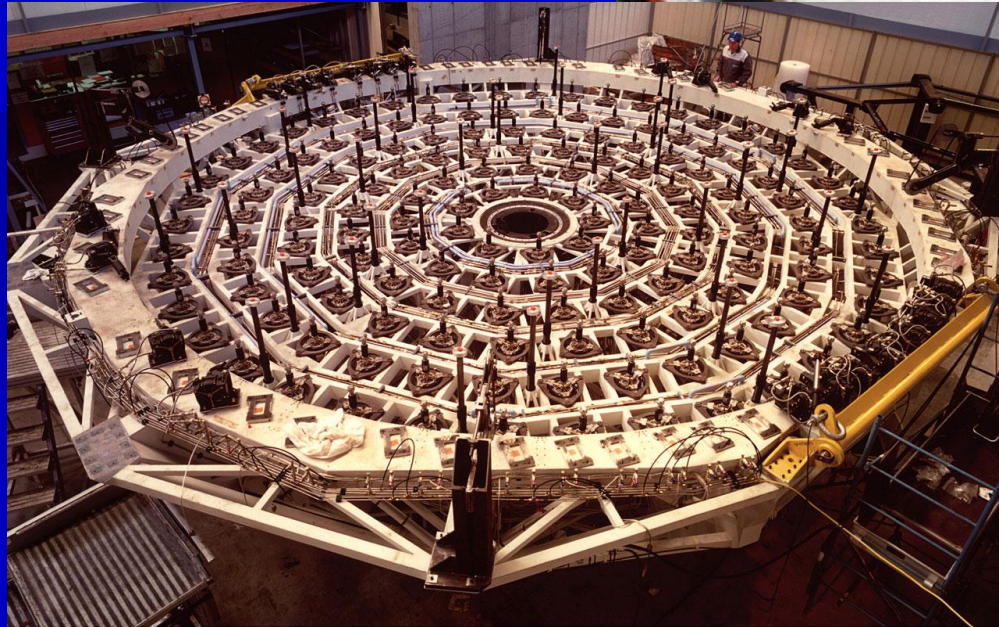
CARMA – Cedar Flat, Sierra Nevada, SAD



LOFAR – Low Frequency
Array – Evropa



Aktivna optika

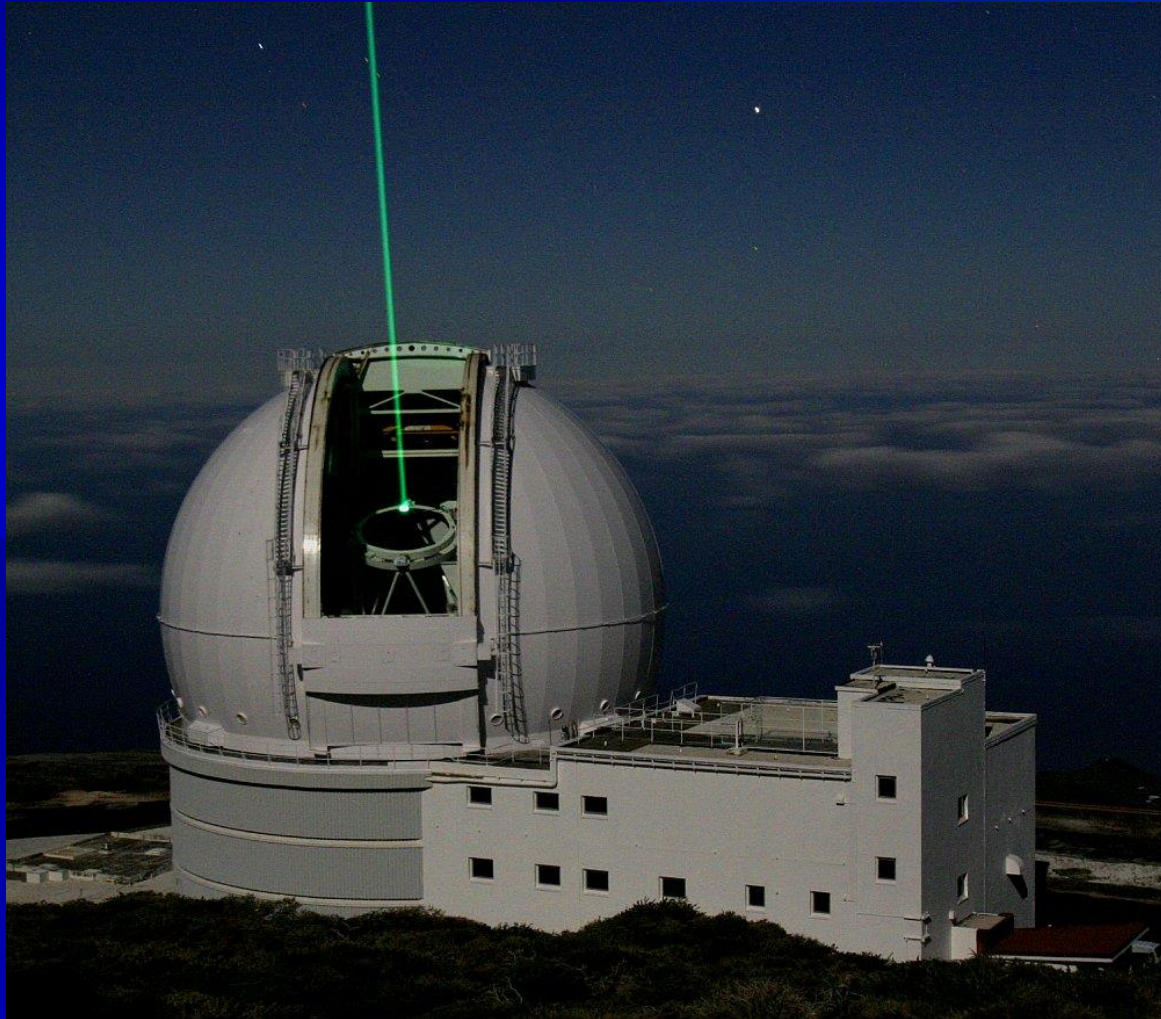


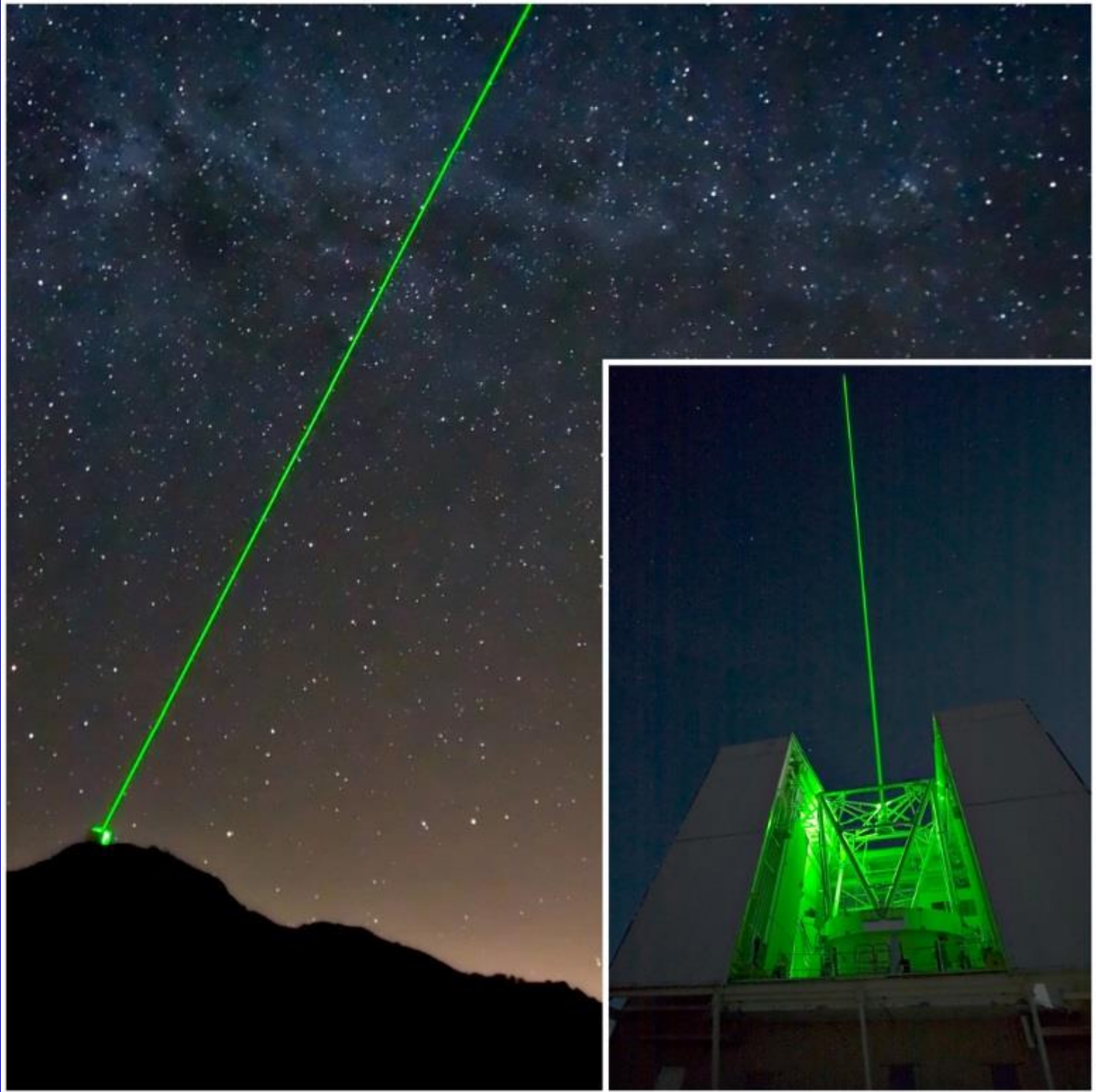
Without Adaptive Optics

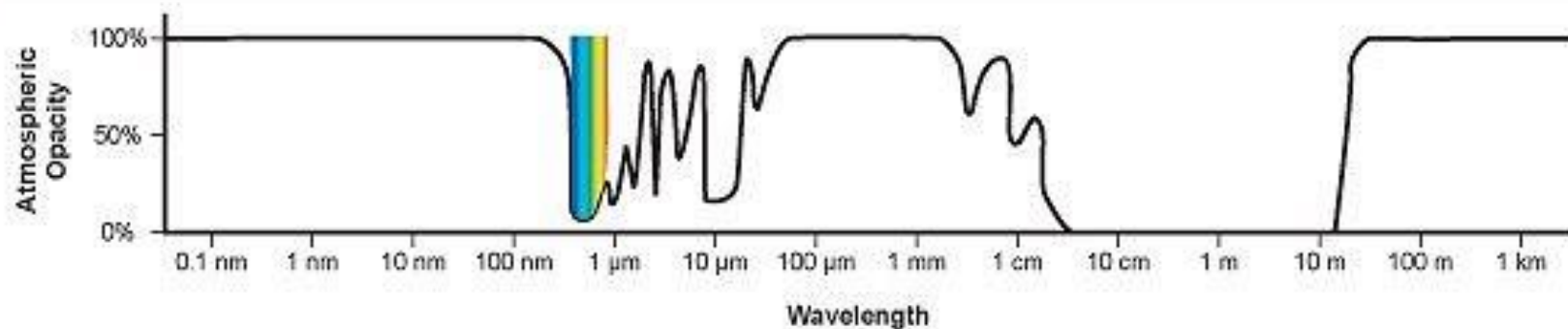
With Adaptive Optics

Aktivna optika

William Herchel Telescope – La Palma, Španjolska







Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).



Visible Light observable from Earth, with some atmospheric distortion.



Most of the Infrared spectrum absorbed by atmospheric gasses (best observed from space).

Radio Waves observable from Earth.

Long-wavelength Radio Waves blocked.



Infracrvena astronomija



IRAS – Infrared Astronomical Satellite

(1983)

12-100 mikrona

0.6 m teleskop

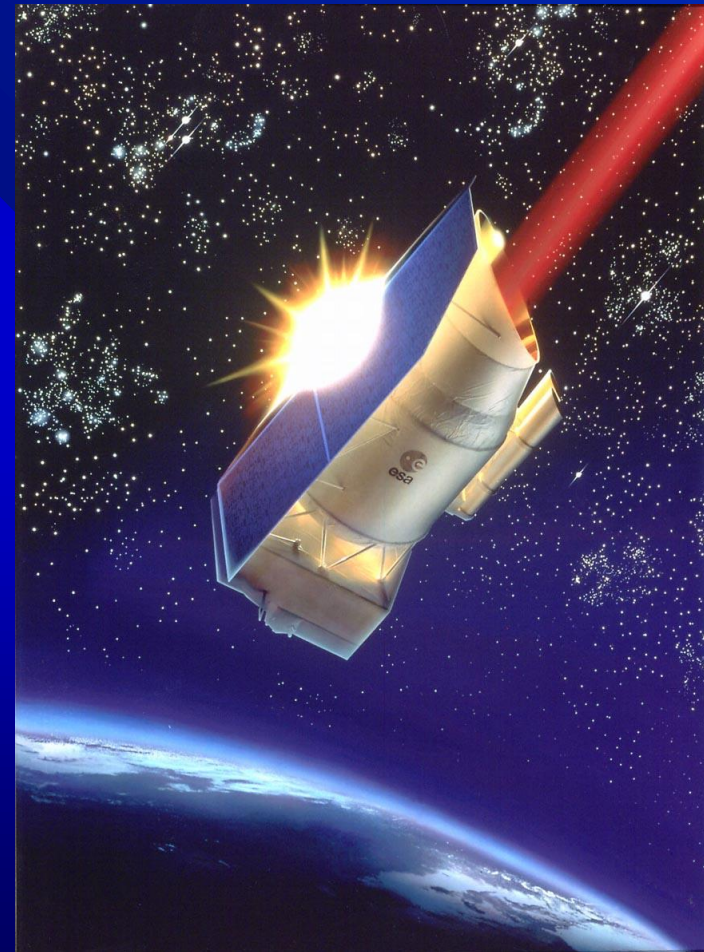
Hlađen helijem

Infrared Space Observatory -

ISO (1995)

0.6m teleskop

1000 puta osjetljiviji



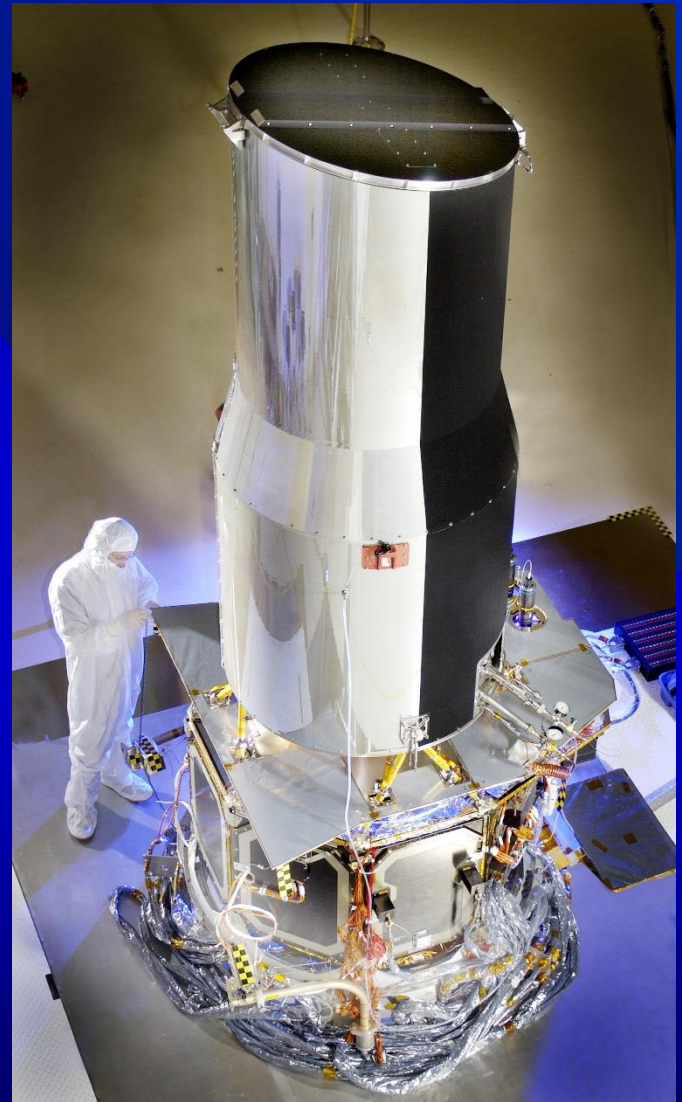
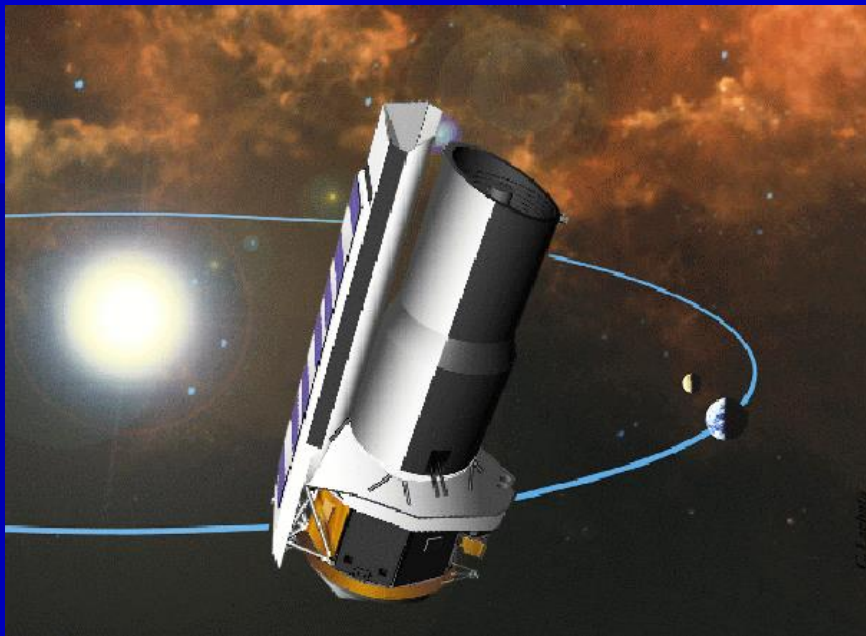
Infracrvena astronomija

Spitzer Space Telescope

(2003)

3-180 mikrona

0.85 m teleskop, f/12





Kozmičko pozadinsko zračenje (2.7 K)

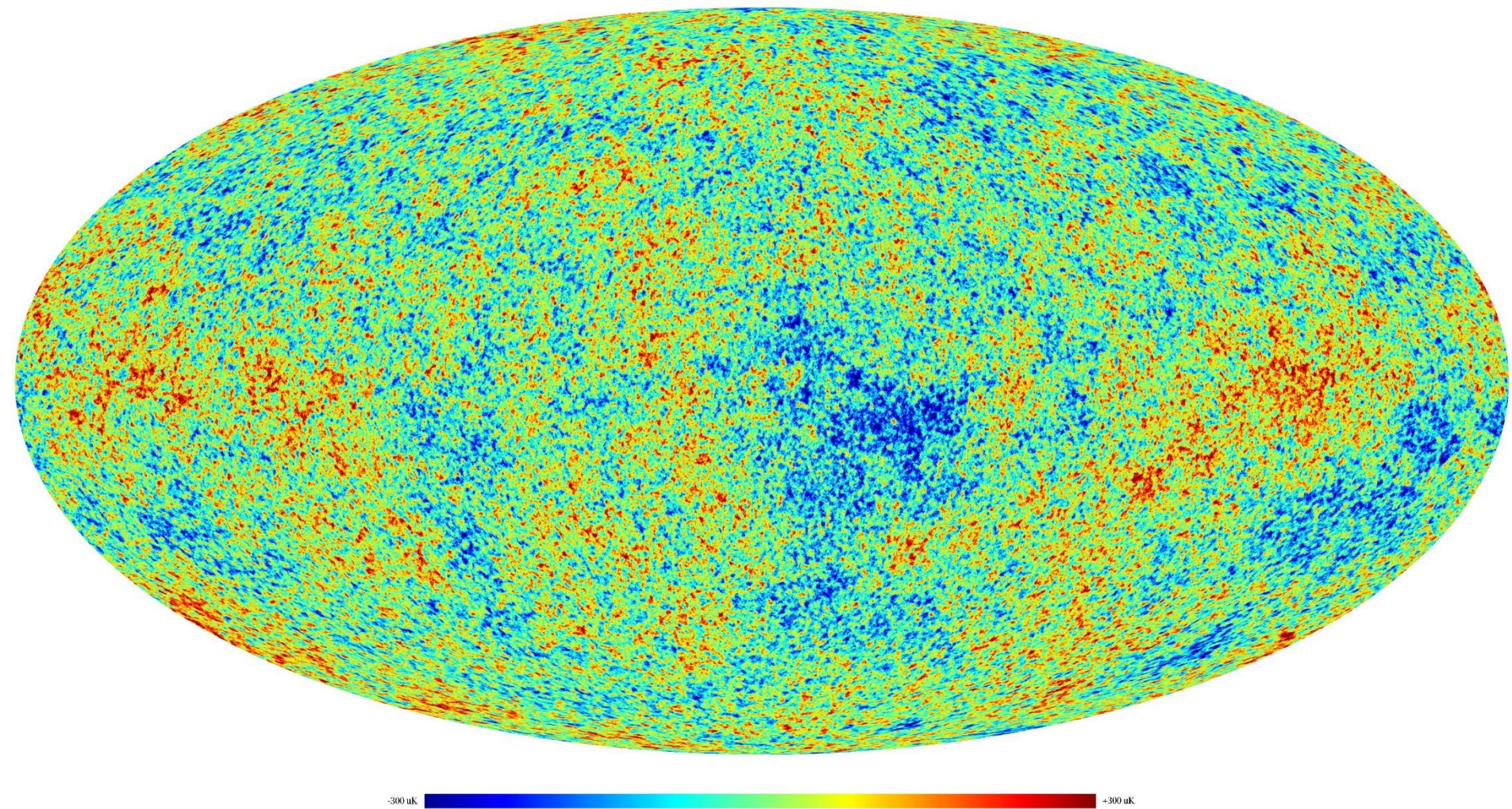
COBE – Cosmic Background Explorer (1989)

WMAP – Wilkinson Microwave Anisotropy Probe (2001)

Planck - ESA (2009)



Kozmičko pozadinsko zračenje



Ultraljubičasto područje

**IUE – International
Ultraviolet Explorer** (1978-1996)

Extreme Ultraviolet Explorer
(1992-2000)
7-76 nm



Rengenska (X-ray) astronomija

UHURU (SAS 1) (1970)

Einstein Observatory (1970-ih)

Izvori gama i X zraka

ROSAT (Roentgen Satellite)

(1990-1999)

0.51-12.4 nm

vruće korone zvijezda

ostaci supernova, kvazari

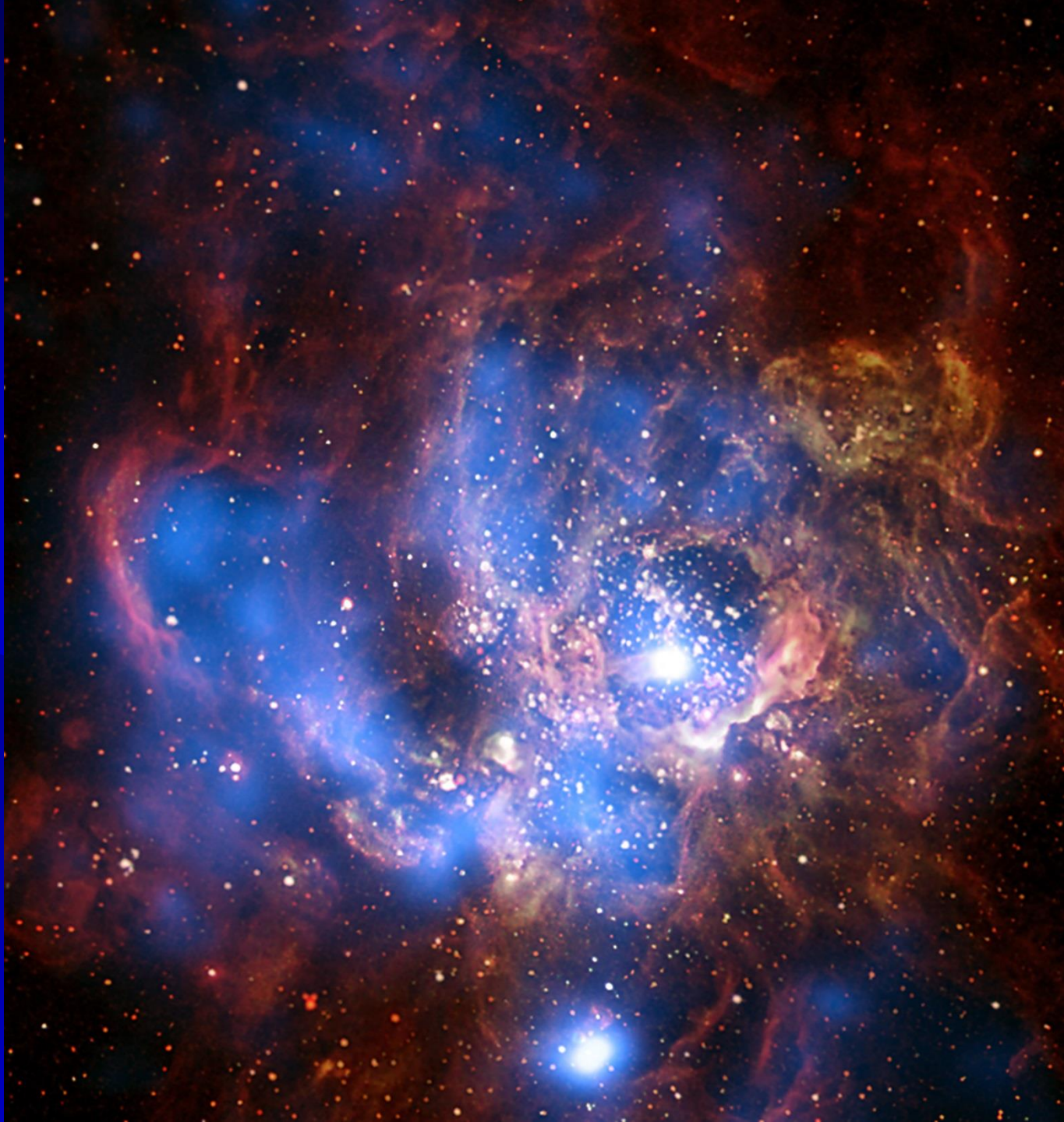
Chandra X-ray Observatory

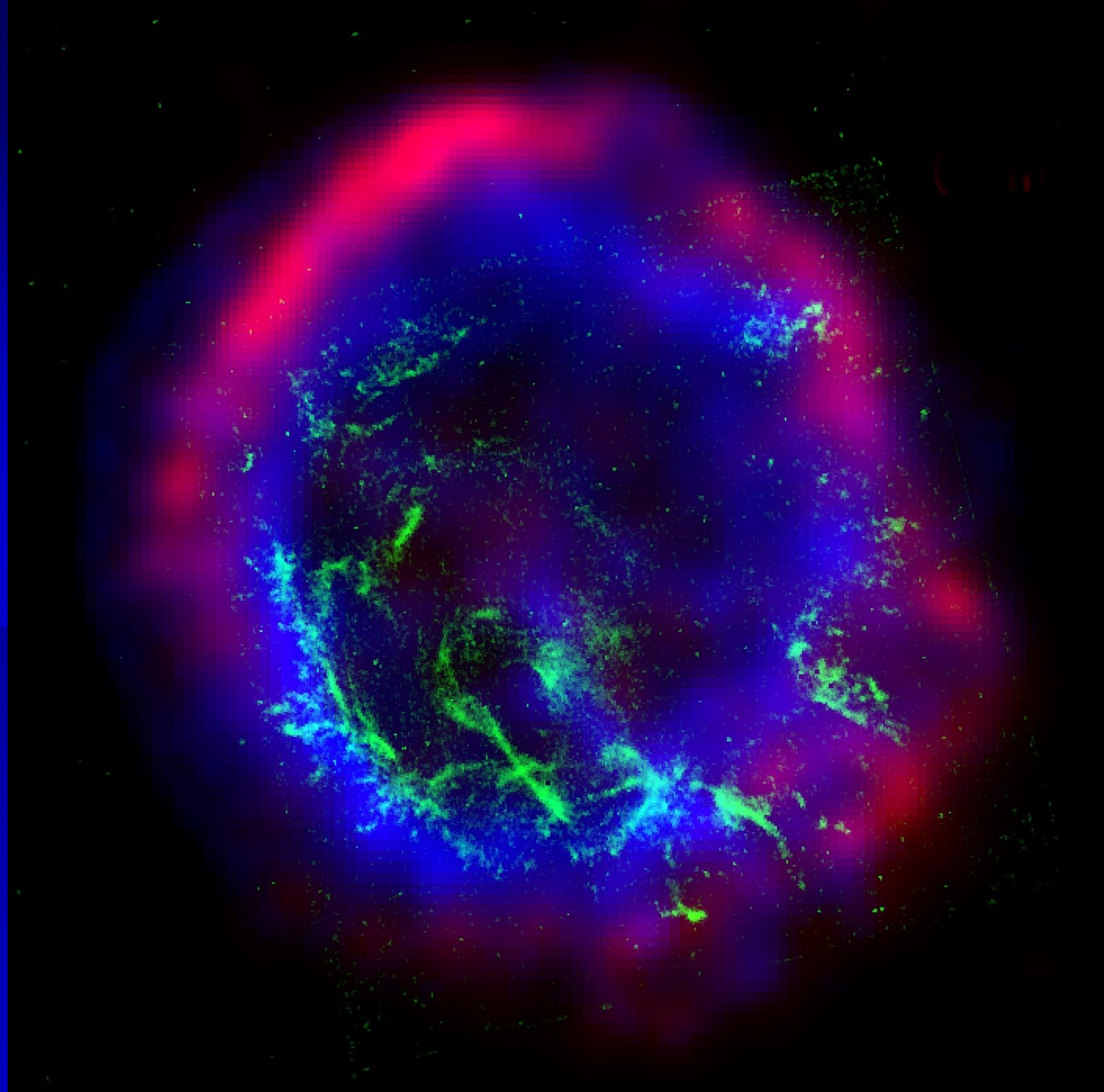
(1999)

0.1-6.2 nm (0.2-10 keV)

0.5" rezolucija







Rengenska (X-ray) astronomija

XMM Newton – X-ray Multi-Mirror Newton Observatory

(1999)

ESA

0.01-1.2 nm



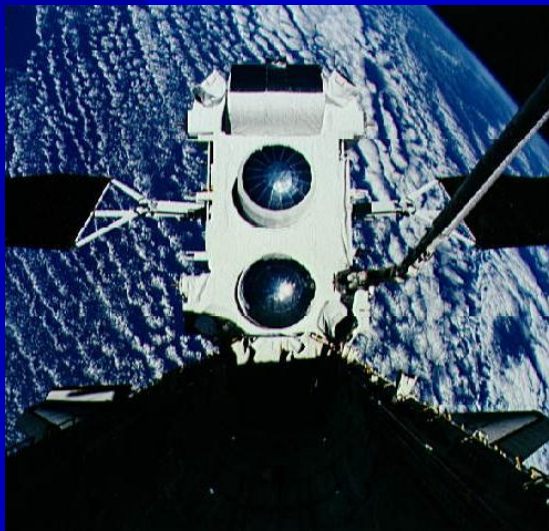
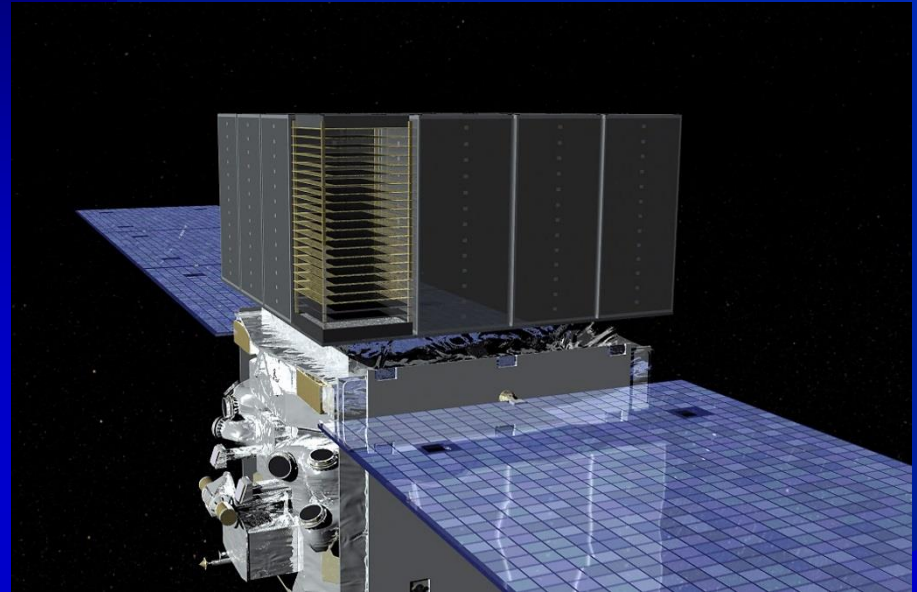
Gama astronomija

Fermi Gamma-ray Space Telescope (2009)

NASA+Francuska, Italija,
Njemačka, Japan, Švedska

LAT (Large Area Telescope) – 30
MeV-300 GeV

GBM (Gamma-ray Burst Monitor)
– 8 keV-30 MeV



Compton Gamma Ray Observatory (CGRO) (1991)

NASA

EGRET – 20 MeV-30 GeV

COMPTEL – 0.75-30 MeV

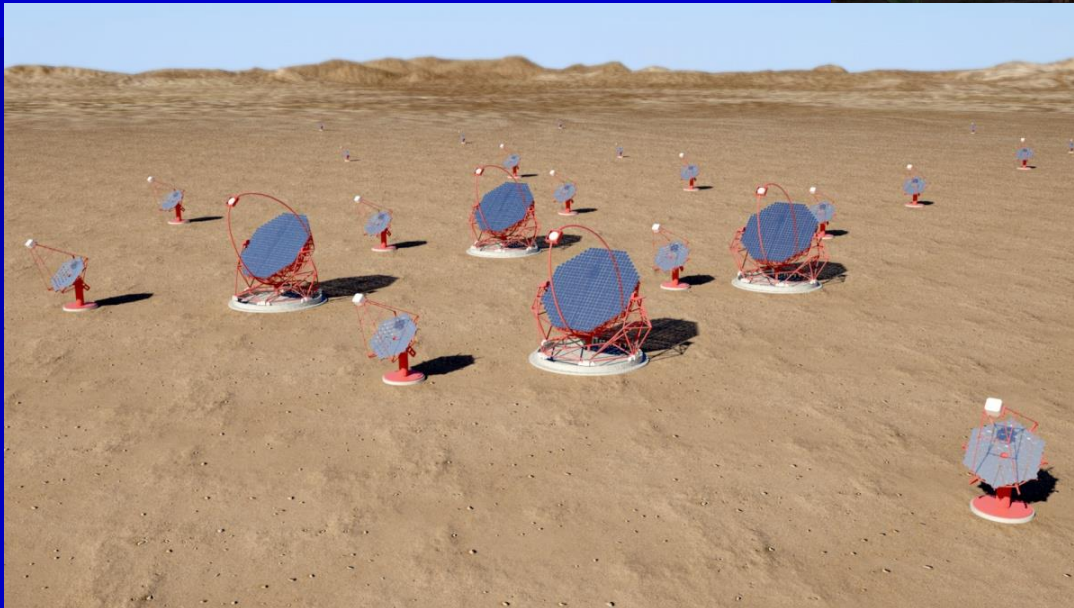
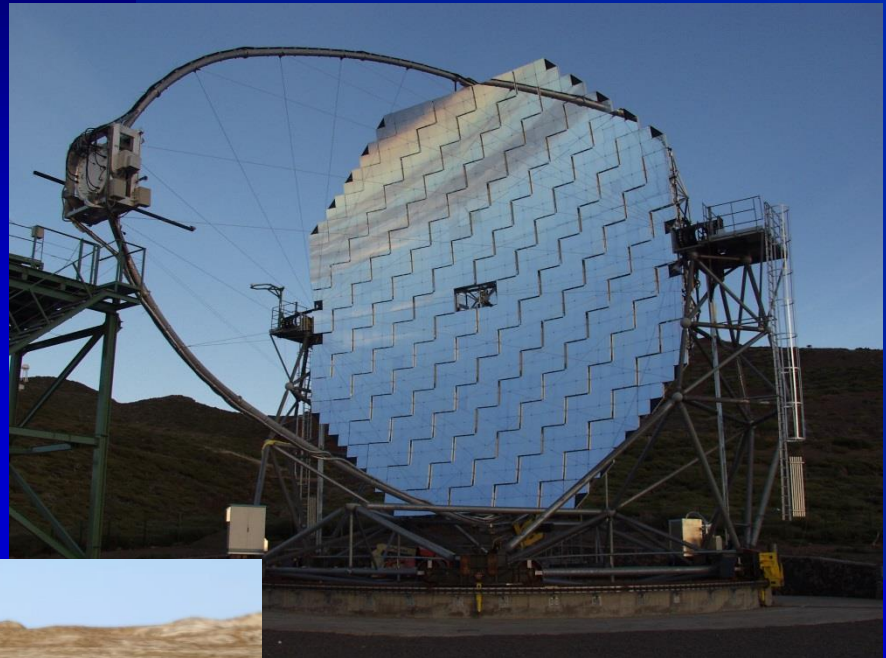
OSSE – 0.05-10 MeV

BATSE – 20 keV-2 MeV

Gama astronomija

MAGIC

La Palma, Kanarski otoci



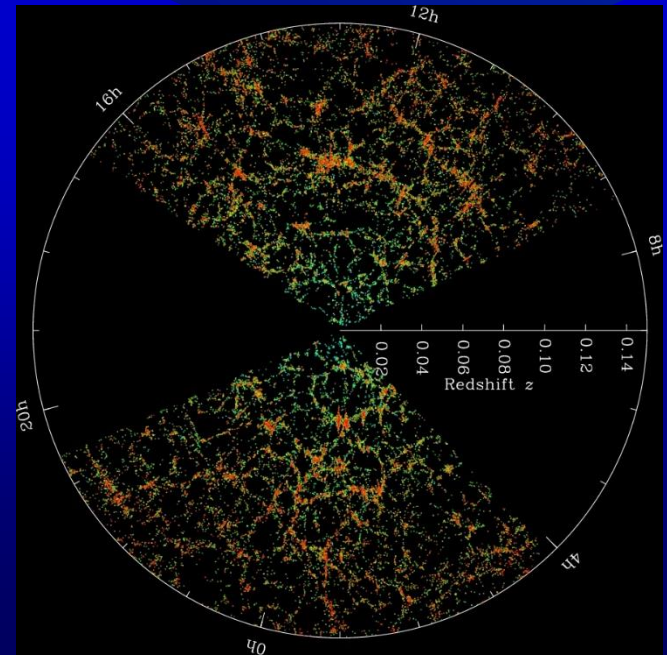
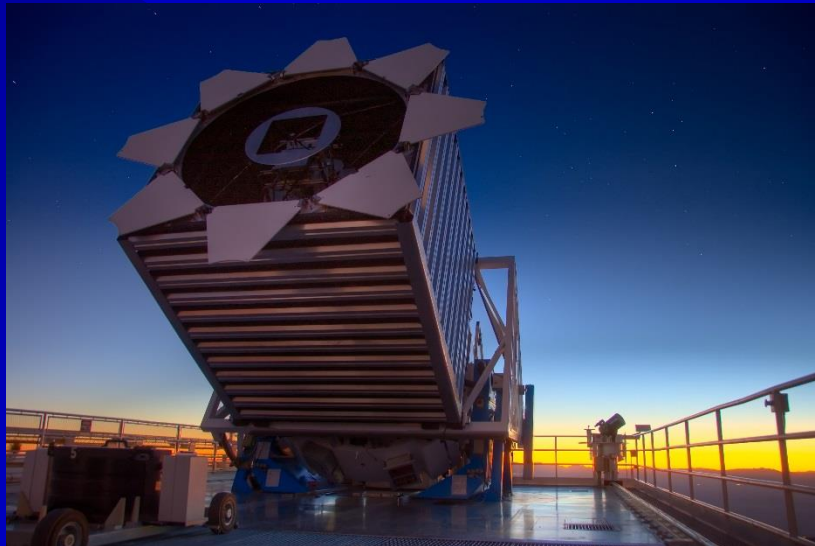
**Cherenkov Telescope
Array**

Veliki pregledi neba



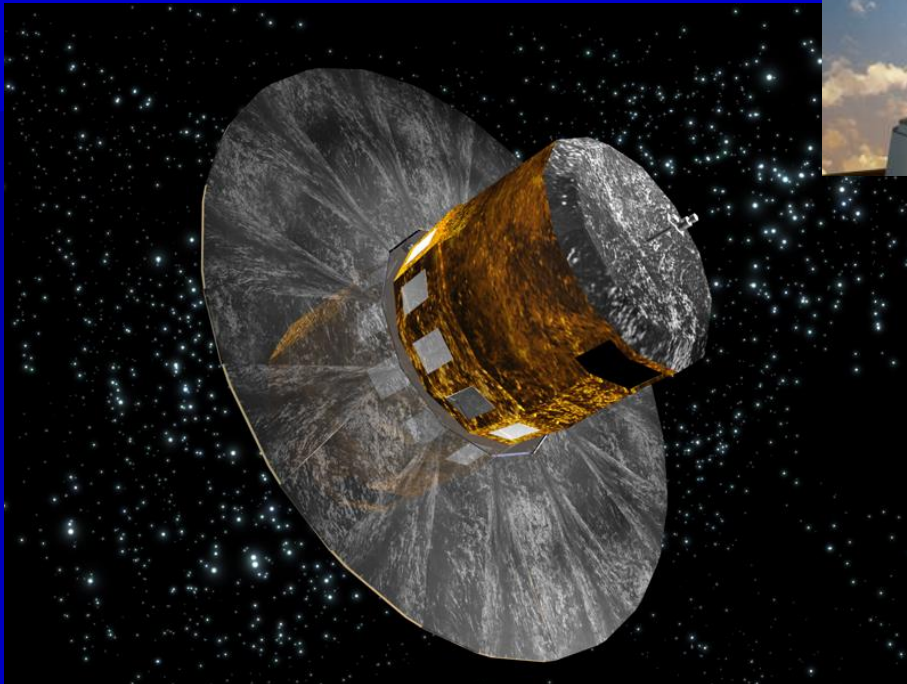
2MASS – 2 Microns
All Sky Survey

SDSS – Sloan Digital Sky Survey



Veliki pregledi neba

LSST – Large Synoptic
Survey Telescope



Gaia – Evropski konzorcij

Hubble Space Telescope

2.4 m teleskop; $f/24$

$\lambda/50$ preciznost

Ritchey-Cretien (hiperboličko primarno zrcalo)

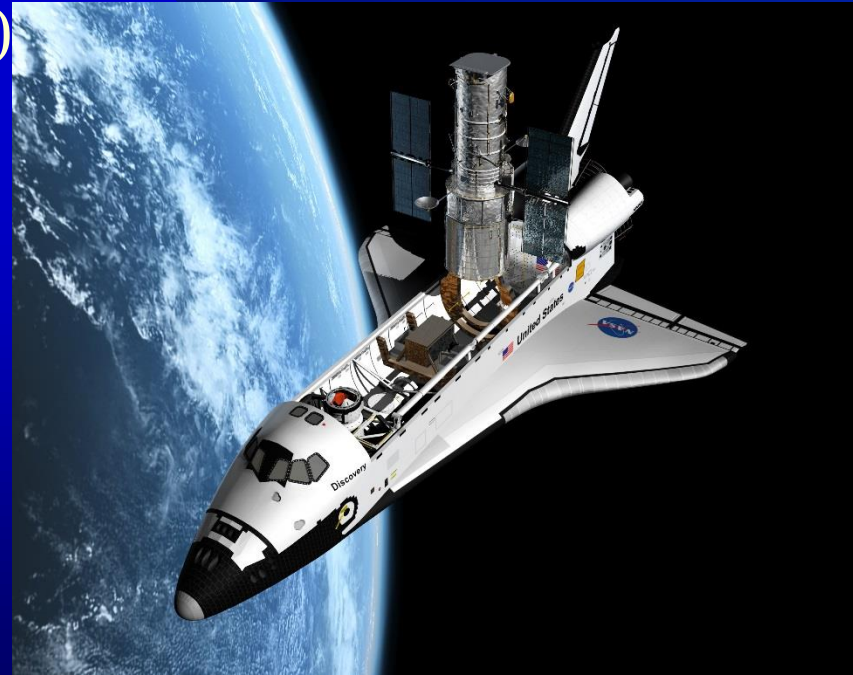
Detektor:

UV do blisko-IR (120 nm – 1 μm)

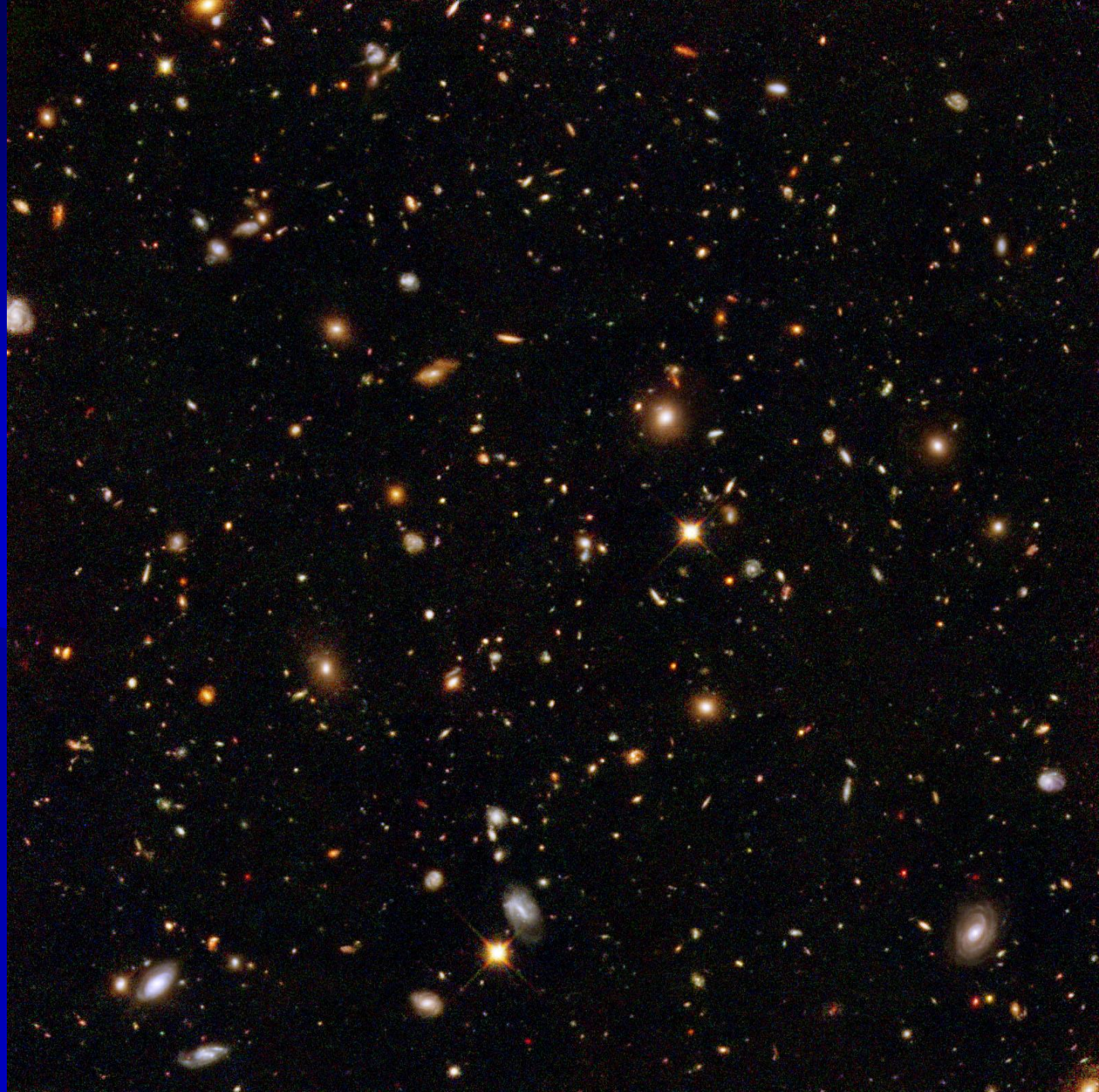


Hubble Space Telescope

- Faint Object Camera (FOC)
- Faint Object Spectrograph
- Goddard High Resolution Spectrograph
- COSTAR (Corrective Optics)
- Wide Field & Planetary Camera (WF/PC 2)
- Advanced Camera for Surveys
- Near-Infrared Camera (NICMOS)

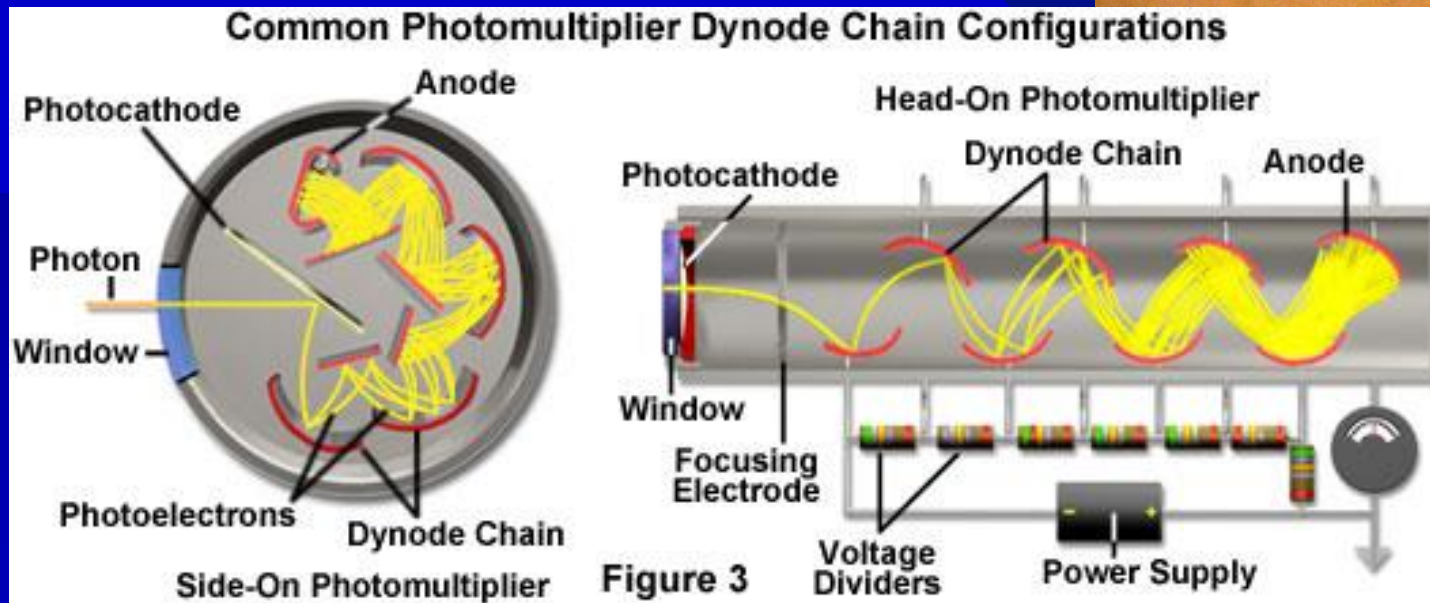
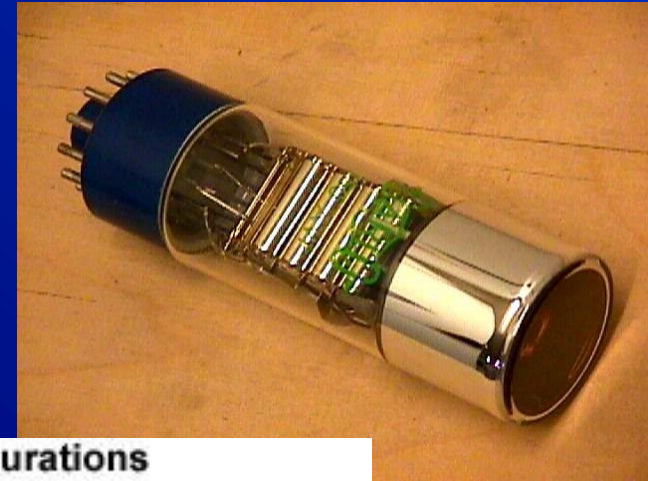






Detektori

1. Fotografske ploče (više se ne koriste)
2. **Fotometri** - fotomultiplikatori

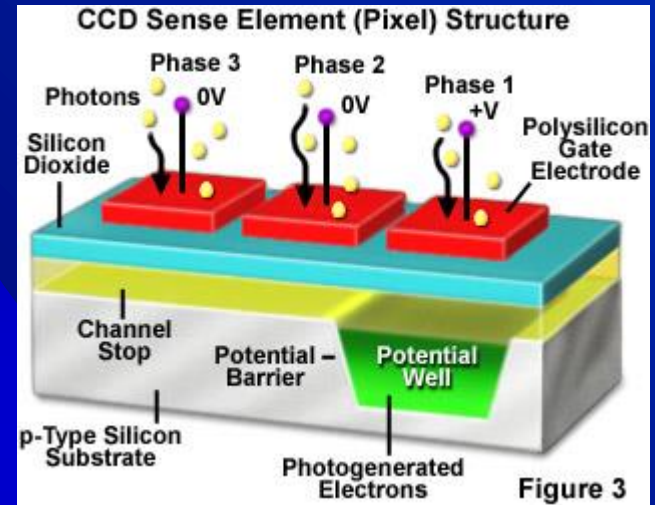


Detektori

3. CCD – Charge-coupled device

Kvantna efikasnost: 60-90%
(ljudsko oko 1%, fotoploča 2-5%)

Linearni odziv: meke X-zrake do IR



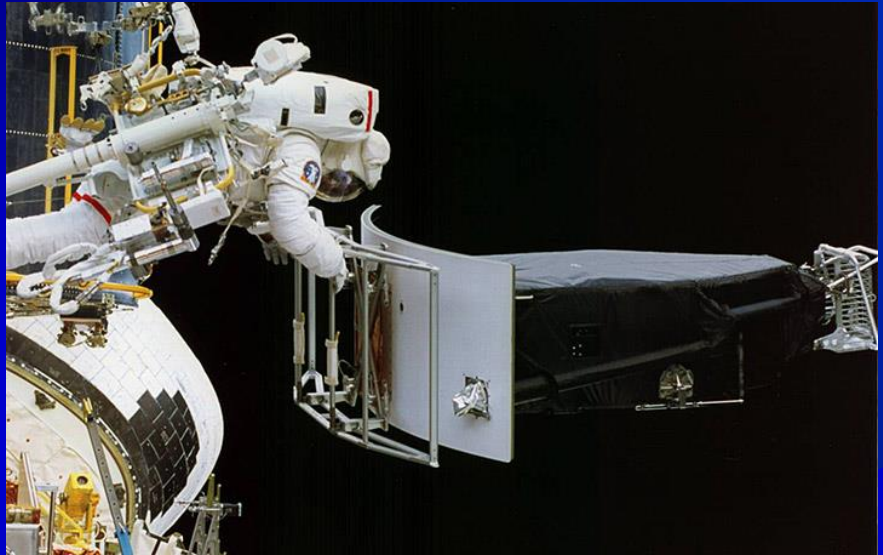
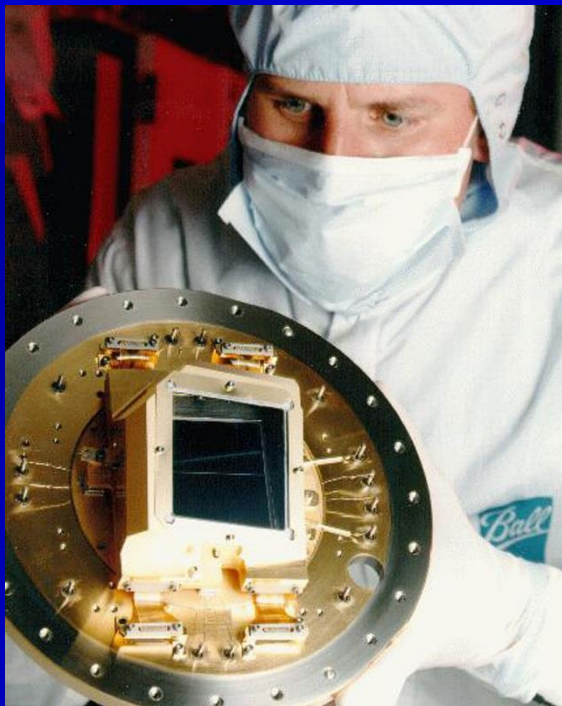
HST detektori:

Wide field and planetary camera
(WF/PC 2):
4 CCD kamere 800x800 px
(2.5 Mpx)

Detektori

HST detektori:

Wide field and planetary camera (WF/PC 2):
4 CCD kamere 800x800 px
(2.5 Mpx)



Advanced camera for surveys
(ACS):
4144x4136 px (17 Mpx)

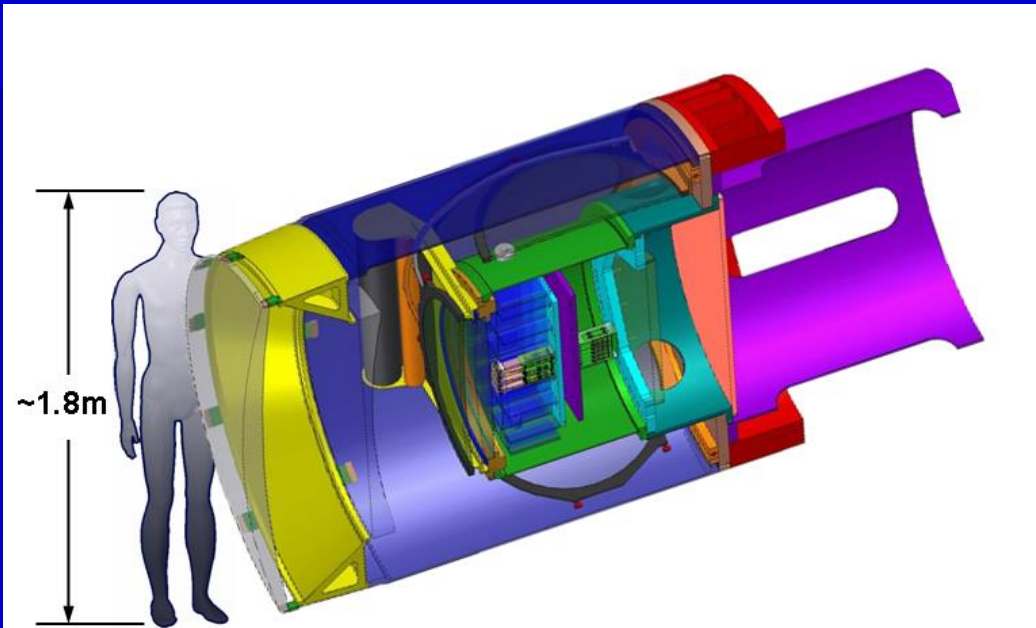
Detektori

LSST kamera

16 Mpx ploče

Ukupno 3.2 Gpx

2800 kg



4. CMOS

(Complementary metal-oxide semiconductor)