Astronomies and Telescopes

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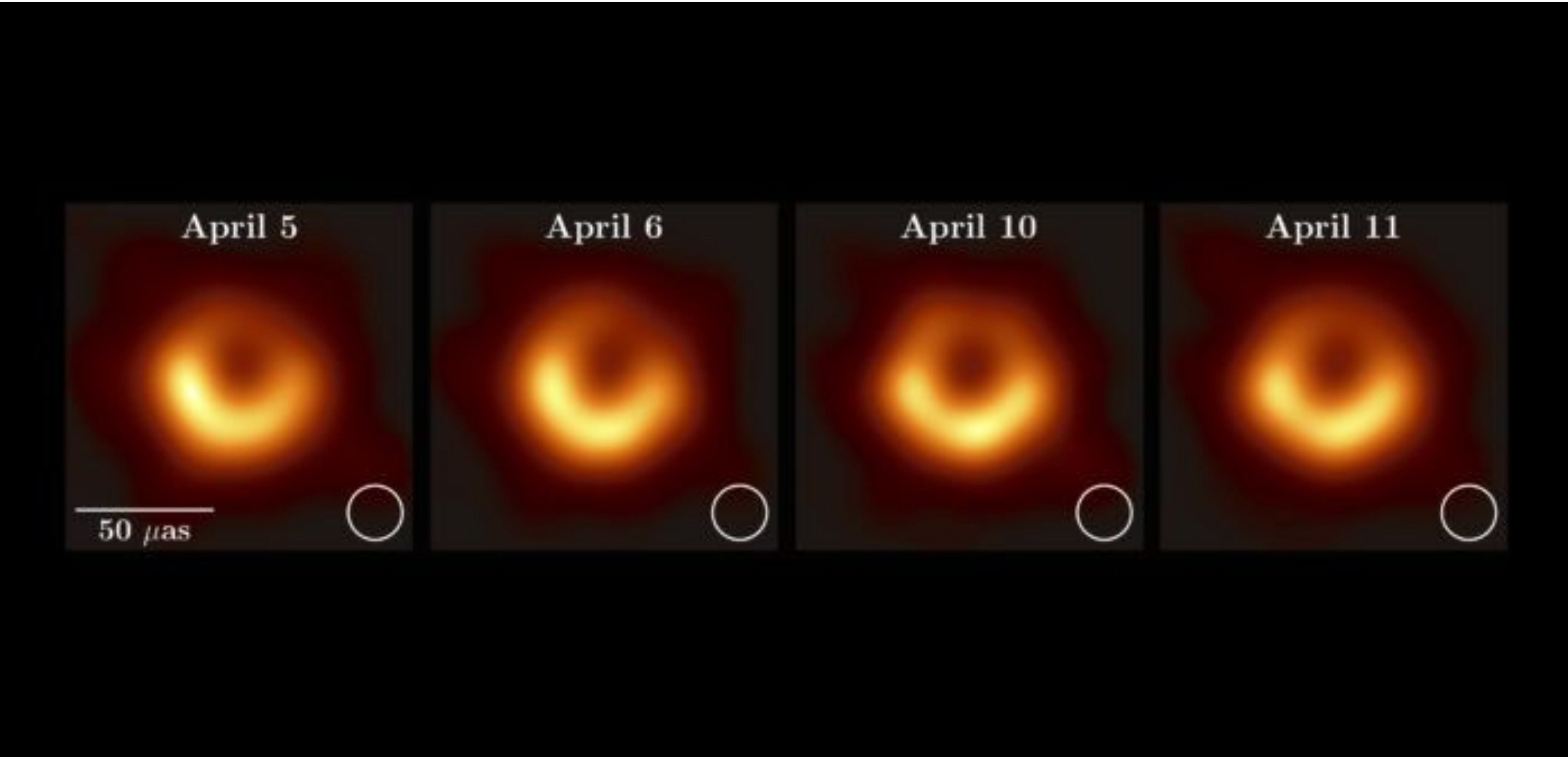
Some Background

- Until ~900 astronomy only in the visual bands and human eye only detector:
  - λ 4000-7000 A
  - Resolution ~ arcmin
  - Field Of View (FOV) ~ 160 deg
  - Depth ~ +8 mag

Improvements

Telescopes and detectors have revolutionized the field

- Angular resolution
- Depth
- Surface Brightness
- Frequency Range



Event Horizon Telescope ~50 uarcsec

Improvements

- Angular resolution
- Depth
- Surface Brightness
- Frequency Range

Hubble Extreme Deep Field ~ 22 days!! → 31 mag

Improvements

- Angular resolution
- Depth
- Surface Brightness
- Frequency Range

Dragonlfy

van Dokkum, Pieter G.; Abraham, Roberto; Merritt, Allison (2014)

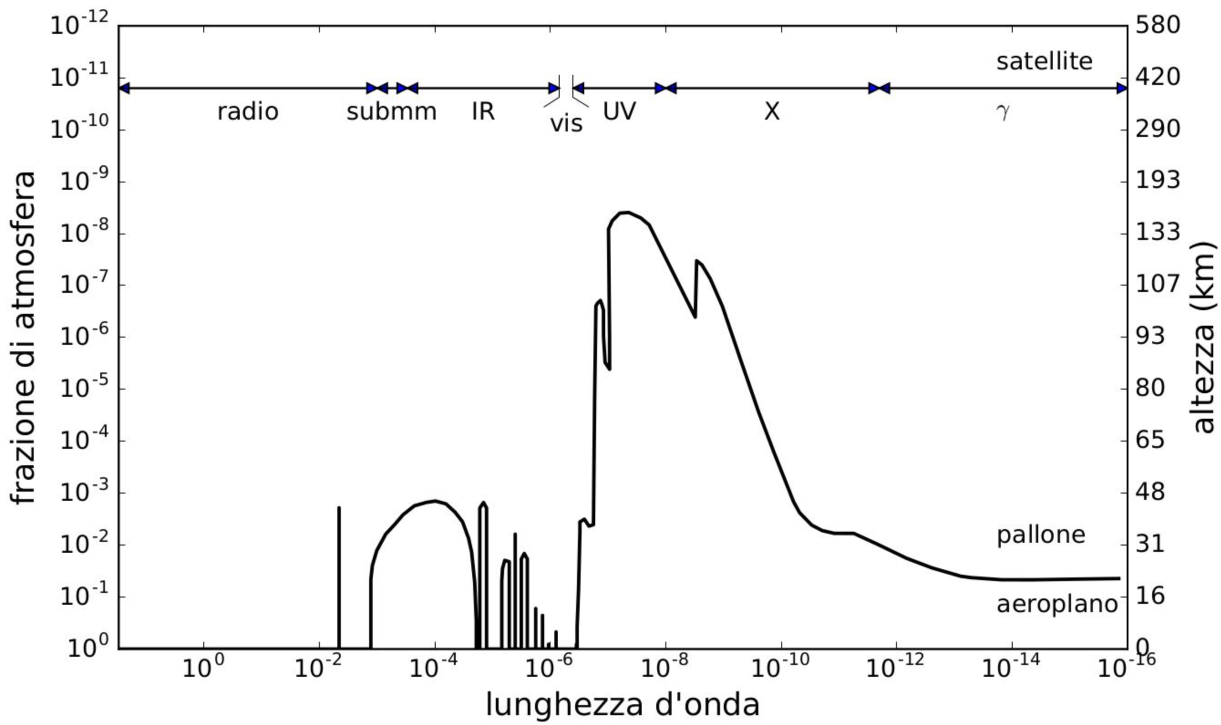
reached ~32 mag/arcsec^2!! Significantly below current limit of 29 for normal telescope (due to nanotechnology improvements)

Improvements

- Angular resolution
- Depth
- Surface Brightness
- Frequency Range

banda	sotto-banda	λ
RADIO	(non oss.) radio microonde	>30m 30m – 3cm 3cm – 1mm
sub-mm		1mm – 300μ
IR	FIR MIR NIR	300μ – 30μ 30μ – 5μ 5μ – 7000Å
ottico (visuale)		7000Å – 4000Å
UV	NUV soft UV EUV	4000Å – 3100Å 3100Å – 912Å 912Å – 100Å
X	soft X hard X	100Å – 10Å 10Å – 0.02Å
γ		<0.02Å

λ	assorbimento	osservazioni
> 300m	plasma interplanetario	opaco
> 30m	ionosfera	(satellite)
30m – 3cm	finestra radio	da terra
3cm – 1mm	H_2O e O_2	alta montagna
1mm – 10μ	H_2O, O_2, CO_2	pallone o satellite
850μ e 450μ	finestre sub-mm	alta montagna
10μ – 7000Å	H_2O, molte finestre	alta montagna
7000Å – 3100Å	finestra ottica	da terra
3100Å – 912Å	O_3	satellite
∼912Å	HI galattico	quasi opaco
$\lesssim$ 100Å	ionizzazione di stratosfera	satellite
$\lesssim$ 0.02Å	*scattering* Compton etc.	satellite
$E > 100$GeV	creazione di sciami	da terra



banda	oggetti visibili	meccanismi di emissione
radio	galassie, AGN, pulsar, SNR HI	sincrotrone, maser H_2O riga 21 cm
mm e sub-mm	Galassia CMB	bremsstrahlung ($T \sim 10^4$ K) cosmologico
sub-mm	polveri nubi molecolari	emissione termica ($T \sim 50$ K) righe di emissione molecolari
FIR, MIR NIR	polveri nubi molecolari stelle K-M	emissione termica ($T \sim 50$ K) righe di emissione molecolari emissione termica ($T \sim 3000$ K)
ottico e NUV	stelle, AGN regioni HII	emissione termica fluorescenza
soft UV	stelle O-B corone stellari regioni HII	emissione termica ($T \sim 10^4$ K) bremsstrahlung ($T \sim 10^6$ K) fluorescenza
EUV e X	corone stellari ammassi di galassie pulsar, binarie X, AGN e SNR	bremsstrahlung ($T \sim 10^6$ K) bremsstrahlung ($T \sim 10^8$ K) Compton inverso, sincrotrone
γ	GRB, AGN, pulsar	annichilazioni, decadimenti, sincrotrone, Compton inverso

Information Content of Radiation

- The rate of arriving photons or flux
  - Constraints on luminosity given assumptions about emission geometry
  - Periodicity or variability in sources reveals physical nature
- The arrival direction or shape of source
  - Resolved versus unresolved- diffraction limit and atmospheric effects
  - Nature of resolved sources
- The photon energy distribution or spectrum
  - Composition of source – atomic features
  - Temperature of source- blackbody or bremsstrahlung
  - Line of sight relative velocity of source or redshift
- The polarization of the photons
  - Presence of magnetic fields with preferred direction
  - Scattering of dust grains

Optical/UV and Infrared

Image Formation

- Incoming parallel light from distant source focused to a point in the focal plane
  - Lens Diameter d
  - Focal length f_L
  - Focal ratio $\Re = f_L/d$ (f/3 has $\Re=3$)
- Focal point varies with angle of incoming light

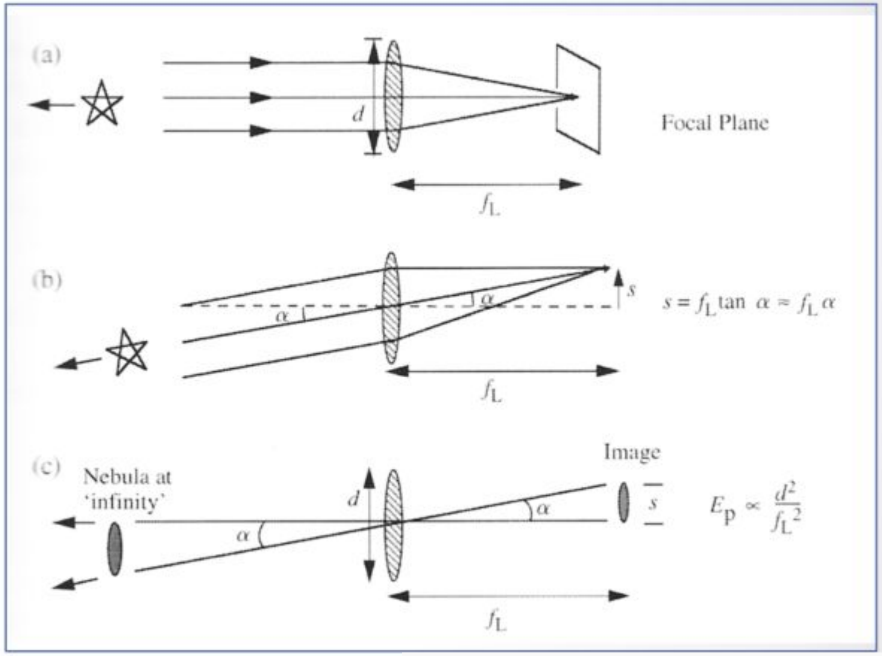
$$s = \tan\alpha \, f_L \approx \alpha \, f_L$$

- Plate scale P_s[rad m^{-1} or "/mm]

$$P_s = \frac{\alpha}{s} = \frac{1}{f_L}$$

- Energy deposited per pixel scales as

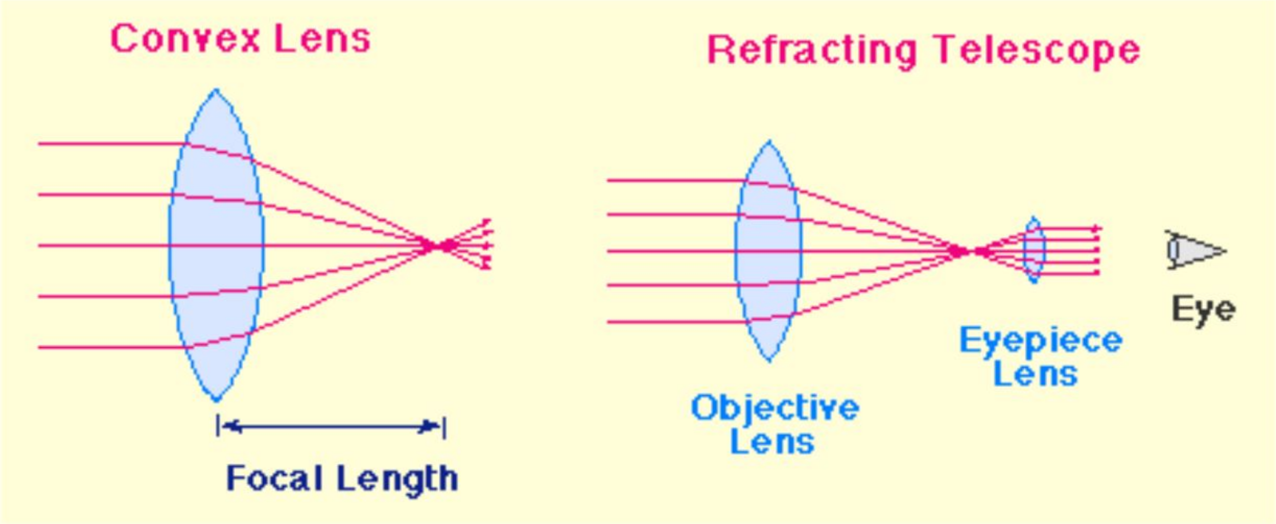
$$E_p / \alpha^2 \propto \left(\frac{d}{s}\right)^2 = \left(\frac{d}{f_L}\right)^2 = \frac{1}{\Re^2}$$

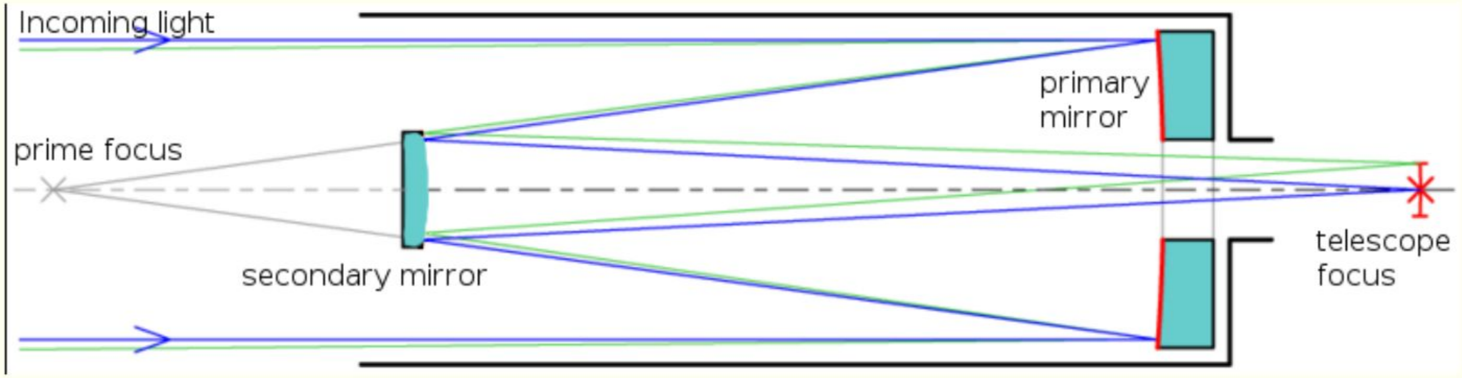


$$\mathrm{FoV} = 2 \cdot \arctan\left(\frac{d}{2f}\right)$$

Fast optical systems:
large Field of View (FOV)
smaller optical systems per mirror d

Telescope Configurations

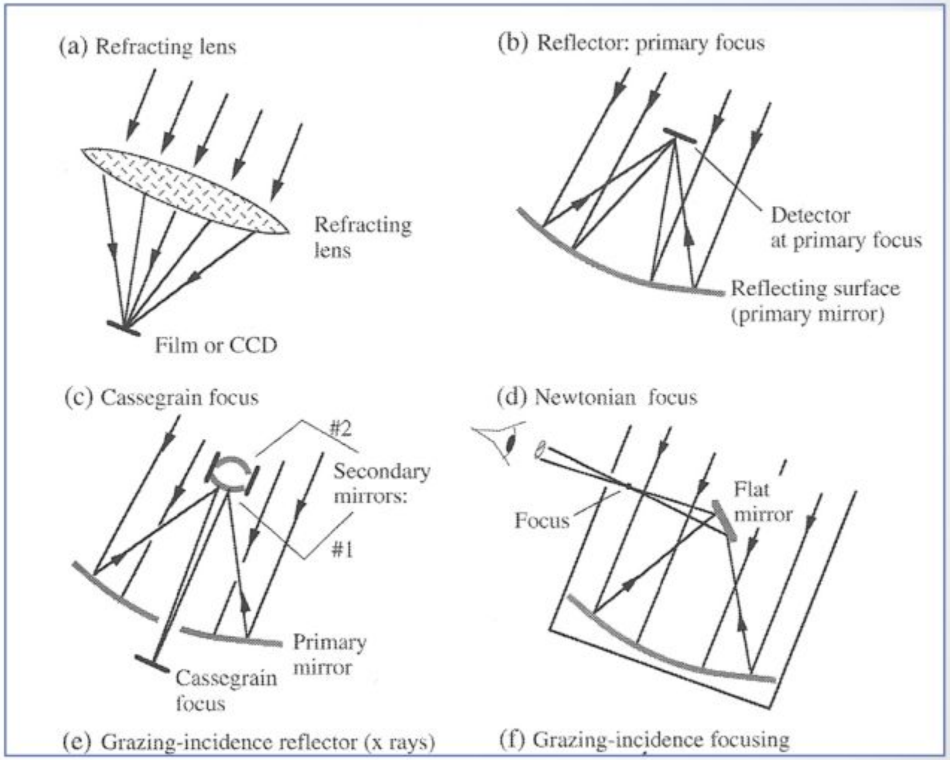




Due to practical limitations in lens manufactury all modern telescopes are reflecting telescopes.

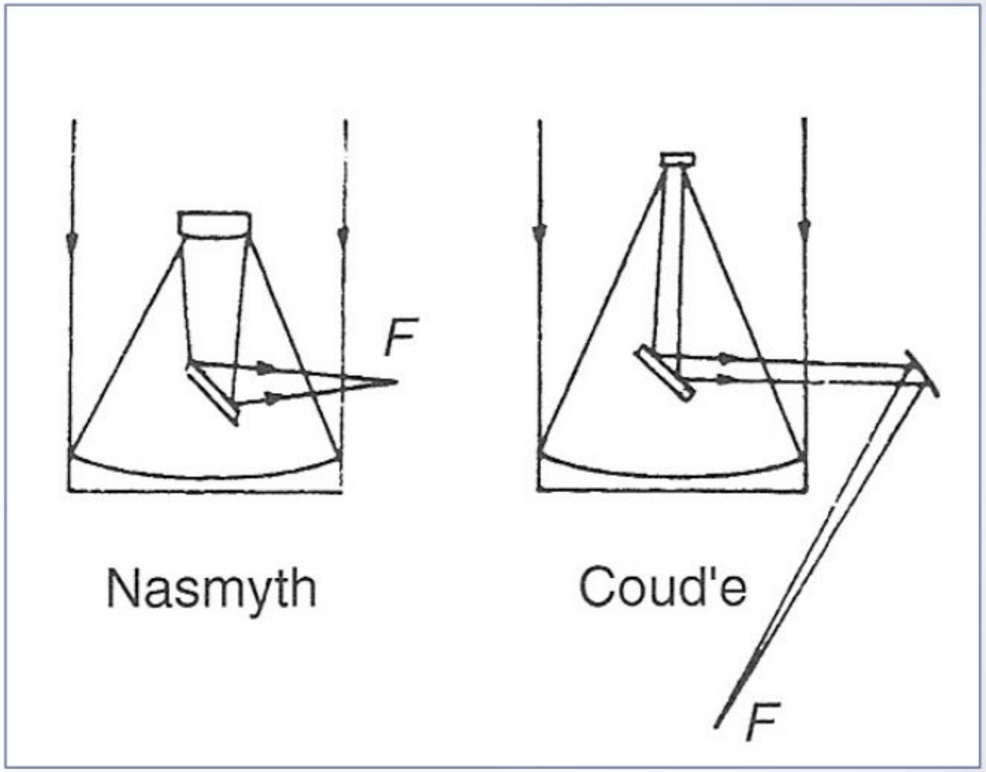
Telescope Configurations

- Elements: Primary, Secondary, Tertiary
  - defined by the path incoming light takes
- Refractor telescopes
  - suffer from chromatic aberration
  - Impossible to support at large d
  - Largest ever made in Yerkes Observatory (Wisconsin, USA) in 1895: 40in
- Reflector telescopes
  - Primary mirror: detector at primary focus
  - Cassegrain has focusing secondary mirror, prime focus behind primary
  - Newtonian has a flat secondary and focus to the side



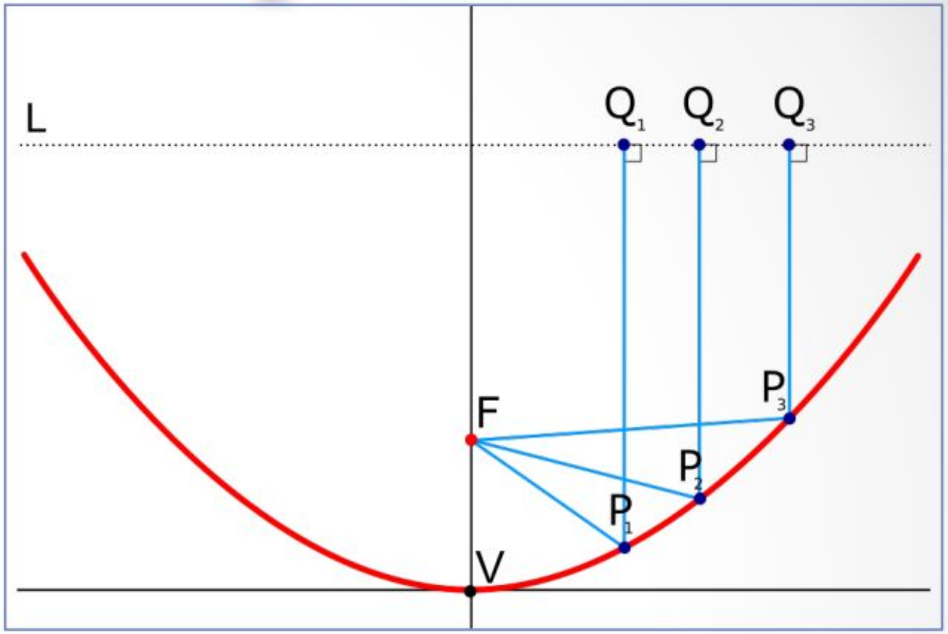
Additional Configurations

- Nasmyth focus uses focusing secondary and a (rotating) flat tertiary; focus lies to side just above the primary
    - Convenient in alt-az telescopes with massive instruments (VLT)
- Coudé focus has very long focal length and uses an additional mirror to transport the focus to a nearby instrument- typically a very stable spectrograph in temperature controlled room

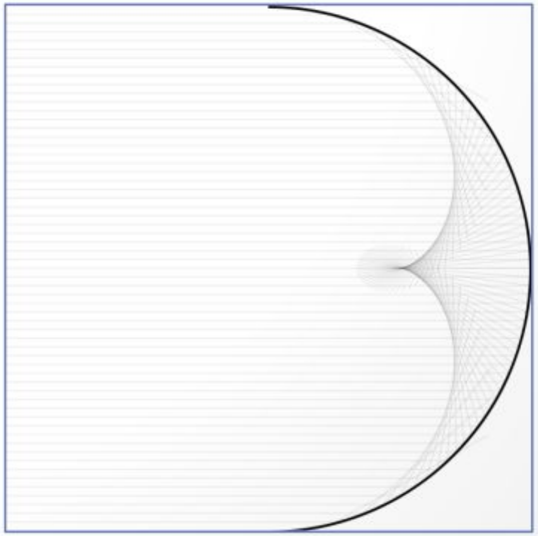


Parabolic vs Spheric

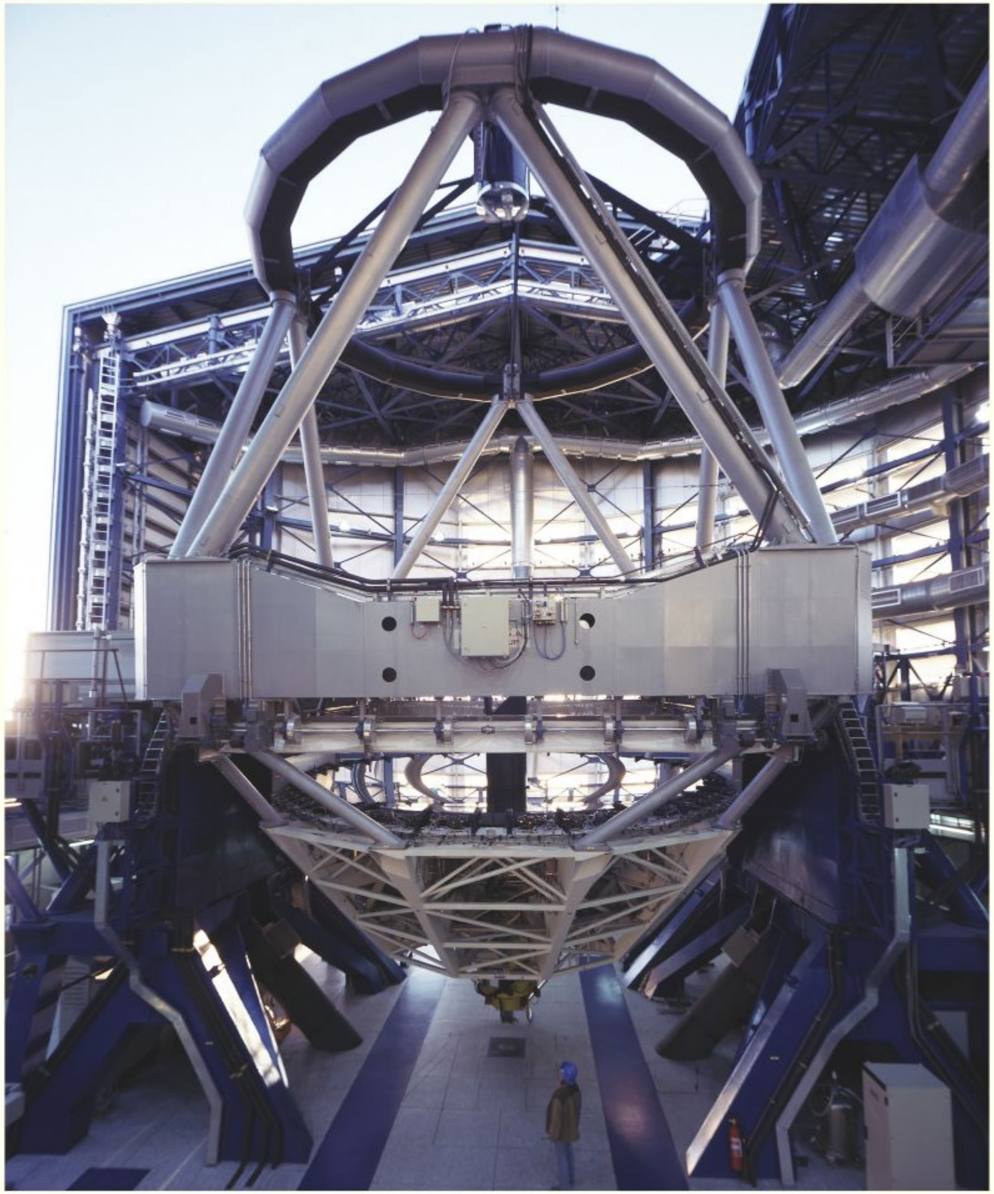
- Parabolic surface focuses all parallel, on-axis rays to a single point
  - Off-axis incoming light is not perfectly focused



- Spheric surface does not focus to a single point, but the aberations are independent of off-axis angle!

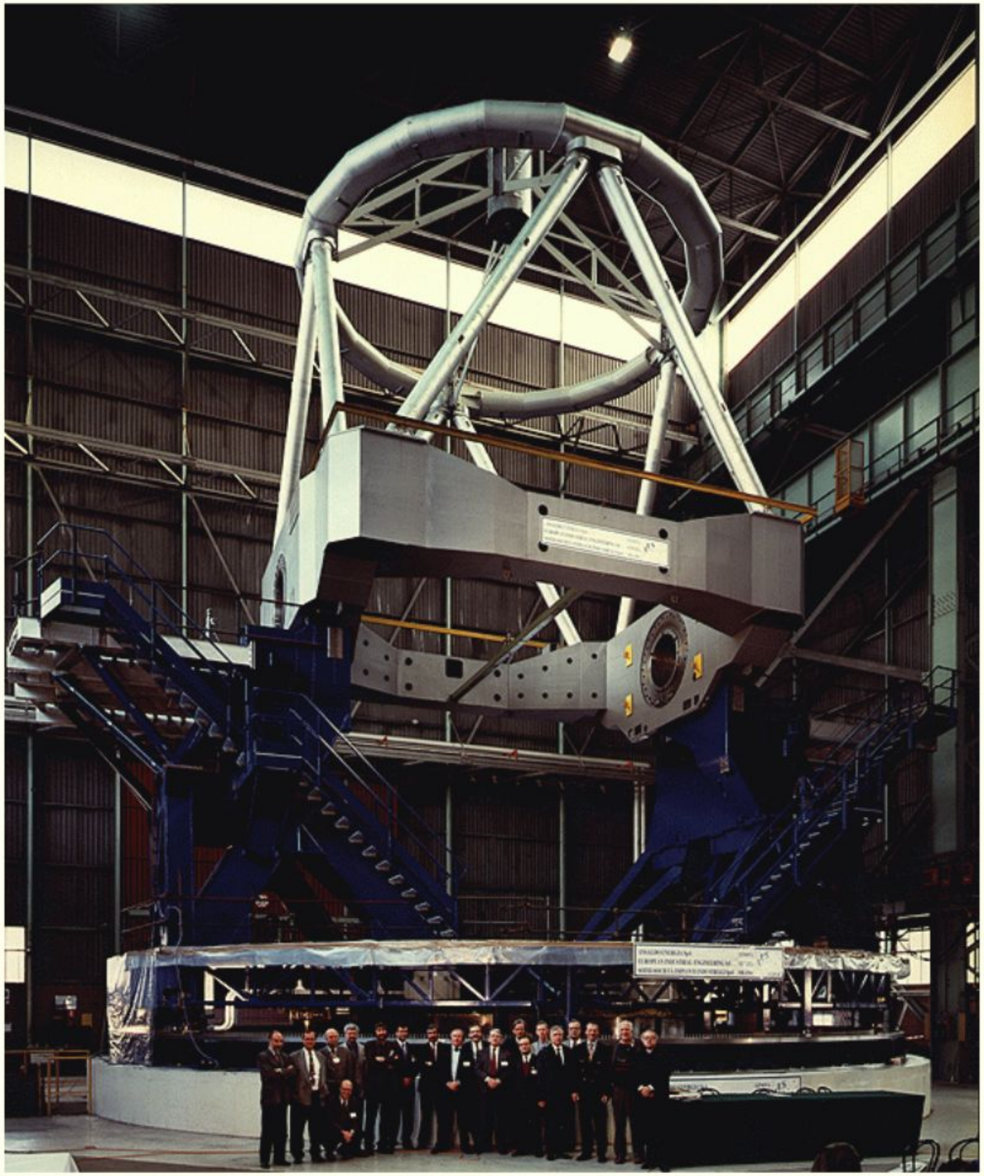


The VLT: Four Foci on an 8.2 m Telescope



One Cassegrain, one Coudé and two Nasmyth foci.

A better view



Northern Telescopes

Table 5.1 Large ground-based optical telescopes in the northern hemisphere

Latitude	Altitude [m]	Site	Country	Diameter [m]	Remarks	Date
47°N	2 070	Zelenchuskaya (Caucasus)	Russia	6	Altazimuth mount	1972
42°N	2 500	Xing Long	China	4	LAMOST siderostat	2007
37°N	2 160	Calar Alto (Spain)	Germany and Spain	3.5		1981
34°N	1 706	Palomar (California)	USA	5	First VLT	1948
32°N	2 130	Kitt Peak, Arizona	USA	3.8	Mayall	1974
	3 266	Mt. Graham, Arizona	USA, Italy, Germany	2 × 8.2	LBT	2007
30°N	2 076	Mt. Locke (Texas)	USA	9.2	Hobby–Eberly fixed elevation	1997
28°N	2 370	La Palma (Canaries)	UK	4.2	WHT (Herschel)	1984
			Spain	10.4	GranTeCan	2008
19°N	4 200	Mauna Kea (Hawaii)	UK	3.8	Infrared UKIRT	1979
			Canada, France, Hawaii	3.6	CFHT	1974
			USA (CalTech)	2 × 10	Keck I and II	1994
			Japan	8.4	Subaru	1999
			USA (NSF)	8.0	Gemini N	1999

Southern Telescopes

Table 5.2 Large ground-based optical telescopes in the southern hemisphere

Latitude	Altitude [m]	Site	Country	Diameter [m]	Remarks	Date
23°S	2 650	C. Paranal (Chile)	Europe	4 × 8.2	VLT	1998
				4	VISTA	2008
29°S	2 280	Las Campanas (Chile)	USA	2 × 6	Magellan	2002
29°S	2 430	La Silla (Chile)	Europe (ESO)	3.6		1977
				3.5	NTT	1989
30°S	2 700	C. Tololo (Chile)	USA	4	Blanco	1974
	2 738	C. Pachon (Chile)	USA	8.1	Gemini S	2001
			Brazil and USA	4.1	SOAR	2005
32°S	1 500	Sutherland (South Africa)	South Africa and others	11	SALT	2005
34°S	1 165	Siding Springs (Australia)	Australia and UK	3.9	AAT	1974

Optical/NIR Detectors

Photographic Plates

- Photographic plates have been used to image the sky and to obtain spectra of astrophysical sources over the past century
  - Palomar Observatory Sky Survey (POSS)
  - UK Schmidt Southern Sky Survey

- A light sensitive emulsion is applied to glass plates

- Plates are exposed and each absorbed photon results in a chemical change in a molecule of this emulsion; plates are then developed in a chemical process

- Plates have non-linear response, because probability of detecting an incoming photon depends on density of light sensitive chemical in plate. As light is absorbed this density falls and the plate becomes less sensitive

Coma Cluster in POSS2 Red

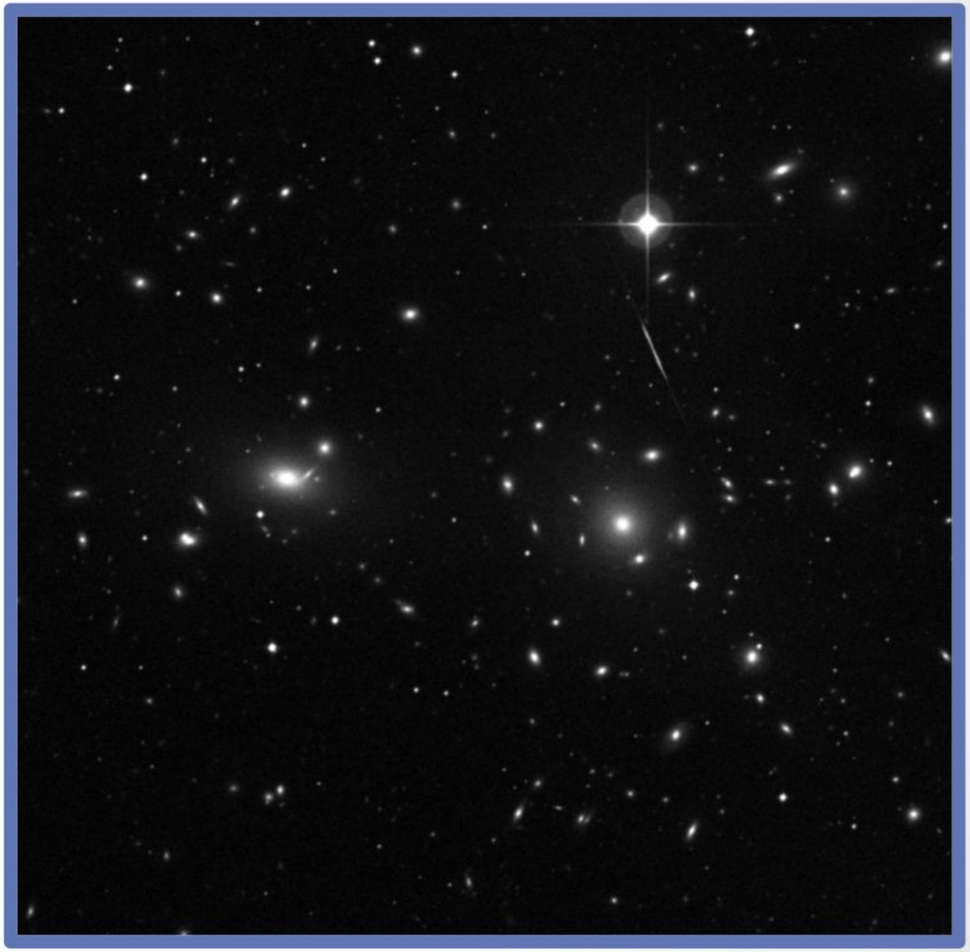
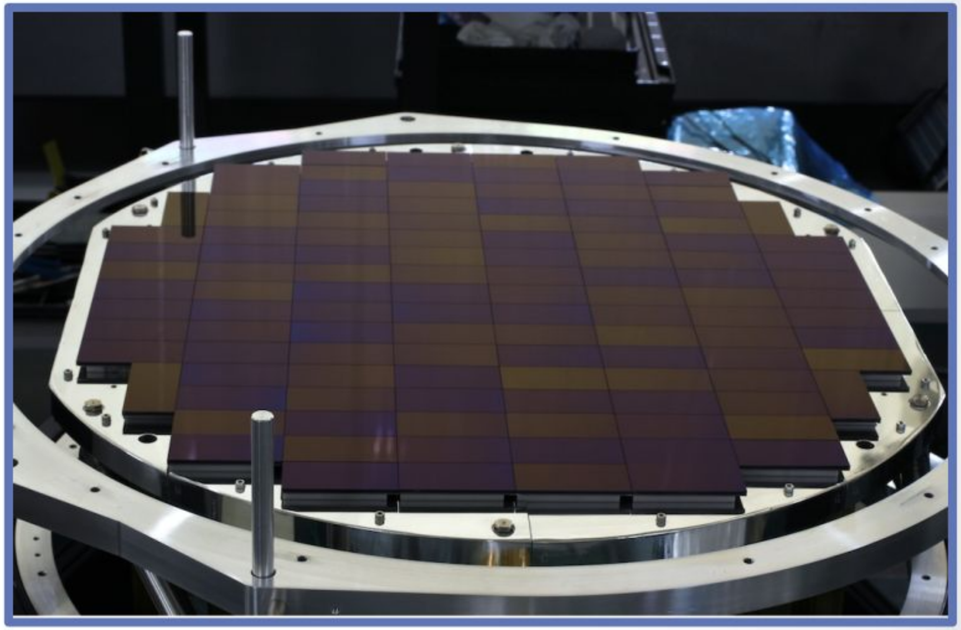


Plate surveys are digitized and available through simple web interface
http://archive.stsci.edu/cgi-bin/dss_form

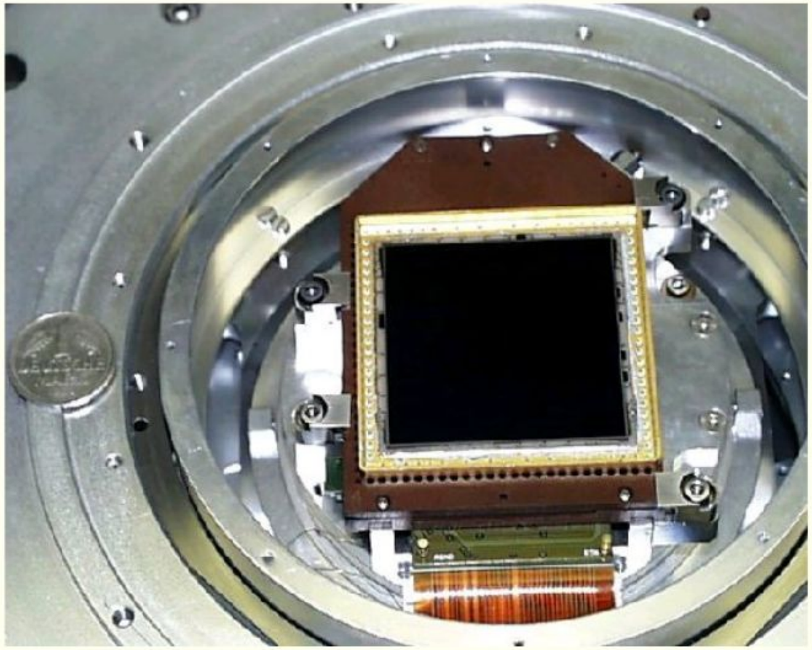
Charge Coupled Devices

- High linearity and broad wavelength sensitivity have made CCDs the detector of choice in optical astronomy
- CCD surface is divided into rows and columns of pixels with characteristic size ~15μm
- Typical sizes are 2048 to 4096 on a side, corresponding to physical extents of ~2.5cm
- Nowadays large sky cameras are built from large arrays of CCDs, enabling efficient mapping of large portions of the sky

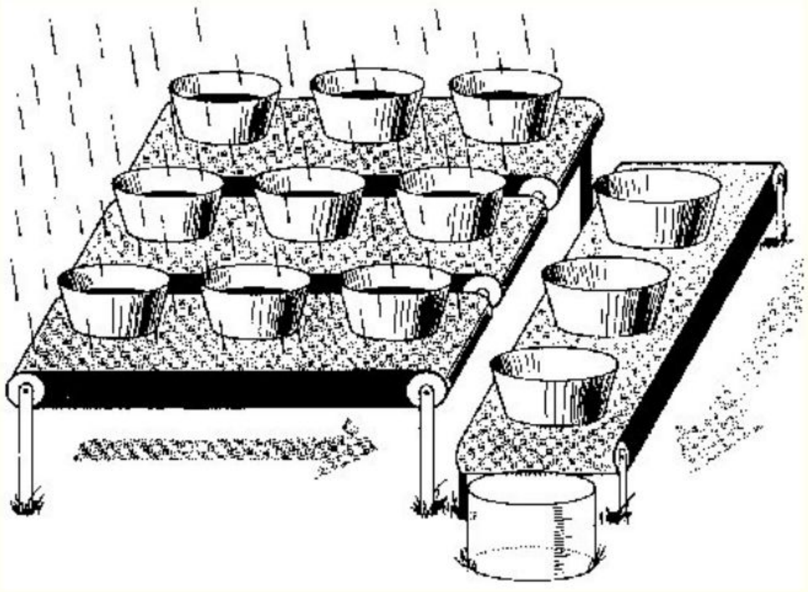


Hyper-Suprime-Cam built for the Subaru Telescope

CCD Exposure and Readout



CCD of the FORS1 instrument



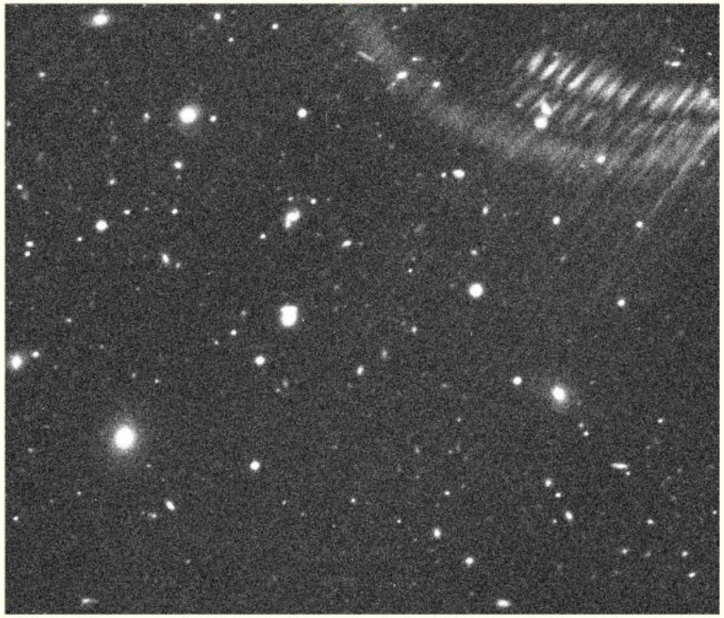
How charge is read out

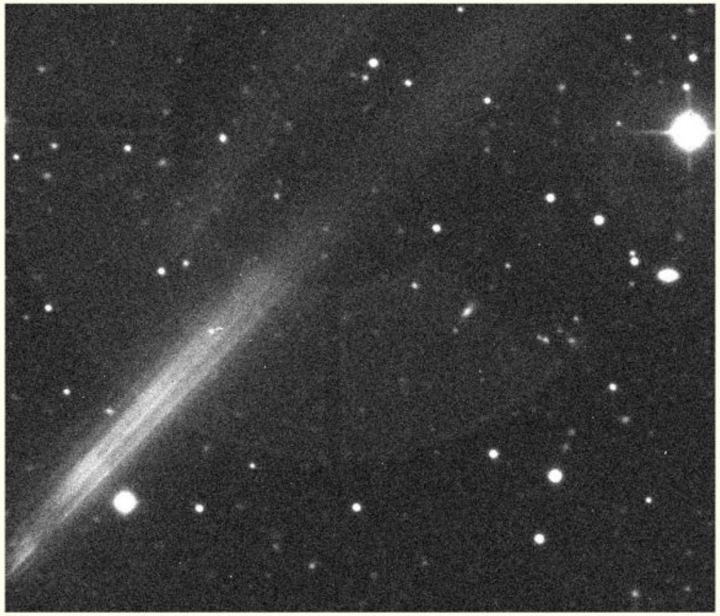
- During exposure collect photo-electrons
- Move charges along columns in serial read-out register
- Transfer to read-out amplifier
- Digitize output voltage (typically 16-bit ADC)
- Store data

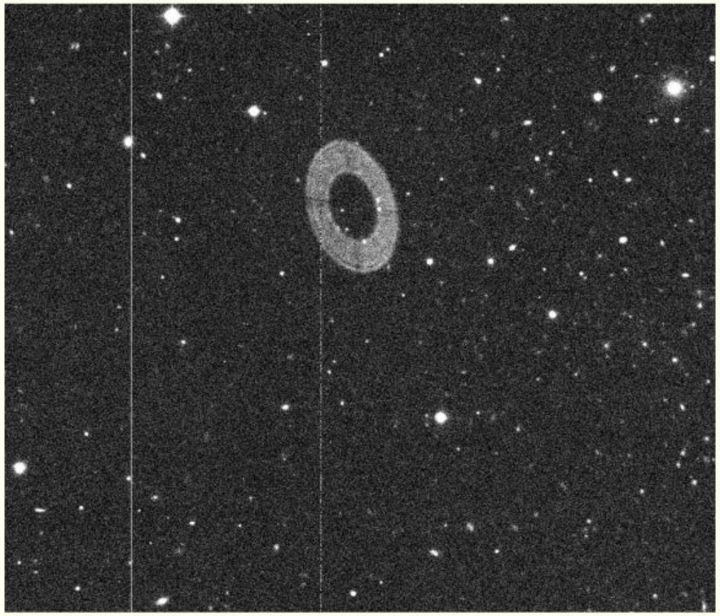
CCD Utility to Astronomy

- CCDs are extremely sensitive with quantum efficiencies reaching 80% or higher
  - Compare to photographic plates or the eye that are ~1%
- Sensitive to photons over a broad range of energies (>1.11eV or <1.1μm, the silicon band gap)
- Linear response over dynamic range of 10^5
  - Compare to photographic plates that are linear over dynamic range of 10^2
- Quantitative astronomy of extended sources suddenly possible
- Large sky surveys undertaken employing CCDs
  - Sloan Digital Sky Survey, Pan-STARRs1 and now Dark Energy Survey

What do CCD data look Like?







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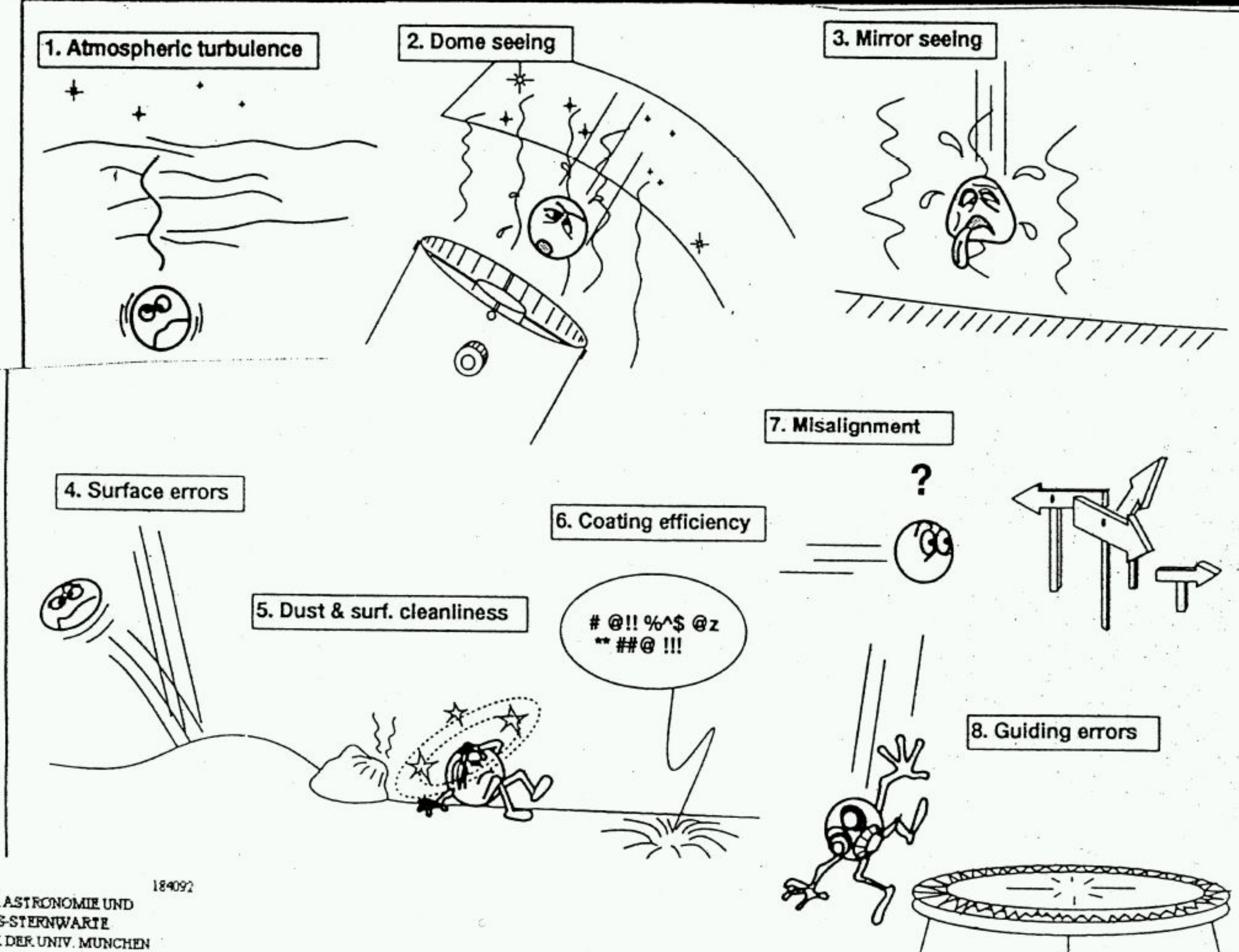
THE HAZARDS OF A PHOTON'S LIFE



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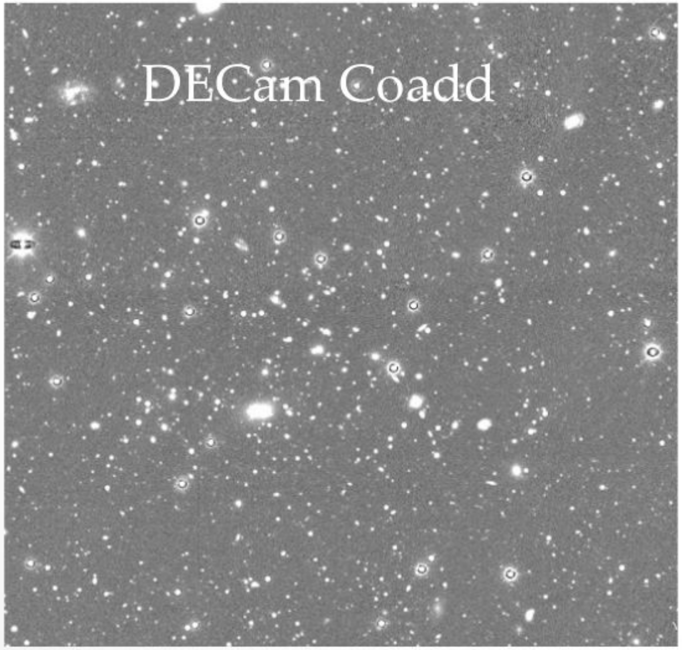
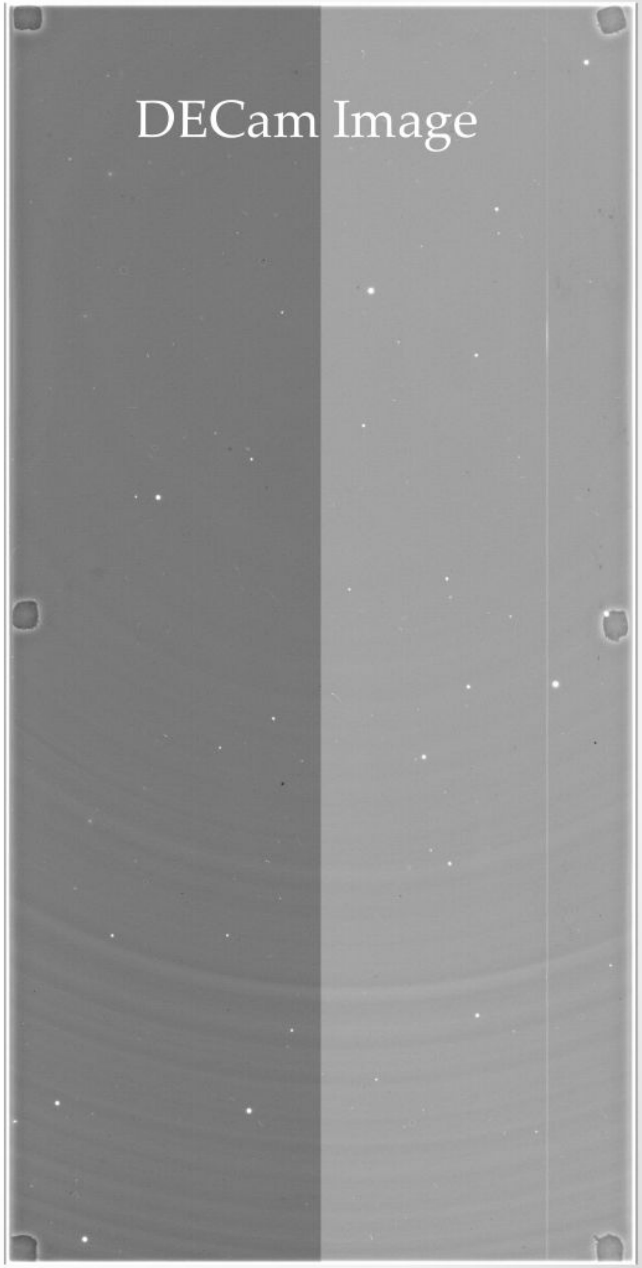
ASTROPHYSIK DER UNIV. MUNCHEN

What do CCD data look Like?

- Raw images from a given CCD typically have unwanted structures
  - Two readouts, each with a different bias level
  - Grooves from either the filter or from CCD itself
  - Bonding points
  - Dead or bright columns
  - In addition, cosmic rays, scattered light, satellite trails, etc

- Coadd images are science ready data
  - Combination of precisely calibrated single epoch images
  - Stitched together or coadded to create high quality image





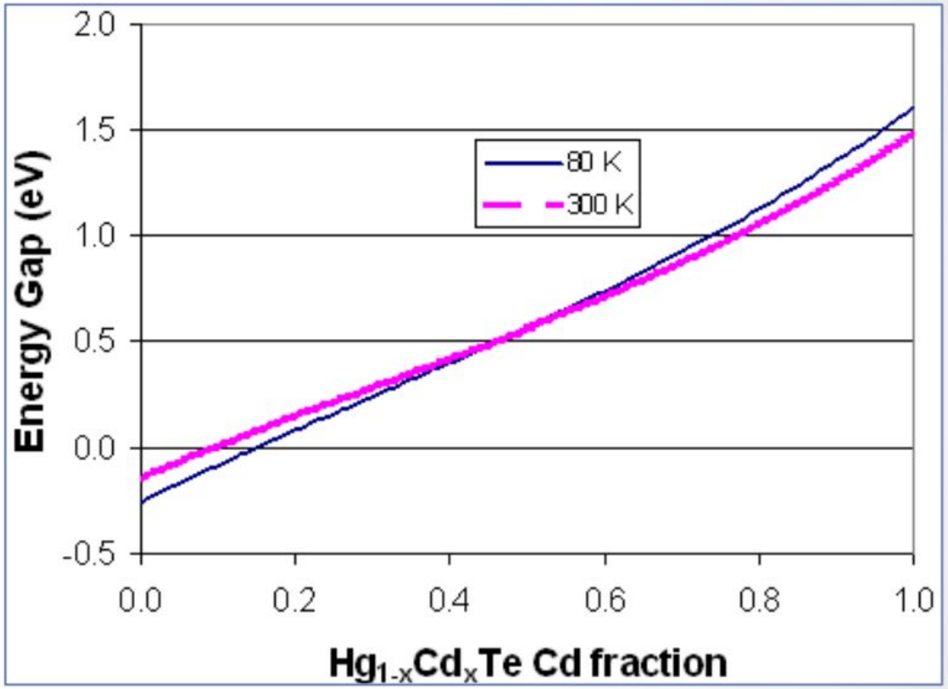
What about IR?

- The silicon band gap makes it impossible to use the standard silicon based CCD at wavelengths beyond ~1μm
- Hybrid Complementary Metal Oxide Semiconductor (CMOS) devices are well suited for infrared photon detection

Hubble IR Image of Tarantula Nebula
IJH bands Wide Field Camera 3 and
Advanced Camera for Surveys

CMOS Detectors

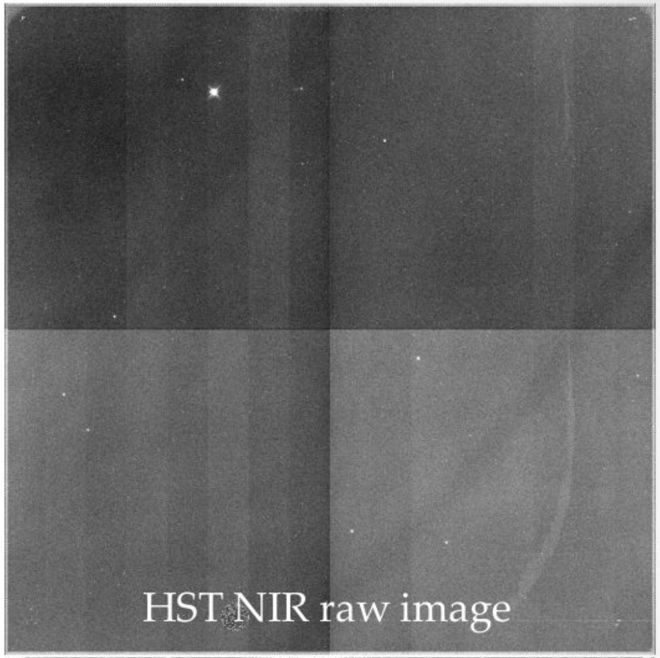
- CMOS devices are IR sensitive, large format arrays
- Each pixel has separate readout, and reads need not be destructive
- Couple photodiode made from material that is photosensitive at the desired wavelength (HgCdTe) to a silicon readout circuit; thus referred to as Hybrid devices
- Sensitivity to low energy photons then requires low operating temperatures to suppress thermal noise (or dark current)
    - LN2 (77K) at $\lambda<2.5\mu m$
    - LHe (4 to 20K) at $\lambda>2.5\mu m$

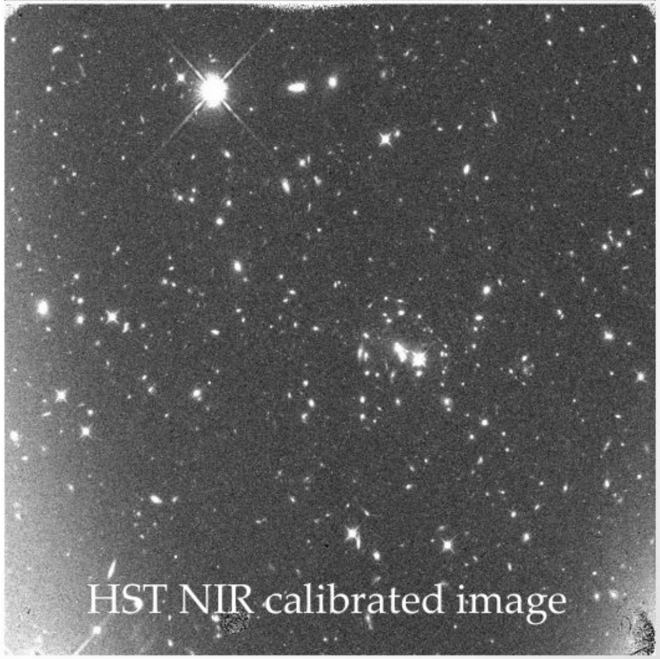


HgTe is semimetal and CdTe is semiconductor. By adjusting Cd fraction one can tune the wavelength sensitivity of the HgCdTe arrays

What do IR data look like?

- Ground based IR images look like noise
  - Sky is so bright that the exposures must be very short (~10s)
  - Large series of images are taken with small dithers
  - Sky is subtracted and images are coadded as with CCD images
- From space the background is much lower, but there is a higher particle background (cosmic rays)
- Similar processing steps are required as for CCD data.





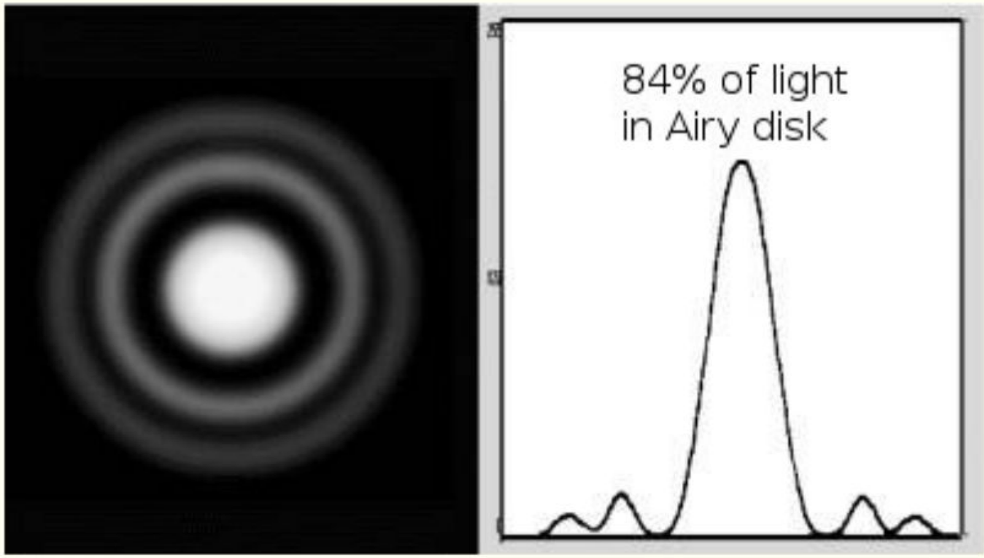
Photometric Passbands

- In Optical and NIR photometry one often encounters measurements in particular passbands
- To the right is a list of the standard broad band filters
- Narrow band filters are often used to seek particular spectral lines or features and/or to improve constraints on the spectral energy distribution of sources

Band	λ_{mid}	$\Delta\lambda$
U	365	66
B	445	94
V	551	88
R	658	138
I	806	149
Z	900	
Y	1020	120
J	1220	213
H	1630	307
K	2190	390
L	3450	472
M	4750	460

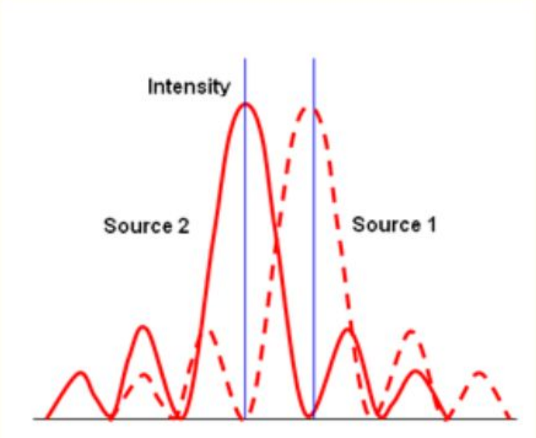
Ground vs Space

Angular resolution



- For space-based or small ground-based telescopes the angular resolution is limited by the diffraction of the telescope aperture.

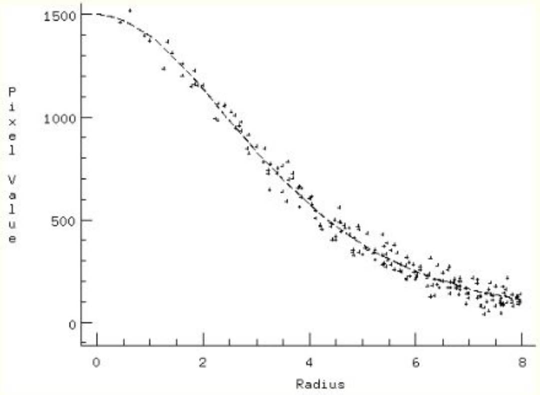
Airy pattern is described by $\frac{J_1^2(\theta/2)}{(\theta/4)^2}$ with minima at $1.22n\lambda/D$.



- Rayleigh criterion for resolving two point sources: $\Delta\theta > 1.22\lambda/D$
- 20% drop in intensity between both sources

Ground vs Space

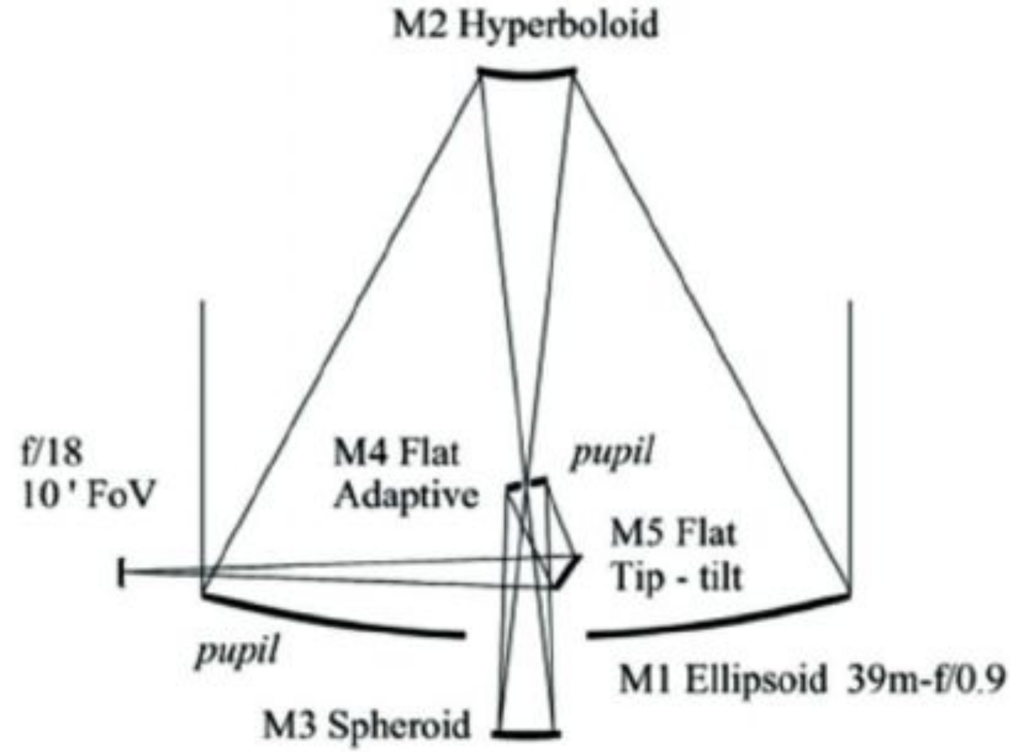
Ground-based Point-Spread Function (PSF)



- For large ground-based telescopes the PSF is a function of atmosphere, rathern than telescope optics.
- The "seeing", the FWHM of the PSF, is given in arcseconds. $0\farcs3$ is very good, $2''$ is bad. Weak lensing requires $< 1''$.

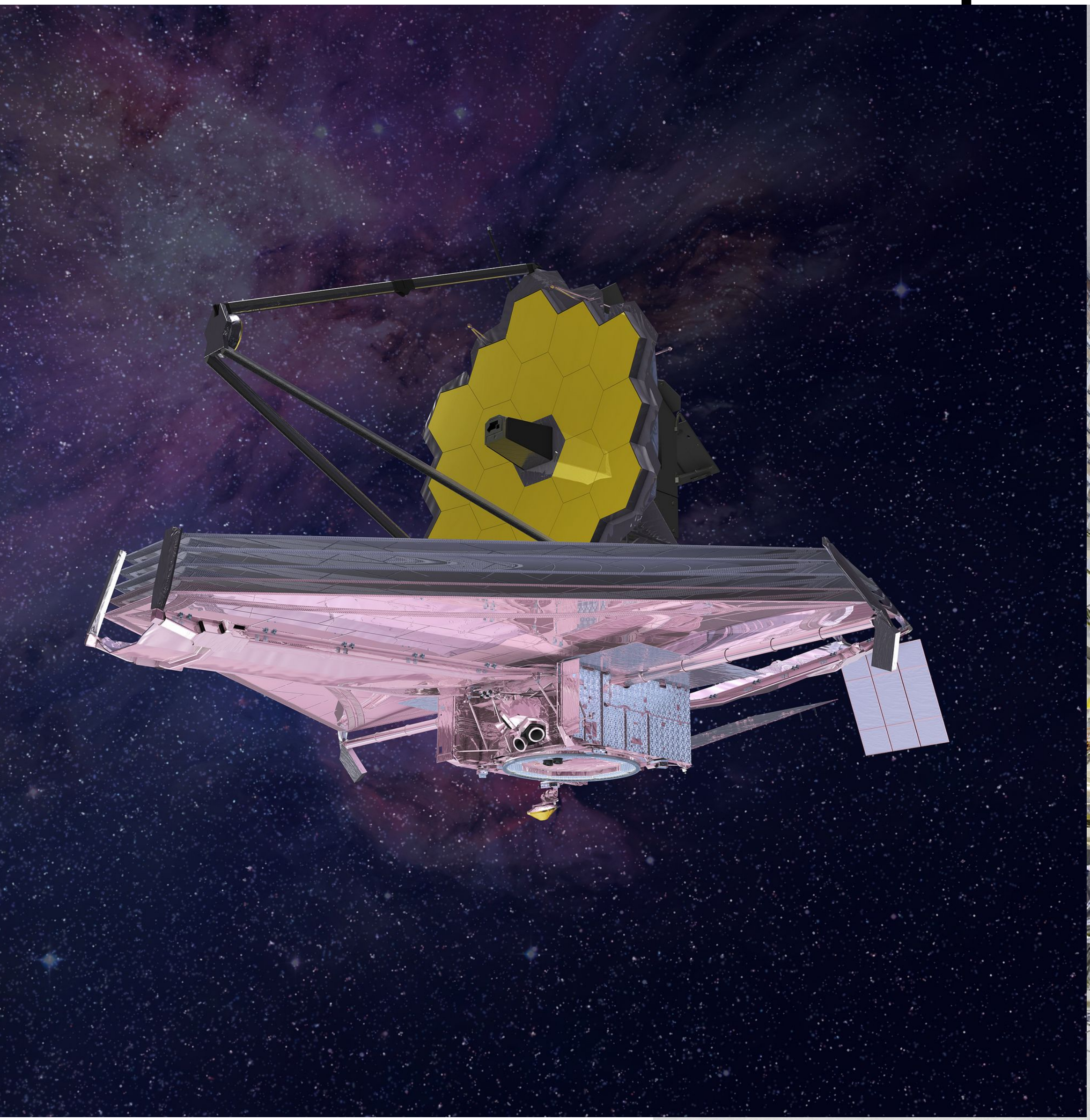
The radial profile is described by a Moffat profile
$I(r) = \frac{I_0}{(1+r^2/R^2)^\beta} + B$
The free parameters are the width of the PSF R and the Moffat parameter β.

Extremely Large Telescope



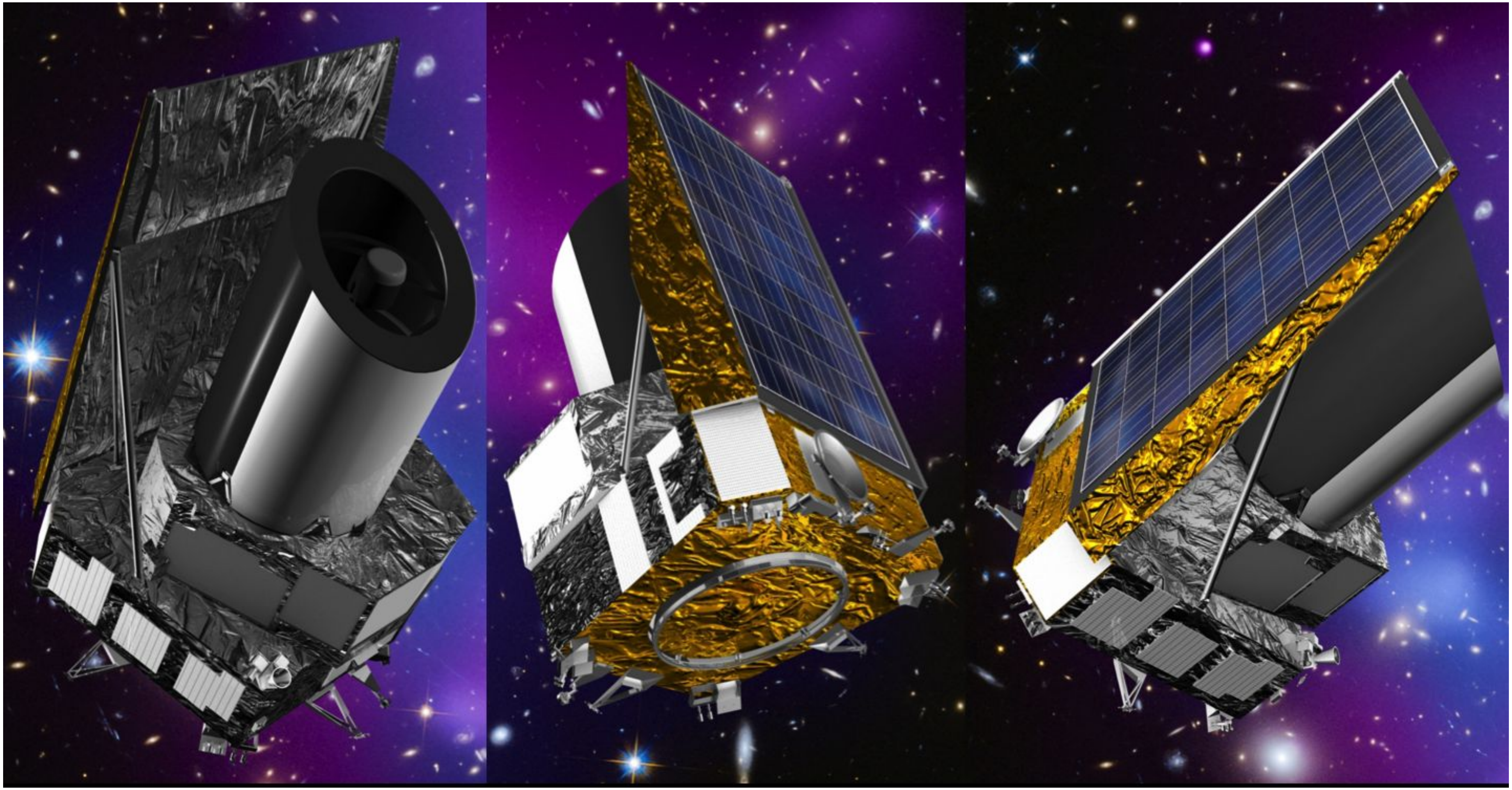
- Primary 39 m
- 2 Nasmyth platforms for instrumentation
- Adaptive Optics
- First Light 2028??

James Webb Space Telescope



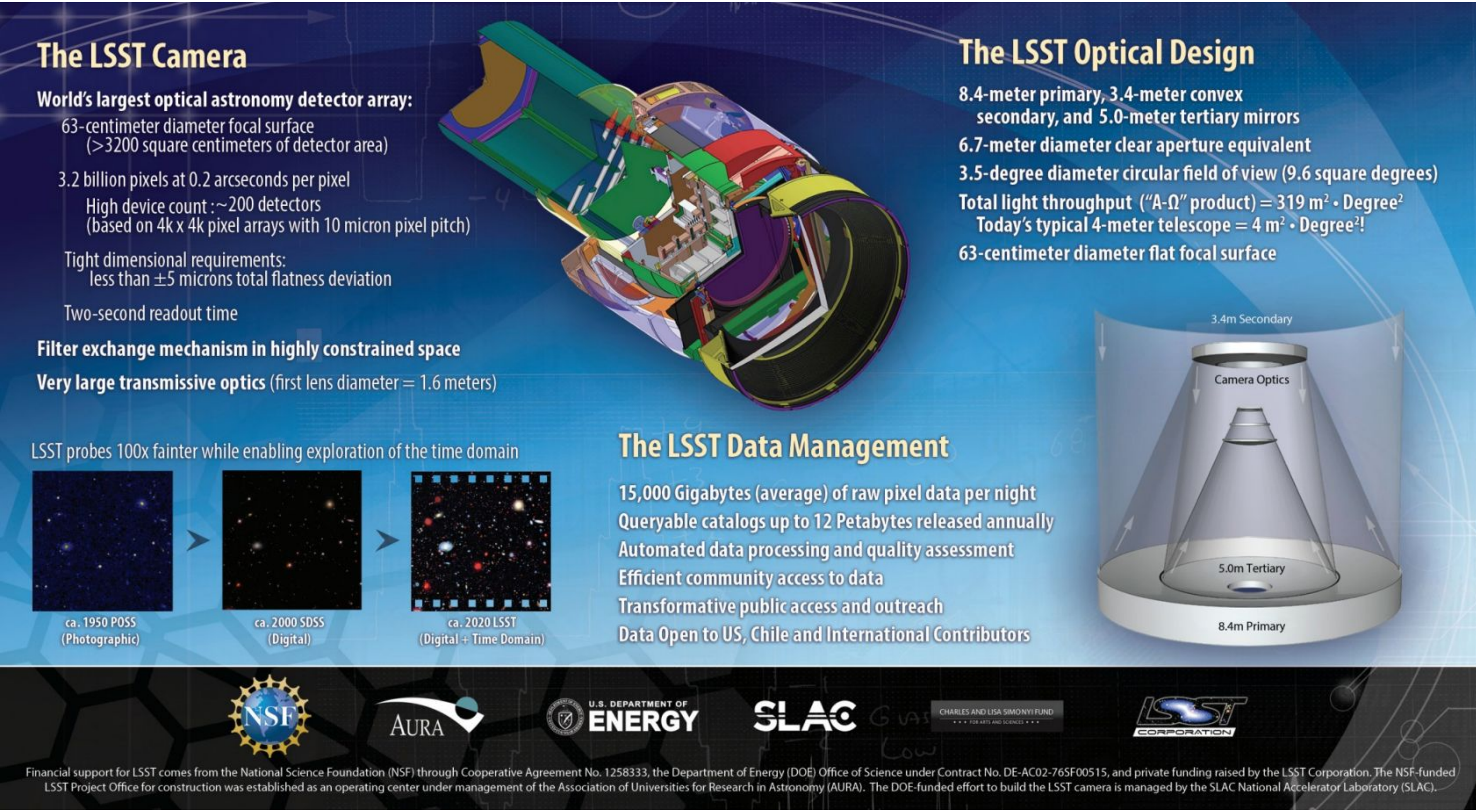
- Primary 6.5 m
- NIR/MIR
- Launched 2021

Euclid



- Primary 1.2 m
- Very Large FOV
- Optical/NIR
- Imaging/Spectroscopy
- 15,000 deg2 survey
- Launched July 2023!!

LSST – Vera Rubin Observatory



- Primary 8.4 m
- Very Large FOV (~10deg2)
- Optical/NIR and time domain
- 18,000 deg2 survey
- Starting operations 2024?

X-rays and γ

X-ray Reflective Optics

- Grazing incidence mirrors needed, because X-rays are readily absorbed by metals
- Wolter type X-ray telescope-
  - Two reflections required to focus- each at ~89degree from the normal
  - Concentric telescopes of different radius provide a focusing mirror
  - X-ray mirrors are traditionally quite massive
  - Off axis aberrations controllable (but problematic), focal lengths are long

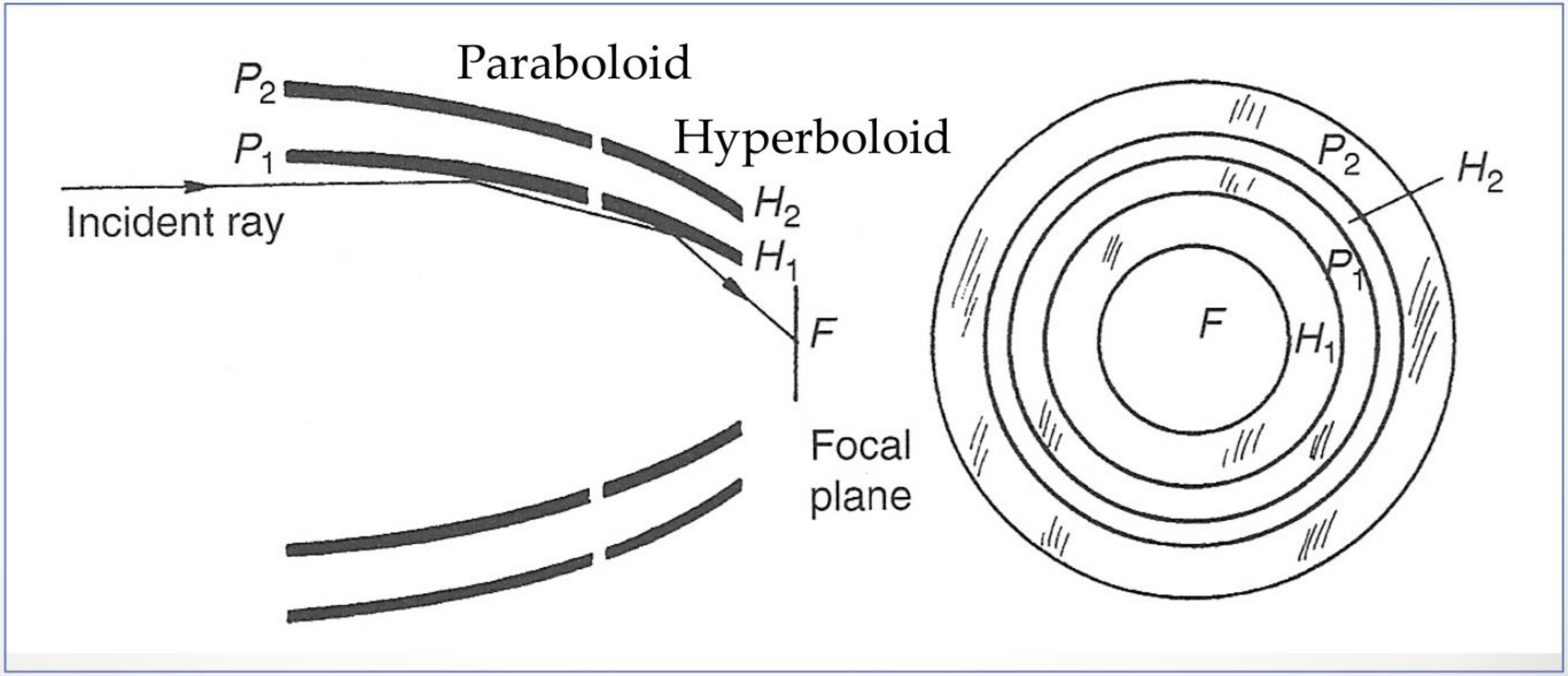


Image Quality

- Efficiency of scattering depends on photon energy
  - Higher energy photons scatter only at the highest incidence angles
- Image quality
  - Not related to diffraction limit, which given small wavelength would be incredibly small
  - Defects in crystalline structure of metallic mirror surfaces and alignment of the concentric telescopes are key to the delivered resolution

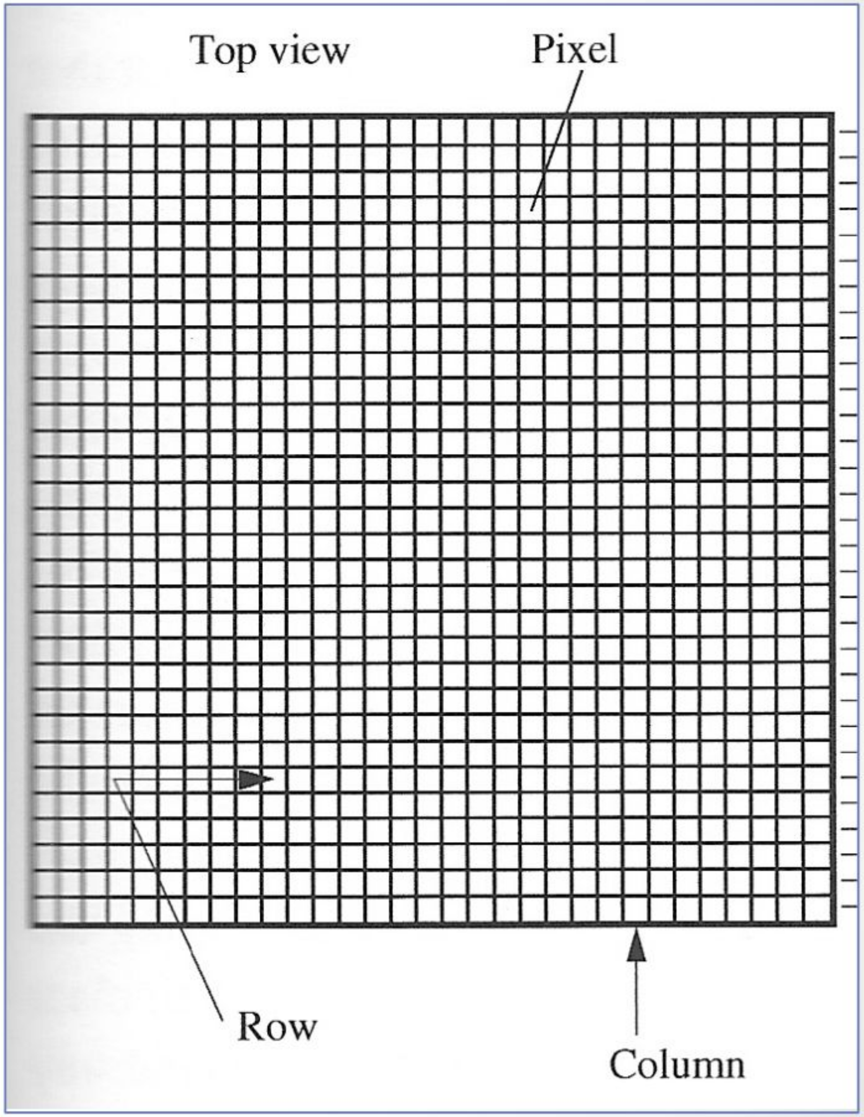
Observatory	Energy [keV]	0′	5′	10′	20′
Einstein	0.28	8″	10″	25″	-
	3	20″	25″	40″	-
Exosat	-	18″	-	-	40″
ROSAT	1	3″	3″	7″	26″
XMM	<2.5	20″	-	-	-
Chandra	-	<1″	2″	5″	20″

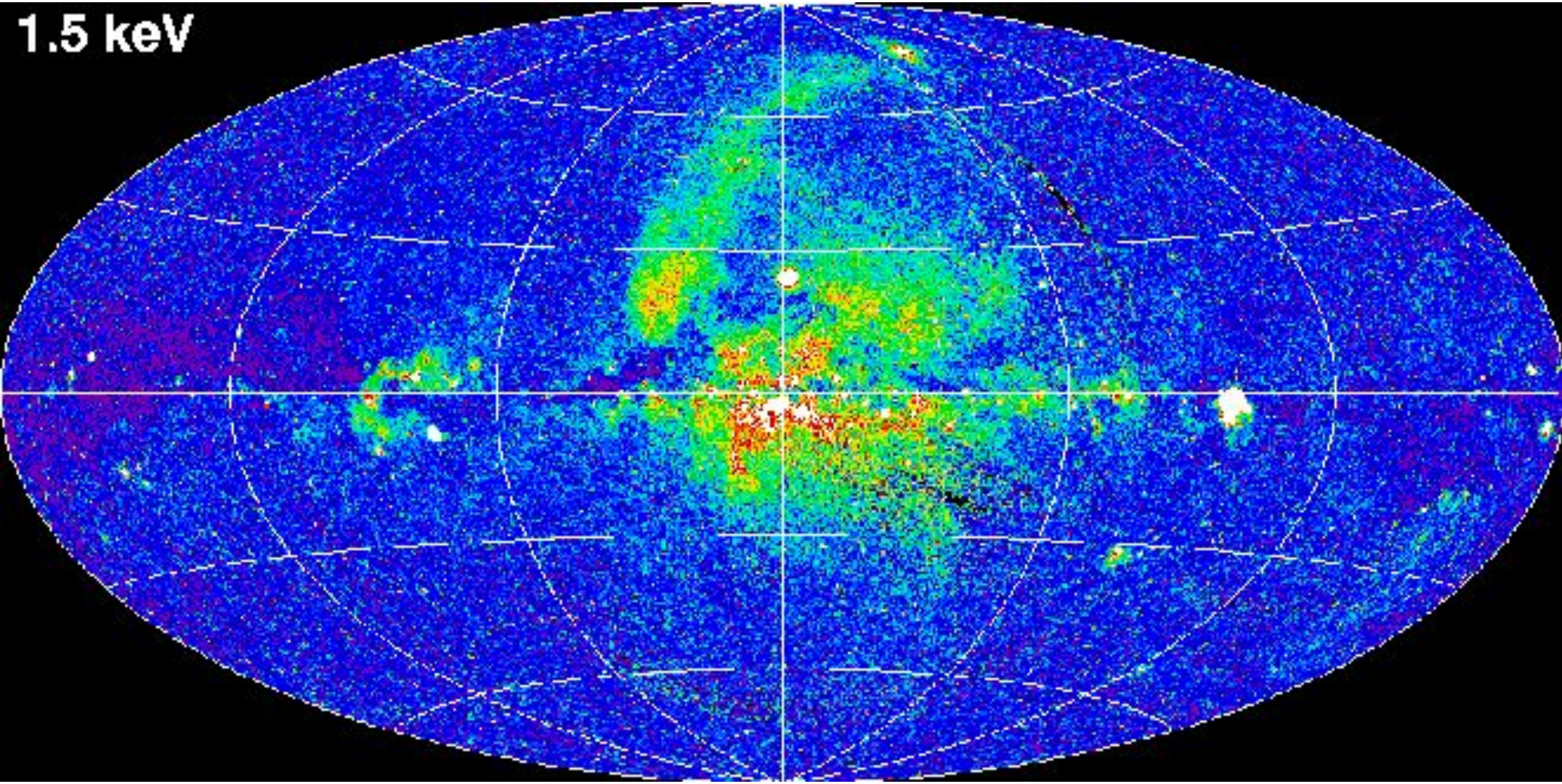
X-ray Detectors- CCDs

- CCDs are excellent X-ray detectors
    - Devices are similar to those we discussed for the optical

- Function
    - Each incoming photons produces many electrons rather than a single electron
    - Event is typically spread over multiple neighboring pixels
    - Mean position of charge distribution gives incoming position of the X-ray
    - Sum of the charge gives the energy of the X-ray
    - Detectors must be read quickly… two events overlapping in pixel space (pile-up) cannot be separated

- These are the detectors of choice for XMM and Chandra





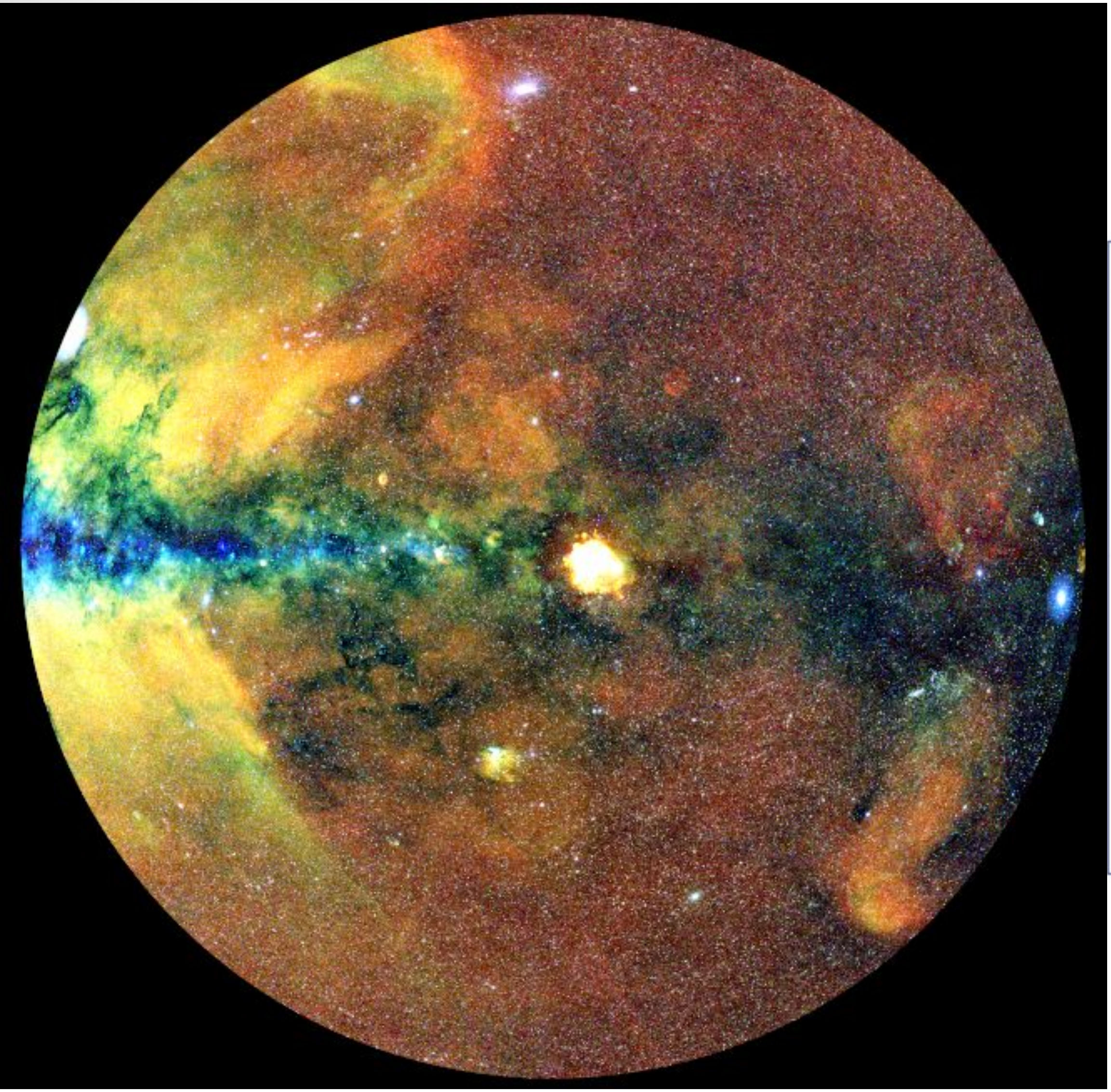
Rosat All Sky Survey
M.J.Freyberg, R.Egger (1999)

eROSITA Survey Mission

- 7 independent telescopes
  - Each with ~30 concentric, nested Wolter grazing incidence mirrors
  - Each has 1 deg diameter FOV
  - Each has collecting area of ROSAT
  - Each delivers ~30" angular resolution
  - Each is coupled to a position and energy sensitive detector

- All Sky Survey
  - eROSITA will operate at L2
  - Satellite rotates around axis defined by it and the Sun, scanning the sky that is ~90° from the Sun
  - Complete sky survey each 6 months due to Earth's orbit

eROSITA Survey Mission



eROSITA-DE Data Release 1 (DR1)
31/01/2024 !!

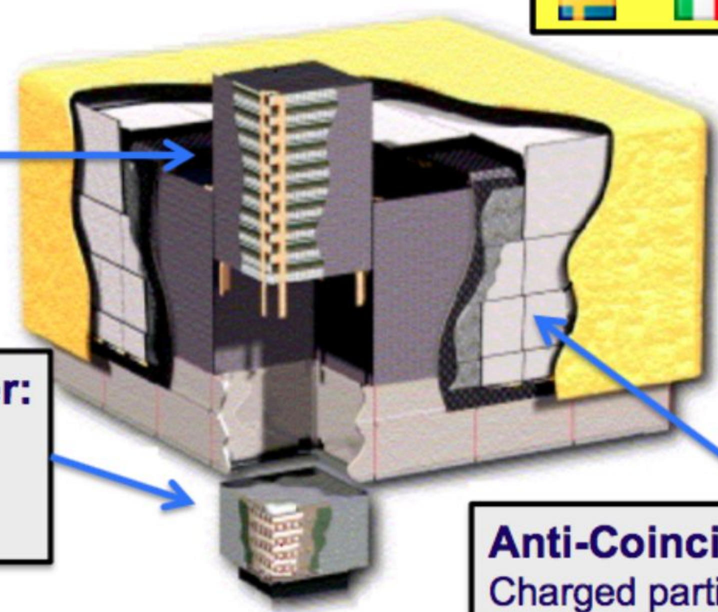
γ-Ray Telescopes

Fermi LAT

Public Data Release:
All γ-ray data made public within 24 hours (usually less)

Fermi LAT Collaboration:
~400 Scientific Members, NASA / DOE & International Contributions

Si-Strip Tracker:
convert $\gamma \rightarrow e^+e^-$
reconstruct γ direction
EM v. hadron separation

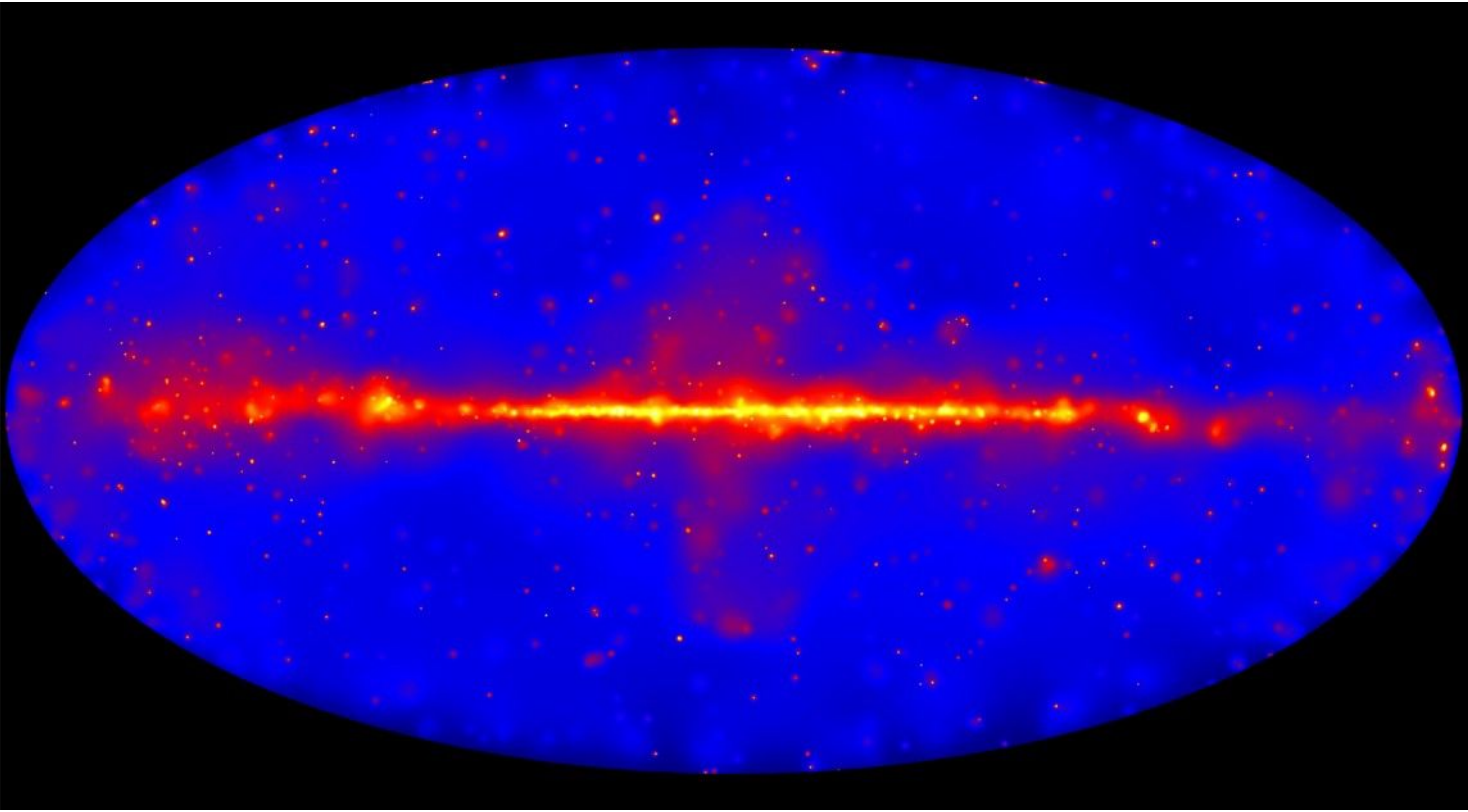


Hodoscopic CsI Calorimeter:
measure γ energy
image EM shower
EM v. hadron separation

Anti-Coincidence Detector:
Charged particle separation

Sky Survey:
With 2.5 sr Field-of-view LAT sees whole sky every 3 hours

Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 HZ

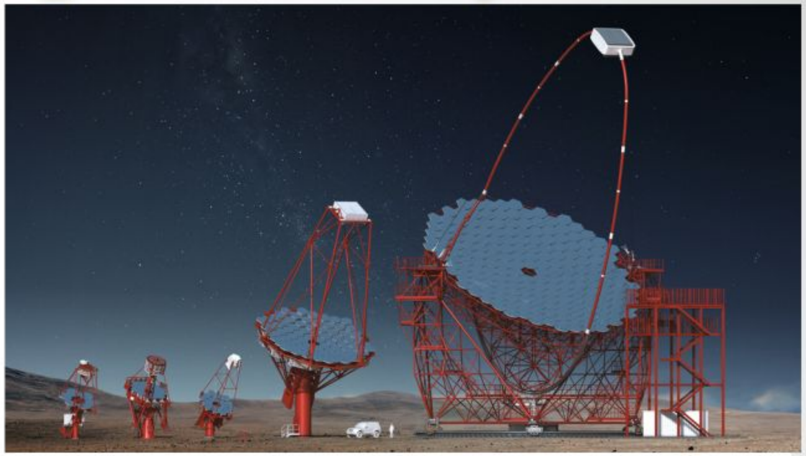


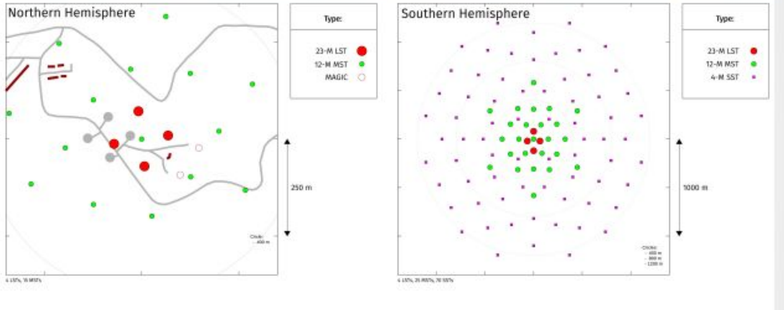
- Fermi-LAT Full Sky
- 20 MeV - 300 GeV
- Angular Resolution < 3.5° (100 MeV), < 0.15° (>10 GeV)

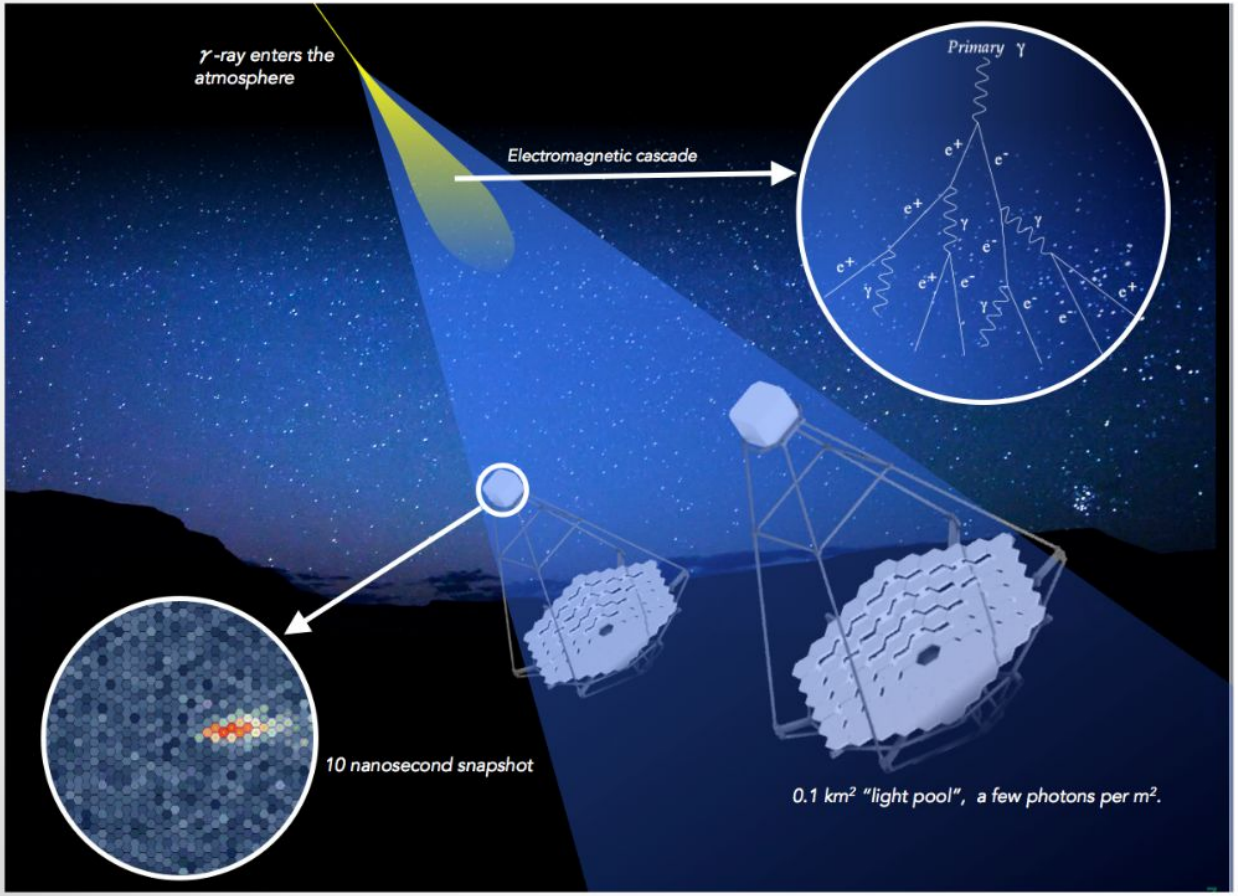
Cherenkov Telescope Array

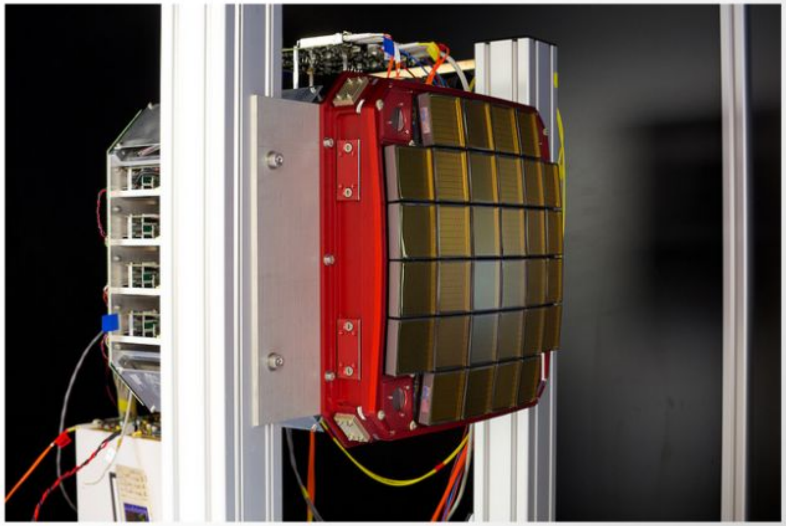
http://cta-observatory.org

- Gamma ray studies up to 300 TeV
  - CTA Southern Site: 4 LST _+ 25 MST + 70 SST (20 GeV – 300 TeV)
  - CTA Northern Site: 4 LST + 15 MST (20 GeV - 20 TeV)
  - LST focus on low energy gammas (<100 GeV), MST in middle (100GeV – 10 TeV) and SST focus on high energy (>few TeV)
  - LST (4.5° FoV, 23m), MST (7° FoV, 12m), SST (9° FoV, 4m),
  - Energy Resolution: E/dE from 5 to 10 andf Angular resolution from 2 to 10 arcmin (68% region half width)

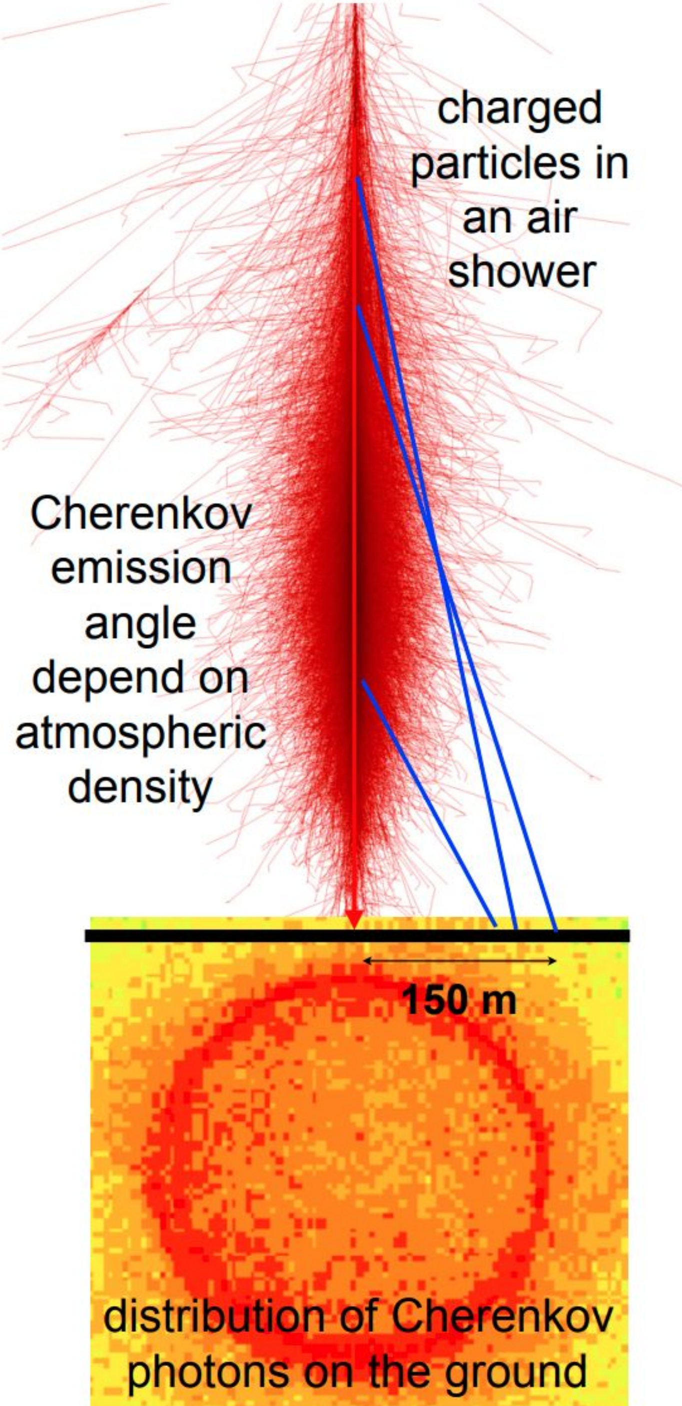


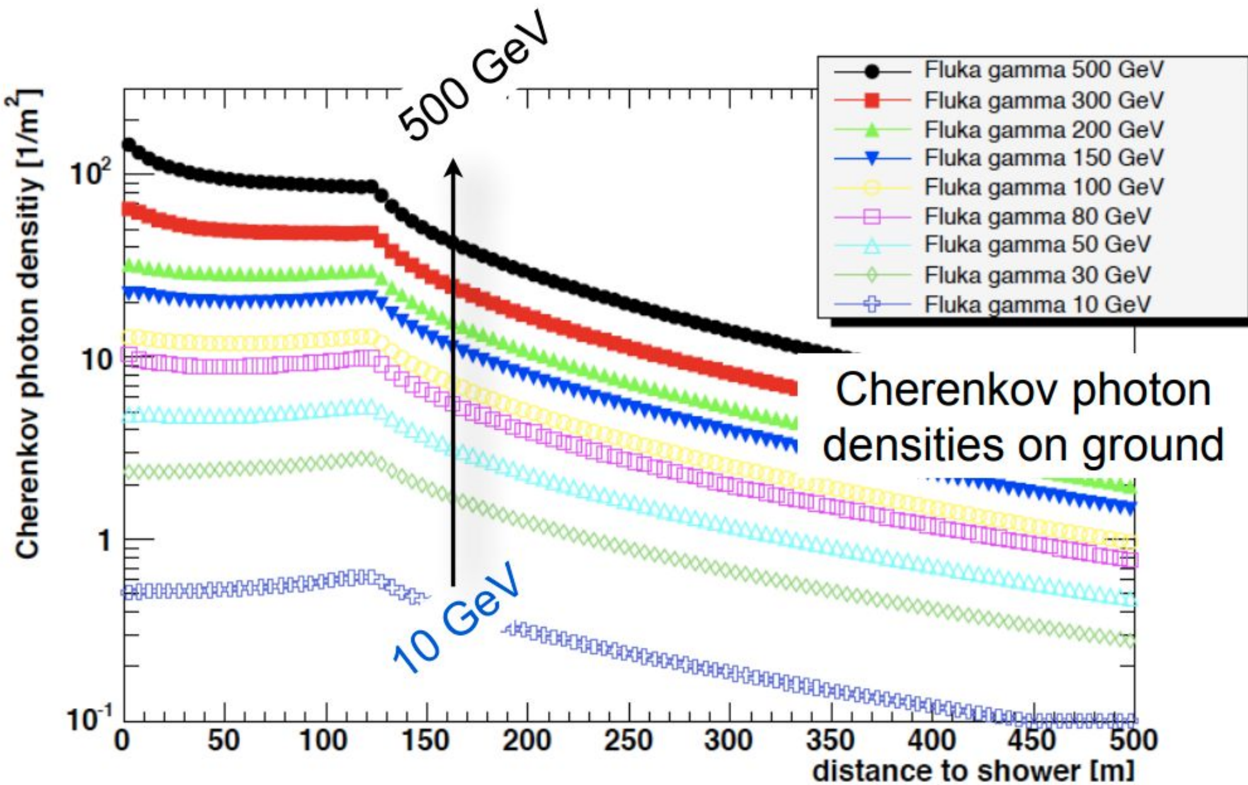




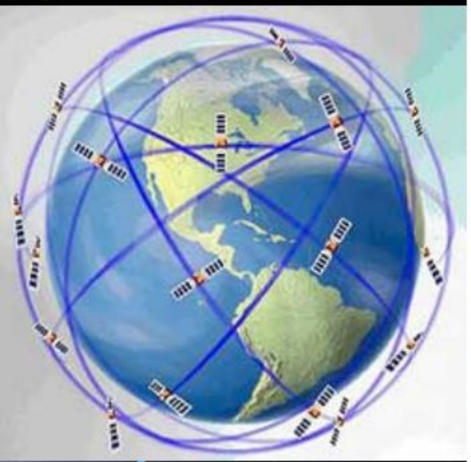


Cherenkov Telescope Array



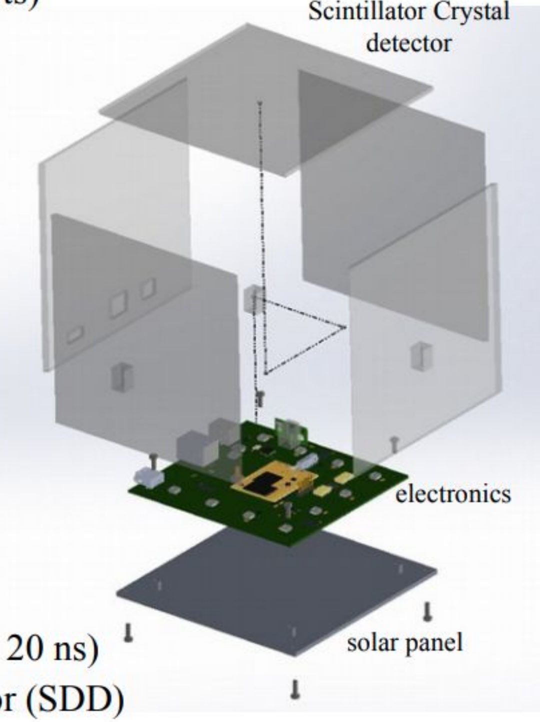


Cherenkov light from air showers: weak (~10 ph/m^2), short (~ns), blue (300-550nm) flash of light



The HERMES mission

High Energy Rapid Modular Ensemble of Satellites
(a nanosatellite swarm monitor for GRB & High Energy GW counterparts)



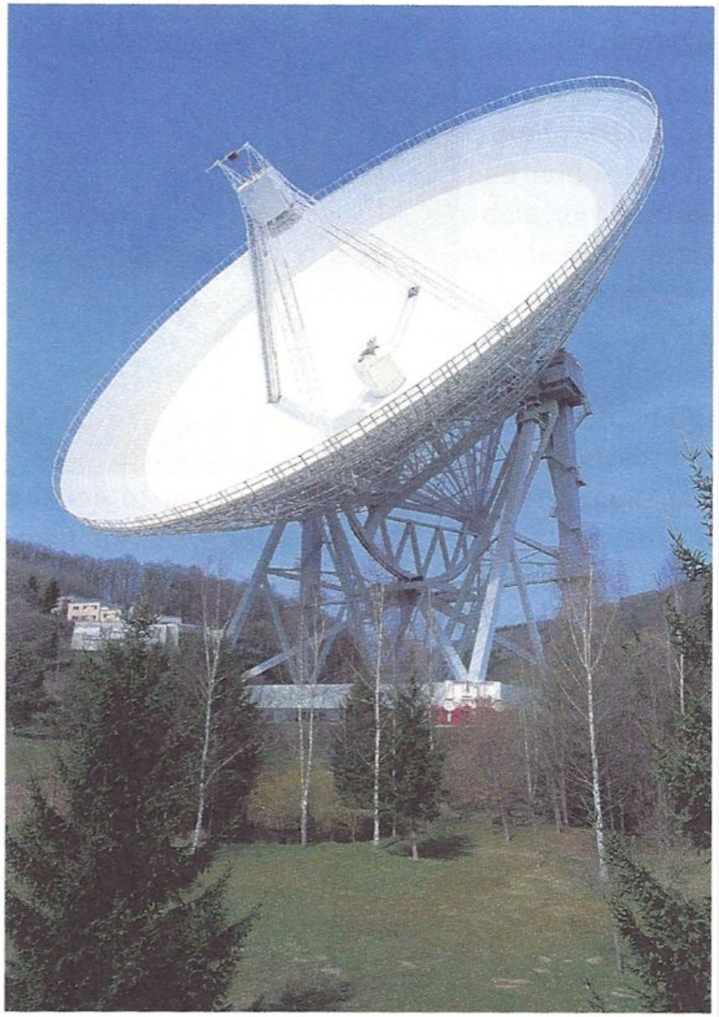
GRB statistics
Average GRBs: 300/yr
Bright GRBs: 30/yr
GRB structure: duration 0.2÷20 s, shot noise $\tau = 1$ ms, rate = 100/s
Instrument
N = 50/100 Nano Satellites (Modules) in Low Earth Orbit
Average separation between Modules: 6000 km
Module (weight $\leq$ 10 kg)
5 Detectors
Field of View of each Detector: 2 steradians
GPS absolute temporal accuracy $\leq$ 100 nanoseconds
GPS based Module positional accuracy: $\leq$ 10 m
Detector
Scintillator Crystals: CsI (classic) or $LaBr_3$ or $CeBr_3$ (rise − decay: 0.5 − 20 ns)
Photo-detector: Silicon Photo Multiplier (SiPM) or Silicon Drift Detector (SDD)
Effective area: 10 × 10 cm
Weight: 0.5/1 kg
Energy band: 3 keV − 50 MeV
Energy resolution: 15% at 30 keV
Temporal resolution: $\leq$ 10 nanoseconds
Mission performance
Accuracy in delays between Average GRB lightcurves of two Modules
(cross correlation techniques): 0.09÷8.7/0.06÷6.1 μsec for Average GRBs
Continuous recording of buffered data
Triggered to ground telemetry transmission
IRIDIUM constellation for trasmission of TOA of GRB (position after few minutes)
Range of accuracy in positioning of GRB: 0.80÷78/0.53÷54 arcsec
Modular structure: overall effective area 1 m^2 every 100 modules

PI Fabrizio Fiore – OATs - http://www.hermes-sp.eu/

Radio and mm

Effelsberg 100m

- Single dish radio telescopes composed of:
  - Large primary
    - Surface accuracy determines limitations in term of frequency ($\lambda/20$ typically needed)
  - Receivers (Detectors) at prime focus
    - Multi-pixel receivers not so common
- Generally operate at diffraction limit
  - imaging resolution determined by λ/D
  - D=50m, resolution=4 arcsec at 1mm, >1° at 1m
- Turbulence in atmosphere less of a problem than in optical
  - Atmosphere becomes serious background at mm wavelengths

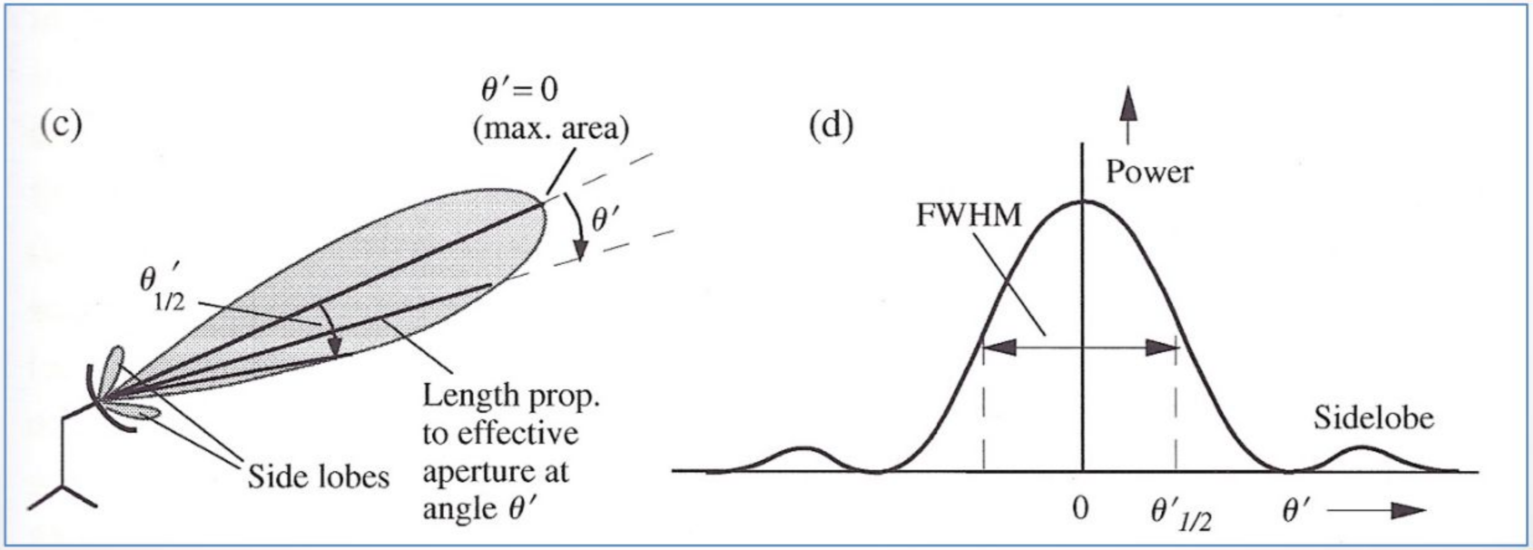


Located near Bonn

Primary Beam and PSF

- Peak sensitivity is in direction telescope points, and it falls off with off axis angle
- Exact shape of the primary beam depends on the structure of the antenna as seen by the incoming radiation
- This primary beam defines the point response function or PSF in the limit of diffraction limited imaging

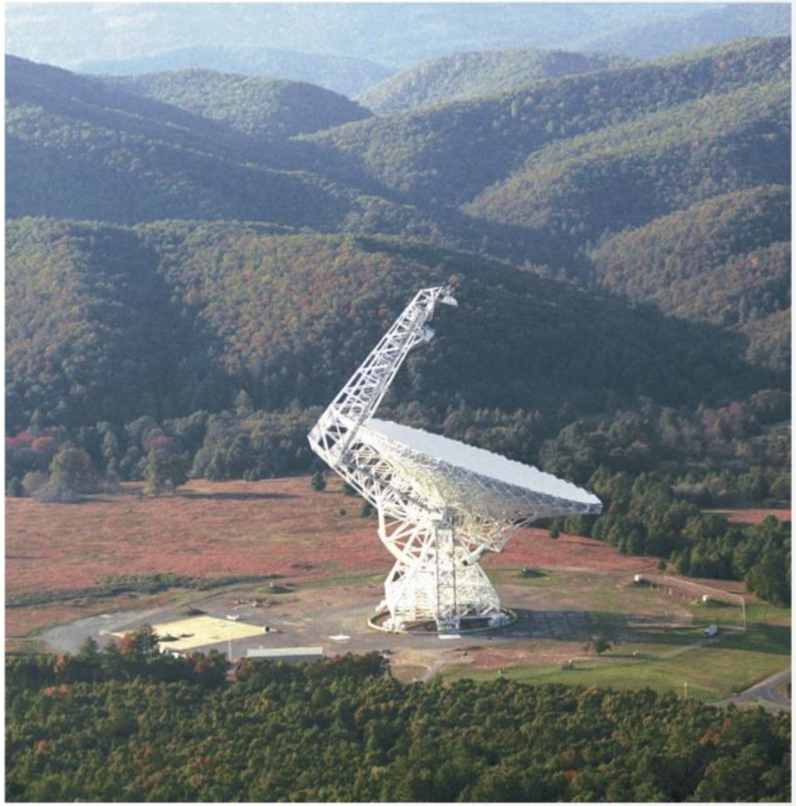
$$\Theta_{\mathrm{FWHM}} \approx 1.2\left(\frac{\lambda}{D}\right)$$



Green Bank Telescope

- Largest steerable radio telescope
  - 110m x 90m
  - Off-axis parabola
  - Removes thermal noise from secondary superstructure and simplifies point response function

- Robert C Byrd Green Bank Telescope (GBT)
  - West Virginia, first light 2000
  - Replaced previous 90m (1962) that just collapsed one day
  - Mapping sensitivity is good with new multiplex detectors
  - Site is suboptimal for mm-wave because of water vapor in these very green mountains



Arecibo

- Largest single dish telescope at 305m
  - Constructed in 1960
  - Spherical mirror
- Secondary assembly adjustable
  - Tracks sources through movement of detectors at prime focus- ~2.5hrs
  - 40 degree cone of visibility

    3” resolution
- Key science: pulsar searches, HI mapping and redshift surveys, searches for extraterrestrial life

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  3" resolution
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FAST - Five hundred meter Aperture Spherical Telescope

SRT
Sardinia Radio Telescope

- steerable parabolic dish with 64 meters of diameter
- detectors sensitive up to 3mm (Mistral)

Large Millimeter Telescope *Alfonso Serrano*

- 50m-diameter millimeter-wave radio telescope
- optimized to perform observations at 0.85 – 4 mm

iram

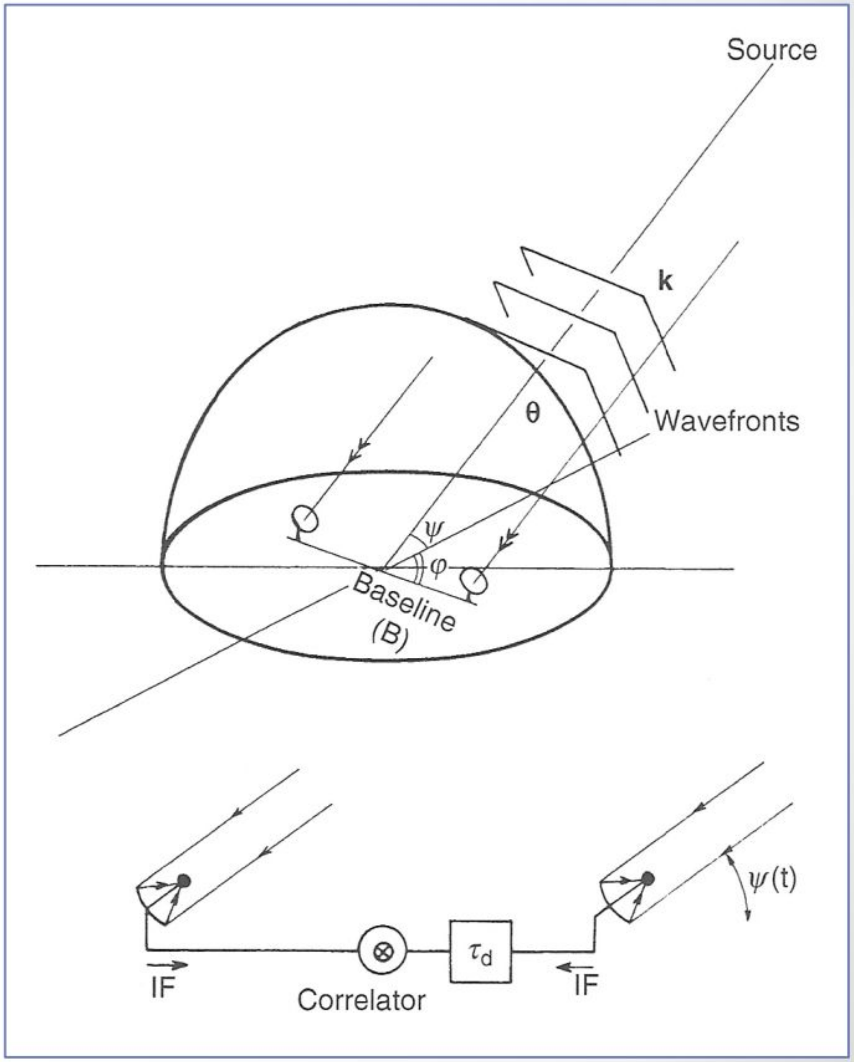
NOEMA

30-meter telescope

12 antennas x15m

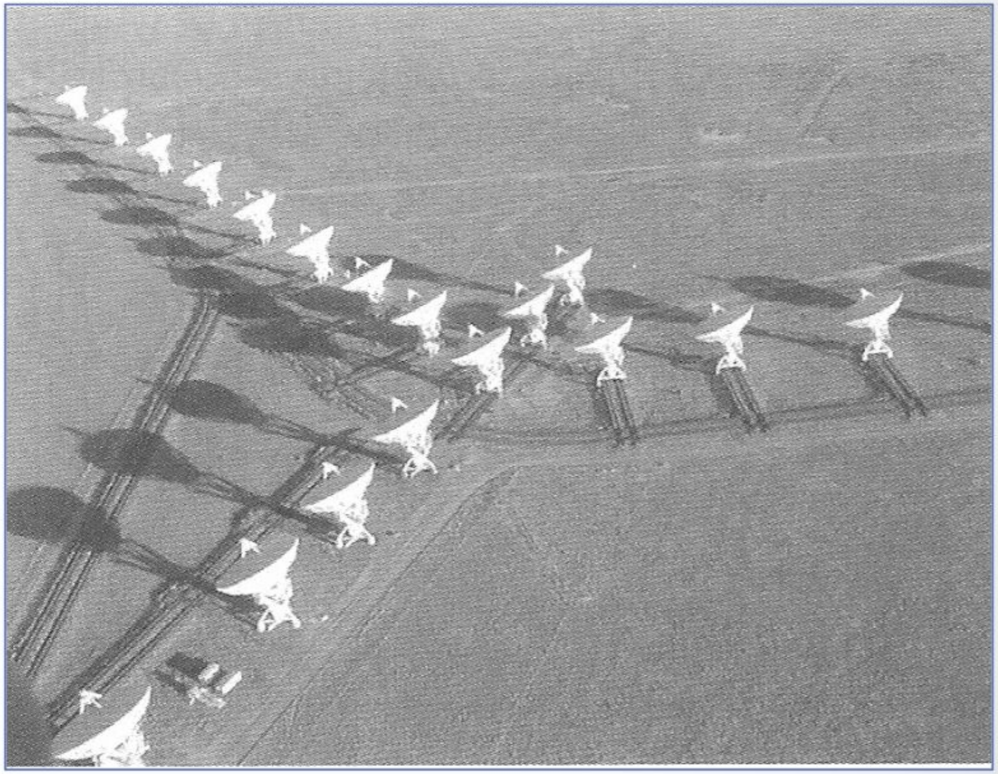
Interferometer

- Interferometers consist of collections of telescopes
- Correlators combine information into *visibilities*, which are related to the Fourier transform of the brightness distribution of the source
  - Include digital delays that account for differences in light path length from source to array elements
  - As source is tracked these delays must be adjusted
- Effective resolution becomes λ/B, the baseline separation between the array elements
- Measuring fringes precisely locates object in sky
  - $\Delta\theta \sim 0.06''$ for B=1km, λ=1cm, fringe phase measured with 10° accuracy



Interferometer

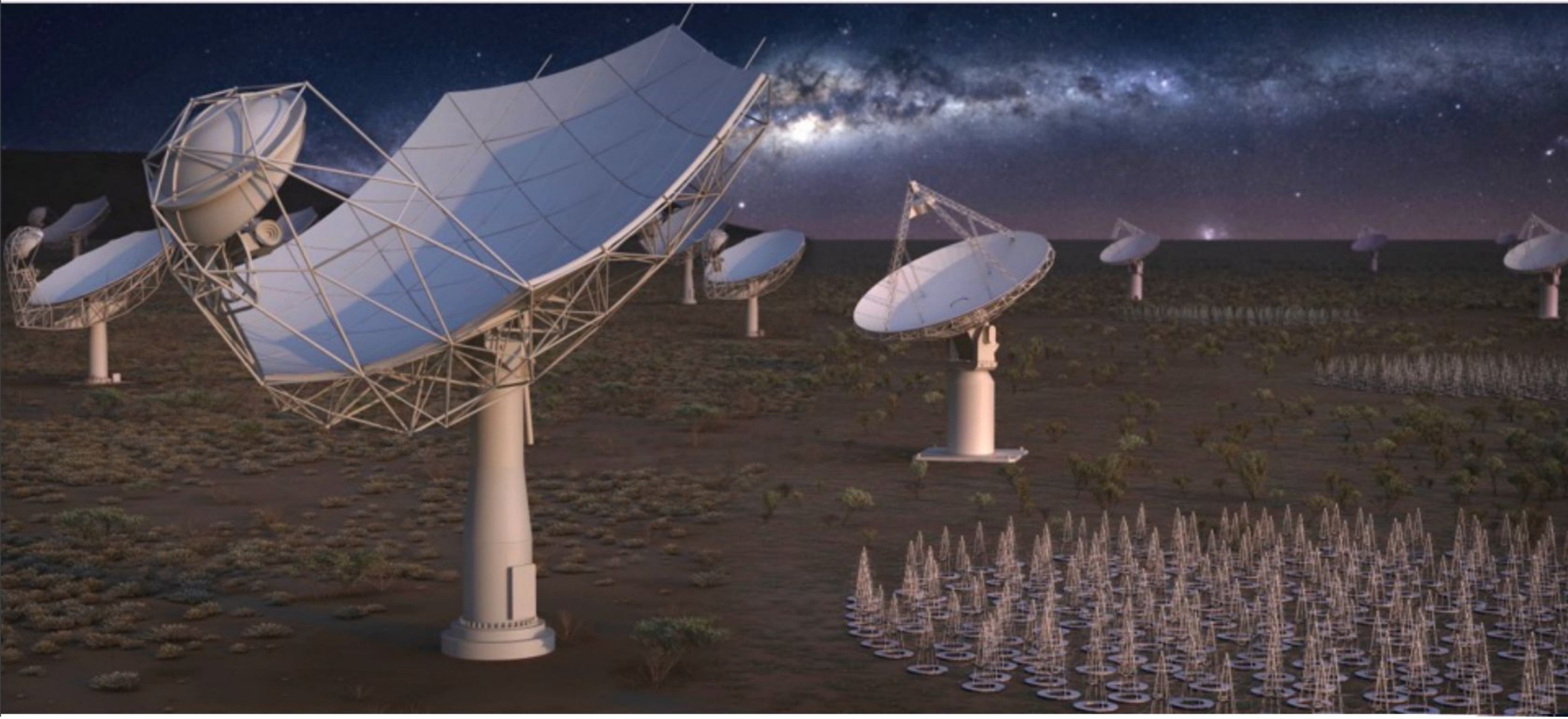
- VLA is composed of 27 (26m) radio dishes
  - 351 simultaneous visibility measurements
  - 1960's era observatory
- Telescopes deployable along arms (train tracks) to create four different arrays
  - Highest angular resolution (A)
  - Closest packed (D)
- Correlator and receiver upgrade just boosted sensitivity by 50X! (e)

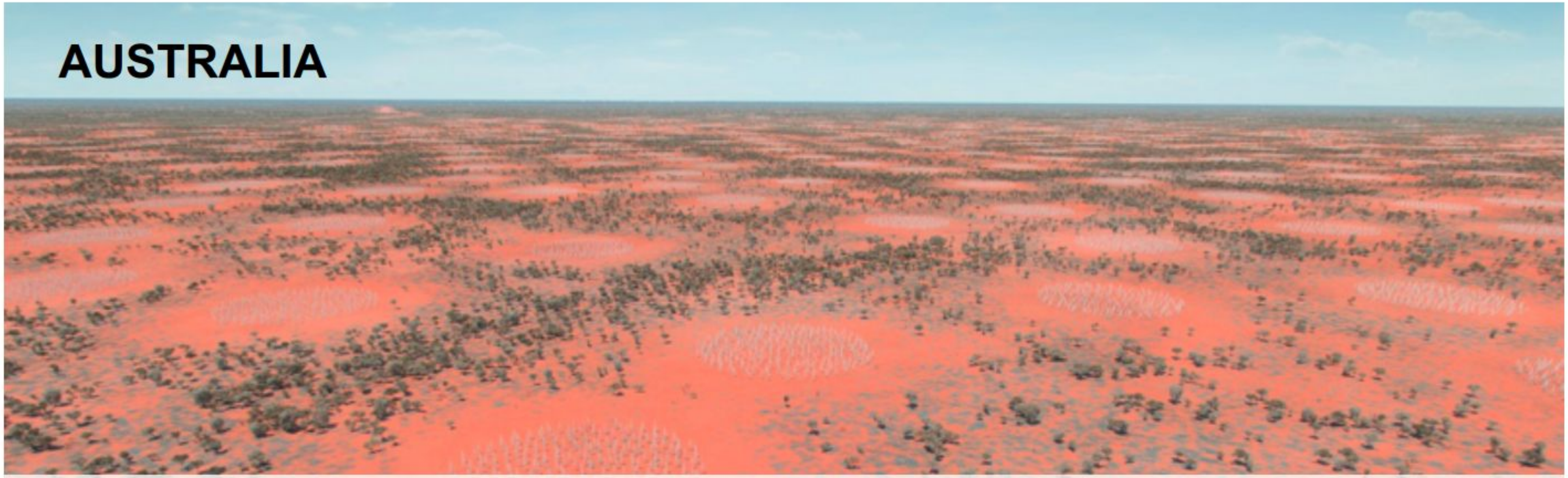


VLBI

- High angular resolution possible by combining information from telescopes spread around the world
  - IF frequency is recorded locally with atomic clock reading
  - Signals are combined in correlator after the fact
  - Limitation is random phase noise due to the atmosphere
- Worldwide network available as combination of regional networks (Europe, US, etc)
  - US network called VLBA

The Square Kilometre Array: Concluding our past, realising our future





International effort to build the World's largest radio telescope

Prime Motivation: Study the history of the Universe in Hydrogen

Will enable transformational science in many other areas

SKA– Key Science Drivers: The history of the Universe

Extremely broad range of science!

SKA Phase 1

3 sites (AUS, RSA, UK-HQ) **2 telescopes (LOW, MID)** **one Observatory (SKAO)**

Construction: 2021-2027 (Science commissioning 2023+)

SKA1-Low: 512 x 256 low-freq dipoles,
50 – 350 MHz
65 km baselines (11” @ 110 MHz)
Murchison, Western Australia

SKA1-Mid: 133 x 15m + 64 x 13.5m dishes,
0.35 – 15 GHz
150 km baselines
(0.22” @ 1.7 GHz; 34 mas @ 15 GHz)
Karoo, South Africa

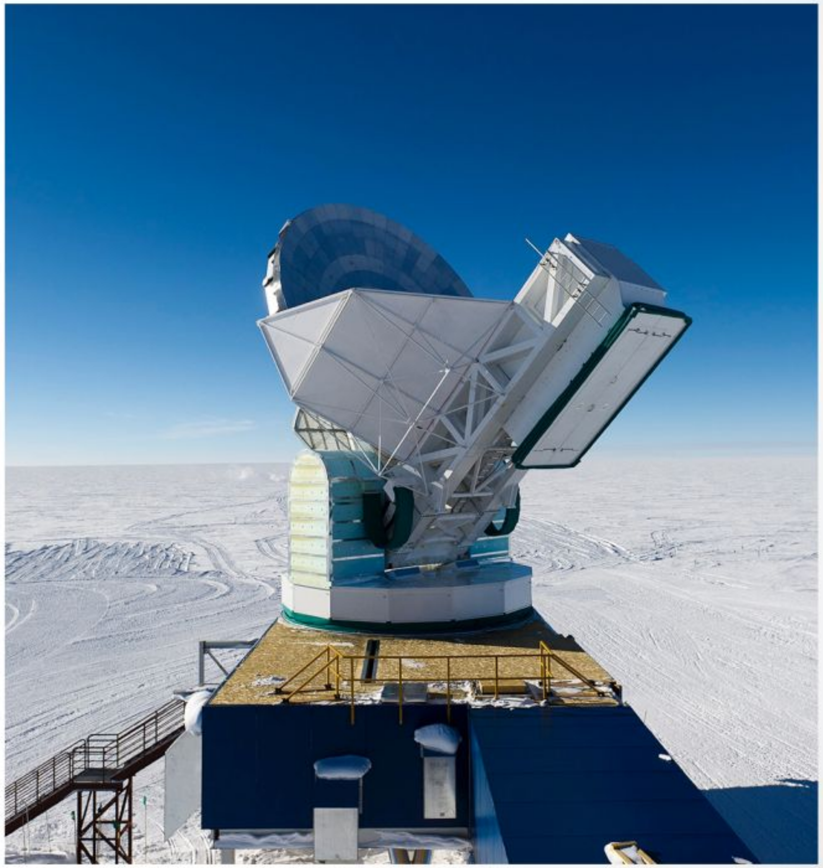
MeerKAT

ALMA

- Chajnantor Plateau, Chile (5100m)
  - Dry, stable atmosphere
  - Fifty 12m dishes spread over 10km mountainous plane
  - Frequency coverage up to 950GHz
- Has been in operation over past couple of years
  - Great location = challenging location

South Pole Telescope

- Mm-wave observatories must contend with noise from the atmosphere
    - Critical to locate them in dry places
- SPT at geographic south pole
    - Driest site in the world
    - Only observe half the sky
    - Stable weather and oscillating periods of darkness and light
- SPT is 10m telescope
    - Off-axis parabolic primary
    - Surface accuracy allows for sub-mm observation
    - Current detector works at mm wavelengths with 10^3 elements operating at 3 frequencies



South Pole Observatory

1 LAT (SPT-3G)

+

4 SATs (BA)

POLARBEAR → Simons Array → Simons Observatory

3.5 m, from 30 to 270 GHz, T and P

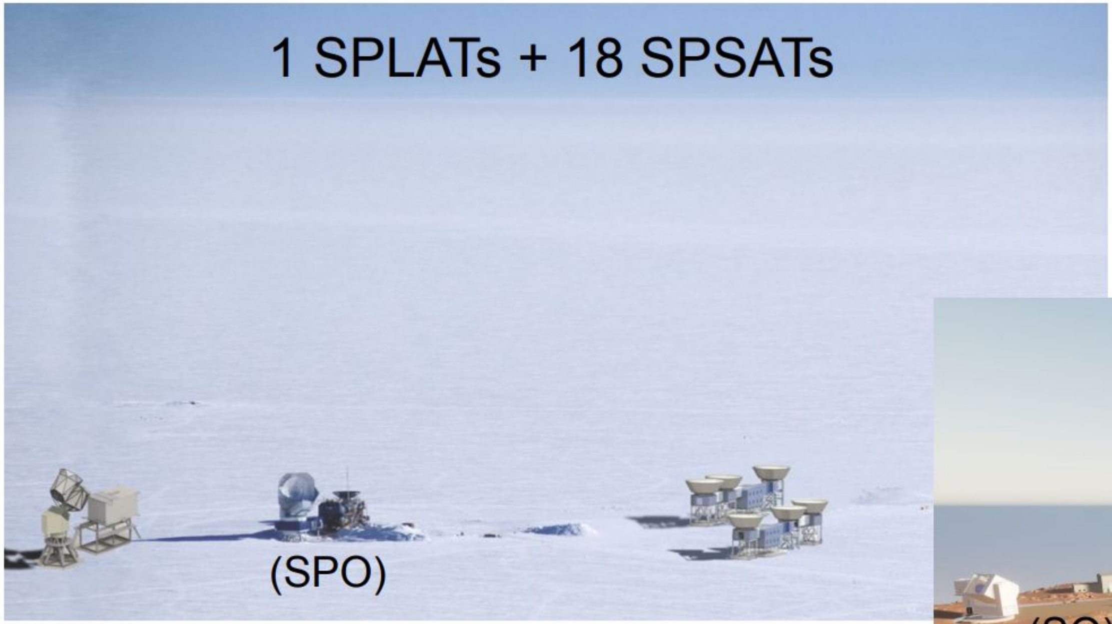
Simons Observatory

½ LAT

+

3-4 SATs

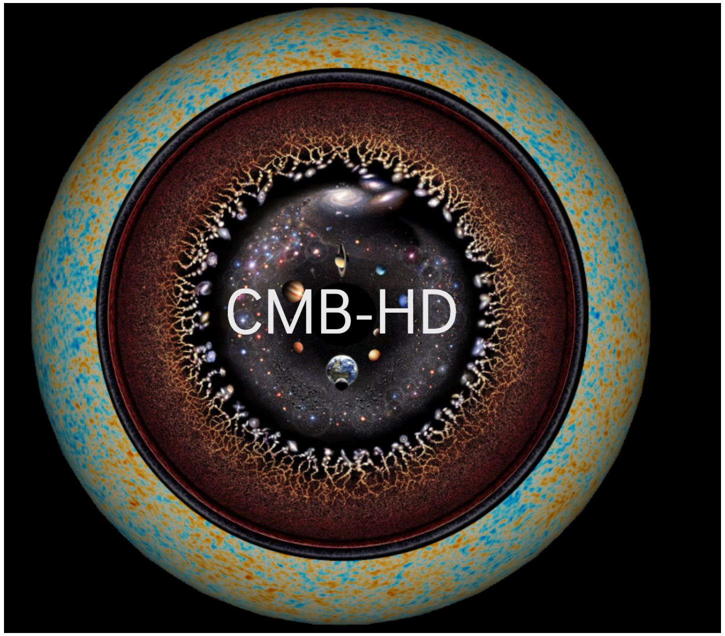
CMB-S4 Baseline Design



Far(ish) Future?

- CMB-HD

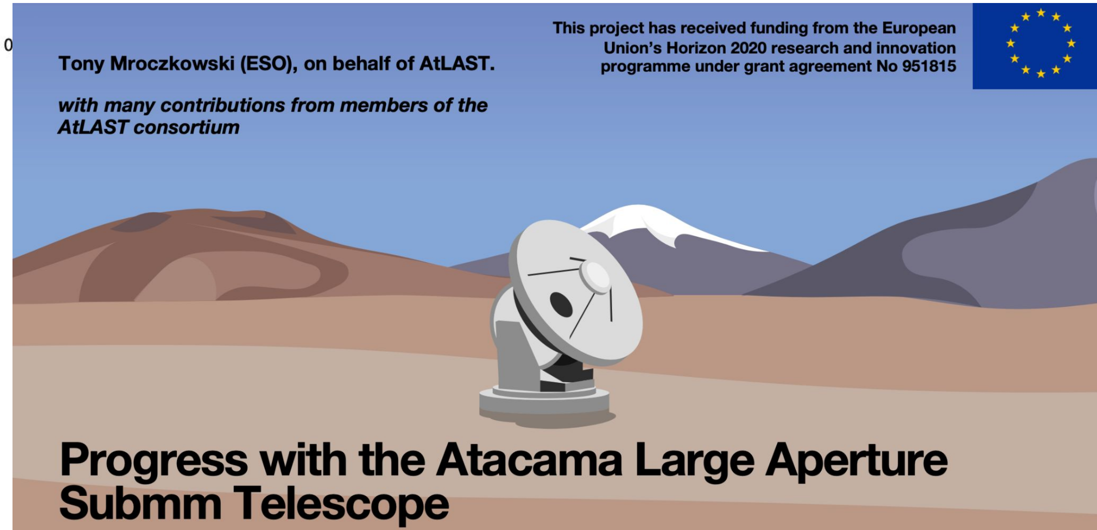
- AtLAST?



Atacama Large Aperture Submillimeter Telescope (AtLAST) Science: Resolving the Hot and Ionized Universe through the Sunyaev-Zeldovich effect

Luca Di Mascolo[1,2,3,4], Yvette Perrott[5], Tony Mroczkowski[6], Stefano Andreon[7], Stefano Ettori[8,9], Aurora Simionescu[10,11,12], Srinivasan Raghunathan[13], Joshiwa van Marrewijk[6], Claudia Cicone[14], Minju Lee[15,16], Dylan Nelson[17], Laura Sommovigo[18,19], Mark Booth[20], Pamela Klaassen[20], Paola Andreani[6], Martin A. Cordiner[21], Doug Johnstone[22,23], Eelco van Kampen[6], Daizhong Liu[24,25], Thomas J. Maccarone[26], Thomas W. Morris[27,28], Amélie Saintonge[29,30], Matthew Smith[31], Alexander E. Thelen[32], and Sven Wedemeyer[14,33]

[1]Laboratoire Lagrange, Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Blvd de l'Observatoire, CS 34229, 0
[2]Astronomy Unit, Department of Physics, University of Trieste, via Tiepolo 11, Trieste 34131, Italy
[3]INAF – Osservatorio Astronomico di Trieste, via Tiepolo 11, Trieste 34131, Italy
[4]IFPU – Institute for Fundamental Physics of the Universe, Via Beirut 2, 34014 Trieste, Italy
[5]Victoria University of Wellington, Wellington, New Zealand
[6]European Southern Observatory (ESO), Karl-Schwarzschild-Strasse 2, Garching 85748, Germany
[7]INAF – Osservatorio Astronomico di Brera, via Brera 28, 20121, Milano, Italy
[8]INAF – Osservatorio di Astrofisica e Scienza dello Spazio, via Piero Gobetti 93/3, 40129 Bologna, Italy
[9]INFN – Sezione di Bologna, viale Berti Pichat 6/2, 40127 Bologna, Italy

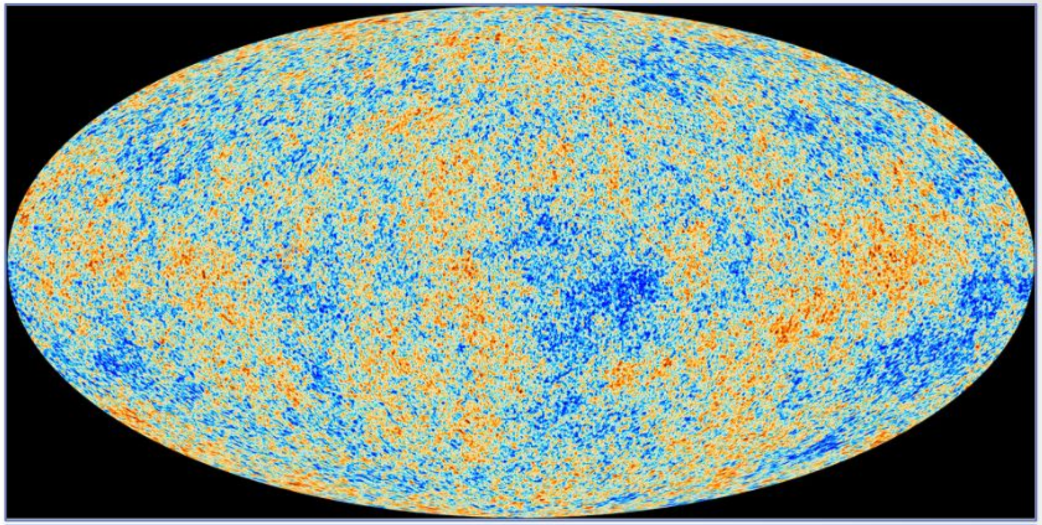


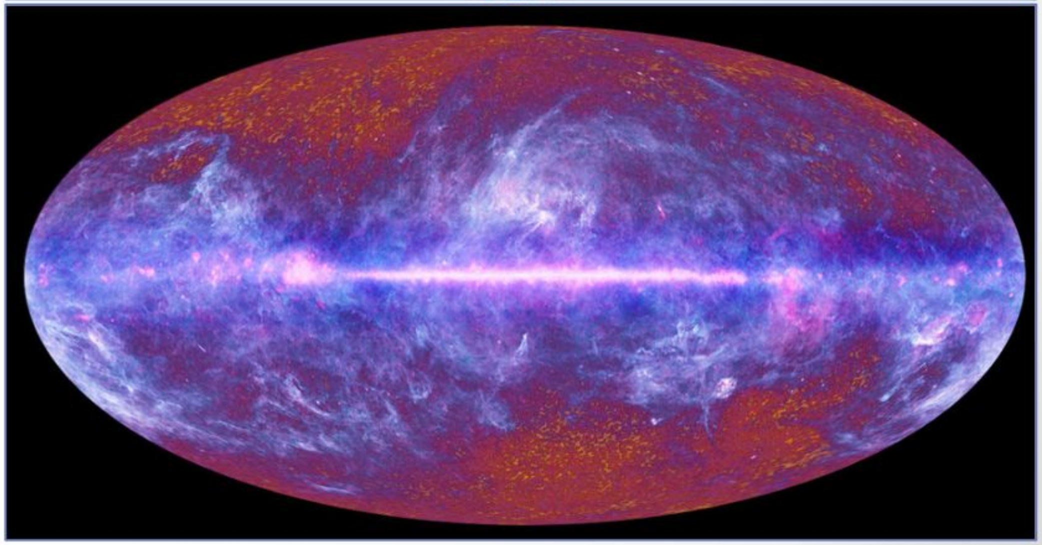
Planck

Planck Space mission operated from L2

1.5m primary telescope
Two detectors:
LFI: 3 frequencies
HFI: 6 frequencies
Angular resolutions ~5-15′

Key contributions to cosmology and to studies of the galaxy. Additional contributions to structure formation, star formation and galaxy evolution.

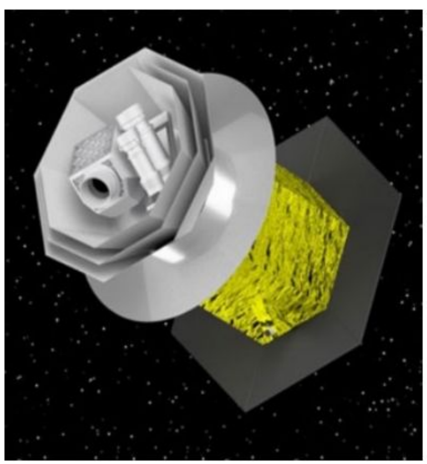


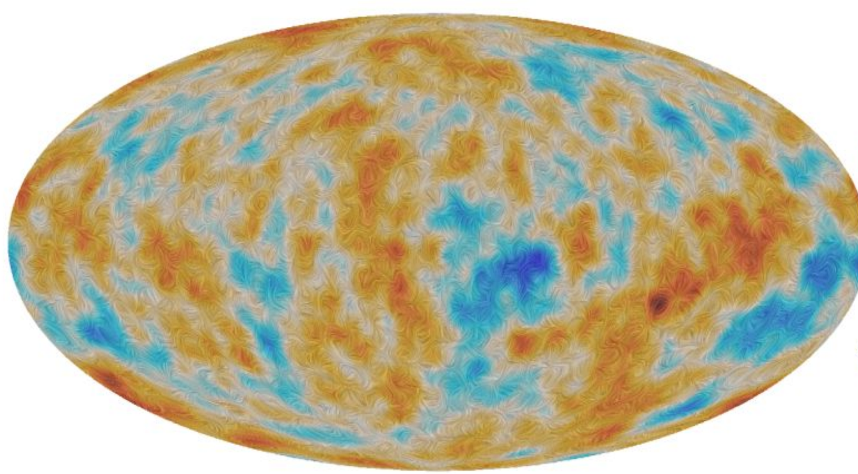


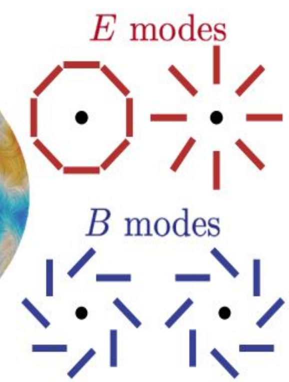
LiteBIRD Overview

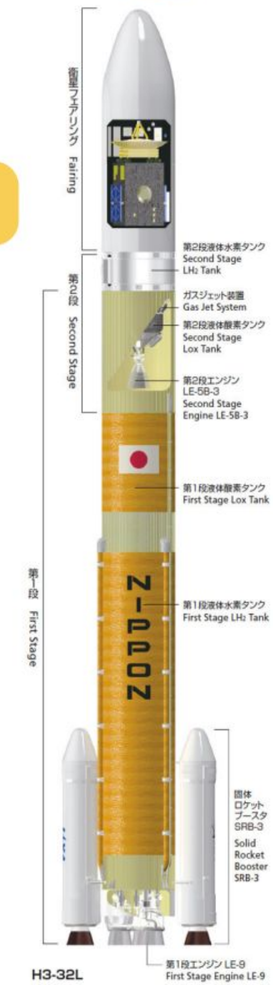
- Lite (Light) satellite for the study of B-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's Strategic Large-class mission selected in May 2019
- Expected launch in late 20s with JAXA's H3 rocket
- All-sky 3-year survey, from Sun-Earth Lagrangian point L2
- Large frequency coverage (40–402 GHz, 15 bands) at 70–18 arcmin angular resolution for precision measurements of the CMB B-modes
- Final combined sensitivity: 2.2 μK.arcmin

📖 LiteBIRD Collaboration PTEP 2022









Multi-Messenger Astronomy

Cosmic Rays

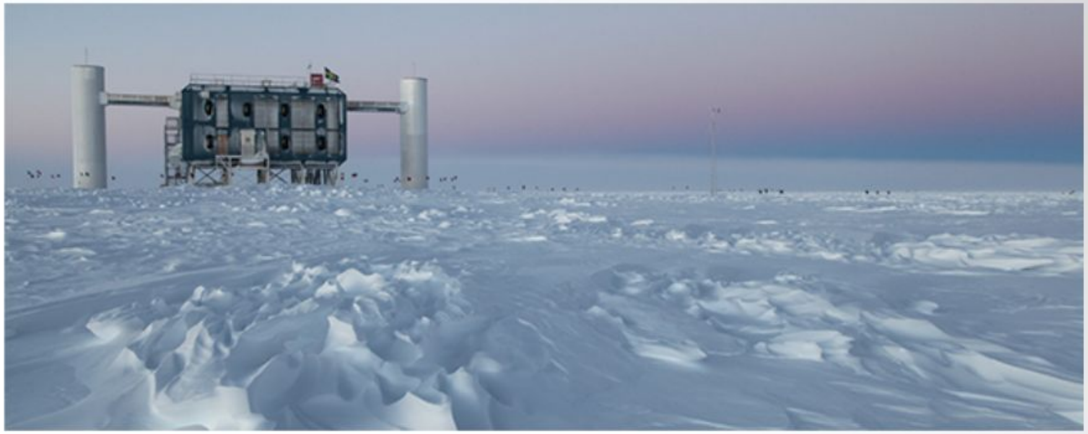
- Cosmic rays are high energy charged particles (mostly protons) that travel through the Galaxy, some arriving on Earth.
- Also the secondary particles produced when these cosmic rays interact in the upper atmosphere
- Discovered by Hess (1912) and named by Millikan (1920s)- mysterious ionizing radiation originating high in the atmosphere
- Storage in Galaxy: magnetic fields act to trap all but the highest energy cosmic rays produced in our galaxy
- Collisions break up heavier nuclei (spallation)
- Cosmic ray elemental abundance differ from solar abundances
  - Excesses of Li, B and Be, all of which are products of spallation

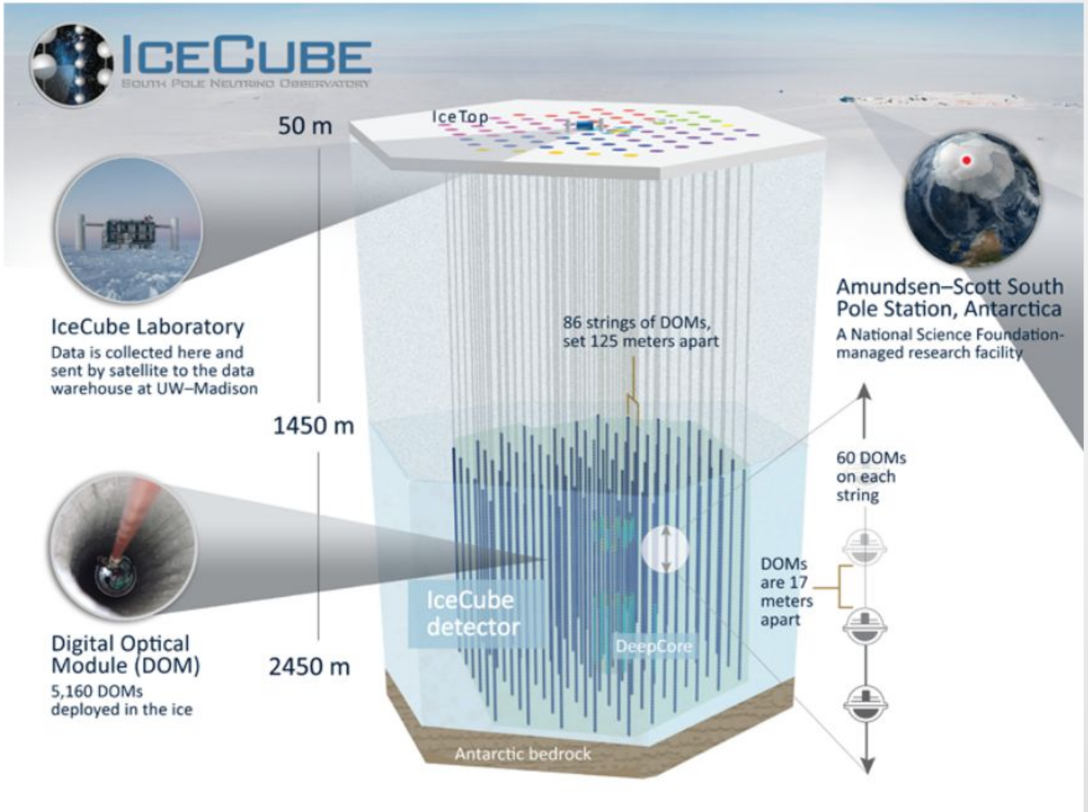
IceCube

http://icecube.wisc.edu

- Detector characteristics:
  - 1km^3 of ice (~0.5 Gton detector)
    - Sensitive to 100 Tev to EeV
  - 5160 Digital Optical Modules
    - 86 boreholds- 125m hex grid
    - 60 DOMs each, 17m offset
    - DOM is upward looking PMT, 2ns time resolution
    - DeepCore: 70 meter grid, 7m offsets (pushes E_ν lim <10GeV)
  - IceTop is for veto and calibration
    - 2 downward facing DOMs

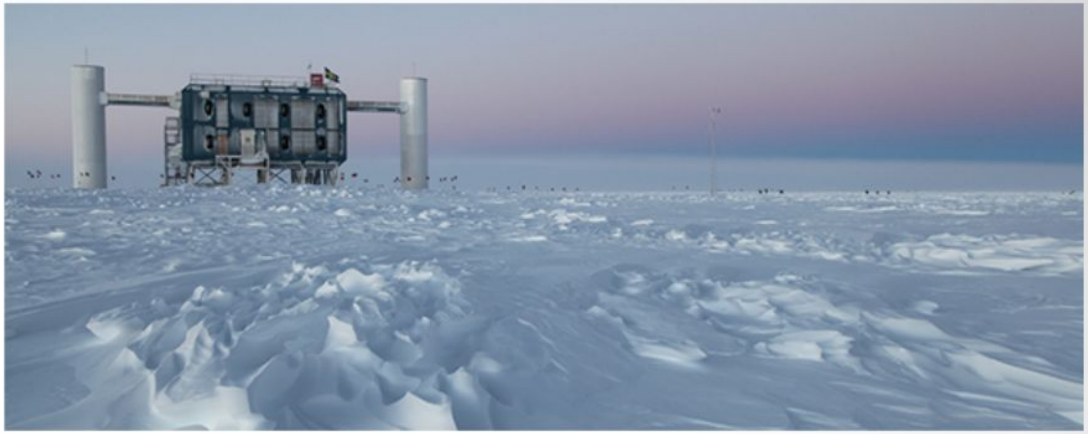
- Science Highlights
  - Ultra high energy neutrinos (exceeding 2PeV)
  - Have mapped the sky but haven't identified source of high energy neutrinos
  - Measured the cosmic ray anisotropy over the southern sky, detecting it at levels of 10^{-3}





IceCube

http://icecube.wisc.edu



- Detector characteristics:
  - 1km^3 of ice (~0.5 Gton detector)
    - Sensitive to 100 Tev to EeV
  - 5160 Digital Optical Modules
    - 86 boreholds- 125m hex grid
    - 60 DOMs each, 17m offset
    - DOM is upward looking PMT, 2ns time resolution
    - DeepCore: 70 meter grid, 7m offsets (pushes E_ν lim <10GeV)
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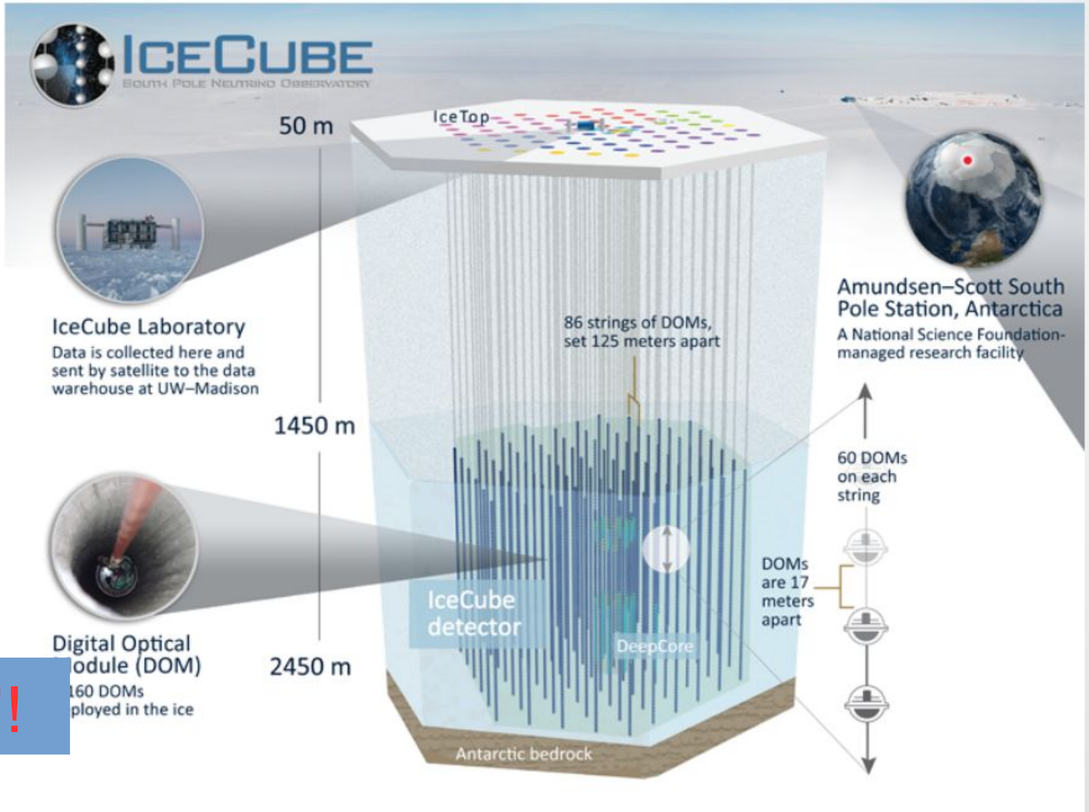


- Science Highlights
  - Ultra high energy neutrinos (exceeding 2PeV)

2017 → blazar TXS 0506 +056!!

  - Measured the cosmic ray anisotropy over the southern sky, detecting it at levels of 10^{-3}

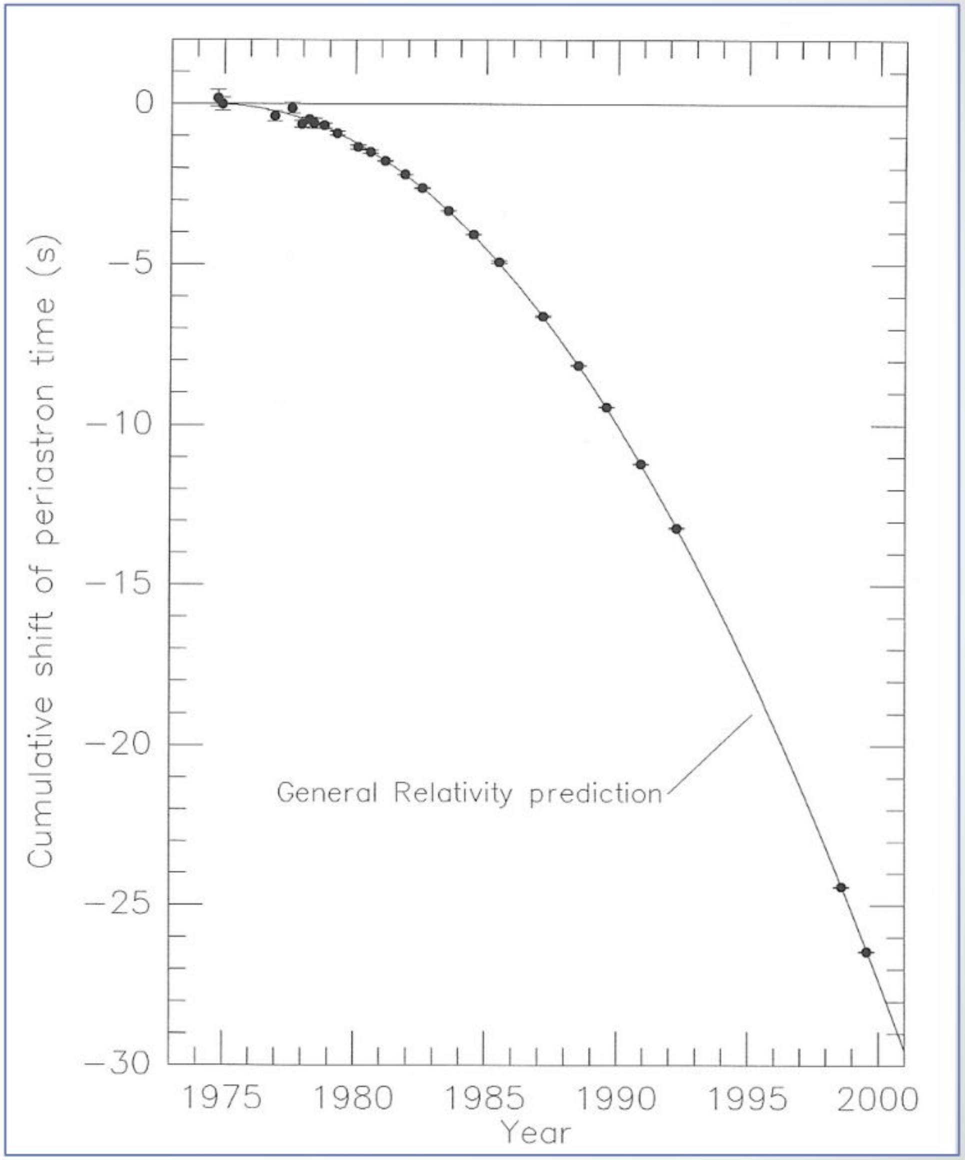
ANTARES++

- Cerenkov detector in Mediterranean Sea
  - 2475m deep (Porquerolles trench)
  - 0.5 degree angular resolution
  - 12 independent detection strings
  - Experiment "assembled" by submarine!
  - 12 strings- each with 5 sectors of detectors and sensors, each 60-70m apart
  - Anchored to seabed, buoy on top, tiltmeter measures orientation of story
  - Acoustic detectors and pingers on the sea surface allow for pinpoint determination of location

- Most sensitive detector in northern hemisphere
  - ANTARES, NEMO and NESTOR joining
  - Cubic km of water
  - 0.1 degree angular resolution

Gravitational Wave Observatories

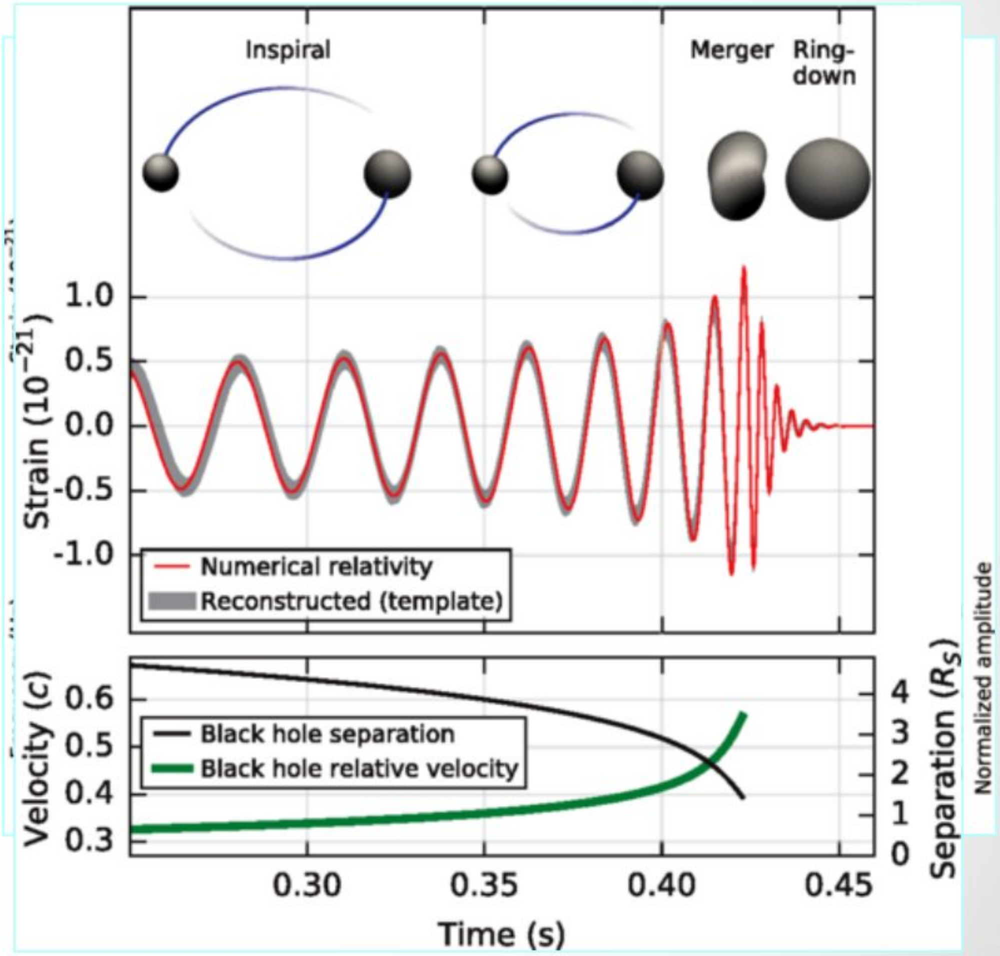
- Implication of Einstein's General Relativity is that G waves exist
- G waves confirmed through energy loss in binary pulsar system
  - Hulse-Taylor system
- Pulsars are spinning neutron stars ~1.4M_o, 10km radius, radio beam sweeps past Earth as pulsar rotates, creating precise periodic signal
  - Doppler effect allows LOS velocity to be measured precisely
  - Binary pulsars are simple systems (two point masses in orbit)
  - Orbital motion creates G waves, and system loses energy, pulsars spiral together and orbital period shrinks
- Evolution of the Hulse-Taylor system in perfect agreement with GR expectation
  - 1993 Nobel Prize!



Direct Detection- Gravitational Waves

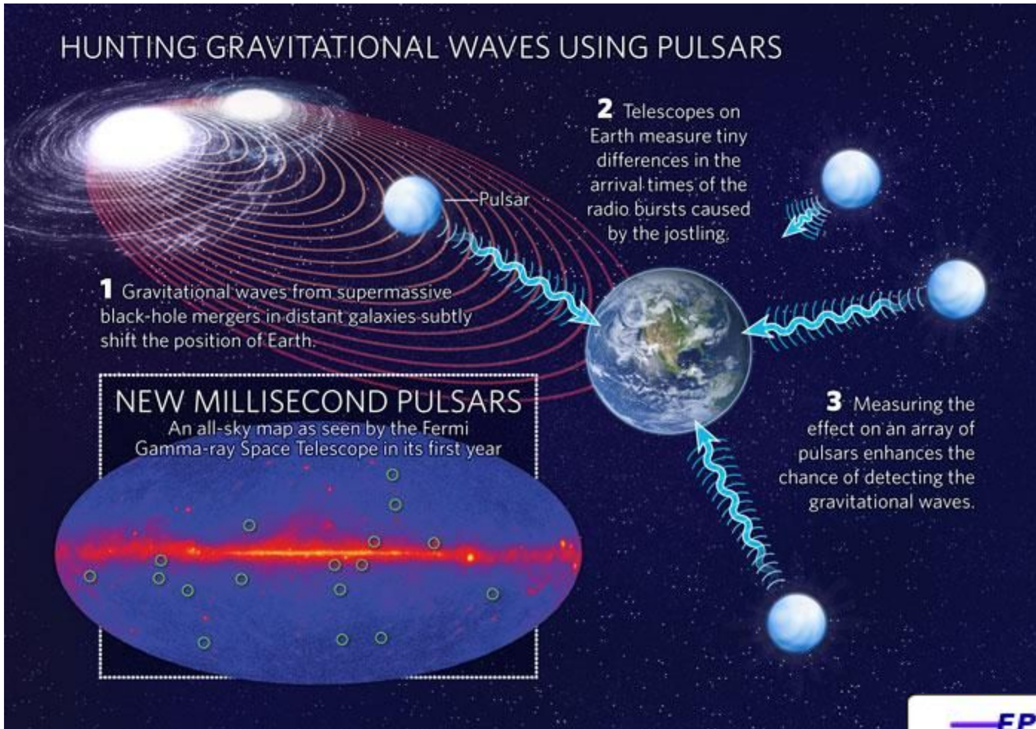
http://www.ligo.caltech.edu

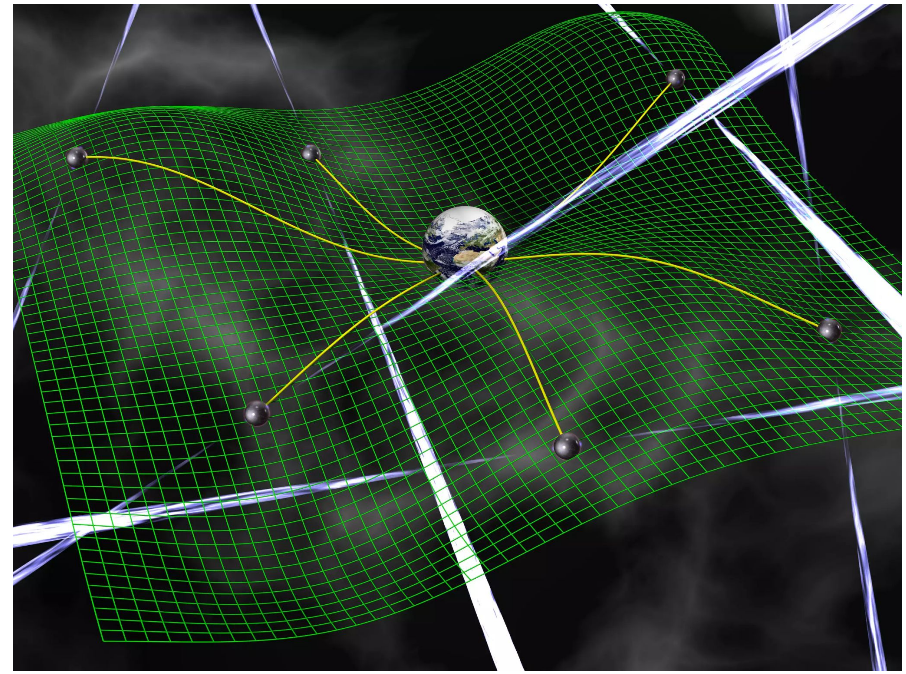
- 14. Sept 2015- detected at two locations
  - S/N=24, with false alarm rate of 1 in 2x10[5] yrs, corresponding to a 5.1σ significant detection
- Binary BH merger (36 and 24 M_o) at distance of ~400Mpc (z=0.09+/-0.03)
- Final mass ~62M_o with ~3M_o of rest mass energy radiated as gravitational wave

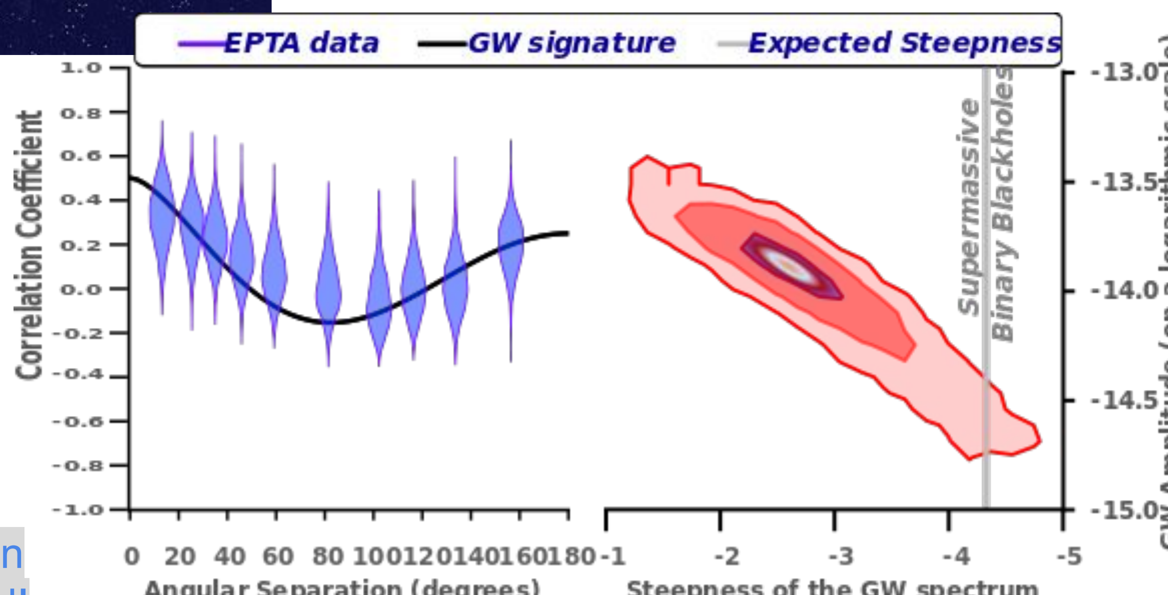


See http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.061102

Pulsar-Timing-Array (PTA)







- PPTA (Australia)
- EPTA (Europe - including SRT)
- NANOGrav (US)
- + GMRT(India), MeerKAT (South Africa), FAST (China)
- InPTA (International ongoing)

26/03/2023: Joint announcement of detection of nanohertz gravitational waves background!