

# Astronomies and Telescopes

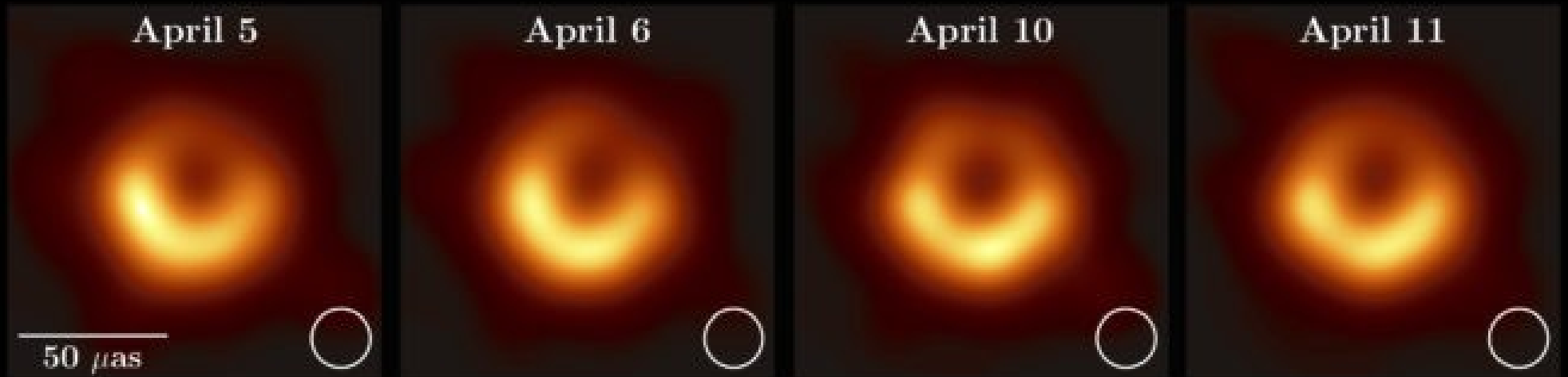
# Some Background

- Until ~900 astronomy only in the visual bands and human eye only detector:
  - $\lambda$  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  $\sim$ 50  $\mu$ arcsec

# 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)

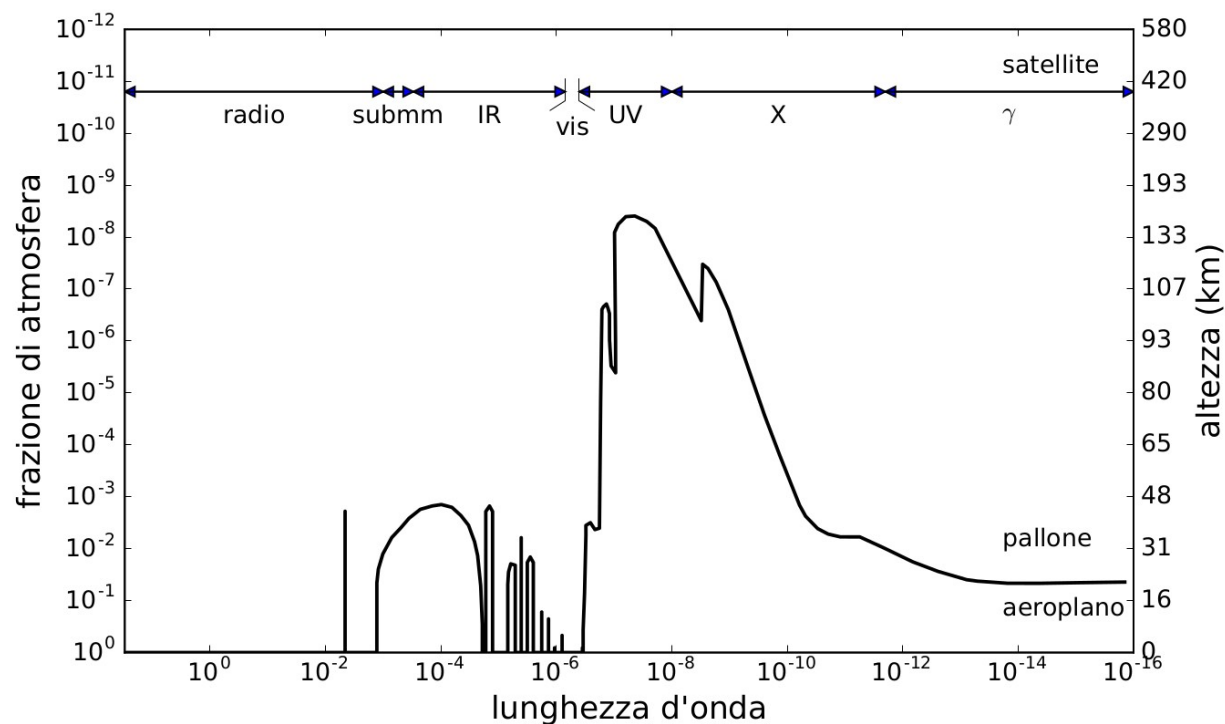


# Improvements

- Angular resolution
- Depth
- Surface Brightness
- Frequency Range

banda	sotto-banda	$\lambda$
RADIO	(non oss.) radio microonde	$>30\text{m}$ $30\text{m} - 3\text{cm}$ $3\text{cm} - 1\text{mm}$
sub-mm		$1\text{mm} - 300\mu$
IR	FIR	$300\mu - 30\mu$
	MIR	$30\mu - 5\mu$
	NIR	$5\mu - 7000\text{\AA}$
ottico (visuale)		$7000\text{\AA} - 4000\text{\AA}$
UV	NUV	$4000\text{\AA} - 3100\text{\AA}$
	soft UV	$3100\text{\AA} - 912\text{\AA}$
	EUV	$912\text{\AA} - 100\text{\AA}$
X	soft X	$100\text{\AA} - 10\text{\AA}$
	hard X	$10\text{\AA} - 0.02\text{\AA}$
$\gamma$		$<0.02\text{\AA}$

$\lambda$	assorbimento	osservazioni
$> 300\text{m}$	plasma interplanetario	opaco
$> 30\text{m}$	ionosfera	(satellite)
$30\text{m} - 3\text{cm}$	finestra radio	da terra
$3\text{cm} - 1\text{mm}$	$H_2O$ e $O_2$	alta montagna
$1\text{mm} - 10\mu$	$H_2O$ , $O_2$ , $CO_2$	pallone o satellite
$850\mu$ e $450\mu$	finestre sub-mm	alta montagna
$10\mu - 7000\text{\AA}$	$H_2O$ , molte finestre	alta montagna
$7000\text{\AA} - 3100\text{\AA}$	finestra ottica	da terra
$3100\text{\AA} - 912\text{\AA}$	$O_3$	satellite
$\sim 912\text{\AA}$	$HI$ galattico	quasi opaco
$\lesssim 100\text{\AA}$	ionizzazione di stratosfera	satellite
$\lesssim 0.02\text{\AA}$	<i>scattering</i> Compton etc.	satellite
$E > 100\text{GeV}$	creazione di sciami	da terra



banda	oggetti visibili	meccanismi di emissione
radio	galassie, AGN, pulsar, SNR <i>HI</i>	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 <i>HII</i>	emissione termica fluorescenza
soft UV	stelle O-B corone stellari regioni <i>HII</i>	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
$\gamma$	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  $R = f_L/d$

- Focal point varies with angle of incoming light

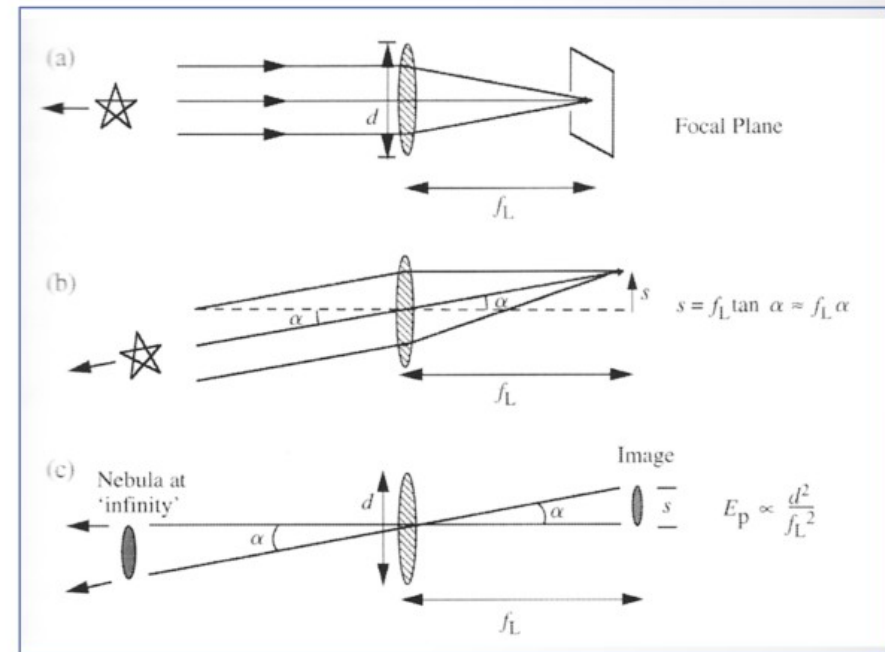
$$s = \tan \alpha f_L \approx \alpha f_L$$

- Plate scale  $P_s$  [rad m<sup>-1</sup> or "/mm]

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

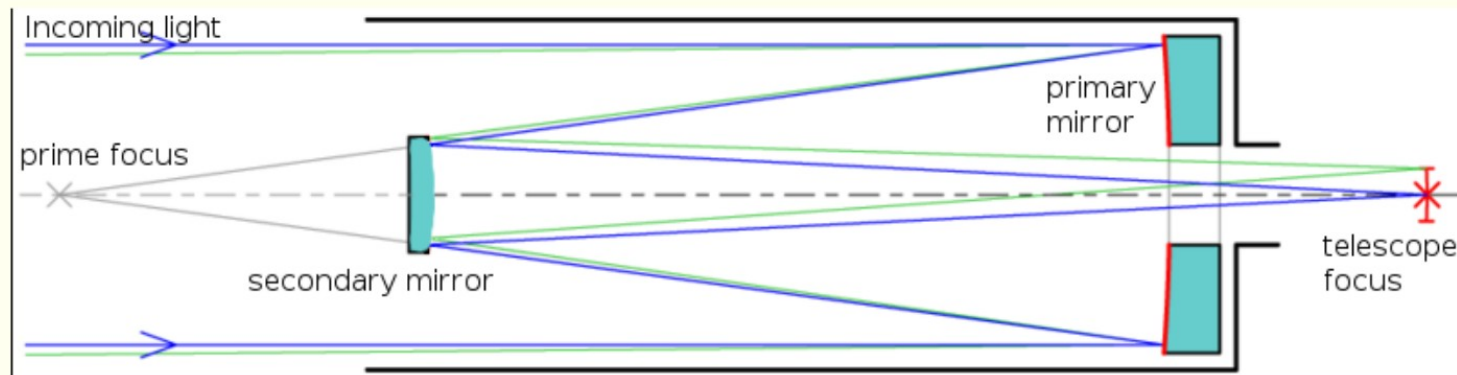
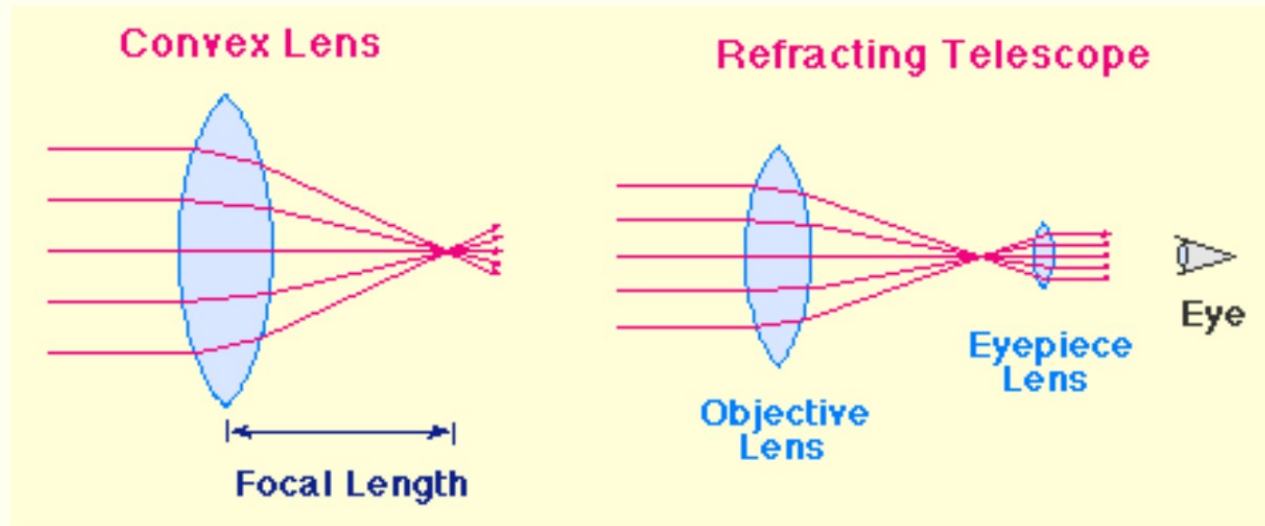
- Energy deposited per pixel scales as

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



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

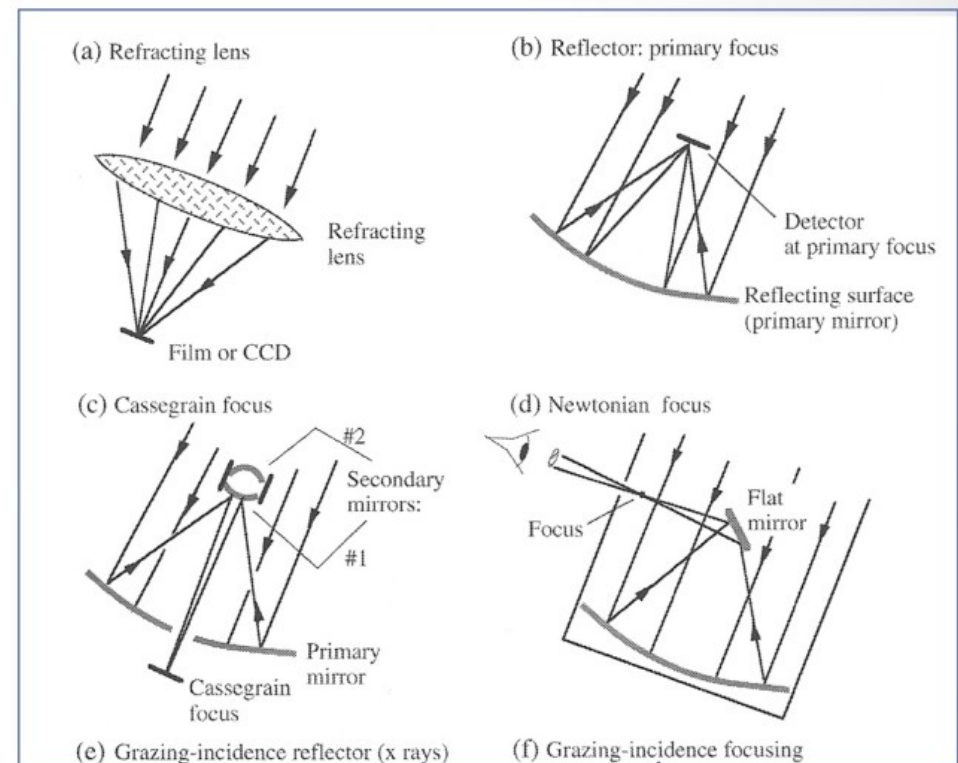
# Telescope Configurations



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

# Telescope Configurations

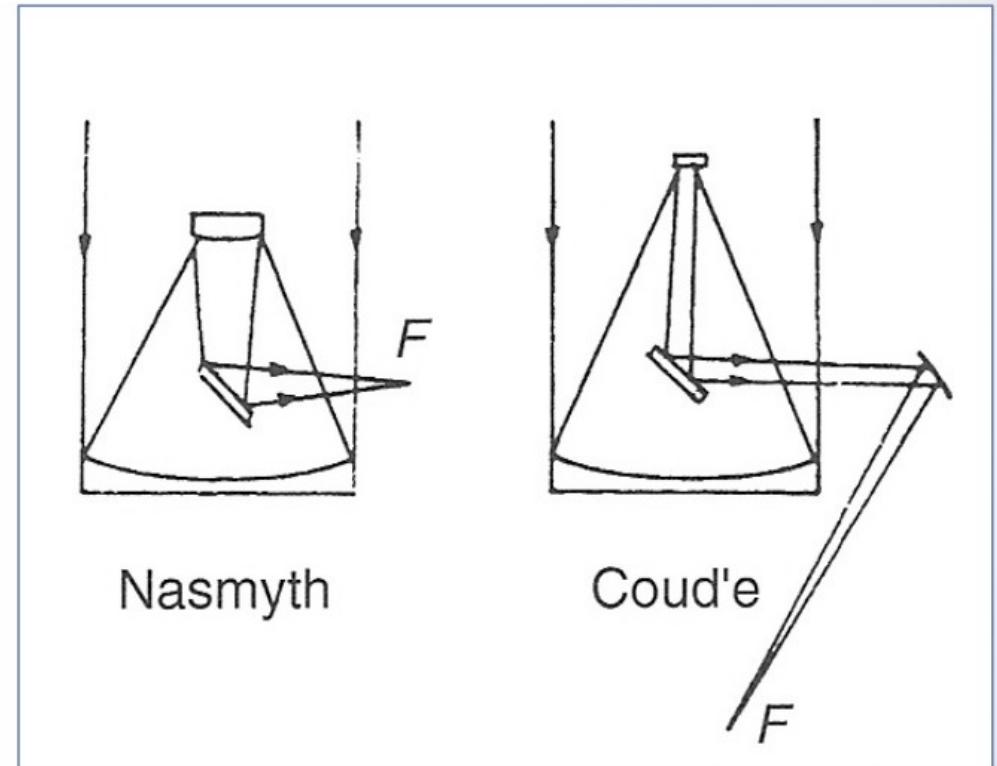
- Elements: Primary, Secondary, Tertiary
  - defined by the path incoming light takes
- Refractor telescopes
  - suffer from chromatic aberration
  - Impossible to support at large  $d$
  - Largest ever made in Yerkes Observatory (Wisconsin, USA) in 1895: 40in
- Reflector telescopes
  - Primary mirror: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





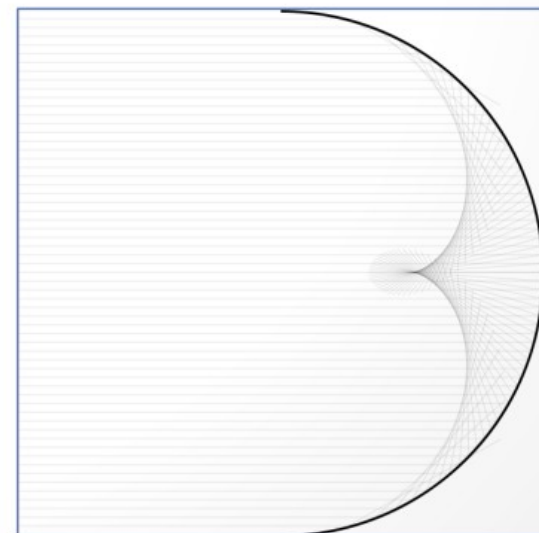
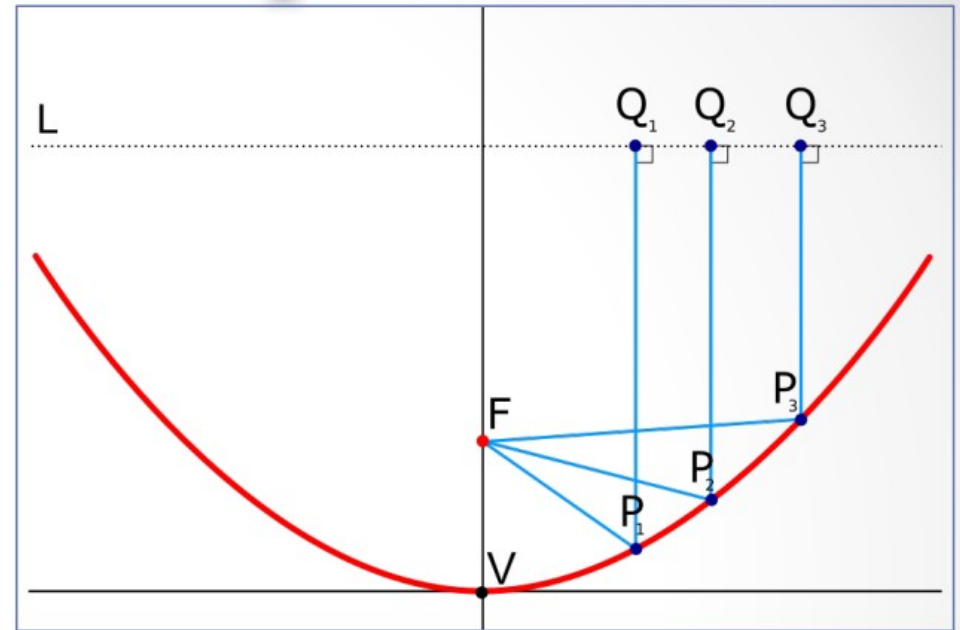
# Additional Configurations

- 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

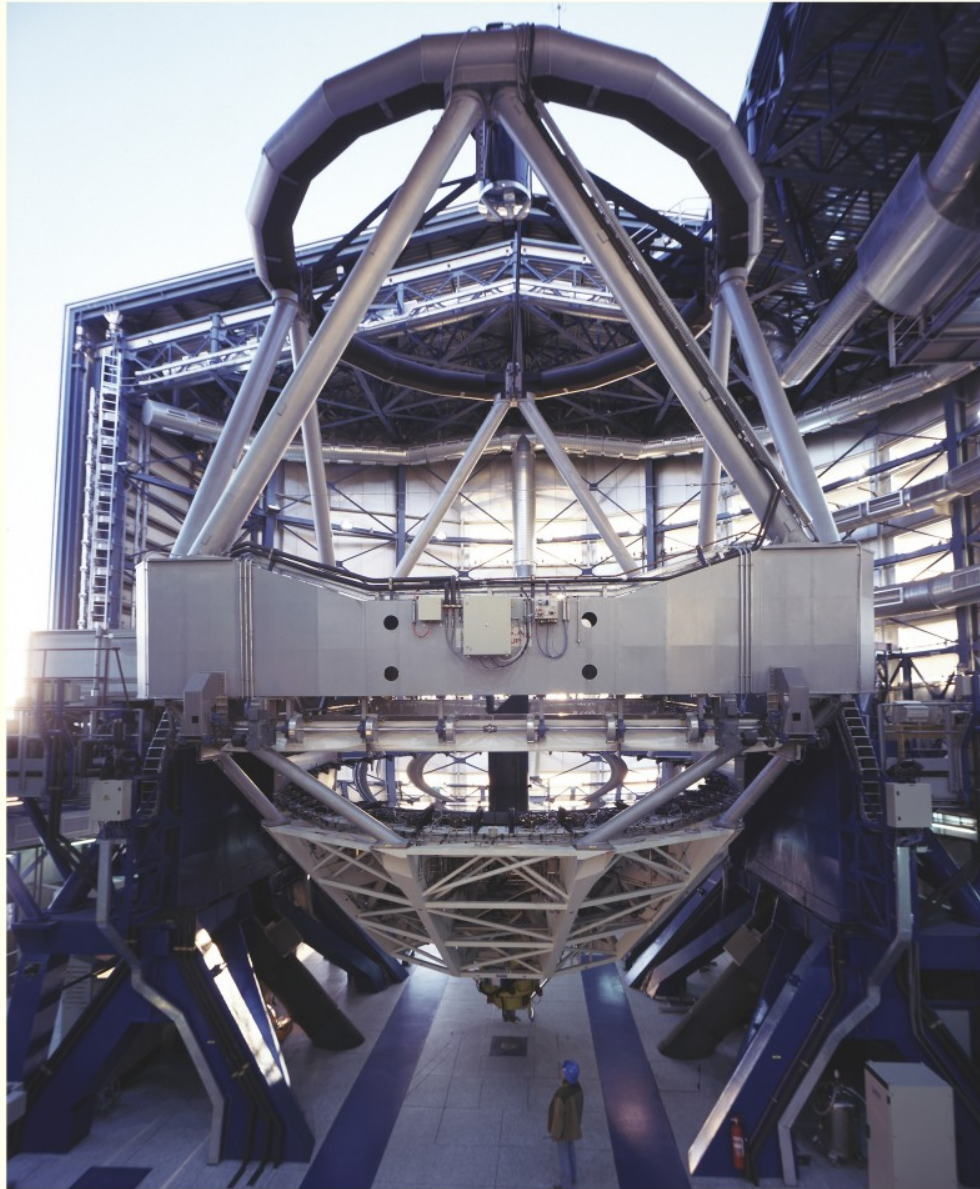


# Parabolic vs Spheric

- 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 aberrations are independent of off-axis angle!

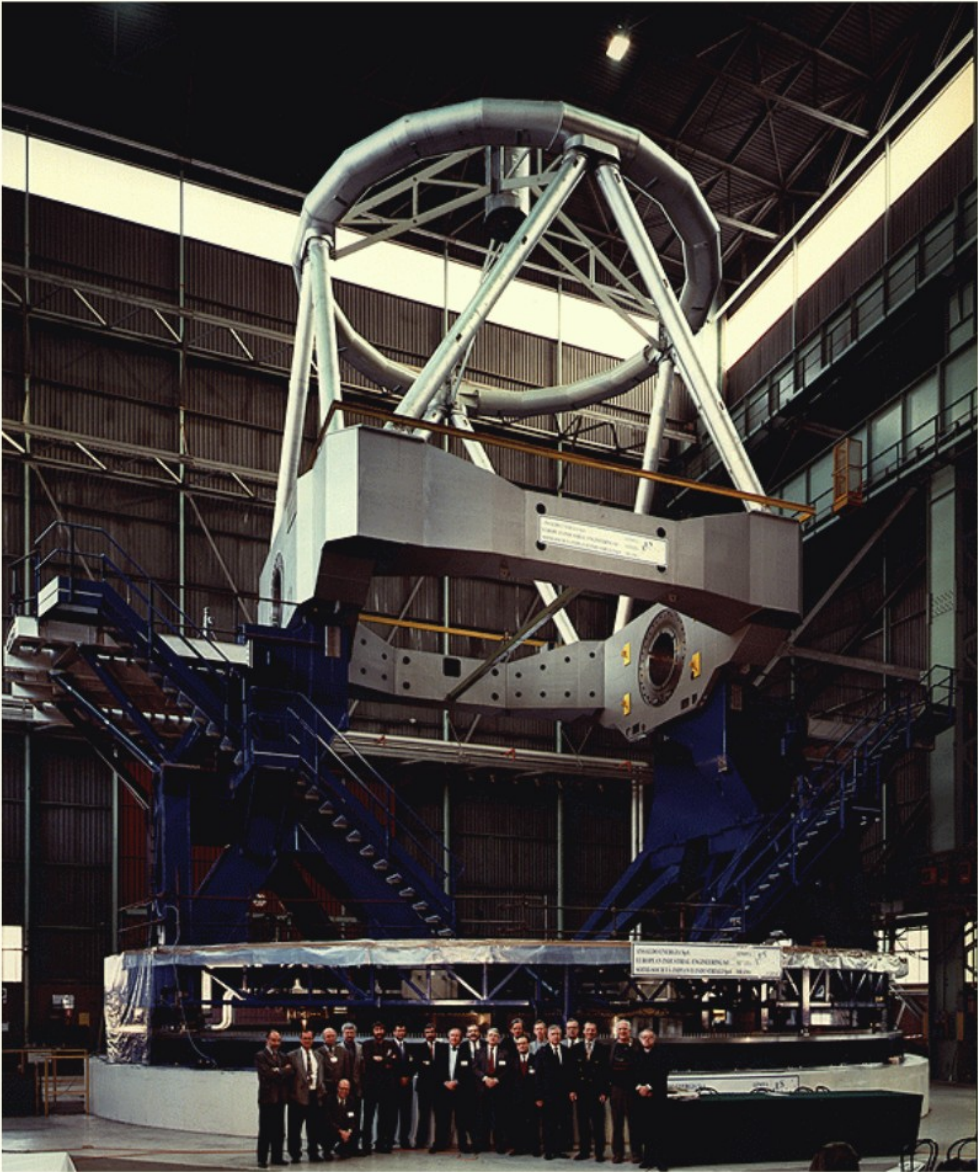


# The VLT: Four Foci on an 8.2 m Telescope



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

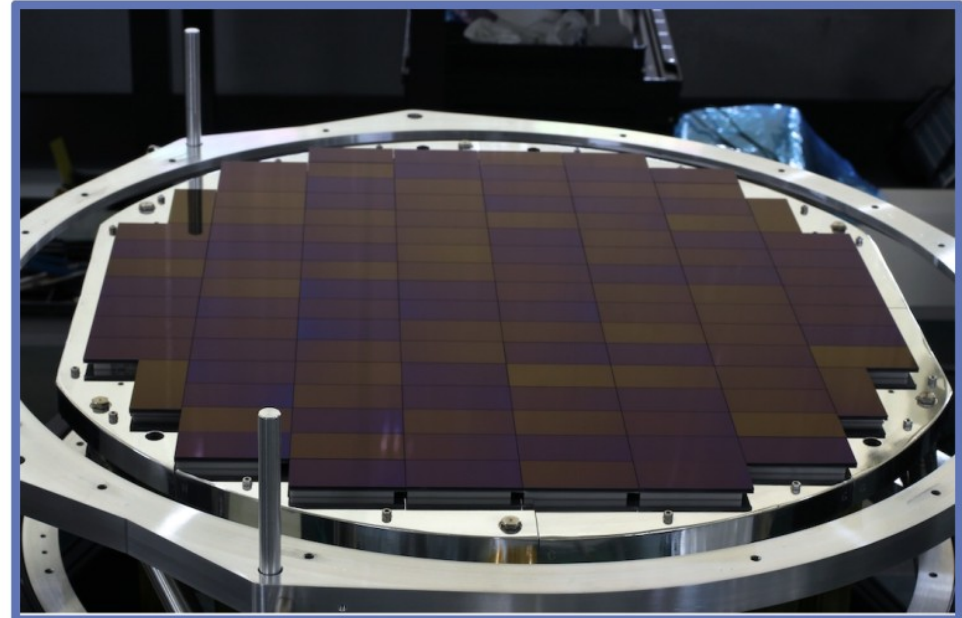


Plate surveys are digitized and available through simple web interface  
[http://archive.stsci.edu/cgi-bin/dss\\_form](http://archive.stsci.edu/cgi-bin/dss_form)



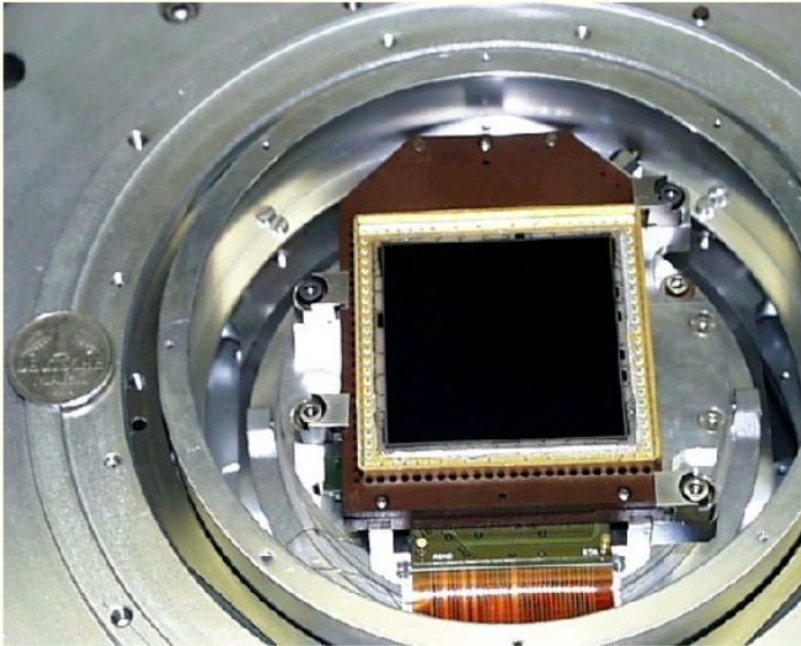
# Charge Coupled Devices

- 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  $\sim 15\mu\text{m}$
- Typical sizes are 2048 to 4096 on a side, corresponding to physical extents of  $\sim 2.5\text{cm}$
- Nowadays large sky cameras are built from large arrays of CCDs, enabling efficient mapping of large portions of the sky

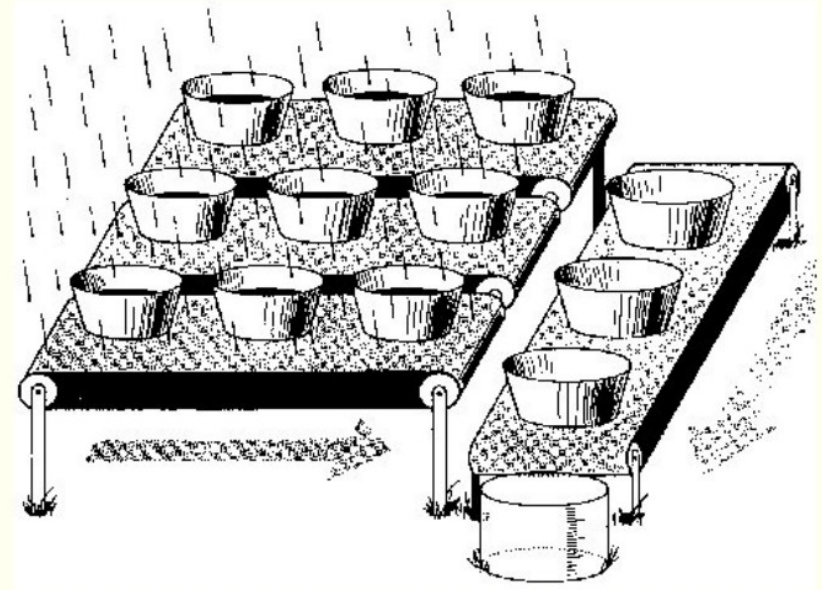


Hyper-Suprime-Cam built  
for the Subaru Telescope

# CCD Exposure and Readout



CCD of the FORS1 instrument



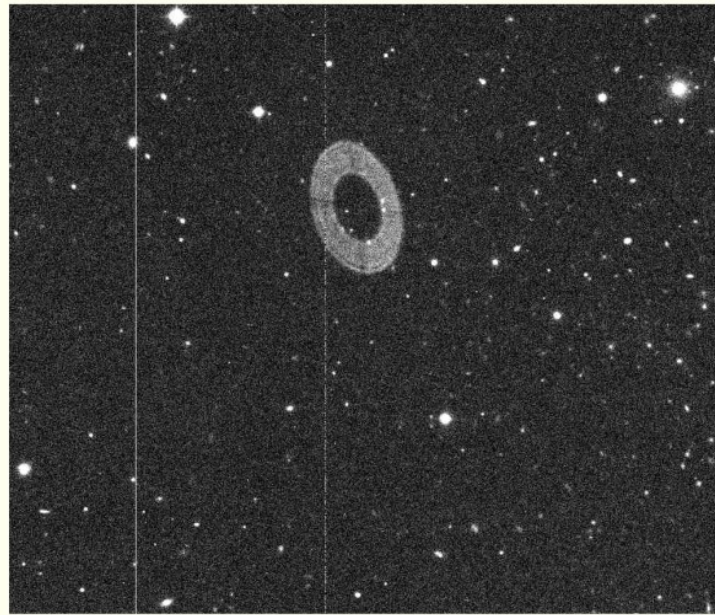
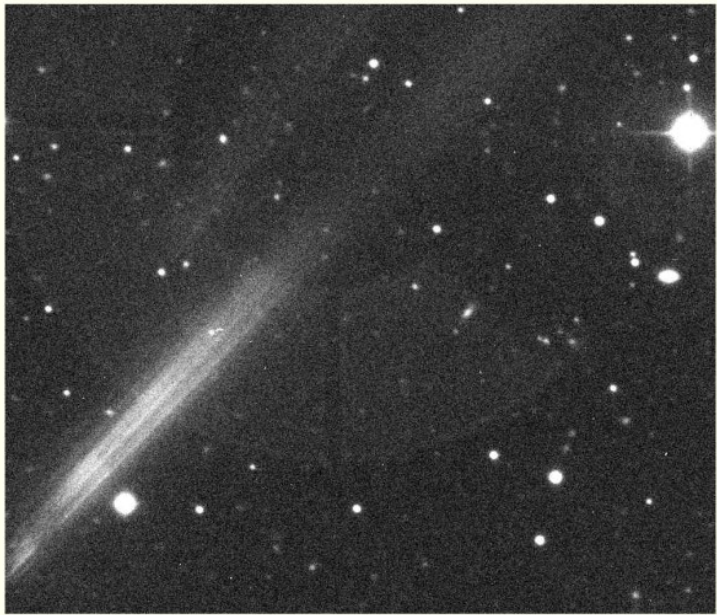
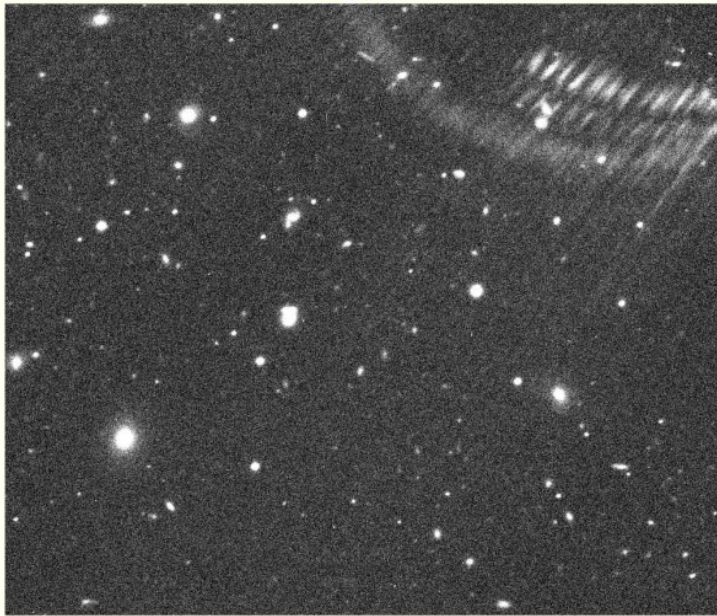
How charge is read out

- ▶ 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

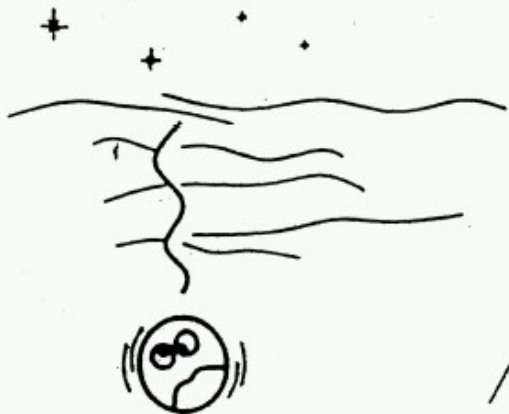
- CCDs are extremely sensitive with quantum efficiencies reaching 80% or higher
  - Compare to photographic plates or the eye that are ~1%
- Sensitive to photons over a broad range of energies ( $>1.11\text{ eV}$  or  $<1.1\mu\text{m}$ , the silicon band gap)
- Linear response over dynamic range of  $10^5$ 
  - 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?

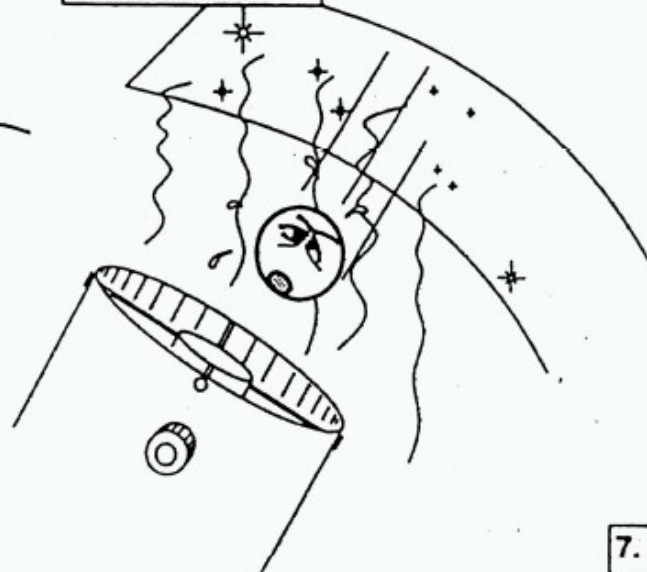


# THE HAZARDS OF A PHOTON'S LIFE

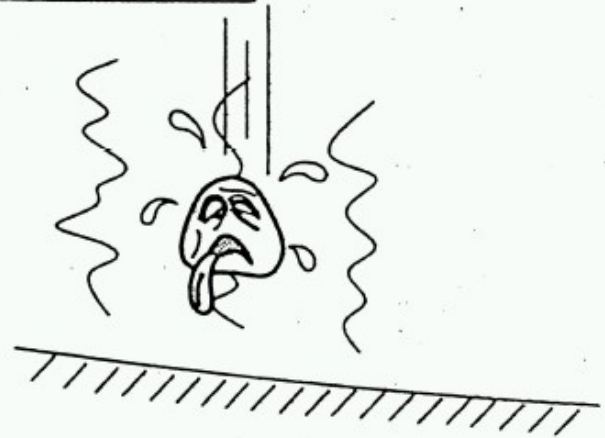
1. Atmospheric turbulence



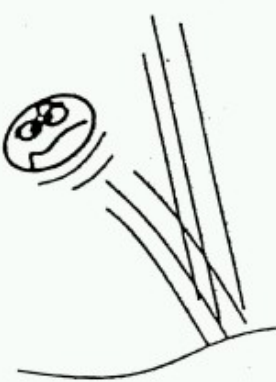
2. Dome seeing



3. Mirror seeing



4. Surface errors



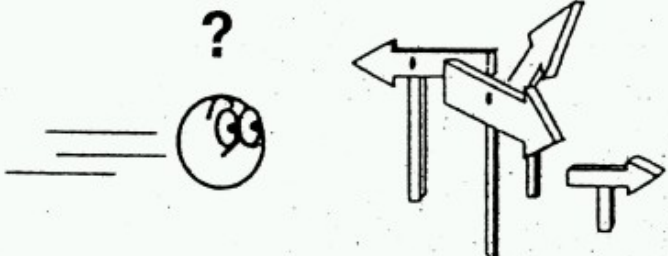
5. Dust & surf. cleanliness



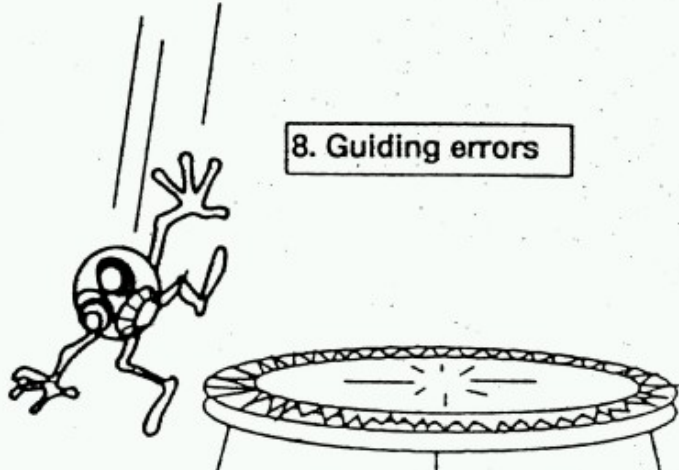
6. Coating efficiency



7. Misalignment

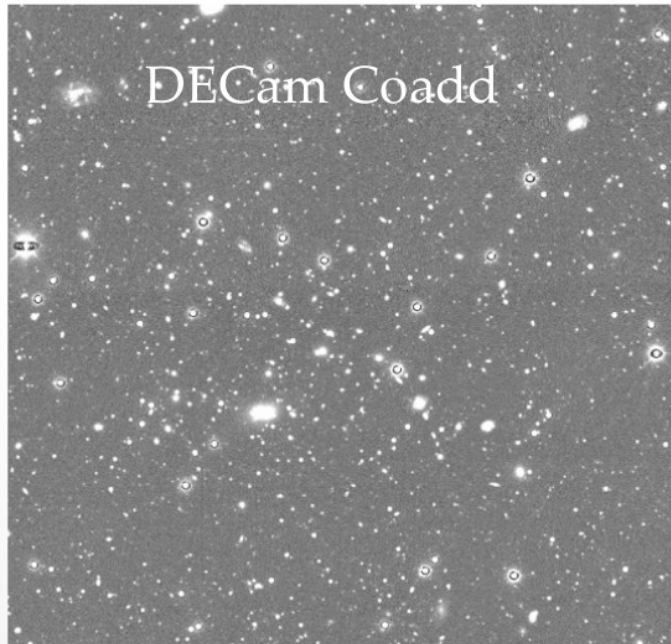


8. Guiding errors



# 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?

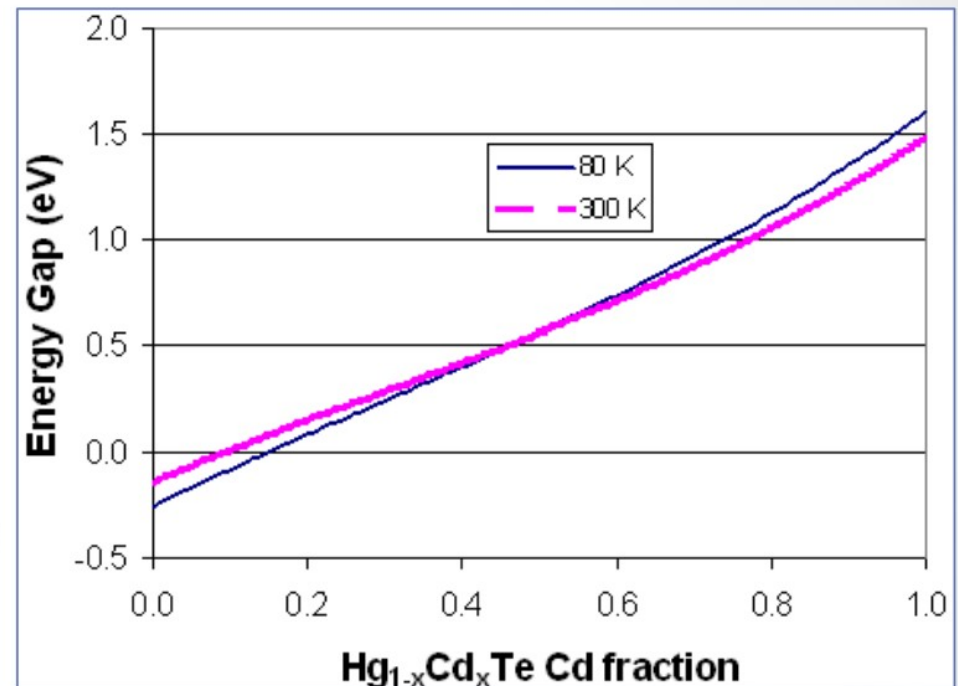
- The silicon band gap makes it impossible to use the standard silicon based CCD at wavelengths beyond  $\sim 1\mu\text{m}$
- Hybrid Complementary Metal Oxide Semiconductor (CMOS) devices are well suited for infrared photon detection



Hubble IR Image of Tarantula Nebula  
I/H 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  $\lambda < 2.5\mu\text{m}$
  - LHe (4 to 20K) at  $\lambda > 2.5\mu\text{m}$

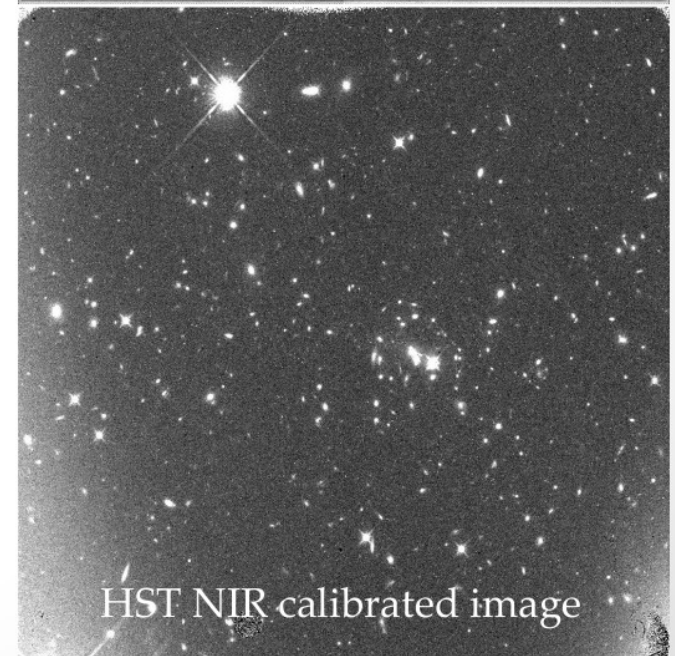
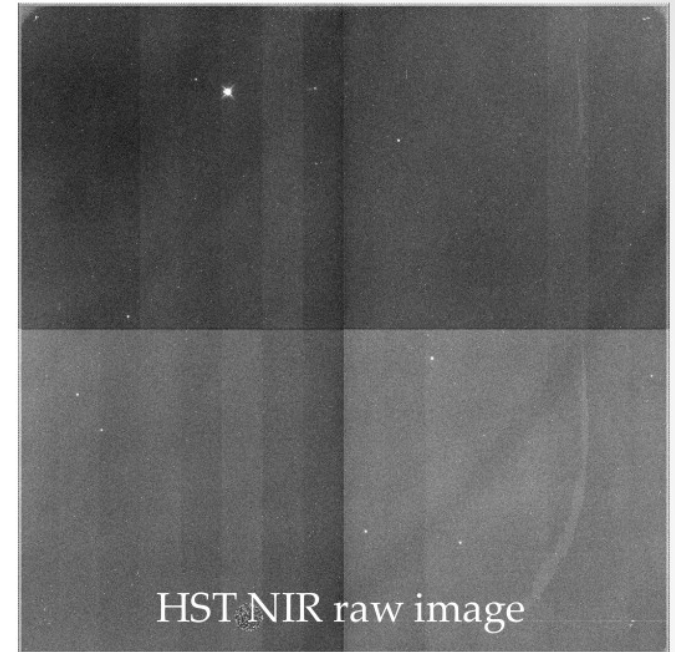


HgTe is semimetal and CdTe is semiconductor. By adjusting Cd fraction one can tune the wavelength sensitivity of the HgCdTe arrays



# 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.



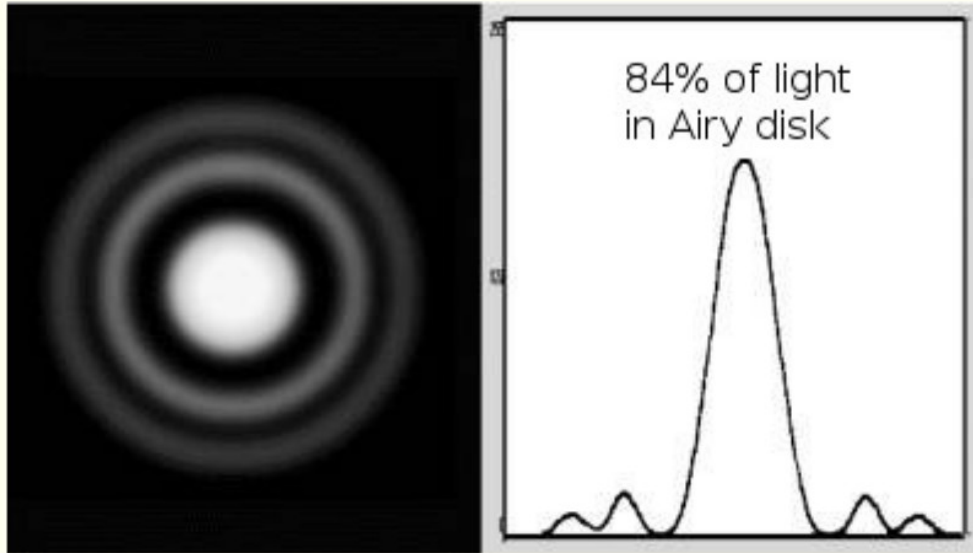
# Photometric Passbands

- 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	$\lambda_{\text{mid}}$	$\Delta\lambda$
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

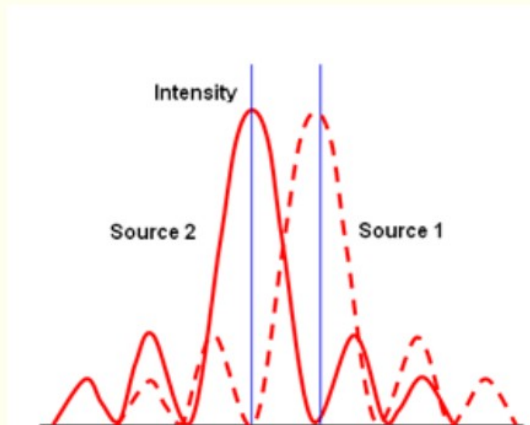
# Ground vs Space

## Angular resolution



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

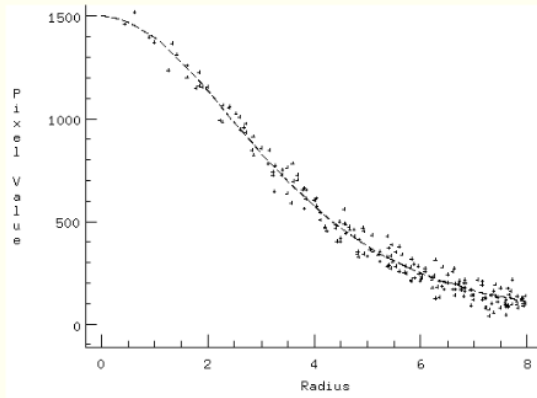
Airy pattern is described by  $\frac{J_1^2(\theta/2)}{(\theta/4)^2}$  with minima at  $1.22n\lambda/D$ .



- ▶ 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)



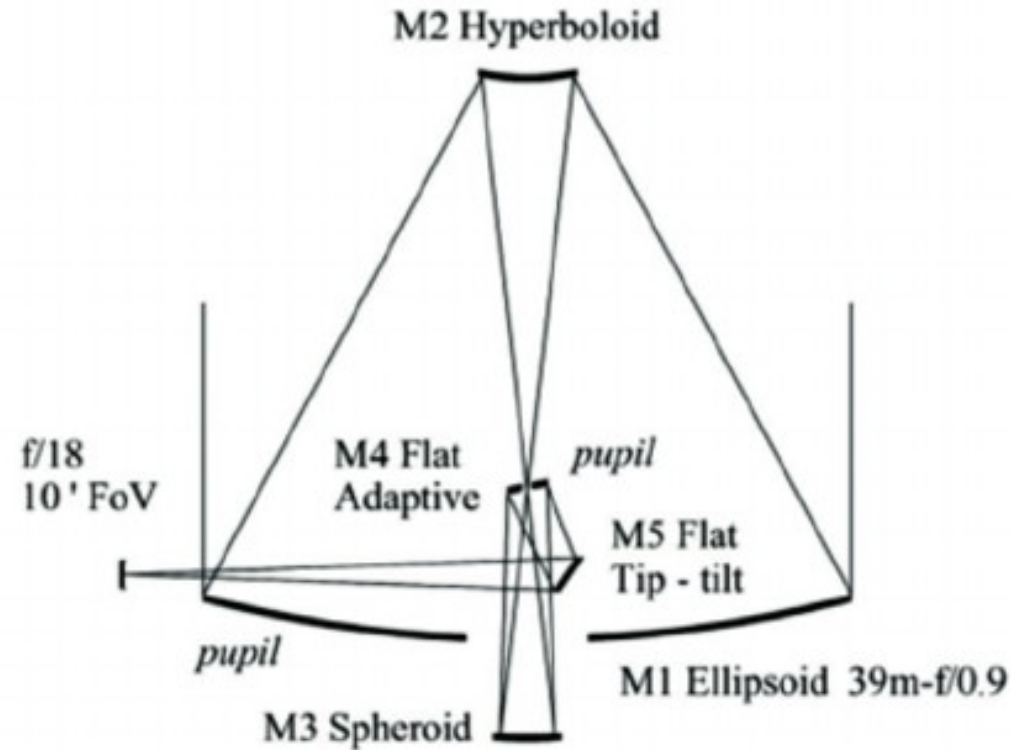
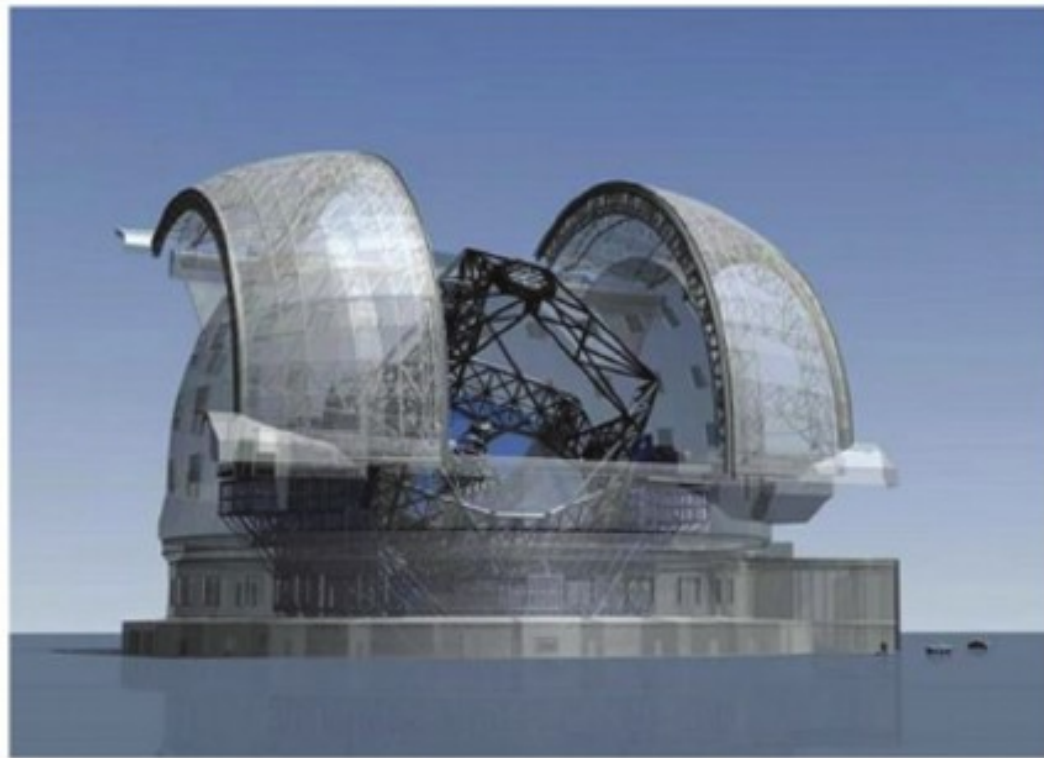
- ▶ For large ground-based telescopes the PSF is a function of atmosphere, rather than telescope optics.
- ▶ The “seeing”, the FWHM of the PSF, is given in arcseconds.  $0''.3$  is very good,  $2''$  is bad. Weak lensing requires  $< 1''$ .

The radial profile is described by a Moffat profile

$$I(r) = \frac{I_0}{(1+r^2/R^2)^\beta} + B$$

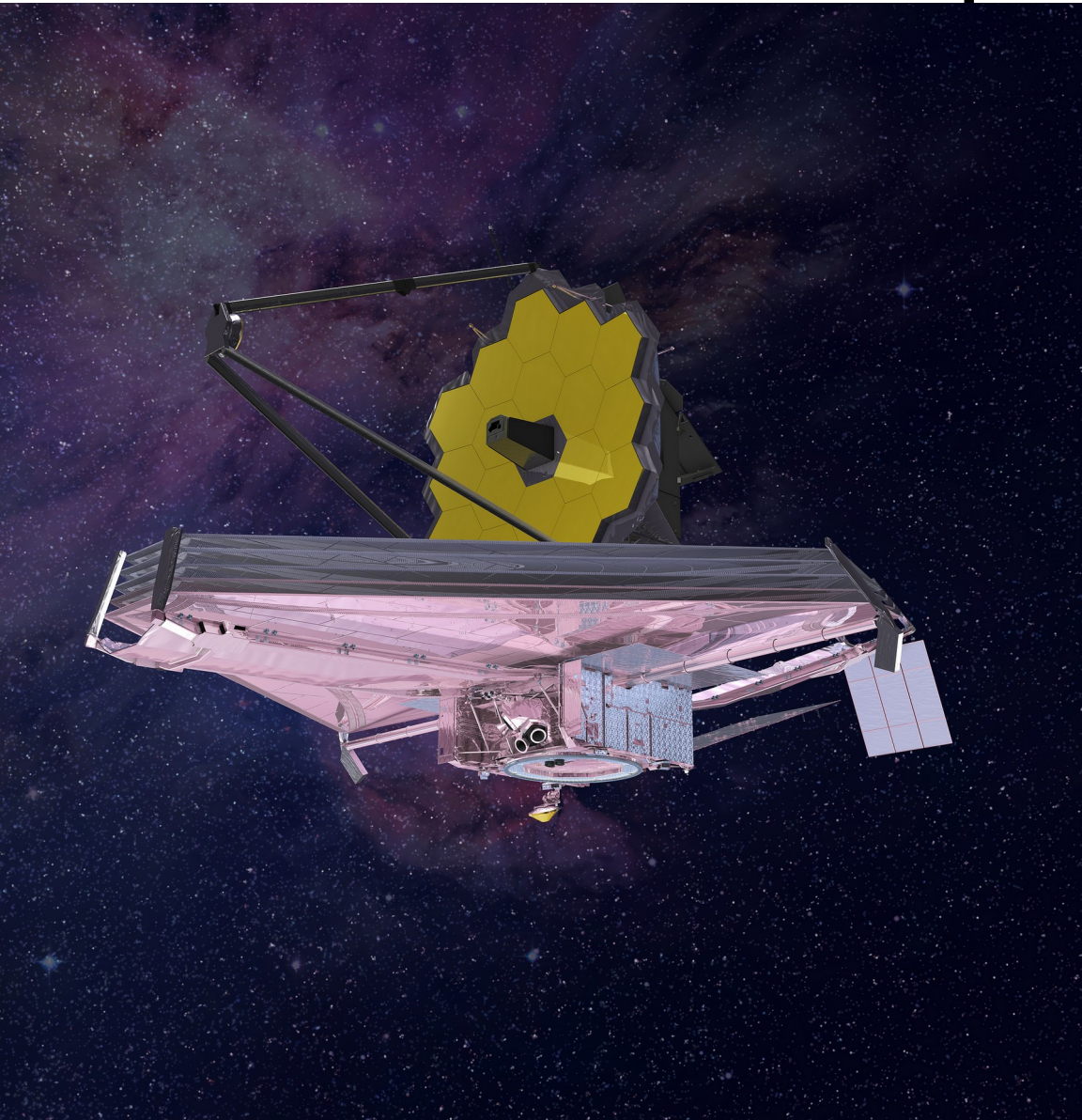
The free parameters are the width of the PSF  $R$  and the Moffat parameter  $\beta$ .

# Extremely Large Telescope



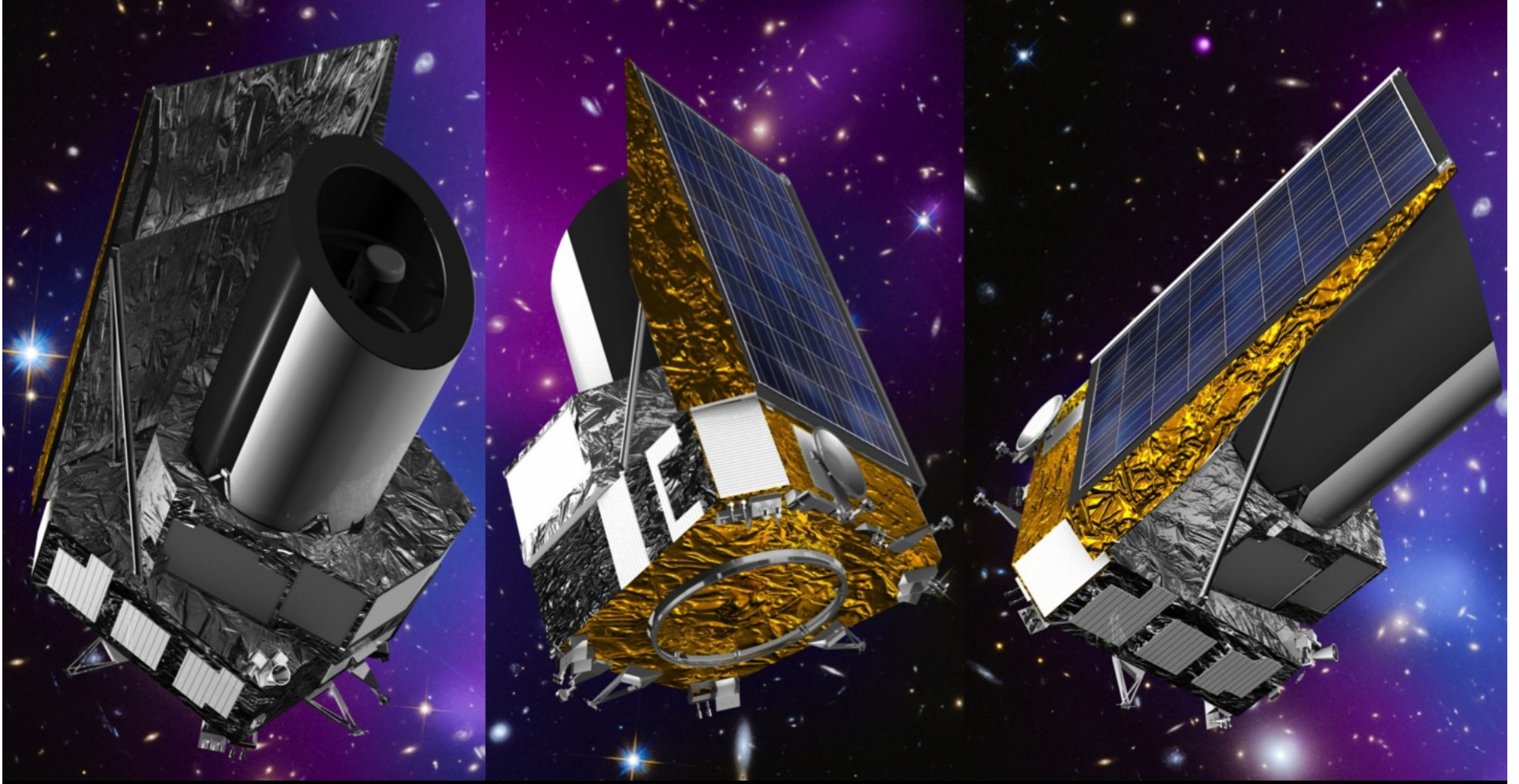
- Primary 39 m
- 2 Nasmyth platforms for instrumentation
- Active Optics
- Adaptive Optics
- First Light 2025??

# James Webb Space Telescope



- Primary 6.5 m
- NIR/MIR
- Launch 2021

# Euclid



- Primary 1.2 m
- Very Large FOV
- Optical/NIR
- Imaging/Spectroscopy
- 10,000 deg<sup>2</sup> survey
- Launch 2023?

# LSST – Vera Rubin Observatory

## The LSST Camera

### World's largest optical astronomy detector array:

63-centimeter diameter focal surface  
( $>3200$  square centimeters of detector area)

3.2 billion pixels at 0.2 arcseconds per pixel

High device count:  $\sim 200$  detectors  
(based on  $4k \times 4k$  pixel arrays with 10 micron pixel pitch)

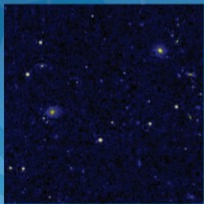
Tight dimensional requirements:  
less than  $\pm 5$  microns total flatness deviation

Two-second readout time

### Filter exchange mechanism in highly constrained space

Very large transmissive optics (first lens diameter = 1.6 meters)

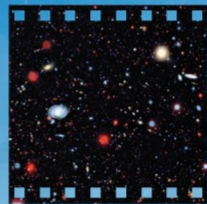
LSST probes 100x fainter while enabling exploration of the time domain



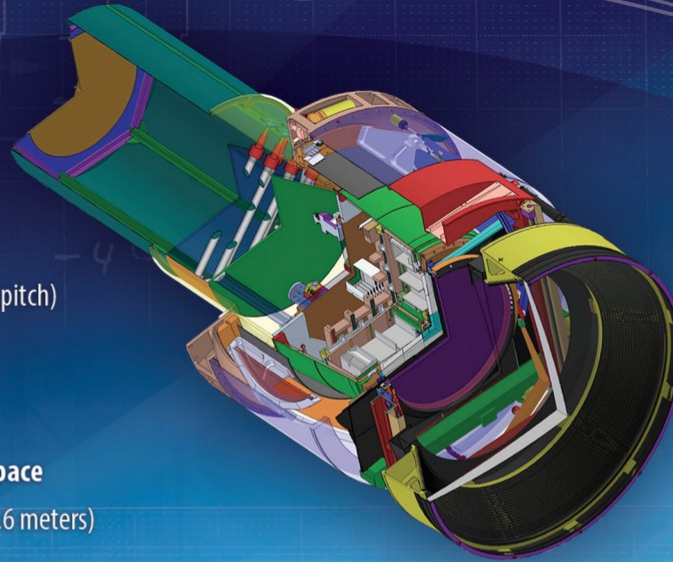
ca. 1950 POSS  
(Photographic)



ca. 2000 SDSS  
(Digital)



ca. 2020 LSST  
(Digital + Time Domain)



## The LSST Optical Design

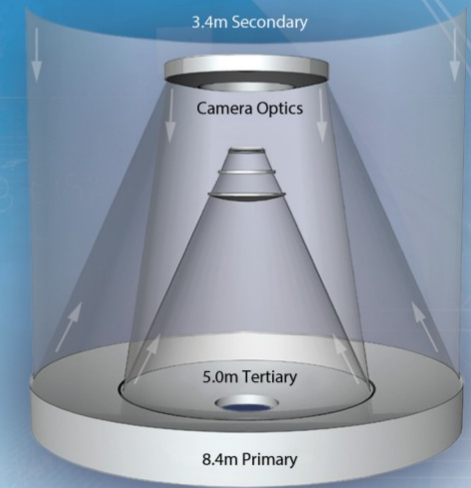
8.4-meter primary, 3.4-meter convex secondary, and 5.0-meter tertiary mirrors

6.7-meter diameter clear aperture equivalent

3.5-degree diameter circular field of view (9.6 square degrees)

Total light throughput ("A- $\Omega$ " product) =  $319 \text{ m}^2 \cdot \text{Degree}^2$   
Today's typical 4-meter telescope =  $4 \text{ m}^2 \cdot \text{Degree}^2$ !

63-centimeter diameter flat focal surface



## The LSST Data Management

15,000 Gigabytes (average) of raw pixel data per night

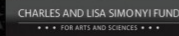
Queryable catalogs up to 12 Petabytes released annually

Automated data processing and quality assessment

Efficient community access to data

Transformative public access and outreach

Data Open to US, Chile and International Contributors



Financial support for LSST comes from the National Science Foundation (NSF) through Cooperative Agreement No. 1258333, the Department of Energy (DOE) Office of Science under Contract No. DE-AC02-76SF00515, and private funding raised by the LSST Corporation. The NSF-funded LSST Project Office for construction was established as an operating center under management of the Association of Universities for Research in Astronomy (AURA). The DOE-funded effort to build the LSST camera is managed by the SLAC National Accelerator Laboratory (SLAC).

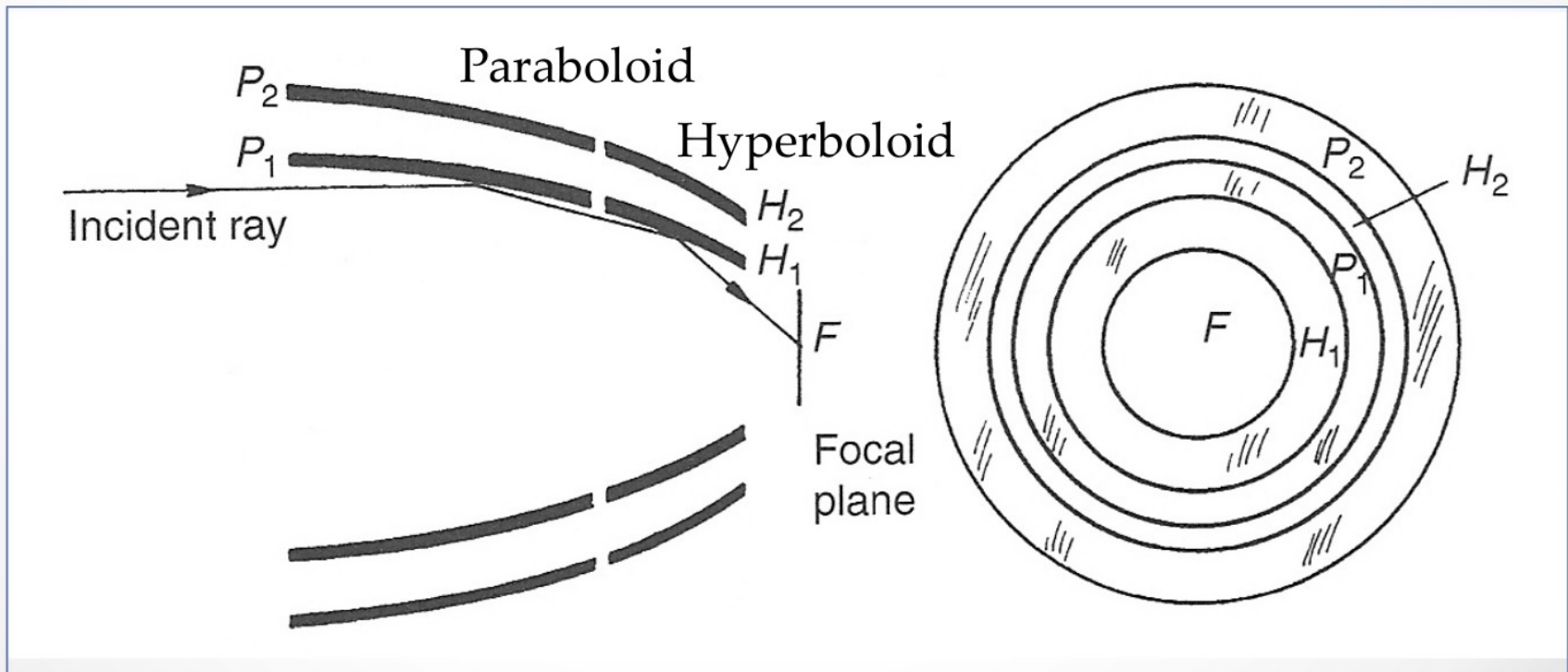
- Primary 8.4 m
- Very Large FOV ( $\sim 10 \text{ deg}^2$ )
- Optical/NIR and time domain
- 18,000  $\text{deg}^2$  survey
- Starting operations 2023?



X-rays and  $\gamma$

# 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  $\sim 89^\circ$  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



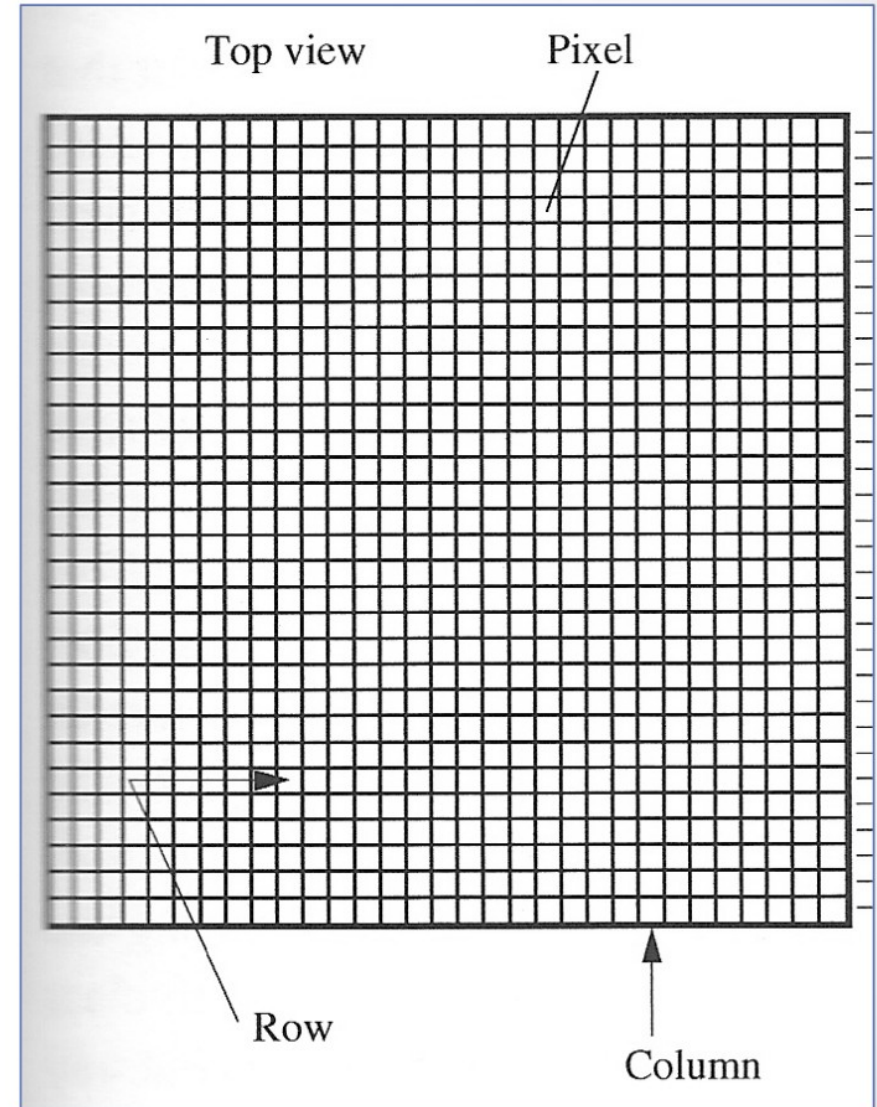
# Image Quality

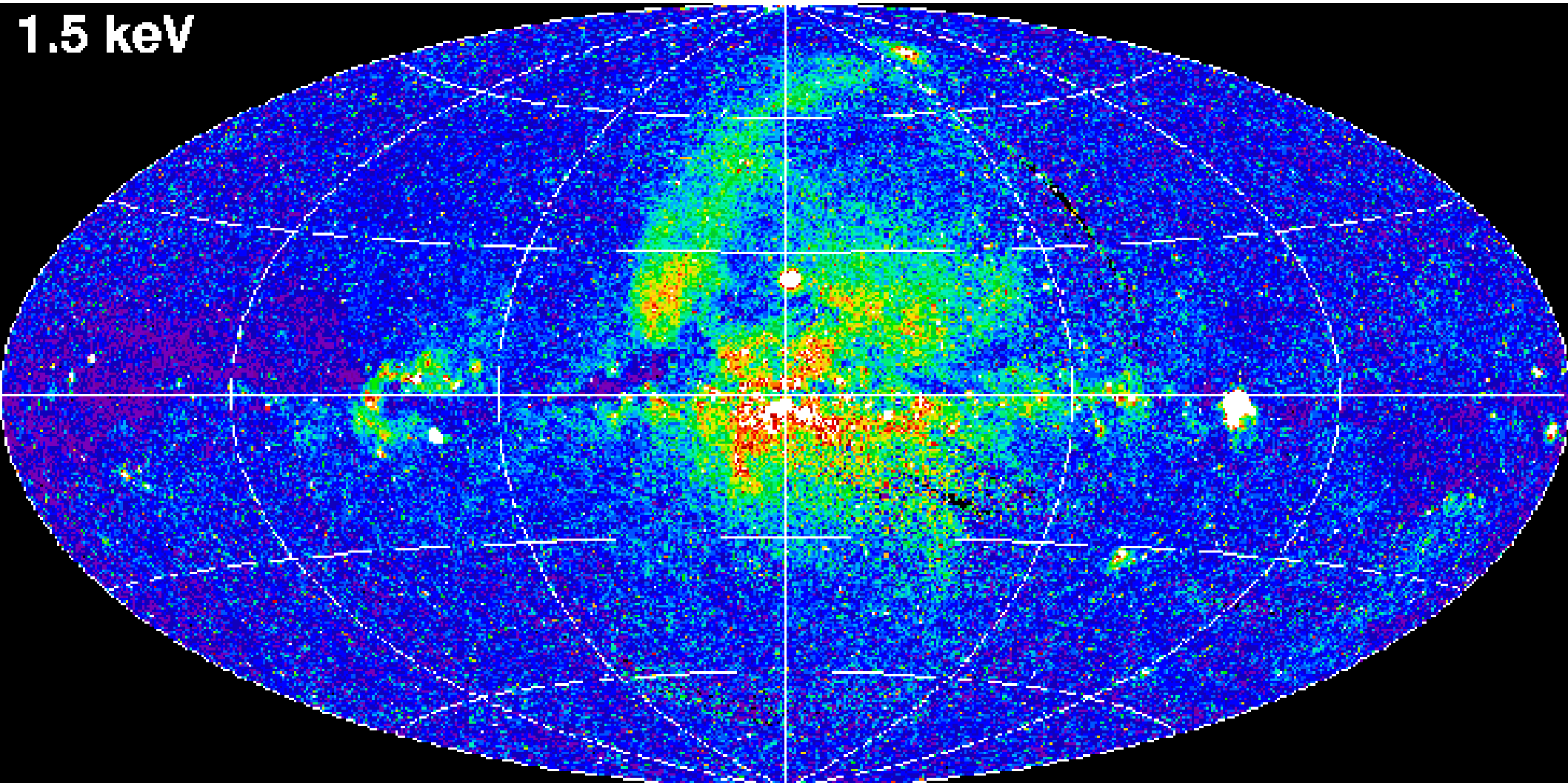
- Efficiency of scattering depends on photon energy
  - Higher energy photons scatter only at the highest incidence angles
- Image quality
  - Not related to diffraction limit, which given small wavelength would be incredibly small
  - Defects in crystalline structure of metallic mirror surfaces and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





1.5 keV

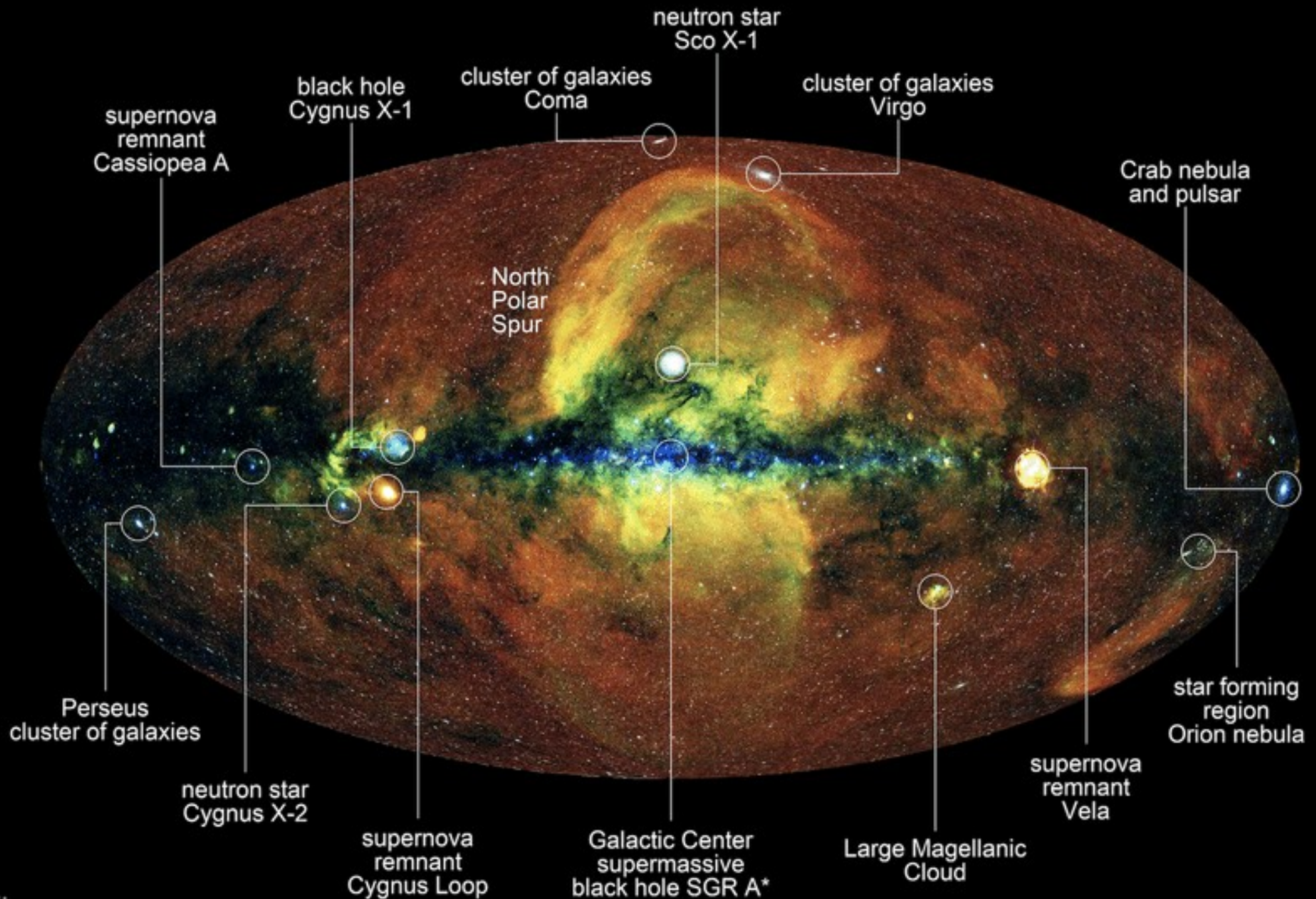
Rosat All Sky Survey  
M.J.Freyberg, R.Egger (1999)

# 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



# First SRG/eROSITA all-sky survey: A million of X-ray sources and the Milky Way.



# $\gamma$ -Ray Telescopes

## Fermi LAT

### Public Data Release:

All  $\gamma$ -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  $\gamma$  direction  
EM v. hadron separation

### Hodoscopic CsI Calorimeter:

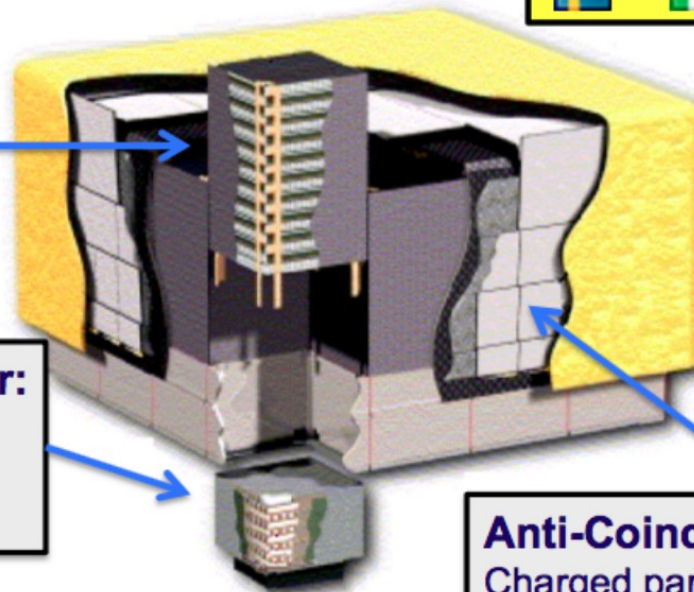
measure  $\gamma$  energy  
image EM shower  
EM v. hadron separation

### Sky Survey:

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

### Trigger and Filter:

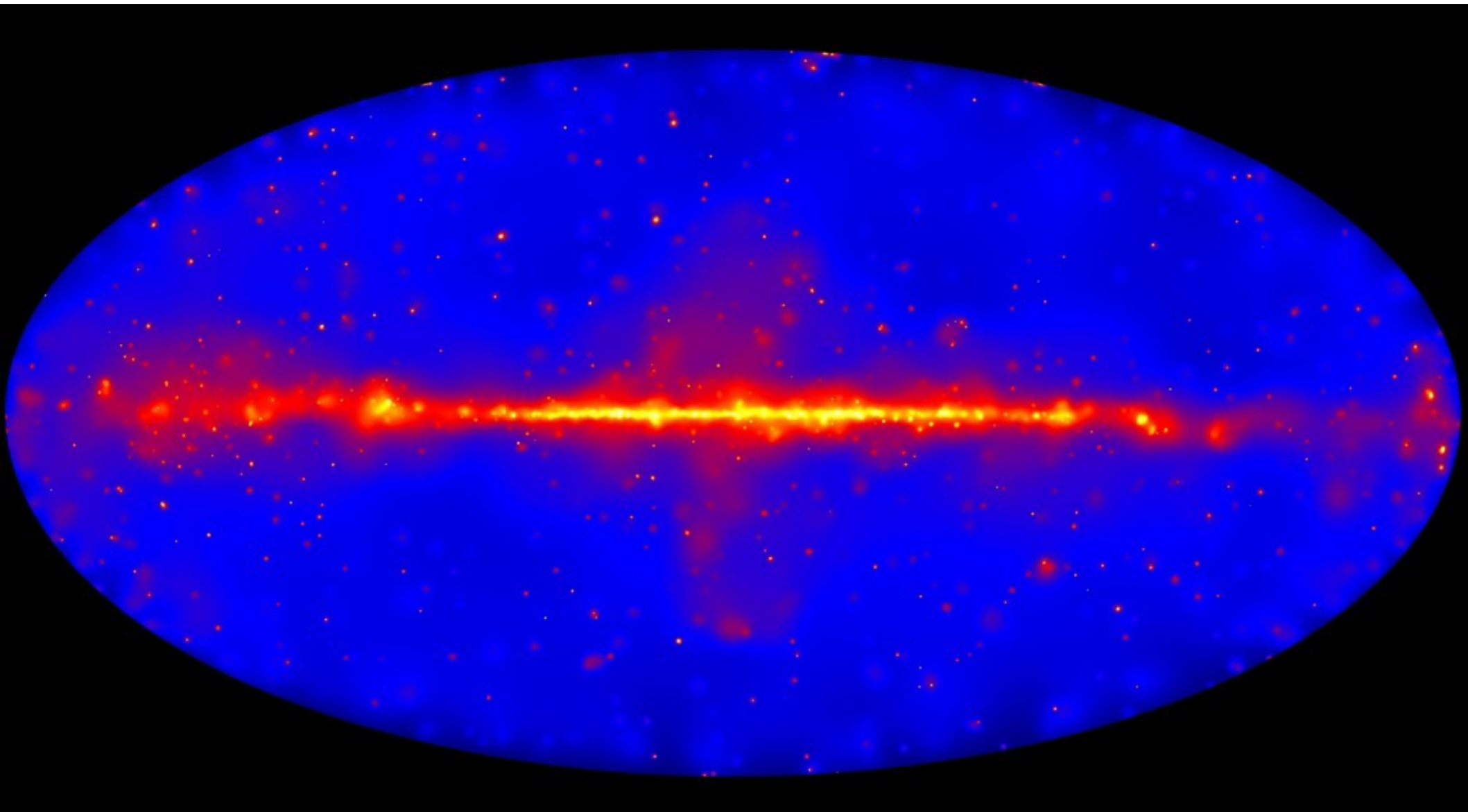
Reduce data rate from ~10kHz  
to 300-500 Hz



### Anti-Coincidence Detector:

Charged particle separation



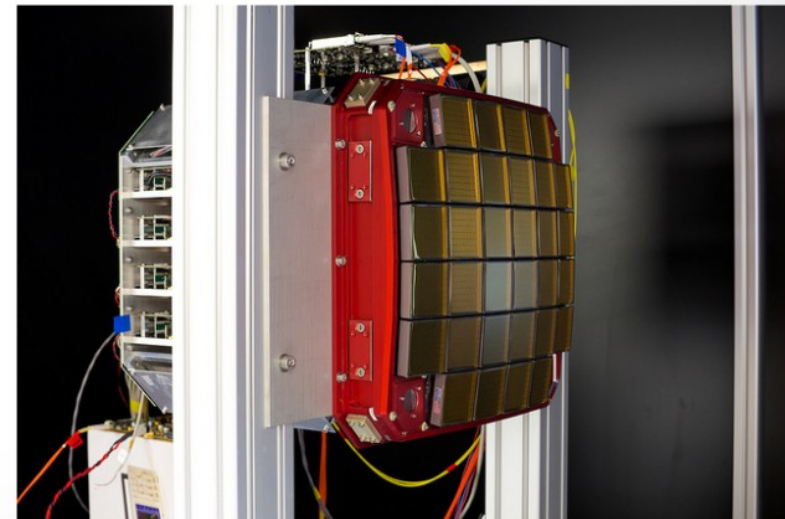
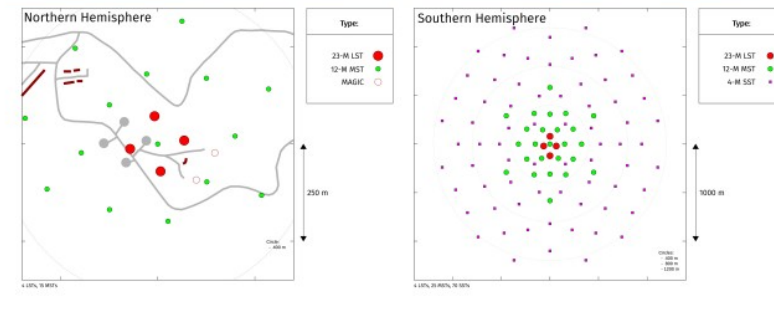
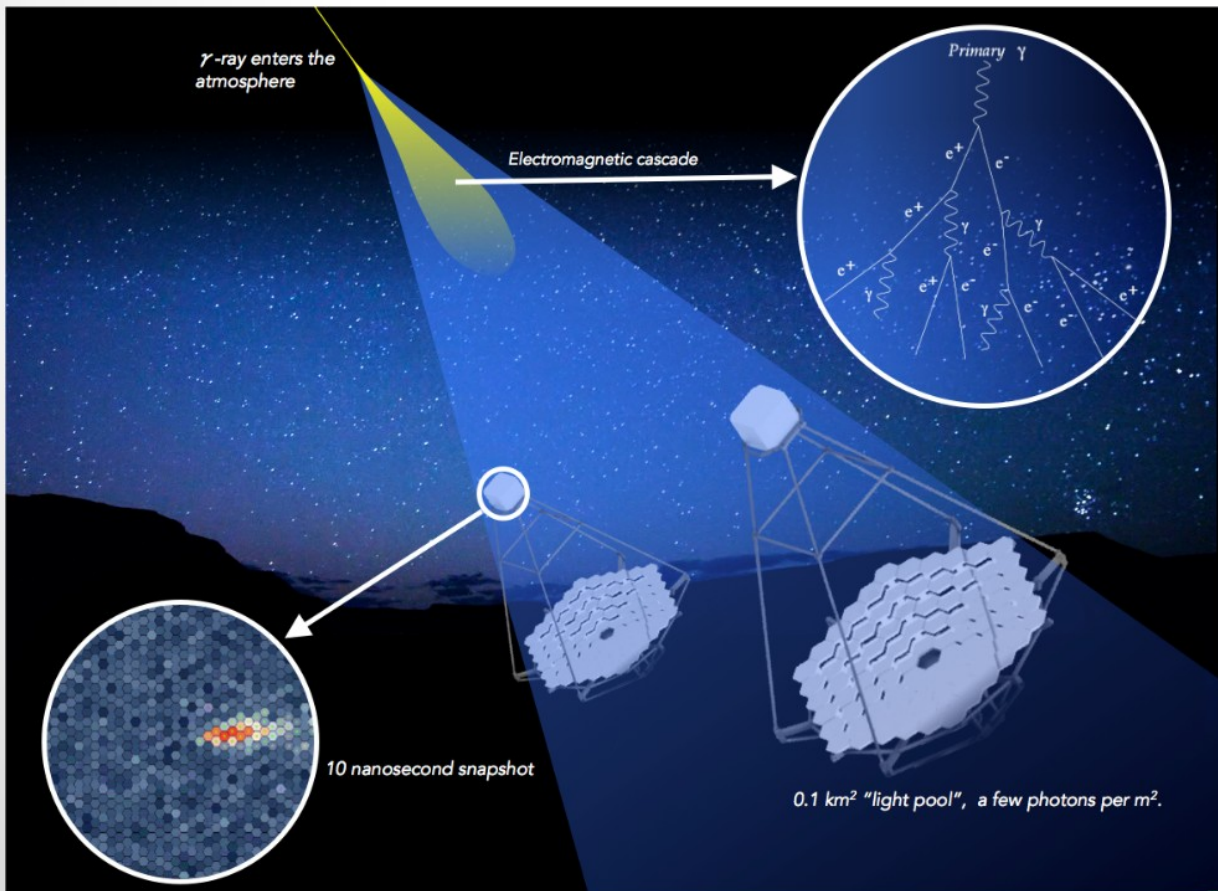
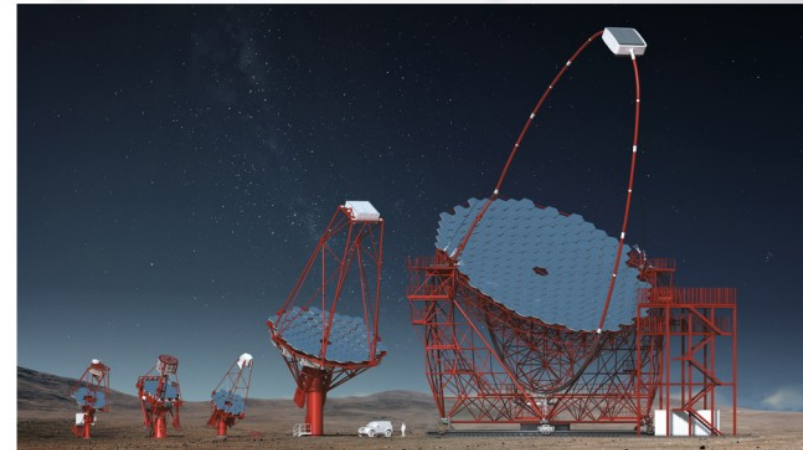


- Fermi-LAT Full Sky
- 20 MeV - 300 GeV
- Angular Resolution  $< 3.5^\circ$  (100 MeV),  $< 0.15^\circ$  ( $>10$  GeV)

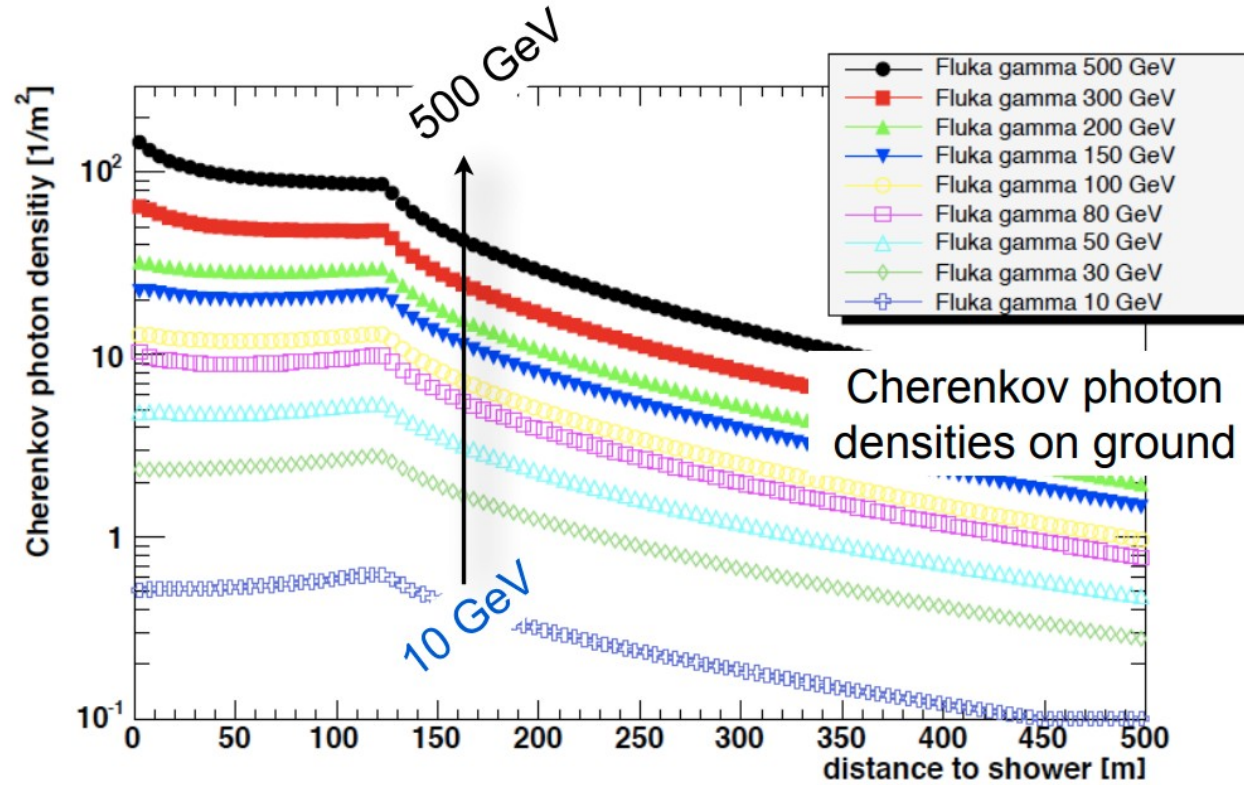
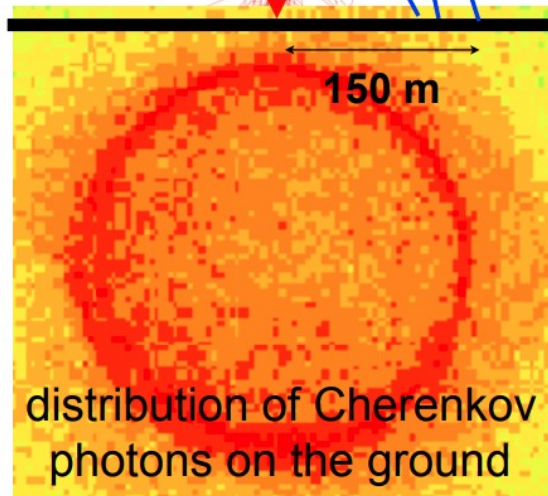
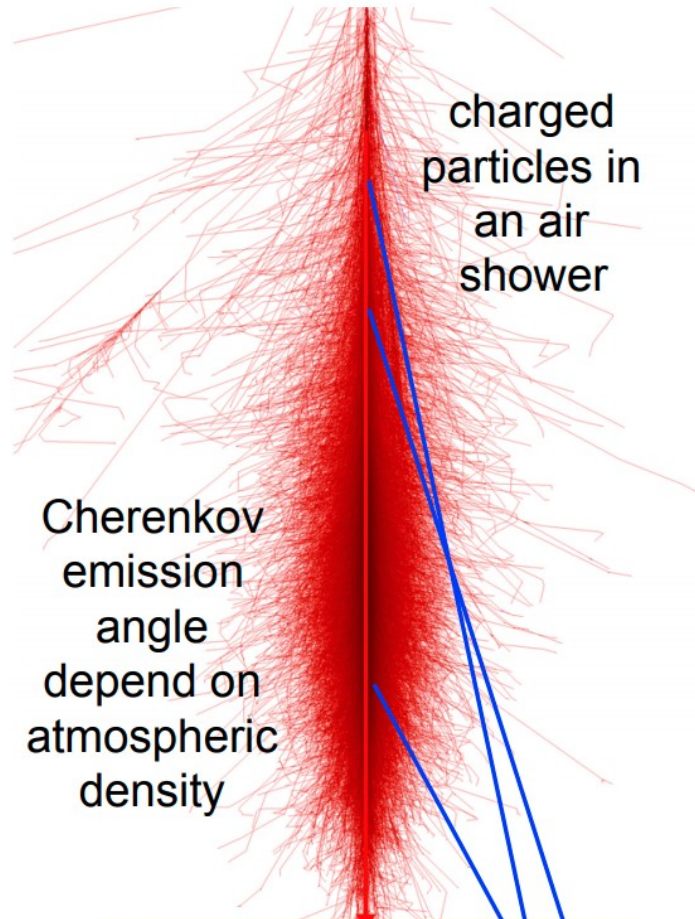
# Cherenkov Telescope Array

<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 (100 GeV – 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 and Angular resolution from 2 to 10 arcmin (68% region half width)



# Cherenkov Telescope Array



Cherenkov light from air showers:  
weak ( $\sim 10$  ph/ $m^2$ ), short ( $\sim$ 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  $0.2 \div 20$  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<sub>3</sub> or CeBr<sub>3</sub> (rise – decay: 0.5 – 20 ns)

Photo-detector: Silicon Photo Multiplier (SiPM) or Silicon Drift Detector (SDD)

Effective area:  $10 \times 10$  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):  $0.09 \div 8.7 / 0.06 \div 6.1$   $\mu$ sec for Average GRBs

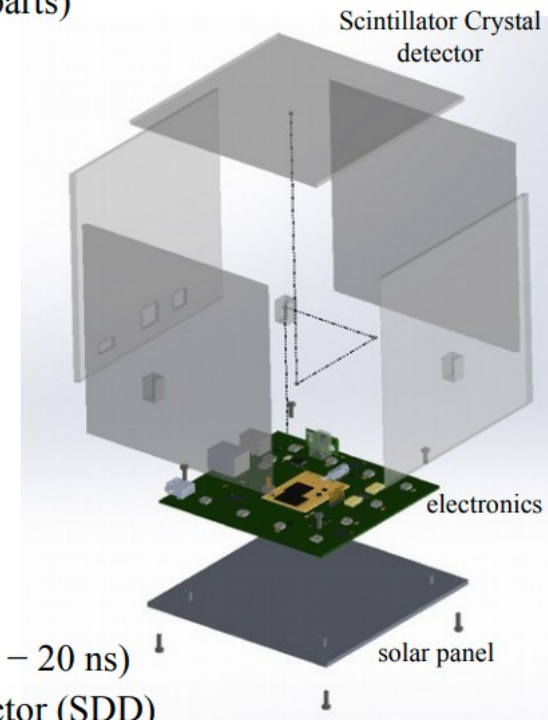
Continuous recording of buffered data

Triggered to ground telemetry transmission

IRIDIUM constellation for transmission of TOA of GRB (position after few minutes)

**Range of accuracy in positioning of GRB:  $0.80 \div 78 / 0.53 \div 54$  arcsec**

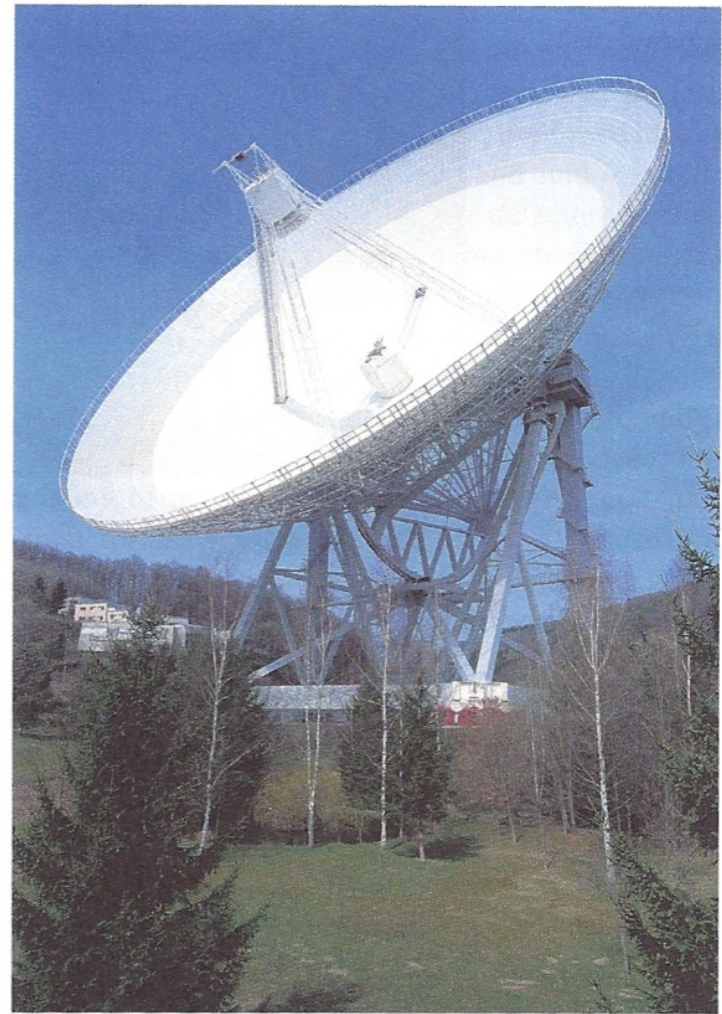
Modular structure: overall effective area  $1 \text{ m}^2$  every 100 modules



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  $\lambda/D$
  - $D=50\text{m}$ , resolution=4 arcsec at 1mm,  $>1^\circ$  at 1m
- Turbulence in atmosphere less of a problem than in optical
  - Atmosphere becomes serious background at mm wavelengths

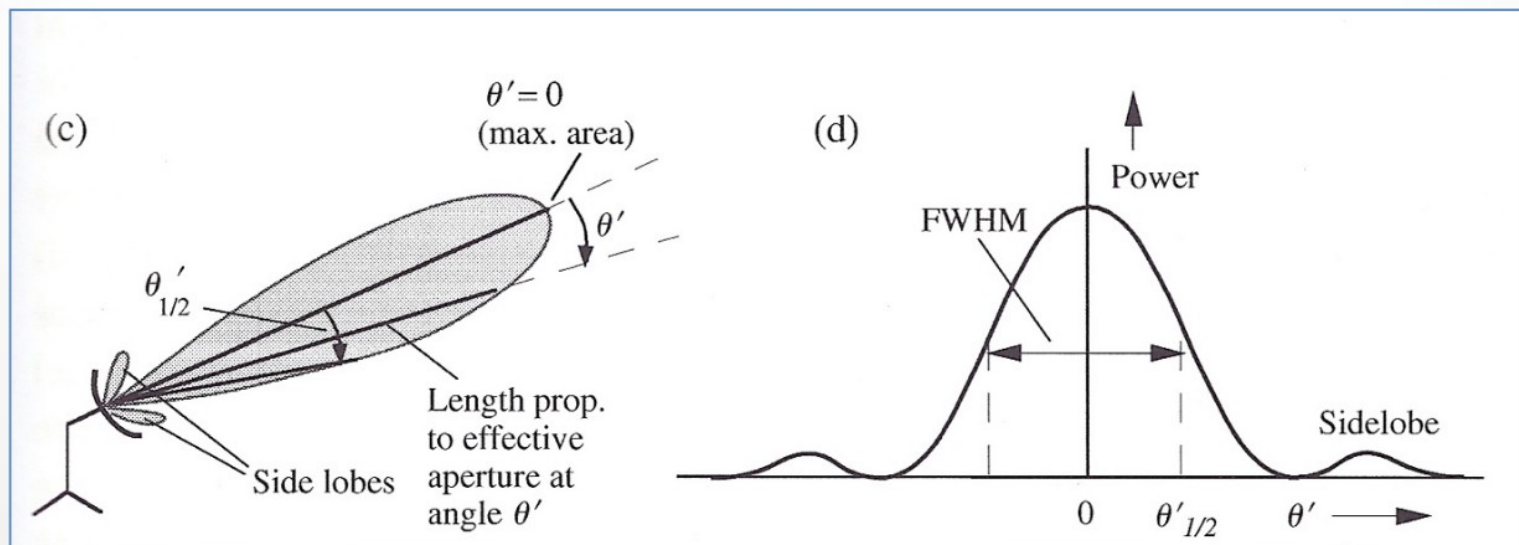


Located near Bonn

# Primary Beam and PSF

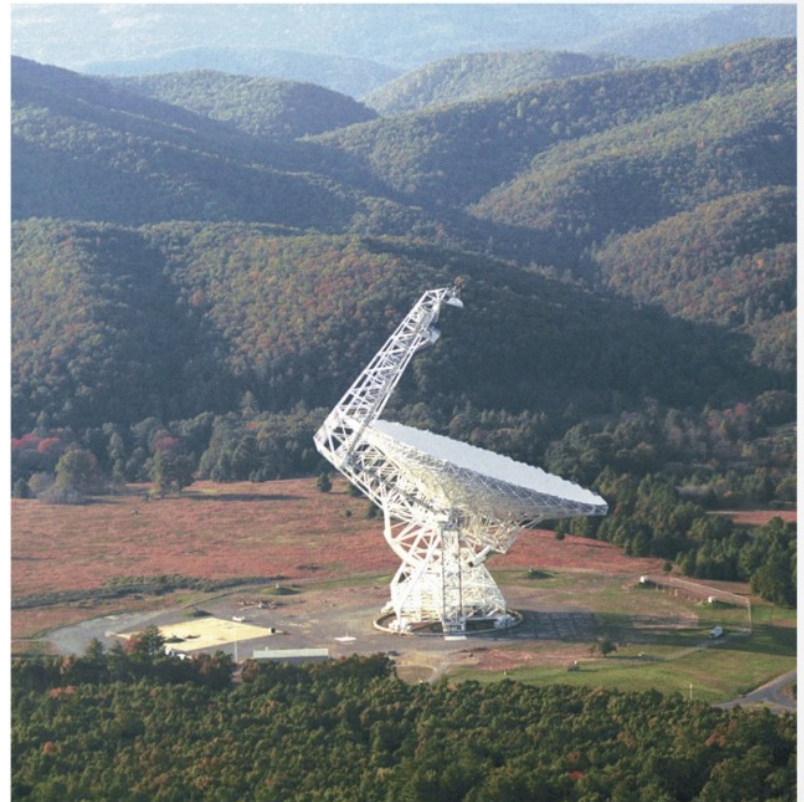
- Peak sensitivity is in direction telescope points, and it falls off with off axis angle
- Exact shape of the primary beam depends on the structure of the antenna as seen by the incoming radiation
- This primary beam defines the point response function or PSF in the limit of diffraction limited imaging

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



# 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





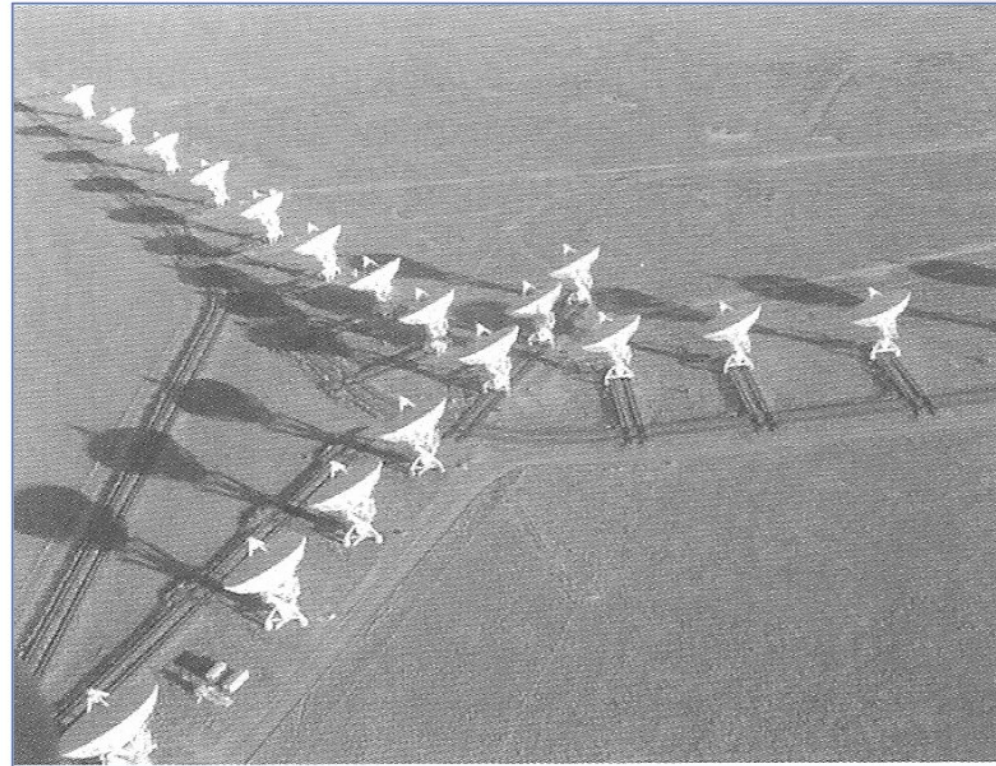
# Arecibo

- 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



# 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

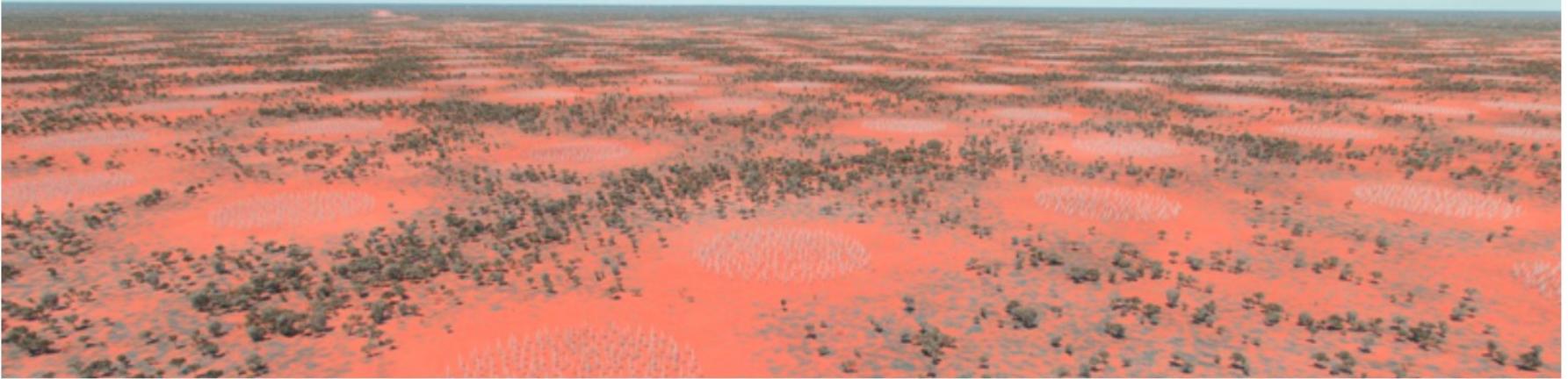
- High angular resolution possible by combining information from telescopes spread around the world
  - IF frequency is recorded locally with atomic clock reading
  - Signals are combined in correlator after the fact
  - Limitation is random phase noise due to the atmosphere
- Worldwide network available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



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



**AUSTRALIA**



**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**



**SOUTH AFRICA**

# SKA– Key Science Drivers: The history of the Universe

Testing General Relativity  
(Strong Regime, Gravitational Waves)

Cosmic Dawn  
(First Stars and Galaxies)

Cradle of Life  
(Planets, Molecules, SETI)

Galaxy Evolution  
(Normal Galaxies  $z \sim 2-3$ )

Cosmic Magnetism  
(Origin, Evolution)

Cosmology  
(Dark Matter, Large Scale Structure)

Exploration of the Unknown

**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 **MeerKAT**  
(0.22" @ 1.7 GHz; 34 mas @ 15 GHz)  
Karoo, South Africa



# ALMA

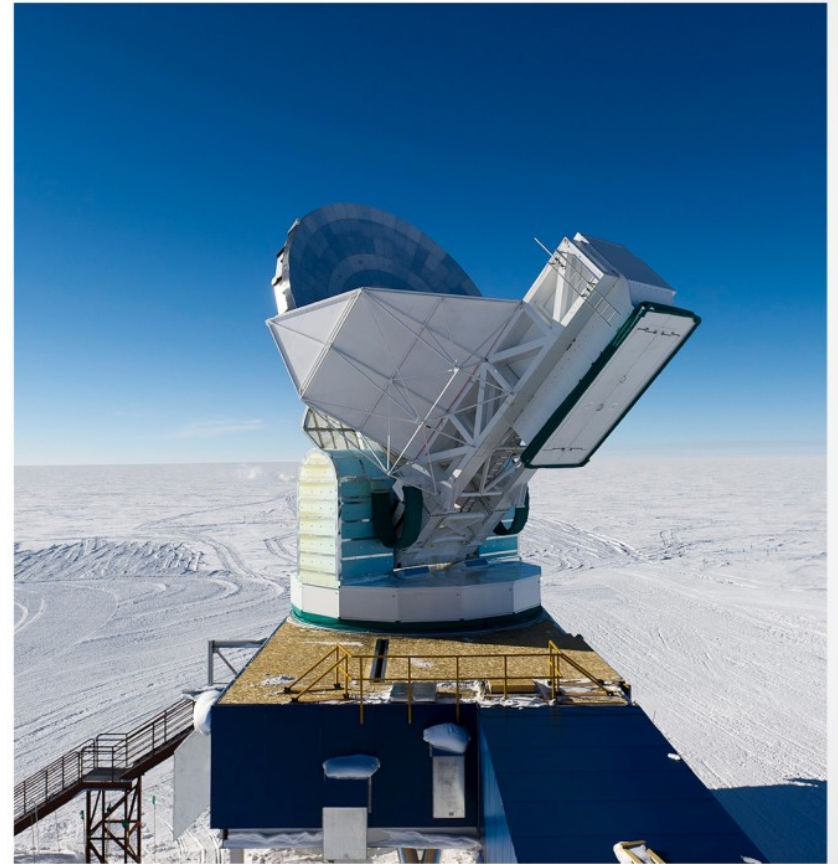
- Chajnantor Plateau, Chile (5100m)
  - Dry, stable atmosphere
  - Fifty 12m dishes spread over 10km mountainous plane
  - Frequency coverage up to 950GHz
- Has been in operation over past couple of years
  - Great location = challenging location





# 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



# Planck

Planck Space mission operated from L2

1.5m primary telescope

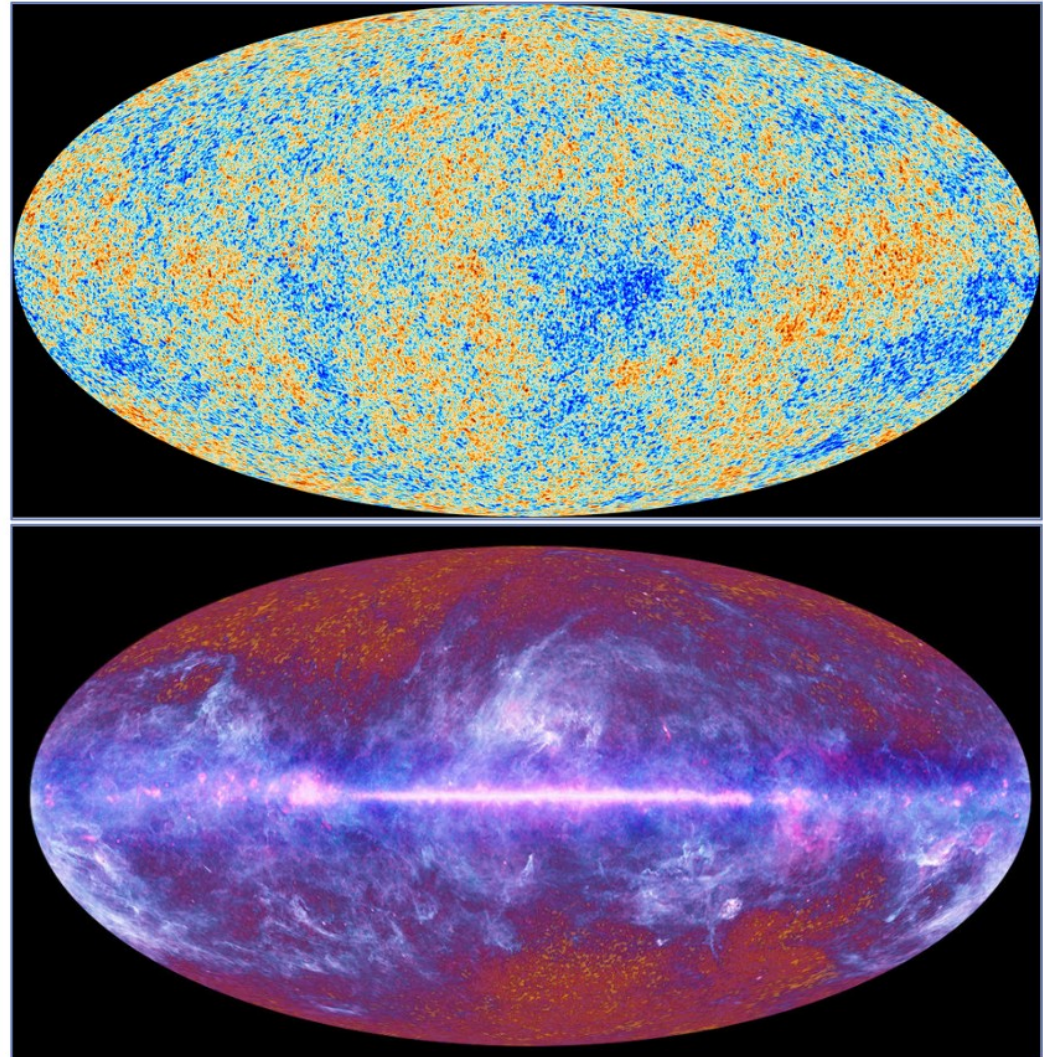
Two detectors:

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.



# 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

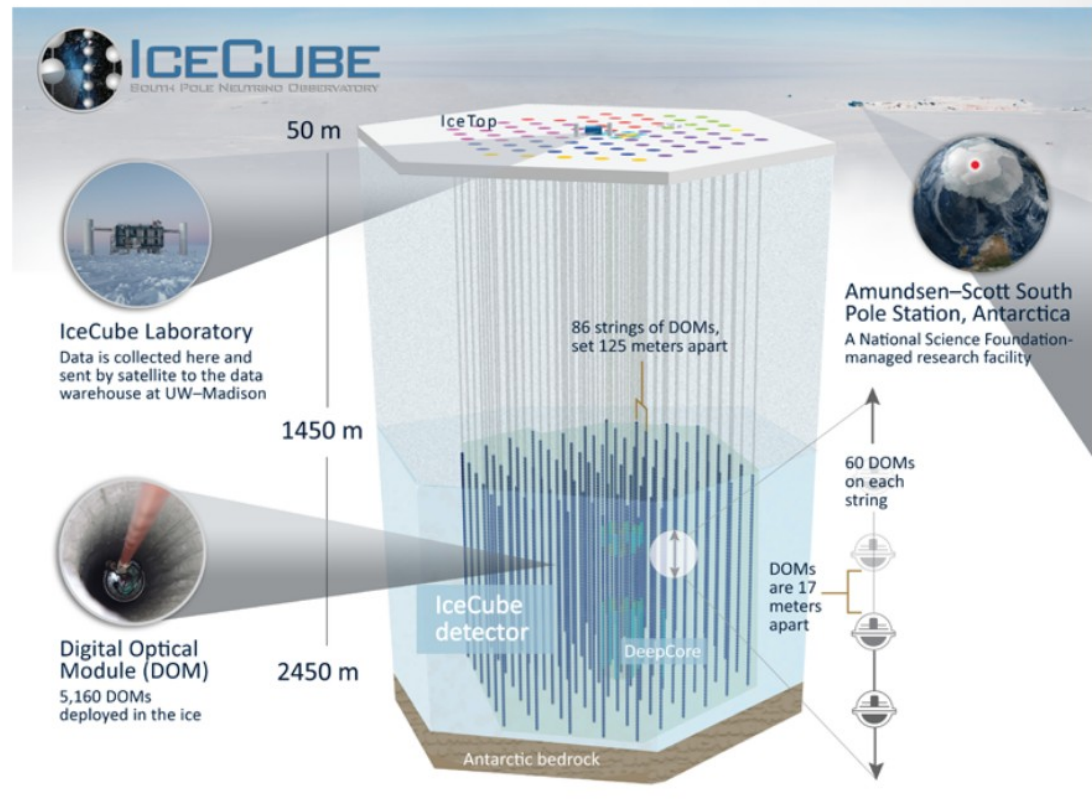
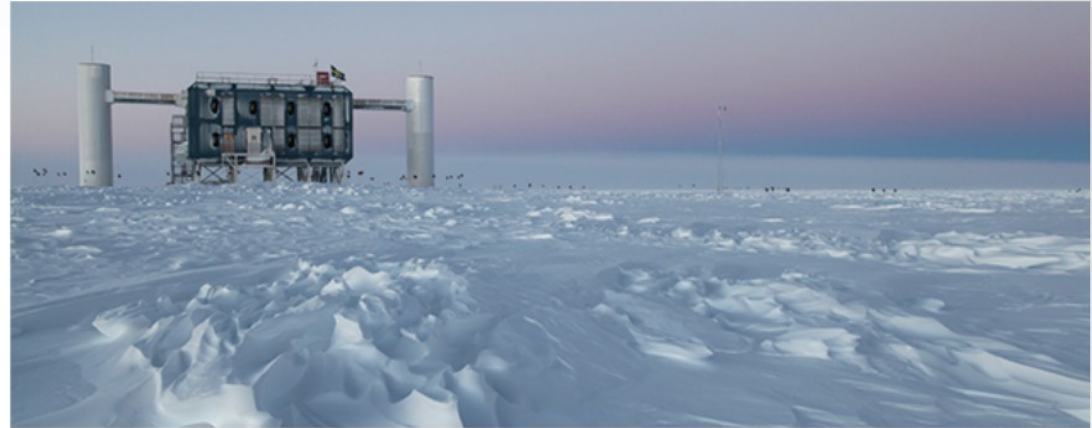
<http://icecube.wisc.edu>

- Detector characteristics:

- 1km<sup>3</sup> 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  $E_\nu$  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<sup>-3</sup>



# IceCube

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## • Detector characteristics:

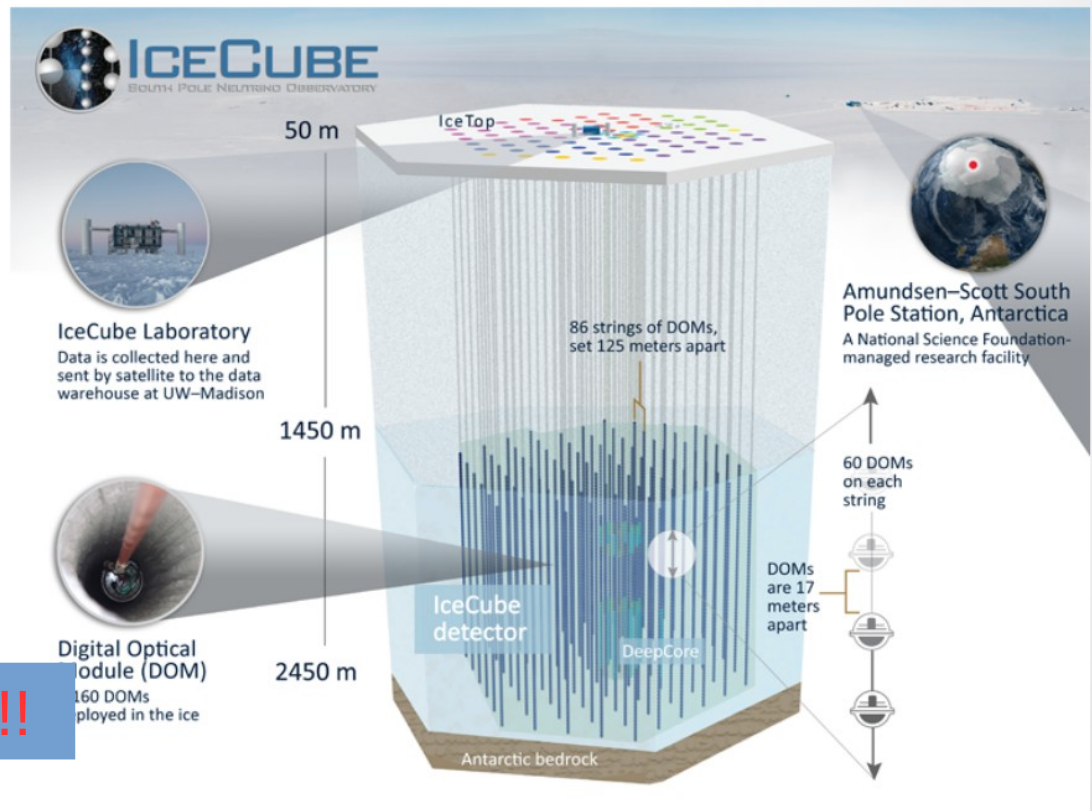
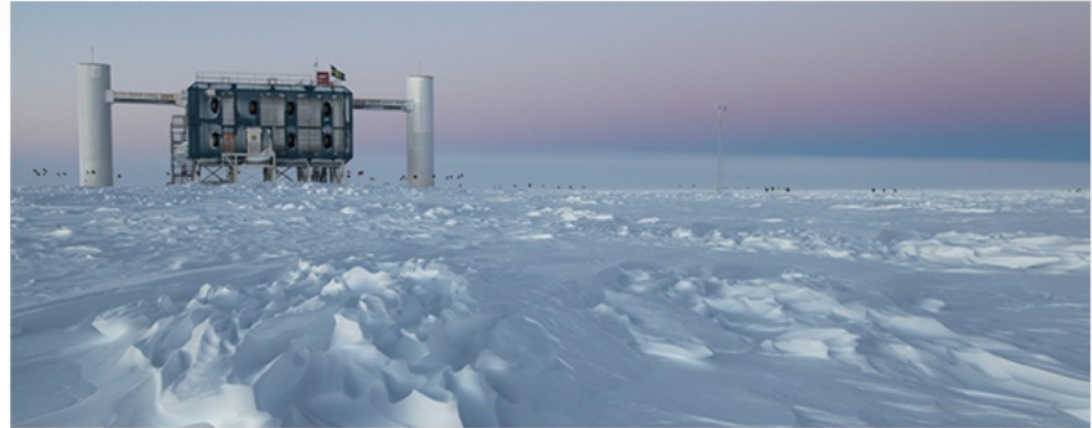
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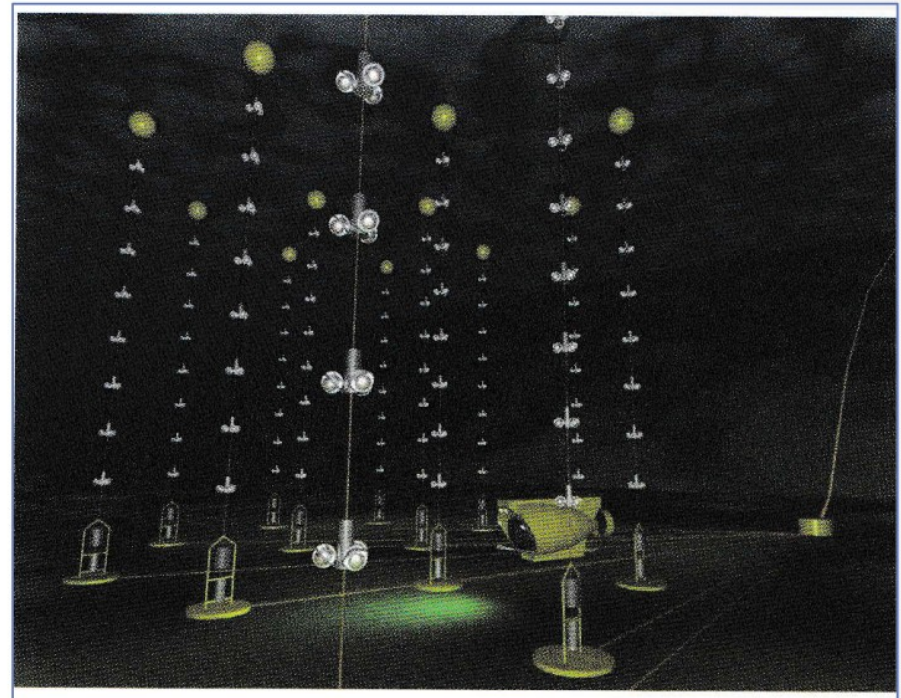
**2017 → blazar TXS 0506 +056!!**

- Measured the cosmic ray anisotropy over the southern sky, detecting it at levels of 10<sup>-3</sup>



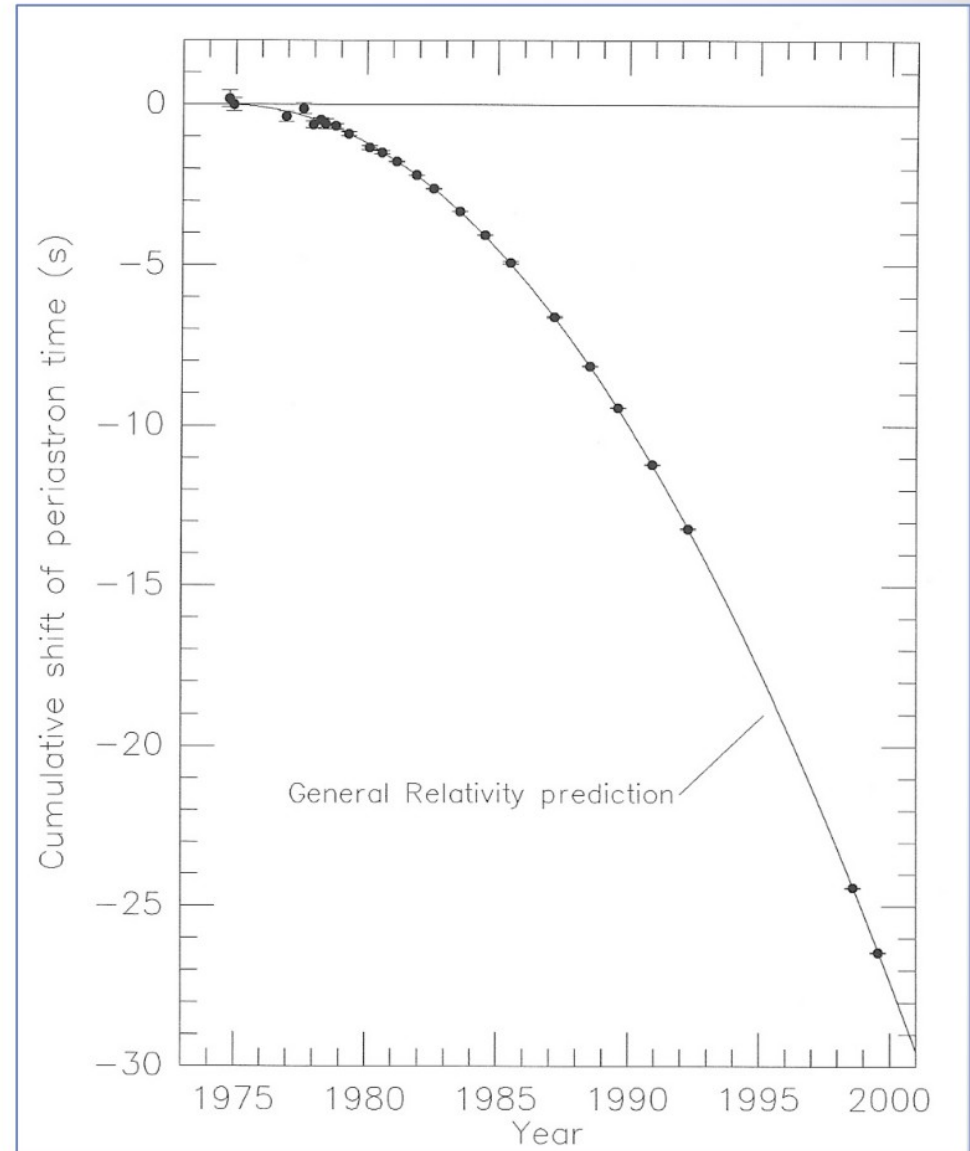
# ANTARES++

- 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 string
  - 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  $\sim 1.4M_{\odot}$ , 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  $2 \times 10^5$  yrs, corresponding to a  $5.1\sigma$  significant detection
- Binary BH merger (36 and 24  $M_{\odot}$ ) at distance of  $\sim 400$  Mpc ( $z=0.09 \pm 0.03$ )
- Final mass  $\sim 62 M_{\odot}$  with  $\sim 3 M_{\odot}$  of rest mass energy radiated as gravitational wave

