Imaging Detectors for Astronomy & Astrophysics

Quantum-Limited Imaging Detectors Workshop
Rochester Institute of Technology
March 2, 2009

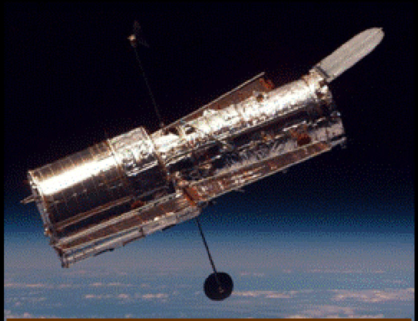
James W. Beletic

TELEDYNE
IMAGING SENSORS
A Teledyne Technologies Company

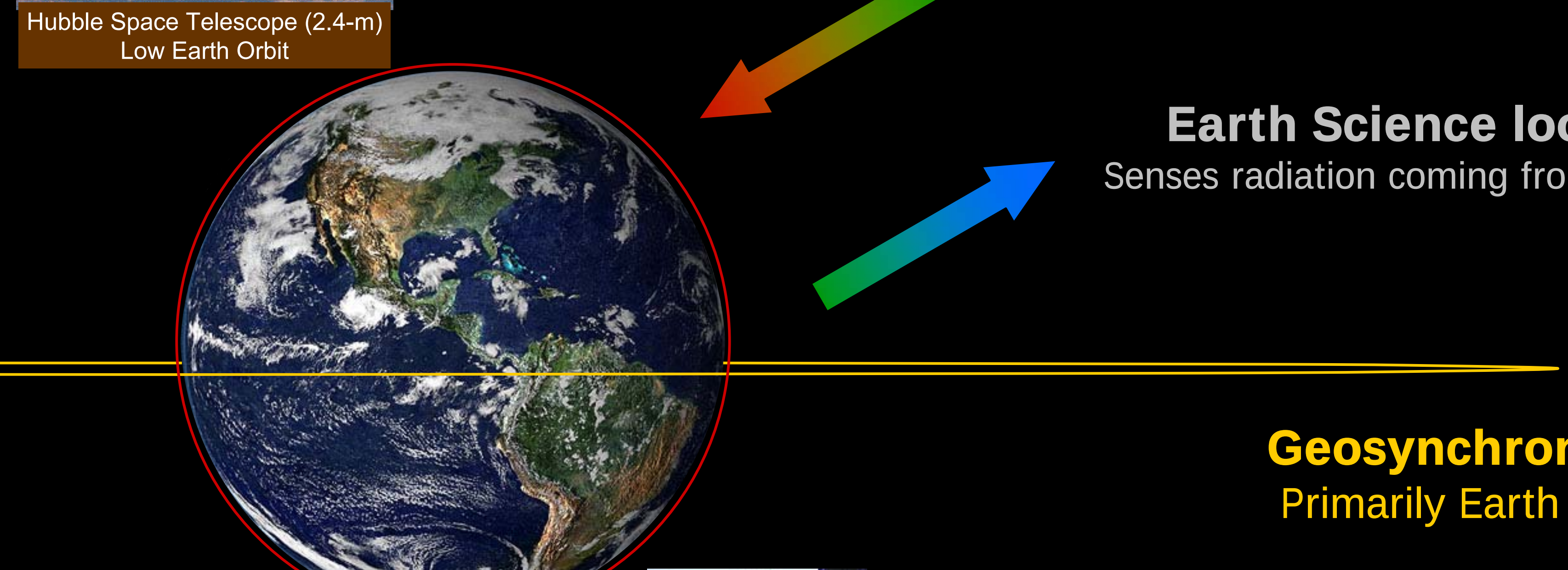
Teledyne

Providing the best images
of the Universe

Domains of Astronomy & Earth Science



Hubble Space Telescope (2.4-m)
Low Earth Orbit



Astronomy looks out
Senses radiation coming in from the universe

Earth Science looks in
Senses radiation coming from the Earth

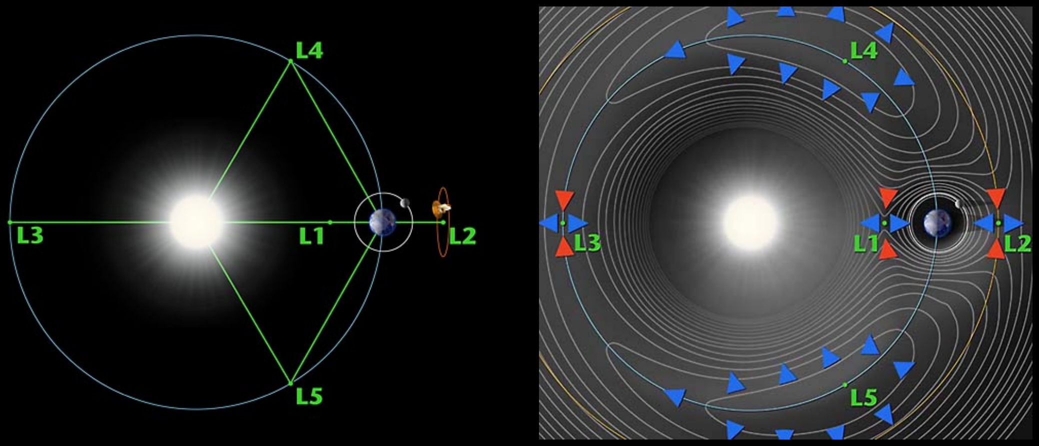
Geosynchronous Orbit
Primarily Earth observation

Low Earth Orbit
Astronomy & Earth Science

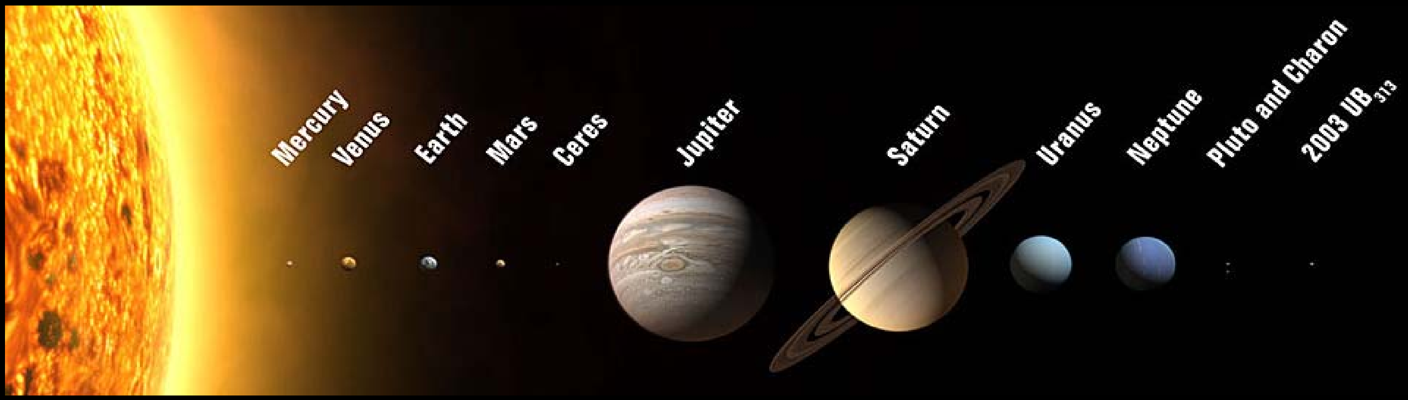
ESO VLT 8.2-m telescope
Ground-based (Chile)

Astronomy & Astrophysics – Vantage Points

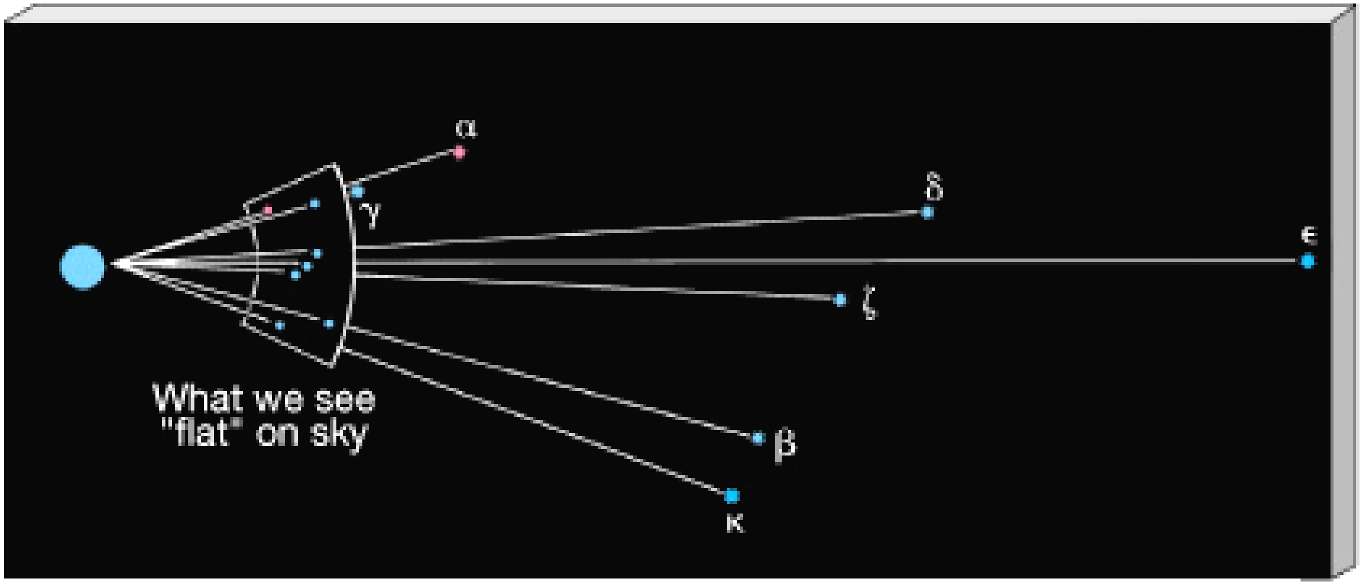
- **Ground-based**
  - Nighttime
  - Daytime (solar astronomy)
- **Low Earth Orbit (LEO)**
  - Hubble Space Telescope (HST)
  - NASA Small Explorer missions
- **Lagrange Point 1**
  - Solar and Heliospheric Observatory (SOHO)
- **Lagrange Point 2**
  - Wilkinson Microwave Anisotropy Probe (WMAP)
  - James Webb Space Telescope (JWST)
  - Joint Dark Energy Mission (JDEM)
- **Planetary missions**



Lagrange Points of the Earth-Sun system
(not drawn to scale!)



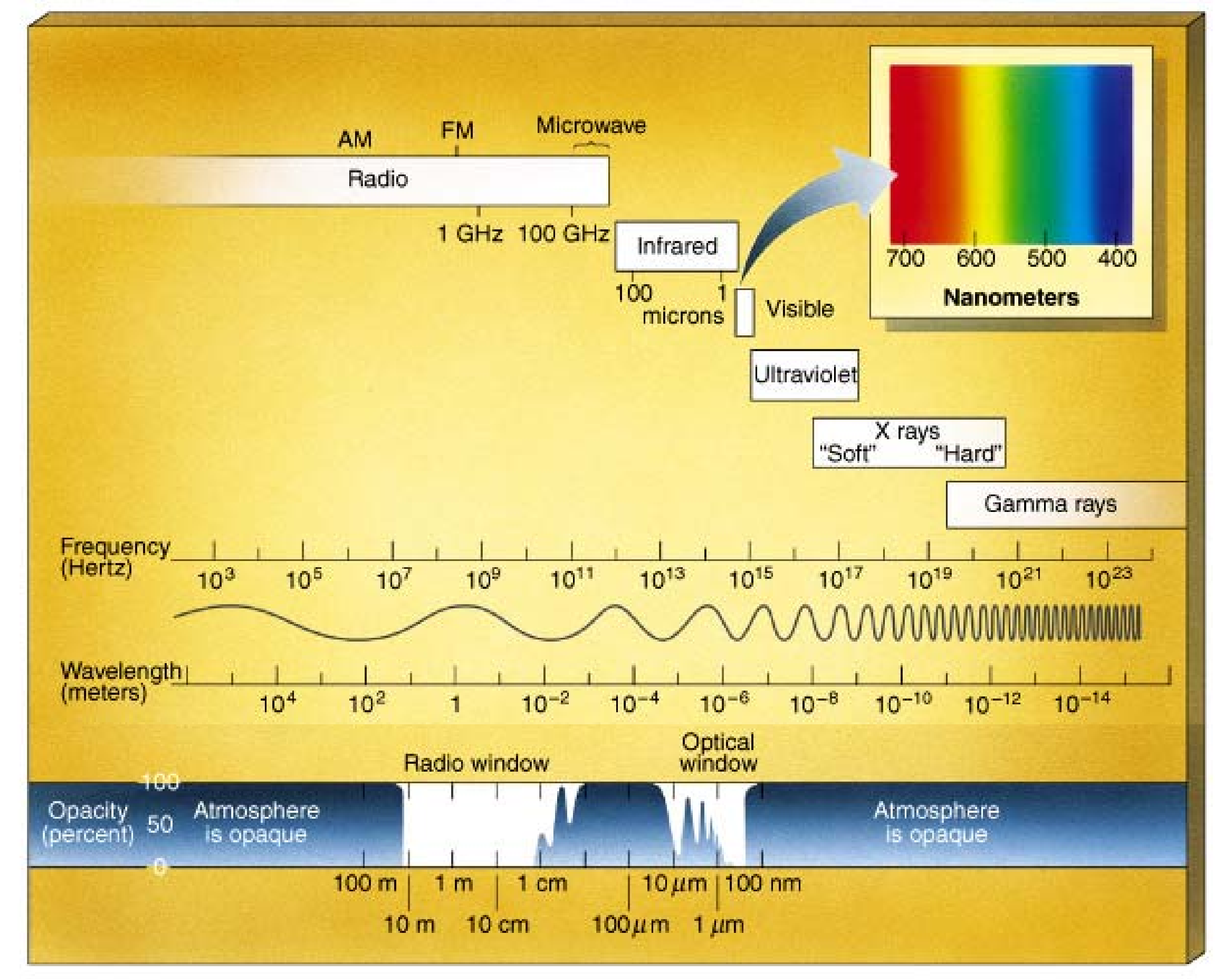
Constellation of Orion



← 1,000 light years →

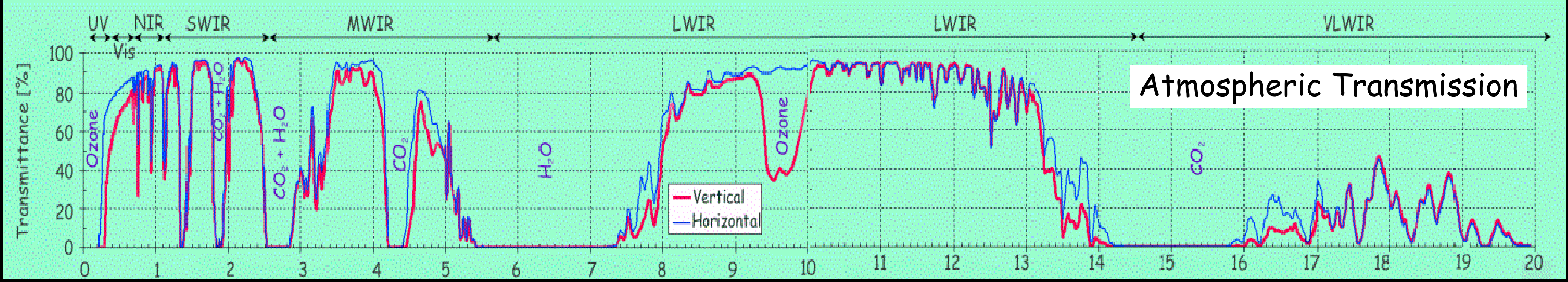
A flight through the local universe

The Electromagnetic Spectrum



Atmospheric transmission

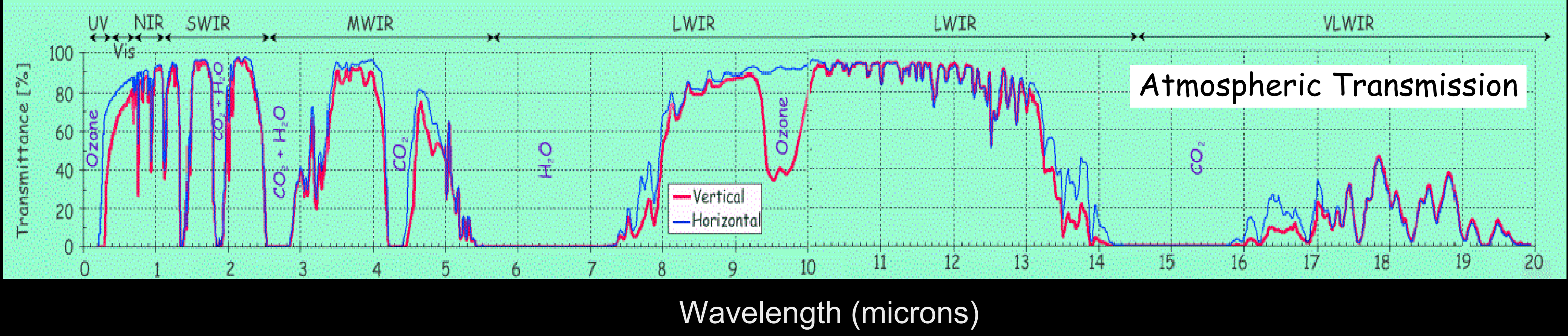
Not all of the light gets through atmosphere to ground-based telescopes



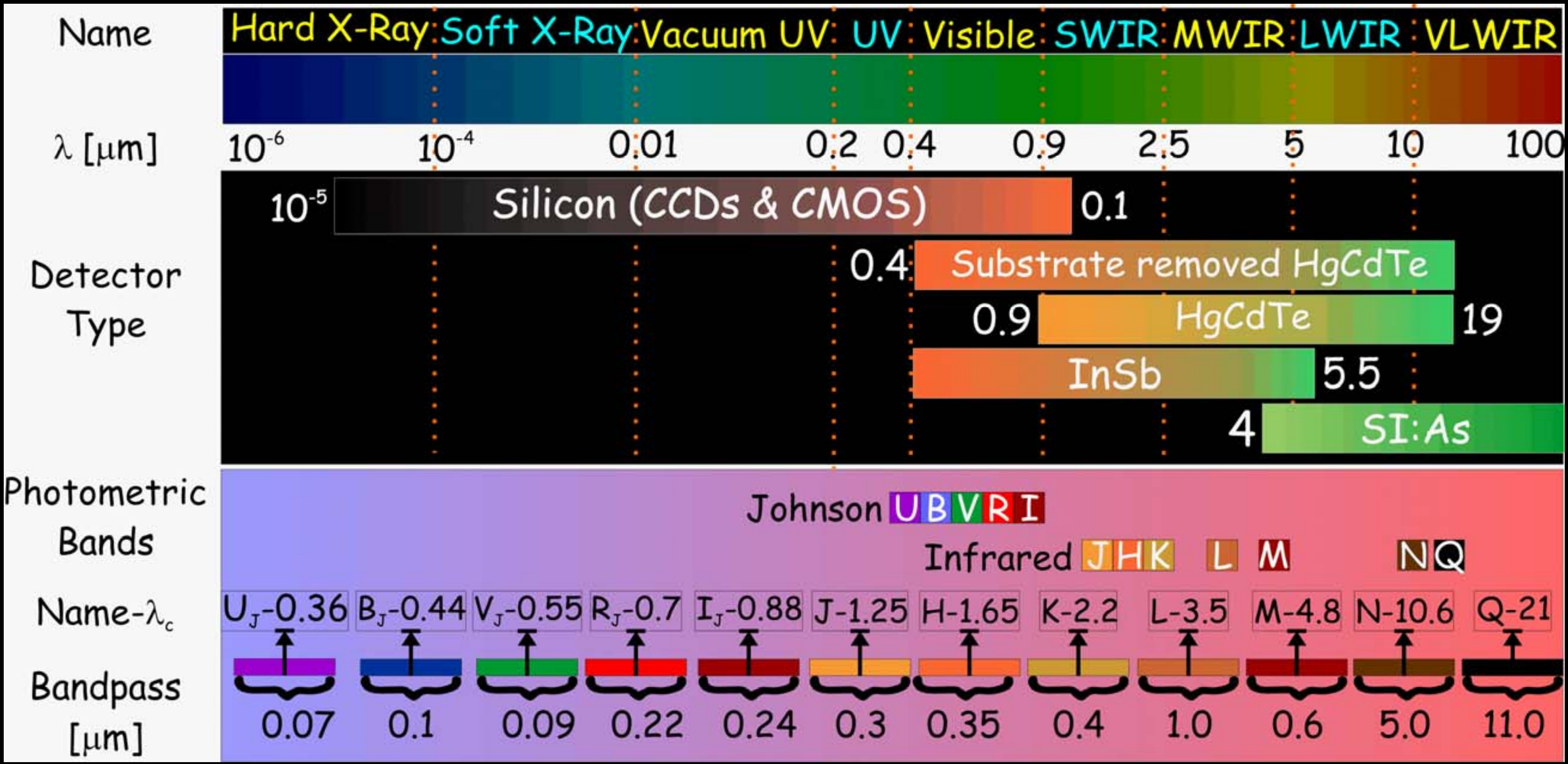
Wavelength (microns)

Spectral Bands

Defined by atmospheric transmission & detector material properties



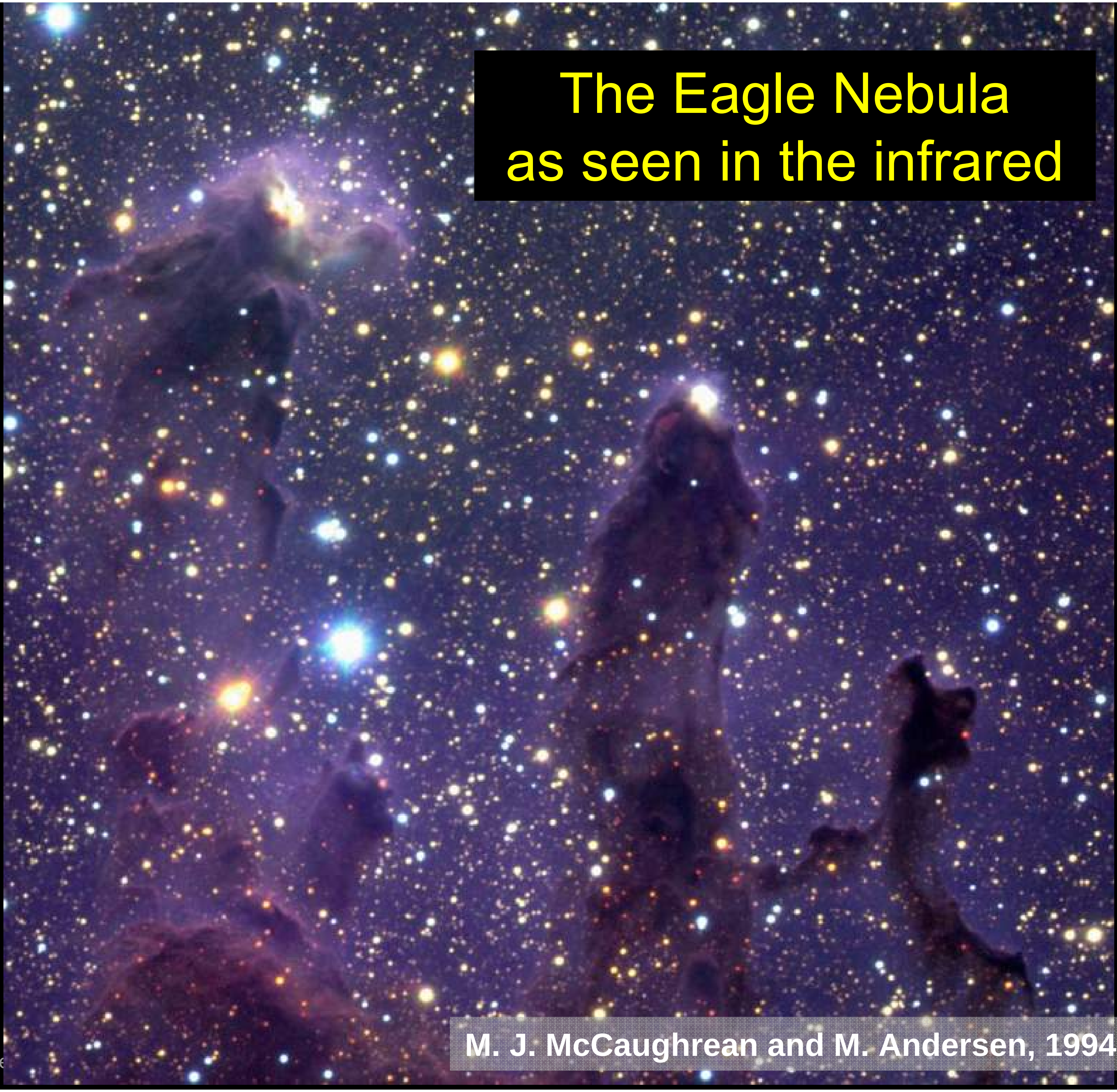
Detector Zoology



Name-λ_c	U_J-0.36	B_J-0.44	V_J-0.55	R_J-0.7	I_J-0.88	J-1.25	H-1.65	K-2.2	L-3.5	M-4.8	N-10.6	Q-21
Bandpass [μm]	0.07	0.1	0.09	0.22	0.24	0.3	0.35	0.4	1.0	0.6	5.0	11.0

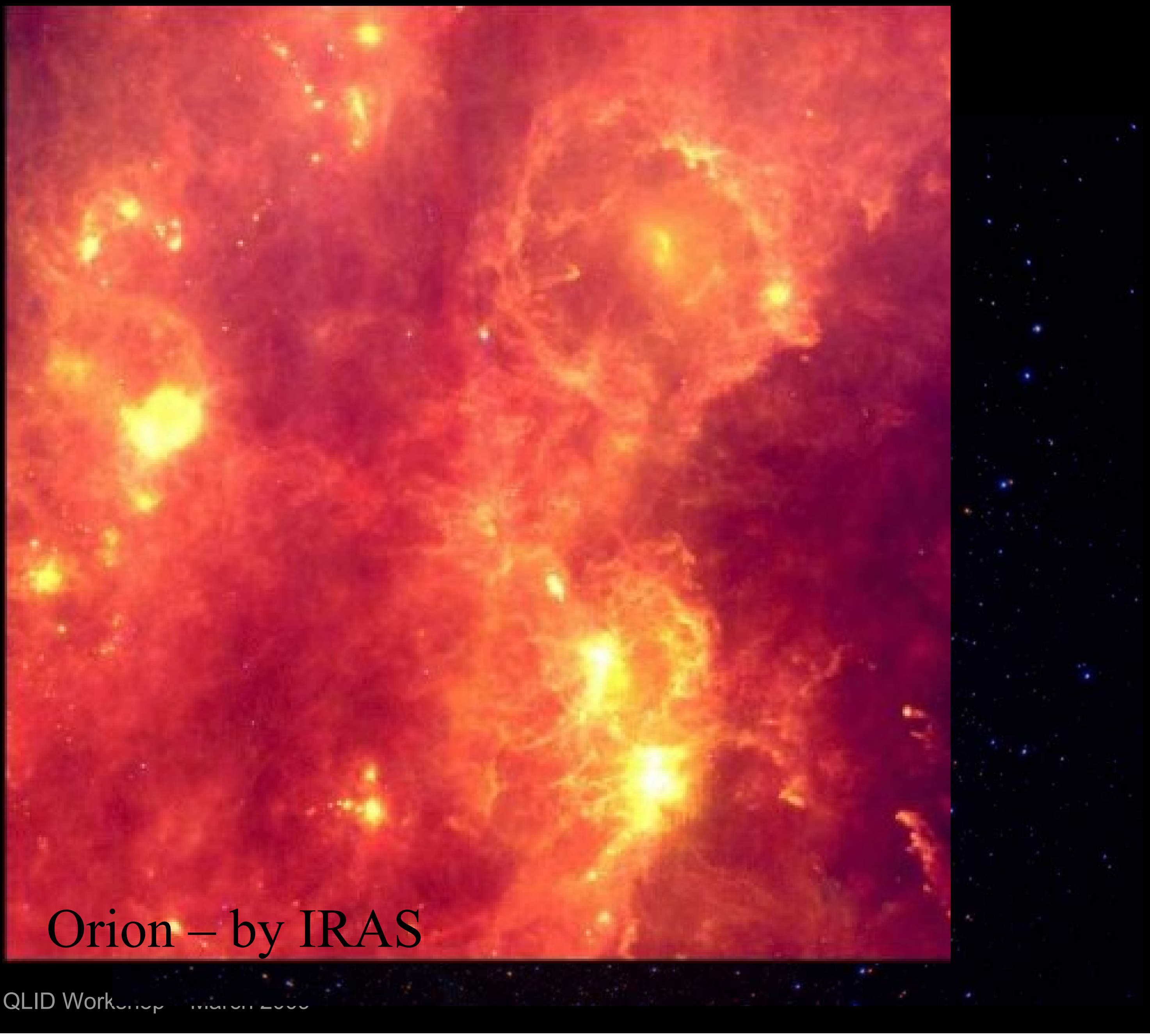
The Eagle Nebula as seen with Hubble

The Eagle Nebula
as seen in the infrared



M. J. McCaughrean and M. Andersen, 1994

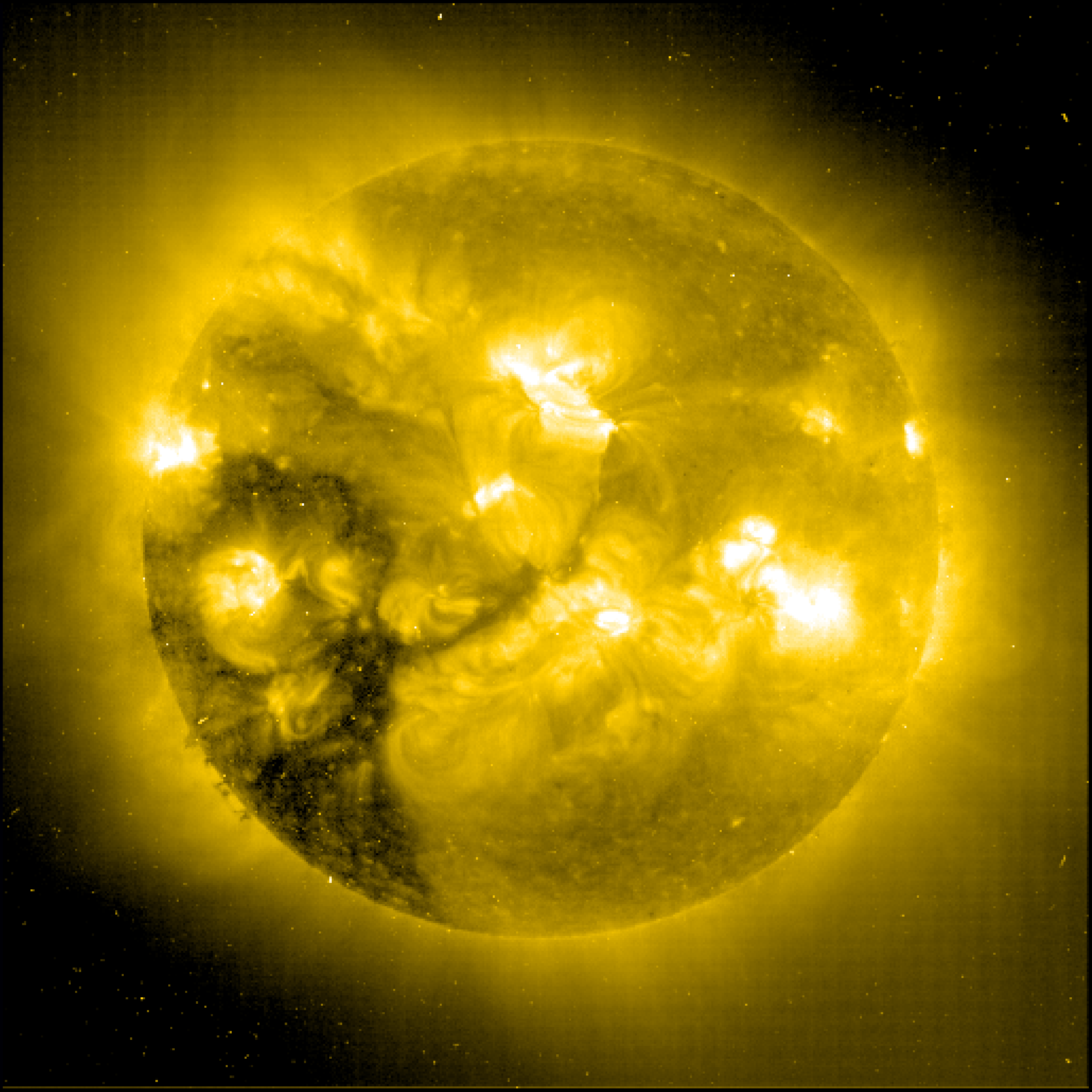
Orion – In visible and infrared light



Orion – by IRAS

Our Sun

Far UV (28 nm)



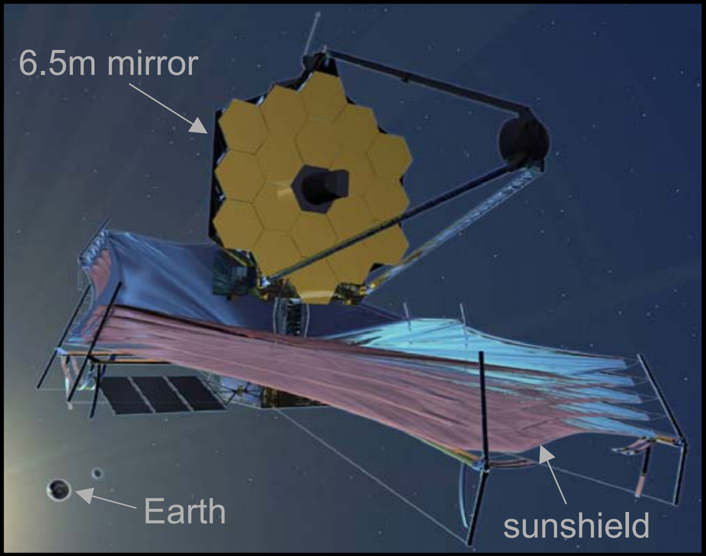
Energy of a photon

Wavelength (μm)	**Energy (eV)**	**Band**
0.3	4.13	UV
0.5	2.48	Vis
0.7	1.77	Vis
1.0	1.24	NIR
2.5	0.50	SWIR
5.0	0.25	MWIR
10.0	0.12	LWIR
20.0	0.06	VLWIR

- Energy of photons is measured in electron-volts (eV)
- eV = energy that an electron gets when it “falls” through a 1 volt field.

JWST - James Webb Space Telescope

15 Teledyne 2K×2K infrared arrays on board (~63 million pixels)



- International collaboration
- 6.5 meter primary mirror and tennis court size sunshield
- 2013 launch on Ariane 5 rocket
- L2 orbit (1.5 million km from Earth)

JWST will find the "first light" objects after the Big Bang, and will study how galaxies, stars and planetary systems form

FGS

(Fine Guidance Sensors)

3 individual MWIR 2Kx2K

- **Acquisition and guiding**
- **Images guide stars for telescope stabilization**
- **Canadian Space Agency**

NIRSpec

(Near Infrared Spectrograph)

1x2 mosaic of MWIR 2Kx2K

- **Spectrograph**
- **Measures chemical composition, temperature and velocity**
- **European Space Agency / NASA**

NIRCam

(Near Infrared Camera)

Two 2x2 mosaics of SWIR 2Kx2K

Two individual MWIR 2Kx2K

- **Wide field imager**
- **Studies morphology of objects and structure of the universe**
- **U. Arizona / Lockheed Martin**

An electron-volt (eV) is extremely small

1 eV = $1.6 \cdot 10^{-19}$ J (J = joule)

1 J = N • m = kg • m • sec^{-2} • m

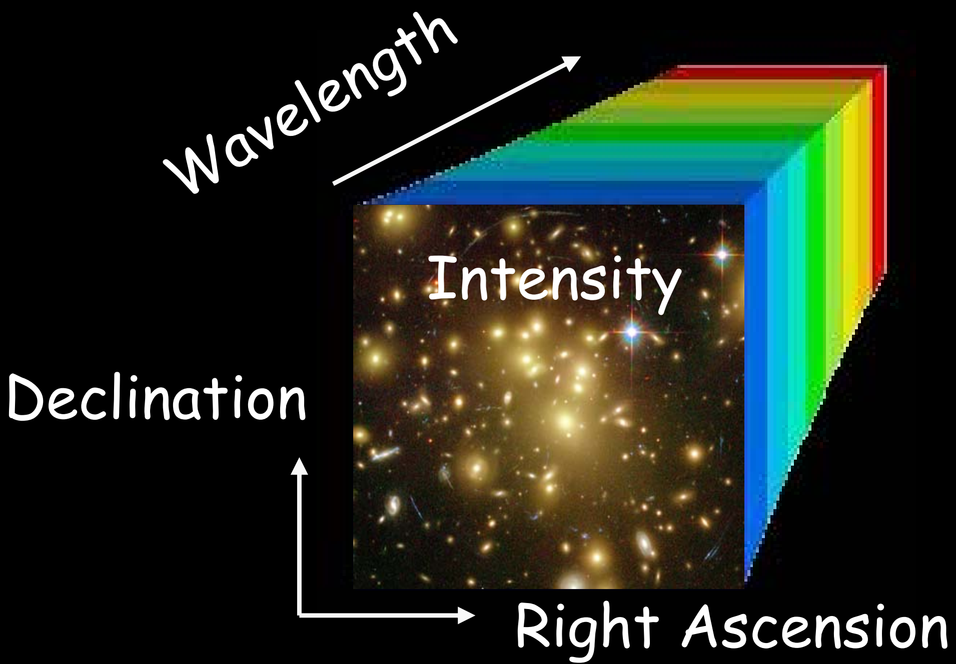
1 kg raised 1 meter = 9.8 J = $6.1 \cdot 10^{19}$ eV

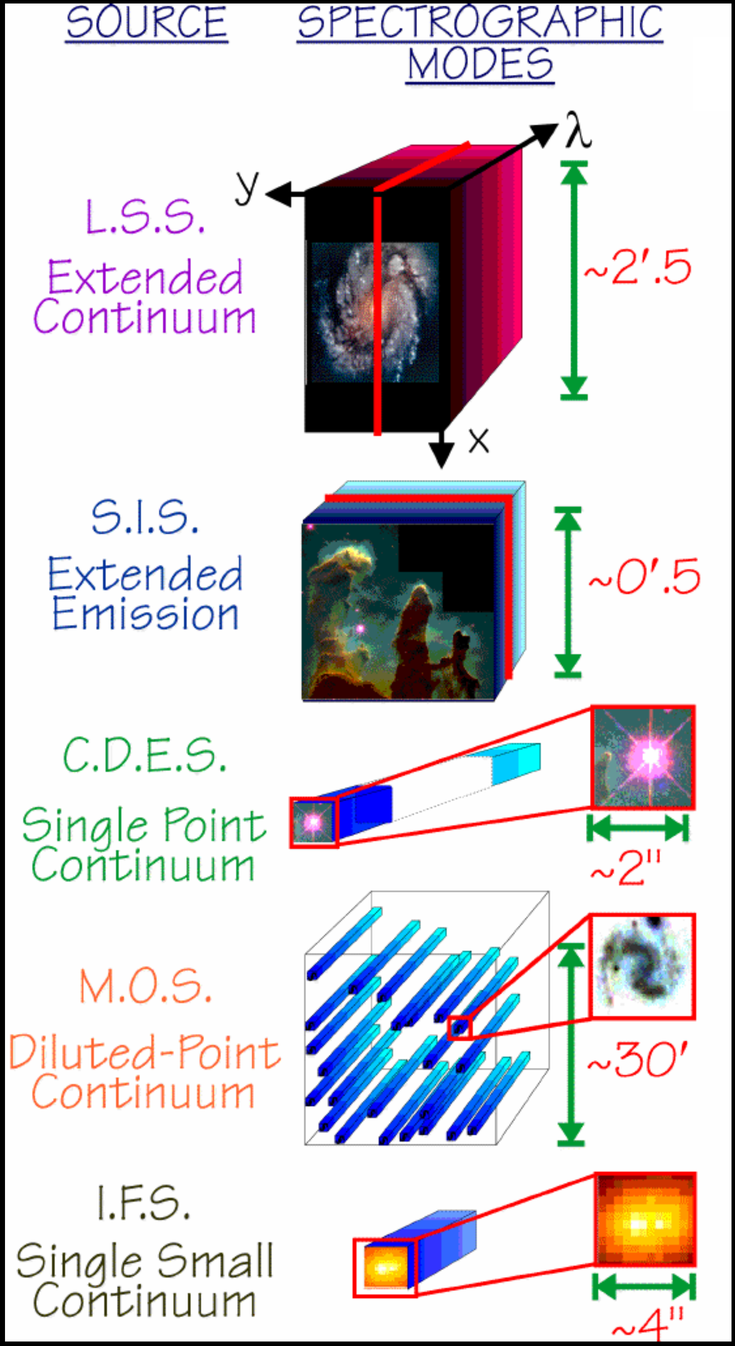
- The energy of a photon is **VERY** small
  - The energy of a SWIR (2.5 μm) photon is 0.5 eV
- Drop a peanut M&M® candy from a height of 2 inches
  - Energy is equal to 6×10^{15} eV (a peanut M&M® is ~2 g)
  - This is equal to 1.2×10^{16} SWIR photons
    - 1 million x 1 million x 12,000
    - The number of photons that will be detected in ~1 million images from the James Webb Space Telescope (JWST)
    - **A 2-inch peanut M&M® drop is more energy than will be detected during the entire 5-10 year lifetime of the JWST !**

The Ideal Imaging Detector

- **Detect 100% of the photons**
- **Each photon detected as a delta function**
- **As many pixels as desired**
- **Time tag for each photon**
- **Measure photon wavelength**
- **Measure photon polarization**

Instrument goal is to measure a 3-D data cube





But detectors are 2-dimensional !

- Detectors are **BLACK & WHITE**
- Can not measure color
- Only measure intensity

Optics of the instrument are used to map a portion of the 3-D data cube onto the 2-D detector

The Ideal Imaging Detector

• Detect 100% of photons	✓ Up to 98% quantum efficiency
• Each photon detected as a delta function	✓ One electron for each photon
• Large number of pixels	✓~1,400 million pixels (>10^9)
• Time tag for each photon	☒ Not for framing detectors
• Measure photon wavelength	☒ No – defined by filter
• Measure photon polarization	☒ No – defined by filter

Plus READOUT NOISE and other “features”

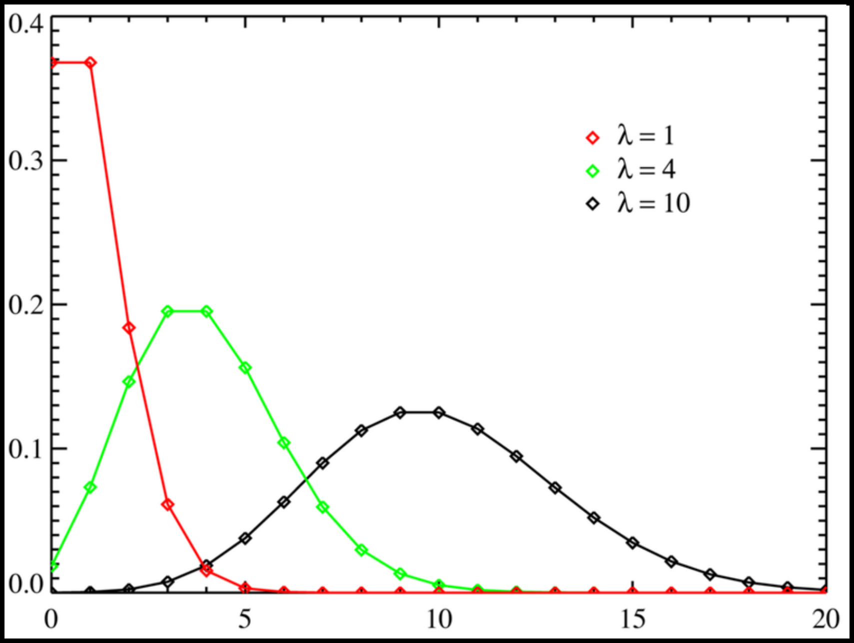
But we can still be quantum-limited in many cases!

Photon Noise Limited Imaging

- An ideal imaging system should be limited only by the Poisson statistics of light detection and the imagination of the user.
- Poisson statistics

$$f(k;\lambda) = \frac{\lambda^k e^{-\lambda}}{k!}$$

  - Variance of signal equals the mean of the signal
  - For mean > 10, Poisson statistics is very similar to Gaussian statistics



Signal-to-Noise Ratio

Ideally, for an imaging system:

$$\mathrm{SNR} = \frac{N_{ph}}{\sqrt{N_{ph}}} = \sqrt{N_{ph}}$$

But we have less than 100% quantum efficiency (QE) and other noise sources:

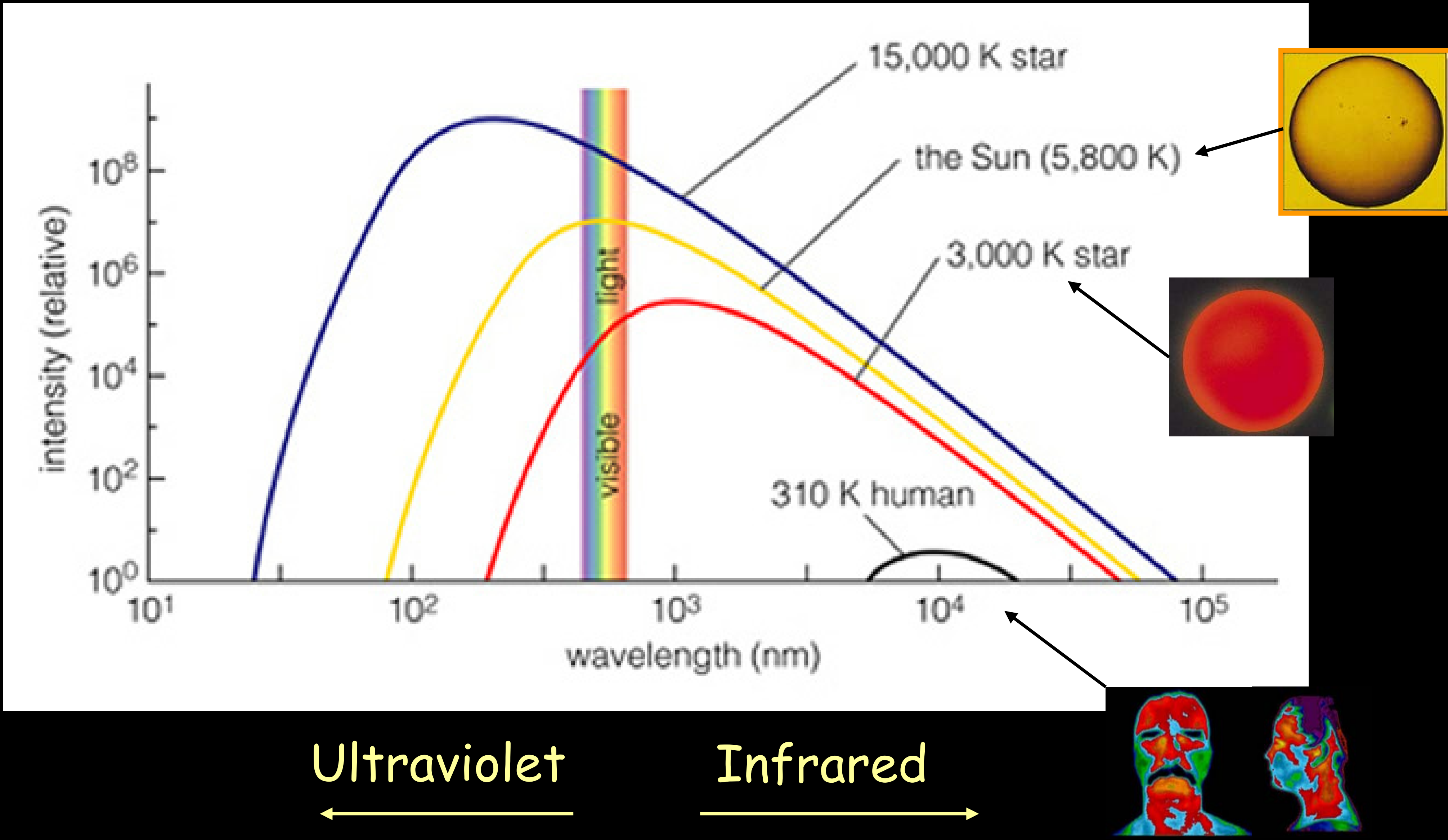
- Background photons, N_b
- Dark current, N_d
- Readout noise, σ_{RN}

$$\mathrm{SNR} = \frac{N_{ph} \cdot QE}{\sqrt{N_{ph} \cdot QE + N_b \cdot QE + N_d + \sigma_{RN}^2}}$$

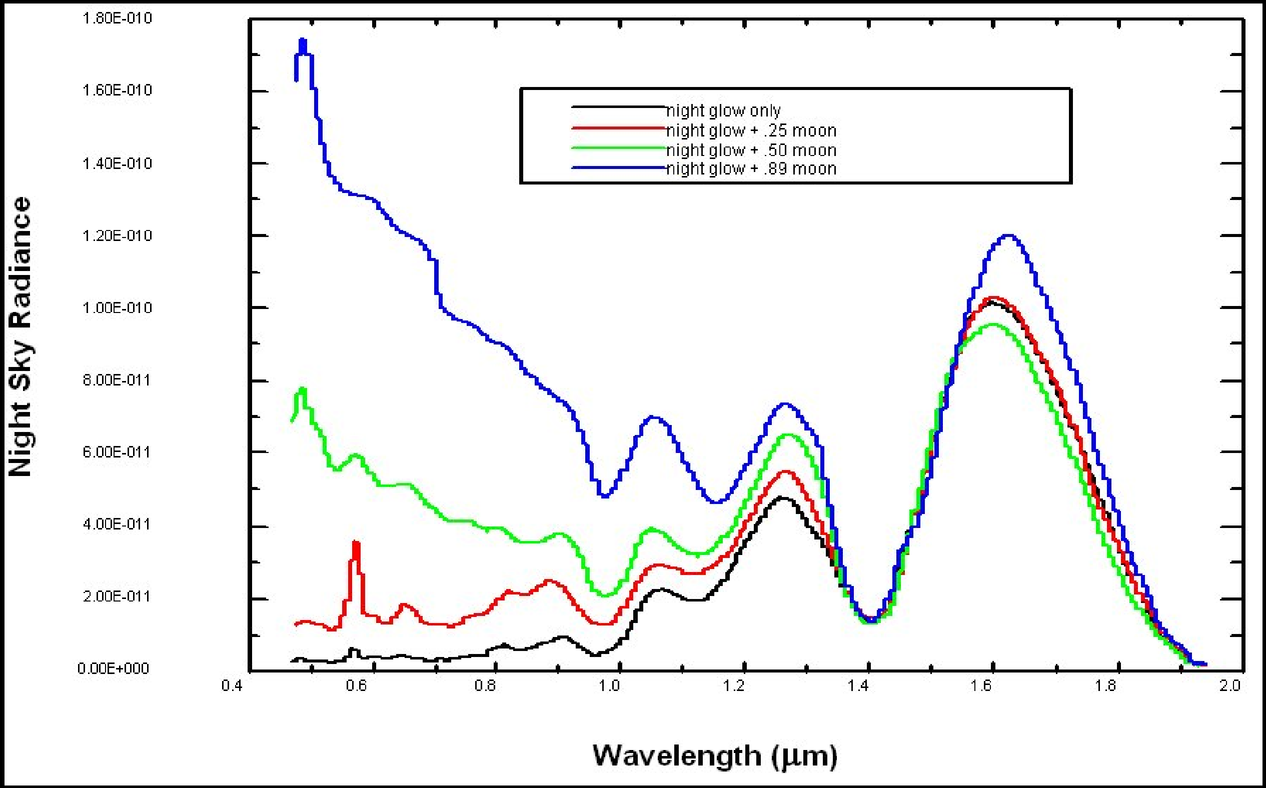
Noise Sources

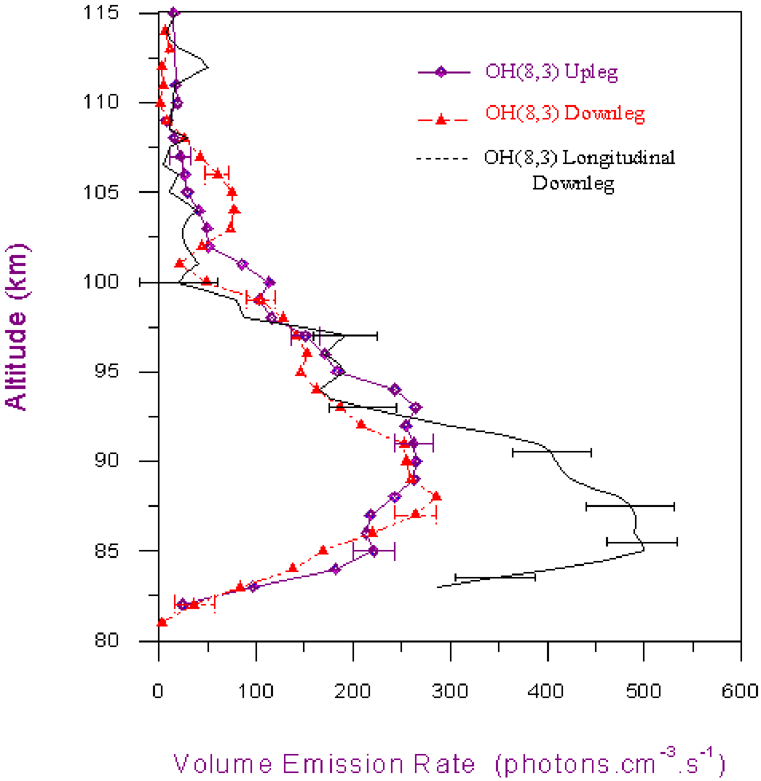
- Background Light
  - Thermal radiation
  - OH airglow
  - Zodiacal Light
- Dark Current

Thermal Radiation



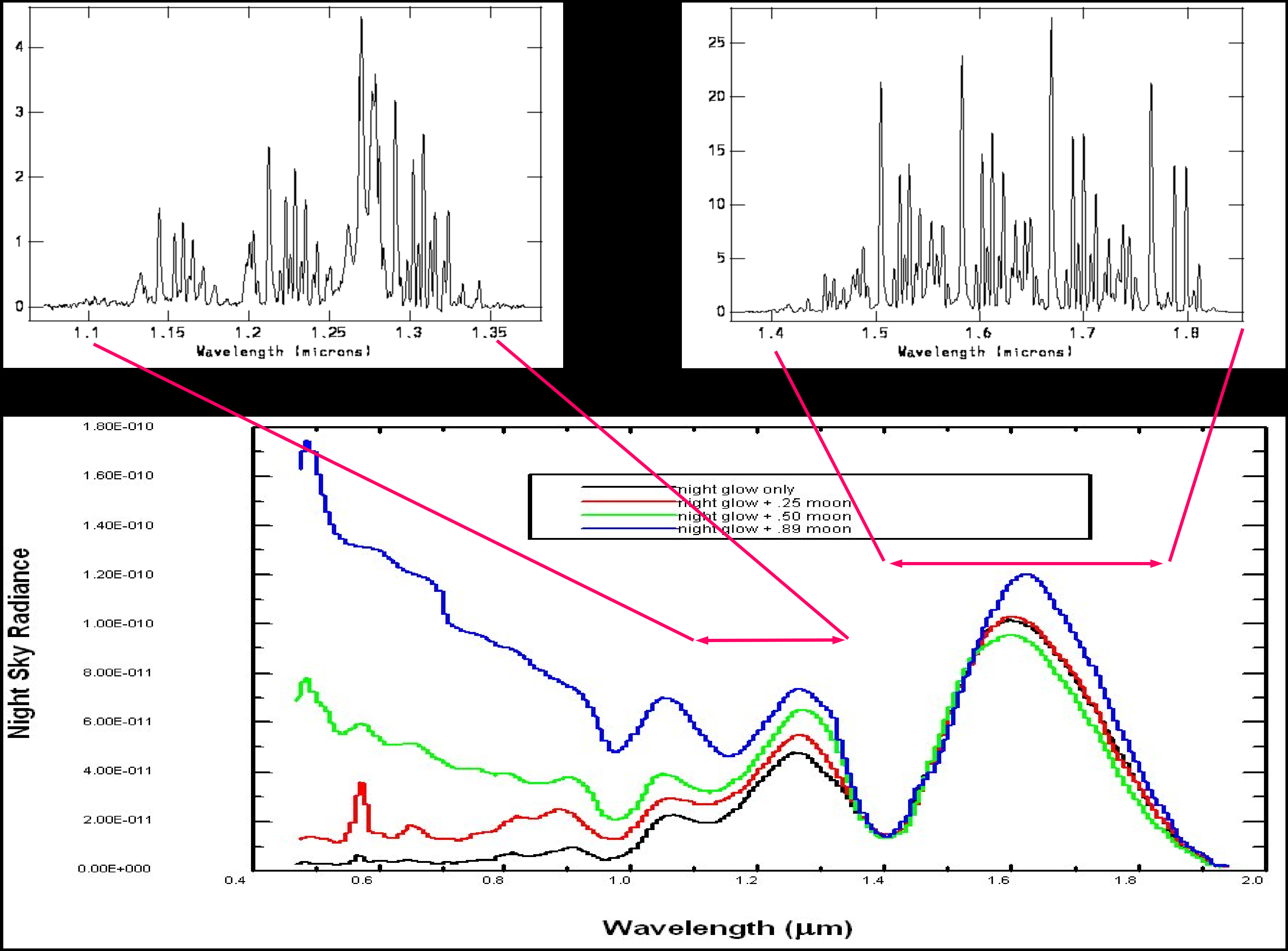
OH airglow (1.0-1.9 μm)



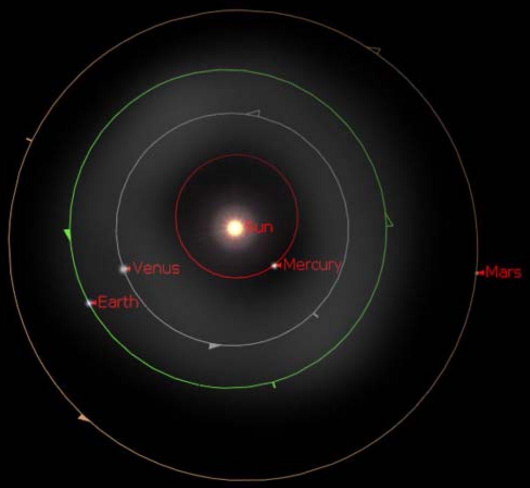


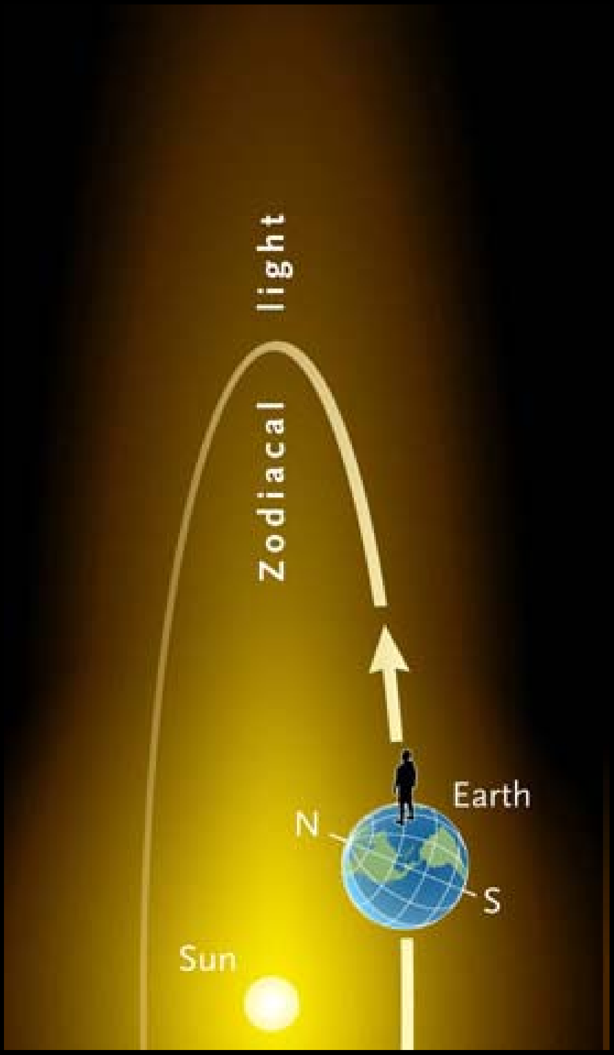
- OH provides a constant source of illumination in the near infrared
- OH created by the reaction: $H + O_3 \rightarrow OH + 0_2$
- Thin emitting layer at ~85 km altitude
- Daytime intensity is 3x nighttime intensity, and intensity drops 40% during the night

OH airglow (1.0-1.9 μm)

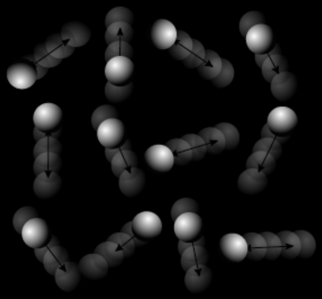


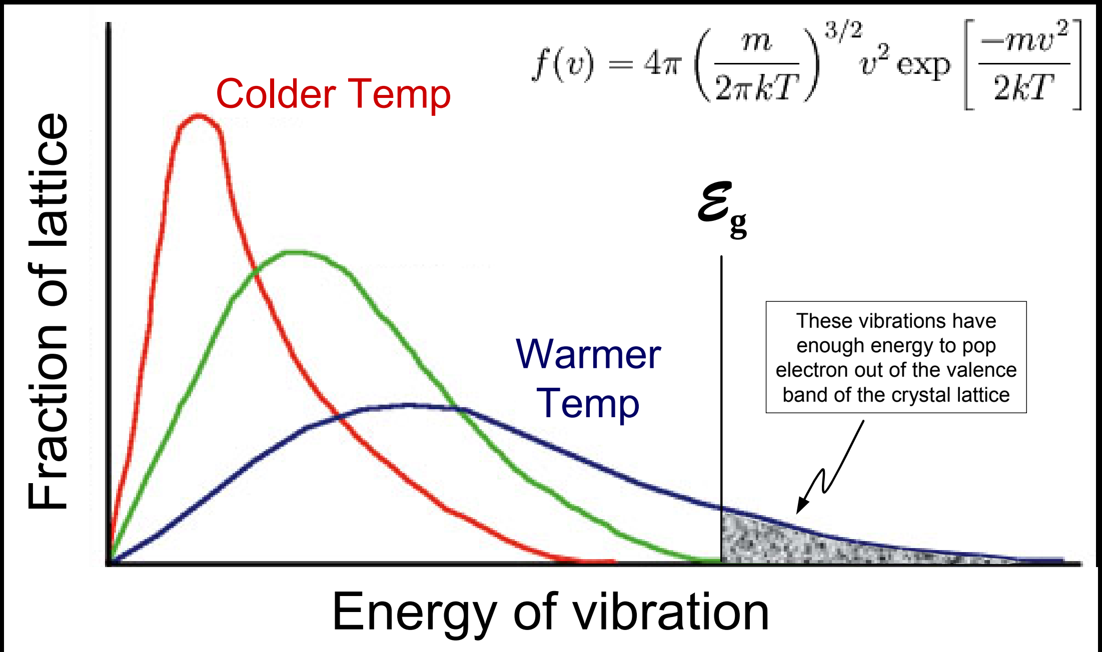
Zodiacal Light – the ultimate limit to faint astronomy



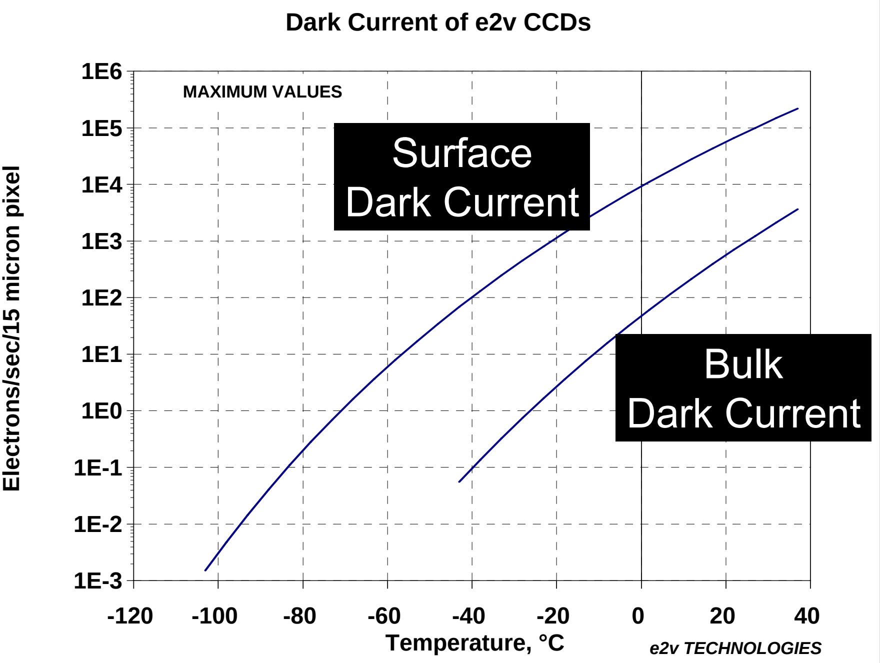


Dark Current



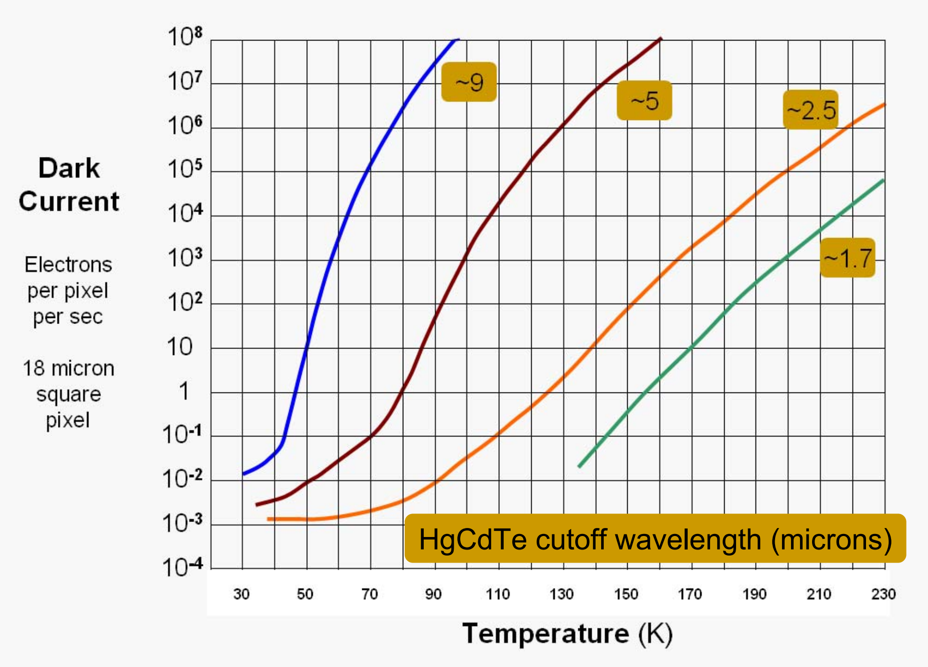


Si CCD



In silicon, dark current usually dominated by surface defects

HgCdTe Hybrid CMOS Sensor



Imaging Detector Parameters

- Wavelength
  - Material
  - Quantum efficiency
- Flux
- Pixel pitch
- Number of pixels
- Frame rate
- Size, weight, power
  - Operating temperature
- Shutter
  - Snapshot (integrate then read, integrate while read)
  - Rolling shutter
  - Duty cycle
- Crosstalk
  - Diffusion
  - Electrical
- Dynamic range
  - Number of bits
- Charge transfer efficiency
  - for CCDs
- Interface
  - Analog control, or digital input
  - Analog output, or ADCs on chip
  - Number of readout ports
- Multiple integration sites per pixel
- Processing on the detector
  - Event driven readout
- Environmental requirements
  - Radiation
  - Vibration
- Storage time / operation lifetime

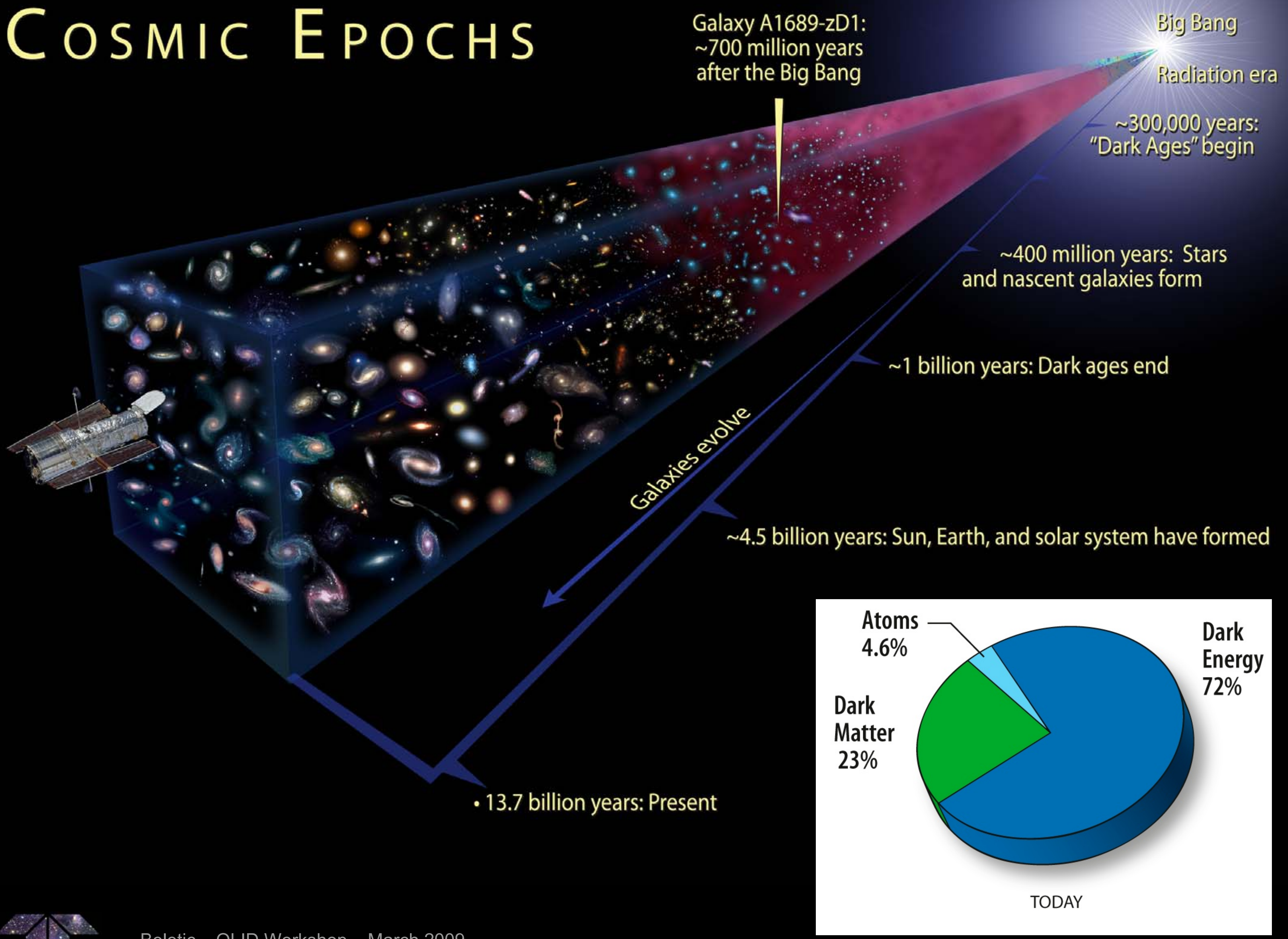
Detectors are a series of trade-offs

Can not optimize all parameters at the same time

Application Areas

- **Measuring the effects of dark energy and dark matter**
  - Expansion history of the universe
  - Detector Challenge: Very long integrations, with very low noise
- **Ground-based adaptive optics**
  - Overcoming the blurring of the Earth’s atmosphere
  - Detector Challenge: High speed, low noise readout
- **Jupiter-Europa mission**
  - Exploring the liquid water world that may be hospitable to life
  - Detector Challenge: High radiation environment

COSMIC EPOCHS



Galaxy A1689-zD1:
~700 million years
after the Big Bang

Big Bang

Radiation era

~300,000 years:
"Dark Ages" begin

~400 million years: Stars
and nascent galaxies form

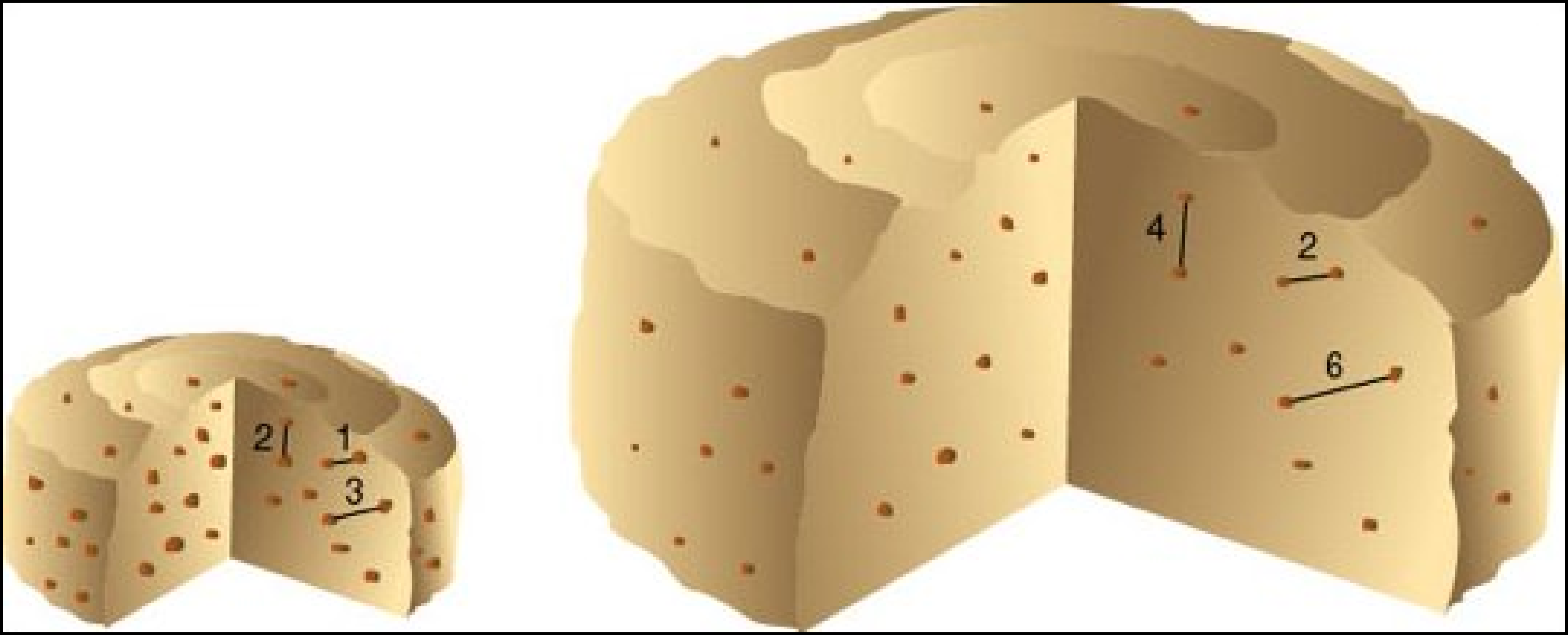
~1 billion years: Dark ages end

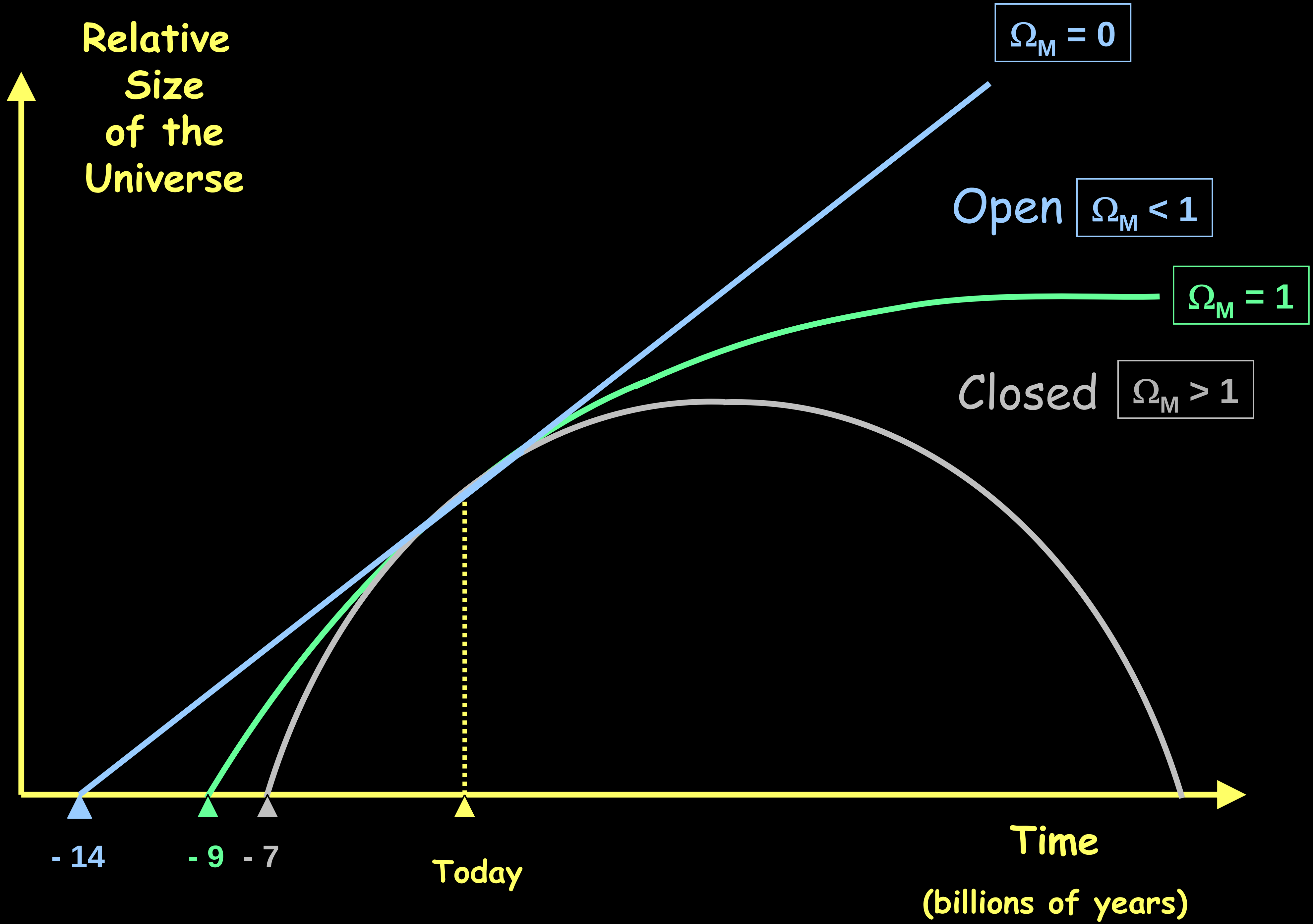
Galaxies evolve

~4.5 billion years: Sun, Earth, and solar system have formed

- 13.7 billion years: Present

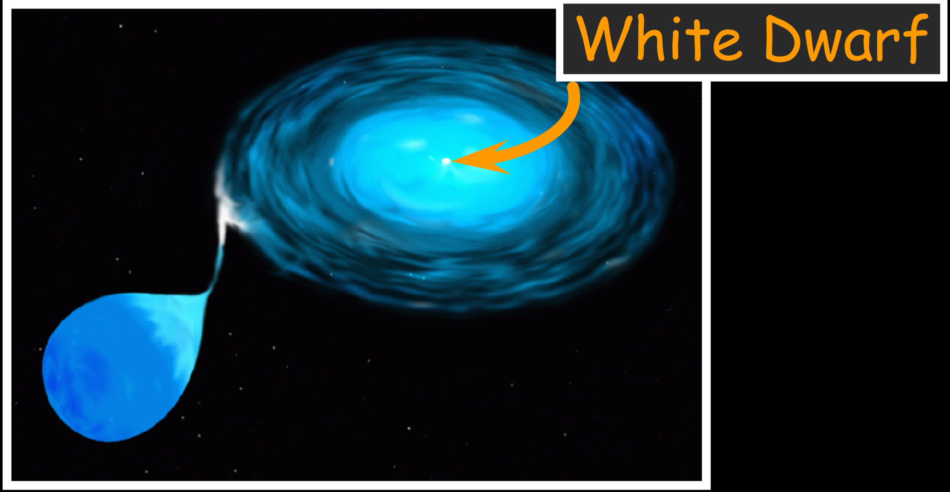
Raisin cake model of expanding Universe

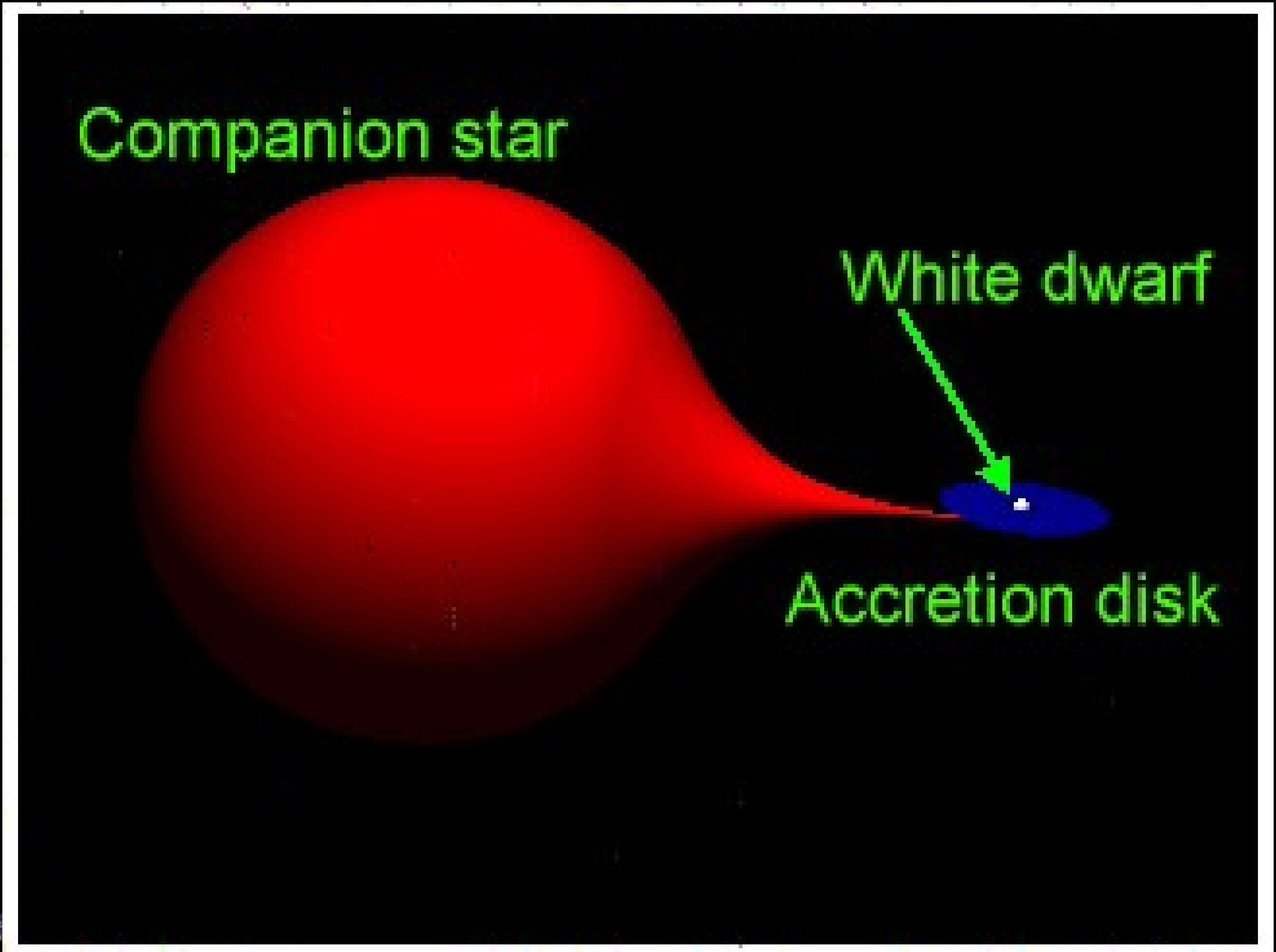



Relative Size of the Universe
$\Omega_M = 0$
Open $\Omega_M < 1$
$\Omega_M = 1$
Closed $\Omega_M > 1$
- 14
- 9
- 7
Today
Time
(billions of years)

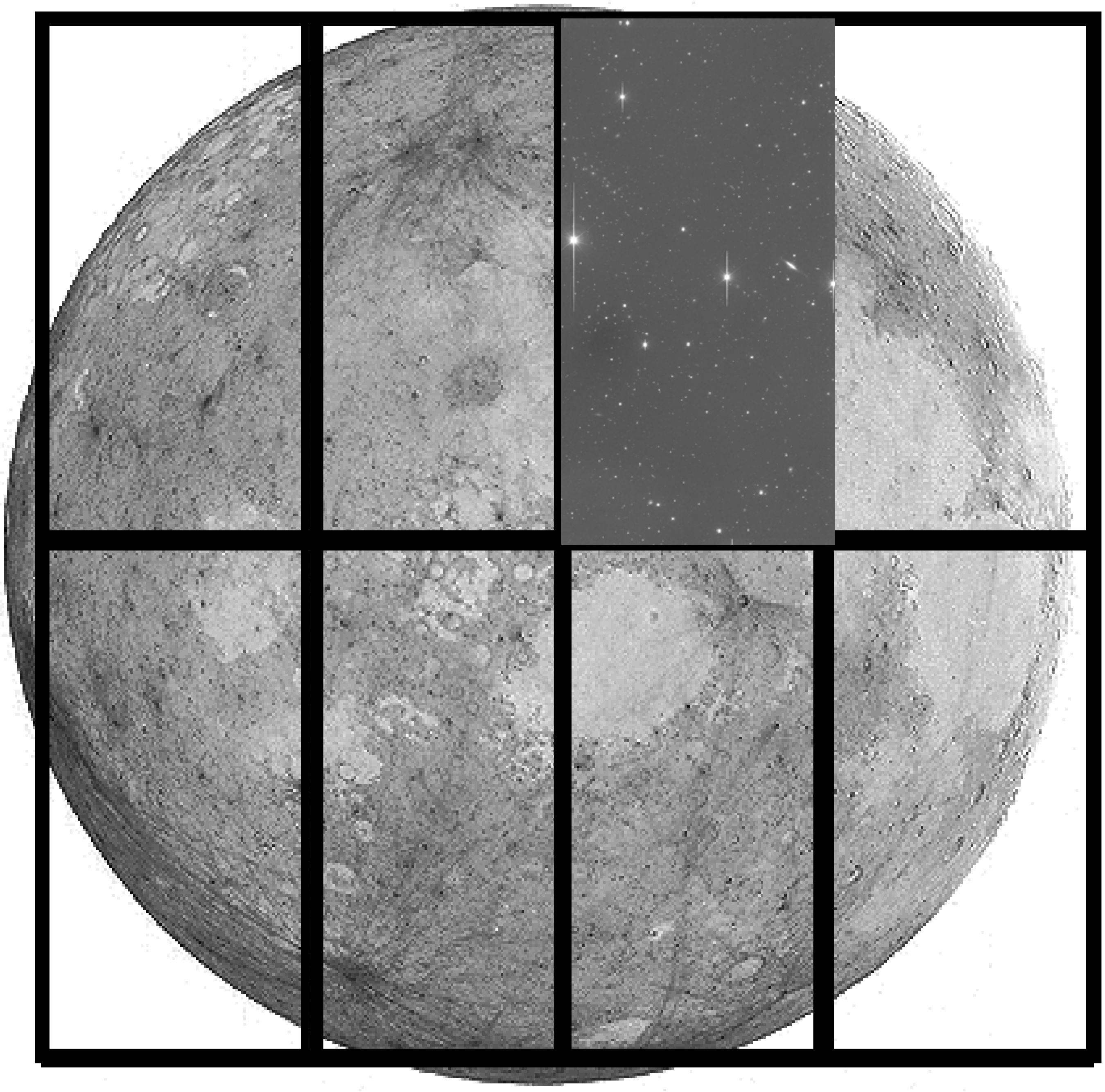
White Dwarfs

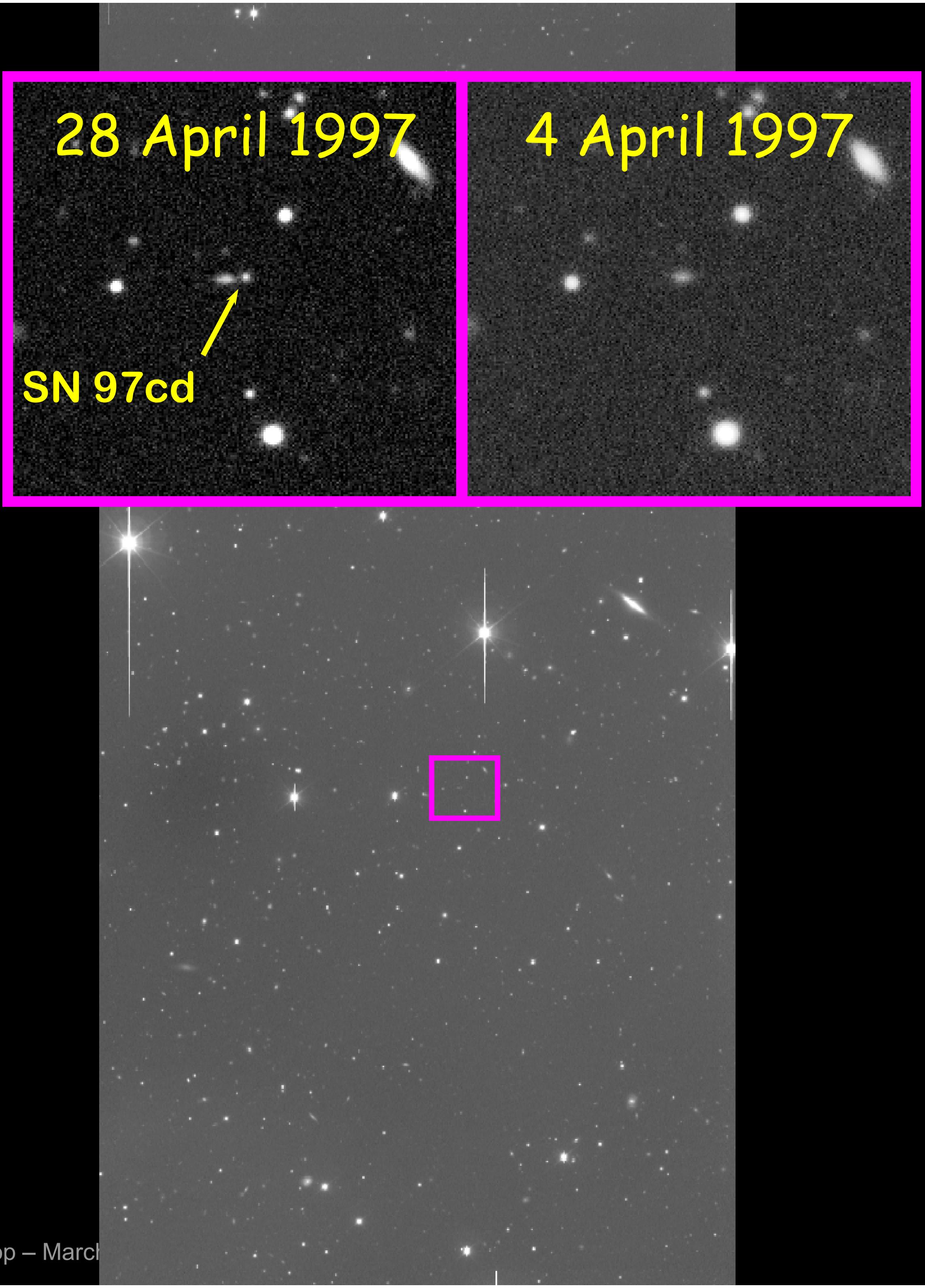
Progenitors of
Type Ia Supernovae

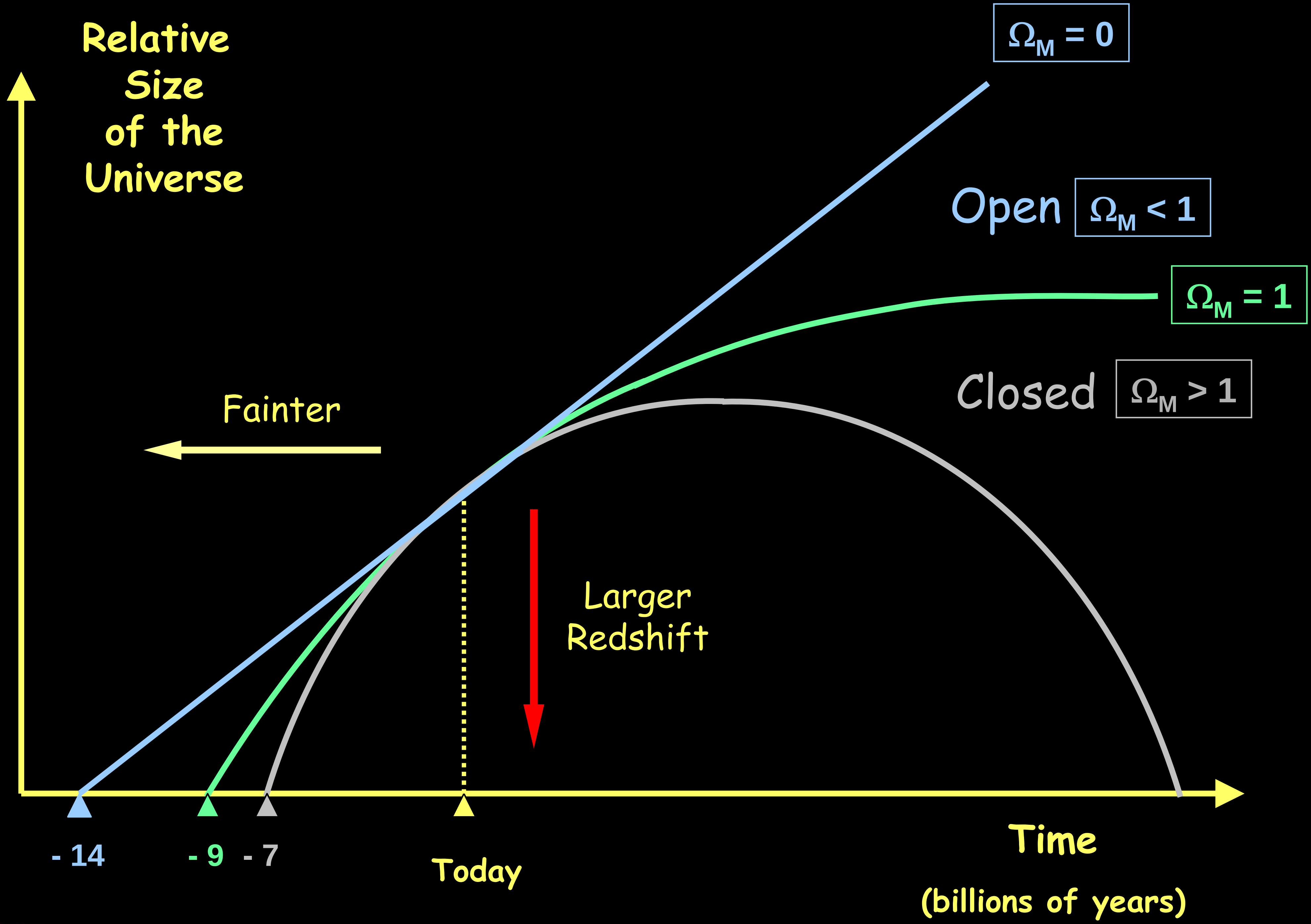


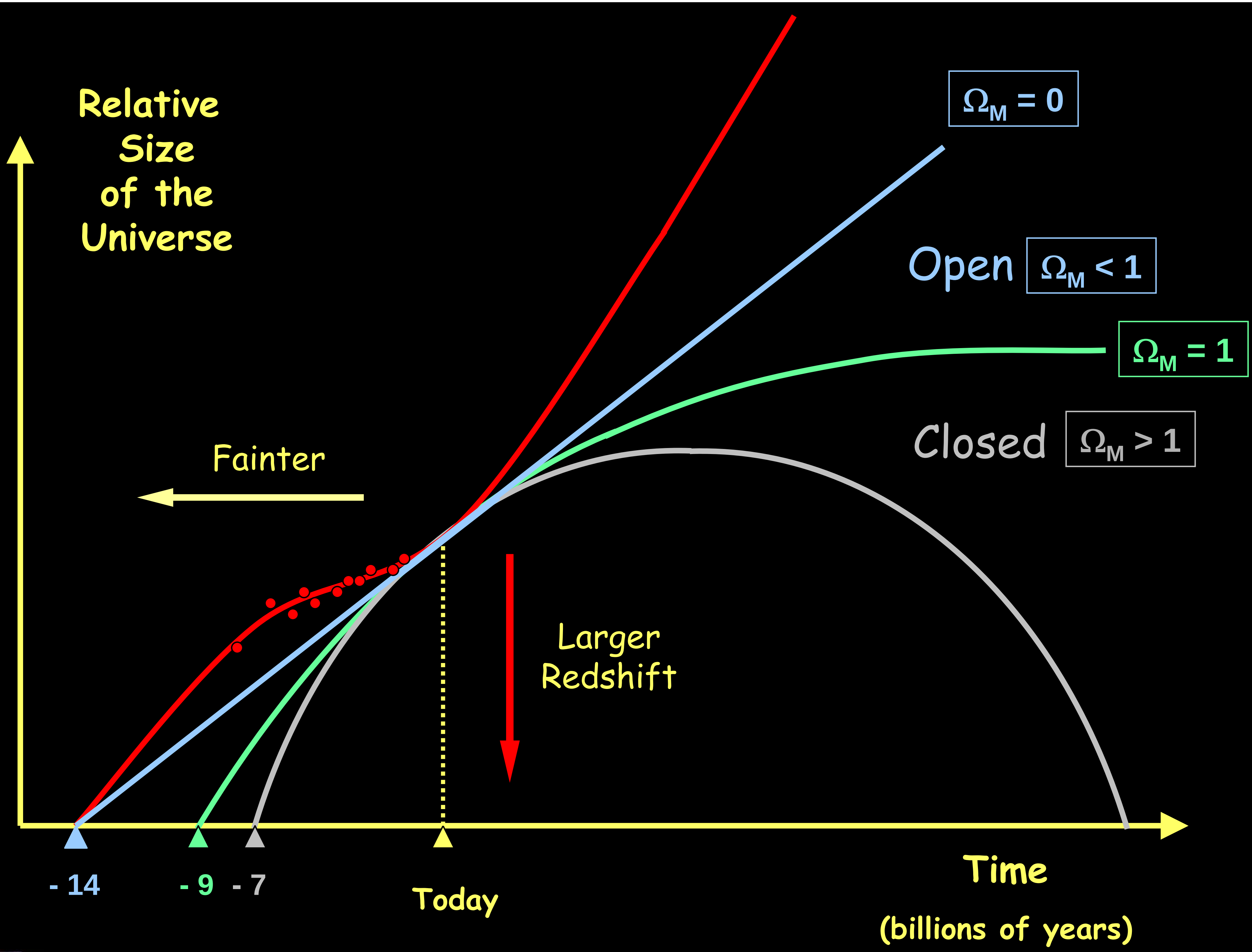


White Dwarf
will explode when
it grows to
1.4 solar masses

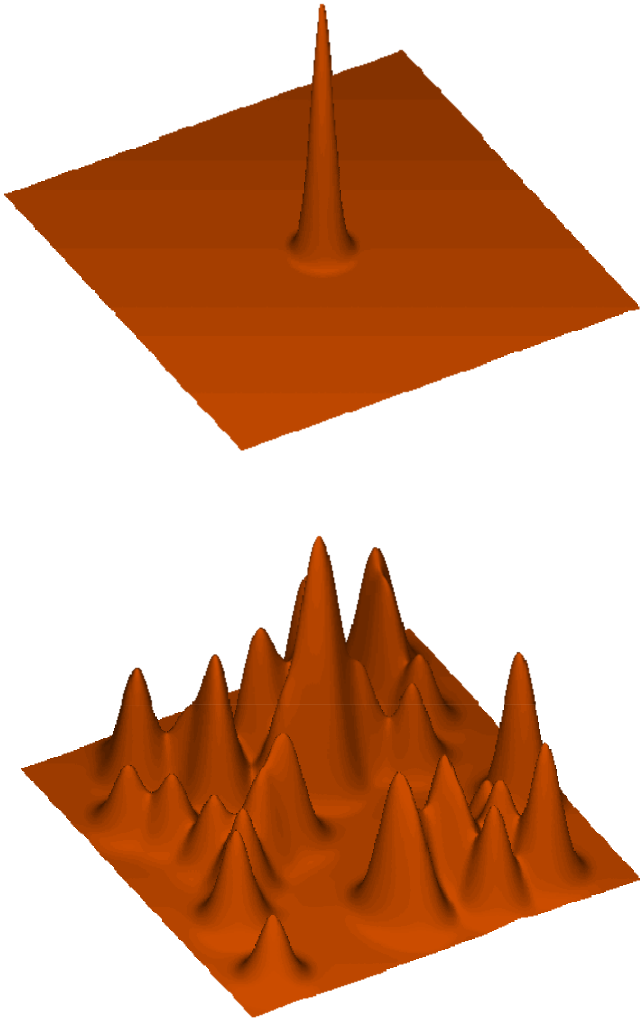


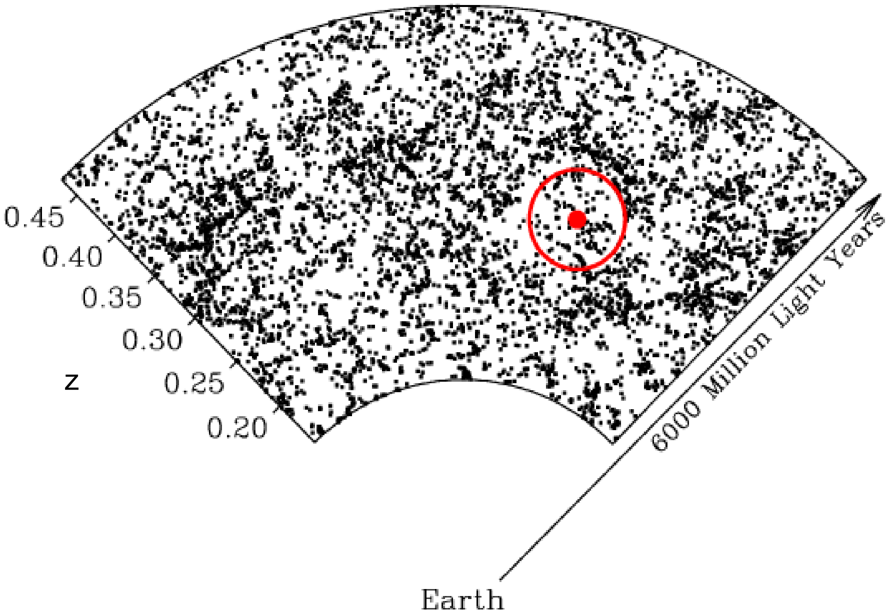

28 April 1997
4 April 1997
SN 97cd


Relative Size of the Universe
$\Omega_M = 0$
Open $\Omega_M < 1$
$\Omega_M = 1$
Closed $\Omega_M > 1$
Fainter
Larger Redshift
- 14
- 9
- 7
Today
Time
(billions of years)


Relative Size of the Universe
$\Omega_M = 0$
Open $\Omega_M < 1$
$\Omega_M = 1$
Closed $\Omega_M > 1$
Fainter
Larger Redshift
- 14
- 9
- 7
Today
Time
(billions of years)

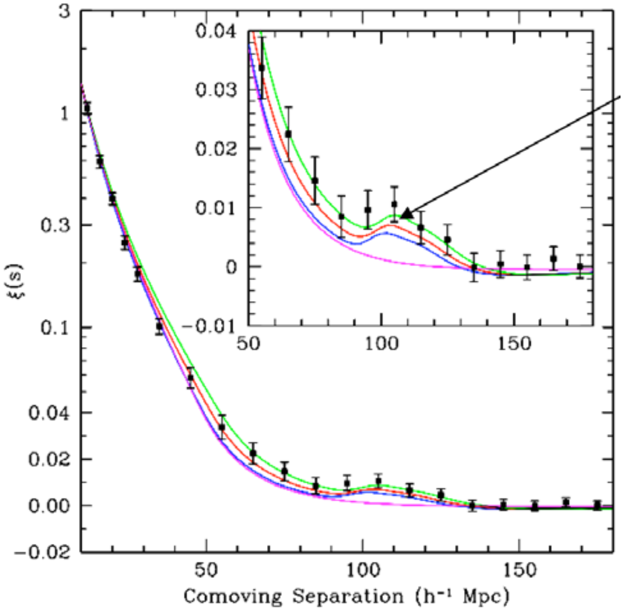
Baryonic Acoustic Oscillations (BAOs)





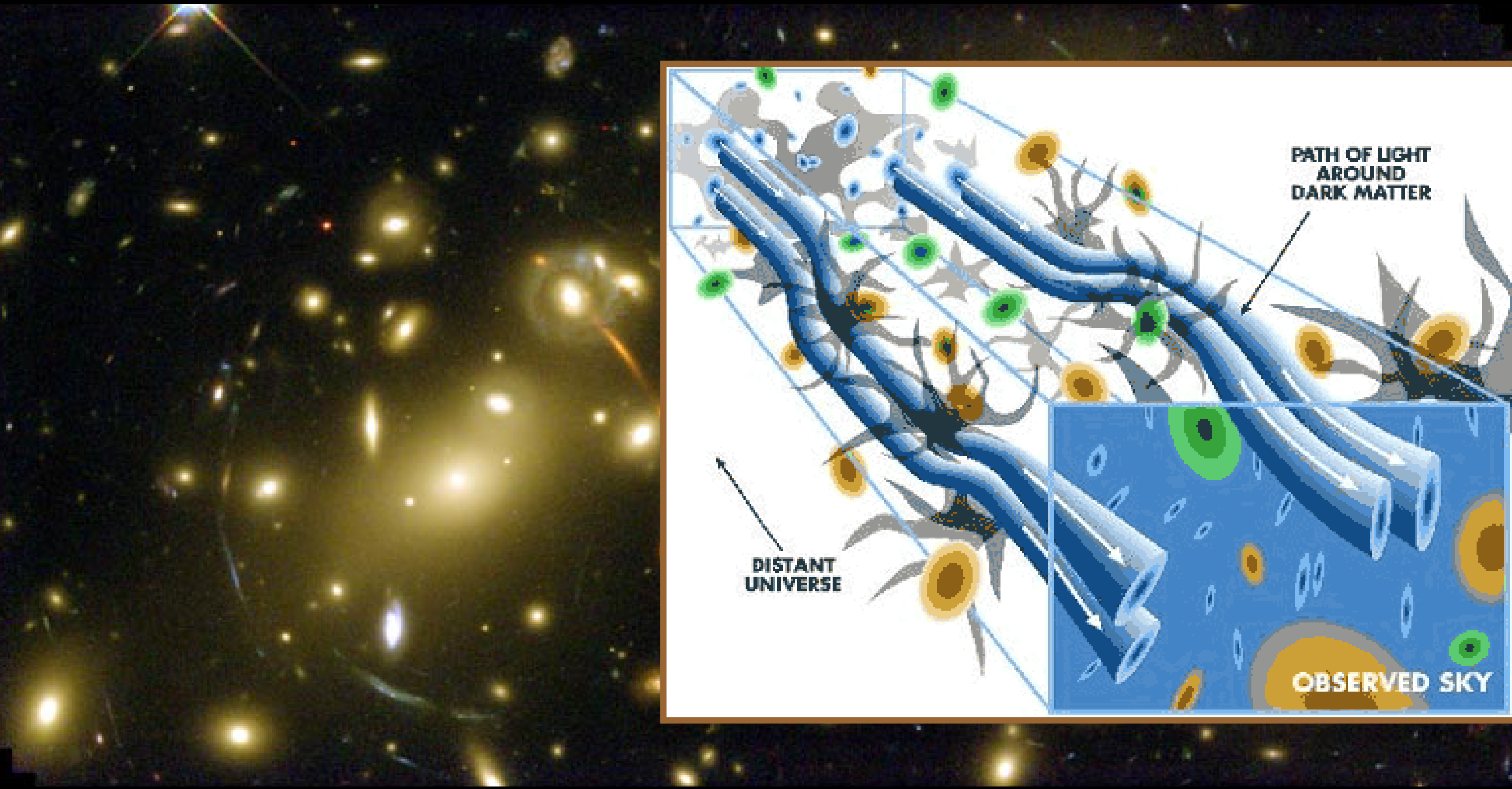
Sloan Digital Sky Survey (2005) provided first measurement of BAO signature.

Was in the local universe ($z<0.5$, 0.5 Gpc^3), with only 47,000 galaxies but it showed the technique works.



Gravitational Lensing

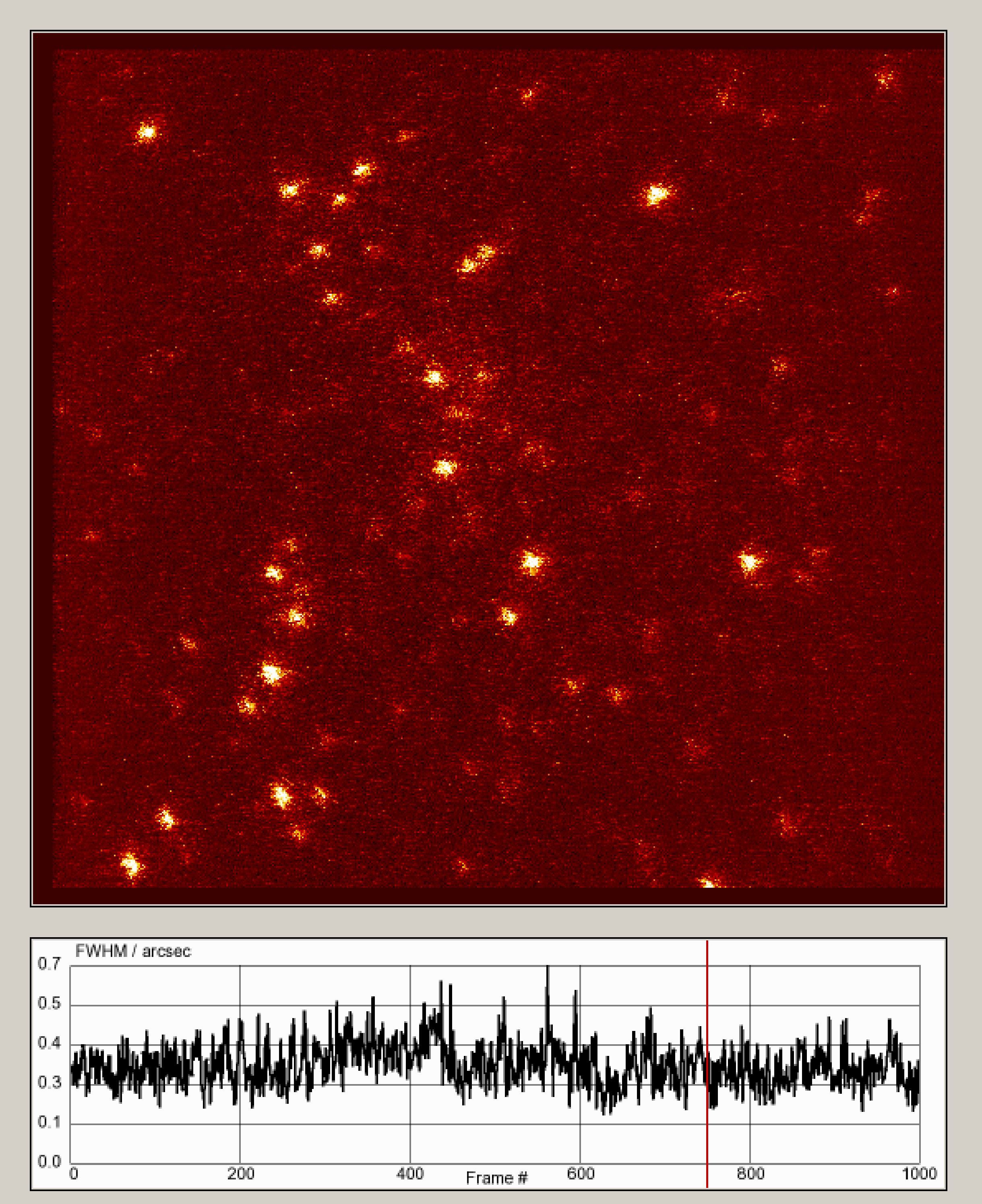
Evidence of Gravity due to dark matter



Dark Energy Mission Detector Requirements

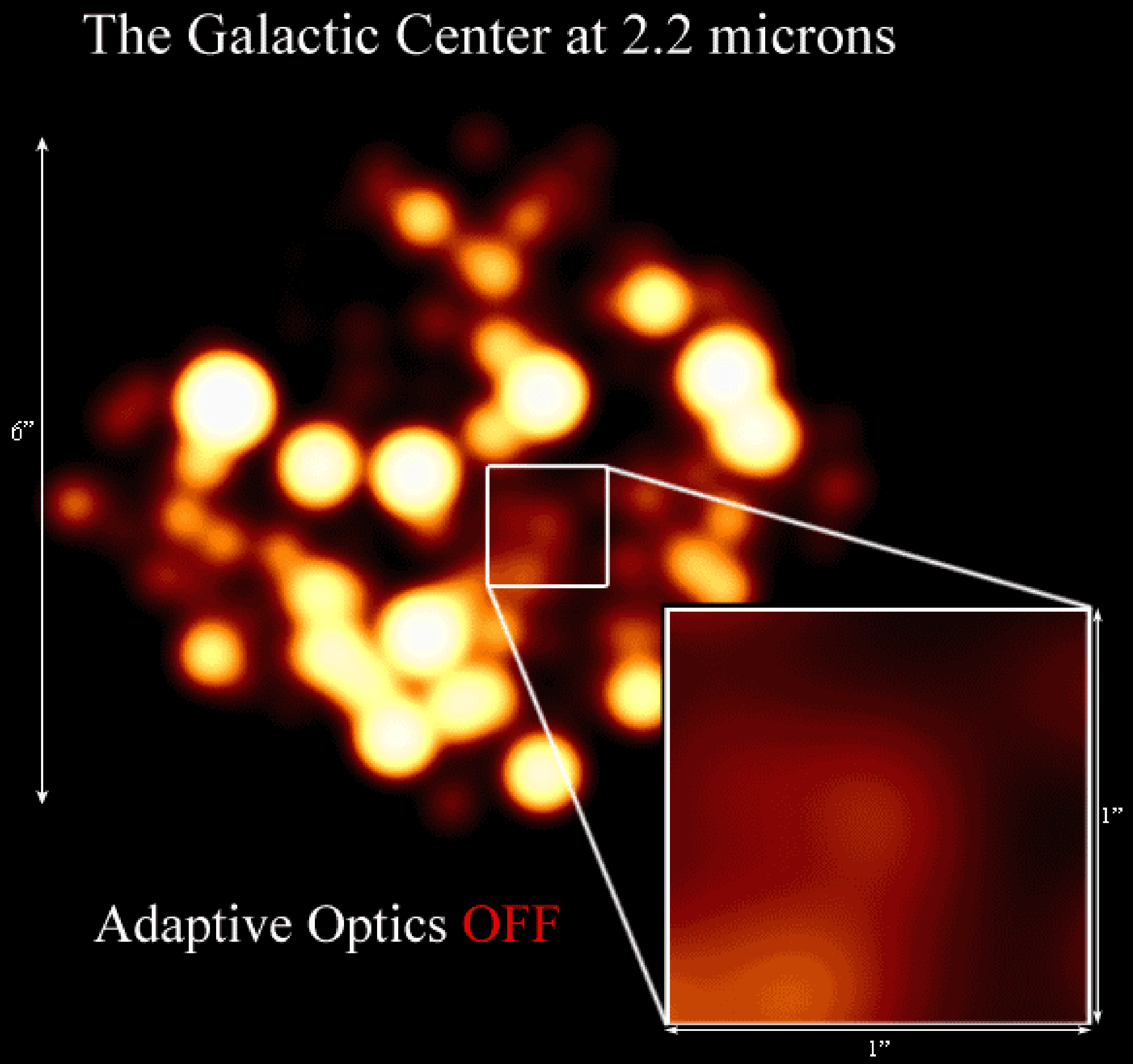
- Measure universe with three methods:
  - Supernovae
  - Baryonic acoustic oscillations
  - Gravitational Lensing
- Detector Requirements
  - High quantum efficiency (>80%)
  - Very low noise
    - Negligible dark current
    - Total noise (readout + dark current) less than zodiacal light
    - Total noise < 7 e-
  - Low power
  - High spatial resolution for gravitational lensing
    - Small pixels for visible light detection
  - **Quantum-limited imaging detectors would be ideal**

Atmospheric Distortions

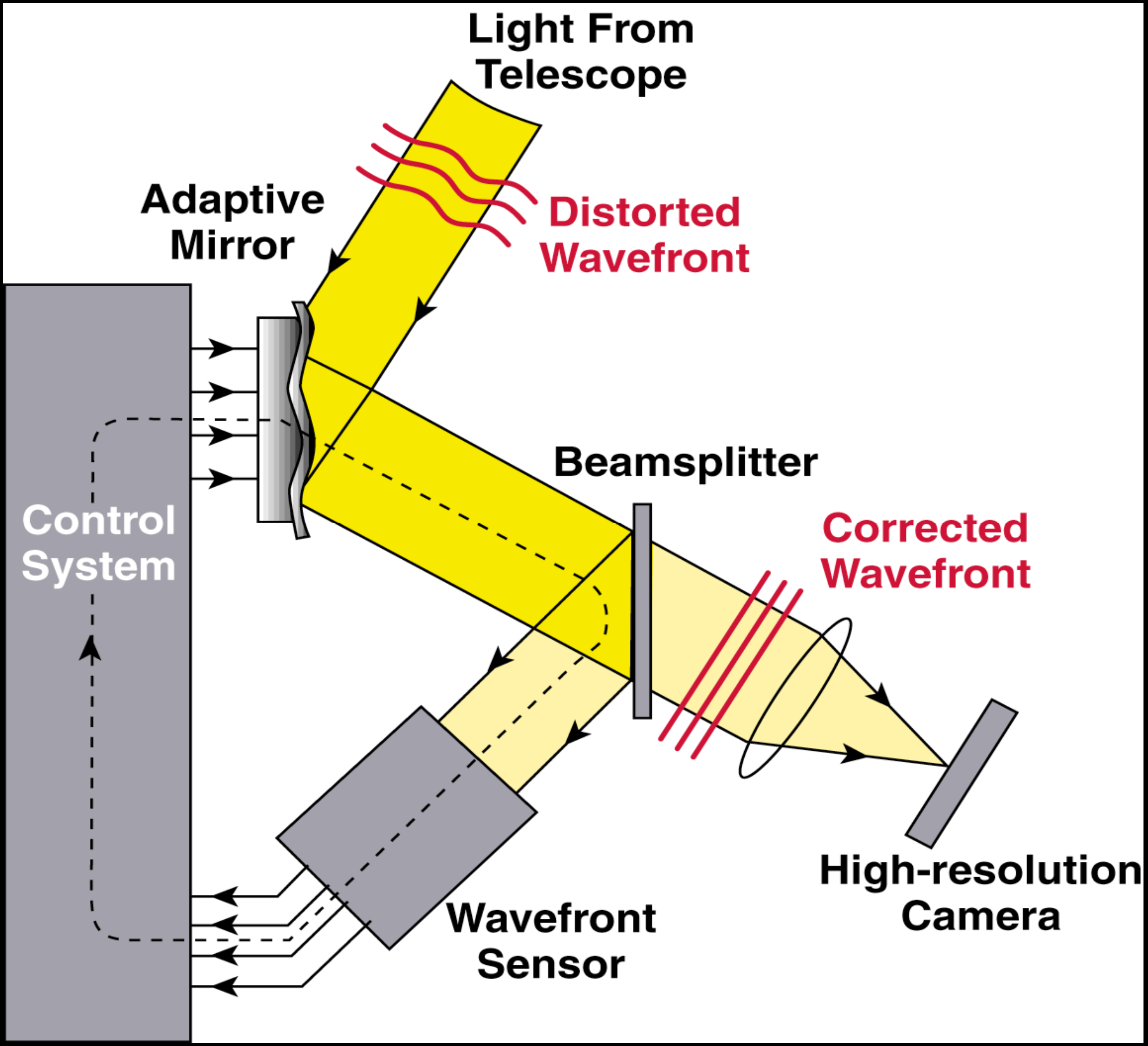


Adaptive Optics Animation

Imaging the galactic center



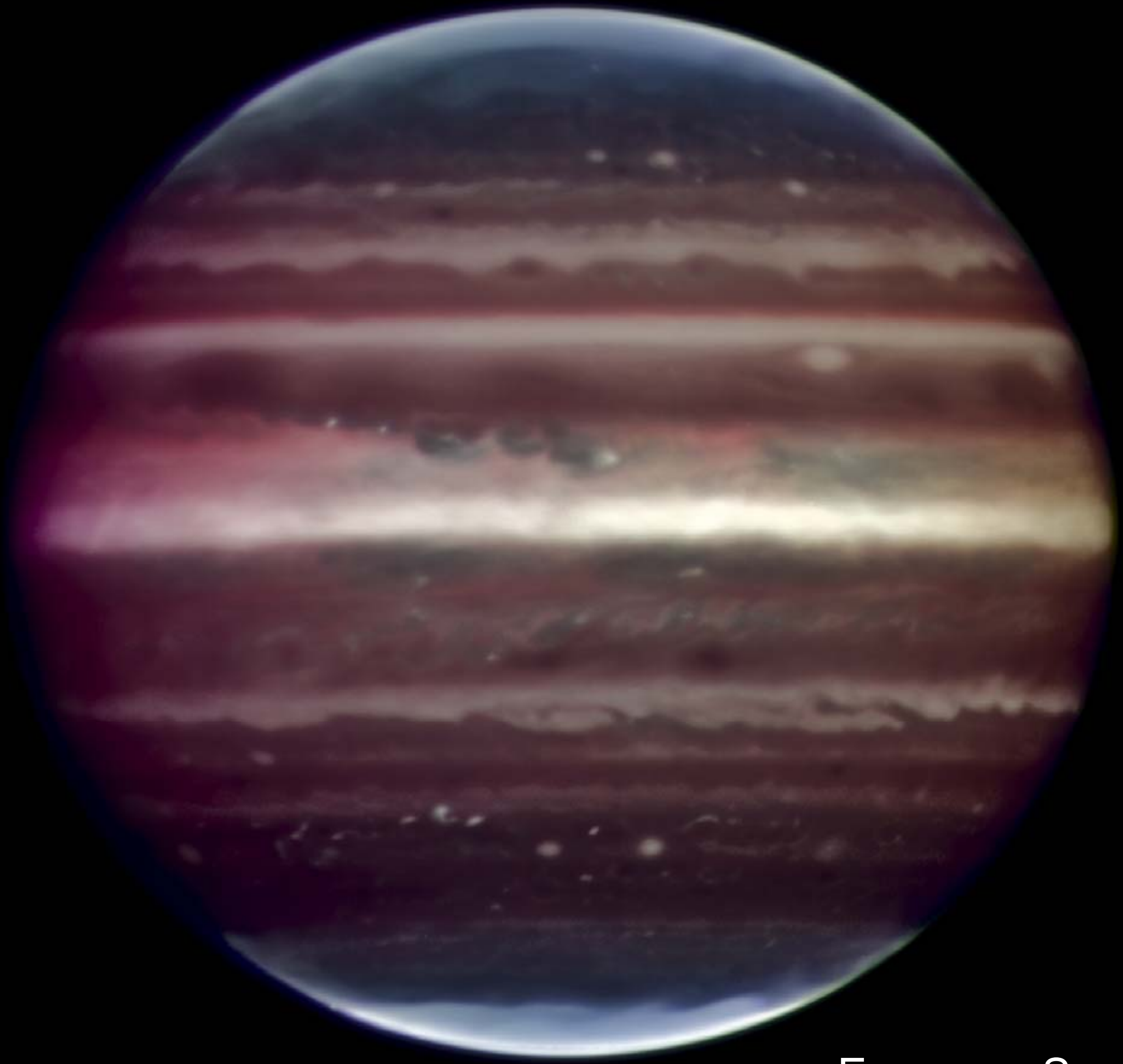
Simplified AO system diagram



Adaptive Optics Wavefront Sensor Detector

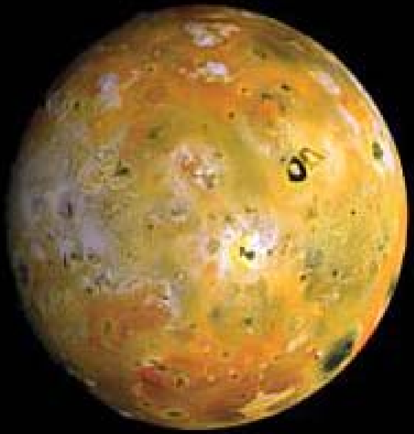
- Requirements
  - High quantum efficiency (>80%)
  - High frame rate: up to 1000 Hz
  - Very low noise
    - Negligible dark current
    - Readout noise less than 5 electrons for infrared
    - Readout noise less than 2 electrons for visible
  - At least 4×4 pixels per subaperture
  - Up to 20×20 pixels per subaperture for elongated laser guide star
    - For the Extremely Large Telescopes (24-m, 30-m, 42-m)
      - 2000×2000 pixels
      - 1000 Hz frame rate
      - < 3 e- noise (~1 e- noise preferred)
  - **Quantum-limited imaging detectors would be ideal**

Image of Jupiter taken by Adaptive Optics



European Southern Observatory

Jupiter’s Galilean Moons



Io

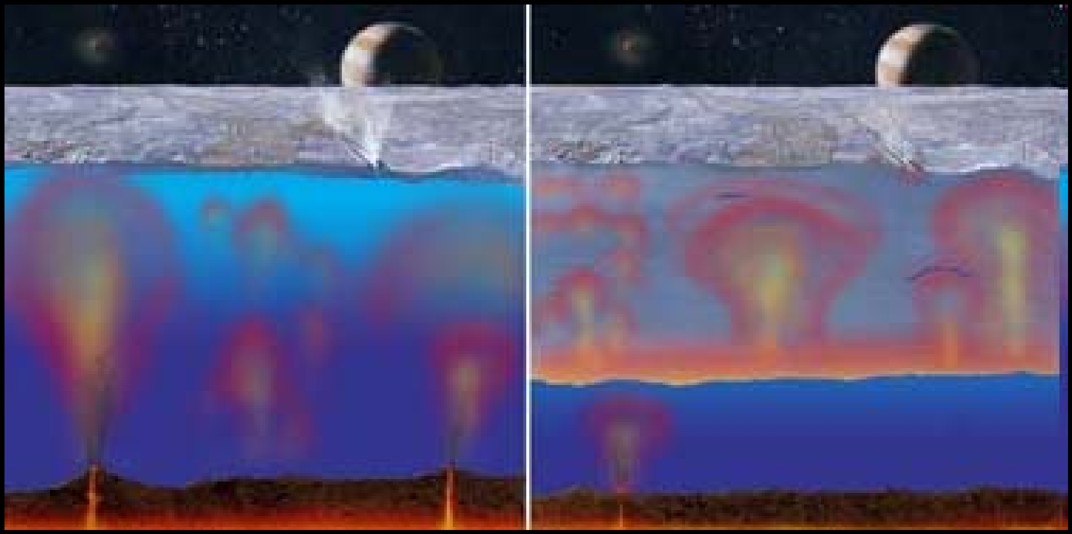
Europa

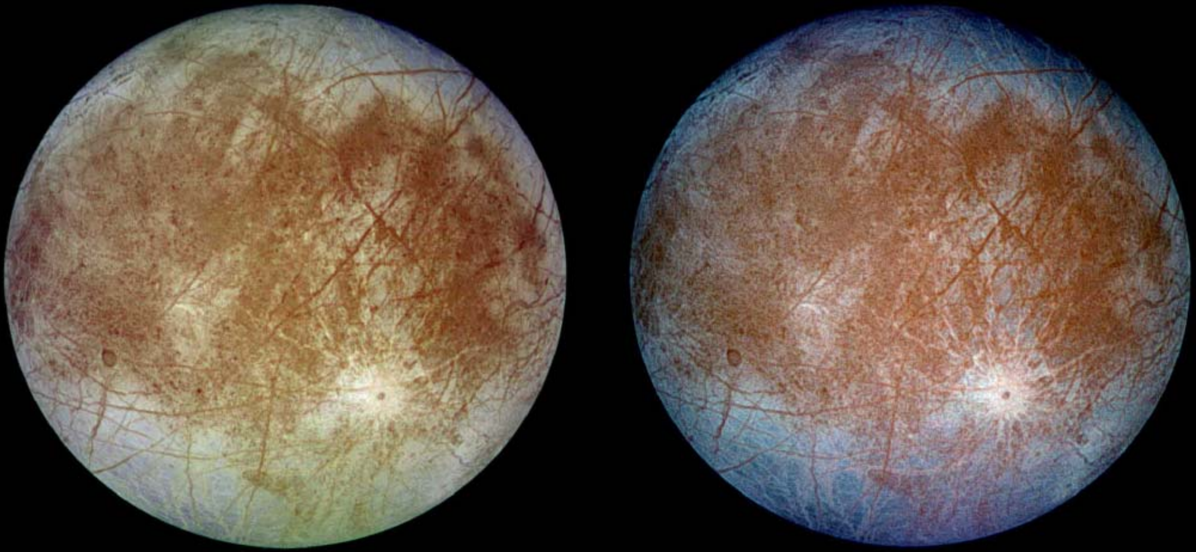
Ganymede

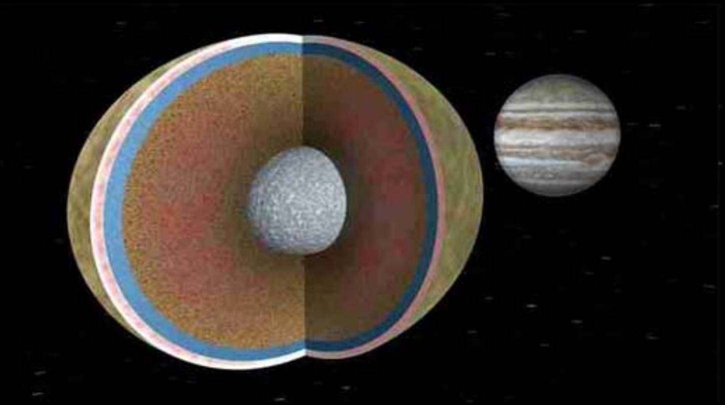
Callisto

Jupiter’s Moon

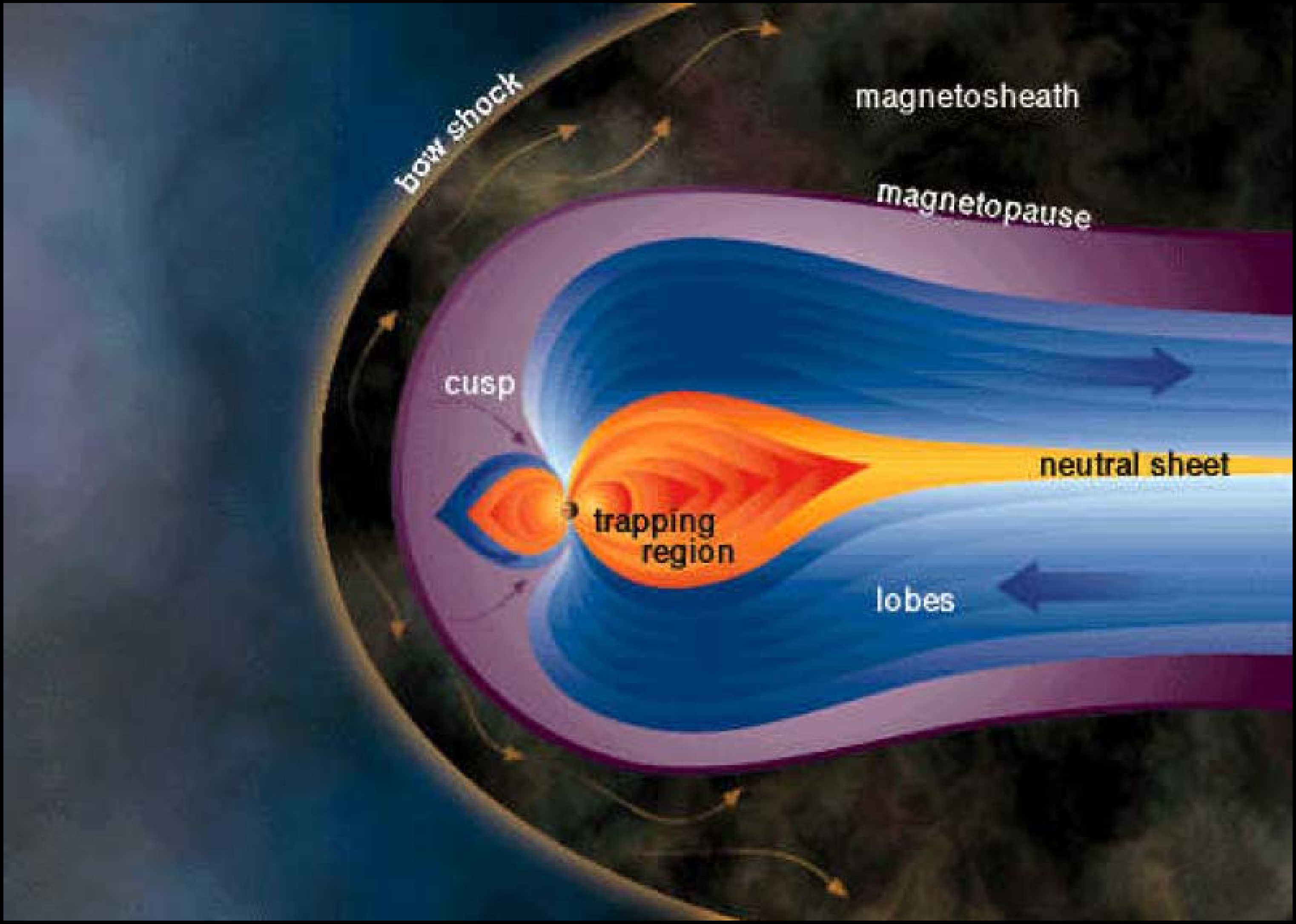
Europa







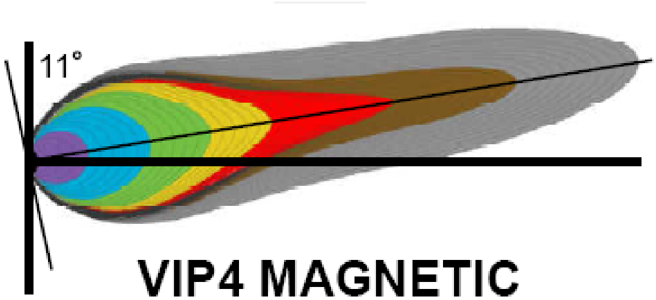
Jupiter's Magnetosphere



Jupiter's Magnetosphere

Characteristics	***Earth***	***Jupiter***
Equatorial radius (km)	6.38×10^3	7.14×10^4
Magnetic moment (G-cm^3)	8.1×10^{25}	1.59×10^{30}
Rotation period (hr)	24.0	10.0
Aphelion/perihelion (AU)	1.01/0.98	5.45/4.95

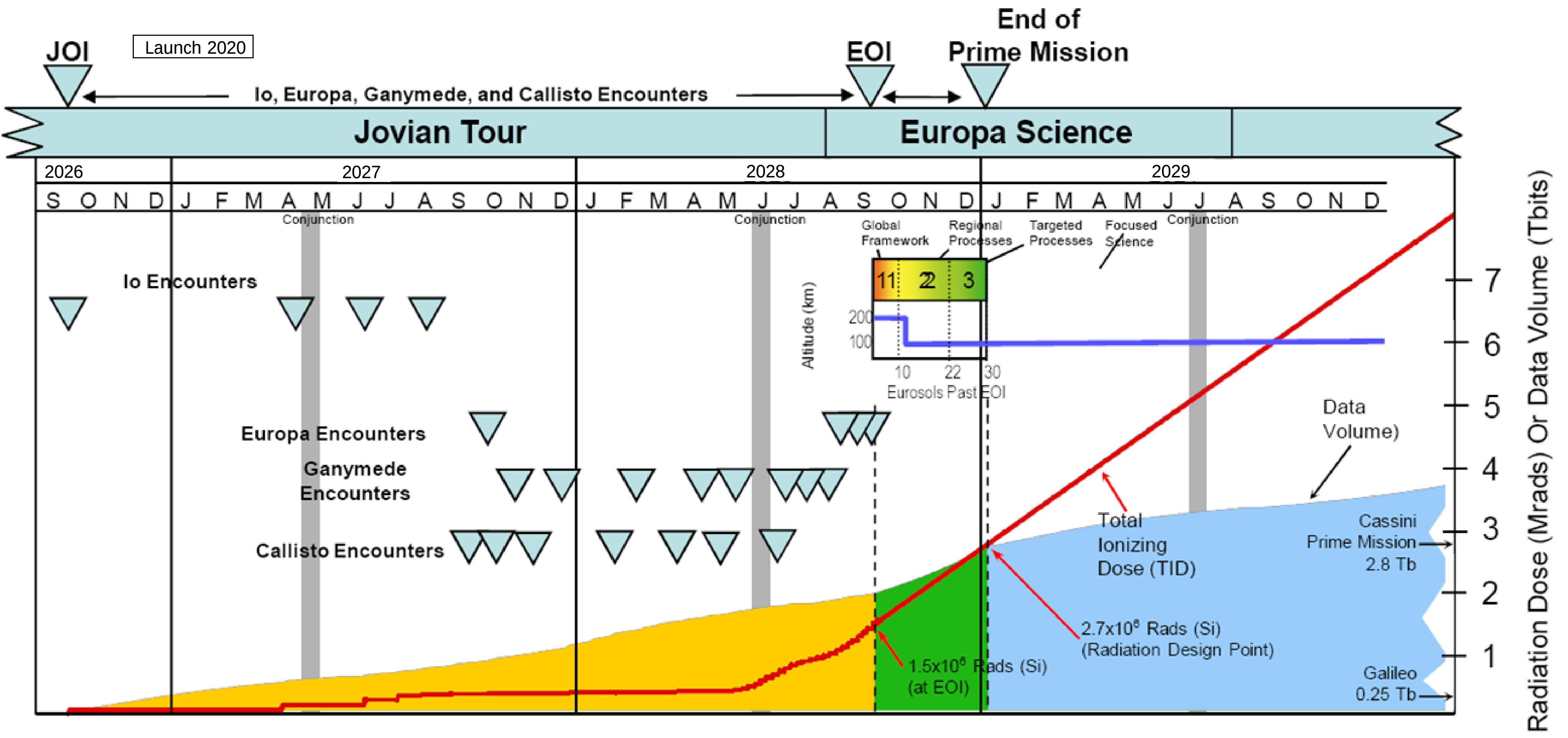
- Jupiter is roughly 10 times the size of the Earth while its magnetic moment is 2×10^4 larger.
- As the magnetic field at the equator is proportional to the magnetic moment divided by the cube of the radial distance, the Jovian magnetic field is proportionally 20 times larger than the Earth's.



VIP4 MAGNETIC FIELD MODELS

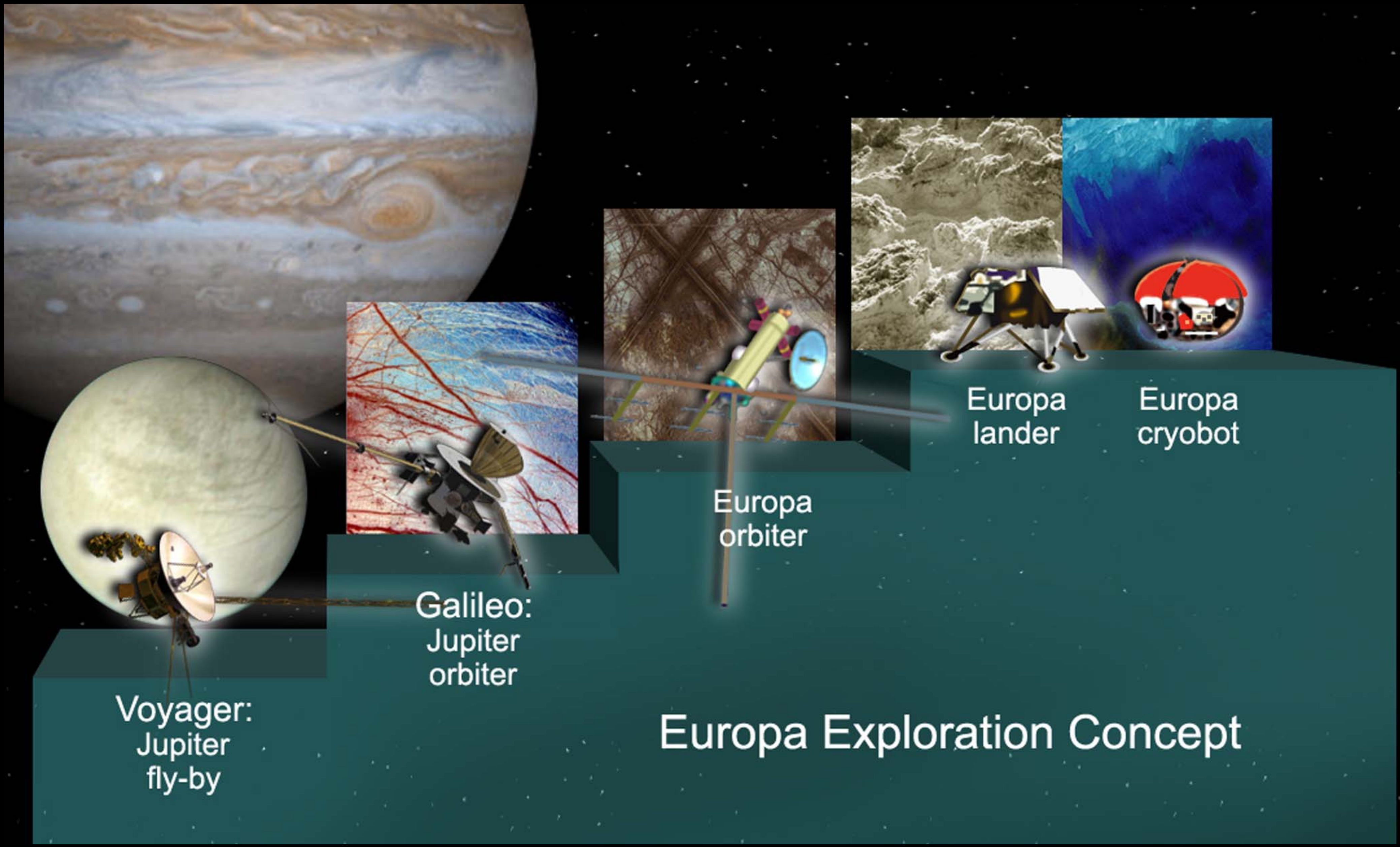
- The energy and flux levels of trapped particles in the Jovian system can be much higher than those at the Earth or in the interplanetary space.

Possible Jupiter / Europa Mission Timeline



Jupiter-Europa Mission

- Special detector requirements
  - Tolerance to high levels of radiation (Mrad level)
  - Planetary protection
    - Ability to “bake out” the detector to kill germs, so no contamination of Europa when orbiter hits surface at end of the mission



Voyager: Jupiter fly-by

Galileo: Jupiter orbiter

Europa orbiter

Europa lander

Europa cryobot

Europa Exploration Concept